DRESSING FOR ALTITUDE

U.S. Aviation Pressure Suits–Wiley Post to Space Shuttle

DENNIS R. JENKINS

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ISBN 978-0-16-090110-2

9 780160 901102 90000

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National Aeronautics and Space Administration

Headquarters
300 E Street SW
Washington, DC 20546

www.nasa.gov

NASA SP-2011-595

Library of Congress Cataloging-in-Publication Data

Jenkins, Dennis R.
Dressing for altitude : U.S. aviation pressure suits-- Wiley Post to space shuttle / Dennis R. Jenkins.
p. cm. -- (NASA SP ; 2011-595)
ISBN 978-0-16-090110-2
1. Pressure suits--United States. 2. Space suits--United States. I. Title.
TL697.P7J46 2012
629.134'43--dc23
2012004448

iii NASA

v Foreword
vii Jack Bassick Biography

ix Preface
xii Acknowledgments
xiii Dedication

15 1: Introduction
15 Horror Vacui
18 Structure of the Atmosphere
20 Atmospheric Pressure
22 Physiological Issues of High-Altitude Flight

25 2: Mark Ridge, Wiley Post, and John Kearby
25 Early Pressure Suits
28 Wiley Post and the Winnie Mae
35 International Efforts
41 Aeromedical Pioneers
43 The U.S. Army Rediscovers the Pressure Suit
69 Summary

71 3: Acceleration Protection
72 The Physiology of Acceleration
74 Human Centrifuges
80 The Beginning of an Idea
83 Australian Cotton Aerodynamic Anti-G Suit
86 Canadian Franks Flying Suit
89 The Americans
92 Berger Brothers
96 The Worcester Connection
105 Cutaway Suits
109 Postwar Suits
110 TLSS and COMBAT EDGE
116 ATAGS and the F-22
118 Rediscovering the Progressive Arterial Occlusion Suit
119 Summary

121 4: Partial-Pressure Suits
121 Pressure Breathing
125 S-1—Genesis of the Partial-Pressure Suit
135 S-2 and T-1—Production Partial-Pressure Suits
141 MC-1—Featherweight Suit
146 MB-1 and MB-2—Ill-Fated Air Defense Command Suits
147 MC-3 and MC-4—Dragon Ladies and Hustlers
161 MC-3A Specials—Manhigh, Excelsior, and Stargazer
165 CSU-2/P—Attempt to Improve the MC-4
167 C-1A and C-4—Navy Capstan Suits
168 CSU-4/P and CSU-5/P—Bladders Only
173 HAPS—NASA Dryden High-Altitude Protective System

179 5: Navy Full-Pressure Suits
215 Russell Colley, Again
218 Mark I
220 Mark II
222 Mark III
227 Mark IV
231 Mark IV Suits for Strato-Lab
233 Mark V
233 Project Mercury Spacesuits

237 6: Air Force Full-Pressure Suits
241 Lines of Nonextension
243 MC-2—A New Beginning
262 A/P22S-2—Production USAF Full-Pressure Suits
264 Sidebar: The Evolving Pressure Suit Depot
279 A/P22S-3—A Navy Suit for the Air Force
283 A/P22S-4 and A/P22S-6—Evolving the Concept
293 Boyle's Law Suit
295 PHAFO—The StillBorn High-Altitude Flying Outfit

301 7: Special Project Suits
301 S901 and S970—Suits for Oxcart
316 S-100—Hybrid Suit for the Original U-2
322 S901J—Initial Suit for Senior Crown
334 S1010—A Suit for the Dragon Lady
339 S1030—Improved Senior Crown Suits
348 S1031—Improved Dragon Lady Suits
349 S1031C—Common Suit
350 S1034—Improved Common Suit
362 Sidebar: The Shrinking Industrial Base

365 8: Space Shuttle Pressure Suits
366 ISSA and EIS—Stillborn Space Shuttle Suits
374 S1030A—Ejection Escape System (EES) Suits
378 LEH—Launch Entry Helmet
382 S1032—Launch Entry Suits (LES)
399 S1035—Advanced Crew Escape Suit (ACES)
410 Comparing Columbia to an SR-71 Breakup

413 Endnotes

471 Index

NASA

NASA

Since its earliest days, flight has been about pushing the limits of technology and, in many cases, pushing the limits of human endurance. The human body can be the limiting factor in the design of aircraft and spacecraft. Humans cannot survive unaided at high altitudes. There have been a number of books written on the subject of spacesuits, but the literature on the high-altitude pressure suits is lacking. This volume provides a high-level summary of the technological development and operational use of partial- and full-pressure suits, from the earliest models to the current high-altitude, full-pressure suits used for modern aviation, as well as those that were used for launch and entry on the Space Shuttle. The goal of this work is to provide a resource on the technology for suits designed to keep humans alive at the edge of space. Hopefully, future generations will learn from the hard-fought lessons of the past.

NASA is committed to the future of aerospace, and a key component of that future is the workforce. Without these men and women, technological advancements would not be possible. Dressing for Altitude is designed to provide the history of the technology and to explore the lessons learned through years of research in creating, testing, and utilizing today's high-altitude suits. It is our hope that this information will prove helpful in the development of future suits. Even with the closeout of the Space Shuttle and the planned ending of the U-2 program, pressure suits will be needed for protection as long as humans seek to explore high frontiers.

The NASA Aeronautics Research Mission Directorate is committed to the training of the current and future aerospace workforce. This book and the other books published by the NASA Aeronautics Research Mission Directorate are in support of this commitment. Hopefully, you will find this book a valuable resource for many years to come.

Tony Springer
Lead, Communications and Education
NASA Aeronautics Research Mission Directorate

FOREWORD

Foreword

The definitive story of pressure suits began long ago and has involved a great many people to obtain the present state of the art as this book well chronicles. Many of these people were visionaries who anticipated the need for such highly specialized equipment long before it could actually be employed in any practical application. A remarkable number of pressure suit designs were developed early on, the vast majority of which never made it into flight, amounting to little more than science projects. Nonetheless, these early "experiments" informed later work, which led to practical pressure suits when they were needed for high-altitude flight.

All successful pressure suit designs have been the result of efforts to address a specific need in a specific application, beginning with Wiley Post's pressure suit designed for use in his Lockheed Vega, the *Winnie Mae*. Long considered the granddaddy of modern pressure suits, interestingly, Post's suit was employed principally for protection from hypoxia rather than decompression sickness, since his Lockheed Vega's altitude ceiling was 50,000 feet.

A key ingredient to successful pressure suit programs has been the close collaboration between vehicle designers, pressure suit designers, and, most importantly, the aircrews themselves. Given that pressure suits are of necessity, totally encompassing, the importance of satisfying all human factors cannot be overstated. Just how effectively pioneering suit designers dealt with human factors is perhaps best illustrated by the fact that the first practical pressure suit design developed for high-attitude flight above 50,000 feet (the capstan-operated partial pressure suit first employed in the X-1 rocket plane in the late 1940s) was subsequently employed in untold numbers of aircraft all over the world, remaining in service until 1989 when the last Lockheed U-2C aircraft was retired.

The snug-fitting, conformal nature of the capstan partial pressure suit necessitated a very close working relationship between suit designers and aircrews, thus fostering an ongoing awareness of human factors and their importance. This awareness became most acute with the advent of the U-2 program, wherein pilots were required to fly well above 50,000 feet, wearing their capstan partial pressure suits for extended periods of time, often experiencing cabin decompressions, which necessitated that they continue flying in their pressurized suit. Thus began a concerted effort to make continuous pressure suit improvements as materials, processes, and technologies allowed, so as to maximize functionality and minimize suit-induced stress and fatigue on the pilot to the extent possible.

The first operational full-pressure suit employed (in the D-558-2 Douglas Skyrocket) for flight above 50,000 feet was also the result of a collaboration between suit designers and the pilot (Scott Crossfield). This close collaboration continued on for the development of the landmark full-pressure suit for the X-15 program. The X-15 suit first employed link-net material, originally conceived for the neck section of early U-2 pilot helmets to aid pressurized mobility, for the entire restraint layer of the suit. This unique material greatly facilitated custom suit fitting and enhanced pilot comfort and remains in use to the present. Thus, the X-15 suit is really the granddaddy of modern-day pressure suits, as it led directly to the standardized military full-pressure suits that followed and continue in service to the present. Further, the X-15's high performance required that the pressure suit be capable of withstanding exposure to extreme altitudes, temperatures, and high-Q ejections, thus setting the stage to satisfy similar requirements for later programs, namely the A-12, SR-71, XB-70, and Space Shuttle.

The development of a versatile thru-helmet feeding and drinking system and a reliable urine collection system in the late 1960s further enhanced pilot comfort and performance. Two later innovations aimed at reducing pilot stress and fatigue were the development of a non-conformal, full-pressure helmet with a moveable visor and breathable gas containers, both of which were originally developed for the U-2 program but were quickly adopted by NASA for the Space Shuttle.

From the dawn of high-altitude flight, the cadre of people specializing in crew protection for this extreme regime has remained relatively small and, consequently, cross fertilization of knowledge amongst the different programs and disciplines was (fortunately) inevitable. Thus, today's advanced state of the art for pressure suits is the result of many people's dedicated work in government, industry, and even academia. However, one program, in particular, stands out for advancing the state of the art of pressure suits over the past 56 years, the U-2 program. From the beginning in 1955, the U-2 program's enlightened management has remained ever supportive of advancements in pilot's protective equipment when/wherever possible. At present, the U-2 program husbands the sole remaining national high-altitude pilot protection capability.

The future of pressure suits remains to be seen; however, it is reasonably certain that man will continue to fly high and fast, and since he must wear something, it would seem prudent to wear an ensemble that affords a large measure of safety as does a pressure suit (witness Lockheed test pilot Bill Weaver's SR-71 incident). The challenge is for designers to further expand the performance envelope of pressure suits by making them even more user-friendly through the use of new and emerging materials, processes, and technologies, such as those offered by the emerging field of nanotechnologies. Leveraging such future technological advancements, while exercising due diligence in addressing human factors, will quite certainly ensure a continued advancement in the state of the art of pressure suits.

Jack Bassick
Director
David Clark Company Incorporated

Jack Bassick Biography

Jack Bassick has worked closely with pressure suits for over fifty years, beginning in 1961 as a physiological training instructor with the United States Air Force before joining David Clark Company in 1965. Jack's tenure at David Clark has included numerous assignments and responsibilities, including pressure suit field service at Area 51 with the CIA's A-12 Oxcart program and Edwards North Base with the Agency U-2 program. Throughout his career, Mr. Bassick has participated in the research, development, qualification testing, production, crew training and field support of numerous partial and full pressure suit systems for a variety of air and spacecraft applications, being awarded a number of pressure suit related patents and receiving NASA Astronaut Corps' prestigious Silver Snoopy Award for his contributions to Astronaut safety. Jack represents the third generation of pressure suit specialists at David Clark Company, following in the footsteps of founder David M. Clark and his chosen successors, John Flagg and Joe Ruseckas. Appointed Director of Research and Development and elected Executive Vice President of David Clark Company in the late 1980's, Mr. Bassick recently retired from active employment, remaining involved with the company as a director.

PREFACE

Preface

Anybody who has watched many movies or television shows has seen them: the ubiquitous silver suits worn by pilots as they explore the unknown. They are called pressure suits, and one can trace their lineage to famed pilot Wiley Post.

Abstractly, the remote ancestor of the modern full-pressure suit is the "dry suit" used by turn-of-the-20th-century commercial salvage divers. Interestingly, although conceptually similar, the two concepts—the diver's dry suit and the aviation full-pressure suit—are exactly the opposite functionally; the dry suit ensemble worn by divers protected the wearer from the hazards of too much pressure (hyperbaric environment), whereas today's aviation counterpart protects the occupant from the consequences of too little pressure (hypobaric environment). In reality, diving suits have played only a small role in the development of aviation pressure suits, and then only prior to World War II.

Much of this history centers on the David Clark Company for several reasons. Perhaps most importantly, Clark, and the company he founded, has been involved in the concept of aviation pressure suits from the modern beginning. Moreover, the company is also the sole survivor among the original pressure suit manufacturers and was very enthusiastic about telling the story. The other principal player in modern American full-pressure suits, B.F. Goodrich, has morphed so many times that the archives—other than a small collection at the University of Akron—for the division that employed pioneering pressure-suit architect Russell S. Colley could not be located. Most of what remains are some minor reports in various Government archives, and there are surprisingly few of those. Unfortunately, therefore, an important part of this story is only lightly touched on.

When I began this project, Jack Bassick, the executive vice president of David Clark Company and a man with great experience with pressure suits, commented that it was appropriate that the National Aeronautics and Space Administration (NASA) sponsor this book. Although NASA seldom directly funded the development of aviation pressure suits, Jack Bassick pointed out that the Bell X-1 program, a joint U.S. Air Force (USAF)–National Advisory Committee on Aeronautics (NACA) effort, raised the state of the art for partial-pressure suits, and the company's early full-pressure suit was first used on the Douglas D558-2 program, which was a U.S. Navy-NACA effort. Major full-pressure suit improvements were made for the X-15 program, which was a USAF-Navy-NACA venture. Ultimately, the Space Shuttle Program, a uniquely NASA enterprise, became the most visible user of aviation pressure suits.

There are several items of clothing that are relevant to high-altitude flight. All operate using a couple of different principles that produce similar results. The first garment is not directly related to high-altitude flight but rather to protecting against high acceleration. Nevertheless, the "G-suit" is highly relevant to this story since it was developed during World War II by many of the same people, institutions, and companies that would go on to develop pressure suits. During the 1940s, and even into the 1950s, it was difficult to separate G-suits and pressure suits—both were commonly designated "altitude suits" by the military, and both were frequently called pressure suits, even by the agencies that were developing them (a G-suit does, after all, apply pressure to the body). This sometimes complicates the story, although I have tried to separate the activities as much as possible.

The G-suit, as finally developed, serves two main purposes. The first is to prevent the pooling of blood in the lower extremities, and the second is to provide firm abdominal support to enhance the straining maneuver pilots use to raise their blood pressure and to support the chest cavity to prevent the shifting of major organs. Preventing the pooling of blood, particularly in the legs, is accomplished by applying external pressure on the thighs and calves to constrict the blood vessels, hence increasing total peripheral resistance. The external pressure exerted by the G-suit cycles in proportion to the +Gz forces being experienced by the wearer. Researchers tried three different approaches to generate the skin counter-pressure. Two approaches used bladders placed against the skin that were covered by a layer of restraining cloth; as pressure inside the bladders increased, the bladders could not expand outward because of the restraining fabric, so they expanded inward against the skin. Almost everybody has experienced a similar concept: the blood pressure cuff, in the doctor's office.

The Canadians and Germans used water to fill the bladders, but this proved to be heavy and uncomfortable for the pilots. The Americans and Australians used gas—compressed air for the Americans and carbon dioxide (CO_2) for the Australians. It soon became clear that the airplane itself could provide compressed air more efficiently than could a tank of CO_2, and all G-suits eventually switched to engine-mounted air sources.

The third way to apply pressure to the legs was, mostly, mechanical. Researchers at Yale University and General Electric developed a capstan—essentially, a fabric tube that ran along the legs—attached to a series of interdigitating tapes. As air pressure expanded the capstan, the tapes pulled the fabric tightly around the leg, constricting it. In theory this should be more effective since it applies relatively uniform pressure around the entire circumference of the limb (most of the bladder systems only applied pressure to the sides of the main muscle groups), but tests showed the capstans could not react quickly enough given the available pressure sources on airplanes. The capstan G-suit was rather quickly forgotten, although the technology later proved critical to early partial-pressure suits.

The next item of protective clothing was the pressure-breathing vest. The human body requires a certain amount of oxygen to survive. As you fly higher, it becomes hard to receive this partial pressure of oxygen just by breathing normal air at the reduced pressure at altitude, so flyers switch to pure oxygen. However, as altitude increases further, the lungs become unable to provide enough oxygenation of the blood due to the insufficient driving pressure. Just prior to World War II, researchers determined that to survive at the midaltitudes it was possible to force oxygen into the lungs under pressure. The problem was that the lack of air pressure outside the chest made it very difficult to exhale—pilots had to deliberately force the air out of their lungs. It was unnatural and tiring and effectively a reversal of the natural breathing process (i.e., one had to actively exhale and inhalation became passive). A partial answer was a pressure vest that operated much like a G-suit. A bladder located on the front (and sometimes back) of the chest inflated and deflated in opposition to the pilot's breathing (the bladder deflated as the pilot inhaled, allowing the chest to expand; as the pilot exhaled, the bladder inflated to force air out of the lungs). This balanced pressure-breathing technique worked satisfactorily up to about 43,000 feet.

Next came pressure suits. There are two kinds of pressure suits: partial pressure and full pressure. David Clark, the man, once pointed out that these were not very good names, but they are the ones that stuck. In a partial-pressure suit, the counter-pressure is not as complete as in a full-pressure suit, but it is placed so that shifts in body fluids are kept within reasonable limits. Essentially, a partial-pressure suit operates much as a G-suit, except it covers more of the body and operates for prolonged times. The suit works by applying pressure over the major muscle masses and thorax while keeping the joints relatively free of counter-pressure. In this way, by striking a balance between counter-pressure and limb freedom, sufficient mobility is retained to permit the use of the suit for limited periods. Partial-pressure suits also need to provide substantial counter-pressure to the chest to aid in pressure breathing. Two different types of partial-pressure suits were developed. The first suits used the capstan principle to provide mechanical counter-pressure on the arms, legs, and across the shoulders and back. Capstans worked here because they did not need to react particularly quickly, unlike the G-suit. These suits used bladders—essentially, a pressure-breathing vest, fitted around the chest. The second type of suit used bladders everywhere, eliminating the capstans. For the most part, researchers expected partial-pressure suits to be emergency "get-me-down" suits to allow crews of high-altitude aircraft to return to safe altitudes following unexpected loss of cabin pressure. However, the suit could also support operations at high-altitudes for a relatively limited time such as when a crew depressurizes the cabin of a strategic bomber before entering a heavily defended area, or when a research pilot takes an experimental aircraft to high altitude for a few minutes of testing. Almost heroically, U-2 pilots wore partial-pressure suits for hours while ferreting out secrets over the Soviet Union.[1]

On the other hand, a full-pressure suit, which is an anthropomorphic pressure vessel, creates an artificial atmosphere for the pilot. Unlike a partial-pressure suit, there is no direct mechanical pressure on the body, and pressure breathing is not required. Instead, a small volume of gas surrounds the pilot, and the body responds as if the pilot is at some predetermined lower altitude, generally between 25,000 and 37,000 feet. The pilot has to breathe pure (or mostly so) oxygen, but it does not need to be forced into his lungs under high pressure, as with a partial-pressure suit. Because the suit is pressurized, it is often fairly stiff, limiting mobility. In fact, providing sufficient mobility has been one of the continuing challenges for developers. However, since the pilot is in a "normal" atmosphere, he can wear the suit almost indefinitely, at least from a physiological perspective.

One type of pressure suit is not necessarily better than the other, and both partial pressure and full pressure suits are still in use around the world. Both type of suits have benefits and limitations and, by and large, pilots dislike both, even while acknowledging their necessity.

All pressure suits protect against several physiological risks associated with high-altitude flying, including:

- Hypoxia: The decrease of oxygen in the blood caused by reduced atmospheric pressure can affect mental capacity, judgment, and vision, and can cause dizziness and reduce muscle coordination. Without an oxygen supply, pilots can lose consciousness in less than a minute after exposure to low pressures at high altitudes.

- Decompression sickness (also known as "aviator bends"): This includes severe joint pain caused by nitrogen coming out of solution in blood and tissues as a result of a rapid decrease in atmospheric pressure. Severe cases can result in death.

- Armstrong Line: The altitude (roughly 63,000 feet) at which water goes from a liquid to a gas (i.e., boils) at body temperature. Exposure above this altitude can cause unconsciousness and result in rapid death due to hypoxia, decompression sickness, and severe gas expansion.

There are, of course, many other pieces of protective clothing that are intimately related to pressure suits, including helmets, gloves, boots, and oxygen masks, plus ancillary equipment such as regulators, controllers, and valves. The focus of this book is on the suits themselves and why and how they were developed and fielded. The other components are covered in passing as seems appropriate, but their detailed development history is left to others.

It should also be understood that the focus of this book is aviation pressure suits, not spacesuits. Although the two pieces of clothing are generally thought to be the same, in reality they differ in several ways. A spacesuit has to provide additional protection from radiation (although some pressure suits also provide limited radiation protection) and impact strikes (from micrometeorites and orbital debris) and also be more self-contained since there is often not a vehicle attached to the suit to provide oxygen and power. A full-pressure suit normally does not provide its own oxygen or power except for very limited times after an ejection or bailout, and it usually has some sort of anti-suffocation feature in which the helmet vents to the atmosphere if the oxygen supply is exhausted. In addition, most pressure suits provide some sort of exposure protection in case the pilot finds himself in water after an ejection. Pressure suits, partial and full, can allow a pilot to survive in a vacuum for a limited period, but that is not their primary focus. The history of spacesuits has been well covered in literature; this book attempts to fill the void regarding aviation pressure suits.

ACKNOWLEDGMENTS

No book can be produced in a vacuum (pun intended), especially one that attempts to cover 75 years of technology development. The project would not have gotten started without Tony Springer at NASA Headquarters. Many people helped during my research, and I am indebted to each of them.

In particular, a small group of people went above and beyond the call, including: Robert R. “Bob” Banks (David Clark Company), John W. “Jack” Bassick (David Clark Company), Ed Dubois (David Clark Company), Dennis Gilliam, Joseph A. Ruseckas (David Clark Company), Dr. Jan Stepanek (Mayo Clinic), and Brett Stolle (National Museum of the United States Air Force).

Others who graciously contributed include: Aric Ahrens (Paul V. Galvin Library), Tom Anderson (SpaceAge Control), William Ayrey (ILC Dover), Dr. James P. Bagian, TD Barnes (Roadrunners Internationale), Roger J. Barnicki (NASA/Dryden Flight Research Center, retired), Dan Barry (David Clark Company), Thomas W. Bowen (9th Physiological Support Squadron, Beale Air Force Base), Steven Bromley (Gentex Corp.), Dr. Fred Buick (Defence Research and Development Canada), Tony Chong (Northrop Grumman), Dr. Jonathan B. Clark, William J. Close (NASA/Johnson Space Center), Kenneth S. Collins (Dutch 21), Daniel Coulom (Hamilton Standard), Regina (Conrad David Clark Company), Rob Coppinger (Flight International), A. Scott Crossfield, William H. Dana (NASA/Dryden), John J. Devine, Jr. (Government Documents Department, Boston Public Library), Duane W. Deal (Brig. Gen, USAF, Ret.), Archie Difante (Air Force Historical Research Agency), John Dodson (University of Sydney), Gail E. Farr (National Archives Research Agency Mid Atlantic Region), Gail Fithian (Government Documents Department, Boston Public Library), Alan Freeman

(David Clark Company), Steve Gaut (Federal-Mogul), Christian Gelzer (NASA/Dryden), Sandy Gettings, Terry Greenfield (NASA/Kennedy Space Center), Richard H. Graham (Col., USAF, Ret.), Wes Henry (National Museum of the United States Air Force), John C. Harper (Chevron), Jan K. Herman (Bureau of Medicine and Surgery Historian), Craig A. Holbert (University of Akron), Marty Isham, Eliza L. Johnson (NASA/Johnson Space Center), Linda F. Jones (Chevron), Donald Lacey (ILC Dover-Johnson Space Center), Tony R. Landis (NASA/Dryden), Ivy Leaf (Webmaster at Corsetiere), Denny Lombard (Lockheed Martin, Ret.), Michael J. Lombardi (Boeing Historian), Betty J. Love (NASA/Dryden, Ret.), Joseph D. Malone (David Clark Company), Daniel R. McCarter (David Clark Company), Jewel M. Melvin (Air Force Material Command/576th Aircraft Sustainment Squadron), Marcel Meyer (Fédération Aéronautique Internationale), Roger Mott (Emil Buehler Library), Mike Moore (Lockheed Martin), Francis J. "Frank" Murray (Dutch 20), Jennifer Ross-Nazzal (NASA/Johnson Space Center, History Office), William Norton, Kenneth Przybyla (Carleton Controls), Don Pyeatt, Gary Ray (NASA/Kennedy Space Center), Dr. Sally K. Ride, Dr. Erik L Ritman (Mayo Clinic), Dr. Angus H. Rupert (U.S. Army Aeromedical Research Laboratory), Bruce W. Sauser (NASA/Johnson Space Center), Carlton F. "TC" Thomas (USA/Johnson Space Center), Kenneth S. Thomas (Hamilton Standard), Tommy Thomason, Malcom V. "Mike" Todd (Red Bull Stratos), Lucien Van Oosten (Gentex Corp.), Col. Donald J. White (USAF/HQ), Maura White (NASA/Johnson Space Center), Lt. Col. Charles P. Wilson (USAF, Ret.), Ronald C. Woods (NASA/Kennedy Space Center), and Dr. James O. Young (Air Force Flight Test Center, History Office).

DEDICATION

During this project, two men intimately familiar with pressure suits passed away. Joseph A. Ruseckas, from the David Clark Company, helped design many of the pressure suits described in this book, while USAF test pilot Maj. Gen. Robert M. White made good use of the suits as he became the first man to fly a winged aircraft above Mach 4, Mach 5, and Mach 6 and higher than 200,000 and 300,000 feet. I had the good fortune to count both men as friends. They made untold contributions to aviation, and both will be missed. Godspeed.

1

1: Introduction

One of the unidentified authors of an Air Force history of the Wright Air Development Center wrote an epilogue that conveyed the awe associated with aviation pressure suits during the mid-1950s.

> The high point in the development of the altitude suit was reached on 17 June 1954 when Maj. Arthur Murray rode the rocket-propelled X-1A to an altitude in excess of 90,000 feet. When Murray reached the peak of his record setting flight, he was atop more than 97 percent of the atmosphere on the planet. Outside the cabin of the X-1A, the rarified air was only about two percent as dense as that at sea level. For all practical purposes, he was in the airless environs of outer space. While he did not use the high altitude suit that he wore, he proved that a man could survive outside the earth's atmosphere for short periods if he took along his own environment. The lesson for the future was patent: The high altitude suit which had evolved in the first decade after World War II probably would—in one form or another—accompany man when he finally escaped the confines of his rapidly shrinking planet and ventured into the vast emptiness of space. In the interim, the altitude suit appeared to be the inevitable armor of man as he strove to continue his climb from the caves to the stars.[1]

Space Shuttle astronauts who donned their David Clark Company S1035 full-pressure suits were living proof.

HORROR VACUI

> Vacuum, adjective; a space entirely devoid of matter; an enclosed space from which matter, esp. air, has been partially removed so that the matter or gas remaining in the space exerts less pressure than the atmosphere.[2]

Although difficult to imagine today, man debated the question of whether a vacuum could exist for centuries. Ancient Greek philosophers did not admit to the existence of a vacuum, asking themselves "how can 'nothing' be something?" Islamic philosopher Al-Farabi (970–850 B.C.E.) appears to have conducted the first recorded experiments concerning the existence of the vacuum when he investigated handheld water plungers, with inconclusive results.[3] Plato (427–347 B.C.E.), mathematician, writer of philosophical dialogues, and founder of the Academy in Athens, thought the idea of a vacuum inconceivable. He believed that all physical things were instantiations of an abstract Platonic ideal and could not imagine an "ideal" form of a vacuum. Aristotle (384–322 B.C.E.), philosopher, student of Plato and teacher of Alexander the Great, believed that a vacuum was a logical contradiction: nothing could not be something. The common view, attributed to Aristotle and held true for a millennium, that nature abhorred a vacuum was called *horror vacui* (literally, a fear of empty spaces).[4] It all made perfect sense at the time.

In medieval Europe, the Catholic Church, a major influence on science and philosophy, held the idea of a vacuum to be heretical since the absence of anything implied the absence of God, and harkened to the void that existed prior to the story of Genesis. The Inquisition made certain this idea was held true.

However, this began to subtly change in 1277, when Bishop Étienne Tempier of Paris decreed there were no restrictions on the powers of

God, which led to the conclusion that God could create a vacuum if He so wished.[5] So, although the concept of a vacuum was no longer heretical, neither was it much mentioned. Another 400 years would pass before the concept of a vacuum was anything but a philosophical discussion, usually conducted in private.

From the science of the 21st century, it is difficult to understand how a sensible concept of a vacuum could emerge without a corresponding concept of pressure. Yet, it took several hundred years for the two ideas to be linked. Interestingly, despite the science of the day not understanding the physics behind the device, suction pumps were becoming increasingly common devices used to move water. The popular understanding was that these devices created a partial vacuum on one end, and water rushed from the other end to fill the void in accordance with horror vacui.

Some questioned this explanation. An anonymous 13th century pupil of German philosopher and mathematician Jordanus de Némore (1225–1260) understood that pressure in a liquid increased with depth, but the publication of Némore's book in which the discussion appeared was delayed for three centuries.[6] Independently, Dutch philosopher Isaac Beeckman (1588–1637) correctly theorized that air pressure was what caused a water pump to work, not horror vacui. Beeckman did not publish his ideas but kept an extensive journal, from which his brother published some of his observations in 1644. However, given the relative obscurity of Beeckman, this went largely unnoticed. In 1615, the Tuscan mathematician, astronomer, and philosopher Galileo Galilei (1564–1642) wrote, "that all the air … weighs nothing."[7]

Against this background, the Italian Giovanni Batista Baliani (1582–1666), among others, noted that pumps would not draw water higher than 34 feet and siphons would not work over hills of the same height. Baliani described this effect in a letter to Galileo, who responded with the usual explanation: the pump or siphon created a partial vacuum, and horror vacui caused water to rush in to fill the void. Nature would not allow the partial vacuum to exist long enough to move water higher than 34 feet.

Baliani, however, did not accept this answer and believed that a vacuum was possible. He also believed that air had weight. To test Baliani's theories, some time prior to 1643, Gasparo Berti and Raffaello Magiotti built a 36-foot tube, filled it with water, and plugged both ends. They placed one end of the upright tube in a basin of water, removed the bottom plug, and watched water pour out into the basin. However, only part of the water in the tube flowed out, and the level of the water inside the tube stayed at 34 feet, the same height others had observed as the limit of a siphon.[8]

Perhaps more important was that this experiment left a space above the water in the tube that had no opening for air to refill. Berti believed the space above the water was a vacuum, although the followers of Aristotle vigorously contested the claim. One of the most vocal was René Descartes (1596–1650), a French philosopher and scientist who argued that the space was filled with a substance called aether, which was able to flow through tiny pores in the tube to replace the receding water.[9]

Magiotti apparently mentioned this experiment to Evangelista Torricelli (1608–1647), who had been Galileo's assistant for the last 3 months of the philosopher's life. Torricelli had radically different theories about why pumps and siphons worked and decided in 1643 to duplicate much of Berti's experiment to prove those theories. In a book written 300 years later, Isaac Asimov provided a description of Torricelli's experiment:

> It occurred to Torricelli that the water was lifted, not because it was pulled up by the vacuum, but because it was pushed up by the normal pressure of air.… In 1643, to check this theory, Torricelli made use of mercury. Since mercury's density is 13.5 times that of water, air should be able to lift it only 1/13.5 times as high as water, or 30 inches. Torricelli filled a 6-foot length of glass tubing with mercury, stoppered the open end, upended

it in a dish of mercury, unstoppered it, and found the mercury pouring out of the tube, but not altogether: 30 inches of mercury remained, as expected.[10]

In conducting this experiment, Torricelli had built the first mercury barometer and developed a convincing argument that the space at the top of the tube was a vacuum. The height of the column was limited to the maximum weight that atmospheric pressure could support. In honor of his contributions, his name was given to one of the early measures of pressure. Oddly, however, unlike Kelvin and Pascal, who were honored using their full names, only half of Torricelli's was used, and then without a leading capital letter: torr. Despite the significance of the experiment, it took 20 years for the first full account to be known. In "De motu gravium," which was published as part of the 1644 Opera Geometrica, Torricelli also proved that the flow of liquid through an opening is proportional to the square root of the height of the liquid, now known as Torricelli's Theorem.[11]

As important as Torricelli's contribution was, the Aristotelian philosophers held fast, and it would take another legendary scientist to finally put the debate to rest. By 1646, Blaise Pascal (1623–1662), a French mathematician, physicist, and philosopher, had learned of Torricelli's experiments with barometers. Having replicated the experiment, Pascal questioned what force kept some mercury in the tube and what filled the space above it. Following more experimentation, in 1647 Pascal published Experiences nouvelles touchant le vide,[12] which detailed rules describing to what degree various liquids could be supported by air pressure. It also provided reasons why it was indeed a vacuum above the column of liquid in a barometer tube. Science was, slowly, supplanting philosophy.

However, Pascal went further. If, as he and Torricelli suspected, air had weight caused by the miles-thick atmosphere, it should decrease at higher altitudes. Pascal wrote to his brother-in-law, Florin Perier, who lived near the Puy-de-Dôme volcano in south-central France, requesting he perform an experiment. Perier was to take a barometer up the Puy-de-Dôme and make measurements along the way of how high the column of mercury stood. In 1648, Perier meticulously carried out the experiment and found that Pascal's predictions were correct: the mercury barometer stood lower at higher altitude.[13] The Puy-de-Dôme experiment ultimately caused the Aristotelian philosophers to admit defeat and concede that air had weight. Within the International System of Units (abbreviated SI from the French "Le Système International d'Unités"), the Pascal (Pa) replaced the torr as the standard measurement of pressure—this time using the entire capitalized surname.

In 1650, German scientist and politician Otto von Guericke (1602–1686) invented the first vacuum pump and demonstrated the force of air pressure with dramatic experiments. The most famous used a pair of 20-inch-diameter copper hemispheres[14] with mating rims sealed with grease. Guericke used his pump to remove the air in the enclosure and then harnessed a team of eight horses to each half and showed that they were not able to separate the hemispheres. When Guericke let air into the enclosure, the halves easily separated. He repeated this demonstration in 1663 at the court of Friedrich Wilhelm I of Brandenburg in Berlin, using 24 horses.[15]

With his experiments, Guericke dramatically disproved the hypothesis of *horror vacui* and demonstrated that the pressure of the surrounding fluids pushed substances instead of a vacuum pulling them. Later, Robert Boyle (1627–1691) and Robert Hooke (1635–1703) improved Guericke's design. In 1659, using his and Hooke's Machina Boyleana, or Pneumatical Engine, Boyle began a series of experiments on the properties of vacuum. Boyle published an account of these in 1660 as "New Experiments Physico-Mechanical, Touching the Spring of the Air, and its Effects."[16] Among the critics of these experiments was a Jesuit, Franciscus Linus (1595–1675), and it was while answering his objections that Boyle made his first mention that the volume of a gas varies inversely to the pressure of the gas. Today this is known as Boyle's Law.

Oddly, the study of vacuum then, largely, lapsed until 1850, when August Toepler (1836–1912) invented an improved mercury piston pump called, logically enough, the Toepler pump. Then, in 1855, Heinrich Geissler (1814–1879) invented the mercury displacement pump and achieved a record vacuum of about 10 Pa (0.1 torr). A number of electrical properties become observable at this vacuum level, allowing Geissler to invent the basic technologies behind fluorescent tube lights, vacuum tubes, and, ultimately, cathode ray tubes. Shortly after this, Hermann Sprengel (1834–1906) invented a continuously operable vacuum pump, naturally called the Sprengel pump. Finally, the concepts of pressure and vacuum were well established.[17]

STRUCTURE OF THE ATMOSPHERE

All of this experimentation, in some form, concerned the atmosphere. The atmosphere is the gaseous envelope that surrounds Earth from sea level to an altitude of about 120,000 miles, held in place by gravity. Without this envelope of gas, life as we know it could not exist. The atmosphere provides breathing air and protection from ultraviolet radiation, and it acts as a layer of insulation to maintain a relatively constant temperature.

The atmosphere consists of several concentric layers, each displaying its own unique characteristics, known as spheres. Thermal variances within the atmosphere help define these spheres. Between each of the spheres is an imaginary boundary, known as a pause.[18]

The troposphere extends from sea level to about 26,500 feet over the poles and nearly 52,500 feet above the equator. Temperatures decrease 3.6 degrees Fahrenheit (ºF) for each 1,000 feet in altitude in the troposphere and continue to decrease until the rising air mass achieves an altitude where temperature is in equilibrium with the surrounding atmosphere.

Table 1—Percentages of Atmospheric Gases

Gas	Symbol	Volume (percentage)
Nitrogen	N_2	78.0840
Oxygen	O_2	20.9480
Argon	Ar	0.9340
Water Vapor	H_2O	0.4000
Carbon Dioxide	CO_2	0.0314
Neon	Ne	0.0018
Helium	He	0.0005
Methane	CH_4	0.0001
Krypton	Kr	0.0001
Hydrogen	H	<0.0001

Source: National Oceanic and Atmospheric Administration at http://esrl.noaa.gov/gsd/outreach/education/climgraph/index.html

The troposphere contains water vapor and the vast majority of weather happens in this layer. The tropopause is the atmospheric boundary between the troposphere and the stratosphere. Going upward from the surface, it is the point where air ceases to cool with height and becomes almost completely dry.

The stratosphere extends from the tropopause to roughly 160,000 feet (about 30 miles). Aviation pressure suits, the subject of this book, are meant to allow humans to survive in this layer, although many will function at higher altitudes. The stratosphere is subdivided into two regions based on their thermal characteristics. Although these regions differ thermally, the water vapor content of both is virtually nonexistent.

The first region is the isothermal layer where temperature is a constant –67 ºF. The presence of fast-moving jet streams, both here and in the upper regions of the troposphere, cause the turbulence traditionally associated with the stratosphere.

Rising temperatures characterize the second region, which contains the ozone layer. This serves as a double-sided barrier that absorbs harmful solar ultraviolet radiation while allowing solar heat to pass through unaffected.

Table 2—Atmospheric Data

Altitude (feet)	Atmospheric Pressure (psi)	Atmospheric Pressure (mm Hg)	Oxygen Partial-Pressure (mm Hg)	Temperature (ºF)	Time of Useful Consciousness
100,000	0.15	8	2	–51	0
90,000	0.25	13	3	–56	0
75,000	0.50	27	6	–65	0
63,000	0.73	47	10	–67	0
50,000	1.69	88	18	–67	0–5 seconds
43,000	2.40	123	26	–67	5–10 seconds
40,000	2.72	141	30	–67	10–20 seconds
35,000	3.50	179	38	–66	30–60 seconds
30,000	4.36	226	47	–48	1–3 minutes
25,000	5.45	282	59	–30	3–5 minutes
20,000	6.75	349	73	–12	10–20 minutes
18,000	7.34	380	80	–5	20–30 minutes
15,000	8.30	429	90	5	30+ minutes
10,000	10.11	553	116	23	Nearly Indefinitely
7,000	11.30	587	123	34	Indefinitely
Sea Level	14.69	760	160	59	Indefinitely

Data for an ISO standard day (59 °F / 15 °C) at 40 degrees latitude.
Source: U.S. Naval Flight Surgeon's Manual, *Naval Aerospace Medical Institute, Third Edition, 1991.*

In addition, this region reflects heat back toward the surface of Earth, keeping the lower regions of the atmosphere warm, even at night during the absence of significant solar activity.

The mesosphere extends from the stratopause to an altitude of 264,000 feet (50 miles). Temperatures decline from a high of 26 ºF at the stratopause to nearly –171 ºF at the mesopause. Consisting of meteor dust and water vapor and shining only at night, noctilucent clouds are a visible characteristic of this atmospheric layer.

The thermosphere, characterized by temperatures that vary in direct relation to solar activity, extends from the mesopause to an altitude of about 310 miles. Temperature ranges from –171 ºF at the mesopause to 2,700 ºF during periods of extreme solar activity. Another characteristic of the thermosphere is the presence of charged ions that are the result of high-speed subatomic particles emanating from the sun. These particles collide with atmospheric gas atoms and split them apart, resulting in a large number of charged particles (ions).

The exosphere extends from the thermopause to 120,000 miles, and from most perspectives, it is indistinguishable from outer space.

The atmosphere contains many gases (although only a few are essential to human survival), including mostly nitrogen, oxygen, and carbon dioxide. Table 1 shows the concentrations of gases commonly found in the atmosphere.[19]

Although a vital ingredient in the chain of life, nitrogen is not readily used by the human body. However, respiration saturates body fluids and tissues with nitrogen, which can result in evolved-gas disorders because of the decreased solubility of nitrogen at higher altitudes due to lower ambient pressure.

Oxygen is the second most plentiful gas in the atmosphere. Respiration unites oxygen and sugars to meet the energy requirements of the body, and the lack of oxygen in the body at altitude will cause drastic physiological effects that can result in death. To function normally, the healthy human body requires approximately 3 pounds per square inch (psi) of oxygen pressure in the lungs—conveniently, about what is available at sea level (21 percent of 14.7 psi is 3.1 psi).

Carbon dioxide is the product of cellular respiration in most life forms. Although not present in large amounts, CO_2 in the atmosphere plays a vital role in maintaining the oxygen supply of Earth. Through photosynthesis, plants use CO_2 to create energy and release oxygen as a byproduct. Because of animal metabolism and photosynthesis, CO_2 and oxygen (O_2) supplies in the atmosphere remain constant.

As designed, human beings are not well equipped to operate at the altitudes normally found in the higher mountainous regions of Earth, let alone in the upper atmosphere. An average person in decent health normally has no problem with daily activities at altitudes below 10,000 feet, although disorders impacting oxygen uptake, delivery, or utilization (such as smoking or lung disease) can result in shortness of breath at any altitude. Above 10,000 feet, even well-conditioned individuals feel the effect of exertion much quicker than at sea level. As altitude increases, there are physiological limits to the maximum time a human can continue to function.

ATMOSPHERIC PRESSURE

Standard atmospheric pressure, or barometric pressure, is the force (that is, weight) exerted by the atmosphere at any given altitude. Atmospheric pressure decreases with increasing altitude, making barometric pressure of great concern to aircrews because oxygen diffusion in the body depends on total barometric pressure.[20]

There are many units of pressure, including millimeters of mercury (mm Hg, for all intents, the same as a torr, and used in this book), inches mercury (in. Hg), inches of water (in. Aq), torr, Pascals (and its standard metric derivatives), psi, and the Standard

Atmosphere (atm). The approximate conversations are as follow:

1 atmosphere = 760 mm Hg (torr) = 14.69 psi = 101.325 kilopascals (kPa).

A close relationship exists between atmospheric pressure and the amount of the various gases in the atmosphere, an effect known as Dalton's Law of partial pressures. Dalton demonstrated that the pressure exerted by a mixture of ideal (nonreacting) gases is equal to the sum of the pressures that each gas would exert if it alone occupied the space filled by the mixture. Put another way, the pressure of each gas within a gaseous mixture is independent of the pressures of the other gases in the mixture. The independent pressure of each gas is termed the partial pressure of that gas. Mathematically, Dalton's Law is expressed as:

$Pt = PN + PO_2 + PCO_2 + \ldots$ (assuming constant volume and temperature)

In this equation, Pt represents the total pressure of the mixture and PN, PO_2, PCO_2 represent the partial pressures of each individual gas (nitrogen, oxygen, and carbon dioxide, in this example).

Dalton's Law illustrates that increasing altitude results in a proportional decrease of partial pressures of gases found in the atmosphere. Although the percentage concentration of gases remains constant with increasing altitude, each gas's partial pressure decreases in direct proportion to the total barometric pressure.

Changes in the partial pressure of oxygen dramatically affect respiratory functions within the human body, and rapid decrease in the partial pressure of oxygen may quickly result in physiological impairment. Although a person may not notice this impairment at lower altitudes, the effects are cumulative and grow progressively worse as altitude increases. Fortunately, within certain limits, the human body can acclimatize and hence improve its performance in a hypoxic environment over days and weeks. Decreases in the partial pressure of nitrogen (N_2), especially at high altitude, can lead to a decrease in the solubility of N_2 in the body and result in decompression sickness.

Decompression sickness (DCS), also called the bends and caisson disease arises from the precipitation of dissolved gasses into bubbles inside the body on depressurization. DCS most commonly refers to a specific type of scuba diving hazard but may be experienced in other depressurization events such as working in caissons, flying in unpressurised aircraft, and space-based extra-vehicular activity. Its effects may vary from joint pain and rashes to paralysis and death.[21]

At altitudes above 28,000 feet, the body requires 100 percent oxygen to remain conscious for any useful time. Breathing 100 percent oxygen at 34,000 feet is physiologically equivalent to breathing air at sea level. Breathing 100 percent oxygen at 40,000 feet is equivalent to breathing air at 10,000 feet. At altitudes between 40,000 and 50,000 feet, pressure breathing must be used wherein the breathing cavity, for example the helmet, is maintained at a small positive pressure. This increases the ability of the body to absorb the oxygen into the blood stream. At altitudes above 50,000 feet, humans must resort to using pressure breathing and a partial-pressure suit or, alternately, a full-pressure suit. Being at very high altitudes without a pressure suit is extremely dangerous and results in a condition in which the free nitrogen in the blood bubbles from solution, resulting in severe organ injury or death in minutes.[22]

There are two absolutes when dealing with humans and ever-decreasing atmospheric pressures: the first occurs at about 43,000 feet altitude and the second at 63,000 feet.[23]

The first, 43,000 feet, is the altitude at which it is impossible, without resorting to pressure breathing, for the lungs to absorb enough oxygen to sustain oxygenation and consciousness, even if breathing 100 percent oxygen. Pressure breathing is pure oxygen delivered under pressure—usually less than 1 psi (52 mm Hg) but enough to physically force the gas into the lungs. Unfortunately, it is necessary to forcefully exhale the carbon dioxide, and then relax sufficiently to allow more pressurized oxygen to enter the lungs. As Donn Byrnes describes in *Blackbird Rising*, "This pressure breathing is conducted under very low mask pressure, usually equivalent to the weight of a column of water about five inches high. Imagine blowing a five-inch plug of water out of your snorkel in the swimming pool each time you exhaled, and doing that for a couple of hours or more." It is hard work and represents a complete reversal of a human being's normal physiology with respect to breathing. Essentially, nobody can function well under pressure breathing for any prolonged length of time, even with specially designed suits that assist with exhalation.[24]

The second absolute is more frightening. At approximately 63,000 feet, called the Armstrong Line, pressure decreases to only 5 percent of sea level. The vapor pressure of water (47 mm Hg) at this altitude is the same as the atmospheric pressure (47 mm Hg) and water boils at the normal temperature of the human body (98.6 ºF). It is important to note that this applies to unconfined water, such as saliva and tears. Normal human diastolic blood pressure is sufficiently high that, contrary to oft-repeated myth, a person's blood will not boil in a vacuum, although there are many other environmental threats such as hypoxia, cold, and trapped gas expansion that will quickly kill an unprotected human above this altitude.[25]

PHYSIOLOGICAL ISSUES OF HIGH-ALTITUDE FLIGHT

The homeostatic responses in humans to sudden exposure to low barometric pressures are limited in their adaptive capabilities since this hostile environment is foreign to human physiology. Hence, there is no opportunity for a sufficient adaptive response. Exposure results in a rapid onset of unconsciousness unless otherwise protected by artificial means. If there should be a sudden or even slow loss of cabin pressurization at altitudes above 40,000 feet, even while breathing 100 percent oxygen at ambient pressures, the time of useful consciousness (TUC), the duration in which the pilot can perform basic emergency tasks, begins to shrink. At 40,000 feet, breathing pure oxygen at ambient pressure, the TUC is theoretically indefinite (ignoring decompression sickness). This ability decreases rapidly, and an increment of only 3,000 feet (to 43,000 feet) makes it necessary to employ pressure breathing to have any TUC. By 50,000 feet, even breathing pure oxygen at ambient pressure provides less than 5 seconds TUC. The physiology and biochemistry of hypoxia in humans is beyond the scope of this book, and only the pertinent details are summarized here.[26]

In high-altitude flight, a structural failure in a pressurized cabin or loss of cabin pressure control would be catastrophic without supplemental protection for the crew. The physiological effects of a rapid decompression include acute hypoxia, effects on the gas-containing cavities of the body, decompression sickness, thermal exposure, and ebullism (formation of bubbles in body fluids). Less rapid but equally debilitating effects of unpressurized flight at high altitude include hyperventilation, fatigue, reduction in effective circulating blood volume, and fainting associated with pressure breathing. Also, acceleration forces during high-speed egress (ejection) can have a profound consequence on the skeletal structure and the cardiovascular system. All of these reactions can have potentially grave effects upon aircrew performance and mission effectiveness and all are avoidable by the employment of appropriate life support equipment and adequate training. Most pressure suits maintain the crewmember at an equivalent altitude of approximately 34,000 feet breathing 100 percent oxygen, which is roughly equivalent to breathing sea level air, thereby preventing most of these problem areas.[27]

Hypoxia: Altitude hypoxia results when the oxygen partial pressure in the lung falls below that comparable to sea level. However, it is not generally significant until the alveolar oxygen tension falls below a 10,000-foot equivalent. At 10,000 feet, the reduced ability to learn new tasks can be measured and consequently 10,000 feet is used as the altitude that supplemental oxygen is considered necessary.[28] As the partial-pressure of oxygen in the inspired air continues to drop, the signs and symptoms of hypoxia become more evident and include loss of peripheral vision, skin sensations (numbness, tingling, or hot and cold sensations), cyanosis, euphoria and eventually unconsciousness at higher altitudes. Up to an altitude of 34,000 feet, increasing the percentage of oxygen allows an approximation of sea level oxygen equivalent. Above 40,000 feet, breathing 100 percent oxygen without additional pressure is not sufficient for efficient aircrew performance. Pressure breathing is required and is accomplished by use of an oxygen system that delivers 100 percent oxygen at greater than ambient pressures. However, the pressures needed to sustain consciousness above 50,000 feet rapidly become intolerable.[29]

Mechanical Effects: During a cabin depressurization, gases trapped within the intestinal tract, nasal sinuses, middle ear, and lungs will expand. The magnitude of the effect on the gas-containing cavities of the body is directly proportional to the range and rate of change of pressure. Serious consequences result when there is an occlusion or partial occlusion between a gas-containing cavity and the environment.[30]

Decompression Sickness: Body tissues contain dissolved gas, principally nitrogen, in equilibrium with ambient pressure. When ambient pressure is reduced, nitrogen bubbles form in the body tissues. If the drop in pressure is not too great or too fast, bubbles evolved in the tissues are safely carried to the lungs by the vascular system, where the evolved nitrogen is eliminated. Prolonged exposure to altitudes in excess of 25,000 feet may lead to one or more of the symptoms of DCS, such as the bends, chokes, and circulatory and neurological disturbances. Recent studies have established the need for increasing the pressure differential from 5 to 7 psi in future aircraft. Air Force researchers believe this increased pressure differential provides less risk of DCS during prolonged exposure to cabin altitudes greater than 20,000 feet.[31]

Ebullism: When the total barometric pressure is less than the vapor pressure of tissue fluid at body temperature (47 mm Hg), vaporization of the body fluids occurs. This occurs in the nonpressurized portions of the body at altitudes above 63,000 feet. However, exposure of peripheral regions of the body (e.g., the hands) to pressures less than the vapor pressure of the tissue fluids leads to vaporization of these fluids with little or no impairment of performance. When combined with low environmental temperatures, the evaporative cooling associated with vaporization may accelerate freezing and drying of exposed tissues. While wearing only a mask for short exposures above 63,000 feet, vision is affected as a result of tearing and blinking during pressure breathing, which effectively blinds the crewmember.[32]

Thermal Extremes: The effects of the low temperatures following loss of cabin pressure at high altitude can cause impaired function and eventual tissue damage to exposed regions of the body; or, if exposure occurs over a longer duration, it could cause a drop in core temperature causing a progressing impairment of performance followed by unconsciousness and, eventually, death. An aircrew member wearing normal flying clothing with a mask and gloves will not suffer any serious damage during a short exposure (5 minutes) to the lowest temperature conditions encountered at high altitude. Exposure beyond this time will lead to more severe peripheral cold injury unless appropriate clothing and heating garments are worn. The garment must also protect against heat when the temperatures on the outer surfaces of Mach 3 aircraft approach 560 ºF, and it also must protect against the thermal pulse of ejection at Mach 3.[33]

2

2: Mark Ridge, Wiley Post, and John Kearby

Pressure suits, usually called spacesuits by the public (although these are but one example of this type of garment), are essentially taken for granted today. Seventy-five years ago, they were the stuff of science fiction. These suits serve several necessary purposes, with supplying the correct partial pressure of oxygen the most obvious, although masks or full-face helmets can also accomplish this somewhat less efficiently, at least at the middle altitudes. Their most important purpose, however, is to protect the pilot against the increasingly low atmospheric pressures encountered at high altitude—pressures that reach essentially zero above about 250,000 feet—and the terrible cold encountered at extremely high altitude.[1] Years before the involvement of large Government, academic, and corporate entities, however, comes the story of a couple of visionaries and the early pioneering work on full-pressure suits.

A distant precursor of the full-pressure suit was, arguably, the dry suit used by turn-of-the-century commercial salvage divers, complete with their brass helmets and weighted boots. During 1920, renowned Scottish physiologist Dr. John Scott Haldane (1860–1936) seemingly was the first to suggest that a suit similar to the diver's ensemble could protect an aviator at high altitudes. There appeared, however, to be little immediate need for such a garment. The normally aspirated piston-powered airplanes of the era were incapable of altitudes much in excess of 20,000 feet, and the major concern at the time was simply keeping the pilot warm. However, the increasing use of supercharged engines during the late 1920s led to the first serious studies into the physiological effects of altitude. As aircraft became capable of climbing above 30,000 feet, the concern was no longer how to keep the aviator warm but how to provide him oxygen and protect him from reduced pressure.[2]

The first known serious concept for a pressure suit came from Fred M. Sample of Jacksonville, OR. On July 16, 1918, Sample received U.S. Patent 1,272,537 for his "Suit for Aviators." Being a smart inventor, never claiming an original item, he instead claimed "certain new and useful improvements." In particular, he expected the suit could supply oxygen for aviators or travelers crossing high mountains. The full suit included a metal (although Sample indicated any suitable material could be used) helmet split vertically, hinged on one side, and latched on the other. The helmet was attached to the suit via bolts "or other securing elements" and had an oxygen hose connected to its back. Under the outer coveralls was an inflatable bladder that provided counter-pressure to the chest. The suit buttoned up the front like single-piece long underwear and did not include integral gloves or boots, terminating instead with elastic cuffs at the wrists and ankles. Conceptually, it was similar to what others would ultimately build, but there is no record that Sample ever fabricated his suit.[3] That brings the story to the other side of North America.

EARLY PRESSURE SUITS

It seems that Massachusetts has an indelible link to pressure suits. The David Clark Company, an entity that will play a remarkable role later on, was founded only 50 miles from where the story nominally begins.

Four years before David M. Clark founded the company that would bear his name in Worcester, MA, Mark Edward Ridge (1906–1962) resided in nearby Dorchester and aspired to do great things. Before he did, however, Ridge would try a meaningless stunt. On January 16, 1931, he parachuted out of an airplane 2,000 feet above the Charles River. Oddly, at the time, Massachusetts had a law prohibiting anybody from jumping out of an otherwise perfectly good airplane, and the police promptly arrested Ridge, who eventually received a suspended sentence.[4]

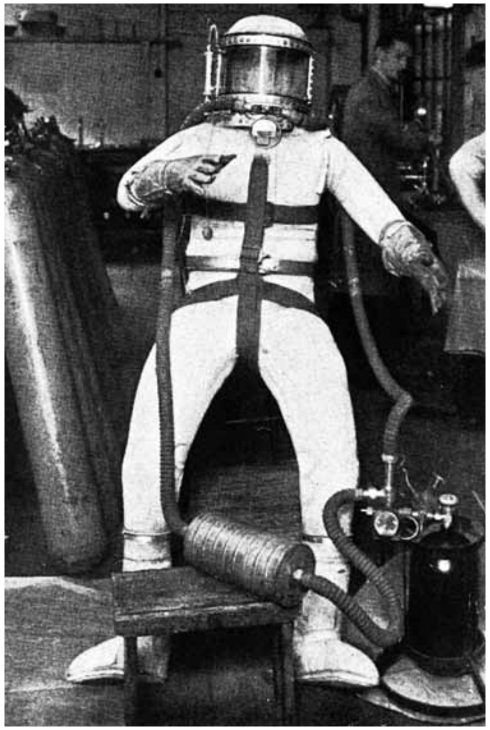
Just two days after the court sentenced Ridge, on May 27, 1931, Auguste Piccard (1884–1962), a Swiss professor of physics at the University of Brussels, and his assistant, Charles Knipfer, reached a record altitude of 51,775 feet over Augsburg, Germany, becoming the first humans to venture into the stratosphere. Their balloon, designated CH-113, was little more than a rubberized cotton gasbag with a 7-foot-diameter pressurized gondola that Piccard designed to combat the effects of high altitude. Funded by King Albert's Fund for Scientific Research, the pair studied the intensity of cosmic rays using a small electroscope. About 15 hours after ascending, the balloon settled on the glacier above the village of Ober Gurgl in the Austrian Tyrol region.[5] Ultimately, Piccard made 27 balloon flights, setting a final record of 72,177 feet. They were altitudes that airplanes of the day could not touch.

Ridge also wanted to set a record. However, he believed that pressurized gondolas were too heavy to exploit the full performance of balloons, so he decided to use an open basket. Although he apparently did not understand the physiology behind the concept, Ridge knew he would need to surround his body with pressure. Lacking a pressurized gondola, he concluded a pressure suit would serve the same purpose. Ridge was certain he had happened upon a crucial idea and began searching for a patron. Repeated correspondence with the U.S. Army and U.S. Navy brought continued disappointment. Ultimately, at the suggestion of Dr. Timothy Leary,[6] the Boston medical examiner, Ridge contacted Dr. John Scott Haldane, Professor of Metallurgy, Gasses, Liquids, and Respirations at the University of Oxford, England, seeking assistance.[7]

Haldane, along with his son John Burdon Sanderson "Jack" Haldane (1892–1964), had spent 30 years experimenting with a small pressure chamber to determine the reason behind decompression sickness in deep-sea divers. In 1908, Haldane and Dr. John G. Priestly published the first meaningful decompression tables for divers, which the Royal Navy subsequently adopted for service.[8] In 1911, Haldane led an expedition up Pikes Peak, CO, to study the effects of low barometric pressure, and he concluded that a pressure suit would eventually be needed by flyers attempting to reach high altitudes. World War I distracted Haldane, who concentrated on the development of oxygen equipment, but in 1922, the professor clearly described a "stratosphere flying suit"[9] developed in collaboration with Priestly.

At the time, Haldane was working with Sir Robert H. Davis[10] of Siebe Gorman & Company to develop improved deep-sea diving suits. Siebe Gorman was the preeminent diving equipment makers of the day, and the company made a range of different diving helmets that could be identified by the number of bolts (6, 8, or 12, depending on the operating depth) used to attach the helmet to the collar of the suit.[11] Diving suits had gone through a revolution during the mid-1800s, much as aviation pressure suits would in the 1950s. The earliest diving suits were nothing more than vests with separate helmets held in place by just their weight. Many divers drowned because they moved in a way that allowed water to enter the helmet. One diver, George Edwards, suggested bolting the helmet to the breastplate of a full suit, making a truly watertight ensemble. Edwards encouraged Augustus Siebe to produce the design, and it was the start of a long and successful series of diving suits from the company.[12]

Less than a month after their initial contact with Ridge, Haldane and Davis had constructed a hypobaric protection suit by substantially altering one of their diving suits. Like the diving suit it was derived from, Ridge's garment was made of rubber and canvas, sewn together into an airtight full coverall



Although undoubtedly not Mark Ridge's suit, this example of a Haldane-Davis full-pressure suit shows that Siebe Gorman was certainly on the right track. The suit is tight fitting, and the straps on the torso are likely to keep the suit from ballooning under pressure.

National Archives College Park Collection

with gloves and boots (minus the lead weights used by divers). A modified brass diving helmet covered the head. Ridge left Boston for London as soon as Haldane confirmed the suit was ready. On November 16, 1933, Ridge donned the suit and became, apparently, the first human to be tested wearing a pressure suit in an altitude chamber. Haldane lowered the pressure to a simulated 50,000 feet altitude (87 mm Hg) and Ridge suffered no ill effects. Two weeks later, on November 29, 1933, Ridge used a suit pressure equivalent to approximately 42,000 feet (133 mm Hg) at a chamber pressure equivalent to 83,500 feet (17 mm Hg); the entire test had taken about an hour, with at least a few minutes at the maximum altitude.[13]

The *London Daily Mail* reported the tests, and the British Air Ministry quickly expressed interest in the suit. Ridge tried to persuade the Ministry to supply an open-basket balloon for flight tests in the stratosphere, but ultimately the British declined. The denial apparently had little to do with concerns over possible injuries to Ridge, but rather it was based on the likelihood the balloon would drift over Europe and that the Haldane-Davis "stratosphere flying suit" would fall into German hands.[14]

Ridge brought his suit back to the United States and quickly realized a flaw in the tests in London. Although they demonstrated that the suit provided protection from the low pressure at high altitude, the tests had not simulated the cold temperatures in the stratosphere. In response, Ridge designed an insulating garment he could wear under the suit. Along with Samuel Ring, a Boston aluminum foil dealer, Ridge made a set of long underwear made up of 12 alternating layers of aluminum foil and cotton cloth. Gloves, socks, and a head covering completed the ensemble. The chamois facemask had three holes: one for each eye and one for the mouth. A set of goggles covered the eyes and a primitive oxygen mask covered the mouth.

The Liquid Carbonic Corporation in Cambridge, MA, agreed to support a test of the suit, largely to obtain the publicity such a stunt would bring. The company lined a steel tank with 1,000 pounds of dry ice, and on March 8, 1934, Ridge entered the tank. Despite carrying a small tank of breathing oxygen, carbon dioxide gas quickly subdued Ridge. The failure was traced to the oxygen mask, which did not seal well. By the time Ridge and Ring could repair it, Liquid Carbonic had a change of heart and refused to allow a second test. For a while, Ridge gave up.[15]

Two years later, on March 25, 1936, Dr. Karl T. Compton, renowned physicist and president of the Massachusetts Institute of Technology, wrote a letter endorsing Ridge's pressure suit to Maj. Gen. Oscar Westover, the chief of the U.S. Army Air Service.[16] Apparently, Ridge convinced Compton to support his cause based largely on grossly exaggerated claims of his tests at Siebe Gorman and Liquid Carbonic. By this time, Wiley Post had already made his record-attempting flights with an operating pressure suit, and the Army was well aware of the technology since Post had tested his suit in an altitude chamber at Wright Field, OH. The Army researchers were more than willing to test Ridge's suit, but Westover overruled them for unknown reasons.[17]

Ridge subsequently wrote to Louis A. Johnson, the Assistant Secretary of War, and finally to President Franklin Delano Roosevelt, neither with any success. Without support from the military and unable to raise sufficient financial support for the cost of his balloon, Ridge could not put his suit to actual use. The courts judged him insane in 1942 and Ridge never again saw the outside of an asylum. Mark Edward Ridge died on April 16, 1962, at the age of 56, without realizing his dream of flying into the stratosphere in an open balloon.[18] Nevertheless, he lays claim to having, with the able assistance of John Scott Haldane and Sir Robert Davis, conceived and built the first full-pressure suit.

WILEY POST AND THE WINNIE MAE

Despite the dreams of Ridge and the pioneering efforts of Haldane and Davis, American adventurist Wiley H. Post (1898–1935) lays claim to being the first to actually use a full-pressure suit. Post was fascinated by the Wright Brothers as a child and by the age of 14, reportedly, had decided to become an aviator. It was not as easy as it sounded. His aviation career finally began at age 26 as a parachutist for the Burrell Tibbs & His Texas Topnotch Fliers flying circus. After making 91 jumps, Post decided the career path did not provide sufficient funds to pursue his real passion of flying, and he went to work as an oil rigger in Seminole, TX. On his second day of work, October 1, 1926, an accident cost him his left eye, but he used the $1,698 settlement to buy his first aircraft—a wrecked Curtiss JN-4 Jenny that he subsequently rebuilt.[19] In August 1928, Post applied for a commercial pilot's license, which presented the Department of Commerce with something of a quandary given the loss of Post's left eye. The flight surgeon agreed that Post's depth perception was better than most people with two eyes, and eventually the Government issued Post a waiver that allowed him to obtain a commercial ticket.[20]

Post used the Jenny for stunt flying, making a better living than he did as a parachutist. While performing in Ardmore, OK, Post met Mae Laine, and later the same day, the couple was married. It did not take long for Post to discover that he could not support a wife by stunt flying. During an air show, Post heard that millionaire oilman Florence C. "F.C." Hall, had recently purchased an airplane and, despite never having previously met the man, Post wrangled a job as his personal pilot. After a couple of years, Hall decided to sell his airplane, and Post went to work as a test pilot for Lockheed Aircraft Company in Burbank, CA. There, he fell in love with the Vega.[21]

Designed by John K. "Jack" Northrop and Gerard "Jerry" Vultee, both of whom would later form their own aircraft companies, the Vega broke ground by using a full monocoque fuselage and cantilever wings. The laminated wood fuselage skin was manufactured using a large concrete mold, and the fuselage halves were then nailed and glued over a previously made wooden rib frame. The metal wing was mounted in a streamlined faring on top of the fuselage and power came from a single 225-horsepower (hp) Wright J-5 Whirlwind radial engine.[22]

The first Vega 1 made its maiden flight on July 4, 1927. The airplane spanned 41 feet across, was 27.5 feet long, and had a gross weight of 4,200 pounds. It could cruise at a then-fast 120 miles per hour (mph) and had a top speed of 135 mph. However, airlines quickly decided that a 4-passenger airplane was not economical, and most of the 68 Vega 1s went to private owners. Despite its commercial failings, the airplane was fast: in the 1928 National Air Races in Cleveland, OH, Vegas won every category. In 1929, Lockheed introduced the Vega 5, which, used the 450-hp Pratt & Whitney R-1340 Wasp engine and carried six passengers. Equipped with a streamlined NACA engine cowling, cruise speed increased to 155 mph and top speed to 165 mph. Unfortunately, its economics were not much better, and almost all of the 64 Vega 5s went to private owners as well. Regardless of its perceived failings as an airliner, the Vega became famous for its use by a number of now-legendary pilots who were attracted to the rugged and long-range design. Amelia Earhart used a Vega to become the first woman to fly solo across the Atlantic, and Wiley Post would fly his around the world, twice.[23]

Post's enthusiasm for the Vega was contagious, and Hall agreed to purchase one if Post would fly it for him. Post agreed, on the condition that he could enter it in the National Air Race Derby from Los Angeles to Chicago. Hall thought it was a good plan. On August 23, 1930, the gloss-white Vega with purple cheat lines landed at the Curtis-Reynolds Airport just north of Chicago after a 9-hour, 9-minute record flight. Hall was ecstatic and promptly gave Post the $22,000 airplane. It was the beginning of worldwide fame for Wiley Post, and the airplane named *Winnie Mae*.[24]

In 1929, the German airship *Graf Zeppelin* (LZ127) circumnavigated Earth in 21 days, 5 hours, and 31 minutes, making a journey that covered 30,831 miles.[25] Wiley Post was certain a fixed-wing aircraft could do the same trip much faster. With Australian Harold Gatty, Post took the *Winnie Mae* around the world in 8 days, 15 hours, and 51 minutes, earning the pair a ticker-tape parade in New York City and lunch at the White House. Two years later, Post equipped the *Winnie Mae* with an autopilot and radio compass, then proceeded to fly around the world solo in 7 days, 18 hours, and 49 minutes, earning himself a second ticker-tape parade. The Fédération Aéronautique Internationale (FAI) awarded Post the Gold Medal and the International League of Aviators (Ligue Internationale des Aviateurs) presented him with the Harmon Trophy.[26] More important, perhaps, to Post was an observation he made during these flights: the higher you fly, the faster you go.

During 1933, Melbourne, Australia, was preparing to celebrate its centennial in October 1934. To properly mark the event, Sir MacPherson Robertson (1859–1945), an Australian philanthropist, entrepreneur, and founder of the Mac Robertson Steam Confectionery Works,[27] offered a cash prize of £10,000 (about $50,000 at the time, or $750,000 today) to the winner of an air race between Mildenhall, England and Melbourne, Australia, via a designated course over Baghdad, Allahabad, Singapore, and Darwin.[28] It was a race Post could not resist. However, Post was also well aware that much better aircraft had emerged during the 5 years since *Winnie Mae* was built. To compensate, Post intended to fly in the thin air above 30,000 feet, taking advantage of the powerful tailwinds he believed existed at high altitudes.[29]

Writing in the 1850s, the pioneering American balloonist John Wise (1808–1879) theorized there was a "great river of air which always blows from west to east" that could take his balloon across the Atlantic.[30] Wise made over 450 flights during his lifetime and was responsible for several innovations in balloon design. Unfortunately, Wise mysteriously disappeared on a trip in high winds from East St. Louis on September 28, 1879, before he had made any progress in further defining his theory.

Based on his observations during his around-the-world flights, Post was certain that Wise was correct and believed that "high winds," as he called them, existed in the stratosphere. If he could find these, they could carry the *Winnie Mae* at greatly increased speeds. These winds are now known as the "jetstream."

During the early 1930s, the physiological aspects of long periods at altitude were not well understood, and neither the engines nor propellers of the day were capable of propelling a meaningful airplane at high altitudes for any length of time. There was an ongoing competition, mostly in Europe, to set altitude records, but these were simple up-and-down flights that provided minimal exposure to the effects of high-altitude flight. Nobody was talking seriously about long-distance flights above 30,000 feet or even 20,000 feet—except Wiley Post.[31]

Despite his lack of knowledge of the subject, Post knew that he needed pressurization to keep him alive. Oxygen masks of the period were ineffective at any serious altitude, and physiologists had not yet discovered the concept of pressure breathing. Post realized that it was impossible to pressurize the wooden fuselage of *Winnie Mae*, and incorporating a separate pressurized cabin into the Vega would be prohibitively expensive. Running out of options, Post decided on the only other course available—he would have to pressurize himself.[32]

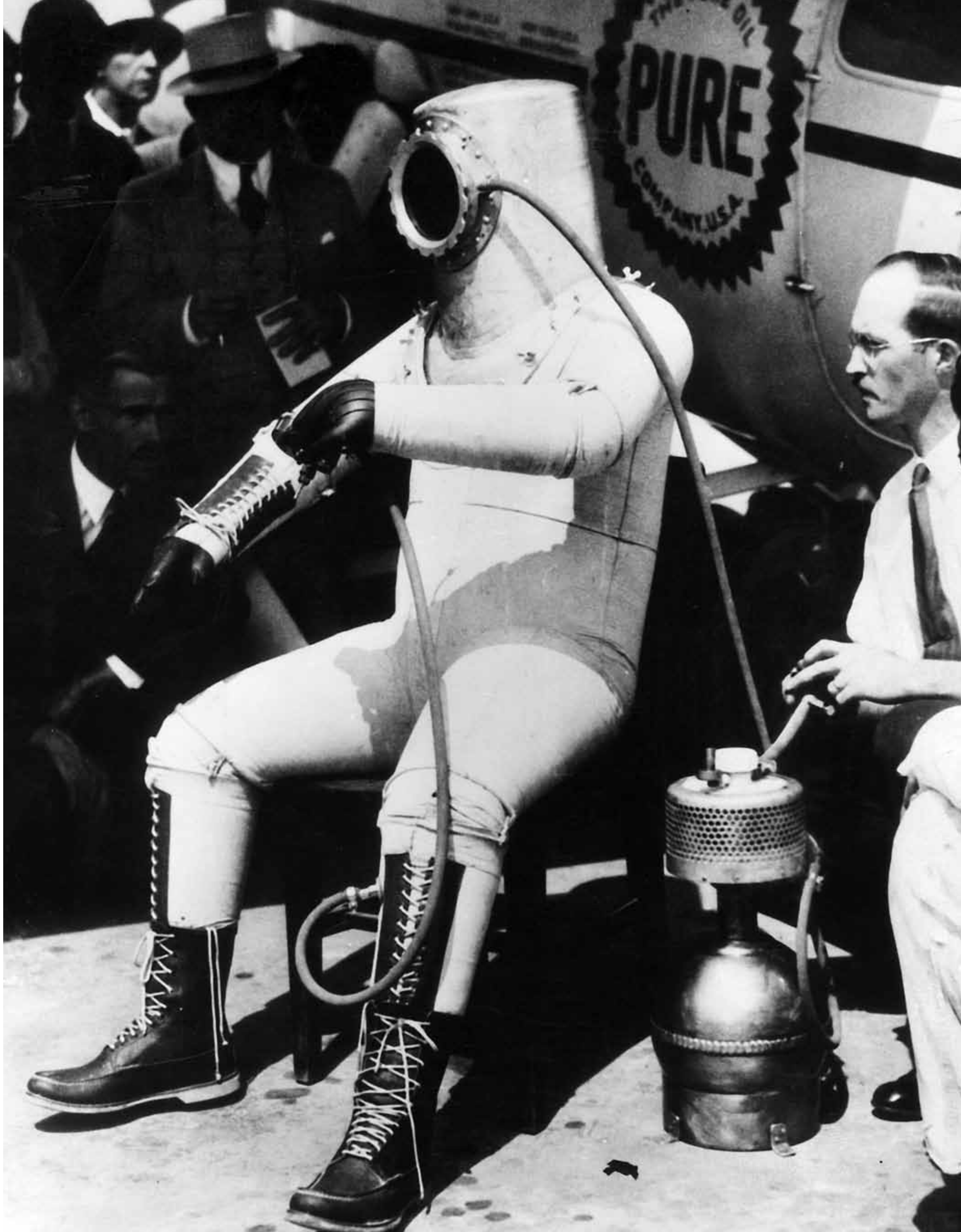
Post's pressure suit seemingly had no connection to the efforts of Mark Ridge around the same time, and it is not clear if Post knew about Fred Sample or John Scott Haldane's theoretical suggestions. In any case, the suit that Post needed was quite different than the one developed by Haldane and Davis. Because of its deep-sea roots, the Haldane-Davis suit was stiff, and even simple movements were difficult to perform when the suit was inflated. This would not have been a major issue for Ridge since flying an open-basket balloon requires little movement; mostly it involves quietly sitting and waiting. Flying an airplane, on the other hand, requires the pilot to move his legs, arms, and fingers almost constantly. This would become one of the defining requirements, and difficulties, in the development of pressure suits.

In the spring of 1934, Post asked for assistance from his friend Jimmy Doolittle, who had joined Shell Oil Company as director of aviation and might have been capable of making a pressure suit. Doolittle referred him to the Research Aviation Department of the B.F. Goodrich Company in Los Angeles. Post first visited the Goodrich plant on April 6, 1934, and requesting, "a rubber suit which will enable me to operate and live in an atmosphere of approximately twelve pounds absolute [5,500 feet altitude equivalent]. I expect to fly through rarefied areas where the pressure is as low as five pounds absolute [27,000 feet]. The temperature incident will be taken care of by heating the air from the supercharger by coiling it around the exhaust manifolds."[33] A new engine supercharger would provide compressed air for suit pressurization and ventilation.

Goodrich assigned William R. Hucks as the project engineer for the development of the suit, with John A. Diehl and J. Stevens assisting in its fabrication. Progress was agonizingly slow, primarily because none of the Goodrich personnel were familiar with making clothes, so Post eventually asked Goodrich to hire a professional tailor to make the initial patterns. Goodrich fabricated the first suit from 6 yards of rubberized parachute cloth with two layers glued together on a bias to minimize stretch. The sleeves were carried to the neckline in a raglan cut, and the suit included pigskin gloves and rubber boots. The two-piece garment (shirt and trousers) sealed at the waist using a Duralumin metal belt.[34]

At the same time, Lowell Peters, a metalworker in Los Angeles, fabricated an aluminum helmet for Post. It generally resembled a welder's helmet, weighed 3.5 pounds, and had a 2.75- by 7.5-inch rectangular visor made of two layers of clear plastic. A bulge covered each ear to accommodate headphones and Post could eat when the suit was unpressurized by opening a small door over the mouth. Addressing another area that would long vex designers, front and rear handles on the lower edge of the helmet allowed Post to tie it down to the suit to keep the helmet from rising when the suit was pressurized. The estimated cost of the pressure suit and helmet was $75 (an unbelievable $1,500 in 2009).[35]

Goodrich tested the suit by pressurizing it to 5 psi. A major flaw quickly became apparent: the pressurized suit would not allow the wearer to raise his arms, which hang uselessly at his sides. Hucks quickly reworked the arms of the suit and subsequent tests showed the arms could be raised with considerable effort. Some leakage was detected near the waist joint, but it was considered acceptable, so Goodrich shipped the suit to Post in Ohio.[36]



Wiley Post shows off his inflated full-pressure suit in front of the Winnie Mae. *Note the wingnut on Post's shoulder, just behind the helmet. The oxygen generator is on the ground next to Post, connected to the left side of the visor. The position of Post's arms shows the relative stiffness of the inflated suit, something that would hamper pressure suit development for another 50 years.*

Courtesy of Chevron Corporation Archives

Post was at Wright Field consulting with the Engineering Division of the Army Air Corps. In particular, he dealt with the Equipment Branch, which was responsible for evaluat-ing flying suits, goggles, and methods of protecting aircrew against cold. Wright Field had an altitude chamber large enough (10 feet high and 9 feet in diameter) for a man, although the Army mostly used it to check altimeters. This chamber had originally been installed at the Medical Research Laboratory at Hazelhurst Field in Mineola, Long Island, NY. In March 1921, a fire destroyed much of the laboratory, but, fortunately, the chamber survived.[37]

During the 1930s, the Army Air Corps was an organization in search of an identity. Funding was at an all-time low, and service only had several hundred operational airplanes, most hopelessly obsolete. Wiley Post and his pressure suit seemed the stuff of science fiction when he showed up and

The Post pressure suit was fairly flexible when not pressurized, allowing Post a reasonable amount of movement and comfort. Note the nipple below the left knee where air exited the suit; normally this was attached to a regulator and pressure gauge. Given that it was the first real attempt at building a workable pressure suit, the Post garment worked remarkably well.

NASA

asked for assistance in testing the garment. On June 23, 1934, while Post was pressurizing the suit to a differential pressure of 2 psi as a demonstration for the Army engineers, a piece of reinforcing tape failed, effectively ending the effort. Nevertheless, according to a press report in *The Cleveland News*, Post apparently made at least one flight in the *Winnie Mae* while wearing the unpressurized suit, most likely to check mobility and vision while wearing the ensemble.[38]

Post took the damaged suit to the Goodrich plant in Akron, OH, where he met Russell S. Colley (1899–1996), who was intimately familiar with using rubber products in aeronautical applications. Colley had been born in 1899 in Stoneham, MA. As a young man, Colley displayed excellent mechanical skills but told his parents that he wanted to design women's clothing. Not agreeing with this career choice, his parents persuaded him to enroll at the Wentworth Institute of Mechanical Engineering. In 1928, Colley accepted a position with the B.F. Goodrich Company as a mechanical engineer and was part of the team that developed de-icing boots for aircraft.[39] Goodrich researchers determined that gluing an inflatable rubber "boot" on the leading edge of an aircraft's wing (and empennage) and alternately inflating and deflating it, caused ice to break off. In December 1931, Colley and Wesley L. Smith, a former Air Mail Service pilot who was then operations manager for National Air Transport, used a Travel Air 6000 mail plane for a series of flights into known icing conditions to test the Goodrich de-icing boots. Colley sat on an orange crate in the mail compartment of the airplane and used a bicycle pump to inflate the tubes, alternating from one tube to the other by means of a manually operated valve. In late 1932, William S. "Billy" Brock flew further tests using a Goodrich-owned Lockheed Vega named *Miss Silver Town*. By 1934, the Goodrich system was becoming standard equipment on American airliners and many lower-speed aircraft still use similar systems (they are not effective on high-speed aircraft that require precise airfoil shapes).[40]

Meanwhile, the MacRobertson Race was only 3 months away. Colley developed a new suit that would work with the original helmet, although he installed an oxygen hose fitting below the visor. Post entered the two-piece suit through the waist, and two large metal plates sealed the torso. Flexible elbow and knee joints allowed improved limb movement when the suit was inflated.[41]

In a turn straight out of a slapstick comedy of the era, the first time Post tried on the new suit, he became stuck in it. Partly, this was because of the hot and humid weather that embraces Dayton in July (and the lack of air conditioning in 1934), but it was mostly because Post had gained several pounds since he had been measured for the original suit and Colley had used the same patterns. The only way to extract Post was to cut the suit into pieces. Nevertheless, Colley and Post learned a great deal concerning the behavior of the suit under static pressure.[42] By now it was obvious that Post would not have a suit ready for the MacRobertson Race.[43]

After the unexpected turn of events with the second suit, in late July 1934, Post and Colley decided to fabricate an entirely new suit and helmet. For the third suit, Colley suggested two separate layers: an inner, body-contoured rubber garment that would contain gaseous oxygen under pressure, and an outer, three-ply cloth garment, made to resist stretching and to hold the rubber suit to Post's body contours. The third suit used a differential pressure of 7.25 psi (0.5 atmosphere), 2 psi greater than the first two suits.[44]

Colley began by taking precise measurements of Post sitting in a position that mimicked what was needed to fly the *Winnie Mae*. He made cardboard limb and trunk forms and used them to cut the fabric for the outer layer. Colley formed the inner pressure layer by pouring liquid latex over sheet-metal forms. Thanks to the new set of measurements, this suit fit much better. Since Colley formed the suit for the sitting position, Post walked slightly bent over while wearing it, although he could stand straight with some effort.

Unlike the first two suits, which Post entered from the waist, an enlarged neck opening provided entry to the third suit. The new helmet bolted to a metal collar after the pilot was securely in the suit. Post could not reach the wing nuts in the back of the helmet and required assistance to don and doff the suit.[45]

The new helmet was considerably improved and included a large round window, made of glass instead of plastic, that Post could easily remove since the faceplate edge had large notches to accommodate gloved fingers. The helmet was wide enough to accommodate earphones and did not have the bulges of the first helmet. Oxygen entered through a port just to the left of the window (Post had the patch over his left eye) to defog the glass. An outlet to the right of the window vented the helmet. A valve, attached to a regulator and a pressure gauge, just below the left inner knee controlled outflow from the suit.

After a detailed evaluation and several static inflation tests, on August 27, 1934, Post made the first altitude chamber test of a pressure suit in the United States. As the simulated altitude passed 18,000 feet, Post screwed in the glass window and the suit began to inflate. Everybody immediately noticed the helmet began to rise off Post's head, and Colley noted the need for some type of restraint. However, the liquid oxygen system was not providing enough oxygen, and after 27 minutes, as the

The Winnie Mae *while it was sponsored by the Pure Oil Company. The Lockheed Vega was 27.75 feet long, spanned 41 feet, and had a gross weight of just over 4,000 pounds. Lockheed designed the airplane to cruise at 140 mph and fly 725 miles at altitudes under 20,000 feet, figures that Post routinely exceeded.*

Courtesy of Chevron Corporation Archives

chamber passed 21,000 feet, Post signaled he needed to descend.[46]

Afterward, Colley added bandolier-type cords, which were looped around the helmet and attached to a semi-rigid, 8-inch-wide sling that Post sat on. On August 29, Post reached 23,000 feet during 35 minutes in the chamber and by all accounts, was satisfied with the performance of the suit.[47]

On the following day, Post took the *Winnie Mae* on the first flight with an operating pressure suit. On September 5, 1934, Post reported that he reached 42,000 feet over Chicago during an altitude-record attempt sponsored by the Pure Oil Company (now part of Chevron) as part of the Chicago World's Fair.[48] The flight revealed that the pressure suit worked well, although some minor adjustments would be necessary, including extending the control stick to allow the inflated glove to better grasp it. The maximum pressure differential on the flight was 3 psi.[49]

From Chicago, Post called Will D. "Billy" Parker, the aviation director for Phillips Petroleum.[50] After explaining that the Pure Oil Company and other sources of financing for his stratosphere experiments were drying up, Post asked if Parker could interest Phillips in sponsoring his flights. Post soon flew the *Winnie Mae* to Bartlesville, OK, to meet with Frank Phillips, sealing a deal.[51]

Post used his pressure suit on eight or nine flights at Bartlesville, reportedly reaching 50,000 feet. However, it takes two independent means to verify a record; in this case, those sources of verification were two barographs installed in the aft fuselage by the National Aeronautic Association, the U.S. representative to the FAI. Unfortunately, the National Bureau of Standards reported that both barographs failed on all but one flight on which one barograph failed and the other recorded only 38,000 feet after corrections for atmospheric conditions. No record for Post.[52]

Despite the setback, Post began to prepare for a coast-to-coast stratospheric flight. He flew to Burbank, CA, for one further modification to *Winnie Mae:* eliminating the landing gear to reduce drag. At the Pacific Airmotive Hangar in Burbank, Jimmy Gerschler and the soon-to-be-legendary Clarence L. "Kelly" Johnson—another person who would have a major influence on later events—designed new main landing gear that could be jettisoned via a handle in the cockpit. A spruce timber was glued to the fuselage for use as a skid during landing, and a strong V-shaped support was placed in front of the lower engine cylinders that ran to the lower front edge of the NACA cowling. Post made five flights at Burbank, all using the pressure suit in preparation for his stratospheric flight.[53]

Transcontinental and Western Airlines (TWA) joined Phillips Petroleum as sponsors of the flight and arranged for Post to carry airmail, including special stamps bearing his picture and the inscription "First Air Mail Strato-sphere Flight."[54] On February 22, 1935, Post took off, but the engine began to leak oil after only 31 minutes, forcing Post to land on Muroc Dry Lake, later home to Edwards Air Force Base, only 57 miles from Burbank. Since Post could not doff his pressure suit helmet by himself, he walked about 400 yards to ask H.E. Mertz for assistance; Mertz promptly fainted. A few days later, Post announced that it was not a broken oil line that had foiled his flight, but rather emery dust that mechanics found in his engine. Someone had deliberately sabotaged the flight.[55]

After repairs, Post tried again. On March 5, he got as far as Cleveland before his oxygen ran out. After climbing out of the airplane and removing the pressure suit, Post learned that he had flown 2,035 miles in the record time of 7 hours and 19 minutes. The *Winnie Mae* had averaged a ground speed of 279 mph, approximately 100 mph faster than she should have flown. Two more flights followed, the first ending at Lafayette, IN, (1,760 miles) on April 14, after the external supercharger failed, and the second ending at Wichita, KS, (1,188 miles) on June 15 after a piston burned-through.[56] Post decided the *Winnie Mae* was too old and tired for further attempts. He had nonetheless proved the practicality of a pressure suit, spending about 30 hours in the stratosphere. The *Winnie Mae* approached ground speeds of 340 mph, more than a third faster than the airplane's normal maximum speed. The Smithsonian Institution subsequently purchased the *Winnie Mae*, which is currently on display at the Udvar-Hazy Center near Washington Dulles International Airport in Chantilly, VA. The helmet from Post's first suit, and his entire third suit, are also in the collection of the National Air and Space Museum.

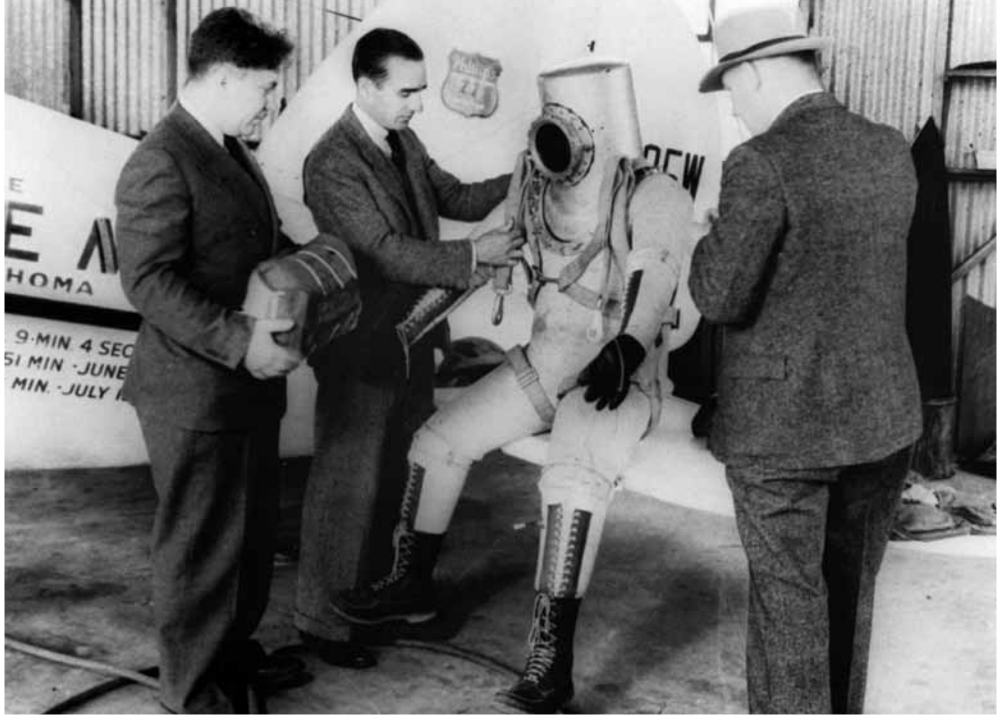
On August 15, 1935, just 2 months after his last flight in the stratosphere, Post made his final takeoff, in a bastardized Lockheed Orion-Explorer seaplane in Alaska. The engine stopped at a low altitude, and the ensuing crash killed Post and his passenger, humorist Will Rogers. Post was only 36 years old but had made an indelible mark on aviation.[57]

INTERNATIONAL EFFORTS

The 1930s saw considerable international competition to set altitude records, and this spurred the development of several pressure suits. It should be noted that almost all of these were simple up-and-down flights that

Wiley Post peers over the top of the Winnie Mae *while wearing his pressure suit. Given it was the first of its type to be used operationally, the Russell Colley-designed garment worked remarkably well.*

Courtesy of Lockheed Martin Aeronautics



Post tried numerous times to set an altitude record, but it was just not to be. Despite his failure at this one endeavor, Post remains one of the early aviation legends.

Courtesy of Chevron Corporation Archives

spent little time at high altitude and did not put the same stress on aircraft, pressure suits, or pilots as does cruising in the stratosphere. In addition to the Americans and British, the French, Germans, Italians, Russians, and Spanish developed high-altitude pressure garments, all of which would later be called full-pressure suits. There were many objectionable features to these early suits since they prevented evaporation of perspiration, greatly restricted mobility when pressurized, and were heavy and bulky.[58] Nevertheless, they worked, mostly.

The Italians developed a suit in 1933 to allow *Regia Aeronautica* pilots to set altitude records using several specially built open cockpit Caproni Ca.161 airplanes. These were conventional biplanes based on the Ca.113 with staggered wings of equal span. The suit, designed by Capt. Cavallotti, was made of several layers of canvas and rubber, with a metal collar that attached to a cylindrical metal helmet with square viewing ports. The electrically heated suit used metal alloy restraint devices, including a breastplate, to prevent the fabric from ballooning. In 1934, Baronessa Carina Negroni reportedly wore the suit to climb to 50,583 feet, undoubtedly becoming the first woman to use a pressure suit. Despite several reports that the Italians, including Negroni, used the suit to set records in the mid-1930s, the FAI database does not reflect this. It is likely that the reported flights took place but were not recognized by the FAI for various reasons.[59] Ultimately, Italian Col. Mario Pezzi took the altitude record from the British on October 22, 1938, when he climbed to 56,046 feet above Guidonia Montecelio, Italy. He used a modified Caproni Ca.161bis that had extended chord wings and a supercharged engine driving a four-blade propeller. However, Pezzi did not use a pressure suit on this flight since the Ca.161bis had a pressurized cockpit.[60]

In France, Dr. Paul Garsaux developed a suit during the mid-1930s with the backing of the Potez Airplane Company. Garsaux was a pioneer of aviation medicine in France and director of the Paul Bert Aeromedical Center at Le Bourget. During World War I, Garsaux developed an aviation oxygen system that used an aluminum mask shaped to conform to the wearer's face, with inflatable face-sealing bladders to ensure a tight seal. The mask had a built-in heating system to avoid the exhaled water vapor turning to ice.[61]

The first Garsaux suit, codeveloped with Dr. Rosenstiel from the French Navy, used two layers of linen, but this proved unsatisfactory and was soon replaced by laminated layers of silk and rubber doped with acetone to make it airtight. Large shoulder joints allowed arm movement and a set of gloves was spring-loaded into a closed-fist position. A round Duralumin helmet had rectangular eye openings made of two layers of glass with an air space in between them to prevent fogging, although the mask also had an electric defogging system. At only 31 pounds, the French suit was lighter than the one used by Wiley Post.[62]

Garsaux demonstrated the suit at Le Bourget in June 1935. Most likely, Marie-Louise "Maryse" Hilsz wore the suit when she set the female altitude record of 46,949 feet on June 23, 1936, flying a Potez 506 over Villacoublay, France. The climb took 36 minutes in the 770-hp biplane. Similarly, Georges Détré likely used the suit when he climbed to 48,698 feet over Paris in a Potez 506 on August 14, 1936, although no documentation was available to confirm he used the suit.[63] Unfortunately, all of Garsaux' work and records were destroyed by German bombs on June 3,1940, and by October all further aeromedical research in France had been halted by the Nazi occupiers.[64]

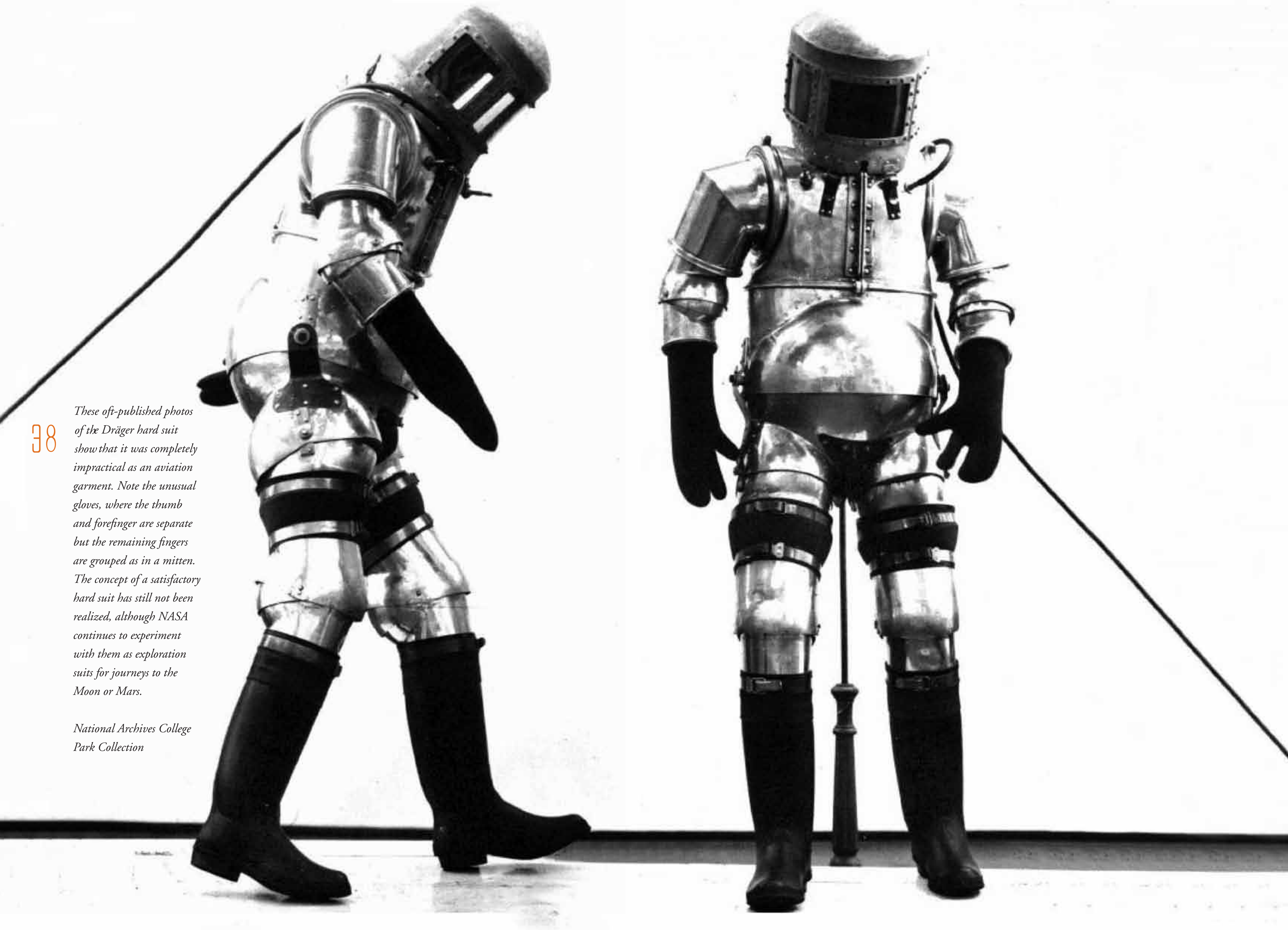
As might be expected, the Germans were not idle. In 1935, Dräger-Werke AG in Lübeck, Germany, began developing a hard-shell, full-pressure suit for the German Air Ministry. Dräger was familiar with technologies that involved pressure, including beer-tap systems that used compressed carbon dioxide, medicinal compressed-oxygen systems, anesthesia machines, and aviation-oxygen systems. Perhaps most famously, the company produced the Dräger underwater breathing apparatus used by the Germans during World War II.[65]

The requirements levied by the Air Ministry included being able to operate at an internal pressure of 11.8 psi (0.8 atmosphere) with a "three-fold safety factor." The ministry wanted a suit that would fit a pilot 5 feet, 10 inches tall and permit "rapid dressing and undressing without additional help."[66] The suit needed to allow free movement of the arms, legs, and fingers to permit the pilot to fly the aircraft and provide the possibility of parachute escape. Electric heaters would protect against the cold at high altitude and prevent fogging of the visor. Dräger calculated that the required test pressure of 35.3 psi necessitated the use of a heavy material that "cannot readily be formed into a garment."[67] Nevertheless, the company produced a series of "hard suits" that looked much like medieval suits of armor.

Based on revised, relaxed requirements, the first Dräger full-pressure suit used laminated layers of natural silk cloth and rubber strengthened by an external layer of silk fishnet cord that was supposed to control the fabric's tendency to balloon under pressure. The helmet, made of the same material, was integral to the suit, but under pressure the ballooning fabric pressed the visor painfully against the pilot's forehead. Despite the silk cord, the entire suit ballooned unacceptably, so the engineers replaced the silk fishnet with steel wire and reduced the internal pressure to 4.4 psi (0.3 atmosphere). This helped somewhat, but the wire presented a safety hazard by catching on any protuberance in the cockpit. In addition, the suit elongated (head to feet) to the point that the pilot could no longer see out of the visor. Eventually, the idea evolved to using chainmail mesh, allowing a pressure of 11 psi (0.75 atmosphere), but this severely restricted mobility and ultimately proved unsatisfactory.[68]

One of the most difficult requirements faced by Dräger, and all future pressure suit developers, was how to provide sufficient mobility at the joints. Dräger started with a tube with longitudinal folds held in place with one longitudinal band. This provided, under pressure, a tube that was flexible in one plane, but it provided insufficient mobility. A careful analysis of pilot movements in the cockpit of large aircraft showed that the arms did not need a full range of movements; only the forearms needed to move enough to manipulate the control wheel and throttles. This led to the development of airtight ball-bearing socket joints used at the shoulders, biceps, elbows, and wrists. By 1942, Dräger was concentrating on aluminum hard suit designs pressurized at 11 psi that still offered satisfactory mobility. In June 1942, Dräger demonstrated a hard suit to the Air Ministry; it was unacceptably heavy, difficult to walk in, and never became operational.[69]

In the meantime, on October 28, 1941, the Air Ministry ordered Dräger to develop an emergency descent suit. Unlike all earlier full-pressure suits designed to be the only protection for a pilot in an unpressurized cockpit, the get-me-down suit provided only short-term protection when an otherwise pressurized cockpit suddenly depressurized. If the cockpit suddenly depressurized as the result



These oft-published photos of the Dräger hard suit show that it was completely impractical as an aviation garment. Note the unusual gloves, where the thumb and forefinger are separate but the remaining fingers are grouped as in a mitten. The concept of a satisfactory hard suit has still not been realized, although NASA continues to experiment with them as exploration suits for journeys to the Moon or Mars.

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of battle damage or equipment failure, the suit would quickly inflate to 2.2 psi to protect the crewmember long enough to descend to a survivable altitude. The crewmember wore an ordinary oxygen mask inside a cloth helmet, and air from an engine-mounted compressor pressurized the suit when required. Ultimately, this helmet proved unsatisfactory and the Germans eventually settled on a completely clear plexiglass[70] dome helmet, but this new helmet still used a separate oxygen mask inside it.[71]

The Luftwaffe experimental station (*Erprobungsstelle*) at Rechlin, Germany, tested a series of get-me-down models, but a flaw in the original logic quickly became apparent. Initially, the Luftwaffe viewed the suit as a method of keeping the crew alive after cabin pressure failed without regard of who would actually be flying the airplane. Unfortunately, the initial suits, when inflated, offered almost no mobility. This led to the development of ball-bearing joints, similar to those developed for the heavy hard suit, at the shoulder, elbows, and wrists. The final suit was made of rubberized silk and was entered through an enlarged neck opening, although work continued on a two-piece suit that was entered at the waist. Again, there is no evidence that the get-me-down suit entered production.[72]

Oddly, in the summer of 1944, the German Glider Research Institute ordered Dräger to develop a rescue suit for use in gliders equipped with pressurized cabins. The pilot was to fly in a prone position, and the Institute indicated that freedom of movement under the 3.1-psi operating pressure was not a concern.[73] There is no evidence that this suit was ever completed.

This Dräger Model 8 get-me-down suit was possibly the most developed of the German suits. Note the large, clear plexiglass helmet. The pilot is not wearing his oxygen mask in this photo, but the shape of the helmet was partly dictated by needing to allow the pilot to move his head side to side within the helmet while wearing the mask. Pleats at the elbows and knees provided at least some measure of flexibility when the suit was pressurized.

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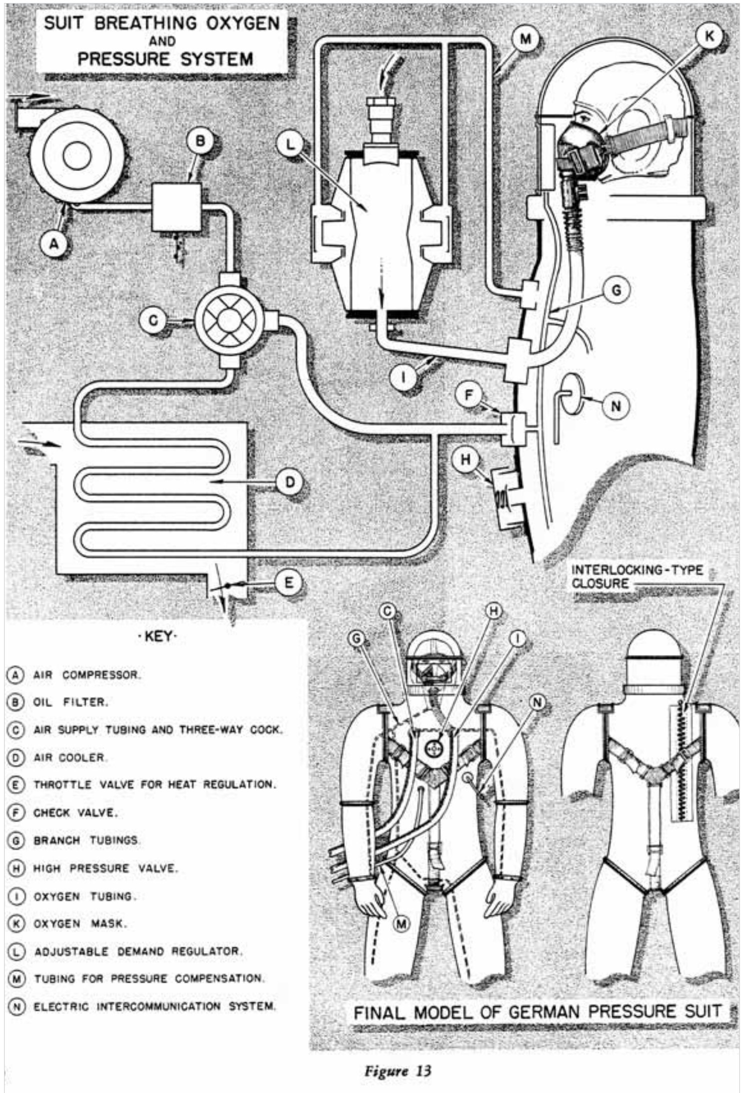
In Spain, Col. Don Emilio Herrera Linares built a full-pressure suit in anticipation of an open-basket balloon stratospheric flight scheduled for early 1936. Unfortunately, the Spanish Civil War intervened. Herrera chose the Republican side and cannibalized the rubberized silk suit to make rain ponchos for Republican troops. In 1939, Herrera fled to France, where he died in exile in 1967.[74]

The Herrera suit used an inner airtight garment covered by a pleated metallic frame with articulating joints for the shoulders, hips, elbows, knees, and fingers. When tested at the Cuatro Vientos Experimental Station, near Madrid, the suit's pressurized mobility was found to be "thoroughly satisfactory" according to its inventor, although this was most certainly an overstatement based on experience with later suits. The helmet faceplate had three heated glass layers: one unbreakable, another with an ultraviolet filter, and the outer one opaque to infrared. Initially, based on the cold atmosphere present at high altitudes, Herrera included an electric heater in the suit. However, when Herrera tested the suit in an altitude chamber, he noticed that even at an ambient temperature of –110 ºF, the temperature inside the suit climbed rapidly to 90 ºF. A trained engineer, he soon realized that the task was not to warm the suit but rather to remove body heat by some method. Herrera called his stratospheric suit an escafandra estratonautica. Unfortunately, mostly because of the urgencies of war, the suit was never used in an airplane or a balloon.[75]

When declining to help Mark Ridge, the British Air Ministry concerns centered on the indeterminate flight paths of balloons, not on the Haldane-Davis suit itself. After Ridge returned to the United States, Dr. Gerald Struan Marshall, consultant and applied physiologist for the Royal Air Force, worked with Siebe Gorman to continue development, resulting in the procurement of several prototype suits. These two-piece garments used rubberized fabric fastened together with a metal and rubber belt at the waist. Instead of a metal helmet like Ridge and Post used, Siebe Gorman used a simple rubber fabric cover with a curved visor made of two layers of Celastoid. Pure oxygen pressurized the suit to a maximum 2.5-psi differential through a flexible tube attached to the right side of the faceplate. Exhaled air exited the left side of the faceplate into a chemical canister that dried the air and removed the CO_2.[76]



After World War II, the U.S. Army Air Forces issued a "Translation of a Report on Development of a Pressure Suit" that contained this diagram of "the final model German pressure suit." The suit is obviously a soft-suit but does not precisely match the description of any specific suit in the report.

Courtesy of the David Clark Company, Inc.

Squadron Leader F.D.R. "Ferdie" Swain[77] used one of these suits to take a Bristol 138a to an altitude of 49,944 feet over Farnborough on September 28, 1936. The Bristol was an experimental all-wood monoplane intended specifically to capture the world's altitude record. A 43,000-foot oxygen-equivalent altitude was maintained in Swain's suit because greater pressures reduced mobility and comfort to an intolerable degree. The suit performed satisfactorily, although Swain complained of some discomfort as the suit inflated and he found it difficult to move his arms and legs. However, as the pilot began to descend after his record flight, the faceplate began to fog over and he found it difficult to breathe. Unable to unzip his suit, Swain had to slice open his visor with a knife as he descended through 14,000 feet.[78] Despite the problem, the FAI ratified this flight as a world record.[79] On June 30, 1937, Flight Lieutenant Maurice James Adam wore a modified suit to set a record of 53,937 feet in the Bristol 138a. On this flight, the canopy failed and the Haldane-Davis pressure suit likely saved the pilot's life.[80]

AEROMEDICAL PIONEERS

Shortly after the first powered flight in 1903, scientific interest in the medical aspects of flight grew dramatically. It quickly became obvious that the aviation environment was very different from the environment on the ground. On the cusp of World War I, the War Department was aware of the need to improve the fitness and efficiency of military aviators to carry out combat operations. In 1917, a Medical Research Board was chartered to investigate all conditions that affected the efficiency of pilots, determine the ability of pilots to fly at high altitudes, develop suitable apparatus for the supply of oxygen to pilots at high altitudes, and consider all matters relating to the physical fitness of pilots. This led to the establishment of the Army Signal Corps Medical Research Laboratory on January 18, 1918, at Hazelhurst Field on the outskirts of Mineola, NY. The laboratory's research scientists initially focused on developing pilot selection standards and understanding the effects on humans of exposure to high altitude.

Already, aeromedical scientists were well aware that the lack of oxygen (hypoxia) was the pivotal hazard encountered during flight. The effects of hypoxia had been investigated by Dr. Paul Bert (1833–1886), a French zoologist, physiologist, and politician, who carried out 670 separate experiments from 1870 to 1878 dealing with the physiologic effects of altered atmospheric pressure. In 1874, Bert subjected two balloonists, Joseph-Eustache Croce-Spinelli and Henri-Theodore Sivel, to a chamber altitude of 23,000 feet to investigate the use of oxygen to prevent hypoxia. On April 15, 1875, Gaston Tissandier, a French chemist, meteorologist, and aviator, joined Sivel and Croce-Spinelli on a balloon flight

Ferdie Swain used a later Siebe Gorman suit to capture the world's altitude record in 1936. The lineage of the suit to the early work of Haldane-Davis is obvious. Although the suit seemed to perform satisfactorily for the short up-and-down altitude flights, it severely restricted movement and was generally uncomfortable.

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that reached 28,820 feet before descending after all three occupants lost consciousness. Although Bert had warned the men about the necessity of using supplemental oxygen at altitude, they apparently failed to heed the advice, and Croce-Spinelli and Sivel asphyxiated, marking the first reported casualties due to hypoxia. Tissandier survived to tell the tale.[81]

During World War I, combat pilots found it necessary to fly above 15,000 feet to avoid ground fire and soon began reporting symptoms including headache, loss of muscle strength, dizziness, and fatigue. In addition, cases of unexplained losses of aircraft began to accumulate. Physiologists soon recognized the root cause as a lack of oxygen and the Army Air Service mounted a major effort to develop the "Clark-Dreyer Oxygen System," consisting of an automatic regulator and a leather and rubber mask, in 1918. However, the war ended before the new oxygen system was actually installed in more than a small fraction of Army combat aircraft.

Shortly before the end of the war, a young chemical engineer, Lt. Harold Pierce, joined the Medical Research Laboratory after completing a physiology teaching fellowship at Harvard University. In 1919, he designed a second-generation altitude chamber fabricated by the Lancaster Iron Works. The chamber, insulated with cork and equipped with a refrigeration unit, enabled researchers to study human response to combined cold stress, reduced atmospheric pressure, and oxygen starvation that occur at altitude. During unmanned tests, the chamber reached an altitude of 75,000 feet at a temperature of –31 ºF. Using this facility, researchers at Hazelhurst built the foundation for modern protective flying equipment.

In November 1919, the Medical Research Laboratory moved to nearby Mitchel Field and was subsequently renamed the School of Aviation Medicine on November 18, 1922. Mitchel Field was named in honor of a former New York City mayor, John Purroy Mitchel, who was killed while training for the Air Service in Louisiana. Before the War ended, Mitchel Field served as a major training base for the rapidly expanding Air Service and proved to be an ideal home for the new School of Aviation Medicine. Four years later, in the summer of 1926, following the rapid postwar drawdown of the Air Service, the War Department moved the School of Aviation Medicine to Brooks Field, TX, to collocate it with the flight training program at that base. The school's research program was redirected to focus on understanding the practical requirements for the selection and care of pilots. The "Mineola Chamber" was declared surplus and subsequently shipped to the Equipment Laboratory at Wright Field, OH. Closing the chamber was based on the school commander's annual report that declared, "There is reason to believe that the facts of physiology which have been so extensively investigated during the past six years are far in advance of the immediate requirements for the Air Service." This conclusion, of course, proved to be false.[82]

In the fall of 1929, Harry George Armstrong graduated from the School of Aviation Medicine and decided his future lay in military aviation. During his first assignment as the flight surgeon for the First Pursuit Group at Selfridge Field, MI, Armstrong discovered how inadequate the equipment used by pilots was. While flying in an open-cockpit Berliner-Joyce P-16 from Minneapolis to Chicago in late 1934, Armstrong discovered his flight clothing provided little protection against the elements. Exposed to –40 ºF air temperatures, Armstrong suffered severe frostbite, his goggles frosted over, and he did not have an oxygen mask. Following his return to Selfridge, Armstrong thought about the obvious physiologic threat to combat effectiveness and wrote a letter to the Air Surgeon in Washington. He concluded his letter with a strong recommendation that the Air Corps Research and Development Center at Wright Field address the deficiencies in protective flying equipment immediately. Sometimes you need to be careful what you ask for. As a result of his letter, Armstrong was transferred to the Equipment Laboratory of the Engineering Section at Wright Field to serve as an aeromedical advisor.

In 1935, now-Capt. Harry Armstrong established the Physiological Research Unit as part of the Equipment Laboratory. He discovered the "Mineola Chamber" sitting idle, covered with dust in a storage room in the basement. Armstrong had the chamber refurbished and used it for 2 years to conduct research on the physiologic effects of altitude. During this period, the Air Corps began developing the long-range bombardment aircraft that redefined the meaning of extreme environments. The Equipment Laboratory was assigned responsibility for development of a sealed pressure cabin for high-flying bombers. Armstrong was tasked to define the physiologic requirements for a pressurized cabin.[83]

To meet this challenge, Armstrong recruited several talented scientists, including J. William "Bill" Heim, who was about to complete postgraduate training in physiology at Harvard University. Heim accepted Armstrong's invitation and remained at Wright Field for more than 31 years. Armstrong and Heim defined the requirements for the pressurized cabin demonstrated in the Lockheed XC-35 during 1937.

Armstrong was among the first to recognize that in addition to the effects of altitude, pilots were becoming exposed to increased g-forces during aerial maneuvers. In response, he designed the first human centrifuge in the United States. Though unsophisticated by modern standards, the Balloon Hangar centrifuge, fabricated by the Equipment Laboratory machine shops, allowed Armstrong to study the effects of accelerative forces on blood pressure, first using goats, and finally humans.

Armstrong's research encompassed virtually all aspects of aerospace medicine, and many of his investigations were the first of their kind to be carried out anywhere in the world. An abbreviated list of the aeromedical problems he investigated during his 6 years as director of the laboratory include the following:[84]

- Hypoxia and requirements for supplemental oxygen;
- Reduced atmospheric pressure effects on the middle ear, nasal sinuses, and dental fillings;
- Explosive decompression;
- The risk of gas bubbles forming in the body and prebreathing requirements;
- High-altitude flight stresses, including cold exposure, loss of body fluids, and flying fatigue;
- Acceleration effects on blood pressure and vision;
- Vertigo, airsickness, and spatial disorientation; and
- Toxic hazards in the cockpit, including carbon monoxide and radioactive materials.

Armstrong understood the human element was an important factor in aircraft design; yet engineers of his time paid little attention to the pilot. Another young physician, Dr. Otis O. Benson, Jr., (then a captain) became the second chief of the laboratory. Under his direction, the Aeromedical Research Unit separated from the Equipment Laboratory and formed three units of its own (Physiological, Biophysics, and Clinical Research). The newly named Aero Medical Laboratory was moved from its overcrowded quarters into a new building of its own on Wright Field, and Benson organized a research program for the laboratory that persisted throughout World War II. He staffed the laboratory with nationally known scientists, drawing significantly upon the contacts that he had developed earlier in his training at the Mayo Clinic and Harvard University. In collaboration with the Mayo Clinic, he established a human centrifuge program to evaluate G-suits and the effects of acceleration on pilots. Prior to World War II, Benson recognized the need for a radically different method of supplying oxygen to aircrews at high altitude and led the development of the diluter demand oxygen system.[85]

THE U.S. ARMY REDISCOVERS THE PRESSURE SUIT

Despite having tested Wiley Post's full-pressure suit in 1934, the Army Air Corps was late to start the development of its own suit. It was not until October 10, 1939 that the Army tasked three companies—B.F. Goodrich, Goodyear Tire & Rubber, and United States Rubber—to investigate the concept of a full-pressure suit for crews of future high-altitude aircraft. Based on these initial studies, during the latter part of 1940, the Army issued contracts to B.F. Goodrich and U.S. Rubber for the development of experimental pressure suits. For the most part, the early pressure suit contracts ran concurrently with the development of the G-suit, although they seldom involved the same companies. Captain John G. Kearby of the Equipment Laboratory at Wright Field was the project officer for the pressure suit contracts.[86]

The requirements levied by the Army on both companies included completely enclosing the aviator, using fabric that could withstand pressure and oxidation effects, and delivering a prototype suit within 120 days. Other requirements, ones that would continue to prove difficult for decades, included permitting the "proper articulation of the limbs and waist" and using a transparent helmet "to permit the full visibility range."[87] At first, the Army used a sequential "Type" number for the pressure suits. Somewhat later, it adopted an "XH" designation (presumably for "Experimental, High altitude"). There was no correspondence between the "Type" designators and the later "XH" designators.

The B.F. Goodrich contract, W535-ac-17000 of November 29, 1940, covered the fabrication of one high-altitude pressure suit at a cost of $6,100. A contract amendment in February 1941 added a second pressure suit of a slightly revised design. Goodrich had an advantage over the other contractors: its project lead, Russell Colley, had already developed a workable full-pressure suit for Wiley Post.[88]

Goodrich delivered the first Type 3 suit, called a "Strato-Suit" by Colley, to the Aero Medical Laboratory in the spring of 1941. This was a two-piece garment made of rubberized fabric that used a large transparent plexiglass helmet. Unlike later suits, this model was pressurized using oxygen and a separate oxygen mask was not required. The oxygen hose attached to the helmet ring directly in front of the face, perhaps not the ideal location. The tight fitting suit had metal arms and articulated metal elbow joints that resembled a medieval suit of armor. Surprisingly, according to Colley these elbow joints did not leak. The body and legs had multiple straps between various locations to control ballooning. During initial testing, the suit was pressurized to 2.5 psi for 10 minutes without serious leakage. The Army thought, however, that the neck joint was overly complicated and that the suit was difficult to don and doff.[89]

The U.S. Rubber contract, W535-ac-18048 of December 19, 1940, covered the fabrication of a single pressure suit at a cost of $500 and one G-suit for $142. The low price and 30-day delivery schedule were the result of the suits having been developed by researchers at Wright Field; U.S. Rubber was simply fabricating them. The 80-pound Type 1 pressure suit used rubberized fabric with a lace-up front closure and a large transparent plexiglass

Table 3—1943 U.S. Army Pressure Suite Designations

Original "Type" Designations		Later "XH" Designations	
Type 1	U.S. Rubber	XH-1	B.F. Goodrich
Type 2	U.S. Rubber	XH-2	U.S. Rubber
Type 3	B.F. Goodrich "Strato-Suit"	XH-3	Goodyear
Type 4	U.S. Rubber	XH-4	U.S. Rubber
Type 5	B.F. Goodrich "Strato-Suit"	XH-5	B.F. Goodrich
Type 6	B.F. Goodrich "Strato-Suit"	XH-6	B.F. Goodrich
Type 7	National Carbon Company	XH-7	National Carbonic
Type 8	B.F. Goodrich	XH-8	Unknown
Type 9	Goodyear	XH-9	Goodyear

The designation systems were separate and reflected different pressure suits (i.e., the Type 1 was not the same as the XH-1).

helmet. Three assistants were required to dress the wearer. The original rubber mittens proved difficult to use, so U.S. Rubber manufactured a steel manipulating device, eerily similar to the one used a quarter century later by the robot on the *Lost in Space* television series, for the left arm only, as an alternative. Elaborate rubber accordion bellows were located at the elbows and knees to provide flexibility under pressure.[90]

Testing the U.S. Rubber suit at the Aero Medical Laboratory disclosed numerous deficiencies, including excessive expansion, leakage, and severe discomfort when the suit was pressurized. But perhaps the most critical problem, and the one that would prove most vexing to correct, was that at 3 psi the suit became so rigid that the wearer could barely move. The Army amended the contract on February 18, 1941, to cover the addition of a single Type 1A pressure suit at the cost of $4,210 and a single Type 1G G-suit for $142, both for immediate delivery. Although the Army tested the two types of suits independently, the goal was to discover the best features of both and eventually to combine them into a single garment.[91]

As had the original Type G, the Type 1G G-suit proved essentially worthless, and the Army did not pursue the design further, explaining why U.S. Rubber is not mentioned in the G-suit chapter. When the Army tested the Type 1A pressure suit, an adjustment strap tore and U.S. Rubber switched its efforts to the Type 2. This revised suit was generally similar to the Type 1A, except it used a zipper front closure and rubber gloves. Since the basic suit was little changed, it too went rigid when pressurized. Despite a relatively poor showing, U.S. Rubber had substantially simplified the Type 2 suit and reduced its bulkiness and leakage.[92]

Shortly after the initial batch of suits arrived at Wright Field, the British Air Commission requested information concerning the American pressure suits. The Materiel Division wrote a special report for the commission including the latest details of the Goodrich and U.S. Rubber suits, and in February 1942 provided an unidentified pressure suit to the Royal Aircraft Establishment at Farnborough.[93]

In a May 3, 1941, memo, Maj. Gen. Henry H. "Hap" Arnold, the acting chief of staff for air, informed Lt. Gen. George H. Brett, the Chief of the Air Corps, that the British were already routinely flying above 35,000 feet using supercharged engines in their fighters. Arnold believed it was essential that the United States be prepared to fly at these altitudes without using pressurized cabins, essentially meaning that pressure suits would be mandatory. To emphasize his point, Arnold commissioned a survey by now-Maj. Harry Armstrong of high-altitude operations in England. Armstrong discovered that, despite British claims, the Royal Air Force (RAF) had not conducted operational flights above 35,000 feet until 2 months prior to the survey and did not routinely fly at such altitudes. Nevertheless, Armstrong endorsed the development of a pressure suit.[94]

When the Army began testing a revised Goodrich pressure suit at Wright Field, it found the new garment considerably improved over the initial suit. After approximately 10 minutes with the suit pressurized to 2.5 psi, Army researchers noted that the overall comfort and freedom of motion were fair and that the normal movements required to fly an airplane were possible with some effort. The researchers also reported that the suit was much easier to don and doff than previous garments. Joint articulation, particularly of the fingers, was possible even at 3 psi inflation.[95]

These tests seemed to indicate that a satisfactory high-altitude pressure suit was attainable, and the Army awarded Goodrich a new contract (W535-ac-21580) on September 25, 1941, for two Type 5 suits. The first suit cost $6,500 while the second cost an additional $7,500. The Army wanted the first suit delivered within 90 days and the second within 180 days. These suits were made of rubberized fabric and used fabric bellows-type elbow joints braced with thin steel rods. There was a steel brace across the front of the chest that connected to shoulder rings that supported the arms. Colley intended this arrangement, incorporated into many later Goodrich suits, to control ballooning. The pressurization hose, electrical wires, and radio connections attached to the left side of the abdomen. Testing showed this suit offered relatively decent mobility and did not suffer from any significant deficiencies.[96]

During 1941, several American aircraft companies expressed interest in developing their own pressure suits. For instance, Bell Aircraft submitted a $12,695 proposal to the Army to fabricate a single pressure suit, reportedly for use in a high-altitude version of the Bell P-39D Airacobra. During an inspection tour, Boeing chief test pilot Edmund T. "Eddie" Allen approached Maj. John W. Sessums, Jr., the assistant technical executive at Materiel Division, about having a Seattle company build a prototype pressure suit and charging the estimated $5,000 cost to the B-17F production contract. Allen indicated that if the suit proved successful, Boeing would purchase at least 10 of them to protect its pilots during flight tests. Sessums knew the problem of pressurizing the aircrew would eventually confront all manufacturers of combat airplanes equipped with turbocharged engines and high service ceilings. Although Sessums declined to allow Boeing to develop a pressure suit, he commented on the desirability of inviting engineers and pilots to Wright Field to coordinate the development of a suitable pressure suit and of familiarizing them with the problems involved.[97]

Sometime in late 1941, the aircraft companies decided to take things into their own hands, at least to some extent. Bell and Boeing joined with the Strato Equipment Company of Minneapolis, MN, to develop a pressure suit. John D. Akerman (1897–1972) had founded the company to develop oxygen equipment for high-altitude flight, as well as iron lungs for patients with respiratory paralysis. Akerman had an interesting biography, graduating in 1916 from the Aeronautical School of the Imperial Technical Institute in Moscow, studying under professor Nikolai Yegorovich Zhukovsky, and enlisting in the Engineering Corps of the Russian Army's air service branch. He immigrated to the United States in 1918 and graduated from the University of Michigan in 1925 with a B.S. in aeronautical engineering. Akerman worked with the Ford Stout Airplane Company and Hamilton Metal Plane Company and advanced to Chief Engineer of the Mohawk Aircraft Corporation. In 1929, he joined the University of Minnesota and founded the Department of Aeronautical Engineering. For the next 20 years, Akerman worked with many aircraft manufacturers and was the Dean of Faculty of Aeronautical Engineering at the University of Minnesota from 1931 until 1959.[98]

Akerman was friends with Dr. Walter M. Boothby at the Mayo Clinic and spent a considerable amount of time working with the Mayo researchers, only 81 miles away in Rochester, MN. Ultimately, between late 1941 and the middle of 1943, Akerman would lead the development of a series of at least nine pressure suits that he designated BABM for Boeing, Akerman, Bell, and Mayo.

Akerman designed the BABM suits to operate at 1.5 psi, meaning a pilot at 50,000 feet altitude would feel like he was at 37,000 feet. This was a much lower pressure than the typical 2.5–3.0 psi used by other suits. All of these tight fitting suits used double-layer construction so that a tear in one layer would not render the suit useless. Pilots wore the suit over regulation underwear and under their flying clothes. Six different valves were used to pressurize each suit, including ones that provided ventilation air for the head, hands, and feet. Unsurprisingly, given the Bell and Boeing connections, various versions of the suit were optimized for use in the P-39 Airacobra and B-17 Flying Fortress. For instance, the model designed for use in the B-17 had a helmet that could be removed from the front of the face rather than over the head, simplifying donning and doffing with a low overhead.[99]

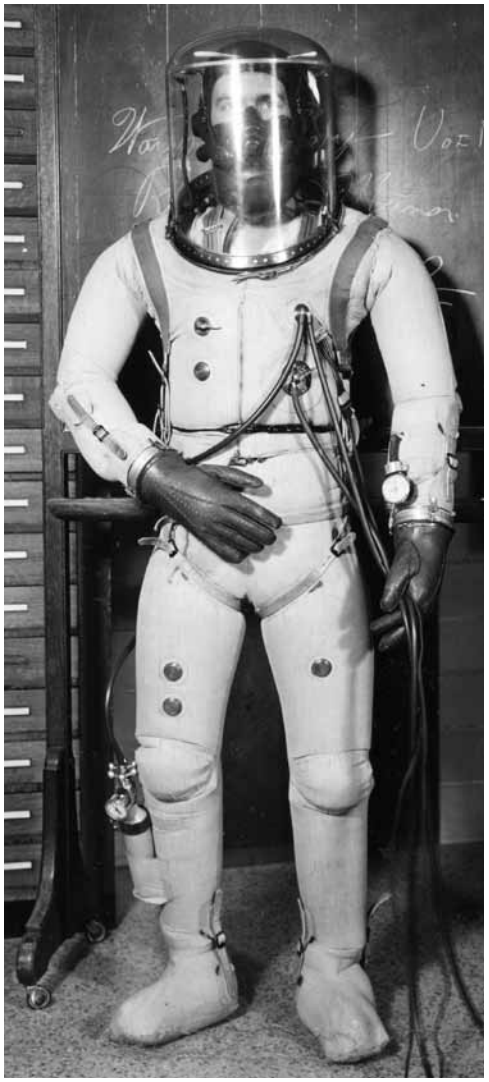
During the week of January 12, 1942, representatives from the Army, Boeing, the Mayo Clinic, and the University of Minnesota held a series of conferences in Seattle to discuss oxygen equipment. Boeing disclosed that it had contracted, using company monies, with Akerman to develop the pressure suit that the Army had declined to fund the previous year. Boeing acquired Akerman's services to further its understanding of high-altitude flight in anticipation of improved models of the B-17 and the upcoming B-29. Akerman had already developed, fabricated, and tested several suits. However, despite progress with the suits, Boeing cancelled scheduled flight tests using a B-17E because the company did not believe they had sufficient understanding of the underlying physiology. At the time of the conference, the BABM suits were cumbersome to don and doff, it was nearly impossible to bend at the waist when the suits were inflated, and the helmets were uncomfortable to wear for long periods.[100]

In a January 12, 1942, letter, Goodyear also expressed interest in manufacturing high-altitude pressure suits despite their exclusion from the initial round of development contracts the previous year.[101] After some negotiations, on July 16 the Army issued a $5,000 contract, W535-ac-31183, to Goodyear for four Type 9 suits. These two-piece garments used a unique fabric that promised significant advantages over previous fabrics. It was claimed that the fabric would stretch at proper joint locations, yet exhibit no tendency to balloon at operating pressures as high as 4 psi. Ward T. Van Orman, a champion balloon racer, headed the development effort. Goodyear estimated that production suits would cost just $200, versus $1,000 for the other suits under consideration.[102]

For 5 days beginning on January 16, 1942, Bell test pilot Mervin E. Erickson wore the third BABM suit, logically called BABM-3, in the newly opened Strato-Lab environmental chamber at Boeing Plant 1 in Seattle. Dr. Walter M. Boothby and Dr. William J. Randolph "Randy" Lovelace II had already evaluated the chamber and pronounced it ready for operation. The chamber had a 108,000 British thermal unit (Btu) refrigeration unit capable of producing temperatures less than –100 °F.[103] Erickson spent 60 minutes in the chamber at temperatures ranging from –57 to –61 °F accompanied by two Boeing technicians wearing electrically heated flying suits. Neither the air used to compress the pressure suit nor the breathing oxygen was heated. The suit had undergone cold weather testing in Minneapolis earlier in January.[104]

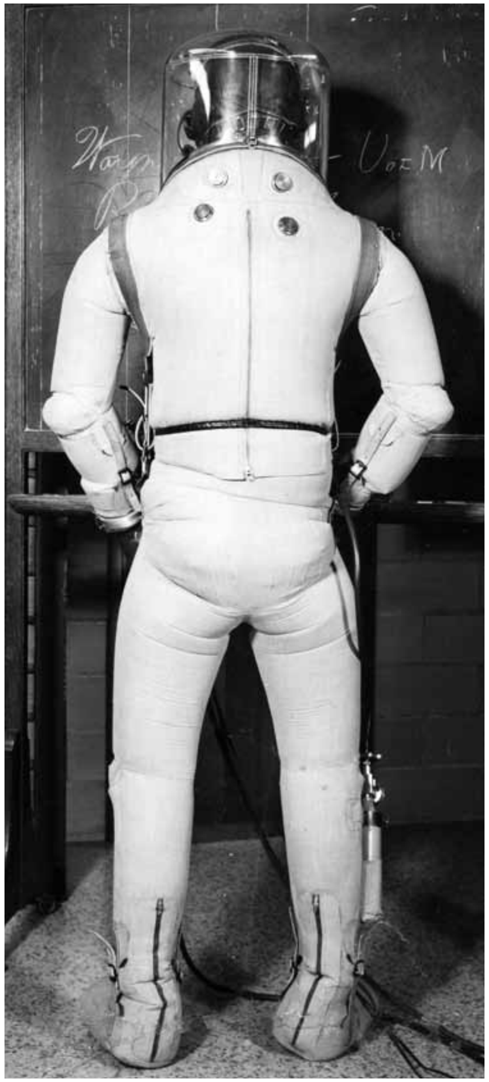
Two days later, on January 18, Erickson and Lovelace went to 53,800 feet in the Boeing Strato-Lab at temperatures as low as –4 °F. Boothby and Arthur H. Bulbulian from Mayo Clinic monitored the test. The following day, Al C. Reed, Boeing chief test pilot, evaluated the BABM-3 in a B-17 cockpit. After donning the suit, Reed spent 30 minutes moving around to acquaint himself with the limitations of the suit and then climbed into the pilot's seat. Compressed air and oxygen were supplied through long hoses from supplies outside the airplane. Reed went through all the motions necessary to fly a mission and had major complaints about only three things: he could not reach the landing light switches, could not see the dials on one of the radios on the ceiling, and had great difficulty seeing instruments on the lower edge of the panel near his knees.[105]

On January 20, 1942, the Army ordered 10 Type 6 Goodrich suits, generally similar to the earlier pair of Type 5 garments, for $34,500. A month later, the Army placed another order, this time for six Type 6A suits. All of these suits had a pressurization hose and electrical connection in the middle of the abdomen. A further modification, the Type 6B, incorporated a conduit that contained the oxygen hose as well as the electrical and radio connectors. The conduit attached to the left side of the abdomen and the wearer could disconnect it in one quick motion if he needed to abandon the airplane. Standard A-9 gloves and A-6 boots were worn over the suit for thermal protection. The Type 6B suit was tested at Eglin Field, FL, in October, and it showed promise, the suit still ballooned and limited mobility more than desired. By April 1942, Goodrich had progressed to the Type 8A suit. Although much improved, it still did not meet the minimum specifications.[106]



At the same time, the Army ordered 10 slightly modified U.S. Rubber Type 4A suits at a cost of $25,000. The 2-piece Type 4A was made from dark, rubberized fabric with an integral helmet, boots, and gloves of the same material. The Aero Medical Laboratory deemed the U.S. Rubber Type 4A suits unsatisfactory, primarily for a lack of mobility. However, the lessons learned from these suits contributed to the development of the XH-2 suit. This two-piece ensemble used detachable rubber gloves and the lower legs and integral boots were detachable at ring joints just above the knees. Unfortunately, the suit was still too rigid and offered inadequate ventilation. This was the final suit produced by U.S. Rubber.[107]

The Army awarded Bell a contract (W535-ac-24203) on February 7, 1942, stipulating the first suit would be delivered within 30 days. Ultimately, developing the helmet would frustrate Bell, as it would most other developers. On February 21, 1942, Bell wrote the contracting officer, indicating they



Right and photos on page 48: Researchers at the Mayo Clinic tested this unidentified BABM suit sometime during late 1942 or early 1943. The suit was typical of the Akerman garments, being tight fitting and well tailored. Note the pleated knee and elbow joints and the leather straps holding the gloves and boots on.

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Left: During one of the tests, a set of cold-weather leather outer clothing was worn over the BABM pressure suit. Note the helmet is somewhat different than the other Akerman suits, with a flat metal top instead of being all plexiglass.

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The XH-2 was the last full-pressure suit produced by U.S. Rubber. Initially, U.S. Rubber had produced suits designed by Army researchers, but the XH-2 was, by all accounts, an indigenous design. Like several of its contemporaries, the suit had detachable gloves and legs to allow some tailoring to individual wearers.

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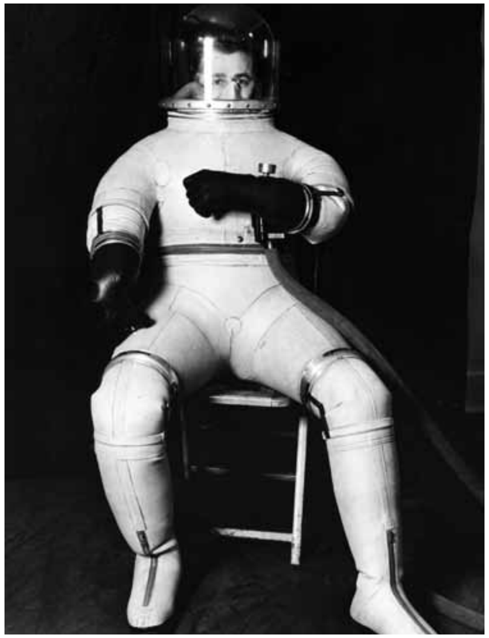

Above: All of the U.S. Rubber suits were extremely stiff when pressurized. The XH-2 used pleated elbows with adjustment straps that afforded some mobility that had been lacking in early suits. Note the position of the wearer's head in the helmet, graphically illustrating suit elongation. Interestingly, the pressure gauge on the left glove stood several inches above the garment.

Courtesy of the David Clark Company, Inc.

Above: The XH-2 was a two-piece design with an upper and lower torso that made donning the suit easy. A zipper ran completely around the waist and required an assistant to close it. Note the neck seal under the helmet and the relatively small hole the wearer had to maneuver his head through.

Courtesy of the David Clark Company, Inc.

were experiencing problems developing a satisfactory method of attaching the helmet to the suit, and would be unable to make their required delivery date. Wright Field agreed to extend the date to April 14, 1942.[108]

While at a conference at the National Carbon Company in Cleveland on February 13, 1942, researchers examined a multi-layer, plastic-fabric pressure suit based on the BABM garments designed by John Akerman. The suit consisted of an airtight Vinylite bladder worn over full-length cotton underwear covered by a tight fitting, single-piece restraint layer. A National Carbon employee modeled the complete 15-pound suit while inflated to 1.5 psi, and the garment appeared to be relatively flexible and offer reasonable mobility. Boothby and Akerman believed the suit was useable to 50,000 feet. Officials from the Aero Medical Laboratory were sufficiently impressed to order the suit, now designated Type 7, to be tested at Wright Field. The suit ultimately proved disappointing and the Army discontinued development, although Akerman later presented a similar suit to the Navy.[109]

The Army held subsequent conferences at Goodrich and the Royal Canadian Air Force Institute of Aviation Medicine in Toronto. At Goodrich, researchers inspected the texture of the material the company was using for their pressure suits and found it was essentially snag-proof and almost self-sealing when penetrated by a 0.50-caliber projectile. Stating the obvious, the conference report commented that, "it was anticipated that if the suit and its occupant were struck by a 20mm ball, or larger, the occupant would have no further need for the pressurization."[110] In Toronto, researchers observed tests in the recently opened human centrifuge. Once more, recommendations included the construction of a garment that combined the features of a pressure suit and a G-suit.

After the conference, Goodrich began development of the XH-1 suit. Made of brown rubberized fabric, the suit used bellows supported by thin steel rods attached to rings at the elbows and knees. The chest brace connected the shoulder ring joints, and wires ran from a waist ring to the knees for additional support and to minimize ballooning. A clear plexiglass helmet was attached to the neck ring and, as usual, the wearer wore a normal soft flying cover, earphones, and a demand-oxygen mask inside the helmet. Standard A-6 boots were worn over the suit's built-in feet.[111]

B. F. Goodrich developed the XH-1 suit, part of a series of increasingly better suits that were ultimately judged the best of the Word War II efforts. Bellows at the elbows and knees provided improved mobility. Note the metal rod stretching between the shoulder rings, an attempt to control side-wise ballooning. This would become a feature on most of the subsequent suits designed by Russell Colley.

National Archives College Park Collection

The suit was also fit checked in a Bell P-39D Airacobra (41-7100). The location is not identified, but given that Akerman was a consultant for Bell, it is likely the Bell facility in Buffalo, NY. It is uncertain if an attempt was made to fly with the suit.

By permission of the Mayo Historical Unit, Mayo Clinic, Rochester, MN

On May 22, 1942, Akerman tested the BABM-5 suit in the Mayo altitude chamber to a maximum of 40,000 feet with no ill effects. The following day, Bell chief test pilot Robert M. Stanley tested the BABM-7 suit in the chamber. Stanley believed the suit was sufficiently developed to try in an airplane, and by June 25, Bell had modified a P-39 cockpit to accommodate the pressure suit. Stanley realized that the suit and airplane were not well matched, primarily because the cockpit was too small to comfortably accommodate the suit. Two controls at the rear of the side of the seat could not be reached when the suit was pressurized, and the landing gear switch was too close to the helmet to be activated with a gloved hand. In addition, Akerman and Stanley determined the pressurized air provided by the airplane contained trace amounts of oil. It is not clear if Stanley ever flew the P-39 while using the pressure suit.[112]

Wayne W. Nay, a senior aeronautical engineer at the University of Minnesota, tested the BABM-9 suit in the Mayo altitude chamber on July 19, 1942. Akerman built this suit for Bell according to anthropomorphic measurements provided by the Aero Medical Laboratory at Wright Field. An airtight, lightweight, close-fitting helmet included built-in earphones, microphone, goggles, and a demand-oxygen mask. The suit had an umbilical that combined electrical connections, breathing-oxygen, connections, and compressed-air connections into a single conduit. Special shoulder-to-hip straps provided a hinge line to automatically facilitate bending and to hold the pilot in the sitting position required by the P-39. The Minneapolis-Honeywell Regulator Company provided the valves and regulators. The suit itself weighed about 8 pounds, increasing to 17 pounds when including the helmet, boots, and accessories.[113]

Nay donned the suit, unassisted, in 12 minutes and doffed it in 5 minutes. During the altitude chamber tests, Nay could write legibly on a chalkboard. The suit, like many of the BABM models, had a unique safety feature built into the neck ring: pulling one clamp separated the ring and allowed the helmet to be removed quickly. Normally, the helmet was removed by releasing a clamp on either side of the neck ring. The suit required between 3.0 and 3.3 liters of air per minute to keep it inflated to 1.5 psi. John Kearby tested the suit at Wright Field and found that it required 80 liters per minute to maintain 1.5 psi; exactly what accounted for the tremendous difference could not be ascertained. Subsequent tests at Minneapolis-Honeywell showed that even with all six vent valves completely open, 1.45 psi could be maintained with only 68.7 liters per minute.[114]

A week later, on July 25, 1942, Al C. Reed, William F. Milliken, Jr., and M.J. Lunier took three BABM pressure suits (a BABM-8, -8a, and -9) to 52,100 feet for 30 minutes in the Mayo altitude chamber. According to Akerman's account, on several occasions Reed, "went to the medicine cabinet, loaded a hypodermic needle, and pretended to give a hypodermic to the other two subjects."[115] This was meant to show the mobility afforded by the suit under pressure. The Mayo researchers monitored an Oximeter in Milliken's ear and determined his oxygen level was normal during the entire experiment.

By the middle of 1942, the Army had consolidated the Goodrich, Goodyear, and U.S. Rubber efforts into classified Project MX-117.[116] This was an overarching effort to provide pressure suits for high-altitude flight and G-suits for high-speed flight. According to a July 1, 1942, report, various companies had delivered eight experimental pressure suits since October 1940, and testing at Wright Field had shown that five were unsatisfactory for various reasons. The contractors had also delivered 10 G-suits, but no formal testing had yet taken place. At the time, Goodyear was under contract to deliver four pressure suits, and Goodrich and U.S. Rubber were to deliver 10 suits each by August 1.[117] Eventually, the Army awarded 13 contracts worth $129,695 in support of MX-117.[118]

Although a good deal of research was taking place on G-suits and pressure suits, it all seemed uncoordinated, at least to some of the researchers involved. The Army attempted to share development information among the contractors and research organizations that were working on the suits, but this effort never proved completely successful. Partly this was just the state of the art at the time; the Internet did not exist, and telephone and mail service was relatively crude and slow. In addition, developments in rubber chemistry and fabrics were often jealously guarded and protected from competitors. Military secrecy further restricted or delayed access to information.

For instance, Dr. Harold Lamport from Yale University stated that while researchers were working on pressure suits at the Mayo Clinic, at Welfare Island, NY, and in England, it appeared, "there [was] a remarkable paucity of reports concerning any of these suits."[119] In retrospect, these criticisms seem exaggerated. The major problem was that development was taking place in many scattered places and happening very quickly, which did not allow researchers to engage in their normal cadence of preparing formal reports, attending conferences, and exchanging ideas.

Partly to address these concerns, in August 1942, the Army published the results of an inspection tour that had examined several of the pressure suits then under development. At Bell, inspectors reviewed the 18-pound BABM-9 suit developed by John Akerman. At Goodyear, John Kearby and Maj. Joseph A. Resch from the Aero Medical Laboratory donned a Type 9A suit and found the 8-pound suit relatively flexible and comfortable at 4-psi pressure. The inspection team believed the suit could be adapted for gunners

The improved Goodyear Type 9A suit was tight fitting, with a large, full hemisphere helmet that provided good visibility. The Aero Medical Laboratory found the suit relatively flexible at its normal 4-psi operating pressure, but the zippers leaked excessively.

National Archives College Park Collection

and men operating in crowded positions in the airplane. One of its major problems was that, like almost all of the suits, it leaked around the zipper. This was solved when

Goodyear continued to improve the Type 9 suit, resulting in the XH-3A, which had detachable limbs to allow sizing the suit to each individual. Like all of the rubber suits, the XH-3A exhibited too much contraction when the elbows and knees were bent, significantly impeding mobility and causing a certain amount of pain for the wearer.

National Museum of the U.S. Air Force Collection

Ward T. Van Orman, now working at Goodyear, developed an airtight zipper with overlapping, interlocked rubber strips. Van Orman filed a patent application on February 9, 1943, and the patent (2,371,776) was granted on March 20, 1945, assigned to the aptly named Wingfoot Corporation.[120]

Based on the results of Kearby's evaluation, Goodyear built an improved XH-3 suit. This suit operated at 3 psi and consisted of a tight-fitting single-piece garment that weighed 12.25 pounds. A detachable transparent plexiglass dome helmet and integral gloves and boots completed the ensemble. The suit was donned through a crotch-to-neck airtight zipper. According to Kearby, it was one of the lightest suits and the easiest to don and doff. However, much like Russell Colley and Wiley Post—and pretty much everybody else—Kearby found the helmet and shoulders lifted upward under more than 2 psi. In addition, the suit was poorly ventilated, causing the wearer to perspire excessively.[121]

Goodyear worked on these problems, and the improved XH-3A had arms and legs that could be detached at ring joints above the elbows and knees. These changes facilitated customizing the size of the suit for each wearer and made donning and doffing a bit easier. Although much improved, the XH-3A still exhibited too much contraction at the 90-degree bend of the elbows.[122]

At the same time, the Army subjected the Goodrich XH-1 to a series of altitude chamber tests that showed the suit still suffered from excessive bulkiness, poor mobility when pressurized, and inadequate ventilation. These faults notwithstanding, Kearby took the XH-1 to a simulated altitude of 60,200 feet on October 2, 1942, and found it offered satisfactory physiological protection. This represented the highest altitude so far.[123]

During 2 weeks beginning on October 4, 1942, a crew using four experimental pressure suits—XH-1, XH-2, XH-3, and XH-6—made 5 flights in a B-17E at Eglin Field. Of these, the XH-1 and XH-3 appeared the most encouraging from a technical perspective, and the crew preferred the XH-3 since it was the lightest and easiest to don and doff. Nevertheless, the crew considered all of the suits too heavy and too restrictive of mobility. The pilots, in particular, complained the suits so affected their balance that movements were slow and awkward and that they lost the "feel" of their airplane. In fact, the Army ended the test program early, after only five of nine scheduled flights. The researchers concluded that none of the suits was truly satisfactory and that all needed further development.[124]

Seeking other opinions, on October 20, the Army loaned one of the Goodyear XH-3 suits to researchers at the Naval Air Crew Equipment Laboratory in Philadelphia for evaluation. Unlike Kearby, who thought the suit easy to doff, the Navy found it impossible to remove without the aid of an assistant. Navy evaluators also found it difficult to stand from a sitting position and impossible to stand upright under more than 2.5 psi pressure.[125]

Akerman demonstrated the BABM-8 suit, tailored for Al Reed of Boeing, at 31,110 feet in the Mayo altitude chamber on October 28, 1942. For this test, Akerman used a 2-pound air compressor that could supply about 55 liters of air per minute. A larger pump, weighing about 6 pounds, was available that could pressurize two suits simultaneously.[126]

On November 15, 1942, Akerman demonstrated the BABM-5 suit to LT Donald W. Gressly at the Naval Air Experimental Center at Philadelphia. Gressly was reportedly impressed with the suit's mobility and many details of the design but felt the 1.5-psi pressure differential was insufficient. Gressly and Akerman discussed designing a suit that used a 3.5-psi differential (the same as most of the other pressure suits then under development), but apparently, no agreements were reached.[127]

In December 1942, researchers tested an improved Goodyear XH-3A suit in a B-17F at Eglin Field. This suit was made using a tightly woven cotton fabric known as "Byrd Cloth" and could be worn over special interwoven double-layer wool-cotton flying suits for greater warmth. Byrd Cloth was named after the fabric worn by ADM Richard E. Byrd and his team during explorations that ranged from the poles to the tropics. The British Army adopted the material in the 1940s, and it was considered the gold standard in military fabrics for a generation. Known to the British as Grenfell Cloth, the material was a lightweight, tightly woven herringbone twill made of long-staple Egyptian cotton. The closely woven fabric allowed body heat to dissipate through sweat evaporation. Unfortunately, Byrd Cloth also tended to tear at seams.[128] Researchers made five flights to altitudes of 10,000 feet, 10,000 feet, 32,240 feet, 39,000 feet, and 40,000 feet and found that the fatigue caused by the suit's restricted mobility limited long-duration flights. The researchers believed that the suit exhibited too much contraction at the 90-degree bend of the elbow and the hose connectors on the underside of the neck ring were too large and heavy. In addition, the weight of the suit and its supporting

John Kearby used a Boeing B-17E, much like this one, to test full-pressure suits at Eglin Field, FL. The airplane could not fly high enough to actually need pressure suits, but it still provided a realistic temperature and motion environment to evaluate the usefulness of the garments.

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equipment added approximately 20 pounds per crewmember to the airplane.[129]

In January 1943, Bell finally delivered its first BABM suit to the Army, 8 months after the revised delivery date. Bell indicated it had successfully tested the suit to 50,000 feet in an altitude chamber, and the volunteers that donned the suit had been comfortable and, after some practice, were able to move about and write legibly.[130] Photographs show three of this model BABM suits in an altitude chamber at the same time, so at least that many were fabricated. At the Aero Medical Laboratory, Lt. Waring L. "Pete" Dawbarn wore the Bell suit for a 1-hour flight in the altitude chamber at 30,000 feet on March 25, 1943. Even inflated to only 1.5 psi, the tests revealed the suit suffered a severe lack of mobility that prevented the proper manipulation of simulated aircraft controls.[131]

Further flight tests at Eglin Field during the first half of February 1943 attempted to determine the usefulness of the various suits in a B-17 and Republic P-47 Thunderbolt. One extended flight in the bomber, to determine fatigue effects, showed that combat personnel could fly at any altitude without additional fatigue caused by the pressurized suits, contradicting earlier tests. Nevertheless, the evaluators suggested changes to the prototypes, and researchers wanted to make additional tests to better determine the pathological results that would accrue through frequent and regular use of high-altitude clothing.[132]

The results of the Army tests led Goodrich to develop the improved XH-1C, which was soon redesignated XH-5, as well as a largely new suit, the XH-6. In addition to the usual Goodrich chest brace, the XH-6 added a flexible wire that ran from the crotch up and across the chest and around the back. The arms and legs were detachable at rings above the elbows and knees, respectively. The separate arms and legs were constructed of heavy rubber to keep them from ballooning, with straps that could be fastened to help the wearer keep the limbs in the desired position. Dawbarn evaluated the suit beginning on April 19, 1943, and found the thick rubber arms and legs overly hindered mobility when pressurized. Work on the XH-6 was cancelled and all effort concentrated on the XH-5.

The Goodrich XH-5 was probably the best pressure suit developed during World War II. The suit was made of laminated rubberized fabric, and ball-bearing joints facilitated mobility at the elbows and knees. A Goodrich-designed self-sealing zipper ran from the crotch to the neck ring. Large, rounded bellows formed the arms and legs to improve mobility, leading to it being called the tomato-worm suit. According to Russell Colley, "I watched a tomato worm bend about 90 degrees, and the pressure in

Although the XH-6B was developed later in the war, Goodrich suspended work on the suit after determining the earlier XH-5 provided better mobility. This photo provides a good view of the neck seal inside the helmet. Note the straps on the knees that could be fastened in a variety of ways to maintain the desired sitting or kneeling position.

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the worm did not change as far as I could see. It did not increase in diameter; so I tried it on the suit."[133] Colley demonstrated the ability to don the 20-pound suit in under 4 minutes without assistance, and he stated it could be done in 1 minute with assistance.[134] Colley filed a patent for this suit on August 3, 1943, listing Carroll P. Krupp and Donald H. Shook as co-inventors and B.F. Goodrich as the assignee. The patent (2,410,632) was awarded on November 5, 1946.

The XH-5 was pressurized using an 8-pound, 24-volt electrical compressor that supplied 5 cubic feet (141 liters) per minute (cfm) at 3 psi and operated up to altitudes of 80,000 feet. The same type of combined umbilical first used on the Type 6B was fitted at the left side of the abdomen. The wearer wore a standard A-14 demand oxygen mask, although Goodrich also developed a smaller mask that could be worn instead.

The Army ordered a single XH-5 on April 10, 1943, at a cost of $3,350, but at least five others were delivered (one photo shows six suits in the Wright Field altitude chamber). Reports indicate more than 30 subjects wore the suits in the altitude chamber during tests as high as 80,000 feet. In September, Armstrong took the suits to Eglin Field and made five flights aboard a B-17F at altitudes up to 25,000 feet. The evaluators determined that despite its advances, the XH-5 was still uncomfortable,

The Goodrich XH-5 was commonly called the tomato-worm suit, in reference to its exaggerated bellows on the arms and legs. The laminated rubber fabric suit was somewhat bulky and sagged when it was not pressurized. This was in stark contrast to the tight-fitting Mark IV suit that Russell Colley would later design for the U.S. Navy.

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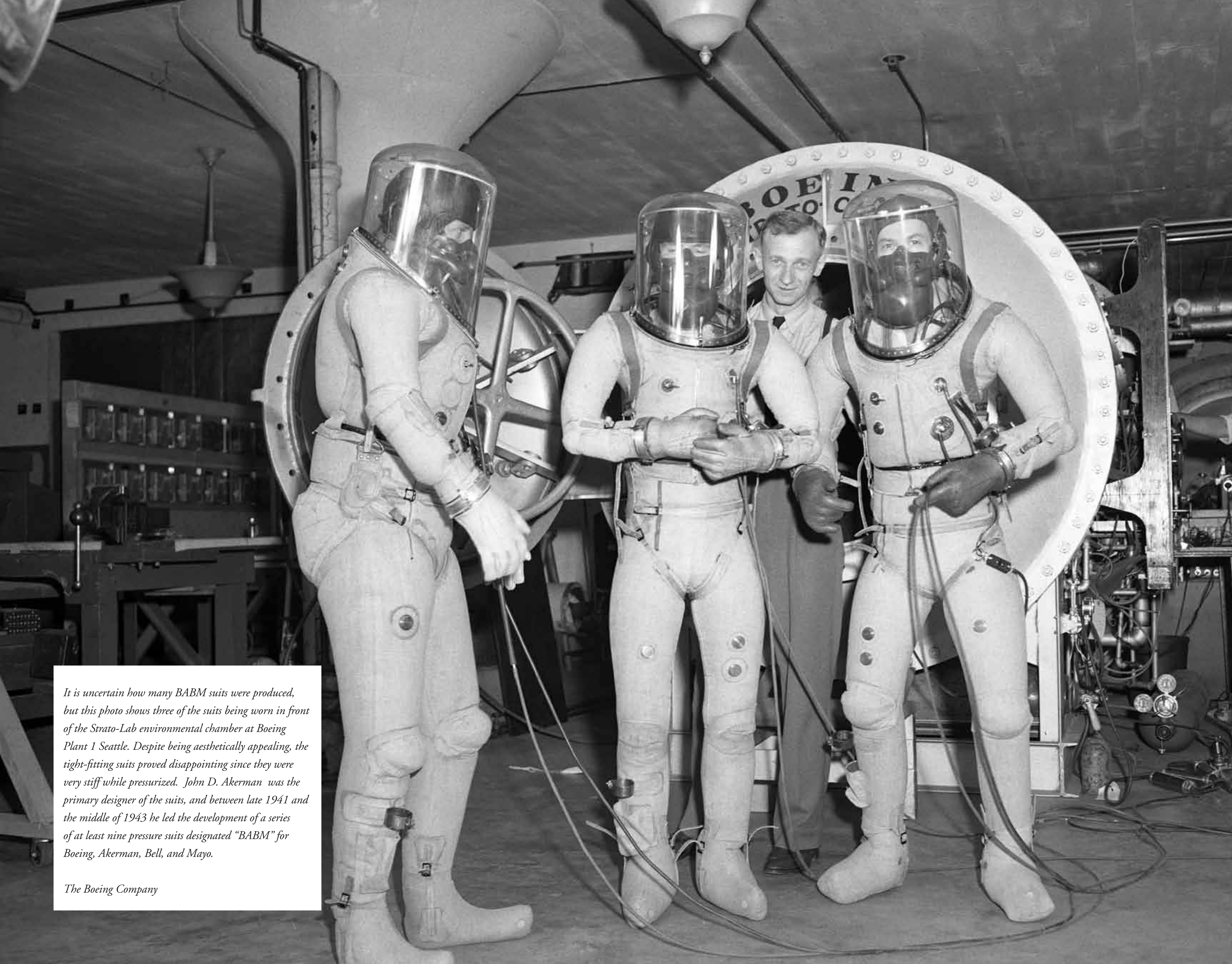
Bell delivered this version of the BABM suit to the Army in January 1943, and the suit was extensively tested by Boeing. The tight-fitting suit provided adequate mobility when unpressurized, but proved extremely stiff when pressurized even to 1.5 psi. The suit still required the use of a traditional oxygen mask inside the large clear helmet.

The Boeing Company



It is uncertain how many BABM suits were produced, but this photo shows three of the suits being worn in front of the Strato-Lab environmental chamber at Boeing Plant 1 Seattle. Despite being aesthetically appealing, the tight-fitting suits proved disappointing since they were very stiff while pressurized. John D. Akerman was the primary designer of the suits, and between late 1941 and the middle of 1943 he led the development of a series of at least nine pressure suits designated "BABM" for Boeing, Akerman, Bell, and Mayo.

The Boeing Company

As with all of the contemporary suits, it was impossible to stand straight while the XH-5 was pressurized. This was not considered particularly significant but served to demonstrate the relative lack of mobility afforded by the suits. Perhaps the most significant advantage of the XH-5 was that it did not elongate excessively, and the pilot's head stayed centered within the hemispheric plexiglass helmet.

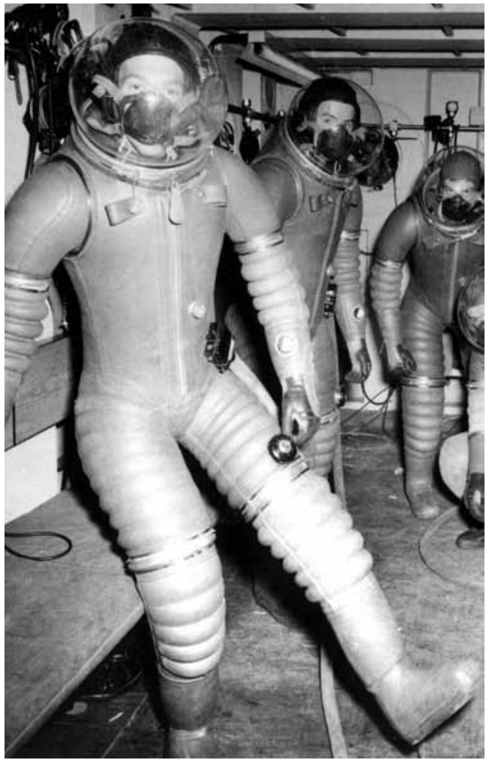
National Archives College Park Collection

suffered from inadequate ventilation, and required too much effort to move the arms and legs when pressurized. Wearers were unable to use the Norden bombsight, the defensive machine guns, or the radio controls on a B-17. Although it might be possible to adapt the airplane to the suit, as built, the suit could not adapt to the airplane.

The Army ordered the final Goodyear suit, the $750 XH-3B, on April 7, 1943, and the suit was tested late in the year. For the most part, this suit was an evolutionary development of the garments that had come before. Van Orman filed for a patent on this suit on October 6, 1943, and it (2,401,990) was granted on June 11, 1946. Ultimately, along with the Goodrich XH-5, this suit came closest to meeting the stated Army requirements for a full-pressure suit.[135]

During the summer of 1943, the U.S. Navy tested several of the Army pressure suits at the Naval Air Crew Equipment Laboratory in Philadelphia. LCDR Donald W. Gressly was the flight surgeon in charge, assisted by mechanical engineer L.W. Meakin. For the most part, the Navy did not identify the suits by a model number, only by a manufacturer, making it difficult to determine exactly what they tested. However, their observations were interesting.

Between February 15 and February 19, 1943, Meakin and physicist W.E. Scott tested a



This photo shows at least four XH-5 suits in the Wright Field altitude chamber (only a part of the fourth suit may be seen at center right in a crouched position). Other photos from this series show six suits. The two suits nearest the camera are not fully pressurized, allowing the wearers to stand straighter than normal (note the hunched position of the suit at the back of the chamber).

National Archives College Park Collection

25-pound U.S. Rubber suit under the supervision of then-Lieutenant Gressly. The suit consisted of an upper and lower torso section, and separate arms and legs attached via metal rings on the upper arms and thighs. Two zippers connected the upper and lower torso with an inflatable rubber tube between them as a seal. A metal neck ring formed a twist-type lock joint with the dome helmet. A Wiggins Type 108A demand regulator supplied oxygen.[136]

At 1.5-psi inflation, arm and leg movement proved possible but difficult, and it was only possible to stand up from a sitting position with great difficulty. The elongation of the suit made downward vision nearly impossible. At 2.5 psi, the suit was even more uncomfortable and less mobile. At this pressure, the helmet had risen to the point that outward vision was nearly non-existent and it was impossible to stand up even with assistance. At both 1.5 and 2.5 psi, the left elbow joint opened unexpectedly. At 3.5 psi, all movement was impossible. Gressly wore the U.S. Rubber suit in the Navy altitude chamber up to 60,000 feet without incident, although perspiration proved to be a problem and movement was largely impossible.[137]

Between June 1 and July 15, 1943, the Navy tested the 22.25-pound B.F. Goodrich Type 5E Strato-Suit that operated at 3.5 psi. Metal shoulder joints with ball bearings allowed 360-degree rotation, and metal arm and leg connector rings allowed various size limbs to be attached as needed. Accordion pleats in the hip, knees, and elbows were designed to facilitate mobility. The pilot donned the suit through a zipper, covered by rubber flaps, which ran from the crotch to the neck. The Goodrich garment used a Wiggins Model A15 diluter demand type oxygen regulator with the diluter side closed off. The suit used a neck seal and a dome helmet connected via a grooved metal ring with a clamp. There was a differential pressure gauge on the left forearm.[138]

During sea-level tests of the Goodrich suit, Greesly and Meakin found the garment leaked around the neck ring and the ring bent easily, making it impossible to secure the helmet until it was repaired. The suit, designed for a 6-foot man, did not fit either of the Navy evaluators particularly well, making it difficult to judge its comfort. When pressurized to 3.5 psi, the shoulders and helmet rose such that the neck ring almost covered the eyes. Standing up from a sitting position was accomplished only with great effort, but arm, finger, leg, and foot motions were "comparatively good." The suit could be self-donned, but mobility, even when unpressurized, was insufficient to enter a fighter cockpit without assistance. When the suit was pressurized, the pilot could not see many of the instruments, could not operate any of the controls on the side consoles, and could not reach up to open or

The B.F. Goodrich Type 5E Strato-Suit weighed 22.5 pounds and was significant in having detachable arms and legs, allowing a certain amount of tailoring for the individual. The neck seal for the helmet is shown at top left.

Courtesy of the David Clark Company, Inc.

close the canopy. The suit was not adequately ventilated, and perspiration accumulated in the gloves and boots. In addition, the location of the oxygen inlets, near the ears, resulted in an unacceptable noise level. Greesly and Meakin found the suit unacceptable in its current form but believed it could be improved relatively easily.[139]

Concurrently with their tests of the Goodrich suit, between July 5 and July 16, 1943, Gressly and Meakin tested a 20-pound suit made by the Strato Equipment Company. The BABM suit the Navy tested was representative of the later John Akerman creations. The suit was made of two layers of rubberized fabric, operated at 1.5 psi, and consisted of five pieces: an upper torso, trousers, a pair of gloves, and a helmet. Metal connecting rings at the neck, waist, and wrists secured the pieces together. There were leather straps running from the waist ring over the shoulders to prevent rising and from the waist to the crotch to prevent elongation. A pocket under each armpit creased by thin wire aided mobility for the arms. Straps across the stomach and thighs provide breaking points in the inflated fabric for forward bending and sitting. Three clamps attached the gloves to a rubber gasket, and a standard Army harness and parachute was worn over the suit. There were five zippers on each suit: one 11-inch zipper on each side, one 11-inch zipper on the trouser at the waistline, one 11-inch zipper on the chest of the torso, and one 11-inch zipper on the back of the torso. In theory, flaps on the inner side of each zipper provided an airtight seal.[140]

The double-layer transparent methyl-methacrylate helmet was 11 inches in diameter with an elliptical top. The front of the helmet sloped down below the neckline to provide downward visibility, and a perforated tube ran around the front side of the top to distribute air and prevent fogging. The helmet was attached to the suit using two clamps on a neck ring. Like all of Akerman's suits, a third clamp provided a way to quickly separate the neck ring and helmet with one motion in case of an emergency. Dry air was trapped between the layers of the helmet to prevent fogging.[141]

Ventilation air was routed through spring tubing to the middle of the back, head, arms, hands, and legs. The head ventilation port was automatically closed when the helmet was removed. The ventilation valve automatically closed when the air supply was disconnected to ensure the suit remained pressurized for a short time. This was intended for use when the pilot bailed out of an airplane. The Type B-12 constant-flow oxygen mask had two inputs—one from the airplane and one from the bailout bottle—and automatically switched to whichever one was delivering pressure. Akerman used a Wiggins Type 15A diluter demand-oxygen regulator.[142]

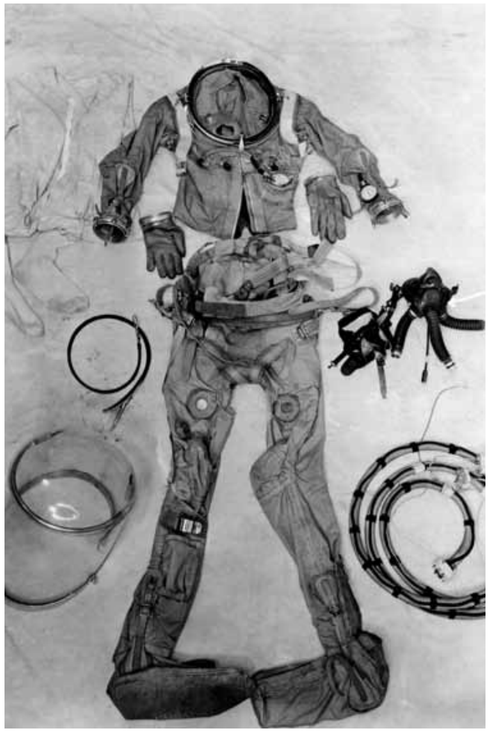
Sea-level testing revealed minimal leakage, but the suit was difficult to don and doff without assistance. Downward visibility was good,

The Type 5E was not particularly flexible, and this hunched-over stance was about as straight as a subject could stand. Although evaluators considered limb motion "comparatively good," a seated pilot could not operate many cockpit controls when the suit was pressurized.

Courtesy of the David Clark Company, Inc.

and elongation and helmet rise were well controlled. The wearer could easily climb into the cockpit of a Vultee SNV-1 trainer (the Navy version of the BT-13A Valiant) without assistance when the suit was deflated. With the suit inflated to 1.5 psi, gross movements were easily accomplished, but fine movements, such as adjusting instruments or controls in the cockpit, were very difficult. The ventilation in the suit was adequate and no excessive perspiration was noted. Perhaps the largest complaint was a pungent odor, likely from the particular plastic, within the helmet that caused extreme nausea. Gressly tested the suit in the altitude chamber to a simulated 50,000 feet. He noted that any movement within the suit, or pressing on the outside of the suit, caused a partial deflation, and because of this, internal pressure varied between 0.7 and 1.5 psi constantly.[143]

Between July 12 and July 21, 1943, Gressly and Makin tested a Goodyear suit that operated at 2.5 psi. The black rubberized fabric one-piece suit weighed 12.25 pounds and used a Wiggins Type 108A demand regulator. Donning the suit was done through a front zipper with rubber flaps that ran from the crotch to the neck ring. A hinge-type clamp attached to the rubber neck ring tightened the ring around the dome helmet to form



The BABM-18, created by John Akerman's Strato Equipment Company, was one of the most advanced of the World War II suits. The suit was fabricated in five pieces: the upper torso, trousers that included pressure footings, a pair of gloves, and the clear helmet. The oddly shaped helmet was a recurring theme on several BABM and early David Clark Company full-pressure suits.

Courtesy of the David Clark Company, Inc.

an airtight seal. A pressure gage was on the left forearm, and built-in restraint straps prevented elongation of the suit.[144]

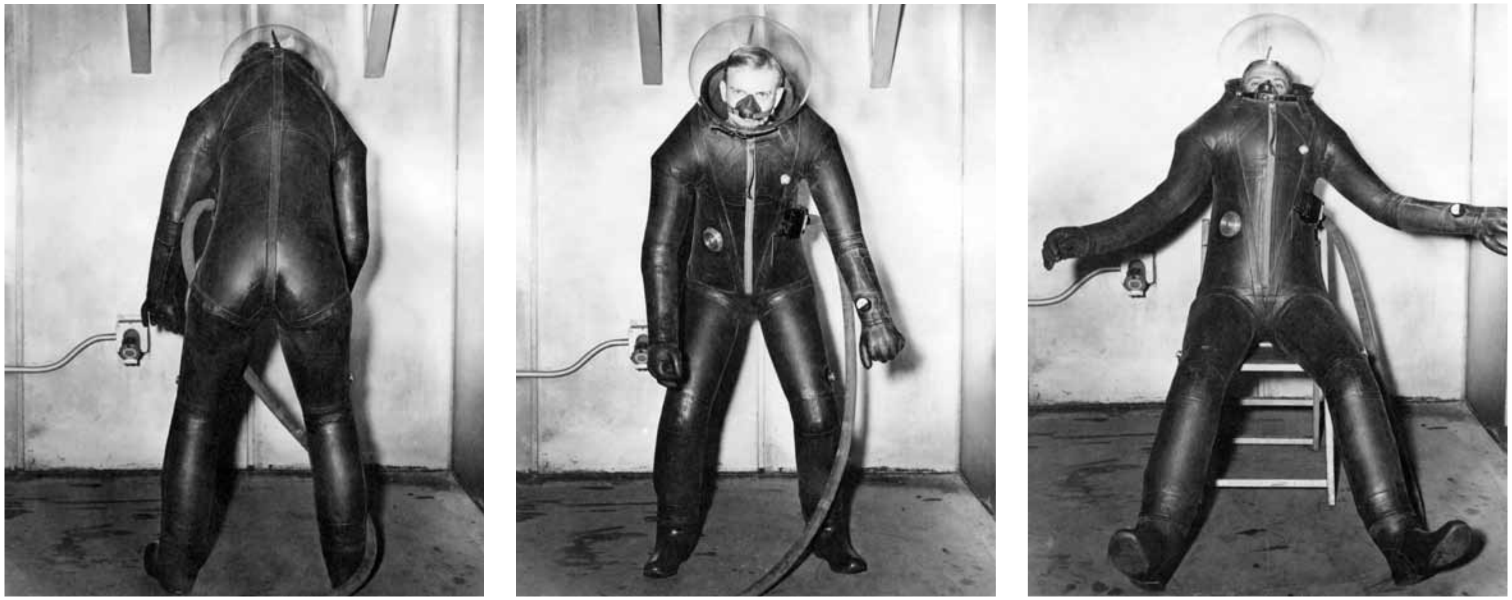
Tests of the Goodyear suit showed that it was impossible to stand up from a sitting position without assistance, and even then it was impossible to stand upright when the suit was inflated. Oddly, Gressly thought the "rubber flap and zipper seal was satisfactory" even though the suit lost 1 psi per minute when the air supply was shut off. Since the suit was made in a single piece, a tear in a glove or leg would render the entire suit useless until it was repaired, unlike the multi-piece suits from Goodrich and others in which a new arm or leg could be attached easily. The cockpit evaluation showed the wearer had a very restricted range of vision and could not see any control or instruments in the airplane. Shoulder, arm, hand, and leg mobility was difficult and tiring, and there was no ventilation in the arms or legs, leading to excessive perspiration. The Navy evaluators also commented that the suit had no provisions for adjusting to subjects of varying heights and weights, meaning that a custom suit would need to be made for every pilot, something the Navy believed unacceptable.[145]

Between November 3 and December 9, 1943, Gressly and Meakin tested a 34-pound General Electric pressure suit. The suit consisted of a one-piece rubberized fabric inner suit, outer trousers, an outer waist section, a methyl-methacrylate dome helmet, gloves, and metal crotch reinforcement. The suit used a neck seal and there were small vents in the toes and back of the gloves to help ventilation. The suit featured hinged metal shoulder rings to improve mobility and restraining straps across the arms, upper thighs, and from the knees to the instep to prevent elongation. The metal crotch support prevented ballooning and facilitated hip and trunk motion.[146]

The Navy found the suit was difficult to don and doff without the aid of an assistant. The rubber neck seal was fragile and tore easily, and despite the toe and hand vents, subjects perspired excessively. When the suit was not inflated, subjects "were able to move about quite freely," but when it was inflated to 2.5 psi, all motions were made with great

The BABM-18 used leather straps that ran from the waist and crotch over the shoulders to control elongation, although the design of the helmet still allowed the pilot to see even if it rose several inches. Note the break points at the knees and waist to allow bending.

Courtesy of the David Clark Company, Inc.



This Goodyear suit was much less sophisticated than the contemporary XH-3A for not having detachable limbs. Like most suits of the era, the suit elongated excessively as it pressurized—note the position of the subject's head within the suit while in the seated position. This, of course, made it nearly impossible to pilot an airplane while wearing the suit.

Courtesy of the David Clark Company, Inc.

difficulty.[147] The suit was worn by a representative of General Electric in the Navy altitude chamber up to 50,000 feet altitude. At 2.5 psi in the chamber, fine motions were jerky and difficult and the subject perspired excessively.

The Navy concluded its evaluation of the Army suits with a note that, "all suits so far tested have been characterized by requiring so much exertion to enable the person within to maintain a normal sitting position that generalized fatigue is outstanding."[148] The report noted that movement was practically impossible at 3.5 psi in any of the suits. The Navy also seemed to place a different emphasis on what movements were important.

> Manufacturers' claims of fine movements in the fingers and hands do not clearly represent the basic problem of mobility for it is in the area of greatest diameter, such as the trunk, thighs, and shoulder rotation where mobility has been found to be greatly restricted by pressure. Also, rotation of the forearm from the elbow joint has been exceedingly difficult. All movements from these areas of greater diameter are of a rough, jerky type and are often of lesser or greater magnitude than intended. In the standing or kneeling positions, as may be required of bombardiers or gunners, the restriction in motions necessary for these men to be efficient are considered too great due either to the inability to perform the motions or the fatigue resulting from such performance.[149]

The Navy also criticized the suits as too heavy, uncomfortable, and not sufficiently ventilated to remove perspiration. Seemingly ignoring the state of the art in airtight fabrics, the Navy

Top Left: The General Electric suit had a one-piece gas container with built-in booties and glove liners. Separate outer gloves were provided. The metal shoulder rings were supposed to allow increased mobility while pressurized, but testing at the Naval Air Crew Equipment Laboratory showed that motion was jerky and difficult, even at a relatively low 2.5 psi.

Top Right: General Electric used a two-piece outer suit to further control ballooning and provide a protective layer for the delicate rubber gas container. The outer suit used integral boots and had a variety of straps to provide some size tailoring and control ballooning.

U.S. Navy photos, courtesy of the David Clark Company

Like most of the full-pressure suits of the era, this General Electric suit ballooned when it was pressurized and significantly restricted mobility. Note the unusual stance of the wearer. GE included a variety of straps on the arms and around the torso in a generally unsuccessful attempt to control ballooning.

U.S. Navy photos. Courtesy of the David Clark Company researchers believed any pressure suit should be made of a lightweight fabric, although they noted that the General Electric and Akerman suits, which used such fabric, tore too easily under pressure. Acknowledging a problem first noted by Russell Colley and Wiley Post, the Navy researchers found all the suits elongated to the point that the helmet rose above eye level. The Navy concluded that "none of the pressure suits … have been able to fulfill the requirements" needed for an operational suit. Much like the Army, the Navy concluded the Goodrich suit, although unsatisfactory, offered the most promise.[150]

The Army program suffered a major setback on August 2, 1943, when Maj. John G. Kearby (1905–1943) was killed after his Lockheed A-28 Hudson crashed. He was returning to Wright Field after flight-testing a full-pressure suit at Eglin Field. In addition to being project manager, Kearby had been the first subject to test an Army pressure suit in an altitude chamber and the first to test one in flight. On October 18, 1943, Maj. Gen. Franklin O. Carroll, chief of the Engineering Division, recommended Kearby be posthumously awarded the Legion of Merit; Maj. Gen. Charles E. Branshaw, commander of the Air Materiel Command, concurred on January 10, 1944. The citation noted that, "Between November 1942 and March 1943, Maj. Kearby personally conducted extensive flight tests of the pressure suit at Eglin Field, running risks which not only endangered his life, but which were far beyond the call of duty."[151]

Despite the setback, the Army tested the improved Goodrich XH-5 and Goodyear XH-3B suits at Eglin Field in September 1943 and found them airworthy but not ready for combat. The Goodyear suit, in particular, severely restricted mobility to the point that it was unsuited for use at any crew position, but it provided sufficient physiological protection to be used on special missions to any altitude readily foreseen as possible. Nevertheless, the improved suits showed remarkable advancements over the original pressure suits tested in 1942.[152]

Researchers concluded that none of the suits tested over the past year were sufficiently advanced to warrant quantity production. At a conference at Wright Field, the Materiel Division stated it was time to either buy the suits as they were or close the project since development had gone as far as possible at that time. The consensus was that Goodrich was at least a year ahead of all the other companies on pressure-suit development. After its evaluation of several Army pressure suits, the Navy stated that, although generally interested, it had no need for high-altitude suits. Many researchers also felt that the entire concept of a pressure suit competed with the concept of a pressurized cabin. Interestingly, the Army had not given company representatives the freedom to work with its suits in actual airplanes or to take its suits to aircraft manufacturers for evaluation, excepting Bell and Boeing, which had developed their own suits. Representatives at the conference concluded that the Army should discontinue the pressure suit development effort but that one suit should be retained to determine fatigue and metabolism characteristics and for characterizing movements physiologically.[153]

On October 12, 1943, Randy Lovelace, chief of the Aero Medical Laboratory, advised each of the contractors that the Army had decided to terminate MX-117. On October 29, the Army officially discontinued pressure suit development and surplused the research equipment that had supported the effort.[154]

A USAF Technical Report released in March 1949 stated that, "basically, all attempts to develop equipment around the principle of full pressurization for survival at altitudes had failed because of the inability to resolve the fundamental paradox of adequate mobility at high pressure."[155] The report further stated that, "it would be extremely unwise and most unfair to state categorically that the fully inflated suit might never be used at high pressures for long periods of time (4-6 hours)."[156]

The relative failure of the Army full-pressure suit development effort did not deter movies and magazines from featuring the suits. For instance, the July 2, 1945, issue of *Time Magazine* contained an article entitled, "Science: A Shape that Came," along with a photo of a "spacesuit" used in the 1933 movie *The Shape of Things to Come* and a photo of a B.F. Goodrich Strato-Suit prototype tested by the Army in 1943. The article said:

> One of the costumes that the cinemadapters of H. G. Wells's The Shape of Things to Come dreamed up is here. The flyer is wearing a "Strato-Suit" developed by the late Major John G. Kearby of the Air Technical Service Command and by B. F. Goodrich Co. Designed for high-altitude flying, the electrically heated, pressurized suit could theoretically keep a man comfortable at 80,000 feet. The plastic bubble enclosing the head has oxygen for breathing, a microphone and earphones for communication. A man can zip himself into the suit in two minutes.[157]

Similarly, the November 1945 issue of *Popular Science* contained an article describing the B.F. Goodrich suit.

> Made of rubberized fabric, a new flexible, pressurized "Strato-Suit" for flyers may enable flyers to go farther than ever before into the stratosphere. Developed by the AAF Air Technical Service Command and B.F. Goodrich Company, the suit has proved practical in pressure-chamber tests equivalent to 80,000 feet, or 15 miles above the earth. When fully pressurized, the suit surrounds the airman with four pounds of air pressure. It provides oxygen for breathing, microphone and earphones for communication, and electricity for heated underwear. All are 'piped in' via a single junction assembly that can be disconnected in one quick movement. A transparent plastic bubble headpiece is removed in less than a second by a secret device. Donned in two minutes, the suit has airtight and watertight zipper enclosures.[158]

If only it were so.

SUMMARY

Although several of the pressure suits developed during the 1930s appeared to work and were even used on a limited number of "operational" flights, none were truly satisfactory. All of them were heavy and had extremely limited mobility. In addition, there was a surprising lack of scientific method applied to their development, most being almost "hobby shop" efforts rather than true engineering projects. The Army efforts of the early 1940s were better organized and funded but failed to live up to the initial expectations. Despite some limited successes, the waxing winds of war turned most efforts to more immediate needs, such as improved oxygen systems, parachutes, and clothing to keep aviators warm. As legendary test pilot A. Scott Crossfield later opined, "During World War II, the armed services, absorbed with more vital matters, advanced the pressure suit not a whit."[159]

3

3: Acceleration Protection

Despite the failure of the U.S. military to develop a workable full-pressure suit during World War II, a separate effort yielded a perhaps more important garment. Pressure suits and "anti-gravity" suits, more often called G-suits within the industry, serve two separate, but ultimately related, purposes, and their development was intertwined. Although not a specific topic of this book, G-suits are discussed since many of the concepts, institutions, and people involved with their development are inseparable from pressure-suit developments.

In the same year, 1903, that the Wright brothers made their first powered flight at Kitty Hawk, an American doctor published *Blood-Pressure in Surgery*, a book that had more to do with aviation than was understood at the time. George W. Crile, a cofounder of the Cleveland Clinic, reported that bandaging the extremities of experimental animals raised their blood pressure and that compression of the abdomen raised it further.[1] Crile believed a suit constructed using similar principles might be useful to maintain the blood pressure of patients on the operating table. To control the externally applied pressure more precisely during human experiments, Crile developed a rubber suit that he could inflate using a bicycle hand pump. However, despite some limited successes during surgery and postsurgical recovery, Crile eventually concluded that the suit was "cumbersome and uncomfortable." As alternate treatments became available, Crile's suit was forgotten.[2]

Blood pressure, what Crile was attempting to control with his suit, plays an important role in any human activity and is one of the key parameters to maintaining consciousness. It has long been known that quick or extreme movement can cause a person to temporarily lose consciousness, or to "black out." This is true of any physical activity, but is perhaps most closely associated with pilots flying highly maneuverable aircraft capable of high g-forces. Ultimately, this phenomenon was linked to blood pressure, and its eventual mitigation is credited to a variant of Crile's suit.

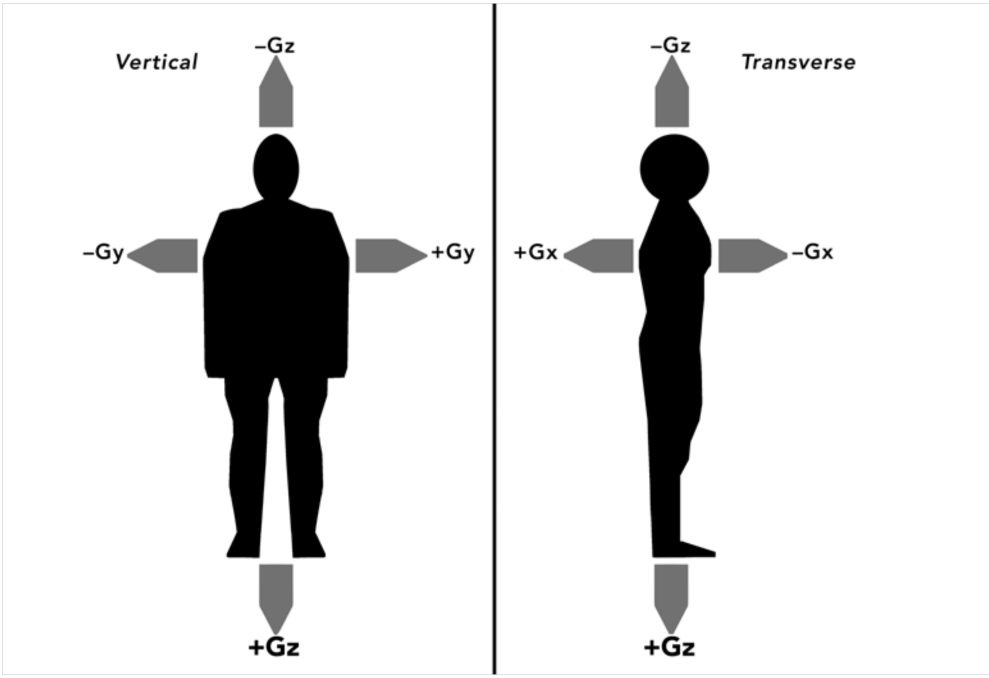
Interestingly, the first blackout resulting from centrifugal force occurred only a week after the Wright brothers flew at Kitty Hawk. The roots of the event went back to the late 19th century when Sir Hiram Stevens Maxim (1840–1916), an inventor with a machine gun and the common mousetrap to his credit, wanted to build an airplane. By 1894, he had largely given up. However, as part of his research, Maxim built a test rig that used two-passenger cars hung using cables from a large spinning frame; as the machine spun, the cars swung outward, simulating flight. Experiments using the machine continued long after Maxim abandoned his attempts to build an actual airplane. During one of these tests, in December 1903, Dr. Albert P. Thurston,[3] an engineer working for Maxim, took a ride and promptly lost consciousness as the car exceeded +6-Gz of centrifugal force.[4] Fortunately, Thurston woke up a little dazed but none the worse for the experience. Despite the incident, Maxim saw a commercial opportunity and further developed the rig into the "Sir Hiram Maxim's Captive Flying Machines"[5] amusement park ride, which was installed for the 1904 exhibition at Earls Court in London.[6] He subsequently built additional rides at the Crystal Palace and various English seaside resorts including Southport, New Brighton, and Blackpool. The Blackpool ride, at least, is still operating.[7]

Despite this early introduction to the potential problem, the issue of what is now called gravity-induced loss of consciousness (G-LOC) was not widely recognized for over a decade. An article published in 1919 by Dr. Henry Head (1861–1940), an English neurologist knighted for his pioneering medical research, observed a phenomenon he called "fainting in the air" in pilots of highly maneuverable airplanes such as the Sopwith Camel. By 1920, experiments had shown that these blackouts lasted about 20 seconds and began as the vertical acceleration exceeded approximately +4.5-Gz. The pursuit airplanes (what are now called fighters) of World War I were certainly capable of rendering their pilots unconscious, but popular legend indicates that the pilots who could train themselves to withstand the maneuvers did not want to talk about it because it made them appear less professional, and those who could not adequately adapt were dead.[8]

After the war, air racers frequently talked about fuzzy vision or loss of concentration while making sharp turns around marker pylons. By the time the Coupe d'Aviation Maritime Jacques Schneider (commonly called the Schneider Trophy) for the highest speed by a seaplane was permanently secured by Great Britain in 1931, loss of visual acuity, or blacking out, had become a serious problem in closed-circuit air racing. The Supermarine S.6B used during the last Schneider Trophy race could easily sustain 6-G in turns around the course markers, but the physiological implications were not thoroughly understood at the time.[9]

THE PHYSIOLOGY OF ACCELERATION

Acceleration is measured in multiples of the normal acceleration due to Earth's gravity, which is 32.2 feet per second per second (ft/sec/sec). The normal force (+1-Gz) applied from head to foot upon a standing person with a mass of 175 pounds is 175 pounds. However, if this same person is subjected to an acceleration of +7-Gz, the force then applied from head to foot is 1,225 pounds, creating obvious problems for the body and



Three axes represent the human body when discussing the forces of acceleration. The X-axis (transverse) runs front to back through the chest, the Y-axis (lateral) is side to side through the shoulders, and the Z-axis is vertical from head to feet. A body can be impacted either positively or negatively in each axis. Aerodynamics dictate that almost all accelerations felt by a seated pilot are in the Gz axis.

Dennis R. Jenkins

internal organs. At +7-Gz, blood is as heavy as iron, and the heart is not capable of pumping enough blood against the acceleration to maintain adequate circulation.[10]

As with any coordinate system, three axes represent the human body. The X-axis (transverse) runs front to back through the chest, the Y-axis (lateral) is side to side through the shoulders, and the Z-axis is vertical from head to feet. A body can be impacted either positively or negatively in each axis. The physiological effects of G-loads vary with the magnitude and duration of the acceleration, what axis of the body the acceleration acts against, and where on the body it is applied.[11]

Aerodynamics dictate that almost all accelerations act upon the seated aviator from head to foot—in other words, Gz. Positive Gz pushes the body into the seat and drains the blood from the head toward the lower extremities. It becomes difficult to breathe as the ribs and the internal organs are pulled down, emptying air from the lungs. The heart has to pump harder to get blood to the brain, partly because the blood weighs more; eventually it is unable to do so. The magnitude of the acceleration is a function of the velocity of the aircraft and the radius of the circle circumscribed. By the beginning of the 1930s, some aircraft, such as the Supermarine S.6B, were capable of sustained +6-Gz maneuvers; by the 1970s, this had increased to +9-Gz. The human body, no matter how fit and well-trained, is incapable of functioning in this environment.[12]

To increase human tolerance to acceleration, it is necessary to maintain blood pressure to the brain. Unfortunately, the elasticity of the human vascular system allows blood to pool in the lower extremities under acceleration.[13] Low arterial pressure first impacts the eyes, beginning around 3-G, when the loss of peripheral vision causes a tunnel vision effect.[14] Slowly, cone vision will start to disappear until vision is completely lost but the individual is usually still conscious.[15] If the acceleration continues, unconsciousness follows. Consciousness is regained as acceleration decreases, although this normally results in the dazed or confused feeling experienced by Albert Thurston. This phenomenon is what Henry Head called "fainting in the air."

Conversely, in a negative Gz condition, much like when standing on one's head, blood is forced away from the lower extremities and toward the head. The first symptom of –Gz is a sense of facial and, especially, eye fullness and congestion followed by occasional visual "red out."

Human tolerances to positive transverse acceleration (+Gx) are much higher than +Gz conditions, commonly reaching about +15-Gx. The key problem with transverse acceleration rests in the increased difficulties of inflating the lungs. Negative transverse acceleration (–Gx) results in breathing difficulties above –10-Gx.[16] Lateral (Gy) acceleration is not a significant concern regarding consciousness, or breathing, but it does have a significant effect on supporting muscles, such as the neck.[17]

Applying science to what pilots had been doing since World War I, researchers—principally, at the Mayo Clinic—developed a series of anti-G straining maneuvers during the early part of World War II to help pilots maintain consciousness. These involve specialized, sequenced isometric muscle contractions and timed breathing routines that allow pilots to manually press with their muscles and lungs to squeeze the heart, forcing blood to the head. The general procedure is to contract the lower extremity, buttocks, and abdominal muscles while taking a deep breath and holding it. At the same time, the pilot began straining immediately prior to the onset of acceleration. This was followed by a strict cycle of rapid inhaling, straining while gradually exhaling through the partially open glotti. This sequence was repeated at 3-second intervals. These maneuvers require practice to achieve proficiency, and they are difficult to perform and fatiguing at the best of times, let alone in combat. A well-executed anti-G straining maneuver provides up to +3-Gz of protection and is a very important aspect of acceleration protection. Many pilots have mastered the anti-G straining maneuvers, often with life-saving results. Just how well an individual pilot is able to handle high accelerations comes down to just how proficient they are in the issues of their domain.[18]

Although everybody agreed the anti-straining maneuvers helped, they were physically tiresome and diverted a pilot's attention away from flying his aircraft and tracking the enemy. Researchers continued to look for tools that would assist the pilot with G-protection and decrease the need for extended straining. The development of the G-suit was a major advance during World War II. As with most new technologies, its gestation was confusing and complicated, although the pressures of war kept it short. What follows is not a definitive history of G-suits but rather an introduction to many of the individuals and institutions that were also ultimately involved in the development of the aviation pressure suits discussed later.

HUMAN CENTRIFUGES

Before delving into G-suits, it is appropriate to examine one of the main tools researchers used to test human tolerance to acceleration: the centrifuge. Erasmus Darwin (1731–1802), physician, physiologist, abolitionist, inventor, and poet, and grandfather of Charles, explored the nature of sleep in his 1818 book, *Zoönomia*.[19] Darwin believed the centrifugal force resulting from rotating a body in circles might be useful to reduce heart activity, suppress fever, and induce sleep. To further this belief, James Watt (1736–1819), the Scottish inventor and mechanical engineer whose improvements to the steam engine were fundamental to the Industrial Revolution, designed a hand-powered "rotative couch" for Darwin. Although it is unlikely the device was ever built, Darwin and Watt were probably the first to envision a human centrifuge.[20]

By 1877, Austrian physicist and philosopher Ernst Mach (1838–1916), best remembered for his study of shock waves and compression theory, formulated a hypothesis that gravity and centrifugal force were equivalent in their action on the sensory organs. Albert Einstein (1879–1955), the 1921 Nobel Laureate in physics, later came to the same general conclusion—that the effects produced by gravity and inertial forces are indistinguishable. Charles-Auguste Salathé was probably the first physiologist to recognize their equivalence for the cardiovascular system.[21] Although largely unrecognized at the time, it was an important realization.

Although human centrifuges were constructed by several nations during the late 1800s for medical reasons, this account will focus on the acceleration work starting in the 1930s in Australia and North America as being particularly pertinent to this story.

Militaries recognized the potential importance of research into acceleration protection, and the U.S. Army Air Corps opened the first human centrifuge in North America on May 6, 1935, inside the abandoned Balloon Hangar at Wright Field. A 20-foot arm allowed the device to produce up to 20-G, and the subject could sit or lie on an adjustable platform at the end of the arm. By 1937, Dr. Harry G. Armstrong (1899–1983) and Dr. J. William Heim (1903–1988) used the Balloon Hangar centrifuge to acquire sufficient data to publish their now-classic paper "The Effects of Acceleration on the Living Organism."[22]

Armstrong played a major role in aerospace medicine in the United States. After attending the University of Minnesota for a year, he joined the U.S. Marine Corps before returning to school. Armstrong received his M.D. from the University of Louisville in 1925 and entered the Flight Surgeon Training Program at the Army School of Aviation Medicine at Brooks Field, TX. In 1931, Armstrong received an appointment as flight surgeon to the First Pursuit Group at Selfridge Field, MI.[23]

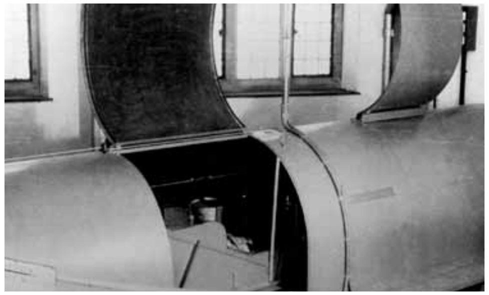
In a 1934 letter to the Federal Air Surgeon in Washington, DC, Armstrong urged giving a higher priority to improving protective flying equipment. As a result, the Army assigned him to the Engineering Division at Wright Field. After a while, Armstrong suggested the need for a separate medical research laboratory to deal with the physiological aspects of flying. In May 1935, the Air Corps established the Physiological Research Unit with Armstrong as its director. Its initial mission was to discover ways to provide aircrew protection from temperature extremes and the lack of oxygen at high altitude.[24] In 1939, Armstrong published *Principles and Practices of Aviation Medicine*, considered the standard text for over two decades.[25]

In 1946, the Army named Armstrong Commandant of the School of Aviation Medicine at Randolph Field, and in June 1949, he became USAF Deputy Surgeon General. The following December, he was named USAF Surgeon General. Armstrong retired from the Air Force in 1957 as a major general and died in 1983.[26]

Back in 1935, while organizing the new Physiological Research Unit, Armstrong sought the advice of Dr. Cecil K. Drinker and his brother Philip Drinker, at the Harvard School of Public Health. Cecil's research included blood circulation and methods of artificial respiration. Philip was an industrial hygienist who, among other things, invented the first widely used iron lung in cooperation with Louis Agassiz Shaw. Several years earlier, Harvard had built an altitude chamber to research pressure related physiology, primarily as it pertained to deep-sea divers. On the advice of the Drinker brothers, Armstrong ordered a duplicate of their altitude chamber and hired their physiologist, J. William Heim, to operate it.[27] Armstrong and Heim, would go on to design the Balloon Hangar centrifuge.

Over the course of the next 6 years, Armstrong developed, among many other things, crash helmets and shoulder-type safety belts. A number of the experiments and investigations Armstrong performed were the first of their kind, and he regularly participated as a test subject. Critical to the story of pressure suits, he discovered what is now known as the Armstrong Line. At approximately 63,000 feet, the vapor pressure of water (47 mm Hg) is the same as the atmospheric pressure (47 mm Hg), and water boils at the normal temperature of the human body. It is important to note that this applies to unconfined water, such as saliva and tears. Normal human diastolic blood pressure is sufficiently high that, contrary to oft-repeated myth, a living person's blood will not boil in a vacuum, although there are many other physiological issues that will quickly kill an unprotected human.[28]

Meanwhile, on the other side of the planet, in mid-1941, the University of Sydney installed a centrifuge in the laboratory of professor Frank S. Cotton (1890–1955) funded by the Royal Australian Air Force (RAAF) and the Australian National Health and Medical Research Council. Charles W. Prescott designed the machine, and White Elevators, Ltd. of Sydney built it. Two 10-hp electric motors drove the turntable to a maximum acceleration of 9.5-G at a radius of 9 feet. Unlike other centrifuges with swinging cabs that were built during this period, this one moved the subject and measuring instruments outward and inward along the radius of rotation. Sets of guide rails ran from the center of the turntable to the outer rim. The chair carrying the subject traveled on one set of rails and on the other set were the counterweights necessary to maintain dynamic balance. The weights traveled inward as the chair travelled outward with the movement occurring as the turntable reached the required angular velocity.[29]



The Australians were early adopters of human centrifuges. This machine was designed by Charles W. Prescott and installed in the laboratory of Professor Frank S. Cotton at the University of Sydney. The device was capable of generating 9.5-G.

Photos courtesy of John Dodson, University of Sydney

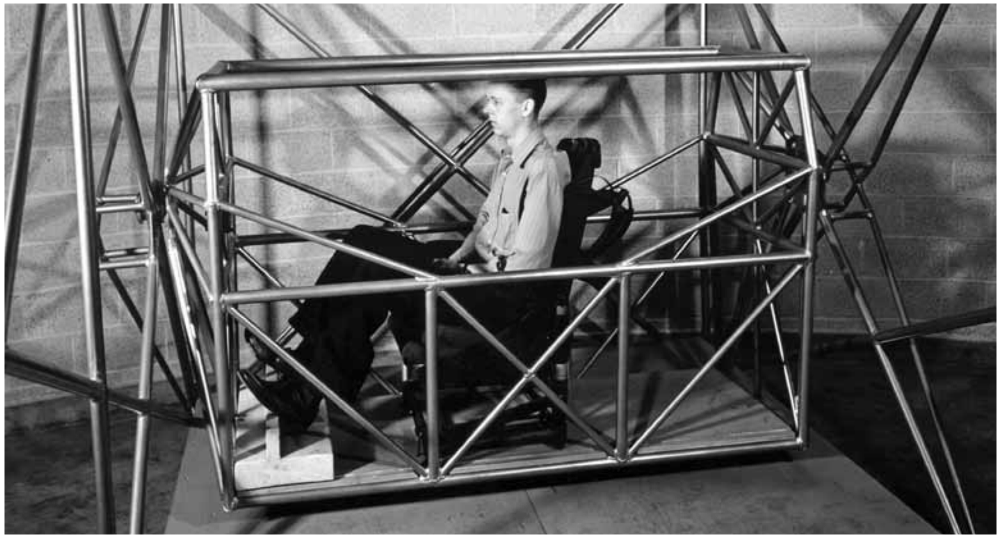
The Royal Canadian Air Force (RCAF) commissioned the first modern human centrifuge in North America (having been predated by the original Wright Field Balloon Hangar device) under the leadership of Nobel laureate Sir Frederick Grant Banting (1891–1941), the codiscoverer of insulin and Chair of the Banting and Best Institute for Medical Research at the University of Toronto.[30] In this case, the centrifuge came in response to a specific need. One of Banting's colleagues, Dr. Wilbur R. "Bill" Franks (1901–1986) was developing a water-filled G-suit and had used a Fleet 16 Finch biplane trainer to test the original prototype. It was obvious to Banting and Franks that a safer and more controlled means of testing was necessary. Not only were flight tests potentially dangerous and subject to the whims of unpredictable weather, but they also did not provide the precisely controlled environment that Franks required to understand and improve his creation.[31]

During 1939, Franks and George A. Meek completed the preliminary design for a high-speed human centrifuge. In 1940, the National Research Council approved C$25,000 funding, and Victory Aircraft built the machine (called an "accelerator") with assistance from various departments at the university. At the time of its opening in late summer 1941, the RCAF device was the fastest and most powerful human centrifuge in the world and was the first that could realistically mimic the effects of aircraft acceleration on the human body.[32] By August 1945, the Canadians had carried out more than 13,000 human runs without a mishap.[33]

A pit 12 feet deep and 31.5 feet in diameter housed the device, which, had a single 8.5-foot horizontal arm attached to a central shaft. A 200-hp electric motor rotated the central shaft, causing the spherical gondola to swing out on moveable joints to an almost horizontal position. The seat was suspended independently of the gondola, allowing the subject to be positioned at different angles inside the gondola, including in an upside-down position to produce negative-G—an unusual feature. The centrifuge was capable of accelerating to 20-G in 3 seconds.[34]

An observer outside the centrifuge would turn on lights and sound a buzzer; the subject responded by turning the signals off. A failure to turn off the lights indicated the subject could not see; however, he was likely still conscious and could respond to the buzzer. A failure to turn off the buzzer indicated the subject was unconscious. Researchers monitored the subjects using electrocardiographs, electroencephalographs, and a photoelectric device attached to the earlobe that measured blood flow to the head. The latter instrument confirmed that high accelerative forces greatly reduced the volume of blood going to the head.[35]

The United States also built several additional human centrifuges. The first came in 1942 at the Mayo Clinic under the direction of Dr. Edward J. "E.J." Baldes (1898–1975) and Dr. Charles F. Code. The pair recognized that researchers would need a repeatable method of replicating flight conditions to uncover the physiological underpinnings of the blackout problem. The Mayo Clinic machine was not as powerful as the Canadian device, but was more capable than most other human centrifuges of the era and designed to specifically allow for optimal biomedical data recording without the necessity of a huge central motor. It was a collaborative design between the Mayo Clinic biophysics staff (especially Adrien Porter) and the Sperry Gyroscope. The device had a 20-foot arm, could generate 2-G in 5 seconds, and add 2-G per second until it reached 10-G. The centrifuge stored rotational energy in two 20-ton flywheels purchased from a Cincinnati brewery, powered by an engine from a "reasonably priced" wrecked Chrysler automobile. The engine drove the flywheels via a normal automotive tire and wheel, although this presented an initial problem as tires were rationed during the war, and Mayo could not explain why it needed one without compromising the security of the project. Fortunately, David M. Clark, who will play a major role in this story, had contacts within the rationing system and procured a brand-new tire for the centrifuge. Once the flywheels reached about 40 revolutions per minute (rpm), the operator popped a clutch to clamp the resting gondola (with the subject inside) onto the spinning wheels. "You'd take off with a tremendous zip," Baldes noted, "and the g would be applied almost instantaneously."[36] The Mayo centrifuge was instrumental in the development of the American G-suit.[37]



The human centrifuge at the Mayo Clinic was essential in evaluating the original American G-suits, particularly those developed by the David Clark Company. The gondola at the end of the arm was a simple tube box with a seat (for sitting experiments) or table (for prone). The gondola was at the end of a 20-foot arm and could generate 10-G.

Courtesy of the David Clark Company, Inc.

The second modern American centrifuge opened in 1943 at Wright Field, replacing the earlier Balloon Hangar device that had been in use since 1935. This machine, located in the Centrifuge Building (Bldg. 55), had a 48-foot double boom with a cab on each end. The device could accelerate to 22-G in 9 seconds. Capt. George L. Maison, chief of the Acceleration Unit, was the first to ride the device. Between its opening in May 1943 and the beginning of 1946, 280 persons made several thousand runs on the machine under the supervision of Lt. Col. F. Gregory Hall, chief of the Physiology Branch.[38]

In late 1943, a group from the University of Southern California (USC) School of Medicine arrived at the Mayo Clinic to study the human centrifuge in preparation for building a similar device in Los Angeles. Included in the group were Dr. Douglas R. Drury, Dr. William G. Clark, and Dr. James P. Henry from the Departments of Physiology and Aviation Medicine.[39] This group, and the centrifuge they ultimately built, would play a major role in the development of pressure suits. The 23-foot centrifuge, funded by the National Research Council, opened in 1944 and could produce a peak acceleration of 20-G with an onset of 6-G per second.

Human centrifuges, it seems, were the special province of James Henry, who later replaced Maison as chief of the aptly named Acceleration Unit at the Aero Medical Laboratory. To his credit, Henry rode just about all of the devices in his domain, although this may not have been much consolation to those who followed. Next to John Paul Stapp, Armstrong probably endured more physical agony in the name of science than any other man of his generation.

Within the U.S. Navy, research in aviation medicine took place at the Medical Department of Naval Air Station Pensacola from 1939 until 1946. To support this research, Pensacola opened a 20-foot human centrifuge in 1945 that could operate at 20-G with a 2-G-per-second-rate of acceleration. On October 1, 1946, the Secretary of the Navy established the Naval School of Aviation Medicine at Pensacola that included the human centrifuge.[40]

By the end of the 1940s, these centrifuges allowed researchers to study the effects of increased gravitational levels, as represented by centrifugal force, on the pressure and

"The Wheel" at the Naval Air Development Center (NADC) in Johnsville, PA, was by far the most sophisticated of the postwar human centrifuges. This device could attain 40-G and was used to train pilots for the X-15 and astronauts for Dyna-Soar, Mercury, and Apollo. The gondola sat at the end of a 50-foot arm and a control room was located above the centrifuge.

U.S. Navy

The original single-person gondola at Johnsville was hardly the high-tech environment of today. The pilot sat on a simulated ejection seat and initially faced an instrument panel that was little more than an oscillograph with a few extra lights. Many early tests involved the pilot moving the control stick to follow a trace on the screen. During the X-15 program, researchers installed a full X-15 instrument panel, complete with side-stick controllers in the gondola. NASA followed with a simulated Mercury capsule instrument panel and controls. Pilots did not think the simulation provided by the human centrifuge was particularly realistic, but it offered at least a hint of the extreme accelerations provided by the X-15 and early manned launch vehicles.

U.S. Navy

distribution of blood in the lungs, heart, brain, and legs. Using these devices, the nature of human tolerance to acceleration was well established, the cardiovascular factors limiting human tolerance to short-term accelerations were identified, and a general theory of the function and operation of the vascular system at 1-G had been firmly established. Many researchers believed they had solved the major aeromedical problems in this area.[41]

Despite the increasing sophistication of the wartime centrifuges, one device would ultimately render all of them obsolete. In 1950, the U.S. Navy dedicated what was then, by far, the world's most sophisticated centrifuge, although it seemed something of a white elephant at the time. Much later, in 1962, the chief of the NASA astronaut corps, Donald K. "Deke" Slayton, opined, "We feel that the centrifuge [Johnsville] has been one of our most valuable training devices."[42] The centrifuge was the centerpiece of the Aviation Medical Acceleration Laboratory, located at the Naval Air Development Center (NADC) in Johnsville, PA. The designers of what pilots often called, with a mixture of pride and fear, "the Wheel" anticipated the rapid growth in aircraft performance and foresaw the need for a new research tool. The resulting centrifuge had a 10-G-per-second-rate of acceleration and could attain 40-G, whereas previous centrifuges were limited to 6-G per second and a maximum of 22-G. Johnsville had a 50-foot radius as compared with other centrifuges that had radii between 10 and 23 feet. An altitude chamber 10 feet in diameter and 6 feet wide on the arm provided the ability to test at any

altitude, including a vacuum, at temperatures from well below zero to nearly 200 °F. A pair of gimbals allowed the altitude chamber to assume virtually any attitude. The inner gimbal provided 360 degrees of rotation at rates up to 30 rpm, while the outer gimbal rotated outward through a 90-degree arc. Although the Navy had originally intended the Johnsville centrifuge for research, it became a primary training tool for the X-15, Dyna-Soar, and Mercury programs. In 1963, the Navy replaced the gondola with a larger unit to accommodate the three-person-wide configuration needed to train for Apollo. Today, the Wheel is a deserted building in an industrial park where the NADC used to be.[43]

THE BEGINNING OF AN IDEA

It appears that the National Advisory Committee for Aeronautics (NACA) had the distinction of employing the first person hospitalized for "overexposure" to acceleration. According to a June 8, 1928, letter from flight surgeon Capt. Ira F. Peak, Jr., to Richard V. Rhode, an aeronautical engineer at the Langley Memorial Aeronautical Laboratory, an Army Air Corps Reserve test pilot on duty with the NACA lost consciousness on a flight in September 1927. Peak wrote:

> On examination he showed generalized conjunctivitis of both eyes. He also showed generalized systemic neurological symptoms leading me to think he had a mild cerebral concussion with some generalized cerebral capillary hemorrhage or at least a marked degree of passive traumatic enlargement. Being interested in the case, I wrote complete descriptions to Doctor Schneider of Western University, and to Dr. Louis H. Bauer, Medical Director of the Air Regulations Division at the Department of Commerce. Both of them agreed with my opinion of the cause and nature of this condition, namely, it was due to sudden changes of centrifugal force while doing high-speed flying in acceleration tests. There was a duty recovery from this condition in about two weeks and complete recovery in about a month. [44]

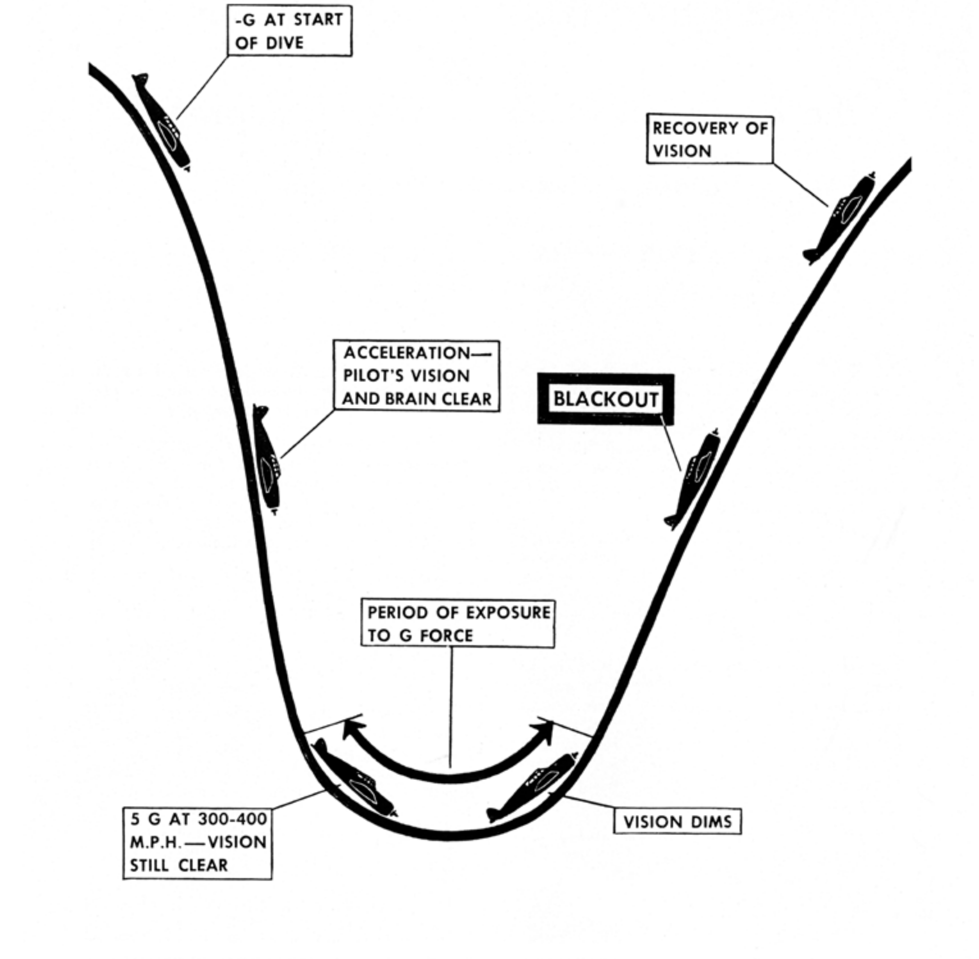
Based on data from the doctors, Rhode concluded airplanes were reaching the limits of human tolerance to violent maneuvers, and that since the "pilot is the limiting factor … there is no need to curtail performance by over-strengthening the airplane structure or by reducing control."[45] In other words, do not build airplanes capable of greater acceleration than an unprotected pilot could endure. Rhode, an otherwise brilliant engineer who later became assistant director for advanced design for NASA, apparently never considered providing any sort of protection for the pilot.

Despite the relatively insignificant budgets that hampered the U.S. military during the interwar years, the U.S. Navy and U.S. Army Air Corps began looking seriously into the blackout problem. During the early 1920s, a pilot practicing for an air race remarked to LT John R. "Jack" Poppen, a nonflying naval flight surgeon, that his vision began to dim as he rounded the pylons at speed but returned to normal on the straight portions of the circuit. The Navy began to investigate the phenomena in 1921, using an accelerometer mounted on a Curtiss JH-4 Jenny to measure aircraft load factors. This was, probably, the beginning of scientific research into acceleration effects on pilots in the United States.[46]

By 1927, Poppen was in charge of the Aviation Section at the Naval Medical School in Washington, DC, and was making great strides toward introducing aviation medicine as a formal discipline. Poppen was a consultant to the NACA committee that established a method of investigating aircraft accidents and was instrumental in changing the way the gyroscopic artificial horizon worked. When Sperry Gyroscope first introduced the artificial horizon instrument, the horizon line remained stationary while the symbol of the airplane moved. When many pilots, including Jimmy Doolittle, experienced difficulty remembering that the moving bar represented the horizon and not the airplane, Poppen realized there was a problem. After a few years of argument, Poppen published an article in 1936 that seemed to settle the matter. Essentially, Poppen's rationale was that the instrument should be an exact analogue of what the pilot was seeing through the windscreen, a standard still in use.[47]

The Navy soon awarded a small grant to the Harvard School of Public Health to study acceleration effects. While conducting experiments on animals exposed to high g-forces, Poppen and Dr. Cecil K. Drinker found that abdominal restraint diminished blood pressure effects when acceleration occurred along the vertical axis of the body. During 1932, Poppen designed a pneumatic abdominal belt that a pilot could inflate with a hand bulb prior to an anticipated exposure to acceleration.[48] Harry Armstrong and John Heim tested the belt on the 20-foot centrifuge at Wright Field in 1936 and found it of "some benefit."[49]

In 1939, the Navy flight-tested another version of the Poppen belt, a device later shown in the 1941 movie *Dive Bomber* starring Errol Flynn and Fred MacMurray.[50] Pilots reported limited, but not adequate, protection, and there was the larger problem of needing to anticipate when to inflate the belt, a luxury of time that combat seldom allowed.[51] Although the abdominal belt had been Poppen's own idea, an indirect link to George Crile had introduced Poppen to the concept of a G-suit. In 1941, Crile was in an aircraft that flew through the remnants of a tornado, and the resulting turbulence caused the flightcrew to lose consciousness;



TYPICAL BLACKOUT SEQUENCE IN DIVE BOMBING MANEUVERS
Preventive equipment also provides fighter pilots with physiological reenforcement for abrupt maneuvers.

This illustration was used by Berger Brothers to describe the sequence of events that often led to a pilot blacking out during a dive-bombing mission. As aircraft became faster and more maneuverable, the problem became more widespread and was not restricted to the vertical maneuvers shown here.

Berger Brothers. Courtesy of the David Clark Company, Inc.

In 1932, LT John R. "Jack" Poppen, a naval flight surgeon, developed what became known as the Poppen Belt to fight the effects of acceleration. The concept was valid, but the belt needed to be inflated using a hand bulb (shown) in advance of being needed (a technique not well suited to the flight environment). A later version of the device was featured in the 1941 movie Dive Bomber.

Courtesy of the David Clark Company, Inc.

the airplane crashed but Crile survived. In his autobiography, Crile wrote:

> After the experience of everyone in the plane, it seems clear to me that the cause of the blackout in aviation must be the failure of the blood to return to the brain and the heart because of the rapid ascent of the plane.
>
> So many times I have seen an unconscious patient restored to consciousness by being placed in the head-down position that the blackout seems to me to be just one more phase of the problem that I have been trying to solve for so long and which I solved years ago theoretically if not practically by the device of the pneumatic suit which provided artificial peripheral resistance, giving control over the blood pressure within a range from 25 to 60 mm mercury. This suit enveloped the body up to the chest. Were an aviator encased in this suit and the pneumatic pressure established, the suit in itself would prevent pooling of the blood in the large vessels in the abdomen and extremities and would maintain the conscious state.
>
> I believe that an aviator thus equipped would be protected against the failure of the blood to return to the heart and hence would have protection against blackout.[52]

Crile understood the principle of a G-suit and took his idea to Dr. Eugene F. DuBois, the chairman of the Committee on Aviation Medicine, one of the branches of the Advisory Committees to the Surgeons General of the War and Navy Departments and the Public Health Service.[53] Crile had already discussed his pneumatic suit with DuBois and now suggested the idea could be used by dive bomber pilots to prevent blackout during the high-G pullout at the bottom of their attacks. DuBois agreed the suit might hold promise to protect pilots during violent maneuvers and suggested Crile contact Poppen.[54]

Separately, in November 1940, Dr. John F. Fulton, an American physiologist at the Yale University Medical School, suggested that pressurized leggings might keep blood from accumulating in the lower limbs during acceleration. This was not a new idea, having been put forward in a German-language book by Dr. Siegfried Ruff and Dr. Hubertus Strughold the previous year.[55] Fulton constructed a set of inflatable leggings that worked with the inflatable abdominal belt to force blood upward from the lower extremities. Fulton did not have access to a human centrifuge for testing, but Dr. William K. Stewart of the RAF Institute of Aviation Medicine flight-tested the leggings at the Royal Aircraft Establishment (RAE) in Farnborough, England.[56] Stewart, a respected British pioneer in aviation medicine, had been investigating the effects of acceleration and found that about half of those who experienced blackout had amnesia and could not remember the event. As the head of a 1940 British research effort, Stewart made a flight expressly to experience blackout. Afterward he was disappointed that nothing had happened—until he saw photographs of himself unconscious.[57]

Stewart decided to test Fulton's leggings. One of the leggings ruptured during the first flight, and it was evident that the covering fabric was inadequate. The RAE fabricated a new set of leggings that underwent limited, albeit inconclusive, testing. In addition, the three-piece assembly (individual leggings and the abdominal belt) was awkward to don.[58]

Although the leggings proved disappointing, they provided an unexpected inspiration for an American who happened to be at Farnborough during the tests. Frederick D. Moller would subsequently play a significant role in the development of a workable G-suit.[59]

AUSTRALIAN COTTON AERODYNAMIC ANTI-G SUIT

Ultimately, American researchers would make the most progress toward a workable G-suit, but the Australians and Canadians also recognized the potential benefits of the device and conducted extensive research that predated most American efforts.

Australian physiologist Frank S. Cotton (1890–1955) was a professor at the University of Sydney specializing in the study of the effects of physical strain on the human body. In 1940, Cotton showed that the cardiac output, which decreases considerably when a change is made from the supine (lying on back) to the standing posture, is nearly fully restored when the standing body is surrounded by water up to the lower part of the sternum.[60]

The war in Europe was in full swing, and the Battle of Britain took place between July and October 1940. This was the first major skirmish fought entirely by air forces, and the RAF Fighter Command gained a well-deserved reputation during the fight. Ten thousand miles from London, Cotton followed the battle in the local newspaper. One article in particular caught his attention: pilots were suffering from acceleration effects during the dogfights taking place daily over England. Cotton was certain he could find a solution to help the pilots avoid the "dreaded blackout."[61]

Cotton already knew a considerable amount about cardiac output. He also knew that German research several years earlier had shown that the hearts of great apes were nearly empty of blood after centrifuge tests; it is difficult to pump blood to the head when there is no blood in the heart. This led Cotton to believe that applying pressure to the lower extremities and abdomen would keep blood available to the heart. The obvious answer was to make a suit containing a set of bladders that automatically inflated to some as-yet-undetermined pressure. Cotton made the first suit by cutting up two women's bathing costumes (long before the invention of the bikini rendered salvaging fabric pointless) and gluing them to a pair of rubber boots. A rubber hose connected the ensemble to an air compressor and pressure valve.

During November 1941, Cotton began testing the suit and found the concept worked as he had predicted. On the advice of the RAAF, Cotton took the prototype suit to Britain, Canada, and the United States on a demonstration tour beginning November 21, 1941. Unknown to Cotton, by this time the water-filled Franks Flying Suit was already in limited production in Canada. Regardless, Cotton met with Bill Franks and exchanged ideas. In the United States, Cotton met with Poppen, who was impressed with the gradient-pressure feature of the suit and passed the idea along to Moller at Berger Brothers for use in their air-filled suit.

After he returned to Sydney, Cotton carried out further trials using the Australian centrifuge. The test subjects were Flight Lt. Robert H. Thompson and Flight Lt. Ken V. Robertson; both men were of similar size and build and could use the same suits. In

The Royal Austrian Air Force conducted operational trials using Curtiss Kitty-hawks. Unfortunately, Australia's Northern Territory capital of Darwin experiences hot weather most of the year, and pilots complained the suit was unbearably hot while sitting alerts in their un-air-conditioned cockpits and readyrooms.

National Archives College Park Collection

March 1942, Thompson began testing the suit using the only Hawker Hurricane (V7476) in Australia, followed by Robertson in April. On one flight, the Hurricane pulled over 10-G, causing minor damage to the airplane without ill effect to the pilot. Preliminary data was sufficiently encouraging that the RAAF ordered the suit into production. Operational trials began on October 20, 1942, using Curtiss P-40E Kitty-hawks at the No. 2 Operational Training Unit at Mildura, Victoria. Six pilots were involved in the tests, including five with extensive combat experience. Flight-tests results generally agreed with the results from the Sydney centrifuge, where a maximum of 9-G had been obtained. Despite its benefits, pilots reported the suit was hot and uncomfortable, not ideal traits for Australia during the summer.

At a conference between the RAF and RAAF on May 15, 1943, the British urged the Australians to continue in which the Australians were developing the gas-filled Cotton suit, the British and Canadians had already fielded the water-filled Franks suit, and the Americans were working on air-filled suits from Berger Brothers and the David Clark Company.

The Cotton suit became operational with No. 452 Squadron at Strauss Airfield near Darwin, Australia, in July 1943. This, however, amplified a major problem with the suit. The squadron was responsible for the defense of northern Australia, meaning that pilots spent long hours on alert, sitting in the cockpit or a nearby readyroom, prepared to takeoff on short notice. Unfortunately, the temperatures in Darwin during July are well above 80 ºF, with 80-to-100-percent humidity. Air-conditioning was largely unheard of at the time, and the crews found sitting around in a rubber suit unbearable. Relief came from an unexpected source: Mac Robertson Steam Confectionery Works provided an air-conditioned chocolate van for the pilots to use as a readyroom. This same company had sponsored the 1935 air race that had inspired Wiley Post to develop the first pressure suit.

The pilots from No. 452 Squadron were generally impressed with the Cotton suit, excepting the complaints about heat. They did note that frequently the suit did not deflate after returning to normal 1-G flight, and this made it difficult to fly the airplane smoothly since the feeling of the controls, particularly the rudder pedals, was different. There was another, potentially more serious issue with the parachute straps between the thighs not spreading correctly when seated. Robertson expressed the concern eloquently in his report, quipping that "I am not yet convinced that one's matrimonial value will not drop to zero if one bails out wearing a suit."[62] He suggested fitting guide loops that would hold the thigh straps apart when seated, or adopting the American-style parachute harness that always stayed separated because of its different design and sewing.

In August 1943, the RAAF conducted trials that pitted a Spitfire Mk V against a Mitsubishi A6M Zero at Eagle Farm, Brisbane, Australia. The Australians assembled the Zero from parts found on Papua, New Guinea, by the Allied Technical Air Intelligence Unit. The tests showed the Zero was more maneuverable than the Spitfire at all altitudes when neither pilot was wearing a G-suit, but the Spitfire could gain the upper hand if its pilot was wearing a suit and the Zero's pilot was not. Based on the results of these trials, the RAAF decided to equip the Spitfires of No. 1 Fighter Wing with the Cotton suit. However, the Australians apparently never used the Cotton suit in combat.[63]

The production model of the Cotton Aerodynamic Anti-G Suit (C.A.A.G.) Mk I was manufactured by Dunlop Rubber Co. Ltd. (Australia) and was commonly called the "Zoot Suit" by operational pilots.[64] The 25-pound suit consisted of a series of overlapping rubber bladders inside a set of rubber latex fabric high-waist short trousers and leggings. Initially, the leggings extended from the soles of the feet, but later models started at the ankles. The short trousers overlapped the top of the leggings, extending about halfway down the thigh. This allowed adjustment to compensate for different body builds. The shorts contained a lower bladder that covered the abdomen and extended into the legs of the shorts and an upper bladder that extended to the lower edge of the ribs. Each legging contained four bladders for the thigh, upper leg, lower leg, and boot. A full-length zipper extended along the front of each legging. A short hose connected the suit to a cylinder of compressed carbon dioxide, and an acceleration-sensitive valve released gas into the suit in proportion to the acceleration it sensed. The suit applied a gradient of 16 different pressures to the body from the ankles to the abdomen.[65]

By late 1944, the Australians had developed the so-called "Kelly One-Piece" (K.O.P.) suit in an attempt to produce a protective garment that was lighter and more comfortable than the original C.A.A.G. suits. The Mk I version of the K.O.P. provided five levels of

The Royal Australian Air Force equipped its Supermarine Spitfire Mk Vs, such as this RAF example, with the Cotton G-suit but apparently never used the suit in combat.

National Archives College Park Collection

gradient pressure from the feet to the waist, while the slightly lighter Mk. II version used only three pressures. Although the suits were an improvement, they still lagged behind the Berger Brothers and David Clark suits being manufactured in the United States and were soon forgotten.[66]

CANADIAN FRANKS FLYING SUIT

The Royal Canadian Air Force developed the first modern human centrifuge in North America under the leadership of Nobel laureate Sir Frederick Grant Banting (1891–1941), the codiscoverer of insulin and chair of the University of Toronto's Banting and Best Institute for Medical Research.[67]

Peter Allen, who wrote a paper on the early years of Canadian aviation medicine for the *Canadian Aviation Historical Society Journal*, gives much of the credit for getting Sir Frederick involved to Maj. A.A. James of the Royal Canadian Army Medical Corps. James had spent a year studying the state of aviation medicine in other countries. "Realizing that all countries except Germany were appallingly unprepared to support their aircrews in the coming war, James was determined to see that situation changed in Canada."[68]

The Department of National Defence formed the Associate Committee on Aviation Medical Research in June 1939.[69] Soon thereafter, using a grant from the Canadian government, Banting purchased the Eglinton Hunt Club near downtown Toronto for use as an aviation medicine research facility. This was initially known as the No. 1 Clinical Investigation Unit and later as the RCAF Institute of Aviation Medicine.[70] In 1940, the institute built a low-temperature altitude chamber.[71]

One of Banting's colleagues, Dr. Wilbur R. "Bill" Franks, was conducting cancer research, and it was not immediately apparent what he could contribute to aviation medicine—until he heard James explaining that fighter pilots were losing consciousness during high-speed maneuvers.[72] The military considered this one of the most pressing problems affecting the performance of their pilots, and James told researchers it would provide an enormous tactical advantage if the G-tolerance of Allied pilots could be increased.[73]

Earlier in his career, Franks had solved a problem with glass test tubes breaking in his laboratory centrifuge by floating them in water while they were spinning. Wondering if the same principle applied to pilots, Franks experimented with mice in his small centrifuge and found they could withstand extreme accelerations (up to 240-G) when "immersed in water up to their necks inside condoms." Specifically, he observed, "that mice, when suspended in a fluid the specific gravity of which approached that of the mouse's body, could withstand, without apparent damage, over 100 times the normal gravity."[74]

It was obviously not practical to suspend pilots in fluid-filled cockpits, so Franks decided to develop a fluid-filled suit a pilot could wear. Although the concept was straightforward, Franks was uncertain exactly how to construct the garment. He approached the Dunlop Rubber Company, Ltd. and Dominion Textiles, Ltd. to develop a suitably strong and nonextensible fabric. The problem then became the joints, which eventually had to use vulcanized fabric.[75]

Oddly, the Canadian government declined to provide funding for the experiment, but fortunately, Harry McLean, an eccentric Toronto businessman known for his philanthropy, donated $5,000 (Canadian dollars), which that allowed Franks to buy the materials and hire a tailor to make the first suit using an old sewing machine in his office.[76] This suit covered the entire body from neck to toes and used a nonextensible outer covering to withstand stretching and direct the fluid inward against its wearer.[77] A rubber inner bladder held the incompressible working fluid, water.[78] Under high accelerations, the fluid was forced inward and downward in the suit, providing sufficient pressure on the lower extremities to prevent the pooling of blood in these areas while supporting them against centrifugal force.[79] This allowed the heart to pump sufficient blood to the head, "thus preventing the occurrence of blackouts and unconsciousness and delaying the onset of fatigue."[80]

Apparently, unknown to Franks, the idea was not new. Dr. Heinz von Diringshofen, a medical officer in the part of the German army that would become the Luftwaffe, had begun researching prolonged acceleration in flight during 1931. Using the centrifuge at the Air Ministry Aeromedical Research Institute in Berlin, Dr. Ruff and Dr. Otto Gauer had been working on fluid-filled anti-G suits since late 1935.[81] Centrifugal force acted on the water in the suit the same as it did on the blood in the body, creating a compensating pressure gradient. Thus, the suit reduced the pooling of blood in the lower half of the body and maintained cerebral circulation.[82] However, Ruff would later conclude that the "idea of using a double-walled, fluid-filled suit (inner wall pliable for adjustment to the body surface and outer wall rigid), although theoretically correct, is practically impossible."[83] Not only had the Germans already invented the Franks Flying Suit, they had dismissed it as impractical. But Franks did not know this—yet.

In May 1940, Franks flight-tested the first suit using a Fleet 16 Finch biplane trainer (No. 1021) at Camp Borden. Oddly, this was the first time Franks had ever flown, and he was initiated with high-speed aerobatics.[84] In two tests, one at 6.2-G and the other at 7.7-G, the onset of blackout was experienced by the pilot, Flight Lt. Beer, who was not wearing a suit, but not by Franks. The researcher reported, "The suit had been cut to fit me perfectly, standing up … in the airplane I was sitting down, and when the pressure hit I thought it was going to cut me in two." Franks found the suit confining, uncomfortable, and very hot.[85]

Franks had already considered this possibility and quickly redesigned the suit to reduce the coverage. During the redesign, Frank replaced the laces used in the first suit with zippers to make donning and doffing easier. Somewhat after the fact, the first suit was designated Franks Flying Suit (F.F.S.) Mk I, while the second suit became the Mk II. On June 2, 1940, RAF Wing Commander D'Arcy Greig began flight-testing the second suit at Malton, Ontario, using an RCAF Supermarine Spitfire (L1090).[86] Although he reported the suit provided a needed measure of protection, Greig believed "the principle involving the design of the suit is sound but in its present form it is not a practical proposition," and "many modifications would be needed" before it could be used in combat.[87] Franks brought an improved suit back to Farnborough in February 1941, but the trip turned tragic when Banting was killed in an airplane crash on February 21 on his way to England.

In addition to the suit modifications, it was obvious that a safer and more controlled means of testing was necessary. Fortunately, Franks and George A. Meek had already developed preliminary plans for a human centrifuge, and in 1940, the National Research Council approved funding. When the device opened in late summer 1941, it was the fastest and most powerful human centrifuge in the world.[88]

Development of the suit continued, and in April 1941, Franks took a prototype of what became the Mk III to Farnborough. It was the same place that William K. Stewart had tested Fulton's leggings 6 months earlier. RAF pilots evaluated the suit using Fairey Battles and Hawker Hurricanes and found it could "prevent blackout up to 9-G."[89] Despite consistent complaints of discomfort from pilots, the evaluation showed the garment performed as advertised. A report released on August 21, 1941, concluded, "In combat the wearer of the suit can follow his opponent however sharply he turns and still retain his vision which will enable him to use his [gun] sights. In the pullout from a high speed dive at low level a protected pilot will be able to force a following opponent to black out or break away."[90] However, a second report, written by Stewart, found "difficulties" with the suit. Most of them concerned comfort, or the lack thereof, and the amount of body heat trapped by the suit while waiting on the ground.[91]

Despite its problems, the suit held much promise, and the British and Canadians ordered it into production. Ultimately, Dunlop produced at least 800 Mk III suits beginning in September 1941.[92] It subsequently became the first G-suit to be used in combat, by the Royal Navy Fleet Air Arm while providing cover for Eisenhower's invasion of North Africa at Oran, Algeria, in November 1942.[93]

Combat trials dragged on for 2 years. Despite several early successes, such as the battle at Oran, and enthusiastic backing from some pilots, British and Canadian fighter pilots ultimately judged the Franks Flying Suit impractical.[94] In 1946, a National Research Council study noted that "… certain objections were eventually raised against the suit, in particular discomfort while 'at the ready,' and difficulty in turning to search for enemy aircraft coming from behind."[95] Franks designed the suit specifically to protect its wearer from the effects of accelerations without regard for the overall operational needs of the pilot. He did this based on somewhat faulty logic due to not being a pilot. Unfortunately, air combat maneuvering was only one aspect of a very complex environment. Fighter missions also involved long hours in the cockpit, and the weight, bulk, and mobility restrictions of the suit made pilots reluctant to wear it. At the same time, the nature of fighter combat had changed since the beginning of the war. Rather than engaging in short, furious dogfights like those during the Battle of Britain, fighter pilots were more likely to find themselves escorting bombers over long distances: a situation that did not endear the heavy and uncomfortable water-filled suits to those who had to wear them. In addition, the "bounce," or surprise attack, especially from the rear, had become the preferred fighter-versus-fighter tactic, and the majority of pilots never saw their attacker.[96] The restricted mobility of the Franks suit made it almost impossible for a pilot to turn and look aft, making them particularly venerable to attack from the rear.

The death knell for the water-filled Franks Flying Suit was the testing on the human centrifuge at Mayo that revealed that using air to pressurize the F.F.S. Mk III provided 2.2-G of protection, significantly more than the 1.5-G it offered when filled with water. Researchers at the Mayo Clinic conducted this testing in late 1943 and reported it to the Office of Scientific Research and Development (OSRD) Committee on Aviation Medicine on January 19, 1944. Based on this information, the pursuit of hydrostatic suits for acceleration protection was largely abandoned in favor of pneumatic suit systems.[97]

The major problem with the Franks suit, like the German one before it, was the weight of the 5 quarts of water. The only possible solution to the problem was to remove the fluid, and this is exactly what the Americans did when they developed a G-suit that used compressed air to provide counter-pressure.[98] The American suit weighed only 3 pounds compared to 18 pounds for the Franks suit.[99] American suits made by Berger Brothers and David Clark Company quickly replaced the Franks Flying Suit in RAF and RCAF service. Nevertheless, the forward-thinking Wilbur Franks received the Order of the British Empire (OBE) in January 1944, and the existence of his suit, previously kept secret, became public knowledge in December 1944.[100]

Late in the war, the Canadians developed the air-activated F.F.S. Mk VI, which was a cutaway (or "harness") G-suit much like that developed by the Americans. This suit used a single, continuous air bladder to provide counter-pressure over the abdomen, thighs, and calves. The suit had zippers on the legs and abdomen and lacing adjustments on the waist, thighs, and calves. The hips and knees were uncovered. The cutaway suit could be worn under or over standard flying clothes. A similar Mk VII suit was a conventional set of trousers instead of a cutaway model. Although these suits were called Franks Flying Suits, three pilots at the Acceleration Section in Toronto largely designed them and they more closely resembled the American G-suits.[101]

THE AMERICANS

On December 2, 1940, Maj. Mervin E. Gross, the Executive Officer of the Materiel Division in Washington, DC, wrote to Dr. Vannevar Bush (1890–1974), the chairman of NACA asking for assistance in determining the equipment necessary for very high-altitude flying. Bush was already a legendary engineer and would later become, in effect, the first presidential science advisor during the Cold War.[102]

Bush responded that the development of a pressure suit would allow aircrew to reach extreme altitude without imposing the same demand on an airplane (primarily weight) that a pressurized cockpit would. He believed the development of pressure suits for pursuit (fighter) pilots was of immediate importance and offered suggestions for a pressure suit development program along with the full cooperation of the NACA. In addition, Bush pointed out that the Canadians were already developing a water-filled G-suit and suggested the Army follow suit. Bush also suggested that the Air Corps enlist the services of the OSRD Committee on Aviation Medicine.[103]

In the years leading up to World War II, Australia, Canada, Germany, Italy, and Japan each looked to solve the problems of acceleration with, at best, marginal results. Not surprisingly, given the enormous resources available for the war effort, it was the Americans who

Although the water-filled Franks Flying Suit Mk III was the first G-suit to see combat, pilots and researchers ultimately rejected the suit as too uncomfortable for operational use. Eventually, the Canadians adopted air-filled bladders with the introduction of the FFS Mk VI cutaway suit. These photos graphically show why this type of suit was known as a cutaway.

Courtesy of the David Clark Company, Inc.

The Frank Flying Suit Mk VII used the same air-filled bladders as the cutaway Mk VI but featured a conventional set of trousers instead of being a cutaway. Some pilots preferred this design since they did not need to wear flying clothes underneath.

Courtesy of the David Clark Company, Inc.

ultimately got the science right and produced a truly workable G-suit.

In early 1942, researchers at the Mayo Clinic, in Rochester, MN, formed the Aero Medical Unit and offered their services to the Army for a dollar a year. A contract was formalized in February 1942. The original group of researchers included Charles F. Code (1910–1997), Edward J. "E.J." Baldes (1898–1975), and Walter M. Boothby (1888–1953). Like many during the war years, "We were motivated by a high sense of loyalty to our country," Code recalled nearly 40 years later.[104]

Aeromedical research at the Mayo Clinic was already well respected. The 1939 Robert J. Collier Trophy, awarded to the "Airlines of the United States for their high record of safety in air travel," gave:

> … special recognition to Drs. Walter M. Boothby and W. Randolph Lovelace, II of the Mayo Foundation for Medical Education and Research and Captain Harry G. Armstrong of the U. S. Army Medical Corps at Wright Field, for their contribution to this safety record through their work in aviation medicine in general and pilot fatigue in particular.[105]

The Mayo Aero Medical Unit had two areas of primary emphasis: one dealing with the threats of the high-altitude environment (lack of oxygen, decompression sickness) and the second focused on the threats of acceleration-induced blackout and risk related to acceleration in general. Boothby headed the high-altitude laboratory, formed in 1935, in close collaboration with Dr. William J. Randolph Lovelace II and Dr. Arthur H. Bulbulian. Baldes headed the acceleration laboratory, formed in 1942, and his physician partner was Code.

Code was no stranger to challenges in life. He suffered from scarlet fever when he was 8, contracted polio at 12, and was told that he would never walk, a prediction that turned out to be wrong, although he wore back and leg braces. After earning a medical degree from the University of Manitoba and a Ph.D. from the University of Minnesota he turned to research. Code was known for establishing the role of histamine in allergic reactions and his basic research led pharmacologists to develop antihistamines.[106]

Baldes was the head of the biophysics department at Mayo. He earned a Ph.D. in physics at Harvard and in physiology at University College in London.[107]

Boothby was the first chairman of the Aero Medical Unit, and he interacted formally with the Committee on Aviation Medicine. In 1907, Boothby and Frederick J. Cotton (1869–1938) invented an apparatus to deliver nitrous oxide, ether, and oxygen for use in anesthesia. Subsequently, Boothby, Lovelace, and Bulbulian developed the Boothby-Lovelace-Bulbulian (BLB) nasal oxygen mask and the later oronasal mask that revolutionized high-altitude flying.[108]

Dr. William J. Randolph "Randy" Lovelace II (1907–1965) studied medicine at Harvard Medical School and graduated in 1934. He joined the Mayo Clinic for a surgical fellowship in 1935 and, having an interest in aviation, became a flight surgeon in the Army Medical Corps Reserves. His interest in the problems of high-altitude flight began during his fellowship at the Mayo Clinic. Lovelace left Rochester in 1942 to work at the U.S. Army Air Forces (USAAF) Aero Medical Laboratory and during World War II conducted high-altitude parachute experiments, including one jump from 40,200 feet during 1943. In 1958, Lovelace was appointed chairman of the NASA Special Advisory Committee on Life Science, where he played a key role in the selection of the Mercury astronauts. NASA appointed him Director of Space Medicine in 1964, but he died in a plane crash on December 12, 1965.[109]

Bulbulian's work as a part of the Mayo Aero Medical Unit led to the creation of a series of civilian and then, finally, military masks, notably the A-14 oxygen mask for the Army. The A-14 mask was frost proof and allowed the pilot to talk and eat while wearing it. Bulbulian also was the first director of the Mayo Medical Museum and designed the exhibits for the Mayo Clinic's display for the *A Century of Progress Exposition* at the 1933 Chicago World's Fair.[110]

The Mayo Clinic evolved from the frontier practice of Dr. William Worrall Mayo (1819–1911) and his two sons, William James Mayo (1861–1939) and Charles Horace Mayo (1865–1939). What is now considered the Mayo Clinic was founded by the Mayo brothers and a group of six other doctors, including Dr. Henry Stanley Plummer (1874–1936), who is considered by many American physicians to be the "architect of the modern medical practice" and a primary reason for the Mayo Clinic's early success.[111] While the Mayo brothers excelled as surgeons, Plummer established the diagnostic, clinical, and, in part, the organizational aspects of the practice. He also designed many of the systems now in use around the world, such as individual dossier-style medical records. In 1919, this group created the Mayo Properties Association, and their private practice became a not-for-profit entity. The Mayo brothers, who had retained ownership of all clinic properties and furnishings, ceded all of their assets to this newly formed association.

Code and Baldes recruited Dr. Earl H. Wood (1912–2009), to run the newly completed human centrifuge at Mayo. After Pearl Harbor, Wood tried to volunteer for the Army Air Forces but remembered, "They refused me, because I was considered essential to teach medical students."[112] He was teaching at Harvard Medical School when Baldes and Code recruited him back to his native Minnesota with the promise that he could be in charge of the centrifuge.

Wood quickly realized that tests with animals could not provide sufficiently accurate information. In fact, "We had to experiment on ourselves," he said, because "we would never do anything on any subject that we didn't first do on ourselves."[113] In the end, Wood rode the centrifuge so many times that he most likely had more blackouts in controlled conditions than any other subject. Code would later comment, "There wasn't anything we did then that was safe."[114]

Wood, realizing how incomplete the scientific explanations for the blackout problem were, quickly ascertained the true major problem. By comparing blood pressure at heart and head levels in the centrifuge, he learned that the heart could not generate sufficient pressure to pump blood to the head during periods of high acceleration. At 5-G, blood weighs five times as much, overwhelming the heart's ability to move it, so blood pressure in the head at 5-G is virtually zero. During his research, Wood found that the force exerted by a tight turn or a dive recovery could drive the diaphragm and the heart down toward the feet as far as 2 inches. That meant the heart had to generate even more pressure to pump blood up to the brain. Compressing veins, as done by a water-filled suit, was not the answer; instead, arteries needed to be compressed to increase arterial pressure.[115]

BERGER BROTHERS

The Berger Brothers company was based in New Haven, CT, and had three major subsidiaries: Spencer Inc., also in New Haven; Spencer Supports (Canada) Ltd, in Rock Island, Quebec; and Spencer (Banbury) Ltd. in Banbury, England. The brothers were Darwin Spencer Berger and George Wendell Berger, and Darwin's son, Spencer Merriam Berger.[116] Beginning in the 1920s, the Spencer companies sold "individually designed supports for abdomen, back, and breasts."[117] The products seemed far removed from aviation.

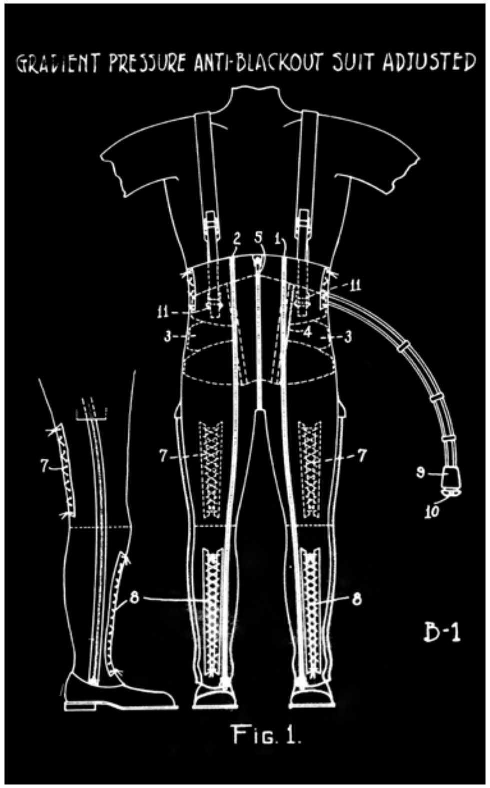
While William Stewart was testing John Fulton's leggings at Farnborough in 1940, the idea caught the interest of an American who happened to be at the base. Frederick D. Moller was an experienced pilot with more than 3,000 flight hours, and he immediately recognized the potential of the concept but believed the entire outfit needed to be simplified. He proposed combining an abdominal belt, leggings, and inflatable sleeves into a single garment that would be easier to don than Fulton's three-piece ensemble. An intricate set of tubes sewn into the garment allowed inflation from a single pneumatic source.[118] Upon his return to the United States, Moller took this idea to Berger Brothers, but it is unclear if Moller had a previous relationship with the company.[119]

Based largely on Moller's enthusiasm, Berger Brothers—makers of corsets and surgical supports—became interested in "foundation garments" for pilots. Urged on by Moller, the brothers decided, without consulting the Government, to begin developing an inflatable garment that would provide positive control of the splanchnic area, a strong support for the spinal column, and a safeguard against hernia. The company began using principles already employed in the Spencer Abdominal Support Belt, a device the company sold to the medical profession.[120] It did not take long for the Government to notice.

Eventually, Moller and Irving "Doc" Versoy produced a simple pneumatic belt and leggings in cooperation with LCDR Leon D. Carson from the U.S. Navy and with the assistance of the National Research Council. The first suit was a set of fitted coveralls with a group of air bladders in the calves, thighs, and abdomen. Zippers, laces, and internal straps allowed the suit to be adjusted to fit. The 20-pound suit progressively pulsated in seven zones from the ankles to the abdomen.[121] Initially, the pilot inflated the ensemble by hand just before he expected to need it, but like Poppen's earlier experiments, this quickly proved impractical.

The Mayo Clinic evaluated the Berger Brothers suit using a tilt table since the human centrifuge was not yet operational. These tests revealed that the suit provided approximately 1-G under the best circumstance, but the military considered this adequate. Even at 1-G protection, the suit allowed pilots to increase the tolerance from 5-G to 6-G, a small but potentially important advantage in aerial combat. In mid-1941, the Navy ordered a few hundred suits for use in the Pacific, but there is no evidence that they ever saw combat.[122]

Further development resulted in the 10-pound G-1, which, consisted of tight, high-waist trousers with built-in suspenders and a girdle containing 17 air bladders in 3 pressure zones.[123] Like the original suit, the G-1 provided the highest pressure over the ankles, an intermediate pressure over the calf area and abdominal belt, and the lowest pressure over the thighs. Engineers at Spencer designed a valve that operated off the same engine-driven air pump that provided vacuum to instruments in the cockpit. The Type B-2 or B-3 vacuum pump used by the Vought F4U-1 Corsair and Grumman F6F Hellcat already supplied air pressure for a variety of purposes, including operating de-icer boots and preventing air locks in external drop tanks. The smaller B-2 pump rapidly lost the ability to pressurize the suit above 20,000 feet, although the larger B-3 pump remained effective to about 30,000 feet.[124]

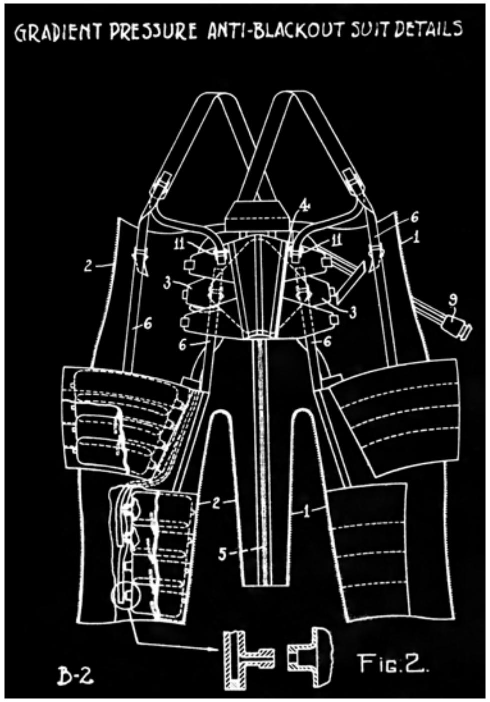


The Berger Brothers G-suit consisted of a set of high-waist trousers and suspenders with a series of inflatable bladders sewn inside. The suit had three zippers, one running from the top of the waist down to the bottom of each ankle (#1 and #2) and another running from the top of the waist to the bottom of the crotch (#5). Various sets of laces (#7, #8, and #11) allowed each suit to be tailored for its wearer.

Courtesy of the David Clark Company, Inc.

From the positive side of the pump, air passed through an oil vapor separator on its way to the cockpit through a 0.625-inch tube to the inlet of the gradient pressure valve assembly. The operation of the valve was completely automatic. The air came into the distributing head of the control valve and a bellows unit held the valve closed until acceleration exceeded 1.5-G. From the control valve, air traveled to the 3-G-compensated gradient-pressure valves actuated by weights and syphons as a function of acceleration. The gradient valve nearest the control valve was the high-rate valve that controlled the ankle bladders. Next was the intermediate valve that controlled the calf area and abdominal bladder. Last was the low-rate valve that transmitted air to the thigh bladders. Once properly adjusted for their specific installation, the valves required no routine servicing.[125]

Because the vacuum pump could not provide sufficient pressure quickly enough to fill a completely depressurized set of bladders, the suit always contained approximately 0.8 psi. The suit began pressurizing at 1.5-G at a rate of a little over 1.1 psi per G. At 4-G, the suit provided 3.5 psi on the ankle bladders, increasing to 7.9 psi at 8-G; the other bladders had correspondingly lower pressures. The Seamless Rubber Company in New Haven, CT, manufactured the bladders, which were generally similar to hot-water bottles made by the company.[126]



Each Berger Brothers G-suit used 17 air bladders in three pressure zones to provide counter-pressure on the legs and abdomen. Since the aircraft vacuum pump could not deliver sufficient volume quickly enough to fill all of the bladders, the suit always contained about 0.8 psi, making it somewhat uncomfortable when worn for prolonged periods. Although the suit afforded a decent measure of protection against blacking out under acceleration, the pilots universally disliked it (and all other contemporary suits).

Courtesy of the David Clark Company, Inc.

In addition to its inflatable bladder, the abdominal belt supported the back and internal abdominal organs, much like a hernia belt. The inflation of the rubber bladder within the nonstretching fabric belt diminished the area within the abdomen where blood could pool. If the pilot felt his vision "graying out," he could push hard with the abdominal muscles against the belt; the tension of the belt made the maneuver more effective than shouting or tensing without a restraint.

Berger Brothers provided suits in four sizes: small short, small long, large short, and large long. The suit had three zippers, one running from the top of the waist down to the bottom of the ankle on each leg, and another running from the top of the waist to the bottom of the crotch. To don the suit, all three zippers were opened completely and then zipped closed around the pilot. A set of adjustment laces was located on the front of each calf and the back of each thigh to allow each pilot to tailor the suit as needed. Generally, once the adjustment laces were set for a pilot, they were not used again, with the pilot donning and doffing the suit using only the zippers. The user manual said "Bear in mind that, while a snug adjustment makes the suit more efficient, it is not necessary for it to be uncomfortably tight under any conditions."[127]

Centrifuge tests at Mayo showed that the Berger Brothers suit provided sufficient protection, and the military did not seem terribly worried about possible discomfort caused by the suit always being slightly pressurized, although the pilots would later decide otherwise.[128] In December 1943, the Army ordered 22 G-1 suits from Berger Brothers, along with the equipment required for aircraft, and sent them to the Eighth and Ninth Air Forces in England. Based on the initial pilot reactions to the suits, the Army ordered 1,000 production suits, although ultimately only 500 would be delivered before the suit was replaced by the improved G-2.

In addition, Navy fighter squadron VF-8 "Ghost Cats" tested the G-1 during combat in the Pacific flying Grumman F6F-3 Hellcats off the USS *Bunker Hill* (CV-17) in September 1943 and again during the attack at Palau in March 1944. Pilots involved in the combat attributed several victories over Japanese Mitsubishi A6M Zero fighters specifically to the advantage provided by the G-suits. In general, the pilots liked the protection provided by the suits but thought they were too hot and cumbersome. Many pilots also worried what would happen if they had to bailout over water while wearing the ensemble—the additional 10 pounds of equipment would not help flotation. The result was that pilots seldom wore the suits after the initial novelty wore off. Based on pilot comments, LCDR Harry Schroeder made several suggestions to the Naval Air

Crew Equipment Laboratory on how to simplify the suit and its equipment. The Navy subsequently sent this information to the Aero Medical Laboratory at Wright Field.[129]

The reluctance of pilots to accept the G-1 suit forced the military to go back to the drawing board. Based on testing with single-pressure David Clark Company suits at Mayo Clinic, the Army decided to forego the gradient pressure concept and settle on a simple, single-pressure garment. Berger Brothers, David Clark Company, and Mayo Clinic all cooperated in the development of the G-2 suit. Outwardly, the suit generally resembled the G-1, consisting of a set of high-waist trousers with suspenders. However, instead of the 17 bladders in the G-1 suit, the G-2 contained only 5 bladders, and weighed 6.5 pounds instead of 10 pounds. The bladders consisted of one rectangular unit over each calf and thigh, plus an abdominal bladder.[130]

The pressurizing valve for the G-2 was different from the gradient pressure valve used by the G-1. Under normal 1-G flight conditions, the valve did not provide any air to the G-suit, keeping it completely depressurized. However, once acceleration exceeded 1.5-G, the valve rapidly increased pressure at the rate of 1 psi per g, meaning that at 9-G the valve was providing 7.5 psi to pressurize the suit. Other than connecting the inflation hose to the valve prior to flight, there was no pilot interaction with the device. This valve became standard equipment on many midproduction Lockheed P-38 Lightnings, Republic P-47 Thunderbolts, and North American P-51 Mustangs that used B-11 or B-12 vacuum pumps. Unfortunately, the B-11 and B-12 pumps suffered the same altitude limitations as the earlier B-2 and B-3 pumps, respectively.[131]

The G-1 consisted of a set of high-waist trousers that contained the air bladders for the legs and abdomen. The progressive feature of the suit, where different pressures were applied to different parts of the body progressively, led to a large and complex set of valves, shown on the table next to the model. The three pressure valves (one to the left and two to the right of where the hoses connect) each provided a different pressure. There were several variants of this valve arrangement, but they all operated similarly.

Courtesy of the David Clark Company, Inc.

On the Mayo Clinic centrifuge, the suit provided 1.4-G of protection, and researchers at Wright Field generated similar results on their centrifuge. Service trials at Eglin Field in February 1944 were satisfactory, and the Army standardized the G-2 suit on June 19, 1944. Within the next year, the military distributed more than 3,500 G-2 suits, made by a variety of manufacturers, to combat zones.[132]

Nevertheless, much like its predecessor, combat pilots did not meet the G-2 with overwhelming enthusiasm. The reports from the pilots, however, contained at least one very interesting observation. Most of the pilots refused to use the G-suits as their only clothing and instead wore the G-suit over their normal flying uniforms. Despite pilots not using the suits as intended, they worked.[133]

THE WORCESTER CONNECTION

Engineer and test pilot A. Scott Crossfield once described David Clark as "one of the most interesting men I have ever met in the aviation world."[134] David M. Clark was born in Massachusetts in 1903 and left school at age 15 to go to work full time. Nevertheless, he continued taking accounting and business classes in the evening, mostly at the urgings of his father. In 1934, he founded a knitting business in Worcester, MA, also with the encouragement of his father. Not having sufficient capital to start the company on his own, Clark convinced two older friends to help finance the endeavor in exchange for equal ownerships in the company. The business apparently suited Clark and, in quick order, he received six patents for improved knitting techniques. Although making a good living from the knitting business, Clark developed a fascination with aviation and, with a World War on the horizon, sought ways to contribute. Taking his cue from the "dreaded blackout" portrayed in newsreels of the time, Clark decided, sometime during 1940, to develop a garment that could protect aviators from high-G environments, apparently unaware of similar efforts by Cotton, Franks, and Moller.[135]

One of Clark's products was a knitted elastic support undergarment for men called the "Straightaway," for which he used an innovative technique to change the knitting from ordinary to elastic fabric at the waist, resulting in an undershirt attached to an elastic

The G-2 G-suit, this one made by David Clark Company, was a major improvement over the original G-1. Introduced into combat in mid-1944, the G-2 contained only 5 bladders, compared to 17 on the G-1. More importantly to the pilots, the weight of the suit was reduced from 10 pounds to only 6.5 pounds. This G-suit found use in most front-line fighters and provided about 1.4-G of protection. Despite all of the improvements, one thing the new suit shared with its predecessor was that pilots universally disliked it.

Courtesy of the David Clark Company, Inc.

abdominal support. This knitting technique eliminated the cross seams that typically caused discomfort. It was an innovative garment for the time, and the Straightaway was the subject of one of Clark's patents. For reasons unknown, Clark decided he could modify the Straightaway into a garment that could help pilots avoid blacking out.

Lacking money to travel, Clark wrote letters to the Army Air Corps and Navy Bureau of Aeronautics, but received no responses. He also paid a traveling stationary salesman friend $50 to show the Straightaway to the military. The particular Straightaway that Clark had supplied for this trip had an inflatable football bladder sewn into the center of the lower part of the abdomen that would apply pressure and help the aviator with the standard grunting techniques commonly used to combat loss of consciousness during high-G maneuvers. Like several earlier concepts, the bladder needed to be inflated using a hand bulb before the pilot anticipated he would need the support.

Apparently by shear chance, the salesman managed to gain an appointment with Jack Poppen, who was seemingly impressed with the garment but not with its operation. Poppen wrote Clark a few days later explaining the concept would not work because "it lacked automaticity that I cannot tell you about."[136] By this time, Poppen was well familiar with the automatic valve used on the Berger Brothers suit, but security restrictions prevented him from discussing it with Clark. Perhaps it was just as well since this forced a separate development effort—competition is always a good thing.

Clark, correctly, interpreted this to mean that he needed a way to automatically inflate the bladder based on changing flight conditions and began a search of a suitable G-valve. Clark built a prototype using iron pipe, a domestic water valve, and a miniature bicycle pump. When swung around vigorously at arm's length, the device would inflate a football bladder very quickly; the bladder deflated when the swinging stopped. Soon, Clark connected the valve to his modified Straightaway via a pair of 10-foot hoses hooked to a compressed air cylinder. Unfortunately, by this time, November 1941, the Navy had transferred Jack Poppen to a new duty station and his replacement, LCDR Leon D. Carson, expressed no interest in the device since the Berger Brothers gradient-pressure G-suit was already in limited production.

Finding no encouragement from the military, Clark wrote letters to the various aircraft manufacturers describing his garment. Only one responded, Boeing Chief Test Pilot Edmund T. "Eddie" Allen, who confirmed that some sort of G-protection was necessary and suggested that Clark contact Maj. Otis O. Benson, Jr., the chief of the Aeromedical Research Unit (soon to become the Aero Medical Laboratory) at Wright Field. A business trip a few days later brought Clark near Wright Field, so he made an unannounced visit. After a few bureaucratic hurdles, Clark and Benson were introduced. Clark explained that he was not seeking contracts but wanted to work with a group that understood the scientific principles, could evaluate his efforts, and offer advice for improvements. The prototype suits would be pro bono since that is how the commercial clothing business worked; companies made prototypes to show to clients and recouped the development costs via production orders. Benson thought this a worthwhile idea and arranged to have Clark issued the appropriate security clearances.[137]

In the continuing connection to Mayo, Benson had spent a year at the clinic in 1939 studying aviation physiology. Afterward, Benson attended Harvard University to continue his study of aviation physiology. He became the second chief of the Aero Medical Laboratory and, still later, commandant of the new School of Aerospace Medicine at Brooks Air Force Base (AFB), TX.[138]

In the late summer of 1941, Benson suggested Clark contact Dr. Hudson Hoagland, at the Physiological Laboratory of Clark University in Worcester, MA, who had recently presented a paper on acceleration protection.[139] Hoagland would leave Clark University in

1944 and, with Gregory Pincus, found the Worcester Foundation for Experimental Biology, now called the Worcester Foundation for Biomedical Research.[140] It is best known for the development of the combined oral contraceptive pill by Pincus and Min Chueh Chang. The institution merged with the University of Massachusetts Medical School in 1997.[141]

Benson and Hoagland both suggested that Clark contact LT Thomas J. Ferwerda at Naval Air Station (NAS) Anacostia in the District of Columbia. Ferwerda had a prototype G-suit, which he called a "Pulsatile" pressure suit, that was ready for testing on the newly opened human centrifuge in Canada. The suit consisted of a heavy open-weave material with seven bladders positioned crosswise in each leg. The pressure pulsated in a wave, traveling from the ankles to the thighs. The suit was tested by the Navy at Cecil Field, FL, in November 1942 but proved disappointing. Ferwerda subsequently modified the suit to include bladders along the arms and abdomen, but this suit also proved disappointing.[142]

However, perhaps the most important suggestion from Benson and Hoagland was to contact E.J. Baldes at the Mayo Clinic, who was also developing a human centrifuge. David Clark had already made preliminary contact with Mayo, sending it a Straightaway for evaluation as a postsurgery abdominal support. An exchange of correspondence with

The second G-suit designed by LT Thomas Ferwerda included air bladders along the legs, arms, and abdomen that progressively inflated (or pulsated). Ferwerda, like Berger Brothers and David Clark, was convinced that progressively inflating a suit from the ankles to the thighs (and wrists to shoulders) would force blood from the extremities back toward the heart. It was a concept that worked in theory but had little practical effect.

Courtesy of the David Clark Company, Inc.

Charles Code at Mayo led to Clark mentioning his conversation with Benson regarding Baldes. Eventually, word reached Baldes, who invited Clark to visit him in Rochester, MN. In a November 1941 meeting, Baldes showed Clark a scale model of the centrifuge, which had a construction budget of $50,000 despite the $1-per-year contract Mayo had with the Government. Unusually, Clark had not brought his suit and valve with him but described the device to Baldes, who approved of the basic concept.[143]

During his discussions with Baldes, Benson, and Hoagland, David Clark determined that ideally a G-suit should "milk" the blood from the lower legs up toward the torso since a simple belly bladder might not be sufficient to delay loss of consciousness. Unknown to Clark, this was not a new concept; the progressive or gradient suits developed by Frank Cotton in Australia and Fred Moller at Berger Brothers shared a similar trait.

Back in Worcester, Clark developed a "bandage" he could wrap around his legs. Hooked to a 50-psi air source, this bandage inflated progressively from the ankle upward, forcing blood from the legs into the torso. Clark demonstrated the garment for Baldes and Code in Worcester as they passed through on their way to convince Earl Wood at Harvard to join the human centrifuge program at the Mayo Clinic.[144]

During 1941, Ernest L. Olrich, the president of Munsingwear,[145] another clothing manufacturer, purchased a majority stake in the David Clark Company by buying out the two older partners. David Clark kept 30-percent of the shares, the title of treasurer, and, by agreement, absolute control of the company. Clark's relationship with Olrich later assisted the human centrifuge under construction at Mayo. After the Japanese attack on Pearl Harbor, the nation went on strict rationing of "luxury items" that contained war-critical materials. This included automobile tires. As designed, the Mayo centrifuge used an automobile tire to transfer power from a Chrysler drivetrain to the flywheels that drove the centrifuge; because of the rationing, it was impossible to acquire tires without violating the security restrictions surrounding the project. Clark knew the Government had appointed Olrich the chief of rationing for Minnesota, and he quickly arranged the delivery of two new tires to Mayo.[146]

Another of Clark's contacts proved handy when it came time to design a more sophisticated valve to operate the G-suit. Henry Wilder, an engineer at the Heald Machine Company, also located in Worcester, had been a Boy Scout with David Clark. After its founding in 1826, Heald specialized in precision grinding machines, especially ones that shaped the inside surfaces of hollow, cylindrical parts. At its peak, the Heald Machine Company had more than 1,300 employees and occupied nearly 500,000 square feet of factory space, but it ultimately closed its doors in 1992.[147]

Clark's original water-supply valve had an important failing; if the source pressure varied, so did the output pressure. This was not a huge issue during desktop and laboratory demonstrations in which compressed air supplied the source pressure, but it would be a major concern in an airplane. Along with another engineer at Heald, Waldo Guild, Wilder developed a valve that was immune to the variance of source pressure. The valve could easily supply an inflation pressure of 1 psi per G. It was a workable, if large and heavy, solution to pressurizing a G-suit.[148]

To create a more sophisticated anti-G garment, Clark needed somebody that could sew better than he could. Julia Greene was the daughter of Irish immigrants and a few years older than Clark. Greene already worked for Clark and was easily convinced to help develop the garment. The new G-suits started conventionally enough; Clark purchased six khaki twill coveralls, two each of three sizes, in a store downtown. Greene altered the coveralls to provide a tight fit in the buttocks and sewed inflatable bladders into the lower legs, thighs, and belly. These became the first Progressive Arterial Occlusion Suits (PAOS).[149]

The abdominal bladder was there not to compress abdominal arteries but to reduce the downward movement of the diaphragm and heart by supporting the abdominal wall. Experimentation with different sizes of orifices between the various bladders led to a configuration where, at 2-G, the suit would inflate progressively to 20 psi at the ankles, 10 psi at the knees, 5 psi at the hips, and 1.25 psi at the top of the belly.[150]

The Mayo Clinic had not yet completed the human centrifuge, so Baldes and Wood tested Clark's suit using the same tilt table researchers had previously used to test the first Berger Brothers suit. The two doctors believed the suits might be able to provide a level of G-protection greater than that provided by the Berger Brothers suit and asked Clark to leave them for further testing.

In November 1942, David Clark witnessed the researchers at Mayo testing his G-suits on the newly completed centrifuge. Earl Wood was the first to try the coveralls in the centrifuge and found that they provided measurable protection. Dr. Edward H. Lambert (1915–2003) then tried them, with the same results. David Clark also got a couple of runs at 5-G, providing valuable experience for the man that was designing the garment. Tests showed the PAOS could increase tolerance up to 3-G, meaning that a pilot that normally blacked out at 5-G could tolerate 8-G with the suit. This was significantly better than the 1-G provided by the Berger Brothers suit.[151]

David Clark returned to Worcester and began designing a new G-suit. Despite the relative success of the Mayo tests, each of the subjects had emerged from the centrifuge with petechiae (small bruises) on their skin where the bladders inflated. Wood thought these might be an indication of too much pressure, or perhaps the friction of the latex bladders which had to stretch considerably as they inflated, caused the bruises. Clark revised the size and shape of the bladders, and switched to a dipped, rubber-coated material to eliminate most of the stretching. The "milking" idea of progressively inflating the suit from the ankles upward did not seem to elicit any positive (or, for that matter, negative) comments from the researchers. Although Clark still believed the idea was potentially valuable, it also added considerable complexity, and he eliminated it from the next prototype suits. These changes resulted in the Arterial Occlusion Suit (AOS).[152]

The AOS was a pair of high-waist trousers with five interconnected air bladders: two fitted around the calves, two around the thighs, and one on the abdomen. They began to inflate at 1.5-G to compress the arteries in the lower half of the body, increasing the blood pressure in the upper half almost instantaneously. In essence, the suit worked on the principle of a tourniquet, placing strong encircling pressure on each thigh to stop the blood circulation to the limbs when the pilot experienced acceleration.[153]

The first AOS provided about 2-G of protection and eliminated much of the petechiae seen with the original PAOS. Although this was less protection than the PAOS provided, it was still twice that provided by the standard Berger Brothers suit. However, the researchers ultimately determined the suit was not acceptable because of the length of time it cut off circulation to the limbs during prolonged maneuvers and the resulting discomfort. Still, it demonstrated the concept was workable.[154]

After these tests, David Clark realized he needed some method of keeping track of the suit designs, so he retroactively called the original PAOS suits Model 1 and the first AOS suit the Model 2.[155] Each of the two-dozen Clark experimental G-suits that followed was different, sometimes vastly so. In one model, there were arm cuffs that provided measurably better protection but at a huge increase in complexity, and they also severely restricted the mobility of the pilot's arms. Often, the suits were similar except for the size of the abdominal bladders: the otherwise identical Model 5 used a 1.5-liter bladder, the Model 6 used 1.0-liter bladder, and the Model 8 used a whopping 4.0-liter bladder.[156]

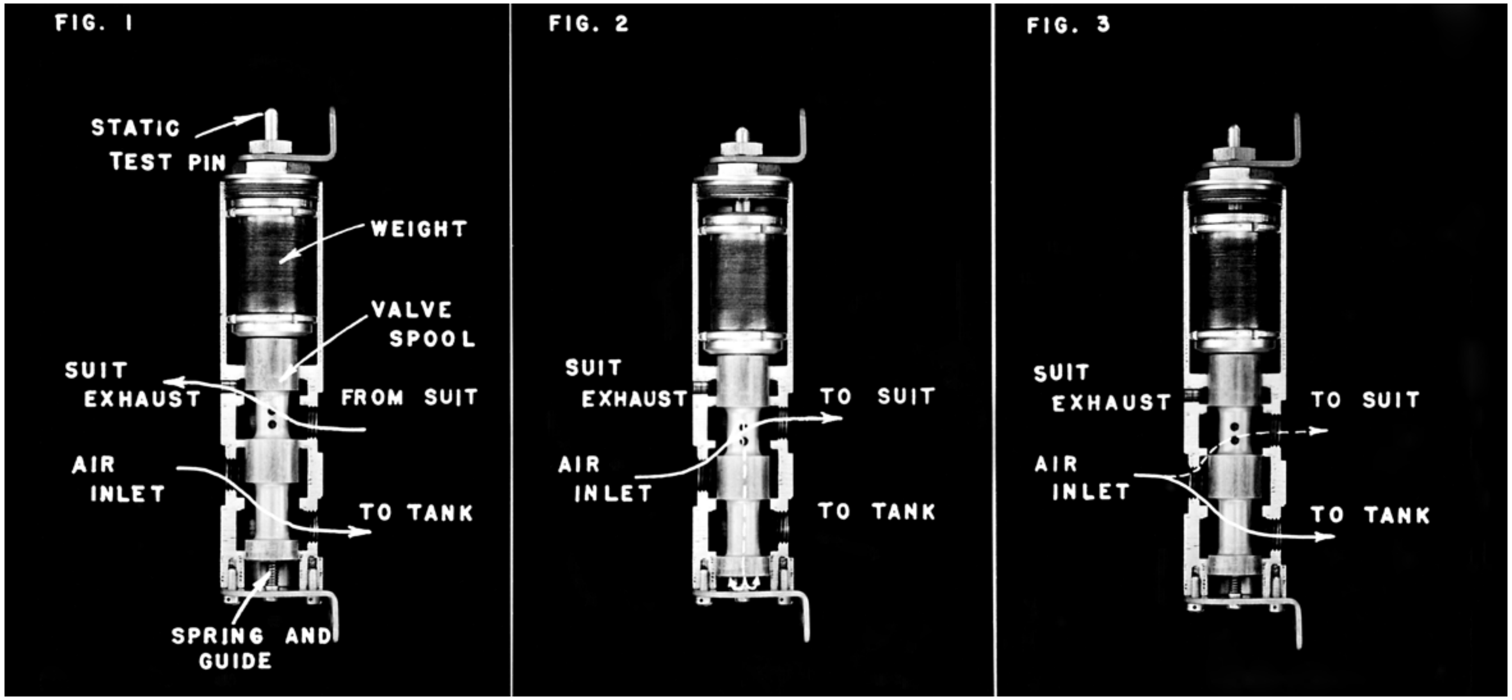
These early rounds of centrifuge studies provided some surprising results that guided the development of future G-suits. Researchers discovered that the chief factor in suit protection was the application of pressure on the abdomen and trunk. Pressurizing the legs was necessary for the effective use of abdominal pressure, but the amount of pressure was not particularly critical. The simplest type of leg bladders should be used, "since it is necessary only that they be of such size as to ensure reasonable pressure transmission to the legs in spite of relatively wide variations in fit."[157]

A conference was held at Wright Field to discuss whether a G-suit, better than the Berger Brothers garment used by the Navy, existed that the Army could field in relatively short order. David Clark, Charles Code, and Earl Wood attended, and the Mayo researchers believed the AOS could fill the need. Clark was not so certain, feeling the suit was overly complicated and probably not sufficiently comfortable for long-term use in a combat zone. In addition, the Heald valves were large, heavy, and designed to operate off a fixed

Left: The David Clark Company Model 8 Arterial Occlusion Suit (AOS) used bladders on the abdomen and around the thighs. Like all of the AOS suits, the thigh bladders functioned almost as tourniquets, increasing the blood pressure in the upper half of the body almost instantly. Researchers, however, worried about the effect of cutting off circulation to the lower legs and pilots objected to the discomfort during maneuvering.

Right: This variant of the AOS used a pair of arm cuffs, in addition to the abdominal and thigh bladders, in an attempt to keep as much blood volume as possible near the heart. Pilots found these made it nearly impossible to hold the control stick during maneuvering, and the concept was quickly dropped.

Courtesy of the David Clark Company, Inc.



The Cornelius control valve for the World War II G-suits was ingeniously simple. A counterweight reacted to G-load and operated a valve that either allowed compressed air to enter the suit or for the suit to exhaust the air as needed. Considering that it contained no electronics or complicated feedback loops, the valve was remarkably accurate.

Courtesy of the David Clark Company, Inc.

50-psi source, not whatever source existed on an airplane.[158] The conference reached no particular conclusion.

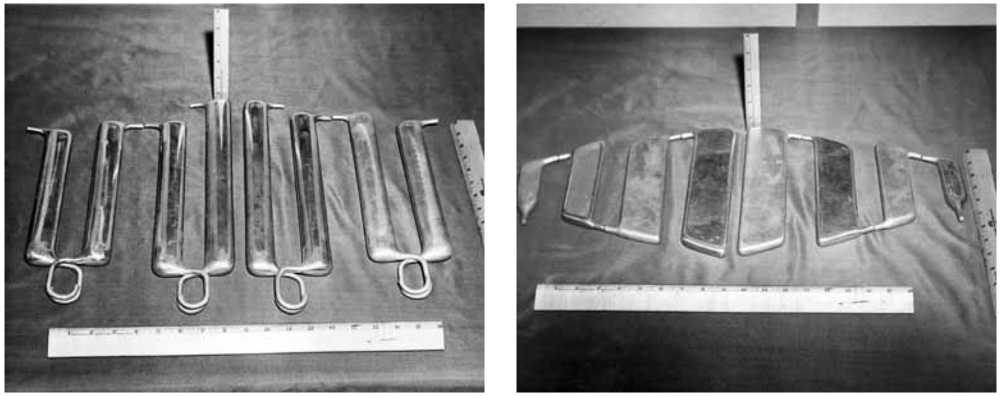
Finding a pressure source on airplane—before the advent of jet engines and their omnipresent bleed air—was a challenge. The Berger Brothers suits used the aircraft instrumentation vacuum pump. Unfortunately, this small pump only provided 14.7 psi at sea level, meaning the suit had to be kept partially inflated (about 0.8 psi) at all times in order to react quickly enough to G-loads. This increased the discomfort level of the suit on long missions since it somewhat restricted movement in the cockpit.[159]

During the Wright Field conference, it became obvious that the Heald valves that David Clark was using would not work in an operational environment. Baldes turned to Richard Cornelius in Minneapolis, who was working with Mayo and Wright Field on pressure-sensitive switches for parachutes. In addition to designing various air compressors for aviation applications during World War II, Cornelius founded a company that has become one of the world's leading suppliers of beverage dispensing equipment, including a foam-free draught system for beer. Cornelius soon developed a suitable valve under the guidance of David Clark and the researchers at Mayo Clinic.[160]

In 1943, Baldes arranged for the Army to bail a Douglas A-24, essentially an olive-drab version of the Navy SDB-3A Dauntless dive bomber, to the Mayo Clinic for in-flight evaluation of G-suits. Showing a good sense of humor, the researchers named the airplane the *G-Whiz*.[161] Lambert instrumented the airplane, and the chief of the Army Reserve contingent in Rochester, Lt. Kenneth Bailey, assisted Mayo with maintenance and flying duties. Bailey soon learned to fly precise, repeatable profiles that allowed researchers to acquire the necessary data.[162]

Most of the prominent researchers in the field of G-protection and Government leaders from the USAAF, U.S. Navy, RCAF, and RAF, convened at Wright Field in early 1944 to plot the course for pilot protective clothing for the rest of the war. One of the decisions that came out of this conference was that the Allies would adopt the simplified Berger Brothers G-suit. Although most present apparently agreed that the Clark AOS provided greater protection, they deemed the Berger Brothers suit adequate, and the pilots preferred it. After the meeting, Earl Wood went to Worcester to tell David Clark.

David Clark was not ready to give up. Overnight, he fabricated a prototype that took the best of the Berger Brothers suit and the AOS. It had a one-piece bladder system that combined all five bladders, in the Berger Brothers suit. The inflation hose passed through the belly bladder and branched through the thigh sections and into the calf sections to ensure the folds of the two layers of fabric could not occlude the flow. Clark carefully shaped the belly bladder to ensure it would not provide uncomfortable contact with the pelvic or rib bones when inflated.



One of the features of the David Clark Company G-suits that made them less expensive to fabricate and easier to maintain was their bladder system. By molding many of the interconnected bladders as a single piece, leakage was minimized, as was a lot of hand assembly. These are some of the molds used to make the bladders during 1945.

Courtesy of the David Clark Company, Inc.

When Earl Wood arrived the following morning to say his goodbyes, Clark showed him the experimental suit. Wood found it quite comfortable, even at full inflation. He cancelled his outbound train, told Clark to make a "more finished" suit, and called Charles Code. Within a few days, Julia Greene and fellow seamstress Rose Arlauskas made three of the new suits in various sizes. Wood took the new suits to the Mayo Clinic and found that the suit provided adequate protection when inflated at 1 psi per G.

Researchers tested the new suit in the Mayo A-24, and James Henry came from USC to evaluate the suit in the airplane. Lambert had installed movie cameras in the airplane so that researchers could review the subjects' reactions to the suits after landing. By now, Bailey had pretty much perfected the art of taking the lumbering dive bomber up to 10,000 feet, putting it in a spiral dive, and producing whatever G-load was required for about 15 seconds.

Coincidences are often critical. As Mayo was testing the suit, E.J. Baldes phoned David Clark with news that he had met Harry Schroeder, the man that had evaluated the effectiveness of the 300 Berger Brothers G-1 suits the Navy had sent to combat squadrons in the Pacific. Baldes steered Schroeder to Worcester, where he met Clark in July 1944. Schroeder stressed that the Berger Brothers suits had worked well, when the pilots conceded to wear them—all were reluctant. The suits were hot in the tropical climates, uncomfortable, too heavy, and did not contribute to survival if the pilot abandoned his airplane for some reason.[163]

David Clark listened intently, and when Schroeder left for Wright Field a few days later, he had an improved suit that weighed only 3.5 pounds. The new coveralls did not use lace adjustments but had several zippers that allowed it to fit each pilot. Testing in the Wright Field centrifuge revealed the suit provided adequate protection, but Schroeder had several ideas to improve the suit, mostly to make it more appealing to the pilots. He had Clark add a large pocket on the front of each shin, a smaller pocket for a hunting knife on the inside of the right shin, large chest pockets that were out of the way of the parachute harness, and a pocket for a pack of cigarettes on the upper left arm. David Clark developed eight standard sizes (four waist sizes in 2-inch gradients, with "shorts" and "longs" in each size).[164] These changes satisfied Schroeder, and he took the modified G-suit to Washington. Schroeder named the new suit Z-1, the Army designated it G-2, and both suits were ordered into production from a variety of manufacturers.[165]

Sometimes a completely different idea comes from an unexpected source. Back in early 1943, Helen Lester and David C. Spooner at the Electric Blanket Division of General Electric (GE) had contacted Harry Schroeder with an idea for a G-suit, developed in consultation with Dr. Harold Lamport at Yale University. General Electric used capstans on the calves and thighs instead of bladders, making it more comfortable for the pilots (the stomach bladder remained). The capstans were large inflatable tubes that ran vertically along the legs on the outside of the suit. Each capstan attached to a series of interdigitizing laces that encircled the limb; as the capstan inflated, it tightened the laces around the limb and provided the required skin pressure. For this to work, the suit had to fit almost perfectly. A loose fit would easily allow the capstans to exceed their useful limit without tightening the laces sufficiently to exert any pressure on the skin. A tight fit provided too much counter-pressure, potentially shutting off circulation to the limb.[166]

Unfortunately, testing at both Wright Field and Mayo Clinic showed the initial suit provided no measureable protection. The major problem was that the capstans and interdigitizing laces could not react quickly enough given the available pressure. After the tests, sometime in early 1944, Helen Lester visited David Clark to discuss the capstan system.[167] David Clark told Lester about the USC centrifuge, and the GE team took their suit to California where James Henry was working on a partial-pressure suit.

Unfortunately, tests at USC also showed the GE suit provided no measureable protection. By the end of the war, the Pioneer Products Division of GE had evolved the concept into the L-12 suit, which, provided slightly better protection than the Clark G-3 on the Wright Field centrifuge. Unfortunately, the L-12 needed higher pressure than was available on combat aircraft of the era, so it was never ordered into production. The capstans, on the other hand, would reappear on the first Henry partial-pressure suit.[168]

In the meantime, David Clark's experimental seamstress, Julia Greene, left Worcester to follow her husband to Burbank, CA, where he had recently gotten a job with Lockheed. This move would prove fortuitous a little later in the story, when Greene went to work for Henry while he developed his partial-pressure suit. Back in Worcester, Alma Charland took over the seamstress duties and, being more experienced at making patterns, redesigned the Z-1 suit to better integrate the shin pockets. The Navy ordered the modified suit into quantity production as the Z-2.[169]

Despite the laboratory success of the Z-2 suit, pilots still did not like it; many preferred blacking out to wearing it. "Pilots are just that way," Wood said. "They don't think they need anything."[170] But the pilots had a point. On the ground, the suit was hot and uncomfortable, and crew rooms without air conditioning felt like saunas in tropical climates. In combat, the suit could actually be painful. During high-G maneuvers of long duration, the pneumatic bladders could stay inflated for up to a minute and feel like tourniquets. The suit could cut off blood circulation to the legs, which would ache with the pain of ischemia like that of a heart attack. If the abdominal bladder inflated too quickly, it gave not the usual hugging feeling but something like a punch in the stomach. Although a clinical success, G-suits were proving to be an operational failure.

This is the David Clark Company version of the Z-2 G-suit. Note the zippered pockets on the shins, chest, and sleeve. Sometimes it seemed as if the location and shape of the pockets were as important as the acceleration protection provided by the bladders hidden inside the suit.

Courtesy of the David Clark Company, Inc.

CUTAWAY SUITS

Up to this point, all G-suits, whether designed by Berger Brothers or David Clark, had been high-waist trousers or coveralls. However, the reluctance of fighter pilots to use the suits, mostly due to discomfort, was worrisome to the researchers. In response, George Maison at Wright Field suggested developing a "cutaway" version of the suit that a pilot could wear over whatever clothing was appropriate (i.e., heavy uniforms in cold climates and lighter uniforms in the tropics). It was largely the same path taken by Wilbur Franks in Canada. This resulted in the G-3 suit, a cutaway version of the G-2 that looked like a set of trousers in which the front of the knees, crotch, and buttock area had been cutaway. There was just enough material to keep the five bladders in the abdomen, thighs, and calves in their proper positions. The suit came in four standard sizes and used lace adjustments for fitting. The David Clark suit weighed 2.25 pounds and the Berger Brothers suit was about a half pound heavier due to its rubber bladders. The G-3 used the same airplane-mounted equipment as the G-2 and was operationally interchangeable.[171]

During testing in the Mayo centrifuge, 12 subjects made 320 runs and researchers used visual symptoms as a subjective measurement and the blood content of the ear and ear pulse as objective measurements. The centrifuge runs lasted 15 seconds with a maximum acceleration of 6-G attained at a rate of 2-G per second. The Army conducted similar tests at Wright Field and the Navy in Philadelphia. All of the tests confirmed the new Berger Brothers and David Clark cutaway suits provided adequate protection, although somewhat less than the earlier coverall type.[172] The Army evaluated both company's suits at Eglin Field in June 1944 and determined that the Clark suit was superior to that from Berger Brothers. The AAF Proving Ground Command recommended that the Berger Brothers suit be discontinued and all future suits be procured from David Clark Company.[173]

Beginning February 8, 1944, the Army Air Technical Services Command (ATSC) sponsored a set of conferences to standardize G-suits and their supporting equipment as part of classified Project MX-389.[174] Darwin Berger, Spencer Berger, David Clark, Fred Moller, and Capt. George A. Hallenbeck from the ATSC attended all of the conferences, with other attendees as required.[175]

Perhaps the most significant agreement to come out of the conferences was to standardize the design for the G-3 cutaway suit. On

A major advance in G-suits came with the advent of a "cutaway" suit. This allowed pilots to wear the G-suit over whatever clothing was appropriate for the conditions they were operating in, such as heavy uniforms in cold climates or lightweight cotton in the tropics. The cutaway contained just enough material to support the five bladders in the abdomen, thighs, and calves. This also reduced the weight of the suit to just 2.25 pounds. The pilots still did not like the suit, but they began wearing it since data showed it significantly increased their kill rate.

Courtesy of the David Clark Company, Inc.

February 10–11, Moller and Doc Versoy from Berger Brothers and David Clark and John Chisholm from the David Clark Company drew up patterns for the standardized G-3 suit using an interchangeable bladder system. One of the major issues was that the Berger Brothers preferred bladders made of rubber or synthetic rubber, while David Clark used Vinylite-coated nylon fabric. In the end, everybody agreed that Berger Brothers would continue to use rubber bladders and David Clark would use coated nylon fabric but that each company would use the same design, making the bladders interchangeable. Somewhat later, the Army directed both companies to switch to neoprene bladders that were even more durable and somewhat lighter.

Things moved much quicker in 1944, and Berger Brothers put the new suit into production on February 25, and David Clark followed on April 15. Munsingwear and several other manufacturers also produced the suits. By the end of 1944, more than 4,100 G-3 suits were delivered to the Eighth, Ninth, and Twelfth Air Forces, and in November 1944 the Army officially accepted the G-suit as standard equipment and began issuing one to every fighter pilot.[176]

The G-3 suit became operational during the fall of 1944, and data soon showed that blackouts and grayouts were happening much less frequently to pilots who wore the suit. None of the safety issues won over pilots but performance data finally did. A P-51 Mustang fighter group of the Eighth Air Force reported that pilots wearing anti-G suits shot down 67 enemy aircraft per 1,000 operational hours, compared with only 33 kills for other pilots. A doubling of the kill rate was persuasive.[177]

Based on comments from the combat zones, a slightly improved Type G-3A suit was soon developed to further improve comfort. The outer suit used a sage-green, basket-weave nylon cloth, and the inside areas around the bladders used an oxford-weave cloth because it tended to slip less around seams. The new suit provided 1.1-G of protection on the Wright Field centrifuge and 1.2-G on the Mayo Clinic machine. The suit came in four sizes: small short, small long, large short, and large long, and laces over the calves, thighs, and flanks provided custom fitting. Surprisingly, the G-3A weighed almost a pound more than the initial Clark G-3. Late in its production, the G-3A came with a device that allowed the suit to be inflated by mouth and used as a life vest if the pilot was forced into the water.[178]

After Germany fell, the United States cutback many defense contracts, but the need for G-suits kept both Berger Brothers and David Clark busy. When V–J Day arrived, the military cancelled many contracts entirely, including the G-suit contract with Berger Brothers. The one with David Clark Company, however,

Pilots universally disliked all of the early G-suits but began to change their minds once the statistics began showing their combat performance, as measured in "kills" of enemy aircraft, improved while wearing the suits. In particular, a P-51 Mustang fighter group of the Eighth Air Force reported that pilots wearing anti-G suits shot down 67 enemy aircraft per 1,000 operational hours, compared with only 33 kills for other pilots.

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continued, although the company again began manufacturing undergarments for the civilian market (they were the "Sears Best" brassiere manufacturer through the 1950s). Showing how the conduct of business differed during the war years, when the end of 1945 came, the David Clark Company realized they had made better than a 10 percent profit on a Navy G-suit contract. This was mostly because they had bid the per-suit cost before production ramped up and the true cost of making the suit was known. The company cut a check for $88,000 and returned the excess profits to the Navy, which, somewhat bewilderingly, accepted it.[179]

Even before V–J Day, there were some major changes in work for G-suits, although neither David Clark nor Fred Moller knew what they were for. For instance, George Maison asked David Clark to modify the pressurization valve to operate from much higher pressure, although details of its intended application were not immediately forthcoming. In fact, the modification was necessary to adapt the valve to use bleed air from the turbojet engines under development at GE.[180]

In due course, the military gave David Clark permission to visit Muroc Army Air Field in California and witness test flights of both the Bell P-59A Airacomet and Lockheed P-80 Shooting Star. At the time, both airplanes were flying without the benefits of a G-suit. Richard Cornelius modified his valve to accept air from the highest stage of the compressor side of the General Electric I-16 and I-40 turbojets (later produced as the J31 and J33).[181]

At the request of the Navy, David Clark also developed a set of full coveralls that contained bladders similar to the G-3. Naval Aviators preferred the resulting Z-3 suit since they wore

The Lockheed P-80 program drove major changes to the way air was obtained to operate G-suits. The P-80 was the first operational jet fighter in the United States and formed the basis of the successful T-33 trainer that saw service for decades after World War II. Somehow, it seems that Lockheed was intimately involved with much of the evolution of G-suits and pressure suits.

National Museum of the United States Air Force Collection

it instead of a normal flight suit, eliminating one piece of clothing; it was also somewhat cooler since only a single layer of cloth covered the belly and legs. These were step-through coveralls made of lightweight, inelastic, porous rayon cloth fitted with one abdominal and two leg zippers. At the David Clark Company, Joseph Ruseckas patterned the suit after the standard summer flight suit, and it came in nine sizes without lace adjustments. While he was developing the patterns, Ruseckas integrated the parachute harness into the garment. The Army bought a limited number of these suits under the G-4 designation.[182]

Although the G-3 cutaway and G-4 coverall suits used similar bladder systems, there were some important differences. The bladders in the G-3 had a volume of 12.1 liters, while the G-4 used only 9.7 liters, primarily by reducing the size of the abdominal bladder. Under identical conditions, this, along with eliminating the leg lace adjustments, had the effect of reducing protection from 1.9-G for the G-3A to 1.5-G for the G-4. These changes made the G-4 more comfortable for the pilots, but in 1947, David Clark introduced the G-4A that used a larger abdominal bladder and provided 1.9-G of protection.[183] Based on service trials on 25 fighter pilots during 1948 using both the G-3A and G-4A, the USAF determined the G-4A was more effective and more comfortable. The USAF subsequently adopted the G-4A as its standard G-suit for the next several decades.[184]

By early 1948, the USAF was having second thoughts about relying completely on the David Clark Company for its G-suits, not because of any failing with the company, but because of competitive "sole source" contracting concerns. Two other companies expressed interest: the Drybak Outdoor Clothing Company of Binghamton, NY, and Warner Brothers of Bridgeport, CT. The USAF asked David Clark to assist both companies in making prototype suits. When the USAF announced the winners of the first competitive procurement, David Clark and Drybak shared the contracts. Eventually, David Clark Company stopped producing G-suits since there were fewer development opportunities, concentrating instead on the development of pressure suits.[185]

Given the head start that Wilbur Franks and the Canadians had on developing G-suits, it came as a crushing blow when the RCAF decided in 1948 to purchase suits from David Clark Company. When Franks arrived in Worcester, David Clark showed them a new suit sewn by Joe Ruseckas. Franks asked for some changes, including a larger belly bladder, and took the suit back to Toronto for testing on the Canadian centrifuge. The RCAF liaison at the Canadian Embassy in Washington soon called David Clark and ordered 50 suits for immediate delivery and indicated an additional order would be forthcoming for an additional 250 suits (this order eventually got sidetracked, through the Mutual Defense Assistance Program (MDAP) scheme, to another supplier). The RCAF was getting ready to deploy to Korea and needed the additional protection for its pilots.[186]

POSTWAR SUITS

Shortly after the end of World War II, the United States essentially halted attempts to develop G-suits that were more effective than the standard G-4A because the aircraft of the era did not appear to need a better garment. Nevertheless, minor modifications resulted in the USAF and Navy using a variety of G-suits through the end of the 20th century.

The CSU-12/P coverall developed for the USAF used pneumatic bladders located at the abdomen, right and left thigh, and right and left calf. The bladder casings were fabricated of chloroprene-coated nylon and the outer cover of interwoven nylon and cotton. Laces at the waist, thighs, and calves, covered by a Velcro flap, allowed individual adjustment.[187]

The CSU-13/P was a cutaway G-suit developed for the USAF that provided essentially the same protection as the CSU-12/P coverall. Bladders were located at the abdomen, left and right thigh, and left and right calf. The bladder casings were fabricated of polyurethane-coated nylon taffeta and the outer cover of interwoven nylon and cotton. Laces at the waist, thighs, and calves, covered by a Velcro flap, allowed individual adjustment. The CSU-13A/P was a slightly revised version that used an outer cover of 95 percent Nomex and 5 percent Kevlar cloth.[188]

The CSU-15/P cutaway G-suit developed for the Navy used pneumatic bladders located at the abdomen, left and right thigh, and left and right calf. This suit differed from contemporary USAF suits by having different sized bladders, additional lacing adjustments, and a longer disconnect hose.[189] A slightly revised version was designated CSU-15A/P. The official description of the CSU-15/P cutaway suit did not differ much from the wartime G-3A:

> The CSU-15/P anti-G garment consists of a fire-resistant Aramid cloth outer shell, which houses a bladder. It is cut away at the buttocks, groin, and knees. The outer shell has waist and leg entrance slide fasteners, six adjustment lacing areas with lacing covers, and two easily detached leg pockets with slide fastener closures. The bladder system is constructed of polyurethane-coated nylon cloth and covers the abdomen, thighs, and calves. The bladder system is fitted with a hose for connecting directly to the aircraft anti-G system. This anti-G garment is available in six sizes.[190]

On February 25, 1982, the Air Force and Navy met at the Naval Air Development Center in Warminster, PA, to discuss standardizing on a single G-suit design to replace the CSU-13/P and CSU-15/P, respectively. Although the construction and placement of the bladders differed somewhat in the two suits, the major differences were external. For instance, the CSU-13/P leg closure zippers closed in an upward direction, while the CSU-15/P used quick-release closures that separated downward. The pocket configuration differed, as did the air supply attachment hose. The Air Force had a large extra-long size that the Navy did not, while the Navy had a small, short size for women that the Air Force did not. The Air Force rated the service life of the CSU-13/P at 12 months, but the Navy used the CSU-15/P for 18 months.[191]

During flight evaluations, pilots generally expressed a preference for the suit they were used to but felt that either suit was satisfactory. Based on the results of the tests, the Department of Defense selected the CSU-13/P as the common G-suit. The specific tri-service model became the CSU-13B/P. This cutaway suit used an Aramid cloth outer shell that contained polyurethane-coated nylon abdomen, thigh, and calf bladders. The outer shell had waist and leg entrance slide fasteners, six lace adjustments with Velcro covers, and two detachable leg pockets with slide fastener closures. The suit came in seven sizes: small regular, small long, medium regular, medium long, large regular, large long, and large extra-long. The suit was fabricated by a variety of manufacturers, including Aerotech Industry Corporation, Life Support International, Inc., and Mustang Survival (Mustang Sportswear, Ltd.). The CSU-13B/P replaced all earlier Air Force and Navy G-suits as they reached the end of their service lives.[192] Pilots commonly referred to the CSU-13B/P (and many other G-suits) as "speed jeans."

Although the CSU-13B/P was the standardized suit, several other G-suits were also used by the United States. For instance, the F-16/PBG was developed by the Air Force Flight Test Center (AFFTC) at Edwards AFB specifically for the F-16 Combined Test Force. The F-16/PBG featured the same G-suit bladder coverage as the standard CSU-13B/P but incorporated inflatable chest bladders into the upper portion of the ensemble to assist with pressure breathing above 5-G. The suit used laces on the legs and torso to provide a snug fit. Below 5-G, the G-suit and chest bladders functioned independently; above 5-G, the G-valve sent a proportionate pneumatic signal to activate the oxygen regulator to proportionately increase breathing-gas output to the chest bladders and the oxygen mask.[193]

As a possible replacement for the F-16/PBG, from June 21 through August 24, 1989, the F-16 CTF evaluated the Swedish Tactical Flight Combat Suit (TFCS). The TFCS was an integrated life support ensemble designed to provide protection from high-G, cold-water immersion, and temperature stress. Components of the ensemble included a lightweight helmet: low-profile, high-pressure oxygen mask: an integrated full-coverage anti-G and immersion suit: and a specialized pressure/survival vest. The suit was tested in a slightly modified General Dynamics F-16B (81-0816) at Edwards. The evaluators felt the TFCS provided better protection than the F-16/PBG and offered a significant improvement over the standard-issue CSU-13B/P G-suit. However, the TFCS was bulkier and more restrictive of movement than either American ensemble. Despite the TFCS vapor barrier, it was no cooler in the hot Edwards environment than the F-16/PBG. The TFCS helmet offered improved fields of view and greater noise attenuation. Notwithstanding the advantages offered by the Swedish garment, the USAF did not procure it.[194]

TLSS AND COMBAT EDGE

Officially, what came next are called "Anti-G Suits," but, in reality, they are closer to partial-pressure suits. To increase pilot performance under acceleration, modern G-suits use pressure-breathing masks and counter-pressure vests in concert with lower-body G-suits. These suits also provide limited altitude protection up to 50,000 or 60,000 feet, although the lack of arm and hand protection limits their use at high altitudes to a few minutes (truly a get-me-down capability). A brief description of the suits and their development

The McDonnell Douglas F-15 Eagle was the first of a new generation of highly maneuverable aircraft that drove the development of improved acceleration protection. These aircraft were capable of sustained +9-Gz maneuvers, well beyond the capabilities of the then-current, wartime-derived G-suits. In addition, the F-15 had a thrust-to-weight ratio of greater than 1:1, making radical vertical maneuvering feasible for the first time.

U.S. Air Force

is presented here instead of in the partial-pressure suit chapter for consistency with what the Government calls the ensembles.

During the early 1970s, Dr. Sidney Leverett and his colleagues at the USAF School of Aerospace Medicine recognized the need for better G-protection to accompany the very maneuverable McDonnell Douglas F-15 Eagle and General Dynamics F-16 Fighting Falcon. These aircraft were capable of sustained 9-Gz maneuvers, well beyond the capabilities of the then-current, wartime-derived G-suits.[195] In response, the Air Force established the Tactical Life Support System (TLSS) program. This effort had a wide range of research objectives that included "NBC" (nuclear, biological, chemical) protection, advanced anti-G protection, moderate high-altitude (60,000 feet) protection, thermal-flash-protection goggles, aircrew cooling (via a liquid-cooling garment), and on-board oxygen generation via molecular-sieve apparatus (onboard oxygen generation system, or OBOGS). Meeting all of the requirements involved the development of several new pieces of equipment, including a new breathing regulator that could interface with the OBOGS and a new type of G-valve to operate the G-suit and counter-pressure vest.[196]

Instead of a competitive development effort, the Government formed a team that included various USAF laboratories, the Canadian Defence and Civil Institute of Environmental Medicine (DCIEM), Boeing, and Gentex. As with most ambitious programs, TLSS ran behind schedule and over budget, and it eventually dropped some of its original objectives.

The DCIEM was responsible for design of the TLSS G-suit and constructed a garment that included a lower-body G-suit and a counter-pressure vest to aid with pressure breathing. The suit featured full NBC and thermal flash-protection goggles. Canada had earlier identified the need for suitable high-altitude protection for aircrews of the new high performance fighter it was planning to acquire. However, when that aircraft turned out to be the McDonnell Douglas CF-18 Hornet, which was limited to altitudes around 50,000 feet, the need for the suit largely went away. Nevertheless, Canada continued to participate in the TLSS program until the end.

The TLSS was flight-tested at Edwards during 1986–87 using an F-15B and F-16B with generally positive results. Four pilots tested the fully integrated TLSS prototype system (including OBOGS) in the front seat of the F-15B during 26 flights that included high-altitude, air-to-air, and air-to-ground roles. A simplified system that used a modified CRU-73 breathing oxygen regulator and the existing G-valve was tested in the back seat of an F-16B by 4 pilots during 24 flights in the air-to-air mode. In addition, the suit successfully survived an explosive decompression at 60,000 feet in the Brooks AFB altitude chamber. Despite its seeming success, the Air Force and Congress ultimately deemed TLSS too expensive to produce in large numbers.

However, the relative success of the simplified system tested in the F-16B resulted in the Air Force redirecting the program during 1988 toward improving G-protection and dropping many of the other original goals. In part, this was the result of a significant increase in gravity-induced loss of consciousness (G-LOC) accidents in the F-16.

The USAF School of Aerospace Medicine undertook an extensive series of centrifuge studies with several combinations of components from the TLSS and other sources to define a workable combination that could be fielded quickly at a reasonable cost. Five different ensembles were ultimately selected for further testing. Ensemble I used the TLSS fully integrated pressure-vest/torso garment (upper-pressure garment, or UPG), TLSS extended-coverage G-suit (lower-pressure garment, LPG), and a modified CRU-73 regulator. Ensemble II included the TLSS component pressure vest/torso garment, standard CSU-13B/P G-suit, and modified CRU-73 regulator. The component pressure vest did not provide complete coverage of the torso like the fully integrated pressure vest. Ensemble III used an extended pressure-vest/torso garment, CSU-13B/P G-suit, and a modified CRU-73 regulator. The extended pressure vest provided more coverage than the component pressure vest, but not as much as the fully integrated pressure vest. Ensemble IV featured the extended pressure vest/torso garment, a full-coverage G-suit, and a modified CRU-73 regulator. The full coverage G-suit used bladders that completely covered the thighs and calves instead of the separate bladders in the CSU-13B/P that only applied counter-pressure to the sides of the limb. Ensemble V used the extended pressure vest/torso garment, full-coverage G-suit, and an experimental (NGL) pressure regulator from the United Kingdom that provided the same pressures as the CRU-73 at lower breathing resistance. All of the ensembles used the TLSS helmet and oxygen mask.

Based on the results of tests on the Brooks human centrifuge, Ensemble III seemed to offer the best compromise between protection and comfort. This was also one of the least expensive options to implement. This configuration became the basis for the Combined Advanced Technology Enhanced Design G-Ensemble, which, became better known as Combat Edge. The TLSS helmet was replaced with the already fielded lightweight HGU-55/P. However, the tests conclusively demonstrated the full-coverage G-suits significantly increased acceleration protection, so their development was continued as the Advanced Technology Anti-G Suit (ATAGS).[197] Various configurations of extended coverage G-trousers were designed and tested, and some of the designs provided almost 100-percent coverage and even included booties to cover the feet.[198]

For all intents, Combat Edge is a description of pressure breathing, and the components of Combat Edge act in unison to sense and respond to high-G conditions. The G-valve sends a signal to the oxygen regulator to increase mask pressure up to 1.2 psi above ambient. This same pressure is routed to the occipital bladder in the back of the helmet, causing it to inflate and push the pilot's face into the oxygen mask. This same pressure is also sent to the counter-pressure vest to balance the breathing pressure supplied to the lungs. Ultimately, Combat Edge maintains pressure in the pilot's chest cavity to help the heart pump blood to the eyes and brain while inhibiting the downward blood flow.[199]

Physiologists differentiate between pressure breathing for G (PBG) and pressure breathing for altitude (PBA) although the differences are so subtle as to be lost on laymen. In the PBG mode, the same pressure that is applied to the vest bladders is supplied to the pilot's respiratory system through the oxygen mask. Combat Edge obtains two beneficial effects from this action. The most obvious benefit is that the pilot can breathe during PBG, but in addition, since the system is squeezing the pilot's chest from the inside as well as the outside, it denies even more volume for blood pooling and more blood is pushed toward the head.

The pressure level of the Combat Edge PBG breathing air supply is controlled by the breathing air regulator, which in turn, is controlled by the G-valve. An important system feature is the interlock between the trousers and vest that is created by this method of control. The system design ensures that the G-trousers are fully pressurized and inflated before the counter-pressure vest can begin to fill and apply pressure. If this interlock did not exist, and the counter-pressure vest filled first, the blood from the legs and abdomen would be trapped and could not rise toward the pilot's head. The G-trouser pressure level is several times higher than the PBG pressure level. The output pressure of the PBG regulator varies in response to the output pressure of the G-valve; therefore, the PBG pressure level also varies as a ramp function in response to higher acceleration levels.[200]

During the early 1980s, the L-1 anti-G straining maneuver replaced the original M-1 developed by the Mayo Clinic during World War II. The L-1 maneuver combines a regular, 3-second strain (Valsalva) against a closed glottis, interrupted with rapid exhalation and inhalation while tensing of all major muscles of the abdomen, arms, and legs. Properly executed, it provides an average pilot approximately 1.5-G protection. This is about the same as the standard G-suit, so combined the suit and straining maneuver provide about 3-G protection. The M-1 maneuver was essentially the same but against a partially open glottis, causing the pilot to audibly grunt during the strain, resulting in lower intra-thoracic pressures. The Navy teaches a slight variation of the L-1 called the Hook Maneuver in which the pilots initiate the strain phase by saying, "hook" as they begin to strain. This helps ensure a completely closed glottis.[201] In either case, the signal to commence straining is the beginning inflation of the bladders, felt first in the G-suit.

While Combat Edge does not replace the straining maneuver, it significantly reduces the effort required to execute it. A common misconception is that fighter pilots tend to make long sweeping turns that produce medium-to-high acceleration levels that are maintained for a relatively long time. In fact, this is seldom the case. Air combat maneuvering (ACM) is a constantly changing acceleration environment, often consisting of a zigzag pattern that generates anywhere between +5-Gz and +9-Gz on each alteration. Except for the straining action, Combat Edge functions automatically. The bladders sequentially inflate and deflate, the mask tightens and loosens, and the pilot is allowed to concentrate on flying the airplane. At the end of a mission, the pilot who has flown with Combat Edge is considerably less fatigued than one flying the same mission in a conventional G-suit.[202]

Despite its improved acceleration protection, the Combat Edge counter-pressure vest has a significant drawback: it is hot to wear. The original TLSS-integrated flight suit used a liquid-cooling system composed of tubing threaded inside the bladder layer. This liquid-cooling system was not carried forward as part of Combat Edge because it was not logistically supportable, leaving the Combat Edge vest somewhat uncomfortable in some climates. Nevertheless, liquid-cooling systems continue to have supporters, and the Eurofighter Typhoon uses one.[203] Recently, the Air Force authorized use of the Combat Edge system without the counter-pressure vest, the justification being enough flight-hours have been accumulated to show that the wearer would not be in danger.[204]

The initial USAF Combat Edge ensemble consisted of the CSU-17/P counter-pressure vest, CSU-13B/P G-suit, HGU-55/P helmet with an occipital bladder, and MBU-20/P oxygen mask. The flight-test community evaluated the first prototypes at Edwards in 1988, and formal testing took place in 1990 using F-15s and F-16s. Operational test and evaluation of the ensemble was completed in 1991, and all F-15 and F-16 aircraft were modified, mostly with new G-valves, to accept the equipment by mid-1995. New production aircraft after that date have the equipment installed at the factory.

The Navy was not completely happy with the Combat Edge ensemble. Instead of the CSU-15B/P G-suit, the Navy selected the Canadian-developed Sustained Tolerance for Increased G extended-coverage G-trouser. The Navy Combat Edge ensemble is designated A/P22P-16 and provides enhanced acceleration protection between +4- and +9-Gz to an altitude of 50,000 feet. Below +4-G, the ensemble provides the same level of protection as the CSU-15B/P. The Navy uses Combat Edge only in the F/A-18 fighter. The ensemble consists of the CSU-20/P cutaway anti-G garment, CSU-21/P counter-pressure vest with a chest-mounted CRU-103/P G-compensated oxygen breathing regulator, HGU-68/P helmet, and MBU-24/P oxygen mask.[205]

The CSU-20/P is similar to the CSU-13B/P with a 40-percent increase in leg- and abdomen-bladder coverage. It has a flame-resistant cloth outer shell with waist and inner-leg slide fasteners, adjustment lacing with covers, and leg pockets with slide-fastener closures. The CSU-21/P vest has a flame-resistant cloth outer shell with a front slide-fastener closure for easy donning and doffing and laces to allow sufficient adjustment for correct fit.[206]

Somewhat before the development of Combat Edge, McDonnell Douglas undertook a program called Atlantis Warrior, led by Dr. D. Lambert, which was conceived around a hydrostatic suit containing 6 liters of water. It was conceptually similar to what Bill Franks fabricated during World War II. A prototype was tested on a human centrifuge, where it reportedly performed well, and where it demonstrated the ability for the pilot to talk under +10-Gz acceleration loads for up to 3 minutes and maintain consciousness at +12-Gz.[207] The suit underwent comparative human prolonged high-G exposure testing during 1996 at Wright-Patterson AFB. These tests showed a higher number of tolerated 5-9-Gz peaks compared to the other suits, and subjects did not suffer any documented episodes of G-LOC.[208] Despite its clinical success, Atlantis Warrior was not produced.

Interestingly, the German Luftwaffe finally fielded a hydrostatic G-suit, 60 years after it initially developed, and rejected, the concept. The Libelle G-Multiplus, developed by Autoflug Libelle GmbH (a joint venture of Life Support Systems AG of Switzerland and Autoflug GmbH of Germany), is a full-body G-suit that uses hydrostatic rather than pneumatic pressure. The suit looks much like what Harold Lamport at Yale and Helen Lester and David C. Spooner at General Electric developed in 1943, with the primary difference being the fact that the capstan tubes are fluid filled instead of air filled.

"Libelle" is German for "dragonfly," because the suit is based on the same principles that protect a dragonfly from the 30-G accelerations the insect generates in flight. The suit uses 0.3 gallons of liquid to exert counter-pressure during acceleration. When acceleration forces push blood toward the lower part of the body, it also pushes the liquid inside the suit in the same direction, providing a counter-pressure that is automatically adjusted by the G-load itself. The suit uses fluid-filled channels traversing the arms, torso, and legs to tension its snug-fitting fabric. The suit is an autonomous, stand-alone system that does not require air or power from the aircraft.[209]

The suit was tested on the centrifuge at the German Air Force Institute of Aviation Medicine in Königsbrück and in more than 200 flights in Pilatus PC-7 turboprop trainers and a Learjet belonging to the Swiss Air Force. With this ensemble, pilots were able to withstand accelerations between –0.9-Gz and +10.4-Gz and at a maximum onset of +5-G per second with no apparent decrease in situational awareness.[210] During 1998, the Swiss and German air forces evaluated the suit in a direct comparison between the Libelle suit and the standard CSU-13B/P pneumatic suit using 10 subjects (8 fighter pilots, 1 M.D., and 1 civilian pilot). At that point, the Libelle consisted of a seat cushion that provided G-proportional pretensioning of the suit to allow for optimal efficacy of the hydrostatic capstan-like principle. The suit performed reliably and did not cause any G-LOC in a passive-acceleration profile and in simulated air-combat maneuvering. The Libelle system achieved a relaxed G-tolerance of +7.1-Gz compared to +6.7-Gz for the CSU-13B/P—a statistically irrelevant difference. Problems with the suit primarily were the very tight fit and the need for a different straining maneuver.[211]

Combat Edge pilots need to perform a straining maneuver as their contribution to the successful system performance. The signal to commence straining is the beginning inflation of the bladders, felt first in the G-trousers. Combat Edge-trained aircrew who have flown the "automatic" Libelle suits note that this physical signal is missing because hydrostatic operation does not offer the sensation of the G-suit inflating at the onset of acceleration. Some of the subjects reported they had to be much more conscious of the maneuvering of the aircraft to add their straining effort at the proper moment. Researchers determined the training requirements for optimum use of the system were almost the exact opposite to those of Combat Edge. Instead of straining (which will cause at least an interruption in normal breathing), the trainee for the Libelle system is encouraged to breathe as normally as possible. This promotes a greater ability to speak during the high-G maneuver. If the Libelle system were to be adopted, the Libelle training regimen would also have to be put in place.

Beginning in March 2000, the Libelle was evaluated by the USAF on centrifuges at Holloman AFB and Brooks AFB and during flight demonstrations at the USAF Test Pilot School at Edwards AFB. The evaluation did not exceed +9-Gz in either the centrifuge or flight tests. In general, the evaluation team had a favorable opinion of the Libelle, which offered certain advantages over the Combat Edge suit.[212] In the end however, the USAF did not pursue the Libelle system. Dr. Ola Eiken and his team also evaluated the suit on the human centrifuge in Sweden in 2002. They studied three pilots in the Saab JAS-39 Gripen extended-coverage G-suit and compared it to the tolerance afforded by use of the Libelle suit. The results showed a G-tolerance of +6.3-Gz with the Libelle suit and +9.0-Gz with the standard pneumatic suit, a result seemingly favoring the older technology.[213] Nevertheless, on January 31, 2005, the Libelle G-Multiplus became operational in Typhoons from Jagdgeschwader 73 of the German Air Force at Laage Air Base.

ATAGS AND THE F-22

As the TLSS program morphed into Combat Edge, human centrifuge tests continued to show that full-coverage G-suits offered significantly increased acceleration protection, so the Air Force continued to develop the garments as the Advanced Technology Anti-G Suit (ATAGS).[214] Various configurations of extended coverage G-trousers were designed and tested. Some of the designs provided almost 100-percent coverage and even included booties to cover the feet.[215]

The final configuration of the G-suit was designated CSU-23/P but is generally still called ATAGS. As a stand-alone garment, ATAGS provides a 60-percent increase in aircrew endurance. Combined with Combat Edge, it increases aircrew endurance by 350 percent over the standard G-suit. Unlike other G-suits, ATAGS completely envelops the legs and buttocks and rides lower on the torso so that it does not push against the chest.[216]

Oddly, unlike all previous G-suits for the past 50 years, the air connections for the CSU-23/P are on the right side of the suit, explaining why it is only compatible with the Lockheed Martin F-22 Raptor. On June 30, 2008, the Air Force awarded the latest contract for 150 ATAGS CSU-23/P G-trousers to Vinyl Technology, Inc. of Monrovia, CA, for $741,501, or approximately $4,943 each.[217] A similar ATAGS suit, designated CSU-22/P, has interfaces on the left side that are compatible with the F-15, F-16, and F/A-18.[218]

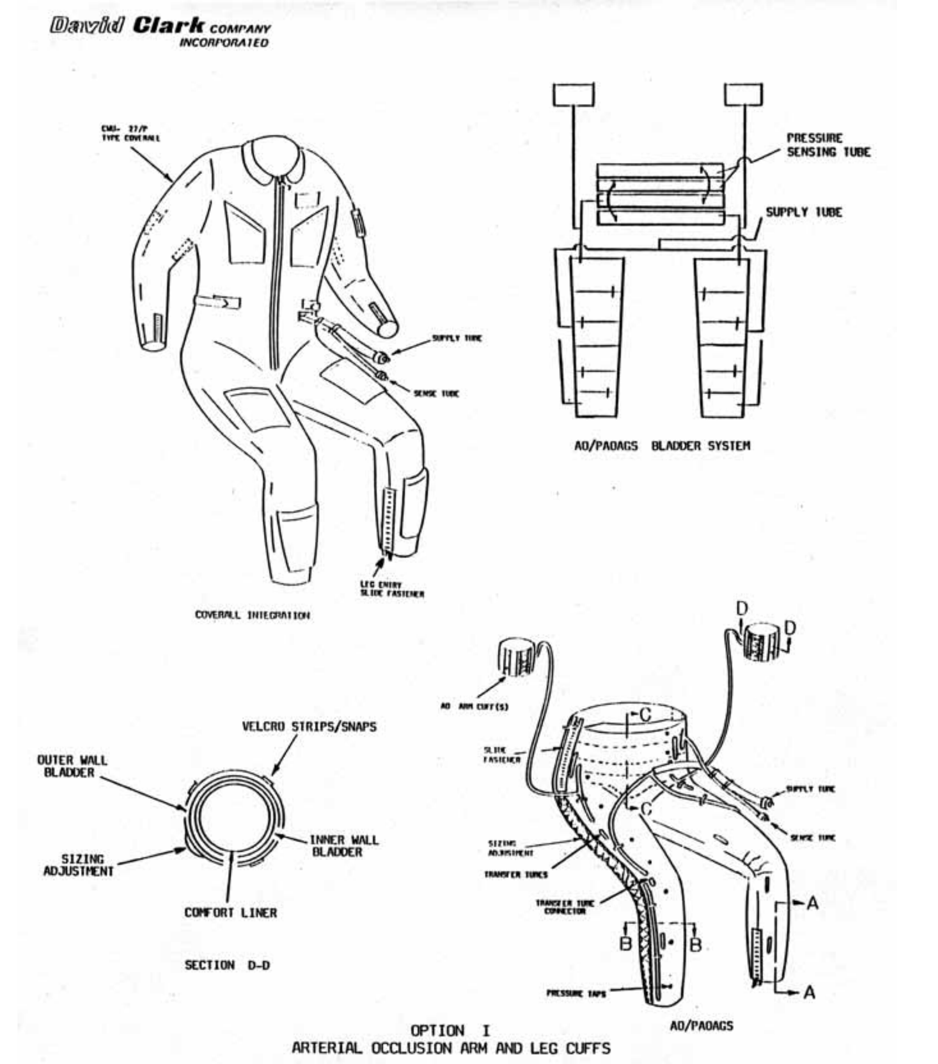
Having a unique G-suit for the F-22 posed a variety of logistical problems for the Air Force, so the Air Combat Command asked the Armstrong Laboratory to evaluate if the CSU-23/P could be replaced by the standard CSU-15B/P from Combat Edge. Of course, the F-22 would still have its interface connections on the right side of the cockpit, meaning either the CSU-13B/P would need to be modified (negating the point of the exercise) or some method would need to be found of connecting a left-handed G-suit to a right-handed airplane.[219]

Since there are no two-seat F-22s, the Air Force decided to use a two-seat F-15B for the evaluations. This presented a problem since the CSU-13B/P is configured to work correctly in an F-15. The solution was to fabricate nine CSU-13B/P suits with the inlet hose moved to the right-hand side. A hose was developed that routed the air across the ejection seat to interface the nonstandard suits with standard left-hand connections. Three test conditions were evaluated, one using a standard left-hand CSU-13B/P suit, one using the modified right-hand CSU-15B/P suit, and the last using the CSU-23/P suit. For each of these, the G-suit was inflated according to the standard aircraft schedule. Pressure breathing began at +4Gz, with a linear increase in pressure of 12 mm Hg per G to a maximum of 60 mm Hg at +9Gz. The maximum possible time for each condition was 90 seconds. Unsurprisingly, the researchers decided it did not matter which side the G-suit hose connection was on.

The researchers did find, however, that the CSU-23/P provided better protection under some conditions than the CSU-15B/P. For instance, the CSU-23/P demonstrated a lower discomfort level and lower heart rate during gradual acceleration. The suit also allowed the pilot to endure constant acceleration for longer periods, and a lower heart rate during rapid acceleration. The test subjects also tended to rate the CSU-23/P better than the CSU-15B/P in overall G-protection and fatigue level after G-exposure.[220]

Instead of joining ATAGS, the Navy initiated a parallel program called the Enhanced Anti-G Lower Ensemble (EAGLE) to develop an improved G-suit. There were significant differences between ATAGS and EAGLE. The ATAGS CSU-23/P had a smaller abdominal bladder than the standard CSU-13B/P G-suit and the leg bladders completely enclosed the legs and feet. The EAGLE CSU-20/P abdominal bladder was the same size as the CSU-13B/P, and the leg bladders completely enclosed and pressurized the upper and lower legs down to the boot, but the knees and feet were unprotected. EAGLE also included a CSU-21/P counter-pressure vest, MBU-24/P pressure breathing mask (an MBU-20/P with Navy communications equipment), and an upgraded HGU-68/P helmet with a bladder. The HGU-68/P helmet featured a much improved, lightweight, and easily adjusted external visor that had been rocket-sled tested at the Hurricane Mesa facility to resist ejection windblast forces in excess of 600 knots.[221]

In 1993, the Air Force Armstrong Laboratory compared the performance of the ATAGS and EAGLE G-trousers. The human centrifuge tests began at +3-Gz for 15 seconds and increased to a maximum of +9-Gz until physiological termination criteria were exceeded or



The retrograde inflation anti-G suit (RIAGS) was a modern incarnation of the 1943 progressive arterial occlusion suit (PAOS) and featured a set of bladders that progressively inflated from the ankles to the abdomen. The goal was to develop a G-suit that offered a significant increase in protection over the CSU-13B/P G-suit that was in widespread service.

Courtesy of the David Clark Company, Inc.

the 15-second limit was reached, whichever came first. The tests found that both sets of trousers provided better protection than the standard CSU-13B/P, although they each had disadvantages such as increased heat load and reduced mobility. The researchers found that, statistically, the ATAGS with pressure socks provided better protection than the EAGLE, which did not include pressure socks. The test subjects also reported less fatigue with the ATAGS.[222]

REDISCOVERING THE PROGRESSIVE ARTERIAL OCCLUSION SUIT

David Clark and Earl Wood's 1943 progressive arterial occlusion suit (PAOS) was briefly resurrected in 1989, when Lloyd D. Tripp, Jr., and researchers from Systems Research Laboratories and the Crew Systems Directorate of the Biodynamics & Biocommunications Division at Wright-Patterson AFB began looking for more effective G-suits. According to the researchers, "the original PAOS design was resurrected because of the G-induced loss of consciousness problem in USAF aircraft and the suit's apparent improvement in G-protection over the standard CSU-13B/P G-suit."[223]

The Retrograde Inflation Anti-G suit (RIAGS) used a series of bladders that progressively inflated from the ankles to the abdomen. In addition, two different sets of arms were developed: one used arterial occlusion cuffs that inflated to 12 psi, and the other used a set of capstans and interdigitizing laces that inflated to 30 psi.[224]

The RIAGS leggings contained a set of urethane-coated nylon bladders on the legs and abdomen that could be inflated to 12 psi. Modern fabrication techniques resulted in bladders that were considerably less bulky than those used on the 1943 suit.

Courtesy of the David Clark Company, Inc.

Fittingly, the Systems Research Laboratories issued a purchase order to the David Clark Company for the fabrication of the experimental suit. The effort included fabricating a G-suit that could be tested in three configurations: the basic abdomen and leg trousers, those with arm and/or leg arterial-occlusion cuffs, and any combination of those with a set of capstan sleeves. Modified medium-long, blue Nomex CWU-27/P flyers coveralls were also fabricated for each of these combinations. The urethane-coated nylon bladders were ultrasonically sealed, resulting in a lighter-weight and less bulky suit than had been fabricated in 1943. The basic G-suit consisted of bladders located on the legs and abdomen that could be inflated to 12 psi. The arm and leg cuffs could also operate at 12 psi, while the 5:1 ratio capstans on the sleeves operated at 30 psi to provide 6 psi of skin pressure.[225]

The suit was tested on the Dynamic Environment Simulator, a 19-foot radius human centrifuge at Wright-Patterson AFB. The results showed that most of the subjects complained about the arterial occlusion cuffs, reporting tingling hands and fingers, decreased dexterity of the hands, and in some cases, pain. The use of the capstan sleeves provided better protection than the standard CSU-13B/P G-suit,

To cover the RIAGS leggings, David Clark Company fabricated a modified set of CWU-27/P flyers coveralls in blue Nomex. Although the suit performed well, by the time the RIAGS tests were completed, the Armstrong Laboratory at Brooks AFB was well along with the development of the Advanced Technology Anti-G Suit (ATAGS) and the RIAGS concept was dropped.

Courtesy of the David Clark Company, Inc.

but the arterial cuffs provided no meaningful increase in protection. When the PAOS suit had been tested at the Mayo Clinic in 1943, the test durations were very short, and the use of arterial cuffs provided a meaningful, short-duration increase in acceleration protection. However, the modern tests ran much longer and showed the cuff actually decremented protection compared to either not having any arm protection or to using the capstan sleeves. By the time the RIAGS tests were completed, the Armstrong Laboratory at Brooks AFB was well along with the development of ATAGS, and the RIAGS concept was dropped.[226]

SUMMARY

The past decade has seen a resurgence of acceleration research, aimed primarily at future generations of highly maneuverable fifth-generation fighters. These efforts are well beyond the scope of this book.

4

4: Partial-Pressure Suits

Ultimately, the Army's wartime effort to develop a full-pressure suit proved unsuccessful. However, the performance of airplanes, particularly a new generation of fighters equipped with turbojet engines and a series of rocket-powered research aircraft developed late in the war, continued to increase. The advent of the workable pressurized cockpit largely relegated the pressure suit to that of an emergency device, much like a parachute. What was needed was a garment that offered protection in the event of a loss of cabin pressure. At one end of this spectrum was a suit that would protect against an engine flameout, which would result in a slow decompression, since the cabin structure would remain intact but the source of pressurization would be lost. At the other end of the spectrum was a suit that would protect against the explosive decompression that would result from the loss of the canopy or a similar structural failure. In response, the Army began seeking an emergency partial-pressure suit.

All previous American pressure-suit-development work had concentrated on the concept of a full-pressure suit. As David Clark, the man, once opined, the terms partial-pressure suit (PPS) and full-pressure suit (FPS) are not particularly descriptive but through common usage have become the accepted nomenclature for the garments. As ultimately defined, a partial-pressure suit protects its occupant through the application of mechanical pressure against the skin, all of which may or may not be covered (the head, hands, and feet were often bare in early suits). The friction of the fabric on the skin offers resistance to motion, and irregularities in body contour result in unequal distribution of pressure, giving both pressure points and unpressurized areas. Pressure breathing is a key part of any partial-pressure suit, which provides sufficient counter-pressure to allow exhalation at extreme altitudes. On the other hand, the full-pressure suit offers protection by applying gas pressure against the skin, creating a mini artificial environment in which the occupant can breathe, more or less, normally.[1]

For a slow decompression, as might happen following a flameout of a jet engine, either a partial- or full-pressure suit provides adequate protection since the pilot has time to close his helmet and pressurize the suit. Ultimately, of course, the full-pressure suit provides better protection, but if the goal is simply to allow the pilot to descend to a safe altitude, either suit works satisfactorily. It is a different story for an explosive decompression. Most operational scenarios from the late 1940s show a pilot wearing an unpressurized suit, mostly to increase comfort and lessen the effort necessary to fly the airplane. Because it is a relatively tight-fitting garment, even an unpressurized partial-pressure suit provides some protection during a rapid decompression. Oddly, although a full-pressure suit would seem to be the garment of choice in such an event, an unpressurized full-pressure suit offers little protection against a rapid decompression since it is loose-fitting. To offer any protection, a full-pressure suit needs to be pressurized to at least a low level all the time.[2]

PRESSURE BREATHING

In the decade after the Europeans traded altitude records, Wiley Post's prediction that aircraft would routinely fly at high altitudes came true. As this was taking place, physiologists realized that standard demand-type oxygen systems were not adequate for extended flights above 30,000 feet. In the demand-type system, oxygen only flows when a person inhales, and then only as much as is required to fill the lungs. Even on pure oxygen at 30,000 feet, the law of partial pressures results in a severe decline in alveolar oxygen saturation levels. At 43,000 feet, the alveolar oxygen saturation produced by ambient pressure can sustain consciousness for only a short period.[3]

During the mid-19th century in Germany, Dr. Louis Waldenburg (1837–1881) carried out the first experiments on breathing at high pressures, generally called pressure breathing (more recently called positive pressure breathing, or PPB), in an attempt to cure various respiratory diseases. From his, and similar, experiments came pneumotherapy, using pressure-breathing devices that were often called Waldenburg apparatuses. The early researchers used intermittent pressure breathing at 22 mm Hg to expand the lungs. It is probable that, under certain conditions, such breathing may have given some benefit to victims of pneumonia or various respiratory diseases, but too little was known about the physiology involved, and the whole matter fell into disrepute and was forgotten.[4]

In the United States, the Aero Medical Laboratory at Wright Field led Army research into aviation medicine. In November 1941, A. Pharo Gagge (1908–1993) reported for active duty, working for Capt. John G. Kearby in the Miscellaneous Unit of the Aero Medical Laboratory. Pharo Gagge (pronounced like baggy) earned his doctorate in physics at Yale University in 1933 and joined the John B. Pierce Laboratory in New Haven, CT. The laboratory, an independent research institute affiliated with Yale, was founded in 1933 across the street from the Yale School of Medicine. The laboratory still exists and is devoted to "studying the ways biological systems interact with their environment."[5] In 1950, Gagge became Chief of Medical Research for the USAF Surgeon General, and from 1955 through 1960, he was Deputy Commander and then Commander of the Air Force Office of Scientific Research. Gagge retired from the USAF in 1963 and returned to the Pierce Laboratory.

Kearby was the project officer for the wartime full-pressure suit development effort. In early December 1941, Kearby asked Gagge what effect "supercharging" air into the lungs would have on human performance at high altitude, believing this might offer an emergency procedure in case of damage to a full-pressure suit during a chamber test. Researchers used breathing pressures of 4, 7, and 11 mm Hg in the altitude chamber, and an oximeter measured a noted increase in arterial saturation.[6] Oximetry is the measurement of arterial oxygen saturation by transmitting light through a translucent area of a patient, usually the earlobe. In 1939, British scientist Glen Millikan developed the lightweight ear-oxygen meter and coined the term "oximeter." Initially used to determine oxygen saturation in aviators, by 1948 a similar device was used to control anoxemia during surgical anesthesia. The Waters Company X-350 Oximeter, based on work by Earl H. Wood at the Mayo Clinic, was the first oximeter to give absolute readings of oxygen saturation without prior adjustment to a known concentration. Similar oximeters were used during cardiac surgery at the Mayo Clinic.

The pressure-delivery device used during these experiments was a compensated metabolism apparatus designed by Gagge when he was at the Pierce Laboratory. The tests demonstrated that human subjects using pressure breathing were able to survive and function effectively at higher altitude. In fact, Gagge was able to ascend to 46,000 feet in an altitude chamber and retain reasonable effectiveness. However, by March 1942, Gagge realized that the compensated metabolism apparatus, as a means of supplying pressure breathing, was incapable of further improvement.[7]

Standard oxygen masks—all derived from the BLB concept originally pioneered at the Mayo Clinic—did not work well as pressure-delivery devices since increased oxygen flow simply pushed the masks away from the face, regardless of how tightly they were cinched around the head. A full-face mask, then an integrated mask-helmet, eventually addressed this problem and forced oxygen into the lungs. As it turned out, this was the easier part of the problem. Now, the pilot had to exhale, and without external pressure on his chest (which normally comes from the ambient air pressure), this proved difficult. Instead of breathing normally, the pilot had to forcibly exhale, an action that is not instinctive and takes more concentration that one would expect. In addition, the lungs are not particularly powerful, as evidenced by the amount of effort it takes to blow up a balloon. Researchers found that many subjects suffered from collapsed lungs while pressure breathing. It was a perplexing problem.

In January 1942, the National Research Council Committee on Aviation Medicine visited the Aero Medical Laboratory to evaluate pressure breathing. Dr. Eugene F. DuBois (1882–1959) was chairman, and the committee included Dr. John F. Fulton of Yale University and Dr. Henry C. Bazett (1885–1950) of the University of Pennsylvania. Showing that it is a small world, Pharo Gagge and Bazett had previously worked together at the Banting and Best Institute for Medical Research in Toronto. The committee was impressed by the results of the pressure-breathing experiments.[8]

However, it was immediately obvious to the committee that if it was going to use more than 15 mm Hg pressure, it would be necessary to apply a balancing pressure on the outside of the chest to prevent lung damage and to make exhaling easier. In response, Dr. Alvan L. Barach (1895–1977), a physician affiliated with Columbia University in New York who had long specialized in pulmonary research, developed a counter-pressure vest. Nominally, the vest maintained the same pressure as the oxygen a pilot was breathing. As the pilot inhaled, the vest deflated, and when the pilot exhaled, the vest inflated, forcing the chest inward and helping the pilot exhale. Similar vests were developed by Bazett, Dr. Walter M. Boothby at the Mayo Clinic, and Professor John D. Akerman at the University of Minnesota. Further, it was clear to at least Barach and Bazett that if pilots were to avoid serious disturbances in the circulatory system, it would be necessary to apply similar pressures to the abdomen and limbs.[9]

Under the direction of Kearby, one of the companies developing full-pressure suits, B.F. Goodrich, fabricated a rubber bladder and rigid outer vest to place around the chest wall. Essentially, this used the same principle as the vests developed by Barach and the others. Pharo Gagge used this vest for the first time in March 1942, and the vest supported the chest sufficiently to allow exhaling against pressures of 30 to 40 mm Hg (enough to usefully survive at 50,000 feet for about 30 minutes).[10]

However, physiologists discovered that lung collapse ensued almost as readily when pressure breathing with a vest as without it. A number of researchers attempted to define the factors responsible for lung collapse and eventually traced the phenomenon to a diminished cardiac output caused by excessive pooling of blood in the veins. The counter-pressure vest reduced pooling in the abdomen, and experiments using inflatable trousers (essentially, G-suits) prevented pooling in the legs—this allowed somewhat higher pressures. Henry Bazett ascended to 51,500 feet for 30 minutes using an inflatable vest and trousers, and others found it possible to get to 55,000 feet using the technique. Ultimately, researchers determined this was the maximum altitude that could safely be supported using a pressure-breathing mask and counter-pressure vest.[11]

Work continued to improve pressure-breathing equipment. In June 1942, the J.H. Emerson Company in Cambridge, MA, specialists in medical respiratory equipment and iron lungs, developed a modified A-12 demand regulator that supported pressure breathing. At the same time, Capt. Francis E. Randall at the Aero Medical Laboratory used anthropomorphic facial measurements to develop a mask that allowed pressure breathing while remaining relatively comfortable to the wearer. The prototype Randall mask was designated Type XA-13, and the Army requested further development from the Mine Safety Appliances Company in Pittsburgh, PA (a company with a long history of research on mining breathing systems). In November 1942, Randy Lovelace tested the Emerson valve and A-13 mask aboard a B-17E flown by Boeing test pilots Al C. Reed and Jim Frasier to 43,600 feet. Using data from the flight, Bradford Holmes of the Pioneer Bendix Company simplified the Emerson regulator so that a single knob controlled the exhalation pressure and diaphragm pressure. Lovelace and Lockheed test pilot Joe Towle tested an early Holmes pressure-breathing regulator in a two-seat Lockheed P-38 Lightning to 45,000 feet over Burbank, CA, in April 1943.[12]

In May 1943, the Joint Services Pressure Breathing Conference convened at Wright Field to discuss the status of various experiments. By this time, several leading authorities in the field of respiration had expressed considerable disbelief that pressure breathing provided any benefit, especially at the relatively low pressures used by the Army. For instance, Dr. Douglas R. Drury at USC believed that pressure breathing afforded protection only when used at very high levels. He thought the enthusiasm for pressure breathing and for increased altitude performance resulted from "high motivation rather than improved physiology."[13] Later, this opinion would prove substantially correct.

Despite the contrary opinions expressed during the conference, Capt. Norman Molomut of the Aero Medical Laboratory demonstrated pressure breathing at 48,000 feet in the Wright Field altitude chamber.[14] Pharo Gagge later stated that "the doubting Thomases still remained, as several even questioned the accuracy of our altimeters and even the mercury barometers. All calibrations later proved accurate."[15]

During the conference, Bazett used an ensemble consisting of a pressure-breathing mask, a pressure vest, and an early G-suit to demonstrate the altitude gains possible while pressure breathing at 35 mm Hg. However, the ensemble did not provide sufficient counter-pressure, and Bazett had to discontinue the experiment without demonstrating a convincing gain in altitude over pressure breathing without any counter-pressure clothing. Nevertheless, Bazett stated that he thought it possible to use a similar ensemble for short fights up to 55,000 feet. The RAF seemed particularly interested in pressure breathing since it would allow a relatively quick method of improving the operational altitude of reconnaissance aircraft. Bazett worked with the Royal Aircraft Establishment at Farnborough, England, to develop a pressure-breathing apparatus that the British quickly pressed into service. The RAF would refine this basic technology for the next six decades.[16]

Pharo Gagge, on the other hand, was generally opposed to counter-pressure clothing, feeling that it overly complicated the military aspects of flying. At the same time that Bazett was working with the British, Drury at USC conducted a separate evaluation of a breathing vest combined with inflatable trousers. He was unable to demonstrate any significant gain in pressure tolerance and dismissed the concept as impractical. This soon became the USAAF position, the successes by the RAF notwithstanding.[17]

By the end of 1943, the Aero Medical Laboratory and its contractors had largely abandoned efforts to gain altitude using counter-pressure clothing, settling instead for the slightly lower altitudes afforded by pressure breathing alone. The 28th Photographic Reconnaissance Squadron at Peterson Field, CO, conducted operational flight tests of the pressure-demand oxygen system in early October 1943. Based on the encouraging results of these tests, the USAAF issued contracts to Mine Safety for 4,000 Type A-13 masks packaged with Type A-14A regulators supplied by the ARO Corporation. The 14th Photographic Reconnaissance Squadron flew the first operational combat mission with the new equipment in February 1944, using Supermarine Spitfire PR.XI aircraft.[18] By late 1944, the Biophysics Branch of the Aero Medical Laboratory, under the leadership of Pharo Gagge, had equipped all Lockheed F-5 Lightning and Boeing F-13 Superfortress reconnaissance aircraft with the Type A-13 masks and Type A-14A regulators.[19]

The United States operated several Supermarine Spitfire PR.XI photo-reconnaissance aircraft and these became the first users of the new Type A-13 oxygen mask and Type A-14A regulators.

National Museum of the U.S. Air Force Collection

S-1—GENESIS OF THE PARTIAL-PRESSURE SUIT

In February 1943, the Office of Scientific Research and Development (OSRD) awarded a small contract to the University of Southern California (USC) Aeromedical Laboratory for the further development of counter-pressure and acceleration protective clothing.[20] Executive Order 8807 created the OSRD on June 28, 1941, to coordinate scientific research for military purposes during World War II. It superseded the work of the National Defense Research Committee and had virtually unlimited access to funding and resources. Former NACA chairman Vannevar Bush, who reported directly to President Franklin Delano Roosevelt, headed the organization. The research involved new and more accurate bombs, reliable detonators, work on the proximity fuze and radar, more effective medical treatments, and (most secret of all) the "S-1 Section," which later became the Manhattan Engineering District and developed the first nuclear weapons. Although contracted and funded by OSRD, the Aero Medical Laboratory at Wright Field had technical cognizance over the USC research.[21]

As World War II progressed, the USC Aeromedical Laboratory became increasingly busy, so the researchers turned many of the lesser tasks over to a young researcher named James Paget Henry (1914–1966). Henry was born to an American father and British mother and graduated from Sidney Sussex College in 1935. He earned a master's degree from Cambridge University in 1938, an M.D. from USC in 1952, and a Ph.D. from McGill University, in Montreal, Canada, in 1955. Henry initially specialized in acceleration physiology using the USC human centrifuge from 1943 to 1947 and designed the first partial-pressure suit. In 1947, Henry moved his pressure suit work from USC to Wright Field as the Chief of the Acceleration Unit of the Aero Medical Laboratory. The following year he became a naturalized American citizen. During the early 1950s, Henry was the director of the Air Force Physiology of Rocket Flight research project and, in May 1952, supervised some of the first successful animal rocket launches at Holloman AFB, NM. He then became the director of the Project Mercury animal research effort for NASA. Henry left NASA in 1965 and returned to USC as a professor of physiology.[22]

In late 1943, a group from USC arrived at the Mayo Clinic to study the human centrifuge in preparation for building a similar device in Los Angeles. Included in the group were Dr. Douglas R. Drury, Dr. William G. Clark, and Jim Henry from the Departments of Physiology and Aviation Medicine.[23] E.J. Baldes introduced each of the members, including Henry, to David Clark who was at Mayo observing G-suit tests. A few weeks later, Henry asked Clark for assistance developing a new type of counter-pressure suit. Unfortunately, Clark had to decline since his small company was overwhelmed with orders for G-suits and other war material. However, Clark offered to send materials, an industrial sewing machine, thread, and the services of his former experimental seamstress, Julia Greene, who had recently relocated with her husband to Burbank, CA. David Clark even agreed to pay Greene's salary while she assisted the USC team.[24]

By this time, USC had become the only group in the United States studying pressure breathing. In November 1943, Douglas Drury assigned Jim Henry to lead a group to investigate the issues associated with pressure breathing. The researchers determined that as long as the lungs were not allowed to overexpand, almost any pressure could be used without danger of aeroemphysema (a swelling condition caused by the formation of gas in body tissue). This relieved their fear of lung damage while breathing at high pressures. In response to this finding, the group embarked on the development of a full-face, high-pressure breathing mask, which would prove crucial for Henry's pressure suit.[25]

During a symposium at Mayo Clinic in early 1944, Dr. Harold Lamport of Yale University presented a paper on using external longitudinal bladders that could, when inflated, tighten a counter-pressure suit evenly and comfortably using interdigitating tapes and the so-called "capstan effect." Helen Lester and David C. Spooner at the Electric Blanket Division of General Electric had developed the concept in consultation with Lamport during 1943 in an attempt to revolutionize G-suits. However, tests on the Wright Field, Mayo Clinic, and USC centrifuges showed the General Electric G-suit provided no meaningful protection. However, the capstan idea struck a chord with Henry, who adopted it for use with his counter-pressure suit.[26] Although the G-suit itself proved ineffective, the capstan and pneumatic lever principle, along with the lace-adjustment feature, would shape most early partial-pressure suits.

The primary difference between a G-suit and pressure-breathing suit was the amount of time available to inflate the capstans. A G-suit needs to react quickly to a changing acceleration environment, inflating and deflating rapidly to provide protection for the pilot without overly hindering actions. The pressure-breathing garment, on the other hand, could inflate relatively slowly and, generally, once inflated it stayed inflated for a prolonged period. Although the capstans could not respond quickly enough to provide meaningful acceleration protection, they seemed excellent candidates to provide counter-pressure over large areas of the arms and legs and, somewhat later, the shoulders and back.

In April 1944, the Requirements Division at the Office of the Assistant Chief of Air Staff, in Washington, DC, asked the OSRD to investigate new types of pressure suits to replace the failed Army effort to develop a full-pressure suit.[27] Specifically, the requirements were for a suit capable of operating at 60,000 feet for at least 30 minutes, while allowing a crewmember to perform his duties with no permanent medical consequences.[28] The OSRD assigned the task to Henry at USC.

Around the same time, the Army asked Dr. Shannon Allen at the Aero Medical Laboratory to develop an emergency get-me-down pressure suit for use with the Bell XS-1 (X-1) research airplane, and Shannon awarded USC a small contract, which quickly found its way to Henry.[29]

These efforts were of particular interest to Lockheed, which was located just up the road from USC and, coincidently, employed

Greene's husband. Engineers, led by Clarence L. "Kelly" Johnson, William P. Ralston, and Don Palmer at the Lockheed Skunk Works were busy developing the second American jet aircraft. In theory, the new P-80 Shooting Star would be capable of much greater operational altitudes than the piston-powered fighters of the era, and Lockheed engineers led by Lloyd W. Jedeka wanted to know if the new pressure suit being developed by Henry could operate at 55,000 feet.

Henry Bazett, representing the Canadian Associate Committee on Aviation Medical Research visited USC in late April 1944 at the request of the National Research Council to demonstrate the pressure vest and mask he had developed for the RAF. Using the Bazett vest and mask and a modified version of the unsuccessful G-suit developed by General Electric and Harold Lamport, Henry made a new type of altitude suit christened a partial-pressure suit to differentiate it from the full-pressure suit effort that the Army had cancelled in late 1943.[30]

The garment began with a set of long-sleeve coveralls. A large belly bladder, lifted directly from a David Clark G-suit, provided pressure to the torso. Capstans and interdigitating tapes covered the thighs and calves to provide counter-pressure when needed. The capstans consisted of a molded, cold-resistant neoprene tube inside a cloth sheath. When the capstan inflated, interdigitating tapes transmitted the sheath tension to the cloth encircling the extremity. The advantages of the pneumatic lever (capstan) over the inflatable bladders used in early G-suits were that there were no bladders in direct contact with the legs and the pressure was applied more evenly over a larger skin area, minimizing discomfort. Since the Army expected the partial-pressure suit to be used for prolonged periods, at least compared with the few seconds or minutes a G-suit was typically inflated, this was an important consideration. The suit used the standard Army A-13 oronasal pressure-breathing mask equipped with a Wildhack-Linde compensated exhalation valve and a microphone. A set of Polaroid-GE electrically heated B-8 goggles completed the ensemble.[31]

At this point, the suit covered the torso and legs, but left the head, arms, hands, and feet

Kelly Johnson was a driving force behind the first operational American jet fighter, the P-80. He would later drive the development of the first Mach 2 fighter (the F-104), the U-2 spy plane, and the Blackbird series of Mach 3 reconnaissance aircraft. All of these aircraft placed new demands on the pressure-suit industry.

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unprotected. Henry conducted the first test in the USC altitude chamber on November 16, 1944, with generally positive results. However, based on early tests, several changes were made to the garment. For instance, the jock strap that held the pressure vest in place proved somewhat uncomfortable, so Henry extended the vest bladder down over the perineum[32] to provide protection against aeroemphysema. To provide mobility, he added transverse break lines to the ventral part of the bladder at the natural bend line at the waist. Henry added capstans over the arms and extended them across the shoulders and up to the neck. In their inflated states, the capstans were 3 inches in diameter on the thighs, 2 inches in diameter on the calves and upper arms, and 1.5 inches in diameter on the forearms. The capstans had a volume of approximately 1 liter and an expansion ratio of 5:1. Henry added a soft leather cap to cover the head, but the suit still did not include gloves.[33]

In December 1944, Henry took the modified suit to 58,000 feet (59.5 mm Hg) for 9 minutes before things began to go wrong. Henry was somewhat anoxic, but responsive to the observers, when his neck and hands began to swell grotesquely. Technicians brought the USC altitude chamber down to 40,000 feet and the swollen areas returned to normal.[34]

The swelling disturbed researchers, although it was not altogether unexpected since earlier tests by Harry Armstrong using rabbits had shown the possibility of serious gaseous swelling. When the ambient pressure surrounding exposed parts of the body fell below the combined pressure exerted by the water vapor, carbon dioxide, and oxygen tension in the tissues, the exposed region would swell, often grotesquely. The obvious conclusion was that water in the hands had vaporized—boiled is the more common term, although technically incorrect—because they were unprotected. A subsequent series of experiments using cats and rabbits showed that unprotected extremities expanded above 55,000 feet but returned to normal at 40,000 feet, with no harmful aftereffects to the muscles and no hemorrhages.[35]

Henry soon discovered that he could control the swelling using tight-fitting gloves. After trying rubber and nylon, Henry settled on a set of carefully fitted kid leather gloves that controlled the aeroemphysema. He also incorporated a set of inflatable socks made by the Hood Rubber Company. Interestingly, the Harvard Fatigue Laboratory developed these socks while researchers were studying trench foot. Later suits used standard flying boots that contained a vinyl nylon bladder between the fleece lining and the outer cover of the boot.[36]

By the end of 1945, Henry had tested his suit during 30-minute runs in the USC altitude chamber at sea level and at 25,000, 50,000, 55,000, and 60,000 feet with satisfactory results. Although not tested above 60,000 feet, the suit demonstrated there was no particular altitude limit at which it could be used, provided adequate counter-pressure was applied across the tympanic membrane. Henry believed that, "some subjects might be able to employ the equipment in its present form for short periods (5-10 minutes) in a vacuum."[37]

Henry delivered his first prototype partial-pressure suit to Wright Field in February 1946. The suit imposed counterpressure on the body using inflatable bladders in the back, chest, and abdomen aided by capstans running along the shoulders, arms, and legs. When these capstan tubes were inflated, a series of interdigitizing tapes applied approximately 10-psi mechanical counter-pressure to the limbs.[38] Although it was universally known as the Henry Suit, the Army called it the Type S-1, beginning a long line of rather disjointed and confusing designations for all types of pressure suits.[39]

Soon afterward, Pharo Gagge at Wright Field called David Clark and asked if he would be interested in producing a version of the Henry Suit. Clark traveled to Wright Field to observe tests of the prototype Henry Suit that Julia Greene had sewn. These tests used the Guardite Strato Chamber at the Oxygen Equipment Test Laboratory at Wright Field. During each run, an experienced chamber operator was present in the small airlock at

Dr. James P. Henry at the University of Southern California, developed the first workable partial-pressure suit. The finished Henry Suit was a tight-fitting coverall that had capstans running from the ankles to the waist and from the neck to the wrists. In their inflated states, the capstans were 3 inches in diameter on the thighs, 2 inches in diameter on the calves and upper arms, and 1.5 inches in diameter on the forearms. A pair of gloves and a leather helmet completed the garment.

Courtesy of the David Clark Company, Inc.

Even with the capstans inflated, the Henry Suit allowed sufficient motion to perform most tasks aboard an aircraft. The capstan principle had its origins with a failed General Electric G-suit and formed the basis for most early partial-pressure suit in the United States and the Soviet Union.

Courtesy of the David Clark Company, Inc.

an altitude of 35,000 feet to render aid in the event of an emergency descent. The main chamber was fitted with a hand-operated, quick-acting dump valve that permitted return from any altitude to 35,000 feet in less than 15 seconds. The chamber was, in theory, capable of simulating 100,000 feet altitude. Henry accomplished runs to 60,000 and 65,000 feet on March 22, 1946; 70,000 feet on March 25; and 75,000 feet on March 29. Additional runs were made to 80,000 and 85,000 feet on May 27 and to 90,000 feet on May 31. Henry spent at least 10 minutes at each altitude.[40]

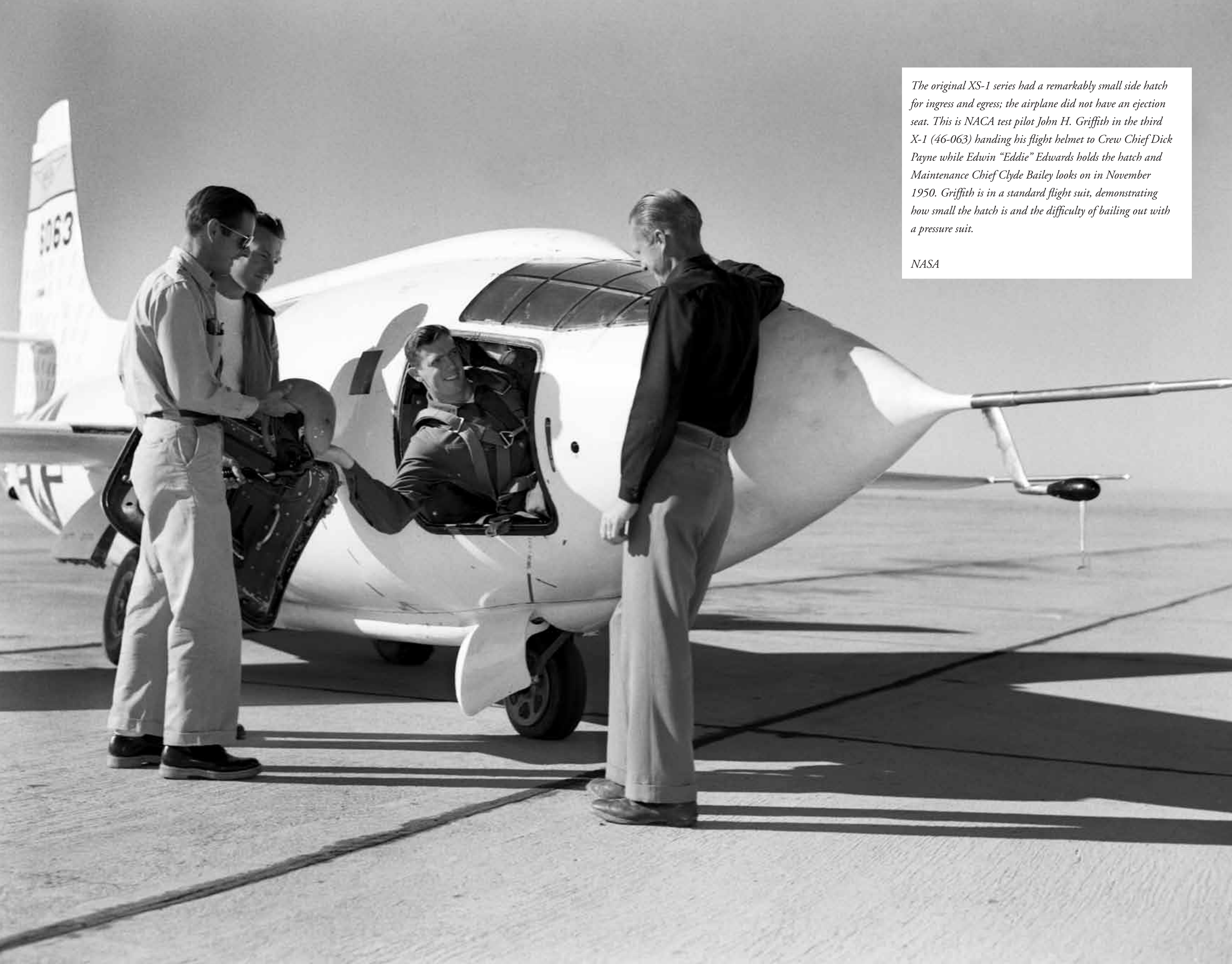
The first three runs used the original soft cap and a black rubber inflatable seal that covered Henry's face but not the ears. The cap was supposed to overlap the suit at the neck but did not quite accomplish this, leaving some flesh exposed to the low pressure. Henry complained of considerable pain during the 60,000 and 65,000-foot ascents, and at 70,000 feet he developed fluid in the middle ear due to increased capillary filtration as the consequence of greatly elevated venous pressure. The fluid was reabsorbed uneventfully within 48 hours, but the incident conclusively demonstrated the need for ear counter-pressure at extreme altitudes.[41]

Henry replaced the cap with a semi-rigid vinylized rubber helmet that used an A-13 mask and B-8 goggles attached to it with rubber cement. This helmet was fitted with dipped latex bladders that covered the head and neck and with a face-sealing bladder fitted into the sealing surface of the A-13 and B-8 components. The bladders were inflated 10–15 hmm Hg above the breathing oxygen pressure. Initial tests showed that the vinylized rubber was prone to distortion under pressure, so a stiffening frame made from aluminum tubing was placed around the outside of the mask. A zipper in the rubber allowed donning and doffing, and laces provided some adjustment.[42]

The last three runs used this improved rubber helmet that provided ear counter-pressure. The suit, helmet, and inflated gloves and boots all performed satisfactorily and provided sufficient protection against fluid loss and aeroemphysema. However, the ensemble was uncomfortable at mask pressures above 100 mm Hg.[43]

Alice King at the Aero Medical Laboratory developed a new helmet that improved on the second Henry design. This helmet used integrated ear- and face-sealing bladders filled with sponge rubber and secured adequately at mask pressures up to 170 mm Hg. The helmet also included an enlarged neck bladder that proved more comfortable than the one used on the second Henry helmet.[44]

Most subjects found the suit in its deflated state no more uncomfortable than a tightly



The original XS-1 series had a remarkably small side hatch for ingress and egress; the airplane did not have an ejection seat. This is NACA test pilot John H. Griffith in the third X-1 (46-063) handing his flight helmet to Crew Chief Dick Payne while Edwin "Eddie" Edwards holds the hatch and Maintenance Chief Clyde Bailey looks on in November 1950. Griffith is in a standard flight suit, demonstrating how small the hatch is and the difficulty of bailing out with a pressure suit.

NASA

laced G-suit. The suit, however, restricted rotation of the shoulders, making it hard to get at the shoulder straps and parachute harness. When seated in an airplane, the suit did not restrict the normal movements needed to fly, although everybody thought that less restriction at the elbows, knees, and shoulders would permit a fuller range of motion when attempting to bailout of a small hatch, such as the one in the XS-1.[45]

When inflated, the suit felt tight, as it was supposed to. With the capstans inflated to 7 psi, it was still possible to pilot the aircraft without undue exertion. At 15-psi inflation, the task was possible but very tiring. The kid gloves did not significantly affect movement of the fingers, and handwriting samples proved quite readable.

Despite its early stage of development, the suit worked. For instance, the fluid loss while wearing the suit was about 5 cubic centimeters (cc) compared to 9 cc using only a pressure-breathing mask and vest. The pulse rate with the mask and vest (breathing at 55 mm Hg for 30 minutes) was 80–110 beats per minute, reduced to 60 to 70 beats wearing the suit. A typical subject could not breathe at more than 40 mm Hg for 30 minutes with the mask and vest but could tolerate 85 mm Hg using the suit. After 1 hour of preoxygenation, simulated 30-minute flights at 55,000 feet resulted in only a single mild case of the bends. Normally, the same individuals using only a mask and vest complained of pains after only 15 minutes at 40,000 feet.

Nevertheless, the suit was far from perfect. Researchers noted aeroemphysema on every ascent above 55,000 feet for more than 15 minutes. Fortunately, it did not lead to anything other than a feeling of puffiness and distention in the tissues involved. This was particularly true of ascents using the original helmet, in which significant portions of the lower head and ears were left exposed. Tests showed that if the capstan system failed at 60,000 feet (due to a pressure-source failure or a rupture in the capstans), the person would still have 1 to 2 minutes of fully useful activity to respond to the situation, compared to only 15 seconds available if a full-pressure suit failed.[46]

Henry and Greene fabricated a second suit tailored to fit Bell chief test pilot Jack Woolams for use in the XS-1. Researchers at the Aero Medical Laboratory tested the suit to 55,000 feet, about all the XS-1 would reach during its initial tests. After the altitude chamber tests at Wright Field, Woolams evaluated the suit at the X-1 test site at Pinecastle AAF, FL. When he tried the suit on, Woolams commented that the suit was sufficiently comfortable in its deflated state and that the helmet and full-face mask were more comfortable than the oxygen masks in operational service. When the suit was inflated, Woolams found that the mobility of his arms, in particular, was significantly impaired, but it was still possible to execute all the motions necessary to fly the XS-1.[47] However, further testing revealed that the suit, as delivered, was not satisfactory, largely because the oxygen mask and helmet used with it caused intense pain in the ears during pressure breathing.[48]

Obviously, further development was needed. Fortunately, Wright Field had $20,000 available for pressure-suit procurement. In February 1946, Col. Bruce B. Price, acting chief of the Aircraft and Physical Requirements Branch of the Engineering Division, stated that only two manufacturers were qualified to develop a capstan-type partial-pressure suit: the General Electric Company in Bridgeport, CT, and the David Clark Company. General Electric, however, had already expressed a decided lack of interest in the project.[49]

On February 28, 1946, the Air Materiel Command executed a contract (W33-038-ac-15165) with David Clark for four modified versions of the Henry Suit. David Clark told Wright Field the first suit would be delivered by April 19 at a cost of $1,500. The second suit, to be delivered a month later, would be tailored for Jack Woolams. Unfortunately, a crash on August 30, 1946, killed Woolams while he was preparing a modified P-63 for the Thompson Trophy Race in Cleveland, OH.[50]

David Clark called Julia Greene and invited her to come to Worcester, MA, for a month to help sew the Henry Suits. Greene had been in California for over a year at this point and was happy to return and visit her friends. After explaining the difficulties she had encountered making the Henry Suits in California, Greene and Clark decided to start over. First, they determined the correct locations on the elbows, shoulders, hips, and knees for the capstans that would prevent them from doubling-up and inhibiting mobility. The pair paid special attention to the elbow and knees to keep the fabric biases correct to improve mobility.[51]

In consultation with Pharo Gagge and others at Wright Field, David Clark made numerous changes to the suit. Most importantly, capstans replaced the breathing bladders in the back, chest, and abdomen, reducing the discomfort and sweating associated with the poorly ventilated areas under the bladders. The lacing adjustments were extended to include the torso and extremities. He changed the material from cotton to a porous nylon-cotton blend, improving the strength of the garment and providing better ventilation. Clark cut the cloth on the bias to provide a uniform distribution of pressure and changed its color from black to sage green to conform to military clothing standards. Two zippers extending from the collar, down over the shoulders, and to the upper part of each arm replaced the original ventral zipper. This prevented the complete loss of counter-pressure in the event of a zipper failure and made donning and doffing the suit easier. Clark tailored the suits in a normal sitting position to permit maximum mobility with minimal discomfort.[52]

Capt. Harold J. "Jake" Jacobs soon arrived in Worcester for a fitting since he was the primary test subject for the first suit.[53] Jacobs would play a major role at Wright Field during pressure suit development, but he would ultimately leave the military and join the staff of Charity Hospital in New Orleans. David Clark delivered the first modified suit, fitted for Jacobs, in April 1946. The Army still used the S-1 designation for the suit, although it was considerably different from the original Henry Suit. The suit also included an improved pressure helmet developed by Alice King at the Aero Medical Laboratory and a special ear counter-pressure device.[54]

With one exception, the Army meant the S-1 suit to be a get-me-down garment to protect the pilot in the event of cabin pressurization failure at high altitude or if the pilot bailed out. Nobody intended to use the suit for extended periods. The exception was the XS-1 program, although even this was not an "extended" period since the rocket-powered airplane only flew for a few minutes at a time.

Once Jacobs had proven the basic suit in the altitude chamber, David Clark fabricated suits for Bell test pilot Chalmers H. "Slick" Goodlin and USAF test pilots Capt. Frank K. "Pete" Everest, Jr., Capt. Robert A. Hoover, and Capt. Charles E. "Chuck" Yeager. The Army had already added funds to the contract to cover the additional suits. The man who had taught David Clark to fly at the Worcester airport, Joseph A. Ruseckas, frequently played air taxi pilot, for instance, shuttling Hoover and Yeager from the Westover airport to Worcester. By now, the helmets being built by Alice King at Wright Field had expanded plexiglass that covered the ears, although the top and back of the head were still covered only by rubberized nylon fabric. Within a few months, Wright Field had changed the vacuum pumps on the Guardite Strato Chamber and tested the suit to 106,000 feet—a new record—using Jacobs as a test subject.[55]

In August 1946, the David Clark Company contract was amended to furnish 10 additional partial-pressure suits at a total price of $4,999, all for delivery within 60 days. These were generally similar to the earlier suits but incorporated improved gloves and boots.[56] The Army subsequently included these S-1 suits as part of Project MX-829 (SEO 660-141), which would evolve to include the first operational S-2 and T-1 suits. This would complicate future procurements since MX-829 was classified "confidential"—secrecy was unfamiliar in academia and relatively new to many of the small companies that would play a major role in future developments. This was especially true at the University of Southern California, mostly because Jim Henry was a British national.[57]

On October 14, 1947, Capt. Charles E. "Chuck" Yeager became the first human to purposely break the speed of sound in level flight when he recorded Mach 1.06 at 43,000 feet in a Bell XS-1 (46-062). Despite many reports that Yeager was wearing the S-1 suit that the David Clark Company had manufactured for him, in fact he wearing only his normal flight suit. Dr. James O. Young, the historian at the AFFTC at Edwards, queried Yeager about this, and Yeager responded that he did not wear his pressure suit for any of the 1947 flights since he did not attempt to fly above 48,000 feet.[58]

After much discussion and personal debate, Jim Henry filed for a patent on his partial-pressure suit on April 13, 1948. Originally, he had wanted to name several others as co-inventors but ultimately filed the patent in his name alone and assigned the rights to the United States of America as represented by the Secretary of the Air Force. The patent (2,886,027) was finally granted on May 12, 1959.[59]

By May 1948, the USAF deemed the partial-pressure suit mature enough to enter limited production. David Clark Company received a contract amendment to deliver 10 suits that incorporated integral G-suits at a total price of $10,000. In addition, the Government directed the company to provide the patterns necessary to produce the suits in five sizes: extra small, small, medium, large, and extra large. The USAF would use these suits to develop further sizes for standardization and to write procurement specifications.

Eventually, the USAF dropped the extra-small size, and the others each came in short, regular, and long variants, resulting in 12 available sizes.[60] To support the sizing efforts, the Aero Medical Laboratory conducted an anthropometric survey, making 132 measurements of more than 4,000 men.[61]

For its part, David Clark Company also had to grow. A friend told David Clark that Joe Ruseckas was looking for a job since the postwar economy was taking a toll on general aviation. At the time, Ruseckas was a flight instructor at the Worcester airport, continuing his love of flying that had taken him over the Hump many times during World War II. Clark immediately hired him as a pattern maker, which somewhat confused Ruseckas since the only patterns he was familiar with were the ones you flew around an airport. It was the beginning of something special.[62]

In 1932, when he was 15, Ruseckas began doing odd jobs around the Worcester airport.

The production S-1 suit looked very much like the original Henry Suit except for the new K-1 helmet. The initial S-1 suits were tailored for the test pilots assigned to the X-1 program and Maj. Frank K. "Pete" Everest, Jr., became the first to use the suit under emergency conditions, on August 24, 1949, after the canopy on the X-1 cracked and the cockpit depressurized. Note the helmet restraint cord on the chest.

National Archives College Park Collection

He became a private pilot, then an instructor pilot, and finally a Civil Aeronautics Administration (CAA, the predecessor of the Federal Aviation Administration) examiner. During World War II, he joined the Army Air Corps, ferrying fighters around the U.S. and eventually flying a Curtiss C-46 Commando over the Hump in the China-Burma-India Theater. He joined David Clark Company in 1948 and participated in the development and fielding of almost every pressure suit manufactured by the company. Ruseckas retired in December 1986 after 38 years with the company and passed away on March 19, 2010.[63]

On June 21, 1948, the Aero Medical Laboratory held a conference at Wright Field to discuss the future of Project MX-829. The ensuing discussion brought several interesting points to light. Researchers had largely directed past work toward developing a satisfactory high-altitude pressure suit for "sonic-type" aircraft, namely the rapidly developing turbojet fighters and rocket-powered X-planes. Because of the high emergency rate of descent of sonic-type aircraft, the laboratory had experienced little difficulty in providing an emergency oxygen system to get the pilot to an altitude where it was possible to breathe. However, bombardment aircraft like the Convair B-36 and Northrop B-49 might have the emergency descent rates as low as 1,000 feet per minute, requiring over 15 minutes to reach a breathable atmosphere. Researchers were now faced with ensuring that the partial-pressure suits, helmets, regulators, and oxygen-storage systems were capable of operating for much longer times than originally expected.[64] It is ironic that partial-pressure suits, originally designed for supersonic research airplanes, would ultimately find their first operational use in the slow-flying, piston-engine Convair B-36 very-heavy bomber.

Attendees at the conference concluded that the existing suit design had to be standardized and production sources identified. In addition, the attendees emphasized that the suit had to be comfortable when uninflated because the crews could only tolerate the discomfort of an inflated suit during emergencies. The researchers defined tolerance and stated that, "operating standards must not be lowered. The user must not forget routine checks. The attention span must not be narrowed. There must be no less of ability in performing complex motor and mental functions, and one's judgment must not be impaired."[65]

In January 1949, Maj. Gen. Franklin O. Carroll suspended further X-1 flights above 50,000 feet altitude pending "certain known improvements to flying clothing to add to the pilot's comfort and to the safety of both airplane and pilot."[66] This was not a major issue since the X-1 had been designed to exceed Mach 1 in level flight, not to explore the high-altitude regime. Nevertheless, by the beginning of 1949 the airplane had exceeded 50,000 feet on at least three occasions, including one to 60,000 feet on May 26, 1948, with Chuck Yeager at the controls. The restriction did not, apparently, last long, and Capt. Jackie L. "Jack" Ridley took the first X-1 to 51,700 feet on April 29, 1949, and Maj. Frank K. "Pete" Everest, Jr., set the maximum altitude for the basic X-1 program of 71,902 feet on August 8, 1949.

Only 2 weeks later, the partial-pressure suit proved its worth. On August 25, 1949, Pete Everest was flying the first X-1 when the canopy cracked and the cockpit depressurized. His partial-pressure suit automatically inflated, allowing him to continue breathing. He landed, uncomfortable, but unhurt. This was the first recorded use of a partial-pressure suit under emergency conditions.[67]

S-2 AND T-1—PRODUCTION PARTIAL-PRESSURE SUITS

On September 2, 1949, in a letter to the Engineering Division, Pharo Gagge summarized the production possibilities for the partial-pressure suit and its component parts. In particular, Gagge believed the David Clark Company had the knowledge and shop facilities to put the modified Henry Suit into production immediately, based largely on its wartime experience manufacturing G-suits and the postwar fabrication of a few dozen

S-1 suits. Eventually, five vendors were qualified to manufacture the suits, including David Clark Company, H.I. Garment Company of Chicago, Kops Brothers of New York City, Drybak Corp. of Bingham, NY, and Berger Brothers of New Haven, CT.[68]

In addition to the S-2 suit (DCC Model S394) that was derived from the modified Henry Suits, the USAF also defined a T-1 suit (S393) that was identical to the S-2 except that it incorporated the acceleration-protection features of the G-4A G-suit. The T-1 was recognizable by having two air connections, instead of the single connection of the S-2 suit. The USAF used the S-2 in bomber and reconnaissance aircraft, while the T-1 suit was used in fighters and experimental aircraft, where acceleration protection was desirable. The suits provided identical protection from short exposures to unpressurized environments up to 65,000 feet. Even as the suits were entering the inventory, the USAF indicated that the suit "in its present form is not a 'space suit;' nor is it the 'ideal' long-range pressure suit." However, the S-2 and T-1 fulfilled the original MX-829 requirement to "provide a practical and dependable emergency garment for use at extremely high-altitudes for short periods of time."[69] It was a start.

Convair test pilots Arthur S. "Doc" Witchell and James D. "J.D." McEachern wear S-2 partial-pressure suits in preparation for a test flight in a B-36 on October 19, 1952, at Fort Worth, TX. Note the variety in footwear.

Courtesy of the Frank F. Kleinwechter Collection

In October 1949, the David Clark Company shipped a prototype 5.3-pound T-1 suit to the Aero Medical Laboratory for evaluation.[70] Maj. Clarence C. Cain and Capt. David I. Mahoney tested the suit since both wore medium-regular size. The laboratory subsequently advised the company that three individuals had tested the suit and found no discrepancies.[71]

Coincident with these activities, the Aero Medical Laboratory and David Clark Company had been working on defining 12 standard sizes for all future flying suits. On January 12, 1950, David Clark submitted a Tariff of Sizes (dated January 3) that was approved by the Aero Medical Laboratory 2 weeks later. These became the standard sizes—small, medium, large, and extra large, each in short, regular, and long—for all flying clothing from all suppliers, not just David Clark Company. These sizes accommodated 92 percent of all USAF pilots. The Berger Brothers pressure suit contract included provisions for custom tailoring to fit the remaining 8 percent of the population.[72]

The official history of the T-1 suit summarizes its benefits:

> The T-1 suit differed from all that had gone before in that it resembled neither the suits developed by other countries nor the earlier, cumbersome full-pressure suits constructed in the United States. Based on an unique mechanical partial-pressure principle and designed purely as an adjunct to the pressure cabin, the T-1 was simply and solely an emergency, or as the British called it, a 'get-me-down' article of clothing. It was a light and flexible type of coverall fitted with capstan tubes. In the case the airplane depressurized suddenly from any cause, a valve in the suit's oxygen supply automatically opened and provided the wearer with the same environment, sort of, that he would have encountered at 40,000 feet. Oxygen was forced into the capstan tubes, which grew in diameter, and pulled cloth levers that tightened the suit so that counter-pressure was applied against the body. The counter-pressure enabled the body to withstand the internal reaction to the very great pressure of the oxygen being forced into the lungs. The flyer only had to keep exhaling, something easier said than done even with the counter-pressure. Inhaling was done automatically as the regulator forced oxygen into the lungs. The purpose of the T-1 suit was to allow the crew time to either bail out of a stricken aircraft, or to maneuver a controllable airplane to a lower, safe altitude. The suit was not suitable for constant use in lieu of a pressurized cabin.[73]

On December 16, 1949, North American Aviation wrote the Aero Medical Laboratory inquiring about the availability of pressure suits for use by company test pilots flying the YF-86D and YF-93A, both of which were capable of operating above 50,000 feet. The company wanted to purchase or borrow suits as the laboratory felt best. Other companies made similar requests over the next year.[74] Col. Walter A. Carlson responded to North American that the Government might furnish T-1 suits, although the suit was still under development. The North American pilots selected to wear the suit would have to travel to Wright Field for indoctrination.[75]

On May 30, 1950, the Air Materiel Command awarded a contract, AF33(038)-13028, to

The first true production partial-pressure suit was the S-2 that was derived from the modified Henry Suits (S-1). The USAF also ordered a T-1 suit that was identical to the S-2 except that it incorporated the acceleration protection features of the G-4A G-suit. The T-1 was recognizable by having two air connections instead of the single connection of the S-2 suit. The USAF used the S-2 in bomber and reconnaissance aircraft, while the T-1 suit was used in fighters and experimental aircraft where acceleration protection was desirable. This February 9, 1954, photo shows a T-1 with its K-1 helmet.

U.S. Air Force

Frank K. "Pete" Everest, Jr., in a T-1 partial-pressure suit standing in front of the Bell X-2 holding the rubber bladder he wore under his K-1 helmet. Everest became known as the "fastest man alive" after he took the X-2 to 1,900 mph (Mach 2.87) on July 23, 1953.

U.S. Air Force

David Clark Company for 251 S-2 and T-1 suits under specifications MIL-Y-3278 and MIL-Y-3280, respectively. David Clark Company bid $372.60 per suit, but the final negotiated price was $344.62 per suit, for a total of $86,155. Two complete sets of underwear were included with each suit. The delivery of the first suit was expected in 90 days, with the remainder within 150 days.[76] By this time, the USAF had determined the partial-pressure suit would be a desired safety item below 50,000 feet and mandatory for flights above 50,000 feet. All North American F-86D/E Sabres and Lockheed F-94B/C Starfires produced using fiscal year 1950 funds were equipped to accommodate the suits.[77]

The S-2 and T-1 suits originally used a K-1 helmet that consisted of a rubber bladder that completely covered the head and sealed using an inverted flap at the neck. A snug, laced-nylon restrainer and a close fitting, two-part (split) white outer shell limited the ballooning of the bladder. Earphones and a microphone were supported by foam rubber padding inside the bladder, and a removable plastic faceplate contained the necessary breathing valves. An improved K-1 helmet used a substantially larger one-piece, (instead of split) green fiberglass outer shell. The initial (split-shell) K-1 helmets used external antilift constraint cable attachments, while the one-piece shell versions moved these internally, to

NACA test pilot Joe Walker used a T-1 suit and K-1 helmet in the Bell X-1E as late as 1956. The second X-1 (46-063) was modified into the X-1E as much to provide the test pilots something to fly while they were waiting for the arrival of the North American X-15 as for any specific research purposes. Nevertheless, the X-1E provided valuable research in the hands of Joe Walker and John B. "Jack" McKay, reaching altitudes of over 73,000 feet.

NASA E-3362

the inner, lower rim of the shell. An upgraded version of the improved K-1 helmet featured a white fiberglass shell, an AIC-10 communication setup, and an improved, high-pressure oxygen delivery hose on its faceplate.[78]

By the time the T-1 partial-pressure suit was announced to the public, it had been worn more than 700 times in simulated runs above 63,000 feet in the Guardite Strato Chamber at Wright Field and multiple times in the USC and Mayo Clinic chambers. Although it was reasonably comfortable and satisfactory from a functional perspective, the K-1 imposed severe limitations on the mobility of the head that adversely affected the field of vision, making it particularly unpopular with fighter pilots.

The MA-1 helmet was the direct result of continued attempts to correct the deficiencies of the K-1. It was designed to serve both as an oxygen mask at lower altitudes and as a pressure-breathing helmet for use in conjunction with either partial- or full-pressure suits. To this end, it was designed with a round (rather than oval) base so that it could be used with a neck ring and was made tight fitting by the use of a special material that resembled foam rubber.[79]

The MA-2, manufactured by the International Latex Corporation (ILC), used a white one-piece fiberglass shell. The MA-2 featured a longer neckpiece that covered the upper chest and shoulders, a deep neck-seal bladder (resembling an inverted "turtle neck"), a three-way stretch insert in the neck to increase mobility, and a new defogging system and oxygen hose. The Strategic Air Command (SAC) crews used a similar MB-5 helmet with the S-2, MC-1, and MC-3 suits. The MB-5 was virtually indistinguishable from the MA-2, except for an AIC-10 headset.[80]

On August 15, 1951, Douglas test pilot William B. Bridgeman wore a T-1 suit when he took the D558-2 Skyrocket to a new altitude record of 79,494 feet. The partial-pressure suits were becoming a standard piece of personal protection equipment for the test pilots at Edwards.[81] NACA test pilot Joseph A. Walker, at least, was still using the T-1 suit as late as 1956 for flights in the Bell X-1E research airplane.

The Department of Defense publically announced the T-1 partial-pressure suit as the "latest achievement" of the Wright Air Development Center on October 4, 1952. The announcement informed the public that the T-1 "resembles to some extent the popular conception of a space suit."[82] Not really, but it was good press in any case. Whatever the public affairs people were saying, by early 1953, there were approximately 200 S-2 and T-1 suits in the hands of operational personnel. In addition to the USAF, the U.S. Navy, Royal Air Force, and Royal Canadian Air Force used the suit. Many civilian test pilots working on military contracts had also been issued suits, including pilots from the Allison

Lockheed modified three Starfighters into NF-104A aerospace trainers by adding a Rocketdyne AR2-3 rocket engine at the base of the vertical stabilizer and a reaction-control system. Here, Lockheed test pilot Herman "Fish" Salmon shakes hands with Chuck Yeager prior to his December 4, 1963, flight to 118,860 feet. Yeager is wearing a David Clark A/P22S-2 full-pressure suit.

U.S. Air Force

Division of General Motors, Avro (A.V. Roe of Canada, Ltd.), Bell, Boeing, Convair, Douglas, Lockheed, Northrop, North American, and Pratt & Whitney.[83] In December 1951, the SAC began issuing the suits to B-36 crewmembers.[84]

Occasionally, a satisfied user thanked the researchers at the Aero Medical Laboratory. One of these was Lockheed test pilot Herman R. "Fish" Salmon. On April 14, 1955, Salmon was flying the second XF-104 (53-7787) at 47,500 feet while wearing a T-1 suit, K-1 helmet, and strap-fastened boots. As he triggered the General Electric M61 Vulcan 20 mm cannon for a test firing, severe vibrations loosened the floor-mounted ejection hatch and the cockpit explosively depressurized at the same time as the engine flamed out. The suit inflated immediately. Repeated attempts to restart the engine failed, and Salmon ejected at 15,000 feet. Fish reported, "I landed in a field of rocks ranging from one foot to five feet in diameter. My right arm was injured and my head struck on a rock. The K-1 helmet hard shell was cracked, but there was no injury to my head. It took me 10 to 15 minutes to get out of the suit with my injured arm. Rescue was effected [sic] by helicopter approximately two hours after escape." Salmon reported that the K-1 helmet was excellent for "rugged parachute landings," and his only complaint was that the "visor may impair vision at extreme altitudes."[85]

MC-1—FEATHERWEIGHT SUIT

Project Featherweight was a major modification that removed most defensive armament and crew comfort items from much of the Convair B-36 very-heavy bomber fleet to extend the range and increase the combat radius of the airplane. The Aero Medical Laboratory initiated the development of the MC-1 specifically to meet the need of the Featherweight B-36 program. In contrast to the get-me-down S-2 suit, the Featherweight B-36s needed a suit that provided "protection against long-term exposure to altitudes in excess of 50,000 feet."[86] As with most partial-pressure suits, the development was assigned to the David Clark Company.

A 1952 flight of a B-36 from Carswell AFB in Fort Worth, TX, showed the urgency of this need. Although a cabin pressure of 34,000 feet was maintained while the aircraft flew at 50,000 feet, 4 of the 12 crewmembers were stricken with disabling bends, and the bomber was forced to make an emergency descent that overstressed its six Pratt & Whitney R-4360 engines to such an extent that all had to be replaced.

The bends, also known as caisson disease, is the result of bubbles of nitrogen gas in tissue released from solution by pressure change. Preoxygenation (denitrogenation)—breathing pure oxygen for a period before the anticipated event—can alleviate this condition to a certain extent. Exactly when, or if, a person gets the bends is dependent upon many factors and varies greatly from individual to individual.

The B-36 episode accented the need for proper cabin pressurization and for breathing pure oxygen for a sufficient length of time before high-altitude flights. It also graphically demonstrated the need for a pressure suit. In response, on July 14, 1952, the Aero Medical Laboratory demonstrated the S-2 suit—the B-36 hardly had a need for the G-suit in the T-1—to the SAC using a B-36H that reached 52,000 feet. Once the airplane reached 10,000 feet, about an hour after takeoff, each crewmember donned his S-2 suit. This occupied the better part of an hour, even in the relatively spacious rear compartment of the bomber. It should be noted that although the B-36, especially the Featherweight airplanes, were capable of exceeding 50,000 (and possibly 55,000) feet, they took a long time to climb to that altitude. B-36 flights typically lasted 24 hours, and many lasted almost twice that. Until the B-36 reached 50,000 feet, the airplane maintained a cabin altitude of 20,000 feet and the crew breathed pure oxygen during the first 90 minutes of the flight. The plan had been to breathe pure oxygen for the entire flight, but the flight engineers noted the airplane's supply was inadequate, so the crew breathed normal air supplemented by oxygen for rest of the flight. Although the

The Convair B-36 drove several requirements for partial-pressure suits during the early 1950s. The bomber could fly higher (over 50,000 feet in some variants) that any other operational aircraft, and frequently flew missions in excess of 48 hours (although a very small percentage of this time was at high altitude). The aircraft was pressurized and heated, but the need for emergency get-me-down suits became apparent after several accidents and narrow escapes.

U.S. Air Force

crewmembers were more comfortable while breathing pure oxygen, they were still able to perform their required duties. The airplane remained above 45,000 feet for 3 hours and there were no reports of the bends. Several crewmembers, however, complained about discomfort with the S-2 suit, although everybody accepted the need for such a device.

Notwithstanding the test and the reluctant endorsement by the crew, researchers still did not know exactly what conditions the SAC wanted its partial-pressure suit to accommodate. On May 3, 1953, in response to a query by Lt. Col. Clarence C. Cain of the Aero Medical Laboratory, the Eighth Air Force stated that the B-36 might operate at a maximum altitude of 53,000 feet. The non-human components of the weapon system limited endurance at that altitude, however, since engineers doubted that "radar equipment will operate reliably at this altitude…it is not expected that under any circumstance can the B-36 be kept at 53,000 feet for more than 3 hours on a strike mission."[87]

This was somewhat disinformation, since there was no intent of routinely flying a B-36 at high altitude for any great length of time. The popular vision of a strategic bombing mission is that the airplane takes off, climbs to its maximum altitude and speed, and flies to its target. Even with an all-jet aircraft such as the B-52, this is not necessarily true, since long range and high speed are usually mutually exclusive. Although the B-52 quickly climbs to its service ceiling, where its jet engines are the most efficient, it settles in at an economical cruising speed for most of the mission, reaching its maximum speed only as it approaches enemy airspace.

Piston-powered airplanes, however, used different mission profiles since their engines and propellers were not particularly efficient at high speeds or extreme altitudes. In the case of the B-36, the oft-quoted 400-mph speed and 45,000-foot altitudes were only applicable for short periods over the target. A typical long-range bombing mission for a Featherweight B-36J assumed a target 4,150 miles distant, for a total mission of 8,300 miles. The outbound cruise portion of the mission was flown at only 5,000 feet, an altitude where the R-4360 piston engines and big propellers were operating at maximum efficiency; the airplane could climb to 5,000 feet in 14 miles and the cruise speed during this portion of the mission was only 279 mph.[88]

The crew of a Convair B-36F (49-2669) pose in their partial-pressure suits before a test flight. When the suit was not inflated, it was relatively comfortable and allowed adequate mobility, as shown by the men kneeling. It was an adequate get-me-down garment in case of a major problem aboard the bomber.

Courtesy of Lockheed Martin Aeronautics

The MC-1 suit was developed specifically to replace the S-2 in the Featherweight versions of the Convair B-36 intercontinental bomber. Because of the long missions flown by the bombers, comfort was a primary driver in the development of this suit. Ultimately, researchers concluded the suit did not provide adequate protection and it was replaced in service by the MC-3. However, by that time, the B-36s were long gone.

U.S. Air Force photo.
Courtesy of the Terry Panapolis Collection

After flying for approximately 3,000 miles, the B-36 would begin climbing to its 45,000-foot combat altitude. It would take almost 2 hours and a little over 550 miles to climb from 5,000 feet to 45,000 feet, and the airplane would reach its combat altitude approximately 500 miles from the target. Fuel was budgeted to fly at maximum continuous power for 15 minutes before reaching the target and 10 minutes after weapons release; this equated to 425 mph and covered just over 175 miles.[89]

Reconnaissance versions of the B-36 flew somewhat higher and farther, and the Eighth Air Force stated that 45–60 minutes were normally required to descend from 53,000 to 40,000 feet and that 25 minutes was probably the quickest the airplane could descend. The Eighth Air Force appeared to believe that the existing S-2 suit might provide adequate protection for the 3-hour period, but physiologists doubted that an airman could remain at extreme altitude for the full period because of the discomfort and inconvenience of the suit.[90]

Toward the end of 1953, the SAC announced a firm requirement for a continuous-wear partial-pressure suit capable of protecting crewmembers at 50,000 feet. Furthermore, by late 1954 they would need a suit capable of operating at 55,000 feet and by 1960, one capable of sustaining crewmembers at 60,000 feet. In response, the Aero Medical Laboratory and David Clark Company began the development of the MC-1 Featherweight suit.

In many ways, the MC-1 was a step back to the original David Clark Company versions of the Henry Suit. The MC-1 added breathing bladders to the chest and abdominal torso sections to reduce the work of breathing. When the airman in-haled, the bladder deflated, leaving room for his lungs to expand in the tight suit. When he exhaled, the bladder reinflated and put pressure on his chest and abdomen, aiding the process. Even though a flyer wore long underwear under the S-2/T-1 suit, he was subject to skin pinches when the capstan tubes expanded. To help alleviate the discomfort, the MC-1 contained antipinch bladders and used smaller arm and shoulder capstans. The new suit was also equipped with bladders in the upper arms that bled into pressurized gloves. The MC-1 used either the K-1 or the MB-5 helmet. Like the S-2 and T-1, the suit was available in the 12 standard sizes, plus custom-fitted versions manufactured by Berger Brothers. By January 1955, the first of 1,200 MC-1 suits were available.

There was a curious issue with the initial deliveries of the MC-1 suit. In many instances, crewmembers discovered the sleeves were too short, even though they were identical in length to those on the T-1 and S-2. It soon became apparent that the discrepancy stemmed from the use of gloves with the MC-1. Pressurized gloves were not worn with the T-1 or S-2 suits, so sleeve length had not been a particular issue.

With the MC-1, the sleeve had to connect with an inflation tube on the gloves, and any shortage of length caused the gloves to separate from the sleeve. David Clark Company quickly, and simply, corrected the situation by adding an individually fitted length of tubing from the sleeves to the gloves.

As it did with all the early pressure suits, the Guardite Strato Chamber at Wright Field played a key role in the development of the MC-1 suit. For instance, during May 1954, two test subjects wore suits at 55,000 feet for 4 hours and two others at 50,000 feet for 6 hours. By the end of July 1955, 17 chamber runs at 50,000 feet had lasted from 1 to 7 hours, and 9 runs at 55,000 feet lasted between 30 minutes and 4 hours. Three runs at 60,000 feet lasted from 1 to 3 hours. Researchers also completed seven runs at 65,000 feet, ranging from 12 minutes to almost 2 hours. Finally, subjects completed two runs above 80,000 feet, with exposure times above 50,000 feet in excess of 45 minutes.

These experiments created a tremendous demand for men to make the chamber runs. The Aero Medical Laboratory found it was not desirable to continually use the same test subjects. So, in addition to persons connected with the project (many of whom made chamber runs repeatedly), the laboratory obtained pilots from other units as subjects. To its credit, the laboratory did not attempt to make these experiments appear glamorous. For example, an advertisement for a test in 1954 announced, "This will require an attempted 11 hour stay at altitudes above 45,000 feet, plus a 2 hour preoxygenation period. Thus an 'all-day' (14–15 hours) experiment is anticipated. In addition, various types of instrumentation will be used, all of which help produce a very long and miserable day."[91] Just what one wanted to do on his day off.

Perhaps not unexpectedly, the "volunteers" generally were not motivated to endure the inconvenience and discomfort nor the actual pain that occurred in a certain percentage of subjects during chamber runs. There was some thought of providing a "graded monetary motivation system" under which subjects would be paid for each hour spent at altitude, but the plan was never put into use since Air Force Headquarters disapproved the request for funds.[92] In its search for subjects to make chamber runs with the Featherweight suit during early 1954, the laboratory came up with the idea of killing two birds with one stone: indoctrinate the B-36 crews in the use of altitude suits while using them for chamber tests. Although an interesting concept, the timing never worked and no operational crew participated in the development tests.

Despite the advancements over the previous S-2 suit, some felt the MC-1 did not provide adequate protection. An in-depth physiological evaluation of the MC-1 was prompted in early 1954 when Air Force Headquarters began considering the development of a "mission-completion" garment. Ultimately, this evaluation demonstrated the ineffectiveness of the MC-1 and led, along with other drivers, to the development of the MC-3 partial-pressure suit.[93]

The evaluation by the Aero Medical Laboratory concluded that the "MC-1 partial-pressure ensemble (MC-1 suit, K-1 or MB-5 helmet, and pressure gloves) clearly demonstrated its gross inadequacy to meet the stated USAF maximum time-altitude requirements."[94] The study found that the probability of three crewmembers being functional at an altitude of 60,000 feet after 1 hour was only about 1 in 7. In most cases, the altitude chamber runs were terminated because of an impending syncope that implied a fainting reaction. Symptoms included pallor, nausea, sweating, weakness, malaise, and a sensation of "being overwhelmed."[95] The researchers found that at 60,000 feet, there was usually only about a minute's warning before a subject fainted.

The MC-1 had only small anterior chest and abdomen bladders that did not offer adequate counter-pressurize on the outside of the chest to equalize the high intrathoracic pressure present during pressure breathing. When the average wearer was subjected to

65,000 feet for 1 hour, remarkable physiological changes occurred.[96]

The most important physiologic response was the alarming frequency of sudden presyncope (lowering of blood pressure). The pattern leading up to syncope was fairly uniform. The subject was exposed to 65,000 feet when he suddenly broke into moderate diaphoresis (sweat) over his entire body, easily discernable on the arms and legs, where the sweat evaporated through permeable fabric, creating a cold sensation. Concomitantly, there was a definite hypotension and a relative bradycardia in which the pulse dropped from 160 to 75 beats per minute. (True bradycardia implies that the pulse is below 60 beats per minute.) With the sudden hypotension and bradycardia, researchers inferred that there was a dramatic decrease in cardiac output.[97]

The time from the first symptom until syncope varied from a few seconds to 2 minutes. Researchers always tried to terminate the test before unconsciousness but were often unable to do so because of the rapid onset of symptoms. When this occurred, the chamber was depressurized from 65,000 to 40,000 feet in about 5 seconds. The subject normally returned to consciousness in 4–6 seconds, although pallor, clammy skin, hypotension, and bradycardia often lasted for a couple of hours.[98]

The reactions varied widely based on the individual. Researchers found the ability of crewmembers to remain at 65,000 feet in the MC-1 ensemble ranged from 2 minutes to more than 2 hours. Not surprisingly, the researchers, largely, could determine which crewmembers would tolerate the tests well and which would not. Physical fitness and medical condition obviously played a role, but the researchers also found that "the aggressive independent individual performs much better than the more submissive type."[99]

Nevertheless, something better than the MC-1 suit was clearly needed.

MB-1 AND MB-2—ILL-FATED AIR DEFENSE COMMAND SUITS

During the development of the S-2 and T-1 suits, which were designed to offer short-term protection up to 65,000 feet, the Aero Medical Laboratory obtained a great deal of background data at lower altitudes. These data disclosed that, from a mechanical stand-point, development problems increased tremendously above 55,000 feet. In January 1953, the laboratory proposed to develop a garment that would be limited to a maximum altitude of 55,000 feet and a maximum pressurized time of 6 minutes. It was expected to provide greater comfort and mobility than the S-2, since only those areas of the body most vital to circulation, such as the legs, abdomen, and chest regions, would be pressurized. Because the suit would eliminate the capstans on the arms and shoulders, arm mobility would be unhampered even when the suit was pressurized. The suit would also be less expensive to procure and maintain than the S-2. The laboratory assigned the development to the David Clark Company.[100]

The new suit was intended primarily to meet the requirements of the Air Defense Command (ADC) and a new generation of interceptors. The concept of dedicated interceptors had come to fruition during World War II—the Messerschmitt Me 163 being an early example of an aircraft intended solely to shoot down enemy bombers over its home territory. After the war, it seemed that all things became more specialized, furthering the concept of dedicated interceptors. This was helped in the U.S. Air Force by the fact that there were two operating commands: the ADC and the Tactical Air Command (TAC). Each wanted its "own" aircraft, and so defensive interceptors and tactical fighters began to diverge in design and capabilities.

Following the end of the war in Europe, relations between the United States and the Soviet Union rapidly deteriorated. However, at that time, there seemed to be little direct threat from the Soviet Union to the continental United States itself. This changed in October 1947, when several Tupolev Tu-4 heavy bombers (reverse-engineered B-29s) appeared at the Tushino air display, and the newly organized U.S. Air Force was now faced with a potential strategic bombing threat from the Soviet Union.

In early 1949, the Air Force issued a request for proposals for a supersonic interceptor to replace the Northrop F-89 Scorpion that was just entering development. This program came to be known as the "1954 Interceptor," after the year that the new aircraft was expected to enter operational service.[101] This aircraft would become the Convair F-102 Delta Dagger, a delta-wing interceptor capable of exceeding the speed of sound. The ADC would also operate variants of the McDonnell F-101 Voodoo and Lockheed F-104 Starfighter before it received its "Ultimate Interceptor," the delta wing Convair F-106 Delta Dart.

The Convair F-106 Delta Dart was the Air Defense Command's (ADC) primary interceptor for several decades and was capable of zoom climbs above 60,000 feet. Because of this, the ADC evaluated any number of full-pressure suits for the airplane, but ultimately it was usually flown without any type of pressure suit.

U.S. Air Force

The MB-1 partial-pressure suit followed the coverall pattern of its predecessors and contained abdominal and chest bladders with smaller capstans on the thighs and calves. Unlike all earlier partial-pressure suits, the arms and shoulders were unprotected. The initial flight tests took place in September 1954 when five pilots from the Air Research and Development Command used the MB-1 on 25 flights with mixed results. Further testing by Air Defense Command pilots showed the suit was unsatisfactory. At a conference held on November 9–10, 1954, the Aero Medical Laboratory discontinued development of the MB-1, and the Air Defense Command adopted the S-2 as its standard partial-pressure suit.[102]

A similar MB-2 suit incorporated G-protection for use by experimental test pilots, but the USAF cancelled it at the same time as the MB-1.

MC-3 AND MC-4—DRAGON LADIES AND HUSTLERS

In 1954, while David Clark Company was developing the MC-1, the Aero Medical Laboratory felt that the SAC would need further improved suits to meet the coming requirements for the Boeing B-52 Stratofortress and Convair B-58 Hustler bombers. The B-52 requirement, stated in December 1953, specified protection for 3 hours above 50,000 feet and for 11 hours above 46,500 feet. The B-58 requirements called for 1 hour between 54,000 and 70,000 feet and 8 hours above 52,000 feet. The laboratory believed that modifications to the basic MC-1 could meet these requirements and be available in time to support initial operations. The MC-1 suit as finally developed gave no time limit for protection to 50,000 feet and up to 105 minutes at 65,000 feet. Nevertheless, it

A new generation of jet bombers, such as the Boeing B-52 Stratofortress (top) and Convair B-58 Hustler drove requirements for improved pressure suits that could be worn comfortably for long periods while operating sophisticated weapons systems. Eventually the Air Force decided that neither the B-52 nor B-58 required a pressure suit.

U.S. Air Force

was uncomfortable and lacked mobility. By the end of 1955, the Aero Medical Laboratory was examining a number of other possibilities, including a new partial-pressure suit and a full-pressure suit, to meet the needs of the B-52 and B-58.[103]

Although the laboratory, and David Clark Company, did not know it at the time, the primary impetus for a new suit would come from a completely different, and unexpected, source. In early 1954, two USAF officers visited the David Clark Company for a security inspection. Given that the company had operated classified projects for over a decade, this raised some eyebrows, but no explanation was immediately forthcoming. A short while later, the company was asked to send technically knowledgeable representatives to a meeting in Washington. David Clark, John Flagg, and Joe Ruseckas made the trip. The men were told that a new aircraft was being developed that would fly higher than 70,000 feet and that a partial-pressure suit was necessary for the project. The Government would not disclose what the airplane was, what it was intended to do, or what company was developing it.[104]

However, the Government did disclose the need for a partial-pressure suit comfortable enough to be worn for 12 hours unpressurized and as long as 4 hours pressurized. David Clark said that, given recent guidance from the Anthropometry Department at Wright Field, it was impossible to manufacture such a suit. The Air Force intended to fit all pilots with a limited number of suit sizes, and this resulted in somewhat less comfortable suits than could otherwise be manufactured. The representatives from the new project were not interested in minimizing the number of suit sizes, and they told David Clark to create custom-fitted suits that were as comfortable as possible. The pilots would be made available in Worcester, where David Clark Company would measure them and fit them for their suits.[105] It was the beginning of David Clark Company's involvement in the most significant series of reconnaissance aircraft ever developed.

During World War II, modified combat types—P-38s, P-51s, and B-29s equipped with cameras—conducted most aerial reconnaissance. Toward the end of the war, recognizing the need for more dedicated platforms, the Army initiated the development of the Hughes XF-11 and Republic XF-12 Rainbow. Neither aircraft entered production, but they demonstrated the substantial increase in capabilities available in designs tailored for the mission. The decrease in defense spending following the end of the war, however, meant that combat types would continue to be used for reconnaissance. The Air Force pressed modified B-36, B-45, and B-50 bombers, as well as a variety of fighters, into service as reconnaissance aircraft.[106]

By 1952, thoughts again turned to a dedicated high-altitude platform, and in March 1953, the Air Force released a formal specification to three small aircraft manufacturers. Each of the companies—Bell, Fairchild, and Martin—received 6-month $200,000 study contracts on July 1, 1953, as part of Project MX-2147 under the codename Bald Eagle. Only Bell and Fairchild were asked to design new aircraft to meet the specification. Martin was tasked instead with designing a modification to its B-57 Canberra, which had originally been designed in the United Kingdom by the English Electric Company.

By the middle of 1954, the Air Force decided the Martin RB-57D would be procured as an interim platform pending the development of the Bell Model 67 hidden behind the X-16

During and immediately after World War II, the Air Force commonly used converted combat aircraft for reconnaissance missions. For most of the early 1950s, the premiere long-range reconnaissance aircraft was the Convair RB-36. These aircraft routinely flew in excess of 50,000 feet and carried a wide variety of camera and electronic ferret equipment, but as far as is known, they never ventured over the Soviet Union.

Courtesy of Lockheed Martin Aeronautics

designation. Fairchild's proposal was never in serious contention due to its unconventional configuration. The competition was disrupted, however, on May 18, 1954 when the Air Force received an unsolicited proposal from Kelly Johnson at Lockheed. The Air Force conducted a thorough, if somewhat hurried, review, and on June 7, notified Johnson that his proposal had been rejected.

Hardly deterred, Johnson decided to pursue funding through other channels. In this case, "other channels" meant the Central Intelligence Agency (CIA), which had discovered that the military could not be depended upon to provide detailed reconnaissance whenever and wherever the CIA wanted it. Since the Soviet Union was embarking on a program to develop and field long-range missiles equipped with nuclear warheads, the CIA considered on-demand intelligence critical. The obvious answer was to create a private air arm, and on November 19, 1954, Johnson discussed the modified design with the intelligence community. The proposal generated a great deal of interest, assuming Lockheed could deliver the aircraft quickly.

Johnson promised the first aircraft would fly by September 1955, less than a year in the future. At the end of November, the CIA formally approved the project under the codename AQUATONE. The CIA awarded Lockheed a $54 million contract for 20 production aircraft on December 9, 1954, although Johnson later returned almost $8 million of this due to cost underruns. By the end of 1954, Johnson and his team of 25 engineers and 81 shop personnel began working 100-hour weeks to meet the schedule. While Johnson did eventually get additional personnel, he never had more than 80 engineers working on the U-2 project.

The Lockheed U-2 looked more like a glider than a spy plane but proved to be an irreplaceable resource. The airplane was extremely tricky to fly, and pilot fatigue on long missions was always a concern before the invention of reliable autopilots.

U.S. Air Force

The design was technologically demanding since minimum weight and drag were essential. On December 10, 1 day after the contract was signed, the AQUATONE design was frozen. Ten days later, Lockheed began construction of production tooling. Around this time, the aircraft became known within Skunk Works as "Kelly's Angel" or simply as ANGEL. The CIA assigned a second code name to the project: IDEALIST. The individual aircraft were known as "articles."

Midmorning on July 24, 1955, the first U-2A (Article 341) arrived at Groom Lake, better known to Lockheed personnel at the time as the "Test Location" or simply "The Ranch." The subject of much speculation and many rumors over the years, Groom Lake is located inside a restricted area (Area 51) near the nuclear test site run by the Department of Energy (originally, the Atomic Energy Commission). It is located approximately 100 miles northwest of Las Vegas, NV.

The U-2 was an unusual aircraft, looking more like a glider than any preconceived vision of a spyplane. The fuselage was 49.66 feet long and the wings spanned 80.10 feet. There was a decided lack of stringers and other forms of stiffening, and the skin was only 0.02 inch thick in places. The unusual construction was indicative of the extreme measures taken to lighten the airframe. This led directly to extremely low maneuvering limits—only +1.8/–0.8-G under some flight conditions, and never more than +2.5/–1.0-G under any conditions. Compare this to the normal USAF standard of +7.33/–5.0-G for fighter aircraft of the era.

The cockpit was small and cramped with a single large control wheel similar to that found in most transport aircraft. The instrument panel was largely conventional except for the inclusion of a 6-inch hooded drift-sight/sextant. The effort to save weight resulted in not providing an ejection seat and even the deletion of explosive bolts to jettison the canopy. If the pilot needed to bail out, he would have to manually detach the canopy prior to leaving the aircraft. This omission later proved fatal and Lockheed corrected it by installing a simple ejection seat.

Static engine runups were conducted on July 27, and the first taxi test came on July 29, 1955, by former air racer and Lockheed test pilot Anthony W. "Tony" LeVier. During the second taxi test, the aircraft climbed to an altitude of approximately 35 feet before LeVier could adjust to the flat featureless desert and determine that he had actually left the ground. After some consternation, LeVier managed to get the aircraft back on the ground, although the brakes caught fire and had to be rebuilt. The first intentional flight came on August 4, 1955, with LeVier again at the controls. Four days later, on August 8, LeVier made the "official" first flight in front of senior CIA officials.

The U-2 had some peculiar flight characteristics at altitude. The most worrisome was that the stall speed and never-to-exceed speed could be separated by as little as 10 knots. In fact, if a pilot turned too sharply, the inside wing could be in "stall buffet" (going too slowly) while the outside wing could be in "Mach buffet" (too fast). Recovery from a stall (too slow) could be difficult since elevator authority was limited, while exceeding the maximum permissible speed by as little as 4 knots could result in the aircraft breaking up. To assist the pilots, Lockheed provided a fairly effective autopilot, but it was still incumbent on the pilot to ensure the aircraft was in the proper speed regime. Luckily, as fuel was burned the margin for error increased, so as a pilot tired on a long flight he actually had more latitude for mistakes.

Early jet engines were not known to be overly reliable, and those modified to operate in the rarified air above 60,000 feet were notably temperamental. Flameouts were a frequent occurrence during the early flight-test program. This was not a pleasant event at 65,000 feet, since the U-2 had to descend below 35,000 feet to effect an air start. Luckily, the U-2 could glide more than 275 miles, taking some 73 minutes to do so.

Two different cover stories emerged to explain the existence of the U-2. Unbelievably, the first indicated that the U-2 (and it was always referred to as a singular entity) was a test vehicle to examine certain flight characteristics relative to the F-104 program. The second story was that the NACA used the aircraft for high altitude atmospheric and weather research. In fact, when the U-2 was first unveiled to the public, it carried fictitious NACA markings, something that was repeated many times over the early years of the program.

The deception, reluctantly agreed to by the Director of the NACA, Hugh L. Dryden, was not completely untrue. The cover story was that the aircraft were being used to collect information on the jet stream, cosmic ray particles, and ozone and, in fact, most early U-2 training flights around the world did carry NACA instruments. The data was turned over to the NACA for evaluation, but the pilots were always CIA cum Lockheed, and the NACA had no say in where or when the data was collected. Eventually, the original U-2s

The U-2 used an unusual landing gear configuration with two main gear in the fuselage and outrigger gear under each wing that fell off as the airplane took off. As the airplane slowed down after landing, one wingtip would drag on the ground until a ground crew replaced the outriggers.

National Archives College Park Collection

would be flown by the CIA, the U.S. Air Force, the Republic of China Air Force (Taiwan), and, ironically, the National Aeronautics and Space Administration (NASA). These airplanes would serve until they were finally retired in 1989, replaced by a larger variant called the U-2R.[107]

Because of the extreme altitudes promised by the U-2, the CIA knew the pilots would need pressure suits. Never being bashful about seeking the best advice, the CIA approached Col. Donald D. Flickinger (1907–1997), the chief of human factors at the Air Research and Development Command. The doctor had a fascinating career. During World War II, Flickinger had been the flight surgeon for the Air Transport Command in the China-Burma-India (CBI) Theater. But he was a flight surgeon like no other and frequently parachuted into the dense jungle to rescue downed aircrews. His most famous rescue came on August 2, 1943, when a Curtiss C-46 Commando transport crashed near the Chinese border. Of the 21 crew and passengers—including newsman Eric Sevareid—only the copilot perished. Flickinger and two other medics parachuted into a clearing where the survivors were camped, and a month later, they walked out of the jungle, little the worse for the experience.[108]

Flickinger received his M.D. from the Stanford Medical School and took post-graduate training at Vanderbilt and Harvard before joining the Army in 1937. He received training as a flight surgeon at the School of Aviation Medicine and reported to the 19th Bomb Group. Flickinger was the medical officer of the day at Pearl Harbor when the Japanese attacked and spent 72 hours straight helping wounded servicemen. After his service in the CBI Theater, Flickinger became the director of research at the USAF School of Aviation Medicine, and in 1951, he became the first director of human factors for the Air Research and Development Command. In August 1955, he became the first commander of the Air Force Office of Scientific Research. His specialty was high-altitude survival and bailout, and Flickinger helped with oxygen systems, parachutes, and pressure suits. Flickinger went on to work with the Lovelace Clinic in Albuquerque, NM, screening the original Mercury astronauts. Left unsaid in most biographies and obituaries was the extraordinary service he performed for the U-2 and subsequent A-12 program.

During the 1954 meeting in Washington, Flickinger discussed the medical requirements for pilot protection with David Clark, John Flagg, and Joe Ruseckas. When they returned to Worcester, Ruseckas got to work developing the patterns for a new partial-pressure suit while Flagg attended to the myriad of other details involved with developing a new product. At the time, the David Clark Company had only a handful of people involved in the pressure-suit business. Besides Flagg and Ruseckas, there were a half-dozen designers and pattern makers and a handful of seamstresses working at the company's facility on Park Avenue in Worcester.[109]

Eventually, David Clark Company learned that the new project was the CIA U-2. Unlike most USAF aircraft that generally had the option of descending to a lower altitude and landing if a problem occurred, the U-2 did not have that luxury; the Soviets would not be amused to find the airplane over their territory. Therefore, the new partial-pressure suit had to be comfortable enough to allow the pilot to control his airplane while wearing it for prolonged periods. Because of its small cockpit, early model U-2s continued to fly with partial-pressure suits until the end of their careers.

During early 1956, the first six CIA pilots arrived at Groom Lake as part of Operation Overflight. These were active duty military pilots who had been "sanitized" by the CIA—their names and backgrounds were fictitious, and officially, they were employed by Lockheed, although their pay came from CIA funds. Each would travel twice to Worcester to be fitted for their new partial-pressure suits. During the first trip, each pilot was carefully measured so that Joe Ruseckas could tailor the generic pattern for a comfortable fit. After the suit was completed, the pilot would return for a fitting and any needed alterations. After everybody was satisfied the suit was tailored correctly, the pilot would head to Buffalo, NY, to try the suit in the altitude chamber at Firewel Corporation, often flown there in David Clark's personal airplane by Joe Ruseckas.

Two alumni of Scott Aviation, Philip Edward "Ed" Meidenbauer, Jr. and Donald Nesbitt, founded Firewel Corporation in 1946. Meidenbauer, a self-taught mechanical engineer, had been director of oxygen research at Scott Aviation, where he developed the original Scott Air-Pak. His brother, Clifford Meidenbauer, a Signals Corp officer during World War II, soon joined the company as the financial officer.[110]

Operating from the basement of Meidenbauer's house, the company began building burners to convert old coal furnaces to oil or gas. By 1947, the company had advanced from conversions to a full line of manufactured furnaces. Looking to expand its business, the company soon received an $80,000 Army contract for an oxygen regulator. In 1951, David Clark contacted Ed Meidenbauer about supplying a regulator for the full-pressure suit David Clark Company was developing for the Navy. Firewel soon became the primary supplier of suit controllers and oxygen regulators to both David Clark Company and B.F. Goodrich. By 1956, Firewel employed 140 people and was a multi-million-dollar corporation. Two years later, the founders sold the company to ARO Equipment Company. In 1985, Todd Shipyards bought the business from ARO, and Ingersoll Rand took over the group in 1990.[111]

Former Firewel employee John Carleton Goodell, along with George Ord, founded Carleton Aviation in 1955 and bought the aerospace part of ARO in 1993. Since then the company has progressed to become Carleton Technologies Inc., a wholly owned subsidiary of Cobham plc, located in Wimborne, Dorset, England. Cobham is a consortium of companies supplying products and services to the aerospace and defense industries. Carleton continues to produce equipment for high altitude and space flight.[112]

During the 1954 tests of the MC-1 suit by the Aero Medical Laboratory, Capt. Terence F. McGuire modified an MC-1 suit with a double-layer, airtight lining from the neck to mid-thigh. The neck seal was extended down under the edge of the suit bladder system, then inverted to cover the neck. These modifications, along with an early MA-2 helmet, provided full-pressure coverage from the top of the head to mid-thigh, leaving only the extremities under partial pressure. Since the arms and legs "are of tubular form,"[113] McGuire thought that the mechanical capstan system was sufficient. The capstans were also left across the shoulders and back, although they were normally overridden by the bladder system. If the torso bladder failed, the capstans could provide the equivalent of a T-1 suit and suffice as a get-me-down garment.

Volunteers tested McGuire's suit as high as 198,770 feet, which is almost a perfect vacuum, with only one three-thousandths of an atmosphere. Some subjects that had performed very poorly using the MC-1 suits were able to remain at 100,000 feet for several hours. This data proved valuable as the design of the new U-2 suit progressed. The suit that David Clark Company developed was a cross between the original S-2 and the modified MC-1 and is often called an S-3 suit, although that appears to be unofficial at best and incorrect at worst. Initially, the USAF called the suit X-91, probably as part of the secrecy surrounding the U-2 program, but ultimately designated it MC-3.[114]

Martin A. "Marty" Knutson was the first operational U-2 pilot to be fitted for a pressure suit. He was "Number 16," the first 15 having been test pilots. Kutson's career in aviation began in 1950 as an Air Force aviation cadet. Following service in Korea flying F-84s, he joined the CIA pilots getting ready to deploy the U-2. He retired from the USAF in 1970 with over 6,500 hours of flight time, much of it flying over the Soviet Union and Eastern Europe in U-2s. The following year Knutson joined NASA at the Ames Research Center and later as the Director of Flight Operations at the Dryden Flight Research Center. Near the end of his NASA career, he was instrumental in getting the USAF to transfer three SR-71s to NASA instead of retiring them.[115]

The MC-3 was a substantial improvement over earlier suits and represented a turning point between capstan (mechanical) and bladder partial-pressure suits. Like its immediate predecessors, the MC-3 used capstans to provide counter-pressure on the limbs, but it was fitted with a full-torso bladder extending from the shoulders to mid-thigh, completely surrounding the chest, abdomen, hips, and upper thighs, and passing through the crotch (the MC-1 had only chest and abdominal bladders). These bladders inflated and deflated with the breathing of the wearer.[116] The leads to the torso bladder and capstans were an extension of the bladder system instead of being separate hoses as in all earlier suits. Additional lacing, extending up the inner thigh, the small of the back, and down the chest, provided better control of the torso bladder and more variation in circumferential fit. A horizontal shoulder zipper made the new suit easier to don and doff. Zippers were also located at the ankle, wrist, and back placket, and a new chest zipper ran from the waist to the neck. The buttock zipper was eliminated, but a shortened front fly zipper was retained. Break lines—cords sewn into heavy seams to "break" the continuity of a bladder when inflated—were located at the waist and groin to make it easier to bend and sit. The MC-3 used the MA-2 helmet, manufactured by ILC Dover.[117]

The initial pilots tested their suits in the Wright Field altitude chamber at 65,000 feet for 4 hours with no major complaints. After the tests, Col. Philip Maher, the USAF liaison on the project, asked David Clark if the company could improve the MA-2 helmet. The pilots were complaining that it was difficult to turn their heads, mostly because the restraint fabric connecting the helmet to the suit was stiff and did not move under pressure. This became the first use for a new "Link-Net" fabric that David Clark developed for the neck section to allow the pilot to turn his head more easily. At first, the USAF sent helmets to Worcester for David Clark Company to add the Link-Net, but eventually David Clark sold preformed Link-Net sections to ILC Dover, which extended the modification to all pressure suit helmets.[118]

In January 1956, the Tactical Air Command issued requirements for a "mission completion suit" for the Martin B/RB-57 Canberra and Douglas B/RB-66 Destroyer to replace the MC-1 suits the command had intended to use. Exactly why TAC was so concerned about providing pressure suits for these light bombers is unclear since neither had an operational ceiling much above 40,000 feet, and seldom operated anywhere near that altitude.

An early MC-3 suit being readied for a U-2 flight from Watertown, otherwise known as the CIA test facility at Groom Lake, NV. This photo shows the interdigitizing laces along the arms and legs to good advantage. The capstan tubes were sewn in such a way that as they inflated, they pulled the laces tight, providing surface pressure against the skin of the wearer. In addition to the capstans, the MC-3 used a full-torso bladder, extending from the shoulders to mid-thigh, completely surrounding the chest, abdomen, hips, upper thighs, and passing through the crotch (the MC-1 had only chest and abdominal bladders). The chest bladder also acted as breathing vest.

U.S. Air Force

Francis Gary Powers wearing an MC-3 partial-pressure suit and MC-2 helmet in front of a Lockheed U-2A. The MC-3 had additional lacing, extending up the inner thigh, the small of the back, and down the chest, to provide better control of the torso bladder and more variation in circumferential fit. Powers was shot down over the Soviet Union on May 1, 1960, and was not returned to the United States until February 10, 1962, in an exchange for Soviet KGB Colonel Vilyam Genrikhovich Fisher (aka Rudolf Abel), a Soviet colonel who was caught by the FBI.

Courtesy of Lockheed Martin Aeronautics

Interestingly, by this time, the SAC had decided the B-52 and B-58 would have "shirt-sleeve" environments and that pressure suits were not required. Nevertheless, some flights, especially early flights in B-58s before the installation of the ejection capsules, used MC-1 or MC-3 partial-pressure suits.[119]

Things took an unexpected turn on February 7, 1956, when Lt. Gen. Thomas S. Power, commander of the Air Research and Development Command, informed attendees at a personal equipment conference in Baltimore that a new "partial-full" pressure suit, "developed for a special application," had proven so successful that it would immediately replace all existing partial-pressure suits. The USAF considered these "mission completion" suits (as opposed to get-me-down suits), and the military expected to use them to "stay up" for up to 4 hours, if needed.[120]

On March 6, 1956, within weeks of Air Force Headquarters selecting the MC-3 for immediate operational use, the Air Materiel Command began negotiating procurement contracts. The USAF set aside $7.4 million to purchase MC-3 suits for the B-57, B-66, F-100, F-101, and F-102 aircraft assigned to the TAC and ADC.[121] Ultimately, Berger Brothers and David Clark Company manufactured the suit, which was available in the 12 standard sizes, plus custom sizes (this time by David Clark Company) as needed for U-2 pilots. The special sizes were particularly necessary for the 30 Republic of China Air Force pilots that arrived at Groom Lake to the fly the U-2.[122]

In the meantime, the USAF cancelled contracts for all other partial-pressure suits and directed that existing stocks of S-2, T-1, T-1A, and MC-1 suits be used only for ground training. Somewhat belatedly, the USAF realized that cancelling the procurement of all existing

The MC-3 was often worn with an outer layer to cover the capstans and laces to ensure they did not get tangled with switches or other objects in the small cockpit of the U-2. The outer covers came in a variety of colors or in this instance, multicolors. This outer cover was used over friendly territory to aid searchers in the event the pilot had to eject; solid sage-green covers were used on the clandestine missions.

Courtesy of Lockheed Martin Aeronautics

suits had been too drastic. Although they were far from perfect, the suits were dependable and much better than no protection at all. Phasing in the new MC-3 suit would undoubtedly be a gradual process, so the USAF reinstated contracts for 1,500 T-1A suits.

There were a wide variety of MC-3 configurations, including those with the hose connections on the left (S621L) or on the right (S621R), those with different helmet hold-down configurations (S621LM), and those without the back capstan (S621AR). As it ended up, David Clark Company only manufactured 1,073 MC-3 suits (884 Model S616 and 189 Model S621) before production switched to the MC-3A (S687 and S799) in 1958.[123]

The MC-4 (BB-MC-4 and S805) began life as an MC-3 with an integral G-suit. However, the designers took the opportunity to again reconfigure the suit closures to increase comfort and mobility, primarily by deleting the shoulder zipper in favor of more lacing. As was the case in all of the partial-pressure suits, the G-suit operated more efficiently when the partial-pressure suit bladders were already inflated.[124]

Before the MC-4 was developed, the Navy ordered modified MC-3s that allowed the pilot to reach the face-curtain ejection handle and provided the same acceleration protection as the C-1A G-suit. These were designated C-4 (S759). After the MC-4 entered production the Navy ordered modified versions as the C-4A (S785).[125]

The MC-3A was identical to the MC-4 without the G-suit, including the vertical shoulder lacing and adjustable break lines. The MC-3A again used the MA-2 helmet although most MC-3 and MC-4 suits were eventually modified so they could use ILC Dover MA-2, Bill Jack MA-3, or MB-5 helmets. Both Berger Brothers and David Clark Company manufactured MC-3A suits (BB-MC-3A and S687,

The MA-2 helmet was usually white, but others colors existed, as shown by this orange helmet on a pilot in front of his bare-metal U-2A. This photo gives a good view of the periscopic sextant just ahead of the canopy and the driftsight on the bottom of the fuselage below the cockpit.

National Archives College Park Collection

respectively). David Clark Company also manufactured a special MC-3A (S799) with the pressure fittings on the left side.[126]

All of these suits used pressure gloves that had the pressure lead on the thumb side, using positive-lock bayonet connections. Berger Brother gloves were all leather, but David Clark Company used leather palms and nylon backs with lacing adjustments.[127]

The MC-4A (BB-MC-4A and S814) suit was the first production suit sized using a new 8-size "height-weight" scheme instead of the 12 standard sizes defined by David Clark during World War II. Instead of using a variety of body measurements, only the wearer's height and weight determined the size of the suit. Milton Alexander of the Biophysics Branch and Fred Moller at Berger Brothers developed the new sizing tariff in 1958 during the development of the CSU-2/P.[128] Except for the sizing, the MC-4A was identical to the MC-4 suit.

The MC-3/3A and MC-4/4A suits used a new Firewel pressure regulator built into a seat kit that was used as a seat cushion in the airplane. This replaced both the on-aircraft regulator and the suit regulator. Under normal

Below: An MC-4 partial-pressure suit with MA-2 helmet on October 3, 1956. Initially, the Air Force ordered the MC-4 as an MC-3 with an integral G-Suit, but the David Clark designers took the opportunity to make other changes that improved the usability of the suit. These changes were subsequently made to the MC-3, becoming the MC-3A.

U.S. Air Force photo.
Courtesy of the Terry Panapolis Collection

Below: This was the standard configuration of the MC-4 with a MA-2 helmet, back parachute, and a seat kit. To provide protection as far down the calf as possible, the Air Force issued lowrise boots (or high shoes). Note the adjustment laces inside the leg and on the chest. The MC-4 was fabricated by Berger Brothers and, as with this particular suit, the David Clark Company.

U.S. Air Force photo.
Courtesy of the Terry Panapolis Collection

Below: This is Joe Ruseckas at the David Clark Company facility showing the back of an MC-4. One of the major changes from the MC-3 was the elimination of the horizontal shoulder zipper. Note the adjustment lacing on either side of the interdigitizing tapes that operated the suit.

Courtesy of the David Clark Company, Inc.

operations, the regulator pressurized the suit and helmet using the aircraft oxygen supply. In case of ejection, the source switched to a 6-minute reserve bottle(s) built into the seat kit itself, with the switchover taking 5–9 seconds. Operation was completely automatic, providing appropriate breathing and counter-pressure up to 70,000 feet. The only controls were an on-off switch and a pressure gauge, along with the press-to-test button that inflated the suit to 6 psi and the helmet to 60 mm Hg for a few seconds.[129]

As an experiment, Ed Dubois and Joe Ruseckas at David Clark Company constructed a suit (S787) similar to the MC-4A that used Link-Net for the shoulder section. This may have been the prototype for the Link-Net shoulder pattern that was used in the MC-2 and S901 full-pressure suits, but nobody at David Clark Company remembers who developed the pattern. A second prototype (S802) expanded the use of Link-Net from the shoulder to the forearm, integrated the G-suit between the altitude bladder and the outer covering, and incorporated a basket-weave ventilation vest. The USAF designated this suit CSU-1/P but did not order it into production since Berger Brothers was already developing the CSU-2/P.[130]

After the late 1950s, SAC crews were no longer routinely required to wear partial-

Above: David Clark Company S612 partial-pressure suit gloves were typical of the gloves used with later pressure suits. The gloves had leather palms and nylon backs. These particular gloves have the pressure lead on the pinky side; the MC-3 and MC-4 suit had pressure leads on the thumb side. Note the lace adjustments on the back.

Courtesy of the David Clark Company, Inc.

pressure suits on operational missions since low-altitude nuclear penetration was by that time the mandated nuclear mission profile. Fighter pilots continued to wear the capstan-type partial-pressure suits into the mid-1960s.

The MC-3A and MC-4A suits were the last of the mechanical (capstan) partial-pressure suits developed by the USAF until the Tactical Life Support System (TLSS) program in the mid-1980s. The MC-3A and MC-4A suits remained in service with the USAF until 1964 and considerably later with various other air forces.

Left and photo on page 160: Ads such as these are familiar to many from the 1960s, selling surplus partial-pressure suits and helmets. The ad claims the suits cost the Government $180, making the $7.95 asking price quite a bargain, as were the $380 helmets that sold for $14.95. It was a bit of a stretch to say the garments were "made for American astronauts."

Courtesy of the David Clark Company, Inc.

Interestingly, during the early 1960s many of these early partial-pressure suits, specifically the T-1, MC-1, and MC-3, along with the K-1 helmet, were sold in military surplus stores. The USAF, however, later recalled the suits for sale to NATO nations under the U.S. Military Assistance Program although a considerable number of these suits remain in the hands of memorabilia collectors. It was a rite of passage for many baby boomer boys to drool over the "Captain Company" advertisements that appeared in James Warren and Forrest J. Akerman's *Famous Monsters of Filmland* magazine, which offered new and unissued K-1 helmets for $14.95 and the partial-pressure suits used with them for only $7.95![131]

MC-3A SPECIALS—MANHIGH, EXCELSIOR, AND STARGAZER

Despite its limitations, in the mid-1950s, the MC-3 represented the best partial-pressure suit available in the western world. The USAF provided MC-3A suits to support a variety of special projects, including three unusual efforts that used very high-altitude balloons.

In December 1955, the USAF established Project Manhigh to investigate the effects of simulated space travel on humans. Since rockets were not yet capable of launching anything significant into space, the pilot would ride in a pressurized gondola above 100,000 feet for a 24-hour balloon flight that would be above 99 percent of the atmosphere and in the functional equivalent of a space environment. The USAF selected three pilots—Capt. Joseph W. Kittinger, Jr., Lt. Clifton M. McClure, and Maj. David G. Simmons—for the Manhigh flights. The pilots wore slightly modified MC-3A (S836) suits in case of sudden pressure loss.[132]

The aluminum Manhigh gondola was 8 feet high and 3 feet in diameter, and it consisted of the upper dome, turret, and lower shell. The turret included six portholes, including one the pilot could open. After rejecting pure oxygen as a fire hazard, the pilot breathed a mixture of 60 percent oxygen, 20 percent nitrogen, and 20 percent helium. The gondola weighed 1,648 pounds including the pilot and scientific equipment. At maximum altitude, the plastic balloon expanded to a diameter of 200 feet with a volume in excess of 3 million cubic feet.[133]

Kittinger flew the first flight, MANHIGH I, on June 2, 1957, and reached 96,784 feet. Simons reached 101,516 feet on August 19–20, 1957, on MANHIGH II. During this flight, Simons took a self-portrait at 100,000 feet that became the September 2, 1957, *Life Magazine* cover photo. The last flight, MANHIGH III, was flown by McClure on October 8, 1958, and reached 98,097 feet.[134]

After his flight, Simons wrote a critique of the MC-3A suit. Simons pointed out that the suit was intended strictly as an emergency garment to be used only if the gondola pressurization system failed. Simons indicated he normally did not wear the helmet faceplate, except when doing pressure checks and switching gas bottles. His overall assessment was, "Although the suit was well designed and served its purpose well, protecting from depressurization, it also caused considerable discomfort with a marked loss of effectiveness and efficiency during the flight." Simons indicated that "at the end of the flight, the inside surface skin of my elbows was literally rubbed raw and covered with scabs from the 44 hours of continuous irritation."[135] He also pointed out that the insulation value of the helmet was considerably greater than that of the suit, making it difficult to achieve a comfortable temperature. Perspiration around the torso bladders soaked his underwear, causing "considerable distress."[136] Simons admitted his use of the suit was outside the norm but offered suggestions to improve future suits, several of which were incorporated into the CSU-2/P and CSU-4/P suits that followed.

The second balloon project was even more interesting. As turbojet aircraft flew higher and faster in the 1950s, the USAF became increasingly concerned with the hazards faced by flight crews ejecting from high-performance aircraft. Col. John Paul Stapp (1910–1999) led the way with his pioneering deceleration research that defined the limits of human tolerance. On December 10, 1954, he earned the title, "The Fastest Man Alive" when he rode the *Sonic Wind I* rocket sled to a maximum speed of 639 mph in 5 seconds and then decelerated in 1.25 seconds with a peak stopping force of more than 40-G. For a brief period, Stapp weighed 6,800 pounds and the windblast and deceleration forces were roughly equivalent to ejecting in an open seat at Mach 3 and 60,000 feet. Stapp personally made 27 of the 73 manned sled tests conducted as part of the deceleration project.

Born in Bahia, Brazil, Stapp received a B.A. in 1931 from Baylor University, Waco, TX, an M.A. from Baylor in 1932, a Ph.D. in biophysics from the University of Texas at Austin in 1940, and an M.D. from the University of Minnesota, Twin Cities, in 1944. He interned for 1 year at St. Mary's Hospital in Duluth, MN. Stapp also received an honorary Doctor of Science from Baylor University. Stapp entered the Army Air Corps on October 5, 1944. On August 10, 1946, he was transferred to the Aero Medical Laboratory at Wright Field as project officer and medical consultant in the Biophysics Branch. His first assignment as a project officer included a series of flights testing various oxygen systems in unpressurized aircraft at 40,000 feet.[137]

Stapp was also interested in determining the capabilities of full- and partial-pressure suits to protect pilots during and after ejections. In 1958, the USAF established Project EXCELSIOR (meaning "ever upward," a name given by Stapp) with Joe Kittinger as test director to study and investigate these high altitude escape problems. Sometime earlier, Francis Beaupre, a technician at Wright Field, devised a parachute system that would allow pilots to safely eject at high altitudes without worrying about entering a flat spin as they descended. The Beaupre Multi-Stage Parachute system used a stabilizer chute that controlled spinning and tumbling at high altitudes. An automatic system deployed both the stabilizer and main

In 1958, the Air Force established Project EXCELSIOR to investigate the issues involved in high-altitude escape, particularly the performance of pressure suits. Lacking the funds for anything more elaborate, the Air Force elected to use to use an open gondola suspended under a large helium balloon. Joe Kittinger made the third EXCELSIOR jump on August 16, 1960 from 102,800 feet and opened his parachute at 18,000 feet.

U.S. Air Force

parachutes at the appropriate speed and altitude. EXCELSIOR would determine if the system worked as designed.[138]

Since EXCELSIOR did not have the resources to use high-performance aircraft to test the new escape system, Wright Field built an open gondola to suspend under a 173-foot-diameter balloon that held nearly 3 million cubic feet of helium. Kittinger made three high altitude jumps from the gondola using the Beaupre-designed parachute system. He made the first jump from 76,400 feet on November 16, 1959, but the stabilizer chute deployed too soon, catching him around the neck and causing him to spin at 120 rpm, resulting in over 22-G acceleration at his extremities. Kittinger lost consciousness, but fortunately, the main chute opened automatically at 10,000 feet, and he landed without serious injury. The second jump, on December 11, 1959, from 74,700 feet was much less eventful.[139]

A ground crew assists Joe Kittinger in removing his flight gear after the successful flight of Excelsior III. The entire jump took somewhat under 13 minutes, with most of that time spent under the canopy after the main parachute opened. The modified MC-3A partial-pressure suit performed as expected except for a failed glove. Despite the appearances, Kittinger was fine.

U.S. Air Force

On the third and final jump on August 16, 1960, Kittinger jumped from 102,800 feet, almost 20 miles above Earth. The ascent took 1 hour and 31 minutes and broke the previous manned-balloon altitude record set by David Simmons as part of Project Manhigh. During the ascent, the pressure seal in Kittinger's right MC-3A glove failed, and he began to experience severe pain in his hand but did not inform his ground crew for fear they would order him to abort the test. After falling for 13 seconds, his 6-foot drogue chute opened and stabilized his fall. With only the small stabilizing chute deployed, Kittinger fell for 4 minutes and 36 seconds, experiencing temperatures as low as –94 °F and a maximum speed of 614 mph (although, contrary to many published reports, Kittinger indicates he did not break the speed of sound).[140]

Years later, as he helped Felix Baumgartner at Red Bull Stratos prepare for his attempt to break the free-fall parachute-altitude record, Kittinger remembered what it felt like:

> When I reached 102,800 feet, maximum altitude, I wasn't quite over the target. So, I drifted for 11 minutes with winds that were out of the east. I went through my 46-step checklist, disconnected from the balloon's power supply, and lost all communication with the ground. From that moment, I was relying totally on the kit on my back. When everything was done, I stood up, took one final look out, and said a silent prayer: 'Lord, take care of me now.' Then I just jumped over the side. I had gone through simulations many times—more than 100. But this time I rolled over and looked up, and there was the balloon just roaring into space. I realized, however, that the balloon wasn't roaring into space; I was going down at a fantastic rate! At about 90,000 feet, I reached approximately 614 miles per hour. The altimeter on my wrist was unwinding very rapidly, but there was no sense of speed. We determine speed visually when we see something go flashing by—but nothing flashes by at 20 miles up in the air; there are no Signposts when you're way above the clouds. When the chute opened, the rest of the jump was anticlimactic, because everything had worked perfectly. I landed 12 or 13 minutes later, and there was my crew waiting. We were elated.[141]

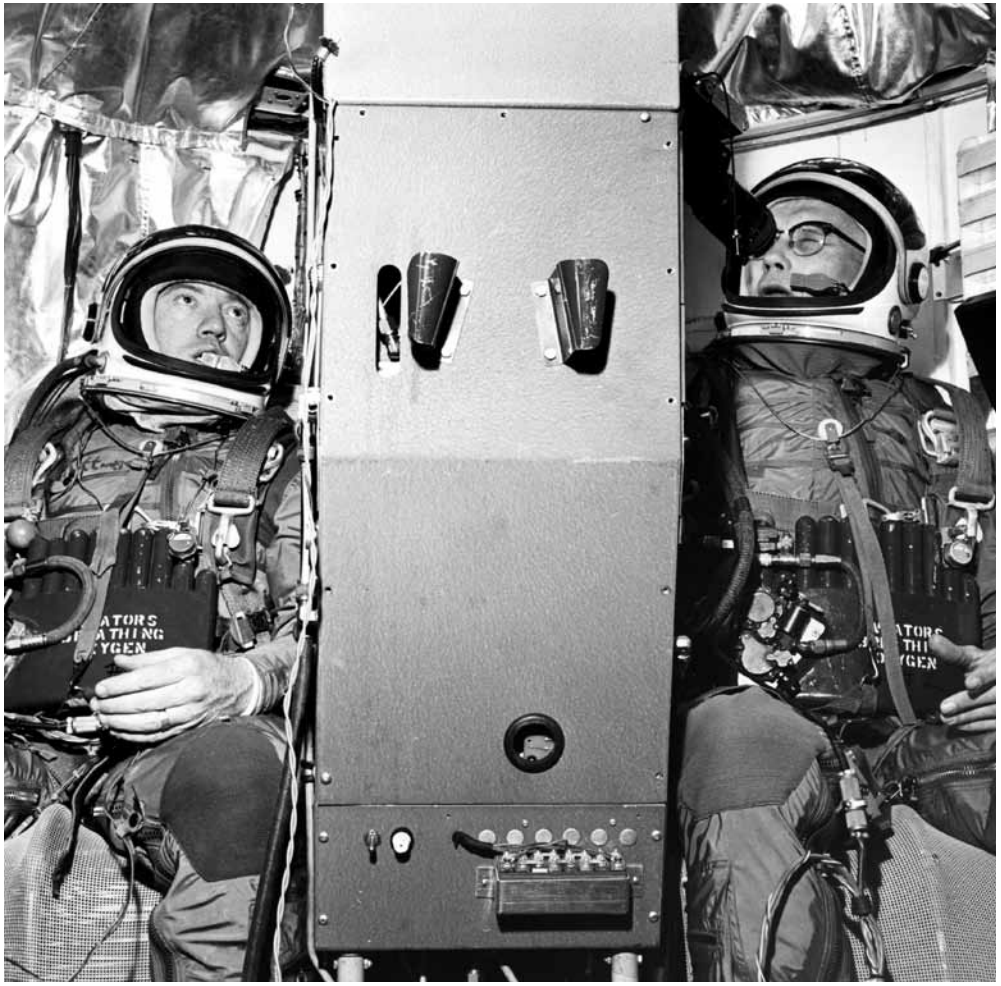
The 28-foot main parachute did not open until Kittinger reached the much thicker atmosphere at 17,500 feet. Kittinger safely landed in the New Mexico desert 13 minutes and 45 seconds after he left the gondola.[142] This jump set records for highest balloon ascent, highest parachute jump, longest drogue fall, and fastest speed by a human through the atmosphere. These are still current USAF records but were never submitted to the FAI to qualify as world records.[143]

The third balloon project returned to scientific research. Back at Holloman AFB, Kittinger also took part in Project Stargazer on December 13–14, 1962. Kittinger and William C. White, an astronomer, spent more than 18 hours above 80,000 feet performing observations. The pilots wore slightly modified MC-3A partial-pressure suits. In addition to obtaining telescopic observations from above 95 percent of Earth's atmosphere, the flight provided valuable data for the development of pressure suits and associated life support systems during a 13-hour stay at the edge of space.[144]

CSU-2/P—ATTEMPT TO IMPROVE THE MC-4

As good as they were, everybody agreed the MC-3/4 suits were not perfect, and the Aero Medical Laboratory gave Berger Brothers the lead in developing a better suit. One objective was to create a relatively loose-fitting garment that provided better comfort when unpressurized and made donning and doffing easier. Creating a loose-fitting garment that offered sufficient protection was a difficult assignment and required rethinking how the capstan principle worked.[145]

The Aero Medical Laboratory suggested investigating two double-capstan arrangements dubbed "double power" and "double take-up." In both cases, two



Project S*TARGAZER was a balloon astronomy experiment in which Joe Kittinger (left) and astronomer William White hovered for more than 18 hours above 80,000 feet to check variations in brightness of star images. The men are wearing modified MC-3A partial-pressure suits. Note the breathing oxygen packs on their chests. Each man wore a parachute in case they needed to bail out.*

U.S. Air Force

capstans were used on each limb, and the interdigitizing tapes run in such a way that one capstan pulled the fabric from under the other capstan (instead of letting it bunch up, as in a single capstan system). Berger Brothers built models of both capstan arrangements and ran extensive laboratory tests to determine which was best. Ultimately, Fred Moller decided to use the double-power capstan arrangement over the torso bladder area and the double takeup system over the shoulders, arms, and legs.

The increased area (compared to the MC-1 suit) of the torso and breather bladders in the MC-3/4 suits resulted in considerable discomfort because perspiration could not easily evaporate. In response, a vinyl-film ventilation layer was added under the torso bladder, next to the underwear, to provide a constant source of ventilating air at appropriate spacing. The ventilation layer covered the back from the upper shoulders to the buttock and the front from the upper shoulder to the groin. The layer was perforated with 0.044-inch holes spaced approximately 0.21 inch apart. In addition, some pilots complained about pain in their feet, so Berger Brothers developed a pair of pneumatic socks with minimal seams, constructed of a lightweight, air-impermeable material that could be worn with the regulation flight boots.

Fred Moller constructed the first prototype (Model 3904-X1) of what the USAF designated CSU-2/P in late 1957. The suit included a "tear-away" outer cover intended to protect the suit during a high-speed ejection, although it also prevented the lacings and interdigitizing tapes from snagging on objects in the cockpit. After a great deal of evaluation, the outer layer was made from Brauer Knitting Company A48C stretch nylon fabric. The low-friction capstan tapes used a nylon-satin weave. Prior to adopting that material, Berger Brothers tried various heavy tapes and lightweight webs using different weaving methods. Some of the yarns were Teflon coated prior to weaving, while others were coated after weaving.

The second prototype, Model 3904-X2, used a zipper extending from the center-front neck down to the waist at a right angle so that the suit opened completely on the right side. The new arrangement "left a lot to be desired" and Fred Moller investigated many alternate zipper configurations to make the suit easier to don.[146] The final scheme consisted of three separate zippers, one inside each leg from the crotch to the ankle and one from the neck to the left thigh. Ultimately, the second prototype was judged to perform adequately and offer greatly increased comfort, but the tear-away layer and zipper arrangement still needed to be improved.

For unexplained reasons, the third prototype (Model 3904-X3) abandoned the double-capstan system and returned to the traditional single-capstan arrangement. Moller developed two different tear-away layers for this suit. The first was a strong, lightweight Dacron taffeta that could withstand the anticipated buffeting during ejection. The second included an aluminized finish that provided a bit more protection, reflected heat, and looked very futuristic. Neither outer layer was judged particularly superior during tests.

While he was developing the CSU-2/P suit, Fred Moller worked with Milton Alexander of the Biophysics Branch to develop a new "stature-weight" sizing tariff to replace the 12 standard sizes defined by David Clark during World War II. Instead of using a variety of body measurements, only the wearer's height and weight determined the size of the suit. Perhaps not surprisingly, given how much research went into the original sizing charts, Berger Brothers discovered that most sizes "required very little change" to match the new sizing criteria.[147] Given the CSU-2/P never entered production, the first use of the new tariff came on the later MC-4A suits and the improved CSU-4/P suits.

Ultimately, the Aero Medical Laboratory decided not to proceed with the CSU-2/P suit and concentrated its efforts on the CSU-4/P that eliminated capstans. This left the MC-3/4 as the last of the mechanical counter-pressure pressure suits used by the USAF until the late 1970s.

C-1A AND C-4—NAVY CAPSTAN SUITS

Ejection seats in USAF aircraft generally used a ring located between the pilot's legs, or a D-handle on either side of the seat base, to initiate ejection. In contrast, early Navy seats used a curtain that the pilot pulled down over his face and chest to initiate the ejection sequence. Therefore, it was necessary for a Navy partial-pressure suit to provide sufficient mobility to accomplish this task, both pressurized and unpressurized. To this end, the David Clark Company developed an experimental C-1 suit (S518) specifically to fit Douglas test pilot William B. Bridgeman. The C-1 was a modified USAF T-1 suit.[148]

Based on the success of this exercise, David Clark Company developed the C-1A suit (S520) with a redesigned shoulder area that provided sufficient arm mobility to reach the ejection seat face curtain. This included lengthening the vertical trunk circumference so that the wearer could raise the clavicle. The arm capstan sizes were

David Clark's Joe Ruseckas demonstrates that it was possible to reach the face curtain handles in a North American FJ-3 Fury while wearing and unpressurized T-1 partial-pressure suit. This demonstration convinced the Navy to adopt modified T-1 suits pending the delivery of the dedicated Navy C-1 suit.

U.S. Navy photo. Courtesy of the David Clark Company, Inc.

reduced to the same "limb to capstan ratio" as the leg capstans since Naval Aviators complained the T-1 capstans were too large over the arms. The crotch area was redesigned to better accommodate the Navy parachute harness and improve leg mobility, and the relief zipper was extended further into the crotch. The normal position of the knees was bent backward to provide sufficient mobility to place the feet in the ejection seat stirrups. A waist-zipper placket was installed to permit the wearer to stand more erect and walk more easily. Finally, the G-suit connect hose was extended to the standard Navy length.[149] David Clark Company also created a version of the C-1A suit (S676) without the integrated G-suit, although the Navy continued to call it a C-1A.[150]

David Clark Company manufactured prototypes in mid-1955, and once these proved satisfactory, the company slightly reworked the 12 standard sizes to conform to Navy expectations by measuring a representative sample of Naval Aviators.[151] During early 1958, David Clark Company created a couple of C-1AM suits (S685 and S830) that incorporated the MC-1-style breathing bladder.[152]

Before the MC-4 was developed, the Navy ordered versions of the USAF MC-3 modified to allow the pilot to reach the face-curtain ejection handle and to provide the same G-protection as the C-1A suit. These were designated C-4 (S759). After the MC-4 entered production, the Navy ordered modified versions as the C-4A (S785). All of these suits used ILC Dover MA-2 helmets and Firewel seat kits and oxygen panels. Berger Brothers, and possibly others, fabricated equivalent suits.[153]

CSU-4/P AND CSU-5/P—BLADDERS ONLY

Although the MC-3A and MC-4A suits offered satisfactory protection in an emergency, they were still uncomfortable and offered limited mobility, even when unpressurized. An attempt by Berger Brothers to develop a more comfortable capstan suit, the CSU-2/P, had not been successful and the suit never reached production.

Since most long-duration high-altitude missions had fallen out of favor for tactical reasons, researchers at the Aero Medical Laboratory decided any new partial-pressure suit would return to the get-me-down philosophy instead of the "mission completion" concept used for the MC-3/4. Development began in October 1956, when the Air Force defined requirements for a new garment that included providing 5 minutes of protection at 70,000 feet plus an additional 4 minutes to descend to 40,000 feet. The suit needed to be quick-donning without assistance and be an outer garment worn over a normal flight suit. It had to provide a significant increase in comfort and mobility over the MC-3/4. In addition, the new suit needed to include G-protection or be compatible with a G-suit, provide adequate ventilation, be compatible with existing aircraft oxygen and pressurization systems, and fit 90–95 percent of the aircrew population.[154]

Researchers agreed that the desired comfort could only be provided by a "loose baggy fit." For this reason, the use of capstans as pressurizing elements was eliminated and the new suit would use only inflatable bladders. This was a major departure from all previous partial-pressure suits. The resulting CSU-4/P emergency partial-pressure suit was developed as a cooperative effort of the Aero Medical Laboratory and David Clark Company. Charles C. Lutz at the Aero Medical Laboratory was the project officer, and Kent W. Gillespie was the task engineer. Joseph A. Ruseckas was the lead at David Clark Company.

The first prototype was fabricated by David Clark Company under contract AF33(616)-3329. The suit had separate bladders covering the upper and lower arms and lower legs. Each bladder was equipped with separable inflation tubes to permit various sections to be disconnected. Initial testing indicated the suit was a great improvement in comfort but also showed excessive ballooning when pressurized at sea level. More disturbingly, eight chamber tests—two each at 50,000, 55,000, 60,000, and 65,000 feet—showed the suit did not provide sufficient counter-pressure.

Chance Vought test pilot Jack Walton climbs into his F7U-3 Cutlass (BuNo 129600) wearing a David Clark Company C-4 partial-pressure suit. There is a parachute on his back, and an emergency oxygen bottle on his left leg.

U.S. Navy photos by Chance Vought via Don Pyeatt

The CSU-4P was a bladder type partial-pressure suit that used Helenca stretch fabric at the knees and shoulders to aid in mobility. The neck consisted of the suit-side neck ring attached to a neck skirt. The neck skirt was tucked under the suit torso at the neckline and attached to the suit torso with Velcro. This suit includes an HGU-8/P full-pressure helmet. Umbilicals for communications, visor-seal pressurization, and breathing oxygen were attached to the side of the helmet. Gloves were the same type used with the earlier capstan partial-pressure suits.

U.S. Air Force

The next two prototypes used different bladder configurations that included overlapped bladders, abutted bladders, and continuous bladders. Ruseckas added various adjustable straps as mobility break lines. These suits were subjected to 17 chamber tests at altitudes up to 90,000 feet. Researchers considered both suits physiologically adequate, but arm and shoulder mobility was still unsatisfactory.

The fourth prototype (S822) added Link-Net to the shoulders, sleeves, and knees. This suit was also the first to integrate G-protection and ventilation features into the garment. The anti-G bladders were placed under the altitude suit bladders (closer to the skin) and provided protection equivalent to the CSU-3/P cutaway G-suit. During the evaluation, researchers determined that the arrangement of the anti-G bladders was unsatisfactory because of excessive bulk and difficulty in donning. Researchers realized that including anti-G features in the basic suit was greatly penalizing its comfort and donning characteristics They reasoned that, since not all users would require G-protection, it was easier to allow those that did to wear the standard CSU-3/P under the suit when needed. Further studies concluded the pilot could wear the G-suit under or over the pressure suit with adequate protection.

The fifth prototype (S822-1) was essentially identical to the fourth, except the G-protection and ventilation features were omitted. Provisions were made to wear the standard MA-3 ventilation garment under the pressure suit if needed. In this suit, the Link-Net material over the arms and shoulders was covered by a layer of two-way stretch Helenca nylon to prevent snagging. Since the suit was intended to be loose fitting, lace adjustments were deleted from all areas except the wrists. This suit also used the new 8-size tariff instead of the traditional 12 sizes.

The full-length zipper on the fifth suit permitted easy donning, but the time required to engage the two parts of the slider prior to closing it detracted noticeably from the improvement. Therefore, the sixth prototype used three separate zippers: one inside each leg extending from the crotch to the ankle, and a front slide fastener starting on the left thigh and extending to the collar.[155] This was essentially the same system recommended by Fred Moller at Berger Brothers a year earlier during the development of the CSU-2/P.

The Aero Medical Laboratory used the fifth and sixth prototypes in a series of altitude chamber tests. All volunteers were members of the USAF or "medically acceptable undergraduate students from the University of Dayton" that had previous experience evaluating pressure suits. Each subject wore a pressure suit, an MA-2 or MA-3 helmet, and a B-4 parachute, and sat in an ejection seat. The tests included 2-hour stays at 100,000 feet and explosive decompressions.[156]

At lower altitudes, all of the subjects felt that the suit, when properly fitted, allowed more mobility than the earlier capstan suits. During the long stay at 100,000 feet, all eight subjects believed they could have continued for another hour. Although none experienced any hand discomfort, the ones not wearing pressure socks complained of tingling and numbness of the feet. The increased suit pressure made mobility difficult, but all subjects completed their assigned demonstration tasks. Researchers determined that the suit did not appear to interfere with normal blood circulation or cause a shift in tissue fluids. All subjects had a normal electrocardiogram (except for tachycardia), no syncope, and expressed few subjective complaints.[157]

After the altitude chamber evaluations showed the suit to be suitable, David Clark Company manufactured nine garments: four were issued to the Air Defense Command, three to the Strategic Air Command, and two to the Air Force Flight Test Center at Edwards. In general, the pilots found the suit to be a marked improvement over the MC-3/4, but as could be expected, each offered suggestions for improvement. Most of the pilots could don the suit in 5 minutes without assistance. This compared to subjects at Wright Field that could do it in less than 2 minutes but had considerably more experience taking experimental suits on and off. Researchers felt that practice would reduce the donning time but admitted that complete dressing (suit, helmet, parachute, etc.) could probably not be accomplished fast enough to permit a 5-minute alert unless the pilot was already wearing at least the suit. Only one subject of the nine wore a ventilation garment under the suit, but the other eight subjects indicated it was needed. David Clark Company sized the test suits to be worn over the standard K-2B flight coverall, but most of the subjects did not do so. Nevertheless, the sizing appeared adequate for use with or without a flight suit underneath.[158]

Based on this evaluation, the seventh prototype (S822-1A) again incorporated a ventilation layer and repositioned the Link-Net in the shoulder area to ease the effort of holding the arm in a forward position to grasp a control stick. Unlike the previous suits, which were standard sage green, the seventh prototype was orange. The Air Defense Command had requested this change to aid in rescue operations. This suit also contained pockets on the thighs, calves, and arms, much like the standard K-2B flight coverall.

The seventh prototype passed its laboratory evaluations and the USAF ordered an initial 50 suits for service tests under operational conditions. Later, David Clark Company developed the CWU-4/P immersion suit to wear over the CSU-4/P during overwater operations.[159] Several different helmets were worn with the CSU-4/P including the MA-2, MA-3, and HGU-8/P. The suit was worn in the Convair F-102 Delta Dagger, Lockheed F-104 Starfighter, Convair F-106 Delta Dart, Martin B-57 Canberra, and Convair B-58 Hustler. The USAF, German

The David Clark Company CSU-4P was the first partial-pressure suit that relied completely upon bladders, instead of capstans, to provide the required pressures. Note the restraints running from the crotch to the shoulders to keep the suit from elongating under pressure. The pilot tightened these after he sat down since it was impossible to stand with the restraints in place.

Courtesy of the David Clark Company, Inc.

Air Force, Royal Australian Air Force, and the Japanese Self-Defense Air Force used the suit.

While not intentionally designed as an exposure suit, the CSU-4/P—or any pressure suit—provides some protection against the elements. Nevertheless, to provide an integrated pressure-exposure suit, in 1960, the Aero Medical Laboratory initiated the development of the CSU-5/P with David Clark Company under contract AF33(600)-36627. Kent Gillespie was the task manager for the Aero Medical Laboratory and Joe Ruseckas was the responsible engineer at David Clark Company.[160]

Ruseckas based the first prototype CSU-5/P (S848) on the final version of the CSU-4/P. The outer bladder served as an anti-exposure coverall that incorporated wrist and ankle seals. Gloves and boots were worn as separate garments. A Goodrich pressure-sealing slide fastener extended from the left lower thigh to the collar, while leg fasteners extended from the ankle to the knee area. An integral ventilation garment covered the chest, back, and thighs. During testing, this garment was not as watertight as desired, so a second prototype included plackets (slits) on the leg and wrist closures, an improved ankle seal, and a roll seal at the collar section. A BDM slide fastener replaced the Goodrich zipper that had created pressure points on the wearer in the sitting position.[161]

Environmental testing of the second prototype made researchers step back and reconsider their approach. Ruseckas decided to adopt the "wet suit" principle that allowed him to eliminate the watertight entry zipper as well as the neck, wrist, and ankle seals. The third prototype also moved the ventilation air inlet next to the suit-bladder oxygen inlet to make the suit more compatible with a greater variety of aircrew personal equipment. Thermal insulation was provided by two layers of U.S. Rubber Trilok (a non-crushable, three-dimensional fabric that allows ventilation), although the innermost layer did not cover the underarm, crotch, or the back of the knees to keep those areas from becoming too thick and limiting mobility.

Testing of the third suit showed that the double layer of Trilok insulation did not warrant its increase in bulk, so the fourth suit deleted one layer. Other changes included making the lower leg pocket zippers larger so the wearer could place his hands in those pockets when huddled in a fetal position. Eyelets were installed in the lower corner of all pockets to allow them to drain after immersion.

The last prototype incorporated a U-entry slide fastener similar to that on the A/P22S-2 full-pressure suit instead of the vertical front slide fastener previously used. The neck collar was made larger to allow the helmet to be attached prior to donning the suit. The ventilation system was similar to that used in the A/P22S-2. The USAF ordered this configuration into limited production.[162]

The development and subsequent standardization of the CSU-4/P and CSU-5/P provided garments with adequate physiological protection up to 70,000 feet that were reasonably comfortable. The counter-pressure bladder concept used in the CSU-4/P became the industry standard for many years and the garment had a long operational career, lasting well into the late 1970s with some users.

HAPS—NASA DRYDEN HIGH-ALTITUDE PROTECTIVE SYSTEM

Despite being the first operational users of pressure suits, the test pilots at Dryden have always wanted something that allowed better mobility. This has manifested itself in a series of slightly specialized versions of the standard David Clark pressure suits (generally variants of the A/P22S-2 or S-6) and also in a couple of local development efforts that in the late 1970s finally yielded a garment that satisfied the test pilots.

In 1972, Dr. William R. Winter at the NASA Dryden Flight Research Center awarded Space Age Control, a small company located in Palmdale, CA, a contract (NAS4-1961) to develop a full-pressure Altitude Protective Garment (APG) for use during flight-test. This 5-month effort eventually spanned about 8 months as NASA and Space Age worked through the requirements and built a single prototype. Jimmy B. Graves was the project manager at Space Age and Roger J. Barnicki was the responsible engineer at Dryden.[163]

Given that Dryden is located in the middle of the Mojave desert, Graves placed primary emphasis on a liquid-cooling garment to remove heat from the pilot and on the shoulder joints to ensure sufficient mobility. The cooling garment fully enclosed the head, torso, arms, hands, legs, and feet. Patterns were presented during a program design review on December 15, 1972, without major comment, and Space Age began fabricating the cooling garment and a prototype shoulder joint.[164]

Roger Barnicki tested the liquid cooling garment during January 1973 and determined that additional protection was needed around the head, so Space Age increased the hood tubing from 25 to 39 feet. Preliminary tests of the two-axis shoulder joint showed it offered good mobility at low torque. A unique load transfer ring allowed the use of two single-axis joints offset by 30 degrees, permitting adduction-abduction and transverse motion. By the end of January, all of the patterns were complete and Space Age began fabricating the pressure garment.[165]

The final design consisted of a spandex- and tygon-tubing liquid-thermal garment, neoprene-coated nylon pressure bladder, and nylon-restraint garment. Entry was via a rear vertical slide fastener and lace adjustments on the arms and legs allowed sizing. The suit used the two-axis shoulder joint and single axis joints in the elbows, thighs, and knees. Designers formed the single-axis joints by pleating (convoluting) the material and stitching a restraint tape over the pleats. The neck and wrist rings, relief valves, dual-suit controller, and most fittings were standard A/P22S-2 hardware supplied by NASA. The suit, helmet, and gloves weighed 23.25 pounds.[166]

Space Age completed the garment in mid-March and began testing it to criteria previously agreed upon with NASA. In a leak check, the suit was pressurized to 3.75 psi for 15 minutes. Excessive leakage was noted but eventually traced to Government-supplied hardware (mostly the suit controller). After fixing these problems, the suit was then pressurized to 5 psi for 1 minute with no failures. A test subject donned the suit and reported that ventilation was adequate. Space Age measured the range of motion measurements with the suit pressurized at 3.75 psi. Although mobility was adequate, the pilots wanted better.[167]

Space Age responded by designing a new shoulder joint using a thrust bearing. A unique feature of this joint was that the bearing was stressed under compression only, eliminating a significant amount of wear and tear usually associated with this type of bearing. Unfortunately, the new shoulder joint did not work as planned. Although the forces required to move the joint were lower than a soft fabric joint, they were excessive for a bearing joint. Engineers traced the problem to excessive flex in the outer bearing race and an uneven load around the scye opening where the shoulder attached to the torso. Because of the flex in the outer race, suit leakage was excessive at more than 1 liter per minute.[168]

It appears this was the end of the Space Age APG effort and NASA Dryden returned to using standard Air Force pressure suits for a couple of years. The next effort began almost as soon as the APG effort ended.

In 1976, a group that included Roger Barnicki at Dryden, Jewel M. Melvin at the Edwards AFB Physiological Support Division, and Thomas R. Morgan at the USAF School of Aerospace Medicine were joined by Dryden test pilot William H. “Bill” Dana and Air Vice-Marshall John “J.E.” Ernsting from the RAF Institute of Aviation Medicine. Their intent was to design a new partial-pressure suit for use during flight tests.[169]

Ernsting spent his entire Royal Air Force (RAF) career at the Institute of Aviation Medicine at Farnborough, specializing in the physiological aspects of flying at high altitudes. He was part of the team that developed the original RAF jerkin garments. By a happy coincidence, during the late 1970s, Ernsting was on sabbatical at the USAF School of Aerospace Medicine and contributed to the Dryden development effort.

The RAF (along with the Canadians and Swedes) have never adopted the concept of a partial-pressure suit, preferring instead to rely on pressure-breathing and later versions of the pressure vest and trousers first developed by Dr. Henry C. Bazett during World War II. By 1956, then-Flight Lieutenant John Ernsting was part of a team that developed a more sophisticated version of the Bazett pressure-breathing ensemble in anticipation of what became the British Aircraft Corporation TSR.2 strike aircraft. The RAF believed that a pilot breathing 100 percent oxygen at 40,000 feet equivalent altitude was thoroughly “capable of the mental and physical effort required to fly an aircraft.” Therefore, the desired system would provide protection for 1 minute at 70,000 feet and an additional 3 minutes for a descent to 40,000 feet. The system would allow nearly unlimited performance at 40,000 feet. The system consisted of a pressure-breathing mask, a set of anti-G trousers, and a jerkin pressure vest. The RAF demonstrated this system could provide adequate protection against the effects of pressure breathing at 78 mm Hg for 7.5 minutes or 107 mm Hg for 5 minutes. As part of the development effort, Ernsting participated in altitude chamber runs up to 100,000 feet using 133 mm Hg pressure breathing.[170]

The term "jerkin" is common within the clothing industry, and it means a short, close-fitting jacket; it was also used to describe a similar sleeveless garment worn by the British Army in the early 20th century. The RAF adopted the term for its revised counter-pressure vest.

Much like the American partial-pressure suit, the British jerkin required a considerable amount of development and evolved over the years. The garment started with the pressure-breathing vest developed by Bazett, with the first major redesign coming during the 1956 effort with Ernsting. The goal of this latter effort was to develop a jerkin that covered as much of the torso as possible. One of the first issues was testicular pain while breathing at high pressures and extending the counter-pressure vest through the crotch did not solve the issue. Researchers finally determined the problem was that the jerkin was rising, much like the American pressure suits, and crushing the genitals. The solution was to create an unpressurized saddle-shaped area around the genitals.

In the early jerkins, the bladders extended only to the top of the groin leaving the inguinal rings completely uncovered when the garment was inflated. Physiologists believed there was a risk of producing an inguinal hernia in some subjects. The RAF G-suit provided little support in this region, although the American and Canadian suits provided more. Eventually, the bladders were extended around the circumference of the upper thigh to adequately cover the area. Conversely, the original jerkins extended far up the neck, causing a choking sensation. The solution was to lower the neckline, although this was limited by a desire to maintain protection to the apices of the lungs that are behind each clavicle in the posterior triangles of the neck.[171]

Originally, the jerkin and G-suit were worn over the flight clothing. Pilots quickly began complaining that their movements were overly restricted when the ensemble inflated. Researchers determined that the jerkin was behaving a bit like the capstans on American partial-pressure suits, pulling the fabric underneath tight as it inflated. The solution was to wear the jerkin under the flight suit (but over elastic long underwear).

Back at Dryden, a new generation of fighter aircraft was again making test pilots desire more comfortable get-me-down garments. Newly arrived F-15s were capable of routine operations between 50,000 feet and 60,000 feet, but the aircraft were not equipped to use full-pressure suits. The Dryden test pilots considered the existing Air Force partial pressure suits too confining for the detailed research flights that NASA needed to fly. The aircraft could be modified to use full-pressure suits—all of the engineering existed for the aircraft delivered to the Israeli Defense Forces and Streak Eagle. However, the test pilots had reservations because the helmet and neck ring reduced the field of vision and the gloves restricted hand and finger dexterity. The pilots felt this resulted in pilot fatigue and reduced mission effectiveness.[172]

As an alternative, Dryden decided to evaluate the get-me-down garment used by the RAF. Although the concept dated to World War II, the then current version had been in service for over 15 years. Roger Barnicki and Bill Dana traveled to the RAF Institute of Aviation Medicine at Farnborough for indoctrination training. The ensemble consisted of a jerkin, a P/Q pressure-breathing mask, and a dual bladder G-suit provided by the David Clark Company. A sample ensemble was brought back to the United States and jointly tested by Dryden and the USAF School of Aerospace

Medicine. Prior to flight tests at Dryden, Tom Morgan at the School of Aviation Medicine conducted altitude chamber testing to validate the ensemble. The test subjects confirmed the need for pressure-breathing training, but the result was enhanced performance at altitude. The results of this laboratory evaluation gave the pilots and life-support personnel confidence in the equipment.[173]

The jerkin provided by the RAF was a torso garment consisting of a single oxygen bladder that applied a pressure to the entire torso. The jerkin bladder was pressurized by the breathing oxygen regulator through a valve in the hose to the P/Q pressure-breathing oronasal mask. The regulator output was proportional to the aircraft cabin altitude with a maximum output of 72 mm Hg. A check valve in the jerkin's oxygen bladder prevented oxygen flow from the bladder to the mask. The G-suit consisted of trousers with two bladders and two inlet hoses. One inlet hose connected to the oxygen regulator and the other to the barometric G-valve. The barometric G-valve responded to a positive G-load or a fall in cabin pressure. The suit operated within the 70-psi pressure available in the F-104s and F-15s operated by Dryden, therefore no modifications to either aircraft type were necessary.[174]

The P/Q mask used a reflected edge seal that could deliver up to 100 mm Hg (1.93 psi) to the respiratory tract without serious leakage. The mask covered the nose and mouth and rested on the anterior portion of the chin rather than under the chin. Two tension settings were available, and the pilot manually operated the tension to the high setting when cabin depressurization occurred. The tension was returned to the low setting when mask leakage was not a problem. The pilots preferred this mask to standard USAF units since it did not rotate down and under the chin during acceleration.[175]

NASA test pilots Bill Dana and Einar K. Enevoldson performed flight tests using a two-seat TF-104G. The pilot in the front seat wore an A/P22S-6 full-pressure suit, and the pilot in the rear seat wore the jerkin. Four cabin decompressions were performed, two at 50,000 feet, and two at 60,000 feet. The pilot in the jerkin had control of the aircraft and did not know when the decompression would occur. In each case, the pilot in the jerkin flew the descent to 20,000 feet, demonstrating the overall performance and safety of the jerkin ensemble.[176]

Based on these results, testing was extended to the fully instrumented F-15A test aircraft. Bill Dana flew the F-15 in level flight at 55,000 feet and Mach 1.4 prior to cabin depressurization. As a result of depressurization, the cabin pressure went from 346 mm Hg (6.7 psi, or 20,150 feet) to 77 mm Hg (1.49 psi, or 53,480 feet) in approximately 11 seconds. Surprisingly, the F-15 has a lower cabin altitude (higher cabin pressure) than aircraft ambient altitude because of the aerodynamics of the F-15, which has a greater ram-air effect than the F-104. At high angles of attack, the-F-15 exhibited even greater reductions in cabin altitude during depressurizations. Therefore, during an emergency, such as the loss of the canopy seal, the pilot in the F-15 could expect a higher cabin pressure (lower cabin altitude) than his indicated altitude. Safety aspects therefore favor the F-15 as a test aircraft due to lower than indicated altitude exposure.[177]

After the F-104 and F-15 tests, the pilots reported that their hand dexterity and field of vision were the same as when wearing a flying suit. The pilots also reported that the British ensemble provided unimpeded mobility in the cockpit and was very easy to don and doff. The only drawback reported was the heat buildup due to wearing both the jerkin and the anti-G trousers while in the aircraft taxing to the runway. Both Bill Dana and Einar Enevoldson considered this preferable to the disadvantages of wearing a full-pressure suit.[178] It should be noted that both pilots had extensive experience wearing various full-pressure suits during flights tests.

Given the unqualified endorsement of Dana and Enevoldson, and the concurrence of Roger Barnicki and Jewel Melvin, Dryden

NASA test pilot William H. Dana shows the jerkin-based flying outfit used by pilots at the Dryden Flight Research Center. This ensemble consisted of a pressure-breathing vest, a P/Q pressure-breathing oronasal mask, and a cutaway dual-bladder G-suit provided by the David Clark Company and it provided adequate protection up to 60,000 feet. The Dryden test pilots found this ensemble provided better mobility and was cooler than any of the available partial- or full-pressure suits.

NASA

adopted the jerkin ensemble as an operational suit for flights up to 60,000 feet. By 1980, however, the RAF supplied jerkins began to reach the end of their service life so David Clark Company made replacement garments that were generally similar to the originals. These garments reached the end of their service lives in the late 1980s, and David Clark Company again fabricated replacements. No further garments have been made, so it appears Dryden no longer has an operational high-altitude suit.[179]

The experience gained with the jerkin ensemble at Dryden formed the inspiration for the Contingency Altitude Protection Suit that became the Space Shuttle Launch Entry Suit after the Challenger accident.

5

5: Navy Full-Pressure Suits

Since 1942, researchers at the Naval Air Crew Equipment Laboratory (NACEL) in Philadelphia, PA, had conducted basic research in biological, psychological, and human engineering aspects of aviation medicine related to personal and safety equipment. Special facilities at the NACEL included, among others, an altitude chamber, underwater test facilities, a complete liquid-oxygen laboratory, and an escape-system recovery net capable of catching ejected free-flight seats and capsules. During World War II, the Navy monitored the progress of the Army MX-117 full-pressure suit program and evaluated several of the suits at the NACEL.

At the time, there was little need for a full-pressure suit since Navy aircraft typically did not fly at high altitudes. However, after the war, the Navy became increasing progressive as the service struggled to maintain its relevance in an era of supersonic aircraft and atomic weapons. In addition, the Navy was looking toward outer space, perhaps even more so than the Army. In early 1947, naval officials proposed the Army continue developing the Henry partial-pressure suit, while the Navy took over the effort on full-pressure suits. The Army, still unhappy from its wartime MX-117 experience, and having lost its lead researcher, John Kearby, to an airplane accident, was agreeable. At least for the short term.

During 1946, the Navy awarded contract NOa(s)-8192 to the Strato Equipment Company of Minneapolis. This was the company founded by John D. Akerman in early 1942, although by 1947 Akerman was listed only as a "consultant." The company had previously developed the Boeing, Akerman, Bell, and Mayo (BABM) series of pressure suits for Bell and Boeing as part of the Army program during 1943. The Navy effort appears to have been separate from the earlier Army effort, although it is unclear if the Model 7 suit that Strato ultimately delivered to the Navy was the seventh developed under that contract or was the BABM-7 suit from the previous effort.[1]

Akerman designed the Strato Model 7 to provide altitude protection up to 60,000 feet and limited acceleration protection. The one-piece, tight-fitting garment covered the entire body except the face, which was covered by a detachable "goggle-mask." The suit, minus the Government-supplied regulator, weighed

The Strato Equipment Company developed this Model 7 full-pressure suit for the U.S. Navy during 1947. Unlike most of the suits created for the Army Air Forces during World War II, most of the postwar suits developed for the Navy were fairly tight fitting.

U.S. Navy photo
Courtesy of the David Clark Company, Inc.

Top: The single diagonal zipper was a preview of what Russell Colley would eventually use on the Goodrich Mark IV suit. The Model 7 used a layer of nylon cloth on either side of the neoprene-rubber gas container, but all of the layers were integrated into a single zipper to make donning and doffing easier.

U.S. Navy photo
Courtesy of the David Clark Company, Inc.

Middle and right: Many of the early Navy suits dispensed with a hard-shell helmet in favor of a pressurized cloth head covering. In the case of the Strato Model 7, the "goggle-mask" had an integral pressure-breathing mask and standard-issue Navy goggles. Note the large oxygen regulator on the chest.

U.S. Navy photos. Courtesy of the David Clark Company, Inc.

13.25 pounds. The single suit that Strato delivered was sized to fit "a very large man," but Akerman believed that only four sizes would cover all pilots since the chest, stomach, helmet, and arm length were adjustable.

Two layers of nylon cloth provided protection for the neoprene sandwiched between them against local abrasions. According to Strato, "the smooth slippery surface makes it resistant to scratches and tears from sharp protrusions in the cockpit."[2]

Five-finger gloves (as opposed to mittens) had zippers along the top to permit donning and doffing. The Model 7 glove used a custom zipper that was "tedious to close," but it could have used the standard Goodyear flap zipper or a new airtight zipper developed by the Durkee Atwood Company of Minneapolis.[3] There was a neoprene diaphragm at the intersection of the glove and sleeve that allowed the suit to remain pressurized when the glove was removed. The gloves had separate ventilation and pressurization channels to provide comfort even when the suit was not pressurized.

The narrow-neck, close-fitting helmet covered the entire head and ears and was fabricated of the same material as the suit. Ventilation and pressurization of the helmet was through three flat, noncollapsible conduits that discharged air just above the ears and into the goggles. "Donuts" made of soft sponge rubber and chamois cloth protected the ears. The goggle-mask consisted of standard Navy goggles and a pressure-breathing mask integrated into a single unit.

Apparently, the initial Model 7 suit functioned primarily as a full-pressure suit. Akerman fabricated a second Model 7 that could function as a heating and cooling garment, a G-suit, a pressure-breathing ensemble, and a pressure suit, or any combination of the four as needed. The suit could also be used as an exposure garment after bailing out of an airplane.[4] The second suit included a pressure-breathing vest that covered the entire chest and abdomen. It was tested in the Mayo Clinic altitude chamber up to 53,000 feet with satisfactory physiological results, but Akerman did not describe how flexible the suit was under pressure. John B. Werlich, a former Army pilot, tested the acceleration protection of the suit on the Mayo centrifuge under the direction of Earl Wood. Werlich also tested the David Clark Model 21 G-suit at the same time as a comparison. The Strato suit provided slightly more protection than the Clark suit but was judged much more uncomfortable at 1-G, not surprising given it was much heavier and bulkier since it could also function as a pressure suit.[5]

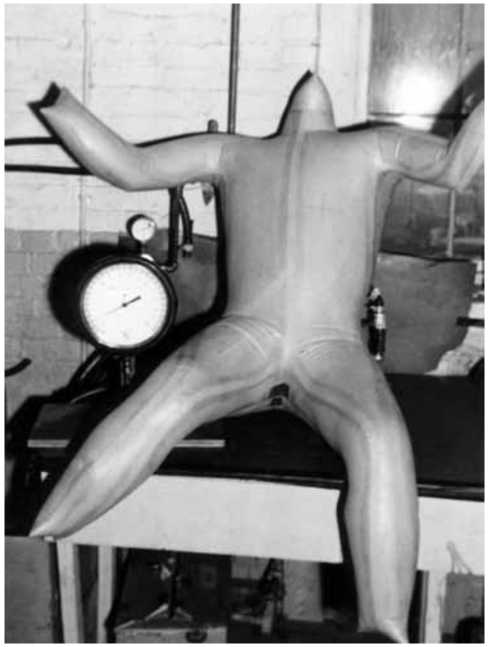
When Strato delivered the second suit to the Navy, it included a list of recommendations that primarily centered on the Navy further funding development of the suit. There were, however, a few other recommendations, such as incorporating an integral life preserver that would automatically inflate and keep the wearer at a 45-degree angle in the water.[6] There is no record that the Navy funded further development of the Strato suit, having set its sights instead on developments at the David Clark Company.

In late 1947, the Navy awarded the David Clark Company contract NOa(s)-9931 for the development of an Omni-Environment Suit for use in emergencies. It appears that, at least originally, this was a get-me-down suit (and was not meant as a primary life support system), although one that could be used for extended periods if needed. During the development effort, David Clark Company used alphabetical designators (Experiment A, B, C, etc.) for in-house experimental suits and numeric designators (Model 1, 2, 3, etc.) for suits delivered against the contract.

David Clark Company constructed the Experiment A suit primarily to determine how much pressure the selected material would withstand and how much it stretched. The designers used the pattern developed for the Henry partial-pressure suit since it had essentially the desired size and shape. The suit was sealed at the neck, wrists, and lower calves, and since nobody would wear it, it did not use a helmet, gloves, or boots. The pressure garment was stitched together using plain 0.375-inch joining seams covered by a single layer of gummed tape. The amount of stretch under pressure was measured at the chest, armpit, bottom torso, and crotch. The chest measurement, for example, increased approximately 1 inch for each psi of pressure applied until it failed at the crotch at 3 psi. David Clark determined this fabric was unacceptable due to the amount of stretch and low failure pressure.[7]

A second suit, Experiment B, was constructed on November 22, 1948, using a bladder-and-case construction technique similar to a G-suit. Neoprene-coated nylon twill bladders held the pressure, and the basket-weave nylon outer case controlled stretch. David Clark Company manufactured the bladder to enclose the entire body, except the neck and head, in a sitting position. An unusual plexiglass helmet was attached using a bayonet seal at the neck, and a compressed-air fitting was installed in the rear left waist area. Zippers on the shoulders, arms, and lower calves cinched the suit tight against the occupant.[8]

LCDR Ralph L. Christy, LT Paul C. Durup, and Dr. Kenneth E. Penrod evaluated the Experiment B suit at Worcester. Penrod was a physiologist at Boston University and a part-time consultant to David Clark Company. He would later leave Boston to become a dean at Duke University School of Medicine, largely ending his day-to-day involvement with pressure-suit development.[9] The suit was



The first of the David Clark pressure suit for the U.S. Navy was this Experiment A. Obviously, this suit was never intended for anybody to wear—it was sewn closed at the neck, hands, and feet. The designers used this suit to determine a candidate fabric's reaction to pressure.

Courtesy of the David Clark Company, Inc.

Dr. Kenneth Penrod, a consultant to David Clark Company, in the Experiment B suit. The unusual helmet showed up in several David Clark suits, as well as those from other companies. The suit allowed a fair amount of mobility, as demonstrated by Pendrod holding his bended arm to touch the side of the helmet. Note the mittens instead of fingered gloves.

Courtesy of the David Clark Company, Inc.

The Experiment B suit in the cockpit of a Vought F4U the Navy had loaned David Clark Company during July 1949. One of the major failings of the Experiment B suit, and most early pressure suits, was a lack of ventilation that caused the wearer to perspire excessively.

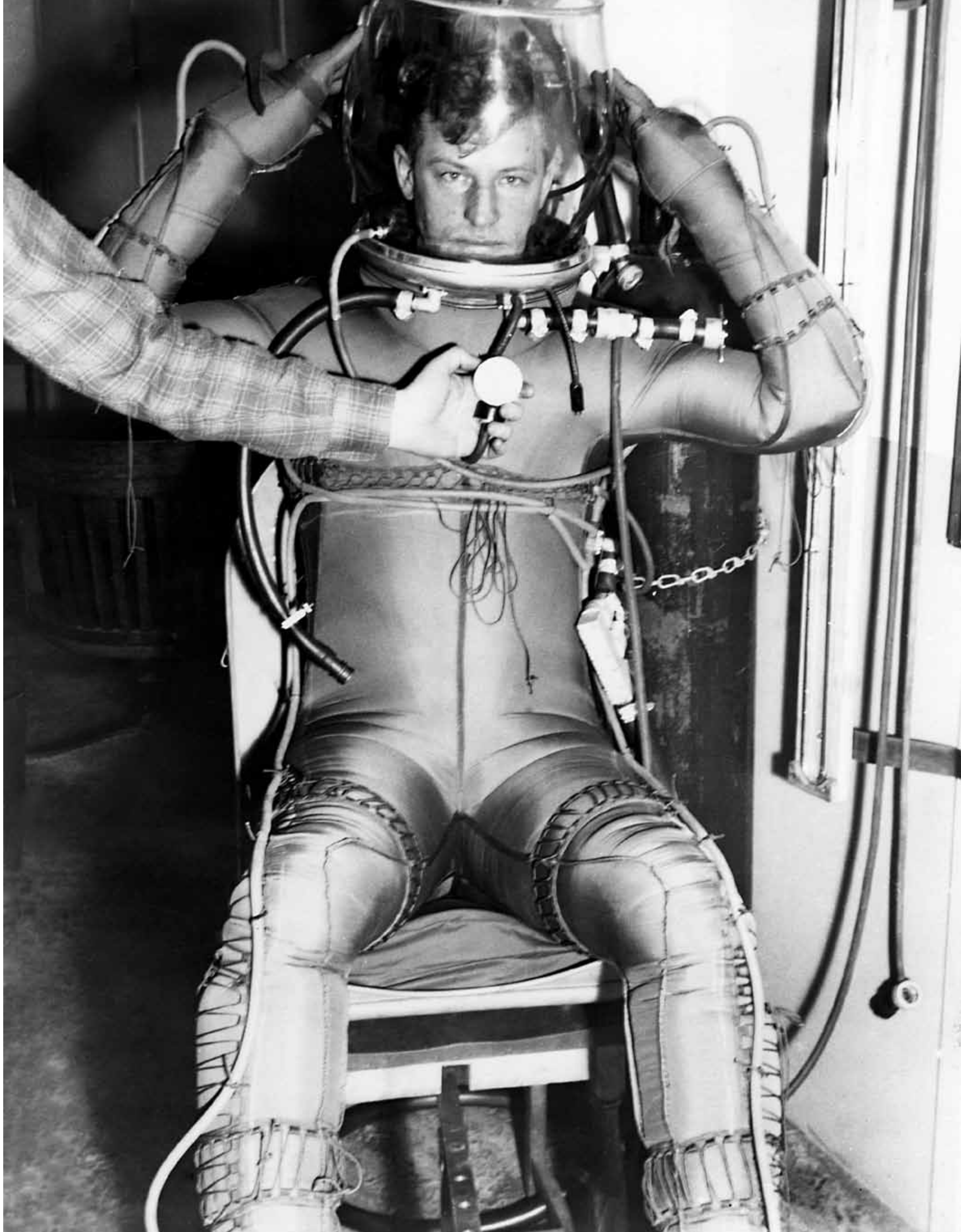
Courtesy of the David Clark Company, Inc.

As could be expected, the Model 1 was generally similar to the Experiment B suit that had preceded it. Here, Joe Ruseckas demonstrates the Model 1 during early 1949. The small-diameter tubes on the legs and wrists were a temporary method of providing some ventilation to the extremities. In general, the military was impressed with this suit, finding it a marked improvement over the wartime suits.

Courtesy of the David Clark Company, Inc.

somewhat too large for Christy and Durup, resulting in unacceptable ballooning under pressures up to 2.5 psi. Fortunately, the suit was a better fit for Penrod who was able to stand, crouch, and move his arms with the suit pressurized at 2 psi. The overall conclusion was that the garment might offer a "practical method of constructing a full-pressure suit which is light in weight, has adequate strength to withstand the required pressures, and will not excessively hamper the wearer's movements in either the deflated or inflated condition."[10] It was noted that the suit needed better ventilation to remove perspiration.

This test provided the confidence for David Clark Company to fabricate the Model 1 that was, in general, similar to Experiment B. The suit approximated the position of a seated pilot and provided limited adjustment via nylon cord lacings to better fit a variety of men. Mittens, where the thumb was separate but the four fingers were together, covered



the hands. The pilot donned the suit through a 34-inch horizontal zipper along the upper back. David Clark noted that the zipper, which his company had designed and manufactured, did not always seal correctly and would need to be modified in the future.

Ken Penrod demonstrated the Model 1 on January 26, 1949, at the NACEL. The suit was pressurized with pure oxygen to between 2 and 3 psi, but the available source was not sized properly and made it impossible to maintain a constant pressure. Overall, the demonstration was a success, although a weakness in the crotch was again evident. Penrod took the suit back to Worcester, and David Clark Company reinforced the crotch and several other seams before returning it to Philadelphia on February 2, 1949. While the suit was in Worcester, Penrod evaluated its mobility in the cockpit of a Vought F4U Corsair the Navy had provided to David Clark Company. Penrod demonstrated it was possible to move the rudder and stick controls to their extreme positions and work the throttle and toggle switches, although everybody admitted the mittens were "quite clumsy."[11] In addition, the back zipper still leaked but David Clark Company was designing a new closure. This suit was also evaluated by researchers from the USAF Aero Medical Laboratory, although it is unclear if they did so in Philadelphia or at Wright Field. The Air Force evaluators found the suit to be a marked improvement over the wartime Goodrich suits but still found it lacking when compared to the partial-pressure suits under development by the Aero Medical Laboratory and David Clark Company.[12]

The Navy and David Clark Company both agreed that it would be prudent to test the absolute strength of the suit by pressurizing it until it burst. Not wanting to sacrifice the Model 1 suit, David Clark Company constructed Experiment C for this purpose. David Clark Company sealed the neck with a circular piece of 0.125-inch-thick plexiglass that proved to be the weak point in preliminary tests, cracking at 6 psi. The designers replaced it with a 0.25-inch-thick piece and it was then possible to pressurize the dummy suit to 10 psi without rupturing it. This was very close to the bursting point, however, since an additional increase of about 0.25 psi caused the inner suit to tear at the left hip. The outer suit did not suffer any damage.[13]

Researchers concluded that the bladder ruptured because it had reached its maximum stretch before the outer case. Nevertheless, the Navy agreed that 10 psi was well beyond the nominal needs and safety factor for any suit, and no further stress testing was conducted. The tests also revealed a great deal about the behavior of the suit in general. For instance, at 1 psi the belly measured 41 inches in circumference, gradually increasing to 42 inches at 4 psi and 43.75 inches at 10 psi, a 2.75-inch increase. The top of the thigh increased from 24.875 inches circumference at 4 psi to 25.375 inches at 1 psi and 25.875 inches at 10 psi. In general, the test revealed that there was little increase in size between 1 psi and 3 psi, which was the nominal working pressure of the suit.

David Clark Company also created a new helmet with a different neck seal that made it easier to don and doff. The entire helmet was made of plexiglass with a saddle-piece base contoured to fit the shoulder. Unfortunately, the helmet could not be used with the Model 1 suit since the shoulder piece made it necessary to lower the rear entry zipper on the suit to a point that it was too difficult to get the head through the neck opening. The company also experimented with detachable limbs so that the length of the arms and legs could be changed for to individual pilots. A quick detaching airtight coupling was made of two plexiglass cuffs, one telescoping inside the other, with a rubber sealing-dam between the two cuffs. A prototype seal was constructed and appeared to work under pressure.

The company fabricated Experiment D in January 1949, building upon what had been learned. For the Model 1 suit, the pilot donned the inner and outer layers as a single unit; for Experiment D, the layers were two garments. This meant that a different method

One of the problems with all previous suits was that each of the researchers and evaluators were different sizes, meaning only a few of them could wear each suit comfortably. The Experiment D suit used a series of lace adjustments to allow some tailoring to fit various individuals. Note the normal five-fingered gloves instead of the quasi-mittens used on the earlier David Clark suits. A close examination of the helmet shows the built-in earphones. Ken Penrod is wearing the suit, with John Flagg (left) and Dave Clark (right) looking on.

Courtesy of the David Clark Company, Inc.

of securing the helmet was needed, and David Clark Company settled on a separating zipper with one half sewn around the neck of the outer garment and the other half clamped to the base of the helmet seal. A vertical front zipper that ran from the neck to the crotch replaced the horizontal back entry zipper. The zippers functioned satisfactorily under pressure, but they were problematic since the tight fit of the outer garment made it difficult to close the upper half of the front zipper, and everybody had trouble getting the separating helmet zipper to start. The designers also tried a diagonal chest zipper (like the much-later Navy Mark IV) but it appeared to offer no advantages over the vertical zipper.

The Experiment D suit attempted to cure ballooning around the feet. The leg of the outer suit extended downward over the instep, and two straps crisscrossed under the arch of the foot and were drawn tight using D-ring

John Flagg wears the Model 2 suit seated next to the F4U cockpit (extreme right) in Worcester with Ken Penrod in the background. For this suit, David Clark Company eliminated the lace adjustments and tailored the suits for each individual. Note the zippers coming down from the shoulders into the arms, across the upper chest, and vertically down to the crotch. Initial attempts at finding an effective manner to don and doff a pressure suit were elusive.

Courtesy of the David Clark Company, Inc.

buckles. This effectively prevented the suit from forcing itself away from the wearer's foot, and there was little difference in appearance in the inflated or normal condition except for a slight bulging under pressure. Normal heavy-duty, high-cut shoes were worn over the bladder suit. With this arrangement, the use of the feet was no longer impeded by oversized footwear not in direct contact with the pilot. At the time, it was believed that this satisfactorily solved the known problems connected with pressurizing the feet.

A series of lace adjustments on the shoulders, arms, and legs allowed the suit to be customized within limits. Steps were also taken to improve the hands by replacing the mittens with five-fingered gloves made of nylon basket-weave fabric. The gloves were made separate from the rest of the suit and restrained from blowing away from the hand by a thong sewn to the cuff of the sleeve and looped over the thumb. The thong was drawn tight by means of small D-rings. Two pieces of 0.125-inch-diameter wire, fastened across the palm of the hand and around the base of the thumb, kept the glove from ballooning. This arrangement made the hand more versatile, and much finer movement of the fingers was possible. Samples of handwriting taken under various pressures showed little change as the pressure increased. Despite this success, gloves continue to be an issue, even today.

The designers discovered that, because of the small volume of the plexiglass helmet, it was not necessary to wear earphones in the customary manner or to speak directly into a microphone. Therefore, the earphones were mounted on the sides of the helmet adjacent to the ears, and a small microphone was built into the base of the helmet in front, removing them from direct contact with the pilot.

Until this time, all pressure suits had been inflated via a single fitting, usually located on the left side of the waist. Experiment D broke with this tradition and used five inflation points: the normal waist fitting, plus fittings near each glove and each foot. The intent was to promote better air circulation to keep the wearer more comfortable. When Ken Penrod tested the suit with a flow rate of about 56 liters per minute, he confirmed it was generally more comfortable and there was less evidence of perspiration than with previous suits.

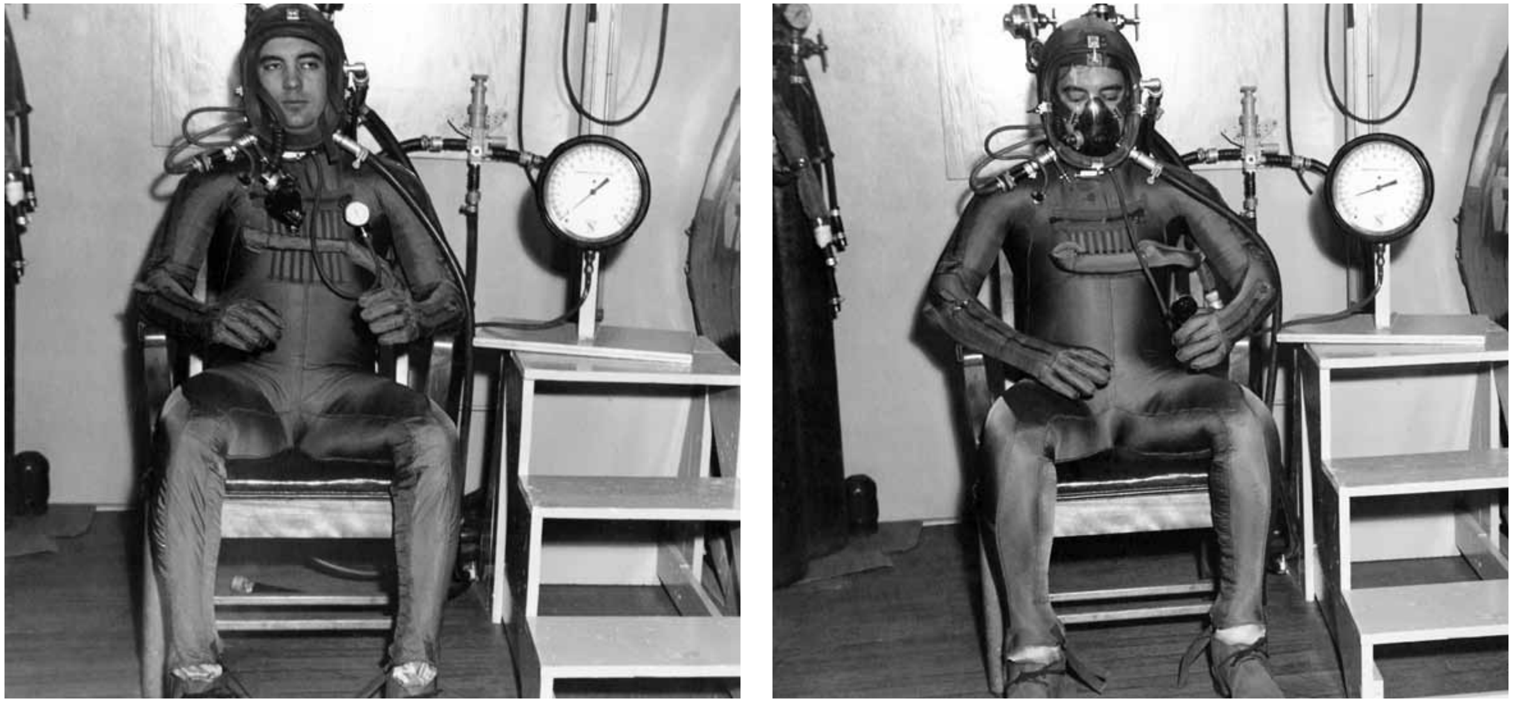
Experiment E was generally similar to D except that it returned to a horizontal back entry zipper, and the bladder suit was permanently attached to the helmet. The five-fingered gloves were also permanently attached to the bladder suit, eliminating the need for the loops over the thumbs to keep them in place. The suit was extensively tested in Worcester, frequently being worn pressurized for 2 hours at a time. After some practice, Ken Penrod could don the suit in under 30 minutes, although an assistant was required to close some of the zippers that were out of reach. Penrod used the stationary F4U cockpit to verify the mobility of the suit, and he could successfully climb into and out of the cockpit wearing the standard seat-type parachute and perform all normal piloting tasks. However, rigidity across the lower waist and groin made it difficult, and at times impossible, for Penrod to bend forward sufficiently to reach the lower parts of the instrument panel. Researchers noted the crash harness made it difficult to reach these areas even while wearing only a normal flight suit.

These experiments gave way to the Model 2, fabricated in April 1949. The David Clark Company made two suits: one to fit a man 6-feet, 2-inches tall and weighing 175 pounds, and the other to fit a man 5-feet, 9-inches tall and weighing 173 pounds. In general, these were similar to the Experiment E suit except that all lacing adjustments were eliminated and each suit was tailored for its wearer. These suits were used for extensive ventilation tests that proved generally satisfactory. In fact, on July 19, Dr. Arthur S. Iberall of the National Bureau of Standards witnessed one of these tests and requested a third suit be manufactured to fit him for further tests in his laboratory. David Clark delivered the Iberall suit on September 15, 1949.[14]

Based on tests of the Model 2 in Worcester, the NACEL requested that David Clark Company freeze the design and manufacture a single suit for LCDR Harry V. Weldon. This Model 3 included a device to resist the tendency for the shoulders and helmet to lift when the suit was pressurized. One of the major objections the Navy had to the Model 2 suit was the cylindrical plexiglass helmet, primarily because it was too

John Flagg shows the bladder of the Model 3 in March 1950. The designers uncoupled the outer restraint layer from the gas container in an attempt to increase mobility. The unusual clear-plexiglass helmet of the earlier suits gave way to a modified partial-pressure suit helmet with a face seal.

Courtesy of the David Clark Company, Inc.



Top right and left: The Model 3 was a tight-fitting suit and did not change substantially in appearance as it pressurized (photo at right). Note the capstan on the chest that pulled excess material down from the neck so that it did not get in the way of turning the head. It should be noted the capstan did not contribute to the pressurization function, as with a partial-pressure suit, but was simply used to eliminate excess fabric bunching up at the neck as the suit elongated. John Flagg is wearing the suit.

Courtesy of the David Clark Company, Inc.

large to fit in most fighter cockpits. For the Model 3, David Clark Company made a helmet using the same fabric as the suit and the inner gas-tight layer was permanently attached to the inner layer of the suit. The outer restraining layer was attached by zippers and telescoped over the neck of the lower suit, floating freely. Initial attempts to permanently attach the outer layer resulted in the head being immobilized since it was necessary to twist the tube formed by the neck. By decoupling the outer layer, a satisfactory amount of turning was possible when the suit was deflated.[15]

However, under pressure, it was only possible to rock the head back and forth and from side to side, and even this limited head mobility required a fair amount of extra material around the neck. To overcome helmet lift resulting from this excess material in the neck, David Clark Company incorporated a capstan about 9 inches long and 8 inches in circumference when fully inflated. The capstan was mounted on a curtain fastened to the bottom of the helmet face frame and to a point on the chest. When the capstan pressurized, interdigitizing tapes took up several inches of fabric to provide the required counter-pressure. The plexiglass faceplate had sufficient volume to use a normal oxygen mask. David Clark delivered the Model 3 suit to the Navy on March 8, 1950.

Although not incorporated into the Model 3 suit, David Clark Company investigated using an open-weave net fabric to counter ballooning and helmet lift. These fabrics contracted vertically, but not horizontally, as the suit inflated. It appeared the fabric might allow making the torso and limbs long enough so that a man could stand erect and move about freely when the suit was depressurized yet eliminate ballooning and the resultant discomfort and limited mobility when the suit pressurized. David Clark Company made an experimental suit from the fabric that CDR Frank S. Voris, LCDR Harry V. Weldon, and H.R. Geider evaluated at the NACEL on March 15, 1950, with generally positive results. The company also noted that the manner in which the cloth was cut was extremely important due to different stretch and contracting features in the warp, fill, and bias directions. The designers believed that, given enough experimentation, the inherent features of the material could be used to control the inflated shape of the suit.[16]

Joe Ruseckas in the Experiment H suit. This suit used the same gas container and helmet as the Model 3, but it used a knit-fabric restraint layer that was supposed to control ballooning and increase mobility. It did not work that way, but the experiments with knit fabrics continued with some successes and may have, indirectly at least, played a role in the eventual development of Link-Net.

Courtesy of the David Clark Company, Inc.

By October 1950, it was obvious to Navy Bureau of Aeronautics (BuAer), David Clark Company, and the NACEL that the open-weave fabric should be used for the entire outer garment of a full-pressure suit. To this end, experimental suits were made to test various aspects of the material. The Experiment F suit used a bladder and helmet identical to the Model 3 with an outer layer of open-weave net fabric. Several different fabrics were used on various parts of the suits to determine which was best. The lessons learned from this suit were incorporated into Experiment G. However, the position the suit assumed when pressurized was not satisfactory—the legs were too wide spread and the arms were not close enough to the torso. Further experiments using this suit convinced David Clark that the net fabrics would not provide a satisfactory answer for controlling torso length although the open-weave fabric limited ballooning and increased comfort for all other areas of the suit.[17]

For the torso, designers were unable to reconcile standing up comfortably while unpressurized and sitting in the conventional flying position at 3 psi without excessive ballooning. The extra length of the front and sides of the torso, required for standing erect, was too

John Flagg shows the "hole in the top" helmet used on the Experiment K suit. This innovation largely solved the issue of helmet rise upon pressurization. Unfortunately, this left the top of the head unprotected and researchers worried this might lead to unknown, and undesirable, physiological problems.

Courtesy of the David Clark Company, Inc.

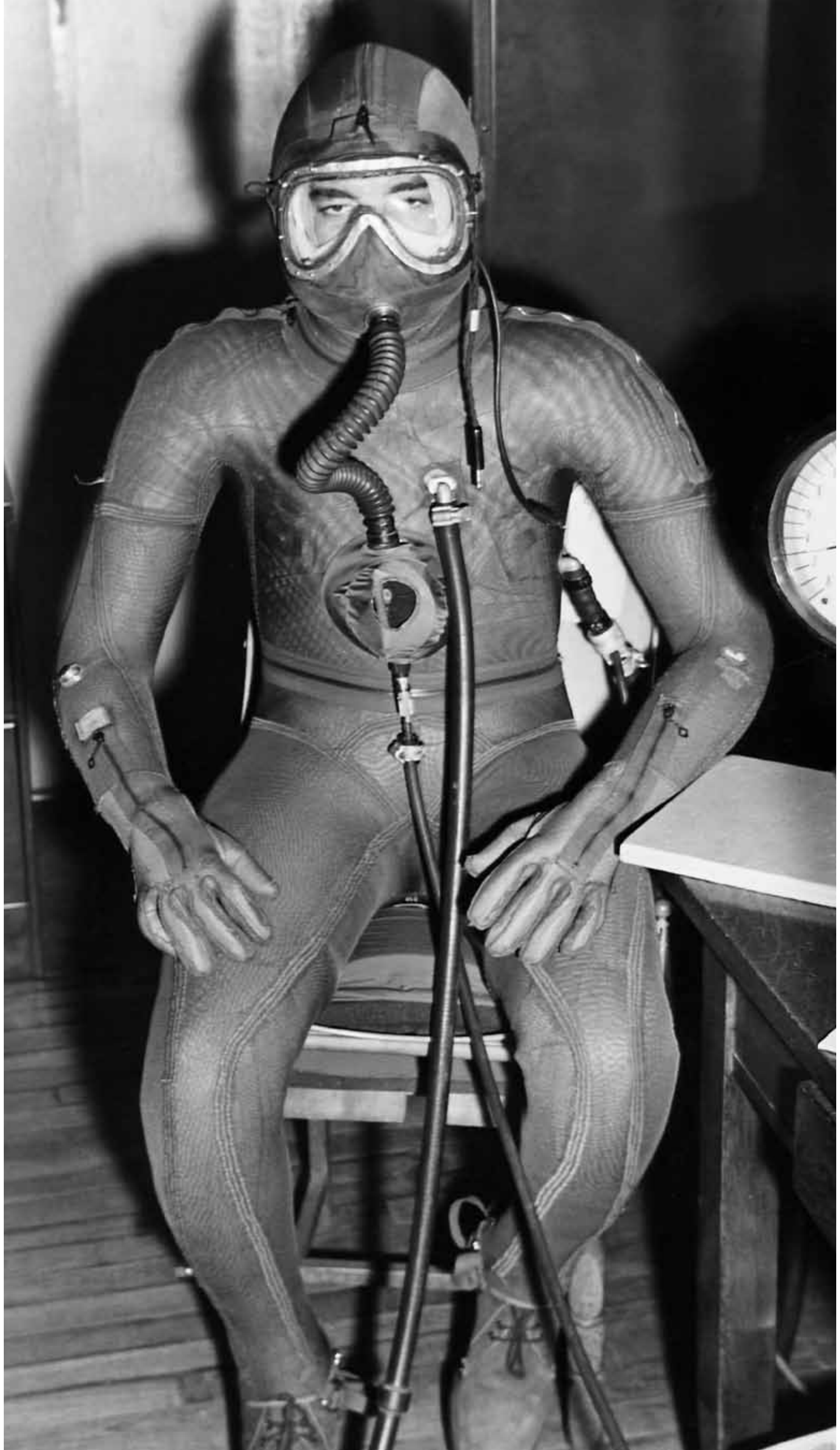
great to be compensate for the contraction of the fabric that occurred when sitting. Several attempts were made to solve this dilemma. The first involved using a vest-like garment with a separate zipper at the crotch that was fastened after sitting down and this effectively kept the torso from elongating (ballooning). A more satisfactory answer incorporated a gusset that used a horizontal zipper across the lower front of the restraining layer. This zipper was open while standing erect and had to be closed before the suit could be inflated. Experiments continued to find a better solution.

A different fabric was used for Experiment H, which again used the same bladder and helmet design as the Model 3. The outer net fabric was finished in such a way as to make it stiff—an attempt to minimize the "slipping" characteristic (the knots of the fabric moving along the threads) of net fabrics and to provide greater strength at the seams. The small gains in these areas were offset by the stiffness, which hindered mobility.

Experiment J returned to the same open weave fabric used on the F and G suits with different sewing techniques. The earlier suits had shown the material was not strong enough to control the torso while pressurized due to the amount of slipping in the fabric and inadequate tensile strength. After considerable experimentation, designers found that cutting two sets of patterns on opposite biases improved the strength of the fabric considerably. Combined with innovative seam stitching, this appeared to offer a solution and initial tests indicated the concept might work.[18] Although not directly related to the later development of Link-Net, it is possible these experiments with open-weave net fabrics planted some seed of an idea into David Clark's mind.

Having largely solved the restraining layer issues, Experiment K returned to the issue of the helmet lifting off the head when pressurized. All previous methods used to hold the helmet down had worked to varying degrees when the suit was unpressurized, but all had eliminated mobility when the suit was pressurized due to tubular rigidity in the neck section and the relatively weak neck muscles. For Experiment K, the fabric helmet had a "hole in the top" that eliminated lift and allowed the head to tilt forward, backward, and to either side. The helmet was built by molding a plexiglass hat band around the subject's head, lining the inner circumference with 0.25-inch-thick sponge rubber, and cementing a sheet of rubber over the sponge that extended about an inch below the bottom of the hatband. A fabric helmet with a plexiglass faceplate was fastened to the outside of the band.

Zippered plackets (slits) permitted the helmet to open to a sufficient size to allow the head to pass through while donning. When inflated, a seal was affected by pressure forcing the



The Model 4A was perhaps the first truly workable David Clark suit. This is John Flagg wearing the suit in January 1951. Note that the gloves are an integral part of the suit, although the long zippers up the forearms eased the problem of donning the tight-fitting garment. Like many of the previous suits, the Model 4A used a soft helmet.

Courtesy of the David Clark Company, Inc.

rubber flap against the head. The rubber flap seal was prevented from being distorted by the snug-fitting, rigid hatband. Tests showed that the suit could be inflated to 2 psi with "remarkably good head mobility" and no helmet lift.[19] The reason was that the head "plugged" the hole in the helmet, and the pressure within the suit, being greater than ambient, forced the head into the hole. Theoretically, researchers believed that given sufficient pressure the entire body could be squeezed through the hole—not a particularly pleasant thought.

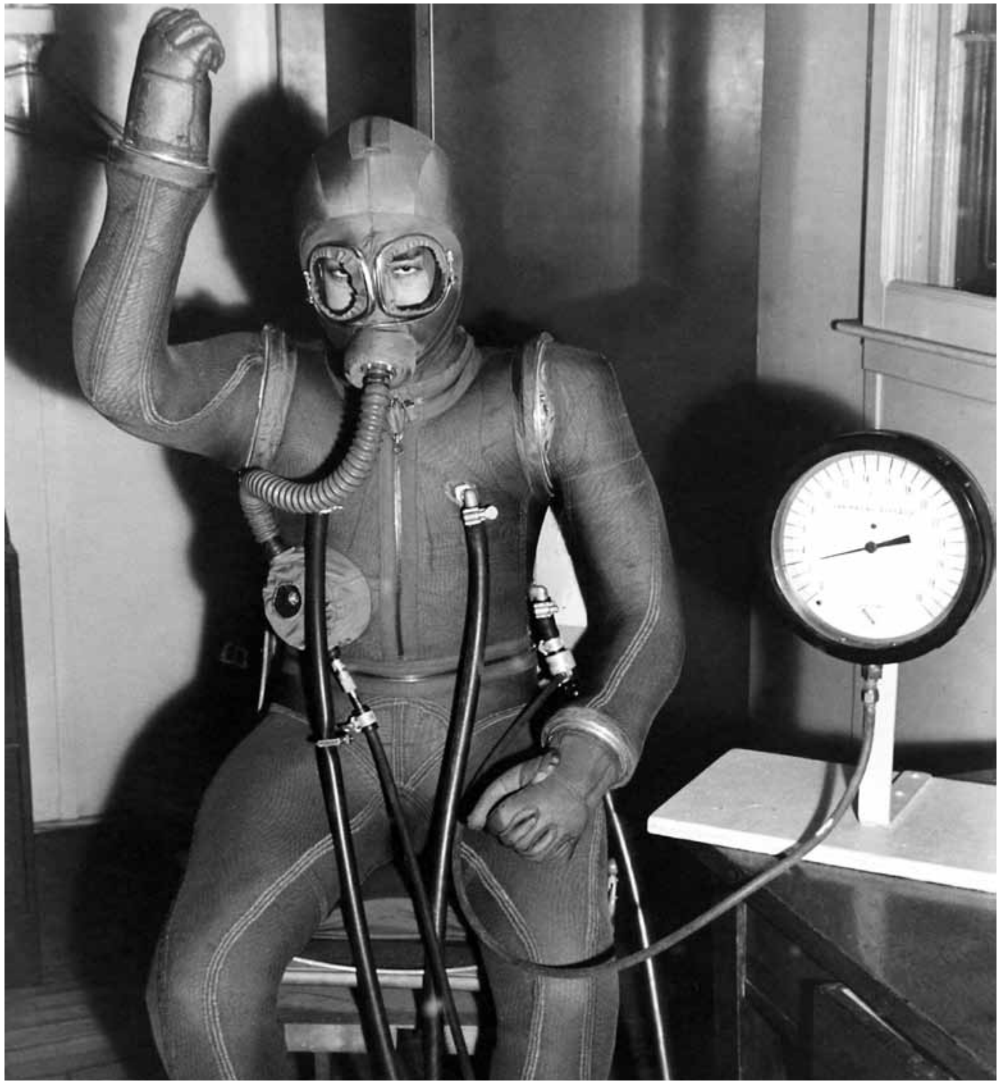
However, given the relatively low pressures used in the suit, the weight of the body, which in effect was being suspended by the top of the head, was enough to hold the helmet down. There was sufficient friction between the seal and the head to prevent the hatband from slipping off the head. It was a completely different answer to the problem. Despite the gains in mobility, neither David Clark nor the Navy continued this line of experimentation since the top of the head was unprotected (exposed to ambient atmosphere), and this might lead to unknown, and undesirable, physiological complications.

These experimental suits resulted in the Model 4 suit that was delivered to the Navy in September 1950. This suit used an outer restraining layer of open-weave nylon net fabric that allowed significant movement while unpressurized yet assumed the flying position when pressurized. The snug, lightweight fabric helmet allowed the pilot to wear a standard flying helmet over it for bump and crash protection. The helmet integrated a goggle-mask that sealed around the face, isolating this area from the rest of the suit. Unlike the Model 3, no external accessory straps were needed to combat helmet lift.

Initial tests at the NACEL were promising, and the Navy requested a second suit sized to fit Harry Weldon. While the suit was being fabricated, David Clark Company incorporated minor modifications to the respiratory system and added special fittings at the request of the laboratory, resulting in the Model 4A. In addition to various unpressurized evaluations, Weldon used the suit in a Link Trainer while inflated to 3 psi. Overall, Weldon thought the suit was workable, but he offered several suggestions to improve the visibility, arm mobility, finger movement, and ventilation.[20]

By the beginning of 1951, the Navy was increasingly talking about using a full-pressure suit for an extended period, perhaps as the only life-support system in the aircraft. Officially, the garments were still considered "emergency suits," but the definition of emergency now extended past simply getting the aircraft to a lower altitude; it now included completing the assigned mission. These were what the USAF called "mission completion" suits instead of "get-me-down" garments. As such, the suits required greatly improved comfort and mobility.[21]

There were avenues available to solve the mobility issues. In fact, the Germans and the Americans with some World War II era suits had already tried them: mechanical joints. The first location where David Clark used a mechanical joint was the shoulder. In all previous suits, the rotating action of the shoulder had been restricted, limiting arm mobility, particularly that required to reach up and pull the face curtain that activated many early Navy ejection seats. The answer was to install a thrust-type ball-bearing ring, with the arm of the suit connected to one race and the shoulder to the other. Since the company was unable to locate a suitable source for an airtight bearing, David Clark Company improvised by stretching the suit fabric over a non-airtight bearing. The Experiment L suit, which was otherwise similar to the Model 4, had ball-bearing shoulder and wrist joints on one side to allow a comparison with the fabric joints on the other side. The mechanical joints greatly improved the turning action of the hand and made it possible to rotate the arm fully. A further advantage was that each degree of rotation was neutral. Once the arm or hand was turned to a certain position, no additional effort was required to hold it in that position (unlike the normal suit, that always



The Experiment M suit, with the irreplaceable John Flagg inside, introduced metal bearings at both shoulders. The wrist bearings were substantially smaller than those introduced on the Experiment L suit. The bearings increased mobility, at least at the joints on which they were used, and only in a single axis, at a considerable increase in fabrication complexity.

Courtesy of the David Clark Company, Inc.

wanted to return to its premade position). The Experiment L suit also used a new lighter weight material for the bladder. The designers hoped that the lighter material would improve mobility, but it was easily damaged and provided only minimal relief.[22]

Based on the apparent success of the ball bearing joints, Experiment M included bearings at both shoulders and wrists. The wrist bearings were substantially smaller than the ones used in the earlier suit and allowed a more natural use of the hands. A deliverable suit, Model 5, was fabricated to fit Harry Weldon, who tested it in the back seat of a Lockheed TO2 Shooting Star jet trainer.[23] Weldon used the pressure suit at 1 psi for 20 minutes in the first flight and at 2 psi for 15 minutes in a second flight. The duration of the tests was not limited by the function of the suit but by the limited supply of oxygen aboard the trainer. Weldon reported that flying the airplane with the suit unpressurized presented no difficulties, and the movements required at 1 psi were possible without too

The Model 5 suit on January 31, 1951. One of the issues with Navy aircraft, in particular, is that naval ejection seats used pulling a face curtain down as the means of initiating an ejection. The handles the pilot used to grab the face curtain can be seen just behind the top of the helmet. Grabbing these handles required the pilot be able to move his arms up and back—a motion most early pressure suits did not allow while pressurized. This was less of an issue with Air Force ejection seats since they used handles between the legs or on the sides of the seats to initiate the ejection.

Courtesy of the David Clark Company, Inc.

much effort. However, at 2 psi, and the few minutes spent at 3 psi on the second flight, considerable effort was required to keep his right hand on the control stick. This was mostly because the type of test aircraft had not been known when the suit was made, and the neutral position for the arm did not align with the control stick. Although it was easy enough to correct the problem by revising the pattern for the suit, this presented a potential problem: If suits had to be made for each pilot for each type of aircraft he might fly, the number of suits could quickly get out of control.[24]

Weldon also complained that the mobility of his head was very limited, a known issue with all pressure suits. Weldon returned the Model 5 to David Clark Company with a request to improve head mobility. The designers decided to use the same ball-bearing concept on the neck as they had on the shoulders and wrist. This modification allowed the wearer to turn the head 52 degrees to each

The delivery of three Model 6 suits satisfied David Clark Company's obligation under its original Navy contract. The waffle-weave fabric used for the restraint layer was the culmination of the research on knit fabrics dating back to the Experiment H suit. In this January 1951 photo, John Flagg is demonstrating the flexibility of the suit while it was unpressurized.

Courtesy of the David Clark Company, Inc.

side while unpressurized, 47 degrees at 1 psi, 37 degrees at 2 psi, and 33 degrees at 3 psi. This was a substantial improvement but did not completely solve the problem. Since it was still difficult to nod the head up and down, David Clark Company continued to work on improved bearings, a better method of attaching the fabric, and reducing the amount of excess fabric necessary to accommodate the rotation of the bearing.

Although metal bearings satisfactorily solved the mobility issue for the shoulders and wrists, the elbows and knees did not lend themselves to that solution. Instead, designers turned to innovative fabric joints, some based on the lines of nonextension explained by Arthur S. Iberall. During the development effort, David Clark Company fabricated 25 different joints to test ideas. In the first experiments, the designers started out making the joint as simple as possible to provide a natural bending plane at the elbow. David Clark Company accomplished this by tying bands across the inside of the joint and integrating pieces of material to make creases. However, it immediately became obvious that breaking the wall force on the inner side, toward which the joint was bending, only solved part of the problem. It was also necessary to provide a means to lengthen the outer side. This can be readily observed by looking at one's own elbow. With the arm straight, there is loose skin over the elbow bone. As the arm is bent, this is taken up until it is tight with the arm fully bent. As the joint is bent, the outside becomes longer and the inside shortens.

The designers at David Clark Company also experimented with bellows, or convoluted joints, much like the Project MX-117 "tomato worm" suits developed by Goodrich. These joints consisted of a tube tied with cords at intervals, forming a series of convolutions.

While all the joints were bendable, there did not appear to be sufficient improvement to warrant their use. The obvious limitation to their greater ease of bending was that it was necessary to compress each of the convolutions on the inner side of the bend. A variation of the bellows joint used V-shaped convolutions that only encountered each other when fully compressed. This, however, pointed out a fallacy, or at least a limitation, with the rigid bellows joint—namely that there is a considerable resistance to bending because the circumference at the top of the joint is greater than at the bottom. When the joint is bent, these must equalize, requiring, in extreme cases, considerable effort. To overcome this, David Clark Company worked on a series of many-sided joints resembling a concertina, which demonstrated good flexibility but had a great deal of complexity and was difficult to manufacture.

While the convoluted joint proved disappointing, it gave the designers at David Clark Company another idea. By using a special nylon waffle-weave fabric, cutting it on a particular bias, and compressing and sewing it in a specific pattern, it was possible to create a cloth bellows joint that was lightweight, comfortable to wear, and reasonably simple to manufacture. Tests showed that the cloth bellows offered minimal resistance to bending at up to 5 psi, considerably better than previous efforts.[25]

The Experiment N suit used cloth elbow and knee bellows joints on one side only, along with the now standard shoulder and wrist rings. In a substantial change, the entire outer layer of the suit was sewn from the same nylon waffle-weave fabric as the bellows joints. During tests in Worcester, these joints permitted extremely easy bending while pressurized at 3 psi.

Experiment P concentrated on improving the mobility of the head, and it returned to a dome helmet instead of the fabric helmet and faceplate. In this case, instead of a rigid plexiglass dome, David Clark Company constructed a dome made of rubberized fabric and flexible transparent plastic—essentially, it was a plastic bag placed over the head. A standard flying helmet could be worn inside the dome, there was no need to individually fit the domes to each pilot, it was easy to store, and it was not subject to breakage. Although a seemingly ideal solution, the head bag did not catch on.

David Clark Company delivered three Model 6 suits that were generally similar to Experiment N, all sized for Harry Weldon, to the NACEL. The inner gas-retaining bladder was made of neoprene-coated nylon fabric, and the outer layer used nylon waffle-weave fabric. Fabric bellows joints were used at the elbows and knees, and ball bearing joints were used at the neck, shoulders, and wrists. The shoulder joints used new stainless-steel radial bearings that were much easier to turn than previous units.

The delivery of the 3 Model 6 suits fulfilled the requirements of the original contract to deliver 10 prototype pressure suits. David Clark believed that the Model 6 was a workable pressure suit and could serve as a prototype for production units. The Navy concurred that David Clark Company had fulfilled its obligations under its initial contract and, on August 1, 1951, awarded the company a new contract—NOa(s)-51-532c—for continued work.[26] The contract requirements called for an omni-environmental suit that operated at 3.4 psi and had a leakage rate of less than 5 liters per minute. Almost immediately after the contract was issued, the need for a full-pressure suit became more urgent, primarily to support the Douglas D558 research airplane program and the Department of Defense afforded the development effort an "A" priority.[27]

The Douglas D558 program was the Navy's 3-phase answer to the USAF rocket-powered X-Planes. Like the Air Force efforts, the D558 program was a cooperative effort with the National Advisory Committee for Aeronautics (NACA). The phase one airplane, designated D558-1 Skystreak, was a jet-powered, straight-wing airplane intended to study the high-transonic flight regime, an area largely ignored by the Air Force effort

The first suit that David Clark Company delivered under their second Navy contract was the Model 7 for the Douglas D558 program. The suit used metal shoulder and wrist bearings, as well as convoluted bellows for the elbows and knees. The designers fabricated the restraint layer from a knitted waffle-weave fabric that offered a fair amount of flexibility while keeping ballooning and elongation to a minimum.

Courtesy of the David Clark Company, Inc.

The Model 7 does not look out of place, even 60 years after it was first used. The knit fabric restraint layer was rather delicate, so an outer layer was worn to protect it from snagging on parts of an airplane. A standard crash helmet was worn over the fabric pressure suit helmet to protect the pilot's head. Note the NACA wings on the helmet.

Courtesy of the David Clark Company, Inc.

Although outwardly resembling the Model 6, the Model 7 suit had the gas bladder and restraint layer sewn together into a single-piece garment. This photo shows the flexibility provided at the normal 3-psi inflation; note the bent arm and raised leg.

Courtesy of the David Clark Company, Inc.

but highly prized by the NACA. The three D558-1 airplanes eventually completed 230 flights and set the last subsonic speed record. The phase two airplanes, designated D558-2 Skyrocket, were unique in the research airplane program since they included jet and rocket propulsion. The jet engine was useful for taking off from the ground, but was eventually removed and the D558-2s were carried aloft under the NACA P2B-1S (B-29) carrier aircraft, much like their Air Force counterparts. The three Skyrockets flew 313 times and became the first aircraft to exceed Mach 2.

The first suit constructed under the new David Clark Company contract was a significant departure from previous efforts. Except for the Model 1, which had connected the bladder and restraint layer together into a single garment, all of the suits made on the earlier development contract had been two-piece designs consisting of separate bladders and outer restraining covers. This concept had presented several issues, most significantly making it difficult, and time consuming, to don the suit. The Model 7 was a single-piece suit that combined the bladder and restraining suits into a single garment by cementing 0.020-inch-thick rubber sheet to the inside of the white nylon waffle-weave fabric used as the outer layer of the Model 6 suit.[28] This was one of the first suits that Joe Ruseckas worked on, "banging metal" for the faceplate. Ruseckas would later become the head of research and development for David Clark Company.

This suit used the same neck, shoulder, and wrist bearings as the Model 6 suit, but it had molded, corrugated rubber sections at the knee and elbow joints. The garment completely enclosed the feet, and insulated boots were worn over the pressure suit. Originally, the rubber sheet was the innermost layer, but the friction of the rubber against skin made the suit difficult to don, so a thin layer of cloth was glued to the inside. The Eclipse-Pioneer Division of the Bendix Aviation Corporation manufactured the pressurizing regulator and the Firewel Corporation of Buffalo, NY, provided the breathing regulator. Tests in Worcester showed the suit was comfortable and allowed easy bending at the knees and elbows at 3 psi.[29]

The Model 7 holds a minor distinction: it was the first full-pressure suit that Albert Scott Crossfield wore. Crossfield was an engineer and NACA test pilot who would eventually accumulate more flight time in the rocket planes than any other individual, and he became a major influence in the development of the ultimate X-plane. Already a legend, in late 1951, Crossfield arrived, unannounced, at the NACEL seeking a suit that was better than the partial-pressure suit he had been using at Edwards. Harry Weldon showed him the Model 7 as "the most advanced thing

The innovative fabric joints, some based on the lines of nonextension explained by Arthur S. Iberall, allowed the Model 7 to offer an acceptable amount of flexibility even when overpressurized to 4 psi. Despite the advances, the neck of the suit was still unacceptably stiff, and the metal shoulder bearings caused pain in the armpits. Nevertheless, the suit was deemed acceptable for the D558 flight tests.

Courtesy of the David Clark Company, Inc.

Seeking a more realistic test environment for pressure suits, engineers at Douglas Aircraft installed the cockpit from the prototype XF4D Skyray in a large altitude chamber at the El Segundo, CA, facility. The David Clark Model 7 was among the first pressure suits evaluated in the test rig, which was representative of, but not identical to, the D558 research airplane.

Courtesy of the David Clark Company, Inc.

we have."[30] Although it could never happen today, Crossfield convinced Weldon to let him try it in the altitude chamber, reaching 90,000 feet. Crossfield was impressed, feeling the suit was far superior to the partial-pressure suit he was used to. Nevertheless, he felt it could be improved upon. As it turned out, this was the first time the Model 7 had been tested in extreme conditions, something Weldon had apparently neglected to mention to Crossfield. It was the beginning, as they say, of a beautiful friendship, with Crossfield and Weldon remaining in touch through the years.

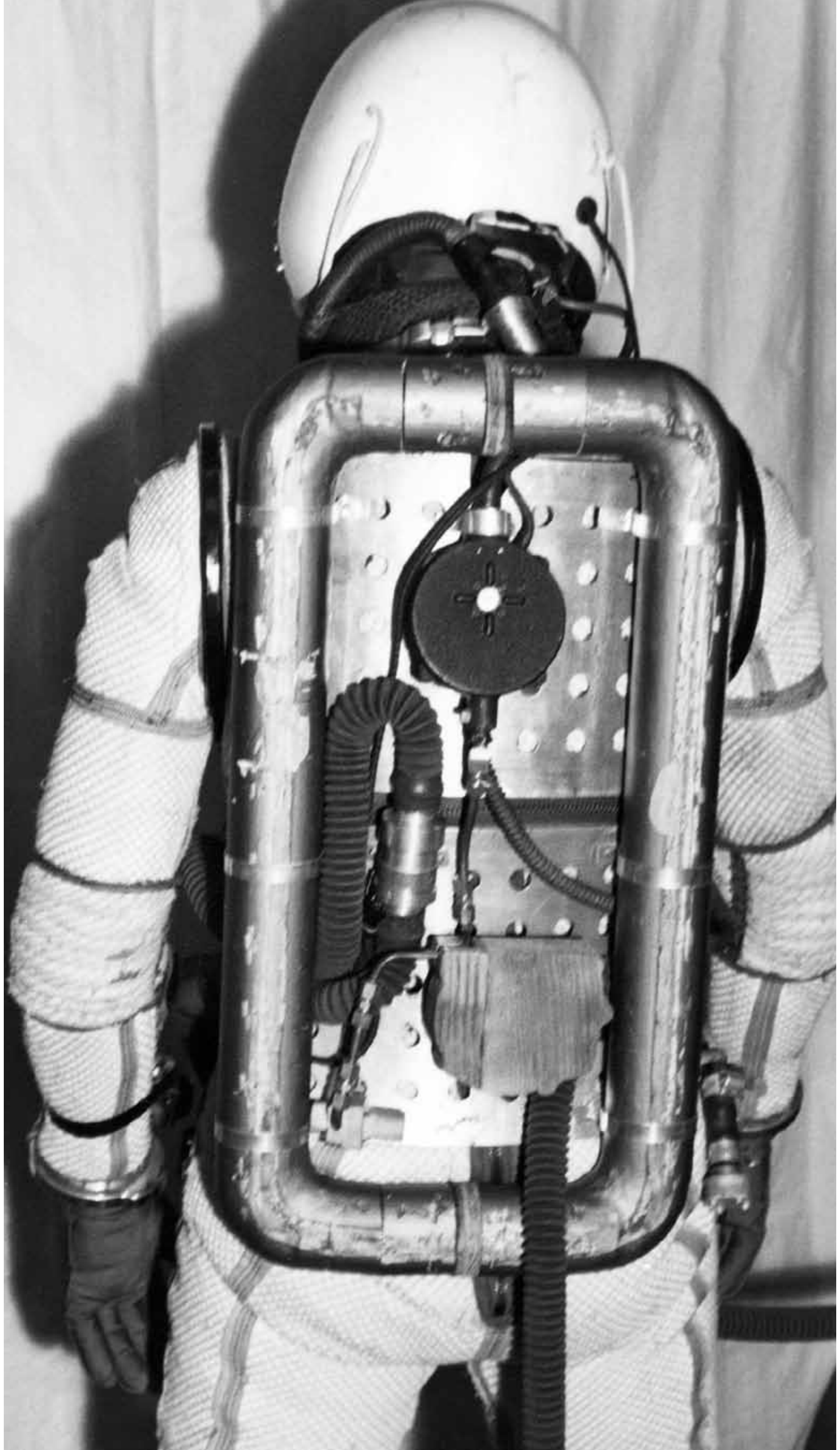
Harry Weldon finally tested the Model 7 on November 12, 1951, at the NACEL. It took the Weldon 15 minutes to don the suit with the help of one assistant. The suit was pressurized to 4 psi for 1 hour, and Weldon reported that the shoulder bearings moved slightly outward under pressure, causing discomfort in the armpit. Knee and elbow bending were good, but neck mobility (turning) was poor. Shoulder rotation was adequate. Most

This photo provides an overall view of the Douglas altitude chamber. The circle on the floor represents the size of the altitude chamber; the cylindrical object at the top lowered to seal with the floor. The XF4D cockpit is sitting inside the chamber. Note that censors scratched out the image of the individual wearing the pressure suit seated in the cockpit because the suit was classified at the time. Scott Crossfield is on the extreme right with John Flagg and Joe Ruseckas behind him.

Courtesy of the David Clark Company, Inc.

importantly, there was no ballooning, elongation, or lift, even at the higher pressure, and ventilation was adequate. A test on November 15 determined the maximum pressure the suit would withstand; the pressure-sealing zipper failed at 7.75 psi, although it resulted in a slow leak, and the suit remained pressurized but required more air volume than before.[31]

By December 1951, the Navy and David Clark Company had tested the suit in flight and in altitude chambers up to 90,000 feet. However, it had not been through a rapid decompression of the type that most worried the designers of the D558-2. Researchers wanted to conduct the test in an actual cockpit to determine if the pilot could still operate the necessary controls during the decompression. The only facility that could conduct this type of test was the Douglas Aircraft plant in El Segundo, CA. Douglas engineers cut the cockpit section out of the prototype XF4D Skyray and installed it in a large altitude chamber. The cockpit could be pressurized while in the chamber, presenting a realistic surrogate to flying in a real airplane. The altitude chamber, 11 feet in diameter and 7 feet high, consisted of a floor and a large cylindrical section with a domed top that hydraulic cylinders could raise and lower to create an airtight enclosure. The chamber could be heated or cooled as needed and was capable of simulating altitudes up to 80,000 feet.[32]



The Model 7 suit controller was mounted in the back kit. The cylindrical ring around the outside of the back kit held emergency oxygen in case the pilot had to leave the aircraft at altitude. Developing a satisfactory suit controller was a major challenge during the 1950s.

Courtesy of the David Clark Company, Inc.

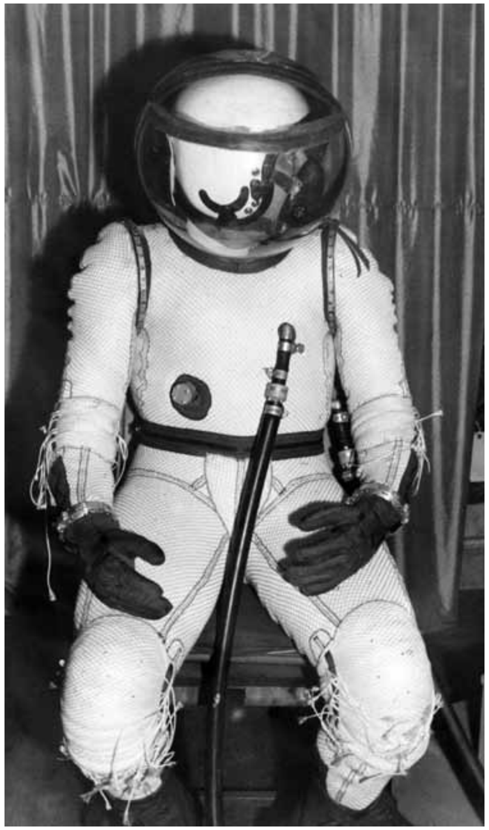
For the test, researchers used a Model 7 suit along with an improved Eclipse-Pioneer suit controller and a chest-mounted compensated breathing regulator designed by the Naval Aero Medical Equipment Laboratory (instead of the original Firewel unit). The first test put the unoccupied suit, pressurized to 3.4 psi, in the XF4D cockpit mostly to evaluate the test setup at altitudes up to 35,000 feet. The second test used an unoccupied suit during an explosive decompression. No damage to the suit was noted, so Harry Weldon participated in numerous rapid decompressions at altitudes between 24,000 and 67,000 feet. At the highest altitude, the decompression took 2.67 seconds. In each case, the suit automatically inflated, maintaining an equivalent altitude of 35,000 feet, and Weldon suffered

The Model 11 was another attempt to find a better solution for the helmet, this time using a flexible dome that was smaller than the Model 8 rigid dome. Regardless, the dome needed to be large since a standard flying helmet was worn underneath it. John Flagg is wearing the suit.

Courtesy of the David Clark Company, Inc.

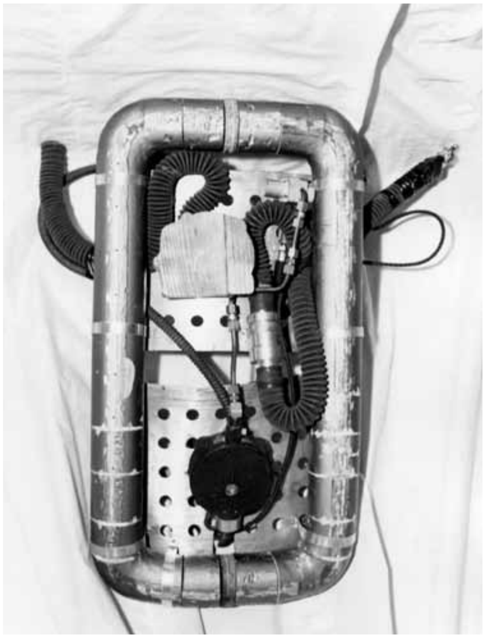
Above: Marine Corps Lt. Col. Marion Carl donning his Model 7 pressure suit inside a Boeing P2B-1S carrier aircraft on August 21, 1953. Carl would subsequently climb into the D558-2 and set an unofficial altitude record of 83,235 feet. Joe Ruseckas, behind Carl, was frequently onboard the P2B to assist the research pilots with donning their suits.

U. S. Navy photo. National Archives College Park Collection via Stan Piet



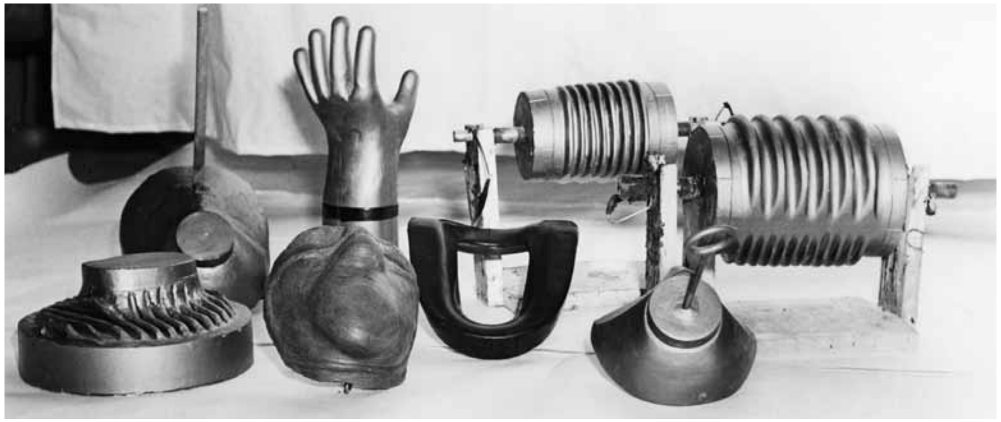
Above: The Model 8 was mostly a minor evolution of the Model 7, but included a large dome helmet that greatly improved comfort and allowed a much better range of head motion. Unfortunately, the plexiglass dome was too large to fit into most fighter cockpits and was soon abandoned.

Courtesy of the David Clark Company, Inc.



The Model 11 back kit was also an evolutionary improvement over the one used on the Model 7. Emergency oxygen was still carried in the outer frame, with the suit controller and breathing regulator in the center area. A standard parachute was worn over the back kit.

Courtesy of the David Clark Company, Inc.



Some of the molds used to make the rubber parts of the gas bladder for the Models 11 and 12 full-pressure suits. At the rear is a hand mold for the gloves, and to its right are the elbow and knee bellow molds.

Courtesy of the David Clark Company, Inc.

The Model 12 returned to a normal soft helmet, although this one included an integral set of goggles that were hinged at the top and could be opened when the suit was not pressurized. This is the suit with the protective outer cover installed. Note the pilot is wearing normal dress shoes.

Courtesy of the David Clark Company, Inc.

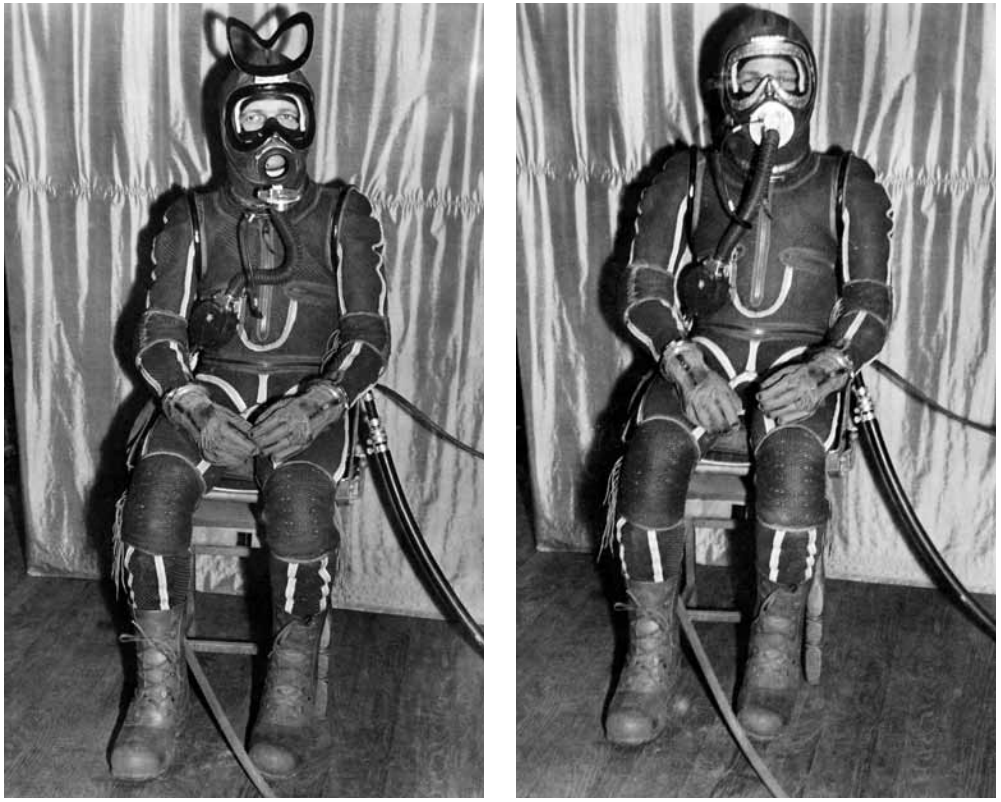
no ill effects and felt he was quite capable of piloting the airplane.[33]

After this, five rapid-decompression and four explosive-decompression tests were run at various altitudes up to 65,000 feet with Richard J. McGowan, Jr., of the NACEL in the cockpit. Each event took between 0.75 and 1.84 seconds to completely depressurize. At no point during these tests did the suit pressure drop below the specified 3.4 psi, and the relative gas expansions of the subject were well within safe limits. During the decompressions, McGowan reported feeling a small amount of air escape from his lungs, a momentary feeling of pressure as the suit stiffened, and, in a few cases, a brief feeling of dizziness.[34]

The Navy did not intend these tests to evaluate the comfort or mobility of the suit. However, both Weldon and McGowan reported that the suit was comfortable and sufficiently flexible when unpressurized. They also reported that the suit was sufficiently comfortable when pressurized except around the oral-nasal mask seal. Weldon wore the suit continuously for 3 hours and underwent three rapid decompressions without undue fatigue. The suit did restrict mobility when pressurized, especially around the neck, but it appeared to be possible to fly the airplane. Nevertheless, the Navy researchers felt that the suit was unsuitable for operational use, although it was adequate for use in experimental research airplanes such as the D558.[35]

Almost concurrently with the Model 7, David Clark Company constructed the Model 8, which used a bladder made of fabric rubberized on only one side along with the restraining layer made of nylon waffle-weave fabric. The two layers were made from the same pattern and joined together so they could be donned as a single garment. This suit included a new type of dome head enclosure consisting of a hard plastic front section with clear soft plastic portions in the rear quarters and upper forward portion. A standard flying helmet and oxygen mask were worn inside the dome, with a rubber neck seal to isolate the dome section from the rest of the suit. The new head enclosure offered almost unlimited visibility but was extremely large and did not fit inside the cockpits of most contemporary fighters.[36]

The Model 9 and Model 10 suits were essentially similar to the Model 7 using different fabrics (a waffle-weave Dacron for the Model 9 and rubberized nylon tricot for Model 10). Both suits were sized to fit Weldon and were delivered to the NACEL in December 1951. The Model 11 was similar to the Model 8, with a flexible dome head enclosure, but it had a better overall fit and was easier to don. It featured one-piece construction, with a lightweight fabric rubberized on one side only (uncoated fabric toward the body) and nylon waffle-weave, seamed together. The waffle-weave cloth provided the necessary strength and tended to prevent elongation; the rubberized fabric of the gas-retention bladder was stretchable. The dome head enclosure was similar to the Model 8 and featured a rigid plexiglass front portion. It also used a soft flexible transparent plastic on the forward portion of the top and the rear quarters for upward and peripheral vision. A rubber neck seal isolated the dome from the rest of the suit. Donning



Like many of the early David Clark suits, the Model 12 was a tight-fitting garment with little visible difference between its unpressurized (left) and pressurized (right) appearance. A variety of zippers made the Model 12 easier to don, and more zippers provided limited size adjustments, although the suit was specifically tailored to fit Scott Crossfield. The metal shoulder and wrist bearings are visible, as are the elbow- and knee bellows joints.

Courtesy of the David Clark Company, Inc.

occurred through a 42-inch pressure zipper extending vertically from the lower back to the head enclosure. Ball-bearing joints were used at the neck, shoulders, and wrists, with fabric knee and elbow bellows as in the Model 7.[37]

Crossfield's quest became official shortly after his visit to Philadelphia. On August 13, 1951, Ira H. Abbott, the NACA assistant director for research, wrote to Maj. Gen. Frederick R. Dent, Jr., the commander of the Wright Air Development Center (WADC). Abbott requested the Air Force provide a full-pressure suit for Crossfield's flights in the D558-2, as well as the Bell X-2 and Douglas X-3. However, at this point, the USAF was still pursuing partial-pressure suits and did not have a full-pressure suit it could supply to Crossfield.

This did not deter Crossfield, and he traveled to Worcester to meet David Clark. Scott Crossfield described Clark as "a stocky man of about fifty-five, with bushy eyebrows and delicate hands which, like his mind, seemed to always be in high-speed motion."[38] Crossfield left with yet another new friend. When he got back to Edwards, Crossfield wrote a letter to NACA headquarters in Washington recommending that the NACA encourage the Navy effort with David Clark.

On October 23, 1951, John W. Crowley, the NACA Associate Director for Research, wrote to the chief of the Navy Bureau of Aeronautics requesting a full-pressure suit for Crossfield. Crowley pointed out that allowing Crossfield to use a suit would provide "a useful field test of the equipment." Interestingly, long before lawyers influenced every facet of American life, Crowley said, "The NACA is aware that the omni-environmental suit is still in its development stage and expects the Bureau of Aeronautics to accept no responsibility in the event of malfunction or failure of the unit."[39] A week later, J.E. Sullivan from BuAer responded that the Navy would provide Crossfield a suit on indefinite loan and requested that Crossfield make himself available as needed for fittings at Philadelphia or Worcester. Harry Weldon and David Clark redoubled their efforts, despite a serious lack of funding.

The concept of a pressure suit was finally maturing. In November 1951, the NACEL requested David Clark manufacture two suits, both similar to the Model 7, for use in the experimental research airplane program at Edwards. The Model 12 suit was tailored to fit Crossfield, who needed the suit for continued testing of the D558-2. The Model 12 used a rubberized Lastex[40] inner suit and a nylon waffle-weave outer suit joined at the same seams so it was, in effect, a one-piece suit. A transverse pressure-sealing zipper, located on a line just below the armpit, circumvented the chest except for approximately 5 inches in the center front. There was also a vertical back zipper running from the buttocks up to the horizontal zipper. Adjustment zippers were located on the back of the calves and wrists. The suit used neck, shoulder, and wrist bearings designed at the NACEL that were machined to finer tolerances, making for smoother operation. Even David Clark Company admitted these were an improvement over previous efforts. The suit was tested in Worcester to 5 psi with minor leakage that was soon corrected.[41]

The Model 12 was taken to Edwards on December 10, 1952, so that Crossfield could evaluate it in the cockpit of the D558-2. After ingressing and egressing from the airplane several times, Crossfield decided the suit did not interfere with any normal or emergency functions he might need to perform. David Clark had brought two different close-fitting helmets, and Crossfield decided that both designs had worthy features but that neither was satisfactory. Accordingly, David Clark Company took the best features of both and created a new helmet that consisted of a facemask with a seal around its periphery that isolated the wearer from the gas used to pressurize the suit. The mask had two parts—the goggles and the respiratory mask—separated by a molded rubber partition that helped reduce fogging of the goggles. A 2.5-inch diameter cover over the mouth could be removed when oxygen was not needed. An airtight fabric cover was cemented around the facemask and connected to the suit at the neck ring.[42]

The gloves also caused adverse comment from Crossfield. The D558 had numerous small buttons and toggles located on the control wheel, and these proved difficult to manipulate with the existing gloves. David Clark Company had been working on a set of partial-pressure gloves, but given the 4-psi operating pressure of the new suits it appeared best to abandon those efforts and concentrate on a new set of full-pressure gloves. The company began looking at how it would incorporate the concepts used in the knee and elbow joints in the relatively small area of the fingers.[43]

Scott Crossfield wore the Model 12 suit when he took the second D558-2 (BuNo 37974, NACA 144) to 1,291 mph on November 20, 1953, becoming the first man to exceed Mach 2, albeit in a slight dive from 62,000 feet. William B. Cassidy from the Navy Aero Medical Equipment Laboratory (AMEL) and Joe Ruseckas from David Clark Company were in the P2B-1S to help Crossfield don the suit.[44]

The Model 13, the second of the suits based on the Model 7, was tailored to fit Marine Corps Lt. Col. Marion E. Carl. A World War II ace, Carl was the last man to set a world's speed record under the speed of sound while flying the jet-powered D558-I Skystreak. During August and September 1953, Carl would make six attempts to set speed and altitude records using the Model 13 pressure suit in the second D558-2. The first launch, on August 13, was cancelled before the airplane was dropped from the P2B-1S because of a

The Model 16 used a waist gusset that could be closed to control elongation while the pilot was seated or it could be opened to allow the pilot to stand erect as shown here. A pressure-sealing zipper running circumferentially around the chest just under the armpits allowed donning and doffing. The neck, shoulder, and wrist bearings were built into the restraint layer and were not part of the pressure bladder.

Courtesy of the David Clark Company, Inc.

One of the more unusual tests conducted on pressure suits was this visor windblast evaluation. The pilot, strapped into an ejection seat, was suspended over an icing chamber that blasted high-velocity air at the visor. Note the frost on the goggles. Similar tests were run with warm air.

Courtesy of the David Clark Company, Inc.

The Model 18 was another attempt to provide a large dome that could cover a standard flying helmet and oxygen mask. The pressure suit itself incorporated many improvements and evaluators were generally impressed with the flexibility and comfort. Like the attempts before it, the size of the helmet proved a major impediment to the suit's use in operational aircraft.

Courtesy of the David Clark Company, Inc.

bad disconnect in the oxygen system that topped off the rocket plane's oxidizer tank. The third, on August 21, set an unofficial altitude record of 83,235 feet. Carl's last flight, on September 2, established a new military speed record of 1,143 mph (Mach 1.728) at 46,000 feet. On all of these flights, Cassidy, Crossfield, and Ruseckas assisted Carl in donning the suit in the PB2-1S. Carl noted that it was impossible for the pilot to don or doff the suit without assistance and said he carried a knife "for the express purpose of cutting his way out should the circumstance arise."[45] Fortunately, it never did.

Crossfield and Carl each followed largely the same procedures during their D558 flights. Immediately after the P2B took off, the research airplane pilot shed his clothes and donned a set of long underwear. Cassidy and Ruseckas helped the pilot don the pressure suit and helmet. At about 7,000 feet, the pilot climbed into the D558-2 and Cassidy and Ruseckas connected the oxygen, radio, and electrical leads. By the time the bomber reached 10,000 feet, a crew chief closed the canopy, and the research airplane pilot began waiting. Five minutes prior to drop, the pilot began his prelaunch checklist. Once the D558 was dropped, the pilot ignited the no. 3 chamber of the Reaction Motors XLR11 rocket engine, followed by chambers 4, 1, and 2.[46] Besides setting several records, the Skyrocket pilots gathered important data and understanding about stable, controlled flight of a swept-wing aircraft in the transonic and supersonic flight regimes. Like all of the early research airplanes, their primary value was establishing a better correlation of windtunnel test results with actual flight data.

Carl provided a lot of feedback on the suit:

> After the suit was properly fitted, two and a half days were spent at AMEL in indoctrination to the wearing and functioning of the suit. As the suit fitted almost skin tight, the first problem was fighting off claustrophobia, which turned out to be quite an item when the pilot became too warm. After the first couple of times in the suit, this was never again of any consequence. In addition to the present schedule for indoctrination, which includes both Link Trainer time with suit inflated and deflated, a run to 80,000 feet in the chamber, and a couple of explosive decompressions, it is felt that a flight in a TO-2 with the pilot flying with the suit inflated for a short time would have been of definite value.[47]

He felt the biggest issue with the suit was temperature control; Carl was either too hot or too cold, although he was usually too hot. He thought better ventilation, particularly around the head, arms, and legs, would solve this problem. Even when the suit was deflated, the pilot could not see the instruments and controls on the rear half of the side consoles. The head could only be turned about 45 degrees and could only be tilted down slightly. Carl complained that mobility, particularly when the suit was inflated, was very limited. Movement of the arms and legs was particularly restricted, and it was difficult to climb into or out of the cockpit. Carl commented he "was continually annoyed by his inability to grasp and feel things properly."[48] The gloves were too slick and too cumbersome, and Carl wanted a larger faceplate and tinted glass to reduce glare. Finally, he thought the weight and size of the back kit—25 pounds and 5 inches thick—was excessive. Despite the criticisms, Carl concluded that the suit was "satisfactory for continued flight use as an interim measure pending improvements, and that it is the best suit for high altitude research flights now available."[49]

The Model 14 was essentially a Model 12 sized to fit Charles C. Lutz of the USAF Aero Medical Laboratory at Wright Field as part of an exchange of ideas relating to pressure suits. The Model 15 was a similar suit intended for LCDR Roland A. Bosee at the NACEL, but the suit was cancelled before it was completed for unexplained reasons.[50]

By March 1952, David Clark Company had developed a completely airtight shoulder bearing that eliminated some of the manufacturing issues with the original cloth-covered ball bearing units, but the company was unable to incorporate the change into the Crossfield and Carl suits because of timing. David Clark Company had also simplified the construction of the cloth knee and elbow bellows joints without sacrificing mobility and had begun experimenting with insulating the outer layer of the pressure suit with reflective foil. The Minnesota Mining and Manufacturing Company, later called 3M, was developing a special technique to coat the spun-nylon waffle fabric with a silver metallic layer.[51]

Unfortunately, the Navy contract ran out of funds in April 1952, effectively ending large-scale development work on full-pressure suits at the David Clark Company. The Navy found sufficient funds to continue a minor effort at David Clark Company, resulting in continued support for the couple of suits used at Edwards and for the fabrication of several derivative suits for further research.

For example, on July 7, the NACA High-Speed Flight Station at Edwards requested several changes to Scott Crossfield's Model 12 suit. These included new arm sections, different zippers, redesigned disconnect and check valves for the breathing regulator, the relocation of the breathing regulator, a redesigned helmet lens, and the manufacture of a special parachute pack and harness. David Clark Company completed these changes in September 1952, and the Navy tested the suit in the NACEL altitude chamber in October 1952.[52]

The Model 16, sized to fit LCDR L. Harry Peck from the NACEL, incorporated some of the changes recommended by Marion Carl. David Clark Company delivered the suit to the Navy on January 12, 1953. The suit consisted of a rubberized fabric inner bladder, a nylon waffle-weave outer restraining garment, and a nylon outer coverall. A pressure-sealing slide fastener opened circumferentially around the chest, and a waist gusset allowed the suit to be configured for standing or sitting by opening or closing a nonpressure sealing zipper on the outside of the suit. Rotatable, nonpressure sealing rings were located at the neck, shoulders, and wrists. The close-fitting

Right and page 211: The torso of the Goodrich Model H used reinforced rubber-impregnated fabric with pleated fabric over the rubber pressure convolutes and was an intermediate step in the evolution from earlier suits that used all rubber-impregnated fabric construction. Note the helmet pressure regulator over the mouth is unlatched and hanging by the pressure supply hose. The upper torso retention/anti-elongation straps are unthreaded from the upper attach buckles. The Air Force evaluated the Navy suit in the XB-58 cockpit mockup in Fort Worth on April 27, 1954.

Courtesy of Lockheed Martin Aeronautics

headpiece used a pressure-sealing slide fastener, a removable faceplate, and a manually accessible oronasal opening. The suit weighed 16 pounds without the Firewel combined compensated regulator or other accessories.[53]

The Navy tested the Model 16 in Philadelphia and using the XF4D cockpit in the Douglas altitude chamber. The evaluators noted that exhaling took noticeable effort when the suit was unpressurized, the intensity of which depending upon the tightness of the straps, the tightness of the parachute harness, and how the suit fit. Using a Link Trainer in Philadelphia, researchers noted that downward and aft vision was poor, the gloves were still too smooth and slippery, and the wrist rings inadvertently touched various switches in the cockpit. At 1 psi inflation, it was extremely difficult to move the neck, shoulder, and wrist bearings and it became nearly impossible to move these bearings at 3 psi. In the XF4D cockpit, the evaluators noted, "only straight and level flight could be accomplished," and the pilot could not reach the ejection face curtain when the suit was pressurized.[54] The Model 16 did not include a ventilation garment, and the evaluators noted excessive perspiration after extended wear. Despite the apparent failings of the Model 16 to meet operational requirements, the suit provided satisfactory physiological protection under all conditions, including explosive decompressions up to 53,000 feet.

The Model H helmet used a retractable visor and a form-fitting headpiece with a crash-protection shell that was permanently attached to the torso garment. Unlike some later Goodrich helmets, the visor retracted on top of the pressure shell instead of into a protective pocket. Note the lace adjustments between the gloves and sleeves. One of the major objectives of the April 1954 evaluation was to determine if the crewmember could reach all of the controls in the XB-58 cockpit.

Courtesy of Lockheed Martin Aeronautics

Initially, the Air Force considered a full-pressure suit mandatory for the Convair B-58 Hustler because of its altitude and speed capabilities. However, the generally unsatisfactory evaluation of the several pressure suits that existed, along with a decision to use self-contained escape capsules that could protect a crewmember in an emergency, eventually led to pressure suits not being used in the aircraft.

National Archives College Park Collection

The Goodrich Model L was generally similar to the earlier Model H but had a detachable helmet. In this case, the pilot used a separate oxygen mask inside the helmet. Perhaps the major external change was that most of the reinforced rubber-impregnated fabric used on the Model H was replaced by lighter and more flexible fabrics.

U.S. Navy

The Model 17 was a development suit dedicated to fabric shoulder joints instead of the metal bearings used in earlier suits. Researchers found that these joints were somewhat easier to fabricate but provided no better mobility.[55]

Model 18 was an entirely new suit sized to fit John E. Flagg, the director of Research and Development at the David Clark Company. The suit included structural modifications that made it easier to don, pressure-sealing shoulder bearings, a redesigned ventilation system, improved glove construction, and a flexible dome that enclosed a standard-issue flying helmet. The suit was demonstrated at the David Clark Company facility in Worcester on January 14, 1953, observed by CDR Kenneth Scott and LT Frank Blake from the NACEL.[56]

Joe Ruseckas delivered the Model 18 to the Navy on April 16, 1953, but the NACEL performed only a cursory evaluation of the suit since it did not fit any of their personnel. Comments included that the gloves afforded relatively good feel and mobility and the visor

defogging system was adequate. The mobility of the suit was good when it was unpressurized and only moderately impaired when pressurized to 3 psi. The new ventilation system appeared adequate at room temperatures and up to 75 °F. The suit survived being pressurized to 4 psi without failure, although the pressure-sealing shoulder bearings leaked excessively and rusted.[57]

The Navy evaluators thought that developers should concentrate on several areas to improve future models of the suit. Primarily, the wrist bearings should be replaced by forearm bearings to eliminate the potential for inadvertent switch actuation, and the shoulder bearings should be improved to eliminate leakage. In addition, the pressure-sealing zipper should be modified to make it watertight in addition to being airtight. Other suggestions included designing a helmet to eliminate the need to wear an oxygen mask and moving the breathing regulator so it was not be mounted on the chest. Lastly, any future suit should include a restraint layer that better controlled ballooning. Still, the Navy acknowledged that progress was being made.[58]

Because of this demonstration, the Navy ordered a Model 19 suit sized to fit LT Frank Blake. The suit was essentially the same as the Model 18 but with a revised facemask and a helmet sized to fit a McDonnell F2H Banshee, a typical Navy fighter of the era. John Flagg and Joe Ruseckas took the Model 19 to NATC Patuxent River, MD, on January 18, 1954, for tests in a Douglas F3D Skyknight, selected because of its large cockpit.[59]

RUSSELL COLLEY, AGAIN

For unknown reasons, at the same time the David Clark Company was running out of funds on its contract, the Navy awarded a development contract to B.F. Goodrich in Akron, OH. Goodrich was well qualified to develop a pressure suit, having done so for Wiley Post in 1935 and for the Army during World War II. The primary Goodrich engineer for the effort, Russell Colley, was one of the few legends in the business. Later, when the National Aeronautics and Space Administration (NASA) selected a modified Navy-Goodrich suit for Project Mercury, Colley would leave Goodrich and join the space agency. Over the course of his career, Colley received 65 patents and NASA awarded him a Distinguished Public Service Medal in 1994. Retiring from NASA, he returned to northeastern Ohio, where he became a watercolor painter and jewelry designer. Russell Colley passed away on February 4, 1996, in Springfield, OH.[60]

The first suit to evolve from the Goodrich contract, the Model H of 1952, looked much like the pressure suits the David Clark Company was developing and, for that matter, the wartime suits various contractors developed for the Army. It is not clear why this suit was called the Model H, but interestingly, Colley had developed seven suits for the Army during World War II, and "H" is the eighth letter.

The Model H helmet, gloves, and boots were permanently attached to the suit torso. The torso construction of the Model H, consisting of reinforced rubber-impregnated fabric and pleated fabric over rubber pressure convolutes, was an intermediate step in the evolution from earlier Goodrich suits that had used all rubber-impregnated fabric construction. The later Model S (which was produced in limited numbers as the Mark I) eliminated the outer rubber coating, making a lighter and more flexible (when unpressurized) suit.

The Model H helmet used a retractable visor, a form-fitting headpiece with a crash-protection shell, and a breathing regulator on the facemask.[61] Colley and his assistant project engineer, Stephen C. Sabo, adopted the same technique used by David Clark for vulcanizing material to provide elasticity, strength, and stability. Goodrich developed airtight bearings that could be used at the shoulders and wrists, as well as semirigid accordion pleats for the knees and elbows. Although Goodrich did not intend the Model H to fulfill all the requirements for an operational suit, initial testing was promising. Researchers at the NACEL evaluated the suit at 60,000 to 80,000 feet

The Goodrich Model S already exhibited several features that would find their way onto the ultimate Navy Mark IV full-pressure suit. The most obvious was the entry zipper that ran diagonally across the chest. Of interest is the figure-eight helmet-tiedown system that ran from the crotch, behind the back, under the armpits and to the helmet. Russell Colley also designed a helmet that was divided into two sections by a face seal, eliminating the need for a separate oxygen mask.

U.S. Navy

for 11 hours, and its performance indicated it might be well suited as a mission completion suit instead of just a get-me-down suit.[62]

In January 1954, the USAF Aero Medical Laboratory met with representatives of the Bureau of Aeronautics and the NACEL to discuss emerging USAF requirements for a full-pressure suit for the Boeing B-52 Stratofortress and Convair B-58 Hustler. The Navy agreed to accelerate its program with a goal of delivering an experimental suit to the USAF in June 1954 at a cost of $244,000. The Aero Medical Laboratory was skeptical of this schedule, doubting that sufficient development work could be completed by the date suggested by the Navy. Nevertheless, Air Force Headquarters transferred $130,000 to the Navy for five suits to be delivered "not later than 1 June 1954," just over 4 months in the future.[63]

In early April 1954, the USAF evaluated a Model H suit in the XB-58 cockpit mockup. According to the Air Force, the suit lacked mobility, was uncomfortable, had restricted vision, inadequate ventilation, poor land-survival qualities, and was difficult to don and doff. It is interesting to note how two different groups—the Air Force and the Navy—can evaluate the same product and come to very different conclusions. Some of this was undoubtedly parochial since the USAF, really wanted to develop its own full-pressure suit, but some of it is also just different priorities and perceptions. By September 1954, it was obvious that the Navy effort would not produce a suit that was acceptable to the USAF and the Air Research and Development Command ordered the Aero Medical Laboratory to develop an independent design to fulfill USAF requirements. This announcement was made in the course of a joint pressure suit development symposium held in Philadelphia on February 1–3, 1955.[64]

In the meantime, a breakthrough came in 1952 when a team at the Firewel Company, headed by Edward Meidenbauer, developed an automatic suit controller that precisely controlled pressurization and oxygen content. Previously, the pilot had needed to adjust the pressurization as he ascended or descended. Since the Navy expected to use the pressure suit in aircraft that rapidly climbed to high altitude, researchers concluded there was no need to dilute the oxygen flow at lower altitudes. With the need for dilution eliminated, as was the need for positive pressure, a simplified miniature regulator was possible. Goodrich and David Clark Company both adopted the controller for all future suits. The controller was, in essence, an aneroid-controlled back-pressure valve that maintained the pressure suit at the equivalent of 35,000 feet (3.5 psi) regardless of the actual altitude of the airplane. Researchers believed that using 35,000 feet as a control altitude was an advantageous compromise of the mobility difficulties of a fully pressurized garment with the physiologic considerations of hypoxia and aeroembolism. At this suit altitude, the pilot could function normally, breathing 100 percent oxygen without pressure breathing.[65]

Concurrent with the development of Model H, the NACEL began explosive decompression studies of humans. Subjects using the Model H were decompressed from altitudes as high as 75,000 feet in as little as 110 milliseconds. Researchers were surprised to find no immediate or residual pathological effects. This was because the suit acted as a buffer during the decompression. Although the chamber altitude went from 18,000 feet to 75,000 feet in 110 milliseconds, it took 3 seconds for the suit to deflate from 18,000 feet to 35,000 feet, where the subject was maintained.

The Model L was a modification of the Model H that used a detachable headpiece to make it easier to don.[66] The suit weighed 25 pounds, and the pilot needed to use a separate oxygen mask under the plexiglass helmet. Despite any perceived limitations, in April 1953, LCDR Harry Peck from the NACEL demonstrated the suit in an altitude chamber at 70,000 feet.[67] By now, the Navy was highlighting that the B.F. Goodrich full-pressure suit was, in fact, a "spacesuit" that could operate in a vacuum.

The Navy realized that other components of the pilot life-support system would have to be improved to support a workable pressure suit, and it assigned the development of these components to three contractors. The Aerotec Company was assigned the problem of developing a composite disconnect, Firewel continued working on regulating equipment, and the Ralph E. Darling Company investigated suitable connecting hoses.[68] Despite the progress made by all involved, at the end of 1953, many Navy researchers believed, "the full-pressure suit looked like an insurmountable problem for application to high performance weapons systems."[69] Development continued in any case.

The Model M of 1954 was a significant advance that used the newly developed Firewel automatic suit controller and eliminated the oxygen mask. Almost all previous pressure suits had used an oral-nasal oxygen mask inside the helmet to reduce potential dead air space in the helmet and permit visor defogging. However, the use of the mask limited visibility and proved uncomfortable for the wearer. The one concern about eliminating the separate mask was that too much carbon dioxide (CO_2) would build up in the helmet as the pilot exhaled. Physiological studies conducted at the NACEL determined that CO_2 buildup in the headpiece cavity was within tolerable limits. The Model M also incorporated detachable gloves to make donning and doffing easier.[70] No records could be located to describe the Model N through Model Q, if such suits existed.

The Model R featured the ability to sit-stand-sit while pressurized and zippers that allowed the suit to be fitted to individuals. Wire palm restraints kept the gloves from sliding off the hands when they were pressurized, and the helmet allowed supplementary tinted lenses to be installed if needed. Tests revealed that the Model R was relatively comfortable and provided sufficient mobility, but several problems remained before the suit could be produced for fleet use. The bearings in the joints were sealed against air escaping from the inside but not against water leaking in—not an ideal trait if one parachutes into the ocean. The boots were unsatisfactory, and, as with many pressure-suit designs, the helmet continued to lift unacceptably under pressure. The Model R, and all previous Goodrich suits, used an internal helmet tiedown harness that proved unsatisfactory since once the harness was adjusted and

The Goodrich Mark III suit was a major step forward in developing an operational full-pressure suit. Interestingly, the pilot is holding a Mark II helmet, identifiable by the visors rotating under a protective cover rather than on top of the helmet. Note that the boots used a single side zipper instead of laces.

U.S. Navy

the suit donned, the pilot could not adjust the helmet. In addition, to keep the helmet in place, the harness had to be tightened to such a degree that it proved uncomfortable to wear for any prolonged period.[71]

MARK I

Russell Colley and the Goodrich team took the Model R and began to modify it to make it watertight and improve the helmet tiedown system. At the same time, they decided to incorporate detachable boots to provide more sizing options and improve comfort. Colley also began to research ozone-resistant materials that would provide a longer life and require less maintenance for an operational suit.[72]

The resulting Model S differed from the earlier Model R in that it used the diagonal "Sam Browne" pressure zipper-entry configuration (as opposed to the U-shaped Model R entry configuration). The Model S was the first to employ zippers for glove attachment (Model R had a piston-ring-type latch), and the suit featured detachable pressure boots and zippered sizing bands in the arms and legs. Seven rotary-bearing joints aided mobility at the expense of excessive bulk and weight.

The Model S used a helmet tiedown system consisting of steel cables that passed from the headpiece through the crotch in a figure-eight design. Altitude chamber tests showed the

system prevented the helmet from rising under pressure, but the cable tension across the buttocks was uncomfortable to many wearers. As a side benefit, the new nylon restraint materials and streamlined fittings gave the suit a more esthetic appearance.[73]

The Mark III-LW was a major modification to the basic Mark III design. The lightweight suit used a smaller helmet ring and, hence, a smaller helmet. Note the parachute torso harness, life preserver, and bailout backpack.

U.S. Navy

A ventilation-insulation garment worn next to the body was followed by a cutaway G-suit. The two-layer pressure suit, with a rubberized airtight and watertight liner and a synthetic-fabric restraining layer, was worn over the G-suit. Flotation gear was integrated with the parachute harness, and the pressure-control equipment and emergency oxygen supply were carried in a back kit[74] or seat kit, depending on the aircraft type being flown.[75]

The interior of the helmet was divided into two sections by a face seal. The forward section was pressurized with breathing oxygen while the back section was open to the rest of the suit. Oxygen flowed through perforations in a tube installed circumferentially around the visor to reduce fogging of the visor. Oxygen was delivered to the forward section at 1.8 mm Hg above suit pressure to overcome possible face-seal leakage. One-way valves passed exhaled gases into the interior of the suit.[76]

Despite not being completely pleased with the new helmet tiedown system, in 1954 the Navy in 1954 ordered the Model S into limited production as the Mark I Omni-Environmental

The Mark III-LW was a major step toward an operational full-pressure suit. Note the pressure-relief fitting on the lower left leg has been capped off for this test. A variety of interesting suits is hangs in the background, and a Mercury suit is on the table.

U.S. Navy

Suit. The suit stretched 30 inches across the shoulders and weighed 26 pounds, making it awkward to cram into the cockpit of a jet fighter. Goodrich produced the suit in only three sizes, essentially ensuring that it fit nobody particularly well. The Navy conducted operational evaluations in the Vought F8U-1 (F-8A) Crusader, and not surprisingly, pilot feedback centered on the overall bulk and weight of the suit, the restrictions imposed by the shoulder bearings, and the discomfort of the helmet tiedown cables on the buttocks.[77]

By June 1954, the Navy had supplied several Mark I suits to various aircraft manufac-tures. For instance, Grumman chief test pilot Selden A. "Connie" Converse used one while testing the F11F-1 Tiger.[78]

MARK II

The Mark II was a somewhat lighter, slightly reconfigured version of the Mark I. This was probably the most flexible of the Goodrich suits, providing very reasonable mobility.

LCDR Richard H. Tabor, MC, USN, in the long underwear he wore during a series of 1958 long-duration tests using a Mark III, Mod II suit. Long John underwear with Trilok spacer panels was worn under all Navy pressure suits, as well as the Mercury suits. The Trilock panels provided a noncompressible mesh that was used where the pressure suit would be in tight contact with the body to ensure airflow was maintained. It was also used at the location of the exhaust-port fitting to ensure the port was not blocked.

U.S. Navy

The helmet, in particular, was innovative and served as the inspiration for several David Clark Company helmets that followed. The retractable clear visor used a pneumatic seal around its perimeter that inflated automatically as it was lowered. The breathing regulator was located on the left side of the helmet and included an "ON-OFF" oxygen control and a visor-seal deflation button. An adjustment knob for sizing the internal straps and pads that held the face seal against the face was located on the right side of the helmet. The clear and tinted visors retracted upward into an enclosed space intended to provide protection against scratching.[79]

The Navy, however, was still concerned about the overall bulk and 23-pound weight of the Mark II, and it found that the shoulder bearings and helmet tiedown cables continued to cause discomfort. Although several dozen suits were fabricated for evaluation, ultimately, the Navy decided to trade some mobility for greater comfort and lighter weight.[80]

MARK III

The Mark III traded the mobility of the Mark I and Mark II for reduced bulk and weight. Colley accomplished this by deleting six of the rotary bearings, eliminating the bulky detachable pressure boots, and using lighter weight fabrics.

The way the Navy pursued pressure suit development was somewhat different from the Air Force and was reminiscent of how G-suit development progressed. Although the Navy had a research and development contract with Goodrich, that did not necessarily mean that Goodrich would be the company that actually manufactured production suits. As the NACEL and Goodrich perfected a part of the suit, the Navy developed requirements that reflected the design and incorporated these requirements into a procurement specification. The Navy then released this specification to industry and awarded production-development contracts to qualified bidders.[81]

In the case of the Mark III full-pressure suit, the specification required the suit to provide a 35,000-foot equivalent atmosphere for the pilot and a minimum of 25 minutes of emergency oxygen. The suit had to withstand, without damage, ejection at Mach 1 at 35,000 feet and provide pilot ventilation, cold-water immersion protection, and flotation.[82]

When the Navy released the bid for the Mark III suit, two companies responded: Goodrich and the Arrowhead Products Division of Federal-Mogul-Bower of Los Alamitos, CA. Arrowhead, under the leadership of research and development manager H. Wendall Nuttall, dubbed its suit, "garment, upper stratosphere" (GUS).[83] Each company presented a design that met the requirements established by the Navy. Both were lightweight models with compact suit-control systems and simple disconnects. The Goodrich suit weighed 10 pounds and the Arrowhead suit 9.5 pounds, compared to 23 pounds for the Mark II suit. The Goodrich suit measured 26 inches across the shoulders while the Arrowhead suit measured 27 inches, compared to 30 inches for the Mark II. Other improvements included a reduction of 0.9 pound in the life preserver and 1.25 pounds in the helmet and the installation of a safety pressure-relief valve on the suit.[84]

Despite the relative success at addressing the deficiencies in the Mark II suit, the helmet neck area continued to present a problem in terms of both development and pilot acceptability. Possible solutions, none of which was incorporated on either Mark III suit, included a dome-type helmet design, cut-down neck rings, and mounting the breathing regulator internally.[85] Nevertheless, Lester M. Snider, the BuAer supervisor of the Mark III project, said the suit was, "less expensive, less fatiguing to wear, more mobile, easier to maintain, and far easier to put on and take off than any other."[86] It was more an indictment of pressure suits in general than an endorsement of the Mark III.

The Navy selected the Goodrich Mark III suit for limited production, although it also procured small quantities of the Arrowhead suit for fleet evaluation. The Goodrich suit consisted of optional waffle-weave thermal underwear, a ventilation garment that distributed air through ducts at the wrists and ankles, a modified Z-3 G-suit, and a pressure garment that came in sage green, silver, and gold lamé. The helmet, gloves, and boots were detachable. The suit controller and oxygen supply could be worn as a seat kit or a back kit, depending on the aircraft being flown.[87]

The Mark III helmet had both clear and tinted visors mounted on top, rather than under a protective cover as on the Mark II, allowing the helmet to be somewhat lighter weight. An inflatable pressure seal around the helmet opening acted upon the clear visor. The breathing regulator was on the left side of the helmet and included an on-off valve and a button that deflated the visor seal. A knob on the right side of the helmet controlled the tension of the internal straps and pads, allowing the pilot to adjust the helmet without removing it. A face seal separated the breathing space from the rest of the helmet and suit. As on the Mark II helmet, oxygen flowed over the visor through a series of perforations in a tube installed around the perimeter. A microphone and headphones were built into the helmet, which weighed just less than 5 pounds, about 2 pounds less than the Mark II. The helmet provided the same level of crash protection as the standard Navy flight helmet.[88]

Goodrich also produced a lightweight Mark III suit that used a smaller and lighter neck ring. This allowed a smaller and lighter helmet, reducing the weight that the pilot's neck needed to support.[89]

On July 25, 1957, Lt. James D. LaHaye, a test pilot with Air Development Squadron Three (VX-3) from Naval Air Station (NAS) Atlantic City, N.J., was testing an early F8U-1. The flight, intended to collect zoom-climb performance data, became a real-world emergency when the Pratt & Whitney J57 turbojet experienced a flameout at 52,000 feet. At that point, the Mark III suit LaHaye was wearing did exactly what it was designed to do: it inflated. Despite the relative discomfort, LaHaye immediately descended and began the air-start procedures as he passed through 35,000 feet, with the engine finally coming back to life at 30,000 feet.[90]

After the flight, LaHaye reported the suit did not overly restrict his movements while pressurized, that he had no difficulty flying the aircraft, and the suit did not restrict visibility. "In the uninflated condition, the visibility afforded by the suit was far better than I had anticipated. Since the back kit of the full-pressure suit moves the pilot forward, I expected to have difficulty in seeing the switches on the after parts of the consoles. But I found that I could see and reach all necessary switches."[91] LaHaye, however, did find that the bulk of the straps and other items at the shoulders had an adverse effect on mobility of the helmet because it restricted the movement of the neck ring.

LaHaye continued, "My overall impression of this suit as compared to the partial-pressure suit is that it has very little less mobility, visibility, and comfort in the uninflated condition. In the inflated condition, it is much more comfortable and affords much more mobility and visibility than an inflated partial-pressure suit."[92] A recurring theme of pressure suits is that pilots frequently find fewer faults with the garments during actual emergencies than they do during routine evaluations. Credit the adrenaline.

In 1958, a 36-year-old naval flight surgeon, LCDR Richard H. Tabor, wearing a Mark III suit, was exposed to simulated altitudes between 30,000 and 170,000 feet for 3 days. This experiment showed that pilots could tolerate pure oxygen at 35,000 feet for 72 hours, that the Mark III suit was tolerable at extremely high altitudes for extended periods, and that humans could function in such an environment with negligible physiological or psychological deterioration. Tabor spent 76 hours and 48 minutes in the suit, including more than 33 hours above 90,000 feet.[93] The Navy was making a case for a spacesuit.

Similarly, on April 14, 1958, LTJG William J. Pfister wore a Mark III suit when he entered an altitude chamber at NAS North Island, CA, and spent 16 hours in a cockpit mockup at 80,000 feet. A week later, LTJG Arthur F. Vohden spent 24 hours in the same chamber and lost 5 pounds in the process. During these tests, the pilots conducted a series of exercises, including head and arm movement and operating flight controls. Physiologists monitored their heart rate, blood pressure, respiratory data, and temperature. On the East Coast, LCDR Jack Neiman, Jr., conducted similar tests at NAS Norfolk, spending 44 hours at chamber altitudes between 80,000 and 110,000 feet.[94]

In addition to protecting a pilot at high altitude, the Mark III suit also had to protect him if he was forced to abandon his aircraft.

The major components of the Goodrich Mark IV full-pressure suit. Missing from the photo are the outer fabric cover, suit regulator (which was a separate component), one earphone assembly, and one outer glove cover-layer assembly. At the lower left of the photo is a complete suit side neck ring along with all the components that make up the neck ring.

U.S. Navy

To demonstrate the insulation properties of the suit, in 1958 NACEL civilian technician Richard J. "Dick" McGowan spent 45 minutes in a tank of freezing brine with an air temperature of –40 ºF above him. He indicated he never felt cold. During an altitude chamber test, McGowan spent 11 hours at 80,000 feet.[95] Experiments like these undoubtedly influenced the NASA decision to use the B.F. Goodrich suit as the basis for the initial Project Mercury spacesuits.

In the summer of 1958, four pilots from Naval Air Test Center Patuxent River wearing Mark III suits made seven flights from the USS *Forrestal* (CVA-59). These pilots—LCDR F.H. Austin, Jr., LCDR A.J. Nemoft, LCDR Richard Jester, and Marine Corps Maj. Roy C. Gray— were performing carrier qualifications for the F8U-1. A secondary purpose was the evaluation of pressure suit aboard an aircraft carrier. Ultimately, between mid-1957 and mid-1958, Navy pilots made more than 180 sorties wearing Mark III suits. Based on this limited experience base, in 1958, ADM Arleigh A. Burke, the chief of naval operations, made wearing pressure suits mandatory for flights above 50,000 feet.[96]

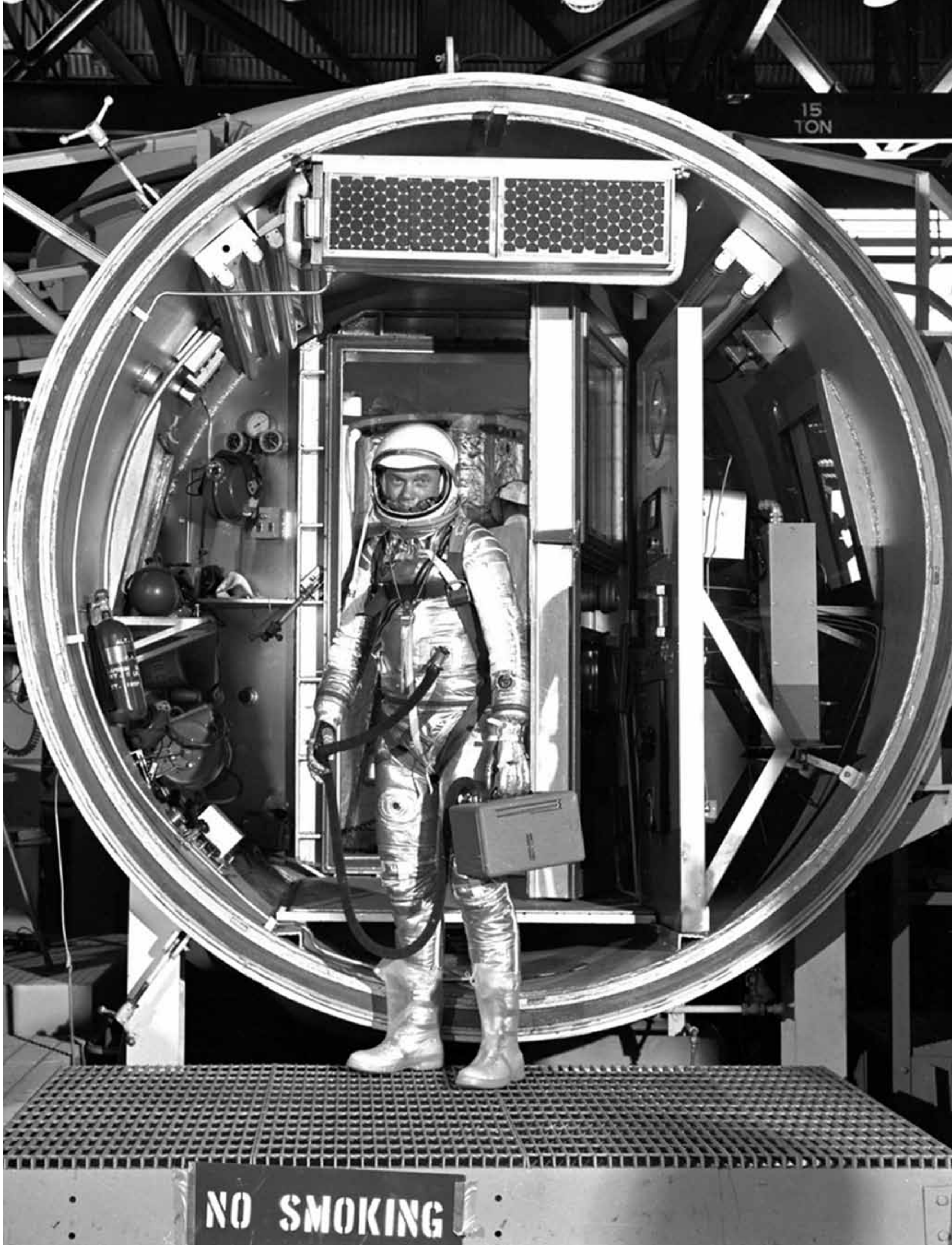
Although all Forestall-class supercarriers had air-conditioned readyrooms, it quickly became evident that additional ventilation was needed for the pressure suits. In response, the Navy developed conditioned air supply equipment (CASE) that could provide air in the readyroom for up to 20 pressure suits. During 1958, the USS *Ranger* (CVA-61) became the first aircraft carrier to have a pressure suit-friendly readyroom installed. This room also contained larger chairs to accommodate pilots in the bulky pressure suits, and each chair had connections to the CASE that the pilot could plug into.[97]

Looking every bit like a spacesuit, this variant of the Mark IV was an early Mercury suit in front of an altitude chamber at the McDonnell Aircraft Company facility in St. Louis, MO.

NASA

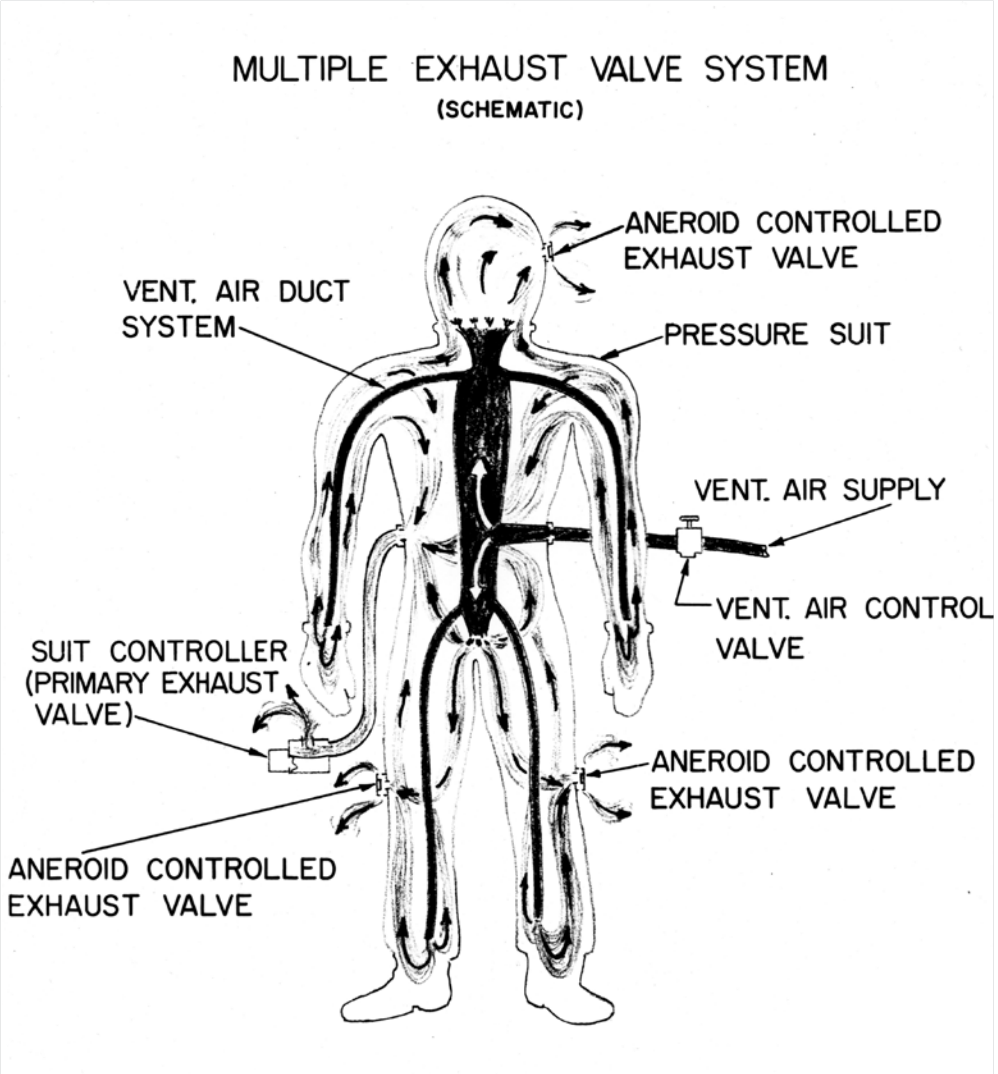
The carriers were also equipped with air-conditioned dressing rooms where the temperature was maintained between 75 and 80 °F with a relative humidity of 45 to 55 percent. Body temperature problems were greatly reduced by this cool, dry atmosphere while the pilot was donning his suit. The dressing rooms also provided space for pressure-suit drying and stowage. Since each pilot required assistance while donning the suit, the rooms were large enough for eight seated persons (the pilots) and eight standing assistants. The Navy subsequently modified all frontline attack carriers to accommodate pressure suits, and all future Forestall class carriers were built with the accommodations.[98]

The A.J. Sawyer Company, under contract to the Bureau of Weapons, developed portable air-conditioning equipment that could ventilate a suit as needed at shore installations or on aircraft carriers not equipped with built-in systems. These 16-pound portable, battery-driven refrigeration units could be used by pilots walking from the readyroom to their aircraft and by pilots waiting in their aircraft if no shore air was available. David Clark Company provided similar units for the Air Force suits.



Providing adequate ventilation for the wearer of a pressure suit has always proved to be challenging. Goodrich used a multiple exhaust-valve system that moved air across the entire body, thereby preventing excessive perspiration.

Courtesy of the David Clark Company, Inc.



TAC Trucks served a similar function and provided an air-conditioned vehicle to transport pilots from the readyroom to their aircraft at shore installations. Each 1.5 ton truck could accommodate eight pilots.[99]

In addition, Grumman manufactured eight portable air-conditioned readyrooms, all delivered by May 1961 for temporary use at locations lacking permanent pressure-suit facilities. Each consisted of two side-by-side 40-foot aluminum trailers that were connected at one end. Four men could set up the facility in 10 hours. The dressing room trailer contained storage lockers, toilet and shower facilities, a drinking fountain, hot water heater, and special storage facilities for the pressure suits. The briefing and alert room trailer contained 16 tilt-and-swivel chairs fitted with small tables, chalk and display boards, and a CASE system for the pilots to connect to while waiting.[100]

In March 1959, the Navy issued Mark III suits to the VF-142 Flying Falcons aboard the USS *Ranger* (CVA-61). The fighter squadron, flying F8U-1 Crusaders, was the first to make a carrier deployment equipped with full-pressure suits.[101]

Although the company was the also-ran in terms of production, Arrowhead gained national attention for its Mark III suit in 1958 when it was featured on the cover of

This Week, a national newspaper supplement. In January 1959, the suit appeared in a ten-minute segment of the *You Asked For It* television show. A few months later, a facsimile of the suit made another appearance. At the time, space themes were popular in Hollywood, and the various producers wanted authentic-looking spacesuits. Arrowhead, David Clark Company, and Goodrich all declined offers to provide movie props, probably afraid to upset their military sponsors. Sometime in 1959, however, Arrowhead relented and created the Garment, Upper Hollywood (GUH), which was worn by actor Lee Marvin in the "Man in Orbit" episode of the *Westinghouse Desilu Playhouse* television show. The episode was based on a story by James E. Gunn that had appeared in the February 1955 issue of *Galaxy Magazine*. The suit was largely identical to a production Mark III but lacked the more expensive features that made it a "real" pressure suit.[102]

MARK IV

The Mark III suit was the culmination of the Navy's search for a lightweight full-pressure suit. However, service trials uncovered a variety of issues, including numerous reliability and wearability problems. In response, the Navy decided to ease the weight requirements in hopes of getting a more robust garment. The NACEL developed the requirements for the Mark IV suit under the direction of CAPT W.L. Jones, CAPT Roland A. Bosee, Lee Snyder, and James V. Correale.[103]

Much as it had with the Mark III, the Navy released the requirements for the Mark IV for bid. The same two companies, Arrowhead and Goodrich, responded. Both companies were awarded development contracts and both suits proved satisfactory. Once again, Goodrich received the majority of the production order, although a limited number of Arrowhead suits were also procured. At Goodrich, Wayne Galway led the development effort.[104]

The Mark IV consisted of the torso, helmet, gloves, and boots. The two-layer torso was a closely fitted coverall encompassing all of the body except the head, hands, and feet. The shoulder, upper arm, and wrist sections did not use bearings but provided mobility by means of Helenca knit stretch fabric tailored into the inner layer of the suit around the

NASA Marshall Space Flight Center Director Wernher Von Braun leaving a suiting-up van wearing an Arrowhead AE-83 version of the Navy Mark IV pressure suit, prepared for a tryout in the MSFC neutral buoyancy simulator. Interestingly, Von Braun is wearing Goodrich helmet and gloves with the Arrowhead suit. Weighted to a neutrally buoyant condition, Von Braun was able to perform tasks underwater, which simulated weightless conditions found in space.

NASA

shoulder, arms, and crotch. The inner air-tight layer used neoprene-coated fabric and coated Helenca fabric in stretch areas, with cold-cemented seams. The suit was entered through a pressure-sealing zipper located on the diagonal across the chest extending over the shoulder and terminating approximately 3 inches below the shoulder cap. Goodrich had used this entry method on several previous suits and pilots had found it preferable to rear entry. The inner layer of the neck section was made of neoprene-coated Helenca fabric and the outer layer was nylon fabric to provide strength. The 9.5-inch-diameter neck ring provided the attachment point for the helmet and contained a breathing regulator and communication system.[105]

The arms and legs were tailored to reduce bulk and the outer ply of these sections used pleated construction to facilitate mobility and a nylon adjustment strap for sizing. These straps channeled along the sides of the arms and legs and were patterned to give a reasonable fit from the 5th to the 95th percentile of the male pilot population. The gloves extended from the lower one-third of the forearm to the fingertips, and the boots extended from the upper one-third of the lower leg to the bottom of the foot. Sock endings for the legs were made of nylon Helenca fabric with a thin ply of neoprene gum. The socks were permanently attached to the inner layer of the suit.[106]

The gloves used neoprene-coated fabric and coated Helenca fabric in stretch areas along with leather palms. A restraining wire bent to fit the hand prevented the palm of the glove from ballooning under pressure. The gloves were available in 15 sizes, consisting of 5 palm sizes with short, regular, or long fingers. The gloves attached using sealed disconnects secured by a slide-fastener zipper.

There were four port fittings located in the upper torso below the left and right armpits: the anti-G fitting at the left front, ventilation-garment fitting at the left rear, suit exhaust at the right front, and pressure-sensing line at the right rear. Some later Mark IV suits had a direct-reading altimeter on the left thigh.

The Mark IV helmet was generally similar to the Mark III unit. The helmet was constructed from phenolic resins and fiberglass cloth and was designed to offer maximum visibility, comfort, mobility, windblast protection, crash protection, and simplicity of operation. It had an internal suspension system and a built-in AIC-10 communication system. The retractable visor was made of Plex II Plexiglas and used a pneumatic seal when closed. A retractable tinted lens blocked 83 percent of the visible light to provide glare protection. A face seal separated the breathing space from the pressurization section using a wide, soft rubber seal mounted to a soft aluminum frame that could be bent to conform to the symmetry of the face. The helmet used a Firewel GR-90 demand-type oxygen regulator.

The helmet holddown system consisted of a cable-and-pulley arrangement that prevented rise under maximum suit pressure and permitted side-to-side movement up to 3.5 psi. The suspension system included a midsection and two side tiedowns that provided a "sit-stand" feature. To stand from a sitting position required releasing the midsection tiedown buckle, thus releasing the webbing restraint and permitting elongation of the torso. The midsection webbing was tightened when the pilot was seated.[107]

Goodrich provided special underwear with each suit. The cotton underwear had three Trilok patches, one on the right side of the torso and one above each thigh, which prevented the ventilation system from being blocked by the underwear. The operating instructions included a warning that this was the only type of underwear that could be used. Accessories included an integrated floatation garment with parachute harness. The pilot wore a standard cutaway G-suit when needed.[108]

The Mark IV suit was fitted to each individual through a selection of properly sized components and the adjustability features of the torso. The torso was supplied in 12 stock sizes consisting of 6 chest sizes in either short

Apparently, the Navy suit could be used in Air Force aircraft. This is CDR Forrest S. Petersen in a Goodrich Mark IV next to JF-104A (56-749) carrying an Air Launched Sounding Rocket (ALSOR) on February 16, 1961. Petersen was an X-15 pilot and was well familiar with the contemporary David Clark Company MC-2 full-pressure suit.

NASA

or long based on the relationship between the expanded chest circumference and the vertical trunk length. The torso could be somewhat tailored using length-adjustment straps and circumferential lacing.[109] The suit weighed 20 pounds.[110] In all, the close-fitting, silver-coated Mark IV was every boy's dream of what a pressure suit should look like, much more so than the more successful David Clark Company suits.

Under normal conditions, with the cockpit adequately pressurized, the Mark IV was unpressurized except for ventilation airflow supplied by the aircraft's air-conditioning system. The air flowed through a series of Trilok ducting that was integral to the torso and exited at the wrists, ankles, crotch, and periphery of the neck ring. It then flowed into the body of the suit to remove excess moisture and exited the suit through the exhaust port, into the cockpit. In addition to ventilating the suit, this air also pressurized it when needed. When cockpit pressure fell below 3.5 psi (35,000 feet), the suit immediately pressurized using the ventilation air. If the ventilation air was also lost, the suit pressurized using breathing oxygen. In the event of bailout, the emergency oxygen supply pressurized the suit and provided breathing oxygen. Because the suit provided adequate physiological protection, there was never a need for pressure breathing.[111] A pilot could survive under water for 5 minutes by breathing the oxygen trapped in the suit.[112]

The Mark IV was used operationally in the McDonnell F4H Phantom II (F-4), Douglas F4D Skyray (F-6), Vought F8U Crusader (F-8), and North American A3J Vigilante (A-5). On December 6, 1959, the Navy used a McDonnell F4H-1 (F-4A) Phantom II to set an altitude record of 98,560 feet. The pilot, CDR Lawrence E. Flint, was wearing a Goodrich Mark IV suit. Pilots complained that excessive pressure built up while the suits were ventilated but unpressurized. A new controller helped but did not eliminate the problem. Goodrich developed new flow valves that went a long way toward curing the problem, but it is unclear when they were introduced into operational suits. Nevertheless, the Navy used the Mark IV operationally far more extensively than the Air Force did with the David Clark Company suits. Despite its apparent success, the operational career of the suit was short-lived.[113]

As it had for the Mark III, Arrowhead developed and manufactured an alternate Mark IV suit. By March 1960, the Navy had qualified the Arrowhead AE-83 suit but had not ordered sufficient quantities to declare it operational. Despite many reports, the Arrowhead and Goodrich Mark IV suits were not identical. Each was the result of a separate development effort to meet the requirements imposed by the Navy.[114]

Although the suits generally resembled each other, there were some significant differences in how they performed. For instance, the Aviation Medical Acceleration Laboratory (AMAL) studied how well pilots could reach the ejection seat controls while wearing pressure suits in the Johnsville centrifuge. The AMAL researchers concluded that the Goodrich Mark IV suit was more flexible and more comfortable to wear (especially across the shoulders), had a more natural head position when the suit was inflated (since the head was erect instead of pitched forward), and was easier to size and adjust. The Arrowhead AE-83 offered easier head movement when the suit was unpressurized; the one-layer glove was easier to don; the single, large spiral zipper made it easier to close than the zippers on the Goodrich suit; and the "Iron Age" boots supplied by Arrowhead were more rugged and provided better support during parachute landings and hiking.[115]

The laboratory concluded that neither suit provided sufficient ventilation even on the highest setting. Each suit also suffered from the absence of any protection for the trailing edge of the visor while in the up position, frequently resulting in the failure of the pivot connection while pulling the ejection-seat face curtain down over it.

In the end, the researchers at AMAL decided, "there is no apparent difference in the

NASA selected a modified version of the Goodrich Mark IV pressure suit as the Mercury spacesuit. Note the clear plastic protectors covering the boots.

NASA

obstruction offered by the Goodrich and Arrowhead full-pressure suits when they were not inflated." This was not as comforting as it sounded since the researchers also concluded that both suits reduced "the probability that a pilot will be able to eject successfully in a Martin-Baker seat equipped with an integrated harness." In addition, the study showed, "inflation of the full-pressure suit further reduces the probability of a successful ejection."[116] This study, although not greatly affecting pressure-suit development, since the Navy abandoned the operational use of pressure suits soon thereafter, was the impetus for the Navy moving from the face curtain actuation method to ejection controls located on the seat arms or between the pilot's legs.

MARK IV SUITS FOR STRATO-LAB

During the late 1950s and early 1960s, the Navy sponsored the Project Strato-Lab high-altitude balloon program under the direction of CDR Malcolm D. Ross. Strato-Lab sought to obtain fundamental data in astronomy, atmospheric physics, and human physiology at high altitudes. One set of experiments demonstrated that protons from solar flare activity

International Latex Corporation (ILC) submitted this SPD-117 full-pressure suit in the Mercury competition. As with the Air Force MC-2 competition, ILC was significantly behind the power curve, and the suit placed a distant third in the NASA evaluation. Nevertheless, it proved a learning experience for the company, and later versions of this suit design eventually went on to win the Apollo suit competition.

U.S. Air Force photos.
Courtesy of the Terry Panapolis Collection

posed a serious risk to humans working in space, contributing to methods of predicting and monitoring solar flare activity. Strato-Lab also contributed to early astronomical observations above the bulk of Earth's atmosphere.[117]

The program made five flights from the flight deck of the USS *Antietam* (CV-36), based at NAS Pensacola, FL. The carrier maneuvered to create zero wind across the deck to simplify launching the missions. The 10,000,000-cubic-foot balloon used pressurized and unpressurized gondolas and culminated in a record-setting flight on May 4, 1961, by Ross and LCDR Victor A. Prather, Jr., to test the Mark IV suit. The 9-hour, 54-minute flight set an altitude record of 113,740 feet and covered a horizontal distance of 140 miles. Ross and Prather were exposed to temperatures as low as –137 °F as they passed 53,000 feet and experienced an ambient pressure of 5 mm Hg (0.09 psi).[118]

As they descended, the balloonists opened their visors as they passed below 15,000 feet. Strato-Lab V landed in the Gulf of Mexico. According to a suit technician on the scene, "The water landing was routine and soft, with three helicopters hovering over them. Ross stepped out of the gondola, sat on the seat lowered to him, and was hoisted into a helicopter. Prather stood on the seat, and when about 25 feet above the water, he fell. He floated on his back, and then started thrashing wildly to get to the gondola. He became tangled in the parachute shroud lines. The diver dove from the helicopter and cut Prather loose from the shroud lines. Prather sank about 10 feet below the surface before the diver got him and brought him to the surface. The ship put out a boat and brought them aboard."[119] Unfortunately, LCDR Victor Prather had drowned.

Despite the tragic loss of Victor Prather, Ross thought the suits performed well: "The suits surpassed our highest expectations with flying colors."[120] President John F. Kennedy posthumously awarded Victor Prather the Navy Distinguished Flying Cross for "heroism and extraordinary achievement" and the balloonists were awarded the 1961 Harmon Trophy for Aeronauts. The flight is still the FAI altitude record for a manned balloon flight.

The USAF procured a limited number of modified Goodrich Mark IV suits as the A/P22S-3, to equip fighter squadrons based in colder parts of the country.[121] It is unclear exactly how many suits were procured and if they were actually issued to operational squadrons.

MARK V

Several references have mentioned a Mark V suit developed in 1967, but no further description could be found.[122]

PROJECT MERCURY SPACESUITS

Although most history gives that the Mark IV was the predetermined basis for the NASA spacesuits used on Project Mercury, the story is actually a bit more complex. Initially, the Mercury capsule was going to provide a shirt-sleeve environment with only a G-suit for the astronaut, much like that envisioned for many of the high-performance military aircraft of the era. However, by February 1959, Maxime A. "Max" Faget from the Space Task Group at the NASA Langley Research Center and USAF aeromedical specialist Lt. Col. Stanley C. White became convinced that an alternate plan would be required based on the difficulties being encountered with designing the environmental control systems for the capsule.[123]

Faget and White believed that the pressure suits being developed by the military could be modified to support Mercury. NASA held the first pressure suit conference at Wright Field on January 29, 1959, and more than 40 companies sent representatives. NASA requested that the USAF Aero Medical Laboratory and the Naval Air Crew Equipment Laboratory conduct an evaluation of available pressure suits to be completed by July. Throughout the spring, the established pressure-suit vendors—David Clark Company and B.F. Goodrich—supported the development of requirements and evaluation criteria, which were published by NASA on March 10, 1959.[124]

A team led by Charles C. Lutz and Dr. Edwin G. Vail at the USAF Aero Medical Laboratory at Wright Field spent approximately 5,700 man-hours between June 1 and July 4, 1959, evaluating suits and documenting them with over 9,000 feet of color movie film and 160 still photos. The David Clark Company, B.F. Goodrich, and the International Latex Corporation (ILC) provided suits for the evaluation.[125]

David Clark Company delivered its suit on June 1, 1959, and the USAF noted a few discrepancies during the initial evaluation, primarily that the leak rate was high, mostly around the neck ring. The suit, made with a liberal use of Link-Net, performed well in the altitude chamber tests, with subjects indicating that comfort and mobility were adequate. The suit had not been tailored specifically for any of the evaluators, and a custom-tailored garment would have been more comfortable and ballooned somewhat less. The suit provided excellent protection against extreme environments (cold), although the evaluators thought an extra pair of socks and better ventilation was needed.

The durability and reliability of the David Clark Company suit was supported by the lack of any serious failures during the evaluation. Lutz and Vail noted that, "most of the Clark suit features which caused loss of points in the scoring system are easily correctable without additional research and development."[126] One possible exception was the shape of the helmet. David Clark Company had provided a cylindrical visor instead of the specified spherical shape, based on comments from engineers at McDonnell Aircraft where the Mercury capsule was being developed. The evaluators also thought the method for attaching the gloves to

Perhaps one of the more famous pressure suit photos was this July 1962 shot of the Mercury Seven. Front row, left to right, are Walter M. Schirra, Jr., Donald K. Slayton, John H. Glenn, Jr., and M. Scott Carpenter. Back row, left to right, are Alan B. Shepard, Jr., Virgil I. Grissom, and L. Gordon Cooper, Jr. All are wearing Goodrich "quick fix" suits based on the Navy Mark IV.

NASA

be very good, although they wanted a bearing that was more easily operated.

Russell Colley delivered the B.F. Goodrich suit on June 17, 1959. Initial testing showed the suit had an exceptionally low leak rate. Unpressurized, the Mark IV was considered comfortable, and the plethora of straps and laces could be overcome by custom-fitting the suits to each astronaut. Comfort when the suit was pressurized was considered adequate. Environmental tests showed the suit had very poor ventilation, and Lutz and Vail did not think the existing design could be modified to correct the deficiency. The helmet shell and visor failed under pressure tests, and the evaluators believed the helmet needed to be redesigned. The helmet also required high-pressure (70 psi) air to seal the visor, and this was not expected to be available on the Mercury capsule.

ILC delivered its SPD-117 (the 117th design—not all pressure suits—from the Specialty Products Division) suit on June 1, 1959. This suit contained several component parts that the company acknowledged as inadequate but were the only ones available within the allocated schedule. These included adjustment laces and joint bellows that had not been designed for this application. Largely because of inadequate development, the suit was judged too uncomfortable: it leaked excessively, and was unreliable. The restraint cable in each shoulder failed during testing, ultimately terminating the test early since there was insufficient time to correct the anomaly.[127] Lutz and Vail concluded that the suit from David Clark Company "most nearly meets all the requirements established by Project Mercury"[128] and demonstrated the best durability and reliability. The researchers believed, however, that all of the deficiencies noted in the Goodrich and ILC suits could be corrected given sufficient time.

A second conference was held at Langley on July 15, 1959, where the chairman, Richard S. Johnston from the Space Task Group indicated that NASA would continue working with David Clark Company and Goodrich to refine its suits. This, however, did not happen. Instead, for unexplained reasons, NASA announced on July 22, 1959, that the Goodrich Mark IV would serve as the foundation for the Mercury spacesuit. Russell Colley, Carl F. Effler, and Donald D. Ewing at Goodrich would lead the development effort.[129]

It was not a bad decision, just unexpected. The Navy always intended that the Goodrich suits would be suitable for use in a vacuum, and the Mark IV suit was designed specifically with that requirement. The Navy required that the suit be capable of operating at 7 psi, although the normal operating pressure was 3.5 psi, with an alternate setting of 5 psi (27,000 feet). Researchers realized they would need to provide facilities and modifications to permit eating while in the suit. However, Navy researchers believed the "suit system can be matched to orbital and space missions with respect to thermal performance, total leakage, restraint requirements, overall work space design, and other bioengineering considerations."[130] Goodrich was designing a dome-type helmet to increase visibility and, hopefully, mobility.

By March 1960, NASA had ordered 21 modified Mark IV suits for use on Project Mercury.[131] NASA designated them XN-1 through XN-4 models, but engineers generally referred to them as "quick fix" suits. Spacesuits are well discussed in existing literature, so they will not be further covered here.

6

6: Air Force Full-Pressure Suits

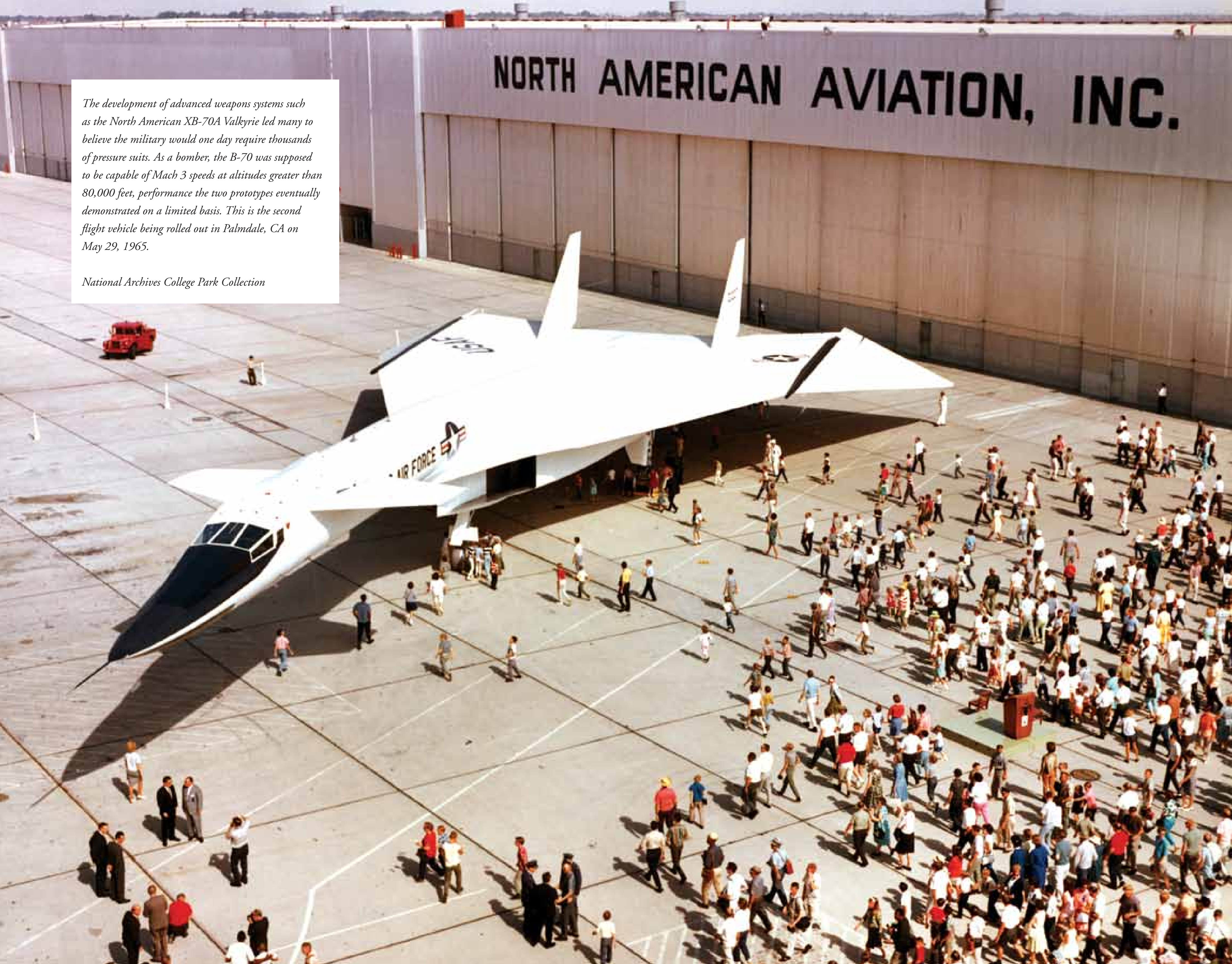
Unlike the Navy, which began developing full-pressure suits almost immediately after World War II, the Army (and, subsequently, the Air Force after September 18, 1947) concentrated on further development of the partial-pressure suit. This was partly the result of the unhappy wartime full-pressure suit development effort and partly because the Henry Suit satisfied the immediate postwar need. The USAF appeared content to honor the 1947 agreement that assigned full-pressure suit development to the Navy, although it continued to monitor the progress being made in Akron, Philadelphia, and Worcester.

For example, the USAF Aero Medical Laboratory at Wright Field evaluated the Navy Model 1 full-pressure suit developed by the David Clark Company (DCC) in early 1949. The evaluators noted that the extreme fatigue experienced by the wearer while pressure breathing in USAF partial-pressure suits was absent in the full-pressure suit. The downside was that the full-pressure suit provided about 40 percent less overall mobility than the partial-pressure suit while inflated. Nevertheless, USAF evaluators believed the David Clark Company full-pressure suit was a marked improvement over the wartime MX-117 Goodrich suit.[1]

A 1955 survey by the Directorate of Research at the Wright Air Development Center showed the maximum altitude performance of U.S. military aircraft increased approximately 3 percent, compounded annually between 1918 and 1954. Although the curve at times dipped below the average, an abrupt increase always brought performance up to the curve at some later date. Surprisingly, the survey showed that steady progress was made despite economic depressions, wars, and the introduction of the jet engine. The directorate estimated that if progress remained constant, the operational ceiling for combat aircraft would increase to 75,000 feet by 1960, 90,000 feet by 1965, and to a staggering 105,000 feet by 1970. Studies of advanced concepts that would lead to the development of the Republic XF-103 and North American XB-70A Valkyrie seemed to confirm these predictions.[2]

The gradual, but relentless increase in altitude had become a problem during World War II, when aircraft reached altitudes above which man could not breathe without the benefit of pressurization. At roughly the same time, piston engines and propellers reached their effective altitude limits, although a few aircraft, particularly the Convair B-36, managed to defy the norm and operate at unthought-of altitudes. During the war, engineers developed workable jet and rocket engines that largely eliminated the altitude restrictions of piston engines. Re-engineering man, however, proved somewhat impractical. The first solution to breathing at high altitudes was to put the crew in a sealed cabin where oxygen, pressure, and temperature could be controlled to maintain a tolerable environment. The Boeing B-29 Superfortress was the first combat aircraft equipped with pressurized cabins, but the Army soon realized the protection of a pressurized cabin could be suddenly nullified by mechanical failure or enemy action. Normally, B-29 crews were instructed to depressurize before going into combat. By the end of World War II, researchers and engineers had been wrestling with the problem for over a decade.[3]

The partial pressure Henry Suit provided an immediate, if not ideal, solution to sustaining humans at high altitude, but researchers kept



The development of advanced weapons systems such as the North American XB-70A Valkyrie led many to believe the military would one day require thousands of pressure suits. As a bomber, the B-70 was supposed to be capable of Mach 3 speeds at altitudes greater than 80,000 feet, performance the two prototypes eventually demonstrated on a limited basis. This is the second flight vehicle being rolled out in Palmdale, CA on May 29, 1965.

National Archives College Park Collection

The Convair F-106 Delta Dart was the last in a long line of interceptors operated by the U.S. Air Force. The aircraft was supposed to be replaced by a Mach 3 interceptor, such as the North American F-108 Rapier, but this never happened. Eventually, modified tactical aircraft such as the McDonnell Douglas F-15 Eagle and Lockheed Martin F-16 Fighting Falcon found use as interceptors, but for the most part, the concept of a dedicated interceptor faded from the lexicon.

U.S. Air Force

looking for a better solution. The Featherweight B-36 bombers provided the impetus to put the MC-1 partial-pressure suit into production and the unanticipated demands of the U-2 resulted in the development of the improved MC-3 partial-pressure suit. At the same time, in early 1952 David Clark Company tailored one of its Navy full-pressure suits to fit Charles C. Lutz at the USAF Aero Medical Laboratory. Lutz conducted an extensive evaluation of the Model 14, finding that it was much better than the wartime suits but still not satisfactory for an operational garment.

The early 1950s was one of the times that aircraft performance took a major leap, much greater than the 3 percent average. The proposed operating altitudes of the Boeing B-52 Stratofortress, Convair B-58 Hustler, McDonnell F-101 Voodoo, and Convair F-102 Delta Dagger made the requirement for a new protective garment urgent. On May 15, 1953, the Air Research and Development Command directed the Aero Medical Laboratory to develop a high-altitude suit that would provide "protection against long-term exposure to altitudes in excess of 50,000 feet."[4] The command stressed that, "since successful accomplishment of the mission and avoidance of enemy action make it necessary for the aircraft to remain at high altitude for considerably longer periods, a comfortable, wearable pressure suit is essential."[5] Based on the anticipated schedule for the B-52, a prototype suit was required by June 1956 for engineering evaluation and full-scale service tests were to begin in June 1957. The Strategic Air Command, however, had a different schedule in mind and wanted the introduction of the new suit to coincide with the delivery of the first operational B-52s, advancing the in-service date to December 1955.

Likewise, the Air Defense Command (ADC) wanted the capability to intercept Soviet high-altitude bombers in the far north near the Arctic Circle. The selected countermeasure was to put an interceptor into a zoom climb at about a 60-degree angle of attack to get above 50,000 feet, lock onto a target, and fire a nuclear-tipped missile. From the subsonic Northrop F-89 Scorpion and Lockheed F-94 Starfire, the ADC began transitioning to the supersonic F-101 and F-102, then to the Mach 2 Lockheed F-104 Starfighter and Convair F-106 Delta Dart. The command was also looking forward to the introduction of a Mach 3 interceptor, such as the Republic F-103 (cancelled August 21, 1957), North American F-108 Rapier (cancelled on September 23, 1959), or Lockheed YF-12A (only three built). In addition to increasingly high speeds, these aircraft were also flying higher, with the F-106 capable of operating at 57,000 feet, and the F-108 and YF-12 expected to exceed 80,000 feet. According to Air Force regulation, to fly above 50,000 feet required the use of a pressure suit.[6]

Although the MC-3 and MC-4 partial-pressure suits used by the ADC provided adequate get-me-down protection for crews of earlier aircraft, they were not "mission completion" suits and were unsuitable for the expected Mach 3 interceptors. The ideal pressure suit would protect against the adverse effects of a high-altitude emergency (loss of cabin pressure) and provide adequate comfort and mobility to complete the assigned mission. In addition, the suit needed to provide protection from exposure in an extremely cold (Alaska or Canada) land or water environment in the event the pilot had to eject from his aircraft.[7]

Researchers at the Aero Medical Laboratory concluded that a full-pressure suit would best meet these requirements. However, the prospect of developing a full-pressure suit placed the USAF in a somewhat uncomfortable position in regard to its 1947 agreement with the Navy. Seeking a solution, representatives from the Aero Medical Laboratory and Bureau of Aeronautics met in January 1954 to discuss the new requirements. The Navy agreed to accelerate its full-pressure suit program with a goal of delivering an experimental suit to Wright Field in June 1954 at a cost of $244,000. The Aero Medical Laboratory was skeptical of this schedule, doubting that sufficient development work could be completed in the intervening 4 months. Nevertheless, Air Force Headquarters transferred funds for five suits, "to be delivered not later than June 1, 1954."[8]

Since 1946, the Navy had conducted a small but active full-pressure suit development program. Although the original contract with the David Clark Company was running out of funds, a new contract with B.F. Goodrich was showing promise. However, the Navy's needs were substantially different from those of the forthcoming B-52. For the most part, the Navy operated short-range fighters, and its needs for an altitude suit could probably be met by the T-1 partial-pressure suit as a get-me-down garment. On the other hand, the USAF was faced with a requirement for an altitude suit that allowed unprecedented long-term comfort and mobility while providing adequate physiological protection for long-range strategic bombing, reconnaissance, and refueling missions. The Air Force also worried about relying on B.F. Goodrich, which had been one of the contractors for the full-pressure suit the Army had cancelled in 1943. There was apprehension within the USAF that the new Navy suit might look very much like the unsatisfactory garment the Army had discarded 10 years earlier.[9]

Another factor in the USAF's skepticism was the division of responsibility between the Bureau of Aeronautics (BuAer) and the Bureau of Medicine (BuMed). Unlike the Aero Medical Laboratory, a physiological research organization that could generally procure whatever services and products it needed to support its development programs, BuMed, the developer, was dependent upon BuAer for all procurement activities. Nevertheless, the Navy program appeared to be moving ahead without undue difficulty.

In April 1954, the Aero Medical Laboratory evaluated an early Navy-Goodrich Model H full-pressure suit in the XB-58 cockpit mockup at the Convair plant in Fort Worth, TX. The Air Force evaluators thought the suit was uncomfortable, lacked mobility, had restricted vision, inadequate ventilation, poor land-survival qualities, and was difficult to don and doff. Interestingly, these were almost the opposite of the conclusions drawn by the Navy. By September 1954, the USAF concluded that the Navy effort would not produce an acceptable suit that could meet the in-service date of the B-52.

The Franklin Institute in Philadelphia hosted the Omni-Environment Full-pressure Suit Symposium, which was co-sponsored by the Air Force and Navy on February 1–3, 1955. During the meeting, several David Clark and Goodrich pressure suits were presented, often under pressure, for the audience. Also during the course of the symposium, the Aero Medical Laboratory announced it was proceeding with an independent full-pressure suit development effort to satisfy USAF requirements. The Navy offered no objections, at least not in public.[10]

LINES OF NONEXTENSION

Independently of the Navy and USAF efforts, beginning in 1947, the National Bureau of Standards funded research by Dr. Arthur S. Iberall that ultimately defined a principle called Lines of Nonextension. If you look at the human body as it moves, there are areas where the skin stretches with the movement of joints and other areas where it does not. The latter are the lines of nonextension. This told designers what parts of a pressure suit needed to be flexible and what areas could remain rigid. Iberall found that

> Since the human body tends to retain its form, taking no appreciable 'set' after ordinary body deformations, its behavior is expected to conform to the laws of physical elasticity. Deformations in an elastic body are described by the strain ellipsoid, in which a small sphere of material deforms to nearly ellipsoidal shape under elastic deformation of the entire body. On the surface of such an elastic body, the projected deformations transform a small circle into an ellipse. Since all points on the ellipse are derived from points on the undeformed circle, in general, there may be two diameters in the ellipse that are not stretched. (They may be noted by superimposing the original circle on the deformed ellipse.) An extension and connection of these radial directions may be referred to as a mapping of the surface of the elastic body by 'lines of nonextension.' Such a theory is expected to be applicable to the surface of the human body. If so, high strength strands of material may be laid along these directions and joined at their interstices for free-rotation capability. These strands can then carry loads developed by the pressure forces transmitted against the strands, without interfering with mobile deformations of the body.[11]

Armed with an ink marker, Iberall spent a considerable amount of time mapping the lines of nonextension on several subjects in leotards. Ultimately, the National Bureau of Standards funded two prototype pressure suits based on this principle. The second prototype, completed in 1951, was a fascinating combination of metal frames, rubber bladders, and net-covered joints pressurized to 2 psi.[12] The netted joints were one of the more interesting aspects of this suit since they were an early attempt to provide better mobility than the various mechanical and rubber joints used in the past. Iberall explained

> Having established the lines of nonextension and having transferred them to an anthropological sizing manikin, patterns were cut in accordance with these lines—first with a coarse decorative fish-net for practice, and then with a Dacron net with about four diamonds to the inch. This net was procured from a local knitter, one of a considerable number of suppliers who can knit net. The major requirements are that high-strength yarn be used (the thread used is two-ply, 1,100-denier yarn), that a sufficient amount of Dacron be packed into the strand (5,000 denier or more), and that a very tight knitting be used. It is desirable that the strand strength be 50 pounds per strand or higher.[13]

In 1954, Iberall moved to the RAND Development Corporation where he continued working on pressure suits. Iberall claims that his netted joints were the basis for all suits that followed, but it is not clear this is the case. In his memoirs, and supporting documentation seems to back up the remembrances, David Clark attributes his company's Link-Net to an idea he had while traveling back from visiting his daughter in Alaska. On the way home, Clark used a string to mock up a collar section of a pressure-suit restraining garment. When he got back to Worcester, seamstress Rose Arlauskas helped Clark refine the sliding mesh-restraint concept that eventually became Link-Net. There is little doubt that Clark and Iberall knew each other, and correspondence indicates that Clark may have assisted Iberall obtaining employment with RAND. However, David Clark was, among other things, a generous person when it came to giving credit where it was due; his memoirs are filled with references to other people's good work. So, it is notable that Iberall is not credited with regard to Link-Net.[14]

Nevertheless, Iberall's research came to some interesting conclusions that were undoubtedly of benefit to the industry. For instance, he conducted research into how human subjects perceived various fabrics and materials. Latex rubber, a common material used in the manufacture of early pressure suit gas containers proved to be a favorite subject. Iberall found, "a thickness of 0.002-inch is almost unnoticeable to the wearer, 0.005-inch is quite comfortable, 0.010-inch acceptable, 0.015-inch tolerable, and 0.025-inch is uncomfortable."[15] It provided a useful basis for others to fabricate gas containers.

While at RAND, in 1958, Iberall fabricated another prototype full-pressure suit. The restraint layer used Iberall's version of a slip-net material made of woven Dacron fiber. He laid the material on a sizing mannequin so that the direction of slip conformed to the lines of nonextension that he had previously drawn on it. Iberall pointed out that the material did not need to perfectly conform, but "only a reasonable approximation to the lines is necessary to permit ample mobility."[16] A second restraint layer consisted of a cloth-like covering over the chest and rigid coverings over the pelvis, thighs, legs, arms, and head, with slip-net lacing between the trousers and vest sections, trousers and thigh sections, and chest and upper arm sections. This layer was worn over the slip-net restraint layer.

Iberall created his 0.012-inch-thick latex gas container by dipping a full-size mannequin into a vat of liquid latex rubber under environmental conditions that ensured the desired thickness would cure after the mannequin was removed from the vat. Iberall fabricated the gas container in four sections: an upper and lower torso and the two arms. After the gas container cooled, a thin leotard was glued to the outside to provide support. Iberall designed the two halves of the torso to be sealed by folding at the waist, much like the contemporary David Clark MC-2 suit.

Iberall used a commercially available fibrous spacer material to construct a ventilation layer, also based on the lines of nonextension. This layer was worn outside a set of long underwear, with the gas container and two restraint layers over it. A fiberglass helmet was fastened to the slip-net restraint layer, and two steel bands held the helmet to the outer restraint layer to prevent rising. A pair of commercial high-laced work shoes purchased at an Army-Navy surplus store and thin kid-leather dress gloves completed the ensemble. The suit was pressurized using a connection on the chest, and air exhausted through connections on the shins and forearms.

Iberall sized the tight-fitting suit for three RAND employees who were used as test subjects. When the suit was taken to the Aero Medical Laboratory at Wright Field, Charles Lutz decided to test the garment, as he had done with nearly all other pressure suits evaluated by the USAF. Although Lutz was somewhat taller than the RAND personnel, the suit fit reasonably well. Lutz reported:

> When I am completely dressed, the suit impairs my breathing because of its tightness. Some relief can be obtained by

> bending over and raising the shoulders and arms. Other areas of discomfort were under the arms and over the shoulder blades. Even though suit donning required about 2 hours, I remained comfortable, temperature-wise, though no vent air was passing through the suit. Pressurizing to about 1/4-psi expands the garment, correcting the breathing difficulty but not the tightness under the arms. At 1 psi, the tightness under the arms was gone, and the suit was very comfortable at all higher pressures, including the highest elected pressure, 4 psi…. Though the garment provides comparative ease of movement and the ability to hold the assumed position, when one relaxes, the suit returns to a neutral position. Also, the elbows cannot be held tightly against the sides of the suit torso.[17]

The Iberall suit was an interesting experiment but was in no way a prototype of an operational garment. For instance, the thin gas container was prone to punctures, and even Iberall recognized that "significantly better solutions will take serious research."[18] The suit offered decent mobility while pressurized to 3.0 psi but was not significantly better than the suits being developed at David Clark Company or Goodrich. Iberall concluded, "Having completed the theory of operation, and fully demonstrated its experimental feasibility, there remains the task of engineering research and development of most suitable materials, and a structural integration of layers into a possible operational suit."[19]

Iberall continued his suit activities at RAND for at least 10 years. Several references, all written many years later, say his 1958 suit competed with the XMC2-DC and XMC2-ILC for the X-15 program, but there is no contemporary documentation that seems to support this speculation. In any case, the RAND-Iberall suit was not, directly at least, chosen for any specific work. Nevertheless, the lines-of-nonextension theory proved useful for other suit designers.

MC-2—A NEW BEGINNING

The requirements for the new USAF suit announced at the 1955 Omni-Environmental Full-pressure Suit Symposium included providing a minimum of 12 hours protection above 55,000 feet in temperatures ranging from –40 °F to the highest cockpit temperature envisioned for aircraft flying at a true airspeed of 1,200 knots. In addition, the suit needed to provide the same protection as the standard USAF G-suit. The "fully mobile suit" needed to weigh less than 30 pounds, operate at an internal pressure of 5 psi, and provide the wearer with sufficient oxygen partial pressure, adequate counter-pressure, and suitable ventilation.[20] Looking forward, by 1965, the Aero Medical Laboratory expected to need pressure suits that provided protection for 9 hours at 1,600 knots and 86,000 feet and, almost unbelievably, for 7 hours at 2,200 knots and 100,000 feet by 1970.[21]

The Aero Medical Laboratory asked 30 companies to bid on a competitive design study for this full-pressure suit. From this group, the laboratory intended to select six to eight firms to conduct preliminary studies that would become the basis for a composite suit design incorporating the best engineering features from each study. After the design was completed, interested manufacturers would bid on a production contract.[22] This was subtly different from the Navy method. The USAF expected a single company to develop the suit, and then the service would compete suit production as a "build-to-print" effort where the winner(s) fabricated identical suits. This was how G-suits and partial-pressure suits were procured. The Navy, on the other hand, issued a functional specification and each fabricator developed its own design that met the requirements, resulting in multiple garment designs that were functionally identical.

The Air Force received bids from 10 companies before the May 16, 1955, closing date, but only four of these covered complete suit systems; five were for component development, and one represented a human engineering evaluation. Funding and schedule concerns forced the laboratory to change its course, and instead of study contracts, the USAF awarded development contracts to the David Clark Company and International Latex Corporation (ILC). Both of the resulting full-pressure suits were designated XMC-2, and to differentiate between the two suits, the initials of the companies became part of the designation. Therefore, the David Clark Company suit became the XMC-2-DC (the Air Force only used the first two letters for David Clark, perhaps because of its familiarity with the man, was well as with the company), and the ILC suit became the XMC-2-ILC.[23]

Despite the needs of the B-52 and other advanced operational aircraft, ultimately three small, black, rocket-powered research airplanes would drive the development and configuration of the first USAF full-pressure suit. Air Force partial-pressure suits and Navy full-pressure suits had performed well in the so-called Round One X-planes—the Bell X-1 and X-2, and the Douglas D558 series. In 1954, the Air Force, Navy, and the NACA agreed that the Round Two X-plane would provide a significant increment in performance. The military would fund the program, with the Air Force taking the lead for the airframe and engine and the Navy providing physiological research and training using the human centrifuge at NADC Johnsville.[24]

Once the basic flight envelope had been opened, the NACA would use the airplanes to explore hypersonic (in excess of Mach 5) heating, aerodynamics, and stability and control at altitudes up to 250,000 feet. In November 1955, the Air Force selected North American Aviation to build the X-15 airframe and subsequently selected Reaction Motors, Inc. to develop the XLR99 rocket engine. Perhaps most significantly, already legendary test pilot Scott Crossfield left the NACA to join North American so he could be more involved in the development of the airplane. The X-15 would become, arguably, the most successful, and certainly the fastest and highest flying, of the X-planes.

At the beginning of the X-15 program, there had been scant success in creating a workable full-pressure suit. The Army's wartime MX-117 experience was almost entirely unhappy, although the Navy was beginning to make some progress with the David Clark and Goodrich designs. This led to a certain amount of indecision regarding the type of garment needed for the X-15. At the insistence of Crossfield, North American proposed a full-pressure suit to protect the pilot during normal operations and emergency escape. It was a controversial decision.

Despite the early state of development of full-pressure suits, Crossfield was convinced one was necessary for the X-15, so on April 8, 1956, North American issued a specification to the David Clark Company for the development, fabrication, and testing of a full-pressure suit. Crossfield had great confidence in David Clark, both the company and the man.[25] As a test pilot, Crossfield used an early David Clark Company suit developed for the Navy when he became the first person to exceed Mach 2 in the D558-2. As an engineer, Crossfield needed to know everything about how the suit worked, and he spent a lot of time in Worcester.

Less than a month later, however, on advice from the Aero Medical Laboratory, the X-15 Project Office advised North American to use a partial-pressure suit in the X-15. It was the beginning of a heated debate. North American—and particularly Scott Crossfield—refused to yield, and during a meeting in Inglewood on June 20–22, 1956, the USAF began to concede. Crossfield demonstrated the David Clark Model 12 full-pressure suit, the same suit he wore on his Mach 2 D558-2 flight, during the preliminary X-15 cockpit mockup inspection. Although the suit was far from perfect, it convinced the Aero Medical Laboratory that, "… the state-of-the-art of full-pressure suits should permit the development of such a suit satisfactory for use in the X-15."[26] There were other reasons that Crossfield, and several NACA researchers, wanted a full-pressure suit. The USAF had decided that all future aircraft, including the X-15, would use an escape capsule of some description. Crossfield, familiar with the

The International Latex Corporation XMC-2-ILC suit was not truly a prototype of an operational suit but more of a conceptual demonstrator. Perhaps its most unusual feature was the lack of gloves or mittens. The suit, however, did contain an innovative helmet holddown system that would soon be adopted by other manufacturers. This suit never stood a chance against the David Clark Company offering, but laid the groundwork for what became the Apollo spacesuits.

National Museum of the U.S. Air Force Collection

concept from the Bell X-2 and Douglas D558 series, was not a believer. Escape capsules were heavy and would adversely affect the performance of the new hypersonic research airplane. They also appeared to hamper, rather than enhance, a pilot's ability to escape from a stricken aircraft. Crossfield thought the best answer was a sophisticated ejection seat to get a pilot out of the airplane and a full-pressure suit to protect him.

During a meeting on July 12, 1956, representatives from the USAF, Navy, and North American reviewed the status of full-pressure suit development and the Aero Medical Laboratory committed to procuring such a suit for the X-15. Although the X-15 contract gave this responsibility to North American, Crossfield agreed that the Aero Medical Laboratory should provide the suit. Crossfield could not legally change the suit from a contractor-furnished item to

Government-furnished equipment, but he agreed to recommend that North American accept such a change. There was little doubt the company would agree. Crossfield insisted, however, that the laboratory design the garment specifically for the X-15 and make every effort to provide an operational suit by late 1957, to support the first flight. The X-15 Project Office accepted responsibility to fund the suit-development program. Although the July 12 agreement effectively settled the issue, the paperwork to make it official moved somewhat slower; the USAF did not change the suit from contractor-furnished to Government-furnished until February 8, 1957.[27]

In the meantime, the Aero Medical Laboratory encouraged David Clark Company and ILC to orient their prototype suits toward the anticipated needs of the X-15, although the suits still needed to satisfy the advanced-weapons-system requirements originally imposed.[28]

The XMC-2-ILC proved to be an unwieldy garment that used convoluted "tomato worm" joints at the shoulders, elbows, and waist. Similar convolutes covered the legs from the thighs to the ankles, with no separate knee joint per se. The ILC convolutes were much finer than those used by Goodrich during the wartime MX-117 program, mostly to minimize the exertion needed to manipulate them. ILC used metal bearing rings under the shoulder convolutes to provide additional mobility. A set of laces ran horizontally around the chest to allow the torso height to be adjusted. Donning occurred through a horizontal zipper around the hips, and the pressurization air inlet was in the center of the chest.[29]

Interestingly, the XMC2 contract did not specifically state that the bidder had to supply gloves, so the ILC suit had large bags at the ends of the arms with no finger or thumb separations. The head was covered by a rubberized, close-fitting cap and a standard Air Force partial-pressure helmet and pressure-breathing mask. An innovative feature that would find future use was the helmet holddown system. A steel cable fastened to the bottom sides of the helmet and ran through a pulley under the chin to the crotch. The pilot could adjust the length of the cable to keep the helmet from rising and also to stand or sit as needed.[30]

Unfortunately, the joint bearings produced painful pressure points on the body, and the Aero Medical Laboratory thought they would present a hazard during bailout or ejection. The suit ballooned unacceptably under pressure and was extremely stiff and difficult to move in. ILC had started the competition at a disadvantage since it had no previous pressure-suit experience, whereas David Clark Company had been developing partial- and full-pressure suits for most of a decade. Although the Air Force did not select the ILC suit for further development, the experience laid the groundwork for what became the ILC Apollo spacesuits a decade later.[31]

In contrast, the David Clark Company built on the experience gained during its Navy full-pressure suit effort. The first task was to evaluate various materials, particularly an airtight fabric with a minimum of bulk that was capable of joint mobility under pressure. Several unsupported sheet-rubber materials were evaluated but all were ultimately discarded since they collapsed when punctured. Efforts then turned to neoprene-coated nylon materials for which a puncture resulted in a small leak but not a sudden expulsion of gas. The restraint fabric was easier to select: a nylon marquisette with a tensile strength of 64 psi on the fill and 130 psi on the warp.[32]

Joseph A. Ruseckas and John E. Flagg at David Clark Company constructed three torso mockups using neoprene-coated nylon and two layers of nylon marquisette on opposite biases. They reinforced the crotch section with an extra layer of marquisette and made the gas container approximately 10 percent larger than the restraint garment. The first mockup survived 510 cycles from 0.5 psi to 5.0 psi without failure. The second torso was used for overpressure tests, surviving 10 psi without incident (a 2-times factor of safety), ultimately failing at

The lower torso of the MC-2 shows the Link-Net restraint over the lower pressure trousers. The subject has not yet donned the upper torso pressure bladder and upper torso-restraint layer. This gives a good image of the rubber flap at the top of the trouser bladder that was folded together with the upper torso bladder to form a waist seal. The upper Link-Net torso-restraint zipped to the lower torso-restraint at the waist. Note the anti-G suit hose on the left side.

National Archives College Park Collection

11.5 psi. Redesigning the crotch allowed this torso to survive 15 psi. The third torso was submitted to 65 inflation cycles from 0.5 psi to 8.0 psi with no fabric or seam failures. At 8 psi, the torso increased about 7 percent in circumference, but it showed no significant increase in length.

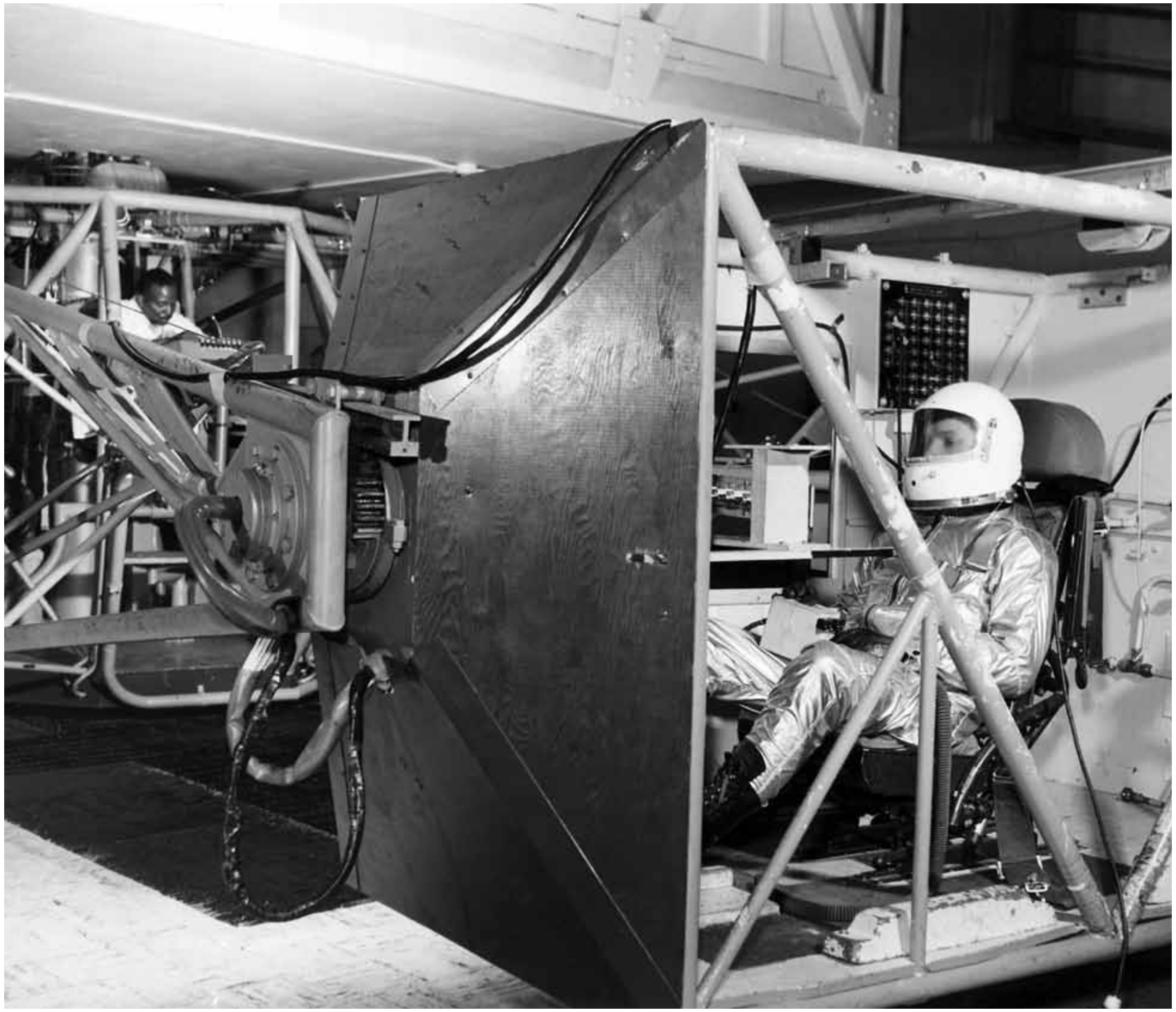
David Clark Company fabricated a fourth mockup using nylon-cotton basket weave for the restraint garment but using nylon Link-Net for the shoulders and sleeves. This was a two-piece garment the pilot entered at the waist. The gas container featured rollup seals 16 inches long, one attached to the top section and one to the bottom. The ends of the seals were rolled together to form a gastight seal. At least that was the theory. In reality, the lap seam used to attach the seals to the rest of the gas container leaked, causing David Clark Company to develop a dipping process that eliminated the seams and the leakage.

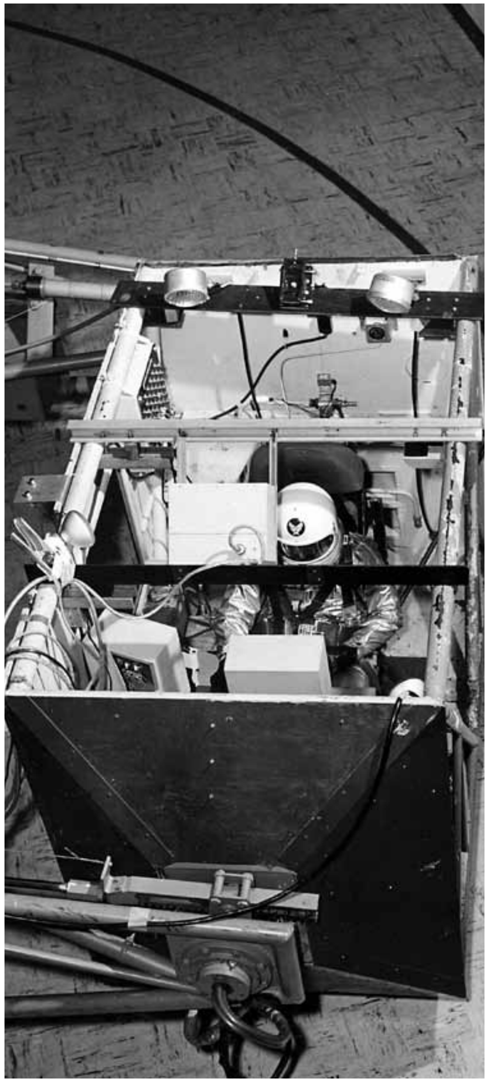
The David Clark Company XMC-2-DC was considerably more advanced than the ILC suit and was the first use of Link-Net on a full-pressure suit. It is impossible to ascertain details of the suit under the aluminized exterior cover. The Aero Medical laboratory tested the suit during 1957 in the Wright Field altitude chamber. The Air Force considered the David Clark suit vastly superior to the ILC garment, but there were still several significant shortcomings.

National Archives College Park Collection

The restraint layer featured a major breakthrough with the use of a new "distorted-angle fabric" called Link-Net, which was used to control ballooning and enhance range of motion. This eliminated the need for the tomato-worm bellows at the limb joints used by ILC and most of the World War II suits. Link-Net is a series of parallel cords that loop each other at frequent intervals. The loops are interlocked but not connected so that the cords can slide over each other and feed from one section of the suit to another. This allowed the suit to deform easily.[33] Ed Dubois, the softgoods expert at David Clark Company, emphasized the fabric was very comfortable when unpressurized because it collapsed instead of bunching up as the wearer moved.[34]

The main characteristic required of Link-Net was the lowest possible resistance to bending and twisting, but the elasticity had to be minimal since the restraint layer could not allow the suit to increase appreciably in size under





Dr. Edwin G. Vail of the Aero Medical Laboratory evaluated the XMC-2-DC on the Wright Field centrifuge during late 1957. These tests included runs at 7-G to demonstrate the built-in G-suit. This was well below the maximum capability of the machine (22-G) but was more than expected from the new X-15 research airplane.

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pressure. The use of a relatively nonelastic cord in the Link-Net made it possible to satisfy these seemingly contradictory requirements. David Clark selected nylon for Link-Net because of its high tensile strength, low weight, and low bulk ratio. The cord and stitch sizes were determined from torsion tests performed on untapered cylindrical sleeves. Researchers rotated one end of the sleeve relative to the other end and recorded the retarding torque as a function of the angular displacement. The tests revealed the best combination of cord and stitch size to give the least retarding torque. For instance, for a given cord size, a larger stitch size was best until the stitches became so large that the gas container forced its way between them. David Clark Company decided to limit the stitch size to 0.3125-inch, and smaller diameter cord provided the net with greater flexibility. Eventually the designers settled on a 36-pound test cord that provided a safety factor greater than 10.[35]

The enormous advantages offered by the Link-Net fabric were initially hard to fully grasp. The fabric allowed David Clark Company to design a suit that provided reasonable mobility without resorting to complicated mechanical or metal joints, saving considerable weight and providing much better comfort. Coupled with advances in regulators and other mechanical pieces, David Clark Company produced a workable full-pressure suit that weighed about 35 pounds. Previously, during the early X-15 proposal effort, North American had estimated a suit would weigh 110 pounds.[36]

"Jack" McKay showing the restraint layer of an MC-2 suit on April 15, 1959. Note the gloves are permanently attached to the restraint layer. The MC-2 was the first suit made by David Clark Company where the entire restraint layer was fabricated from the breakthrough Link-Net.

NASA

Developing the XMC-2-DC (DCC model S794) suit provided a tremendous learning experience for the company. The suit included lower-leg and ankle sections made of nylon marquisette, a side-opening zipper, and a strap that slipped under each foot to keep the torso section from elongating under pressure. The initial anti-G bladders were fabricated using neoprene-coated nylon, but they failed during testing. New bladders incorporated a nylon-oxford restraint cover, and these passed the pressure tests. David Clark Company included an automatic bleed feature in the G-suit outlet; if the pilot ejected while the G-suit was inflated, the bleed automatically relieved the counter-pressure during descent. Once the G-suit bladders were completely empty, the bleed closed to seal out water.[37]

For the gloves, David Clark Company evaluated leather/nylon, leather/nylon/Link-Net, and all leather. Eventually, the company determined the best combination

The new "distorted-angle fabric," development by David Clark Company, Link-Net, was one of the breakthroughs that allowed the company to fabricate a workable full-pressure suit that offered reasonable mobility.

Courtesy of the David Clark Company, Inc.

It's a posed publicity shot, and the MC-2 is not representative of production suits, but the photographer managed to catch the mystic surrounding full-pressure suits during the 1950s. There is no record of the silver boot covers being used operationally. This is the Wright Field thermal chamber during 1957 or 1958.

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was leather covering the hand with a stainless steel palm restrainer stitched inside nylon tape that was supported by nylon tape around the back. The glove used Link-Net from the wrist to the top zipper and a black cabretta top seam. However, test subjects quickly found that gloves constructed in the straight hand position made it impossible to hold an object—such as a control stick—for more than 15–20 minutes while the glove was pressurized. When the company used a natural semiclosed position for the glove, the subjects could hold an object up to 2 hours without undue discomfort. Perhaps the most surprising material used in the prototype suit was for the boots: kangaroo leather, which ended up being soft and comfortable but sufficiently durable.[38]

During the Aero Medical Laboratory evaluation, the David Clark Company suit was clearly superior to the ILC prototype. Although there was obvious room for improvement, there was little doubt that David Clark Company was much closer to

Each of the early MC-2 suits was subtly different as researchers worked through various problems. It is not certain which of the preproduction MC-2 suits these are, but they differ in numerous details. For instance, the suit on the left has a two-pulley helmet-holddown system and the forearms and gloves differ significantly.

Courtesy of the David Clark Company, Inc.

developing a satisfactory full-pressure suit than ILC, and the Air Force declared the company the winner. Subsequently, the Aero Medical Laboratory, using funds provided by the X-15 Project Office, awarded David Clark Company a contract to develop the definitive X-15 full-pressure suit, although the suit also needed to meet the existing weapons-systems requirements.

The construction of two "production" MC-2 suits (S794-1 and S794-2) followed. The suits consisted of heavy wool underwear, an integrated G-suit, a gas container, upper and lower restraint layers, an exterior cover, a parachute harness, gloves, boots, and a helmet. The exterior cover was made from aluminized green nylon and made the MC-2 look every bit the spacesuit that the popular press made it out to be. The two suits were similar except the first had the pressure vent fitting located at the back, near the shoulder blades, and the second located it on the left thigh. In addition, the gloves on the first suit were removable, using a rollup seal like the waist, while the gloves were permanently attached to the second suit.[39]

One of the major changes in these suits was extending the use of Link-Net material further from the joints to increase the amount of "draw" and provide additional mobility. Eventually the David Clark Company designers concluded that the entire restraint layer should use Link-Net. David Clark delivered these two suits to the Aero Medical Laboratory at Wright Field for evaluation and used the lessons learned to construct the first X-15 suit for Scott Crossfield.

The third suit (S794-3C) incorporated several changes requested by the Aero Medical Laboratory after a brief evaluation

Table 4—Pressure Time Log for the S794-3C Suit			
Date	**Time**	**Location**	**Notes**
Sep 18, 1957	3 hours	David Clark Company	
Sep 19, 1957	2 hours, 50 minutes	David Clark Company	
Sep 22, 1957	2 hours, 20 minutes	David Clark Company	
Sep 23, 1957	3 hours, 10 minutes	David Clark Company	
Sep 28, 1957	5 hours	Firewel Company	Altitude Chamber
Sep 29, 1957	4 hours	Firewel Company	Altitude Chamber
Sep 30, 1957	2 hours, 15 minutes	David Clark Company	
Oct 7, 1957	3 hours, 30 minutes	North American Aviation	
Oct 8, 1957	5 hours, 35 minutes	North American Aviation	
Oct 9, 1957	2 hours	North American Aviation	Altitude Chamber
Oct 10, 1957	3 hours, 25 minutes	North American Aviation	
Oct 11, 1957	2 hours, 15 minutes	North American Aviation	
Oct 14, 1957	1 hour, 20 minutes	Wright Field	Centrifuge
Oct 15, 1957	1 hour, 40 minutes	Wright Field	Centrifuge
Oct 16, 1957	1 hour, 15 minutes	Wright Field	Hot Box
Oct 16, 1957	1 hour, 45 minutes	Wright Field	Hot Box
Oct 17, 1957	2 hours, 10 minutes	Wright Field	Centrifuge
Oct 17, 1957	1 hour, 30 minutes	Wright Field	Altitude Chamber
Oct 22, 1957	3 hours	David Clark Company	
Oct 24, 1957	1 hour, 40 minutes	David Clark Company	
Oct 27, 1957	2 hours, 15 minutes	David Clark Company	
Nov 13, 1957	2 hours	Wright Field	
Nov 15, 1957	1 hour, 45 minutes	Wright Field	
Nov 21, 1957	45 minutes	David Clark Company	
Nov 26, 1957	6 hours, 15 minutes	David Clark Company	
Total Time	66 hours, 40 minutes		
Source: "Development of a Full-pressure Suit System," David Clark Company, ASD Technical Report 61-116, May 1961.			

Another posed photo showing Scott Crossfield at NADC Johnsville in front of the human centrifuge. The neck seal is evident in this photo, as is the parachute harness integrated into the outer cover garment.

National Archives College Park Collection

of the first two "production" S794 garments. The complete suit, with helmet, weighed just shy of 37 pounds. Of this, the back pan, regulator, and emergency oxygen supply weighed 13.5 pounds, the helmet 5 pounds, the boots 3 pounds, and the underwear and socks 3 pounds. The pressure suit itself, including the gas container, G-suit, restraint layer, exterior cover, and gloves weighed 12.5 pounds.

David Clark shipped the third suit to Inglewood for evaluation in the X-15 cockpit mockup for 6 days beginning October 7, 1957. While at North American, the suit underwent pressure checks, X-15 cockpit compatibility evaluations, ventilation checks, and altitude chamber runs. Unfortunately, the North American altitude chamber effort proved pointless since the chamber only went to 40,000 feet and the suit controller had been set to pressurize above 40,000 feet.[40]

Crossfield then took the S794-3C to the Aero Medical Laboratory for evaluation. On October 14, he demonstrated the suit in the Wright Field centrifuge during two


One of the qualification tests required before pilots could use the MC-2 in the X-15 was rocket-sled evaluations up the maximum dynamic pressure predicted during an X-15 ejection. Surprisingly, this test is not as extreme as one would first imagine, simply because the X-15's maximum speed was at high-altitude (over 80,000 feet) where air pressure is negligible. In this May 1958 test, an anthropomorphic dummy is strapped into a boilerplate version of the X-15 ejection seat on the rocket sled at Edwards AFB, CA.

U.S. Air Force

of the T-33. Tests in the F-104B proved more comfortable, primarily because high-pressure air was available for suit ventilation but also because the cockpit was somewhat larger. The pilots suggested various improvements after these flights, many concerning the helmet and gloves, but overall the comments were favorable. The suit accumulated 8.25 hours of flight time during the tests.[43]

David Clark Company designers took these comments and rebuilt the S794-4 suit. The revised suit used a two-piece Link-Net neck to minimize helmet rise and increase mobility. Tests showed that the changes seemed to help, but the helmet still rose, possibly because the torso was stretching. The new neck increased head mobility, and the helmet could be moved forward, until the neck ring touched the chest, and slightly aft and sideways. The same neck construction was used on the S794-5 suit. The shoulder was redesigned, mostly by abbreviating the shoulder ring to an underarm contour, eliminating the outboard tape at the shoulder, and extending the contour to the neck tape at the top of the shoulder. David Clark Company also reworked the knees using a two-way stretch material and installed a compensated G-bladder dump valve. The revised suit was delivered to Wight Field on July 17, 1958.

On April 10, 1958, the Aero Medical Laboratory advised the X-15 Project Office that David Clark Company planned to deliver the first flight-qualified suit (S794-6) for Scott Crossfield on June 1, 1958. The laboratory cautioned, however, that the X-15 program would only receive four suits under the current contract. The laboratory planned to order other MC-2 suits for service testing in operational aircraft, but these were not compatible with the X-15 cockpit because the X-15 ejection seat used a back kit instead of a seat kit. As the name implies, this is the location of the emergency oxygen and other equipment needed to support a pressure suit. If additional suits were required, the X-15 Project Office would need to provide the Aero Medical Laboratory with additional funds.[44]

Given a lack of funds for further suits, the X-15 Project Office investigated the feasibility of using a seat kit instead of the back kit used on the first four suits. This would allow the use of suits designed for service testing and would permit X-15 pilots to use the suits in operational aircraft. The benefits of using a common suit would have been substantial, but by May 1958, it was too late, since the X-15 design was too far along to change. Although the X-15 Project Office continued to evaluate the idea, the X-15 suit remained different than similar suits intended for operational aircraft. The X-15 Project Office subsequently found funds for two additional suits.[45]

Since the USAF intended the use the MC-2 in aircraft other than the X-15, David Clark Company fabricated a suit (S794-7) that used a seat kit instead of the back kit used for the X-15. In theory, this made the suit compatible with just about every modern jet bomber and fighter in the inventory, but there is little evidence the suit was used in many of those aircraft.[46]

On May 3, 1958, the configuration of the S794-6 suit to be delivered to Crossfield was frozen during a meeting in Worcester between representatives of David Clark Company, North American, and the USAF. The decision was somewhat premature since the suit configuration was still in question during a meeting 3 months later at Wright Field. This indecision had already resulted in a 2-month delay in delivery, and the need for further tests was apparent. Fortunately, in a perverse way, the entire X-15 program was running behind schedule, so the delay in the suit was not critical—yet.[47]

Nevertheless, the X-15 Project Office advised the newly assigned chief of the Aero Medical Laboratory, Col. John P. Stapp, that the suit delays might postpone the entire X-15 effort. To maintain the schedule, the X-15 program needed to receive Crossfield's suit by January 1, 1959, a second suit by February 15, and the remaining four suits by May 15. Simultaneously, the X-15 Project Office confronted Stapp with a growing controversy concerning the use of a face seal instead of the neck seal preferred by the Aero Medical Laboratory.[48]

In a full-pressure suit, a mechanical separation is needed between the air space in the suit and the space surrounding the mouth and nose. To control the temperature within the suit, it is necessary to continually ventilate the free space between the suit and the wearer's skin to carry off heat and water vapor, both of which rapidly accumulate to uncomfortable levels in an unventilated suit in the usual cockpit environment. Oxygen for breathing is carried aloft at considerable expense in terms of weight and space requirements. Before the advent of liquid oxygen systems, it was impractical to ventilate the suit with oxygen; therefore, the suit was usually ventilated with ambient air or nitrogen, and a seal separated the suit space from the breathing space.[49]

As with many things in life, the use of a face seal has some advantages and some disadvantages. Its chief advantage is the smallness of the breathing space and the resultant limited rebreathing. To obtain a truly satisfactory seal, the wearer's face is pushed into a rubber seal by an adjustable harness behind the head. Such a method makes each helmet a truly personal piece of equipment, as some time is required to fit the seal properly to the face so that it is reasonably comfortable. With his face firmly held in the face seal, the wearer must move the entire helmet in order to turn

Jack McKay models an MC-2 suit. Note the orientation of the emergency oxygen cylinders in the back kit. Other photos show the cylinders running horizontally instead of vertically.

NASA

his head to either side. This is accomplished by rotating the helmet on its neck ring. Not only must the head be rotated in a fixed and somewhat unnatural plane, but movements are slow and difficult. An advantage, however, is that since most of the head is removed from the breathing space, it can be ventilated with the rest of the suit, generally increasing comfort. This arrangement became known as a conformal helmet.

The alternative to the face seal is a neck seal. With a neck seal, the head can be turned easily and naturally within the helmet. Properly constructed, a neck seal should be more comfortable than the face seal as the face must be continually pushed into relatively unyielding materials to produce an effective seal. Perhaps offsetting these advantages are the necessarily increased breathing space and poorer ventilation. The breathing space is increased both because the entire head is now in the oxygen space and also because the dome-type helmet that must be used with the neck seal is somewhat larger in the lateral (ear-to-ear) dimension than the face seal helmet to allow nose clearance when the head is turned. For most movements, the helmet remains stationary while the head turns inside it, although the wearer can manually turn the helmet with his hands if desired. The only ventilation of the head with the neck seal is coincident with the oxygen movement generated by breathing. This arrangement became known as a nonconformal (or dome) helmet.[50]

North American believed the pilot should be able to open the faceplate on his helmet, using the face seal as an oxygen mask. The Aero Medical Laboratory disagreed. Since engineers had long since agreed to pressurize the X-15 cockpit with nitrogen to avoid risks associated with fire, a neck seal meant the pilot could never open his faceplate under any conditions. Eventually, the program adopted a neck seal for the MC-2 suit, although development of the face seal continued for the A/P22S-2 that came later.[51]

Subsequently, the X-15 Project Office found additional funds for the MC-2, and David Clark tailored eight suits for the individual X-15 pilots. These included Neil A. Armstrong (NASA), Scott Crossfield, Capt. Iven C. Kincheloe, Jr. (USAF, killed prior to his first X-15 flight), John B. "Jack" McKay

Before he landed on the moon, Neil Armstrong was an X-15 test pilot. During his 7 X-15 flights, Armstrong reached 3,989 mph and 207,500 feet. The MC-2 suits were custom tailored for each X-15 pilot, necessitating several visits to the David Clark Company facility in Worcester, MA. Note the neck seal on the MC-2.

NASA

(NASA), LCDR Forrest S. Petersen (U.S. Navy), Lt. Col. Robert A. Rushworth (USAF), Joseph A. Walker (NASA), and Maj. Robert M. White (USAF). Each suit consisted of a ventilation garment, chloroprene-coated nylon twill upper and lower-torso gas containers, Link-Net upper and nylon lower-restraint garments, and a one-piece aluminized exterior cover. The neoprene-coated ripstop-fabric ventilation garment also included a porous wool-insulation layer. The upper and lower gas containers formed a seal at the waist by having their edges folded together three times. The lower gas containers incorporated a G-suit similar to standard USAF G-suits that provided protection up to about 7-G. The suit included a biomedical instrumentation pass-through that accommodated in-flight medical monitoring of the pilot. The helmet holddown system consisted of a steel cable that attached to the bottom of the helmet and ran through epaulets on the restraint layer.[52]

The exterior cover was not required for altitude protection, but the reflective

NASA test pilot Joseph A. Walker made 25 X-15 flights. Although the MC-2 allowed X-15 flights to begin, David Clark Company was already working on the improved A/P22S-2, and ultimately only 36 of the 199 X-15 flights used the MC-2.

NASA

aluminized-nylon sunback-fabric cover contained the seat restraint, shoulder harness, and parachute attachments, and it provided a small measure of additional insulation against extreme temperature. It also protected the pressure suit during routine use and served as a sacrificial garment during high-speed ejection. This was among the first of the silver "spacesuits" that found an enthusiastic reception on television and at the movies.[53]

The X-15 provided gaseous nitrogen to pressurize the portion of the suit below the neck seal. The airplane also supplied the modified MA-3 helmet with 100 percent oxygen for breathing, and the same source inflated the G-bladders for acceleration protection. The total oxygen supply was 192 cubic inches, supplied by two 1,800-psi bottles located beneath the X-15 ejection seat during free flight. The NB-52 carrier aircraft supplied the oxygen during ground operations, taxi, and captive flight. A rotary valve, located on the ejection seat, selected which oxygen source (NB-52 or X-15 seat) to use. The suit-helmet regulator automatically delivered the correct oxygen pressure for the ambient altitude until absolute pressure fell below 3.5 psi (equivalent to 35,000 feet); the suit pressure then stabilized at 3.5 psi absolute. Expired air vented into the nitrogen-filled suit through two one-way valves in the neck seal and then into the aircraft cockpit through a suit pressure-control valve. During ejection, the nitrogen gas supply to the suit below the helmet was stopped (since the nitrogen source was on the X-15), and the suit and helmet were automatically pressurized by the emergency oxygen supply located in the back kit.[54]

David Clark Company delivered the first flight-rated MC-2 full-pressure suit on December 17, 1958, just over 6 months later than originally planned. In a report dated January 30, 1959, the X-15 Project Office attributed much of the credit for the successful development of the full-pressure suit to Scott Crossfield.[55]

The number of details required to develop a satisfactory operational pressure suit were staggering. For instance, initially the MC-2 suit used visors heated at 3 watts per square inch, but the conductive film overly restricted vision. The visors were heated for much the same reason as a car windshield: to prevent fogging from obscuring vision. The USAF gradually reduced the requirement to 1 watt in an attempt to find a compromise between heating the visor and allowing unimpeded vision. Tests in the cold chamber at the Aerospace Medical Center during late January 1961 established that 1-watt visors were sufficient for their expected use.[56]

Despite working reasonably well, pilots did not particularly like the MC-2 suit. It was difficult to don and doff, was cumbersome to wear, restricted movement, and had limited peripheral vision. It was also mechanically complex and required considerable maintenance. Nevertheless, there was only one serious deficiency noted in the suit: the oxygen line between the helmet and the helmet-pressure regulator (mounted in the back kit) caused a delay in oxygen flow such that the pilot could reverse the helmet-suit differential pressure by taking a quick, deep breath. Since the helmet pressure was supposed to be greater than the suit pressure to prevent nitrogen from leaking into the breathing space, this pressure reversal was less than ideal, but no easy solution was available.[57]

The Air Force originally intended the MC-2 as a true production full-pressure suit that would be used in all USAF aircraft that needed altitude protection, but that never happened. David Clark Company only fabricated a few suits beyond those procured by the X-15 program, mostly because something better was already in the works. Ultimately, only 36 of the 199 X-15 flights used the MC-2 suit.

A/P22S-2—PRODUCTION USAF FULL-PRESSURE SUITS

Although the MC-2 was usable for the initial X-15 flights, the USAF awarded David Clark Company a new contract to develop an improved pressure suit using what had been learned during the MC-2 effort. Charles C. Lutz was the Aeronautical Systems Division project officer, Maj. Richard G. Willis was the task engineer, and Joseph A. Ruseckas and Forrest R. Poole at David Clark Company were the principal designers.[58] Ultimately, the A/P22S-2 became the first standardized full-pressure suit in the Air Force inventory, and it was the beginning of a line of suits developed by the David Clark Company for the CIA and USAF.

The suit would also be the first to use a new designation system. "A/P22S" was the prefix for a category called "Personnel Support Apparel" that would be used for standardized USAF full-pressure suits during the 1960s and 1970s. There is no record of what A/P22S-1 was assigned to (perhaps reserved for the MC-2), but the -2, -3, -4, and -6 designations would be used by full-pressure suits. Later A/P22S designations would be used by "Extreme Cold Weather Survival Clothing Outfits."

Joe Ruseckas developed a mockup of the new suit based on the multi-layer MC-2 that included anti-exposure features, G-protection, and a ventilation system. The individual layers consisted of heavy long underwear, a ventilation garment, a gas container with integrated G-bladders, a restraint layer, and an insulated exterior cover with an integrated parachute harness. Ruseckas never intended this suit as a real prototype, but it provided David Clark Company a working model to evaluate and refine various features. In addition, David Clark Company further refined the Link-Net fabric for strength and flexibility.[59]

Similar to the MC-2, the chloroprene-coated, nylon-twill gas container was made in upper and lower torso sections with a roll-up seal at the waist. Cotton-flocked rubber gloves and boots were attached to the gas container. The entire restraint layer was made of nylon Link-Net, compared to only the upper half of the MC-2 restraint layer. Ruseckas and Poole redesigned the leg section of the restraint layer so that it would assume an optimum sitting position when pressurized without overly compromising the unpressurized sitting and standing positions, thereby allowing greater mobility and comfort. The helmet antilift arrangement consisted of the same shoulder epaulets and cables used on the MC-2. The aluminized-nylon sunback exterior cover had an integrated parachute harness, also similar to the MC-2. The full-pressure helmet was essentially identical to the MC-2 and attached to the suit using a rotating pressure-sealing neck ring.

Ruseckas started making major changes to the second suit. The heavy underwear was discarded in favor of light underwear with a fishnet fabric on the outside (away from the body) to allow a little space between the underwear and ventilation garment. The ventilation garment itself was modified by replacing the original inner layer of neoprene-coated ripstop fabric with oxford nylon and substituting Trilok synthetic fiber for the white embossed torso-fabric spacer layer. Ruseckas considered vent holes unnecessary since the oxford nylon was sufficiently porous to support the desired airflow. Neoprene-coated ripstop was used for the outer layer. This garment provided better airflow over the wearer and was significantly less bulky.

A new gas container used neoprene-coated nylon instead of chloroprene-coated nylon twill. The new fabric was woven with a smaller denier yarn and higher pick-count weave, and it offered less resistance (friction) when in contact with the restraint fabric, improving mobility because of its flexibility and slipperiness. Except for the shoulders and parts of the chest, which used Link-Net, Ruseckas made the restraint garment from marquisette. This was less Link-Net than on the MC-2, primarily because the fabric was difficult to fabricate and the expected large-scale production of the A/P22S-2 demanded a simpler solution. The two-piece gas container joined at the waist gave way to a one-piece design with a U-entry zipper that started at the front of one shoulder, went under the arms and around the back, then ended on the front of the other shoulder. This arrangement became standard on all USAF full-pressure suits for the next decade.[60]

The exterior cover for the second suit consisted of two layers instead of one. The outer layer was high-tensile-strength black nylon, and the inner layer was a sage-green nylon sunback. This suit did not use an aluminized coating. David Clark Company made a new helmet based on a Bill Jack fiberglass shell. Ruseckas subjected the second suit, and the materials it was constructed from, to an extensive battery of tests to determine the strength and flexibility of each component.[61]

These evaluations led to improvements in the third prototype that reduced its bulk by 30 percent. Ruseckas and Poole constructed the third suit primarily to investigate better ways to don and doff the garment. The designers replaced the six individual layers used in the earlier suits with only four layers that covered the torso to the neck, the arms to the wrists, and the legs, including the feet. The four layers included a nylon-oxford ventilation layer, gas container, restraint layer, and exterior cover. In this case, the cover was international orange nylon oxford. The separate ventilation garment and long underwear were eliminated.

Sidebar: The Evolving Pressure Suit Depot

The original Physiological Support Division (PSD) was formed in 1957 at Edwards AFB, CA, by Col. John Paul Stapp, M.D., Ph.D. (1910–1999). As conceived by Stapp, the PSD would be a physiological research facility to complement the X-15 research airplane and subsequent high-speed and high-altitude programs. It was a grand plan that everybody supported, at least in public. However, by the time the Government finally authorized the PSD, Stapp had retired and gone on to other things and the facility was never used as originally intended. For instance, the facility included a large altitude chamber that Stapp wanted to use for evaluating pressure suits. Ultimately, however, it was mostly used to conduct routine physiological training. When support for the X-15 was being organized, the PSD was the logical organization to maintain, test, and repair the MC-2 pressure suits, in cooperation with the nearby NASA-FRC life-support shop managed by Roger Barnicki.[62]

As the Air Force began acquiring MC-2, A/P22S-2, and A/P22S-3 suits during the early 1960s, Air Force Headquarters had not given overall authority to any single organization to control maintenance or logistical support or to track the flight safety of the suits to any single organization. The Air Defense Command (ADC) was the intended user of the majority of the suits, and in 1962, it established a Physiological Training Unit at Tyndall AFB, FL. This organization was extremely limited in experience and facilities, and although it attempted to provide the best possible support, the condition of the suits deteriorated rapidly, necessitating the continual expansion of acceptable tolerances and a high rate of suit condemnation. However, by the end of 1967, the ADC had largely ceased using full-pressure suits and—excepting the special projects suits for classified programs—the primary users were the 58th Weather Reconnaissance Squadron at Kirtland AFB, NM, and the Air Force Flight Test Center (AFFTC) at Edwards AFB.[63] Nevertheless, the Tyndall facility provided pilot training and pressure-suit maintenance, testing, and logistical support until 1976.

By 1970, the AFFTC was lobbying to become the only USAF pressure-suit organization. Part of the argument was that it would then be possible to evaluate pressure suits at the same time as new aircraft were being tested at Edwards. The AFFTC also pointed out that no additional facilities would be required since a complete physiological support unit, laboratory, and altitude chamber already existed on the base.[64] This finally occurred in 1976, when the Tyndall depot closed and all standard Air Force pressure-suit assets were consolidated at the Edwards PSD. This organization supported all high altitude flying at Edwards and the NASA-FRC, including the Aerospace Research Pilots School Test Pilot School and the XB-70A, YF-12, SR-71, and lifting bodies programs. The PSD also offered support for the British jerkin used by NASA-FRC for its high altitude F-15 and F-104 flights.[65]

In March 1972, the U.S. Department of Defense (DoD) designated the USAF, specifically the Life Support Special Project Office (LSPRO), as the lead DoD organization for all pressure-suit development, acquisition, and logistics support. The Navy, specifically the Naval Air Development Center in Warminster, PA, interfaced through the LSPRO to ensure its requirements were met.

Of course, none of this affected the two primary users of pressure suits in the Air Force: the U-2 and SR-71 programs. The U-2 suits were always maintained wherever the airplanes were based: Groom Lake; Laughlin AFB, TX; North Base at Edwards; and then Davis-Monthan AFB, AZ. The USAF established a PSD at Beale AFB in 1965 to support all SR-71 pressure suits and physiological training. In June 1976, U-2 operations moved from Davis-Monthan to Beale, and the two PSDs were consolidated at Beale. During the mid-1990s, the USAF closed the Edwards PSD and all U.S. pressure-suit activities, excepting Space Shuttle operations, were consolidated at the Beale PSD to support the USAF U-2 program, as well as the NASA WB-57F and ER-2 programs.[66]

One of the major improvements introduced on the A/P22S-2 was a U-shaped entry zipper that started at the front of one shoulder, went under the arm, around the back, and then ended on the front of the other shoulder. There was also a smaller relief zipper over the crotch.

Courtesy of the David Clark Company, Inc.

The pilot entered the suit through a U-entry pressure-sealing slide fastener, and there was a 7-inch relief zipper installed over the crotch. Leather boots were integrated into the garment using separating slide fasteners. The helmet holddown straps were 0.75 inch nylon webbing anchored to the restraint layer at the groin lines on each side of the relief zipper and at the center back just above the main entry-slide fastener.

The designers attempted to produce one-piece detachable gloves that would be sufficiently flexible and pliable at 3.5 psi to allow the pilot to perform all the functions expected of him. Four different designs were produced, but none was truly satisfactory. The company also produced a new helmet with a fiberglass shell and plexiglass visor and sunshade. Unusually, the visor was automatically lowered at the pressure equivalent of 9,100 feet altitude. It was later modified to allow the pilot to lower the visor below that altitude if needed. When the visor sealed shut, it actuated the regulator that pressurized the helmet and provided breathing oxygen. The breathing regulator and all plumbing were installed inside the helmet shell, with a spray bar around the periphery of the visor that defogged the visor. A face seal separated the front of the helmet from the back, and the back compartment was pressurized with the suit, separately from the breathing space in the front of the helmet. Adjustable chamois-covered foam ear pads allowed individual fitting to each pilot. The basic helmet design, and many of the details, was copied directly from the Navy-Goodrich Mark II helmet.[67]

The third prototype weighed 19.25 pounds, including the suit, helmet, gloves, and boots. Joe Ruseckas delivered the suit to the Aeronautical Systems Division at Wright-Patterson AFB on April 23, 1959, to undergo formal testing. The Air Force took the suit to Edwards on July 27, 1959, for flight-testing, using the same JTF-102A that had been used to evaluate the MC-2. While the suit was at Edwards, several of the X-15 pilots evaluated it and made suggestions for minor improvements, although all thought it much improved over the MC-2. The USAF approved the suit on October 19, 1959.[68]

Despite the USAF approval, Joe Ruseckas believed the suit could be further improved. He developed a fourth prototype that more closely conformed to the eight-size tariff then in vogue. Ruseckas redesigned the torso to reduce bulging in the back when the suit was pressurized, and he added laces at the shoulder area to permit some tailoring to individual pilots. Laces were also added at the forearm, calf, and around the waist. He extended the U-entry zipper farther up the shoulders to make the suit easier to don and lessen the stress across the chest.

In addition, David Clark Company changed the exterior cover from nylon oxford to Duplan Weatherbar polyurethane-coated nylon because it was water resistant and could serve as a wind-breaker. The helmet received numerous interior changes to provide more room and improve comfort. Ruseckas added an anti-suffocation feature to the helmet that would automatically open the visor if there were no oxygen flow for 90 seconds. During those 90 seconds, the pilot would have increasing difficulty breathing, triggering a warning to descend to a lower altitude. Finally, David Clark Company succeeded in permanently positioning a flocked rubber glove inside a leather outer glove, providing a flexible glove for the suit. Testing in Worcester showed the new suit had a leak rate of 0.5 liters per minute (lpm) at 5 psi, and the helmet leaked at 0.7 lpm, giving a total of 1.2 lpm for the entire ensemble. The suit and helmet could withstand an internal pressure of 6 psi for 15 minutes without failing, well above the 3.5 psi operating pressure.[69]

David Clark Company delivered the fourth prototype to the Aeronautical Systems Division on October 25, 1960, for evaluation. After tests in the altitude chamber, centrifuge, and environmental chamber, the Air Force took the suit to Edwards for flights in the JTF-102A. Although the Air Force would not formally approve the suit for use until July 3, 1961, it told David Clark Company to manufacture a small quantity of service-test suits, including custom-fitted versions for X-15 pilots Maj. Robert A. "Bob" Rushworth, Joseph A. "Joe" Walker, and Maj. Robert M. "Bob" White.

NASA test pilot Joe Walker made the initial attempt at using the A/P22S-2 in the X-15 on March 21, 1961; unfortunately, telemetry problems caused the launch attempt (2-A-27) to be aborted. Nine days later, Walker made the first flight (2-14-28) in the A/P22S-2 and reported the new suit represented a significant improvement in comfort and vision over the MC-2. By the end of 1961, the A/P-22S-2 had a total of 730 hours in support of X-15 operations; these included nine X-15 flights, 171 flight-hours in the JTF-102A, and 554 hours of ground time. It is interesting to note that although the X-15 pilots were still somewhat critical of the lack of mobility afforded by the full-pressure suits (particularly later pilots who had not experienced the MC-2), this was only true on the ground. When the suits occasionally inflated for brief periods during flight, an abundance of adrenaline allowed the pilot to easily overcome the resistance of the suit. At most, it rated a slight mention in the postflight report.[70]

By mid-1961, 61 individuals had tested the A/P22S-2 at simulated altitudes ranging from 7,000 to 100,000 feet. The suit had successfully passed explosive-decompression tests in altitude chambers at 35,000 and 65,000 feet. In a particularly demanding test, a mannequin wearing the suit was ejected from the back seat of a Convair F-106B Delta Dart flying at 22,500 feet and 730 knots (Mach 1.58), providing a maximum dynamic pressure (Q) of 1,580 pounds per square foot. The Air Force conducted three rocket-sled tests at Edwards using the suit—two using an X-15 ejection seat and one using an F-106 seat—ranging from 0.68 to 1.08 Mach (650 to 1,615-Q). The USAF formally approved the suit on July 3, 1961.[71]

The A/P22S-2 was clearly superior to the earlier MC-2, particularly from the pilot's perspective. Some of the improvements included:[72]

Increased visual area: The double curvature faceplate in the A/P22S-2, together with the use of a face seal in place of the MC-2 neck seal, allowed the face to move forward in the helmet so that the pilot had a lateral vision field of approximately 200 degrees. This was an increase of approximately 40 degrees over the single contoured lens in the MC-2 helmet, with an additional increase of 20 percent in the vertical field of view.

Ease of donning: The MC-2 was donned in two sections: the lower rubberized garment and its restraining coverall, and the upper rubberized garment and its restraining coverall. This was a rather tedious process and depended on folding the rubber top and bottom sections of the suit together to retain pressure. The A/P22S-2 was a one-piece garment with a U-entry pressure-sealing closure that was zippered closed in one operation. It took approximately 30 minutes to properly don an MC-2; it took only 5 to 10 minutes to don the newer suit.

Removable gloves: In the MC-2, the gloves were permanently attached to the upper rubberized garment. The A/P22S-2 had removable gloves that contributed to general comfort and ease of donning. Removing the gloves also prevented excessive moisture from building up during suit checkout and preflight inspections, and it made it easier for the pilot to doff the pressure suit by himself if that should become necessary. Another advantage was that a punctured glove could be changed without having to replace the entire suit.

Of special interest to the X-15 program, the A/P22S-2 featured new biomedical electrical connectors installed through a pressure seal in the suit, avoiding the snap-pad arrangement used in the MC-2 suit. The snap pads had proven to be unsatisfactory for continued use; after several operations, the snaps either separated or failed to make good contact because of metal fatigue. This resulted in the loss of biomedical data during the flight. In the new suit, biomedical data was acquired through what was essentially a continuous electrical lead from the pilot's body to the seat interface.[73]

The standardized A/P22S-2 ensemble consisted of the CSK-6/P22S-2 coverall, HGK-13/P22S-2 helmet, and HAK-3/P22S-2 gloves.[74] David Clark Company called these S926 (with an altimeter on the thigh) and S926A (without the altimeter).[75] The suit was fabricated in the now-standard eight sizes, although the arms, legs, and torso contained covered laces that could be adjusted to tailor the suit as needed. The X-15 suits (S906 and, later, S940) were still custom fitted to

The A/P22S-2 air inlet and suit controller was on the right side of the suit and the air exhaust was on the left. Note the diagonal zippers for the U-shaped entry. Joe Ruseckas is wearing the suit while sitting in an ejection seat used for fittings.

U.S. Air Force

The David Clark Company facility at 360 Franklin Street in Worcester, MA. Most pressure suit fabrication takes place in the portion of the building fronting Franklin Street (foreground), with the remainder of the facility supporting the company's noise-attenuating headset and intercom business.

Courtesy of the David Clark Company, Inc.

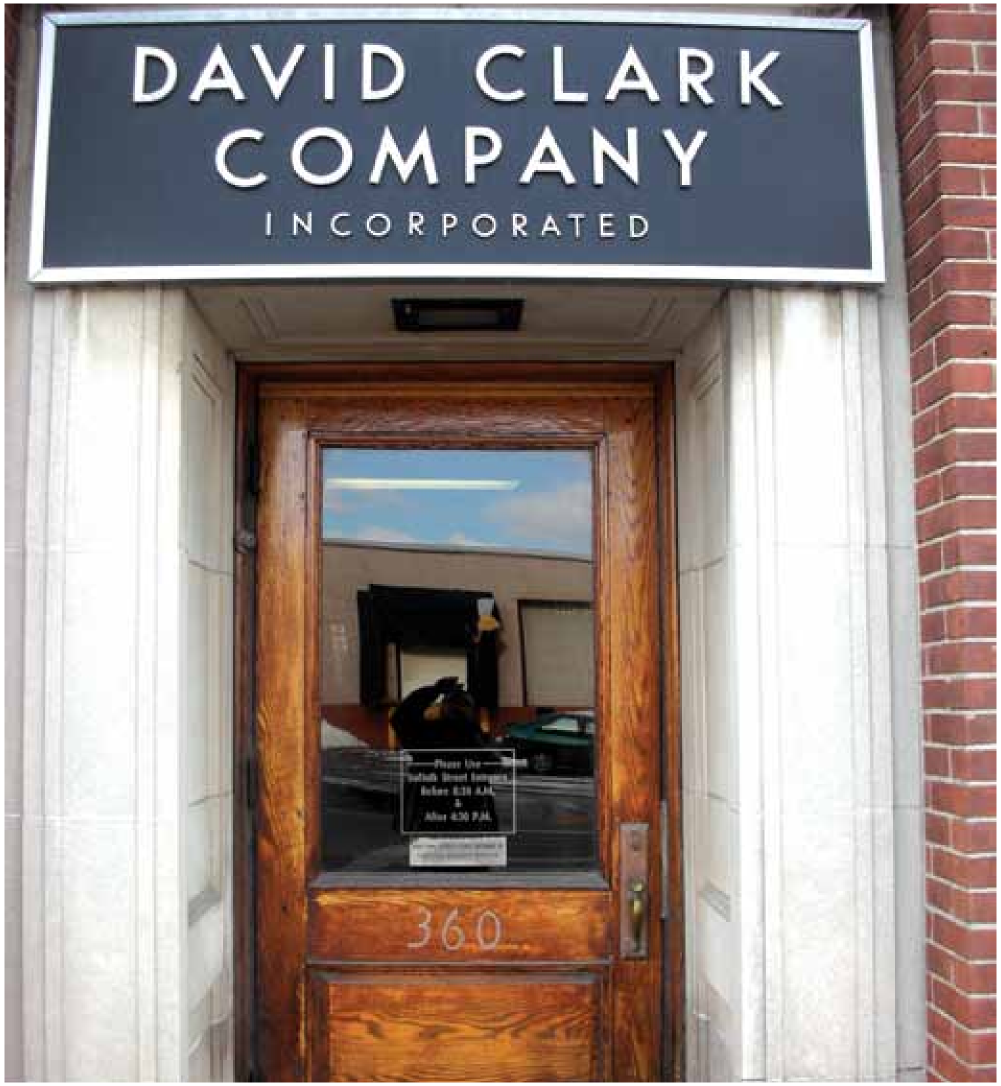
each pilot. The helmet came in a single size, although 3 sizes of crown pad were available, and the gloves came in 12 sizes. The suit was manufactured to specification MIL-F-27628.[76]

The A/P22S-2 helmet used an electrically heated stretched-acrylic visor procured from the Sierracin Corporation. The early visors had the electrically conductive coating applied to the inside of the acrylic, and the coating was not particularly durable, requiring extraordinary care during handling. David Clark Company eventually solved this with the introduction of a laminated heated visor, where the electrical heat element was sandwiched between two layers of acrylic. This required a new development effort since nobody had laminated a heated double-curvature lens, although Protection Incorporated in Los Angeles had done some preliminary work on the idea at company expense. David Clark Company supplied laminated visors with later models of the A/P22S-2 suit.[77]

Another requirement came via an unusual source: Project Excelsior. Researchers evaluating the effects of the high-altitude free fall during Joe Kittinger's record balloon jump on August 16, 1960, realized that the X-15 pilot would need to be able to see after ejecting from the airplane. This involved adding a battery to the seat to provide electrical current for visor heating during ejection.[78]

Despite its tremendous improvements over the MC-2, the A/P22S-2 was not perfect and Joe Ruseckas modified the suit based on initial X-15 flight experience. The principal changes included improved manufacturing, inspection, and assembly techniques for the helmet ring to lower the force required to connect the helmet to the suit, as well as the installation of a restraint zipper that removed the structural load from the pressure-sealing closure to lower the leak rate of the suit. Other changes included the installation of a double face seal, to improve comfort and minimize leakage between the breathing space and suit, and modifications to the tailoring of the Link-Net restraint garment around the shoulders to improve comfort and mobility. David Clark Company also solved a weak point involving the stitching in the leather glove by including a nylon liner that relieved the strain on the stitched leather seams.[79]

Around this time, Sears, Roebuck and Co., a major David Clark Company customer for its "Sears Best" brassieres, cancelled its contract with David Clark Company due to a dispute over access to cost-accounting data. This presented David Clark Company management with a challenge to keep its workforce employed. Fortunately, within



The front door to the David Clark Company shows the understated presence the company has maintained for decades. Much of the original wartime development of G-suits and early pressure suits was accomplished on handshakes or using company funds. The company continues the tradition of providing the best possible value to its customers, and is the last remaining Western pressure suit manufacturer.

Dennis R. Jenkins

a short period, the company won a NASA contract to develop the Gemini spacesuit and won a contract with the Air Force to develop the Dyna-Soar spacesuit. This all happened as the company was completing its move from rented space on Webster Street and Park Avenue into its own building on Franklin Street, all in Worcester.[80]

When the Air Force initiated the development of the A/P22S-2 in 1958, it had grand ambitions that almost all of its fighter and bomber pilots would be wearing full-pressure suits as they soared through the stratosphere. The initial production contract with the David Clark Company included provisions for the eventual delivery of "thousands" of suits, and the company procured the material necessary to fabricate this large quantity. Ultimately, of course, reality set in and the Air Force realized that although it was procuring aircraft capable of flying at 50,000 or 60,000 feet, very few flights actually went that high. In the end, only about 500 A/P22S-2 suits were produced, leaving the company with a huge supply of surplus material.[81]

Shortly after the suit was approved for operations, other organizations began looking at the suit to fill their needs. The original Lockheed U-2 models used a partial-pressure suit for their entire careers, mostly because the cockpit was too small to reasonably accommodate a full-pressure suit. That did not mean the idea was not investigated. One of the operating bases for the U-2 was Patrick AFB and the heat and humidity of central Florida caused certain problems. Most missions required a minimum of 50 minutes of oxygen prebreathing, including at least 20 minutes in an ambient atmosphere after the pilot entered the cockpit and was strapped in, and the airplane was pulled out of the hangar and readied for engine start. These conditions caused excessive heat fatigue for the pilot in a partial-pressure suit, and some pilots perspired intensely enough to obstruct their vision.[82]

Major Harry Andonian, chief of the Special Projects Operations Branch of the Air Force Flight Test Center at Edwards and a former U-2 test pilot, ordered an evaluation of using the new A/P22S-2 in a U-2. Captain Budd F. Knapp conducted the evaluation at Edwards using a suit borrowed from the X-15 program. Knapp noted that the X-15 suit included G-protection that would not be required on U-2 missions, and this added a small amount of bulk to the suit.

Captain Robert M. White, an X-15 pilot, showing off a non-X-15 version of the A/P22S-2. Note the backpack parachute and the seat kit that were intended for use in operational aircraft such as the Convair F-102 Delta Dagger and F-106 Delta Dart interceptors.

Courtesy of the David Clark Company, Inc.

On November 14, 1961, Maj. Ralph N. Richardson, chief of the Physiological Support Division at Edwards, provided a ground demonstration in the U-2 for Knapp at the detachment on North Base. Even inflated at 5 psi, Richardson, who was 6-feet, 2-inches tall and weighed 195 pounds, could reach all of the essential switches and controls in the U-2 cockpit. Two days later Knapp had an altitude chamber run to 125,000 feet, and on November 28, Knapp had a familiarization flight in the JTF-102A that he indicated, "… added little to the evaluation… but was required by regulation."[83] He found the suit easier to get into than the MC-3 partial-pressure suit normally worn, with the entire donning process taking less than 5 minutes. The suit had two pressurization levels available: 5 psi, which maintained the equivalent of 27,000 feet, and 3.5 psi, equivalent to 35,000 feet. Both offered more protection than the 45,000-foot equivalent skin pressure afforded by the MC-3 partial-pressure suit.

The modifications to the U-2 to accommodate the A/P22S-2 were few and simple to implement, mostly bringing high-pressure oxygen to the correct location to connect to the suit and an electrical connection for the visor heat. On November 30, 1961, Knapp flew a 3-hour and 15-minute flight in a U-2 while wearing the A/P22S-2 inflated to 5 psi. Unlike flights using the MC-3, prebreathing prior to the flight was not required with the full-pressure suit. The flight reached a maximum altitude of 50,000 feet and replicated a typical weather mission that required operating switches at the cockpit extremities. Knapp "failed" the cabin pressurization at 49,000 feet and reported "mobility is not as good as the partial-pressure suit at this altitude."[84] The pilot reported, however, that based on his altitude chamber flight, the A/P22S-2 offered superior mobility above 55,000 feet. Knapp reported that visibility was much better in the A/P22S-2 than the MC-3.

Knapp flew a second flight on February 15, 1962, at the "peak performance altitude" of the U-2 with the suit inflated to 3.5 psi. After this flight, Knapp reported that on both flights, he could, with some effort, reach the defrost fan switch located on the extreme rear of the left console.

Knapp noted that oxygen consumption was about double using the A/P22S-2, and he indicated that the second flight, which had been planned for 8 hours, was terminated after 5.5 hours when the oxygen supply was depleted. In general, Knapp characterized the A/P22S-2 as more comfortable than the partial-pressure suit, but he criticized the helmet and gloves. The helmet issue appeared to be a fit problem, but Knapp noted the gloves did not seem to provide any ventilation for the hands, resulting in excessive perspiration. In addition, it was difficult to manipulate some switches when the gloves were inflated.

In the end, Knapp reported that the A/P22S-2 was "not acceptable at this time for all around mission accomplishment in the U-2."[85] This was based largely on the oxygen-consumption rate that would not allow operational missions to be flown. Nevertheless, Knapp thought the full-pressure suit offered promise and suggested a continuing evaluation. It is unclear if this ever took place, but the original U-2 models used partial-pressure suits until they were finally retired in 1989.

Back to the suit's intended users, in late 1961 the Air Defense Command (ADC) conducted a comparative test of full-pressure suits and concluded that the A/P22S-2 met its needs better than the A/P22S-3 (Navy-Goodrich Mark IV). The relative merit of the Navy suit was a subject that would not go away and several other evaluations would take place over the next few years.[86]

At the end of 1961, David Clark Company introduced the S931 model, intended specifically for the F-106 interceptor. This suit included a side zipper at the waist; helmet holddown straps that were anchored on the back of the suit, and a new adjustment on the front of the suit; reconfigured neck and wrist rings; ventilation for the feet; relocated controller and vent fittings; and gloves that used Link-Net on the back.[87]

The minor improvements of the S931 notwithstanding, as early as March 13, 1962, the ADC recommended the Air Force undertake an effort to develop an improved A/P22S-2. Primary among the improvements desired by the ADC was to alleviate the glare and reflection from the inner surface of the helmet sunshade and visor, include a warning device to indicate a loss of pressure in the visor seal, and improve the ease of connecting the wrist and neck rings. In addition, the ADC wanted a lighter, more durable suit that was easier to don and doff, with a more reliable pressure-sealing zipper. The gloves were singled out for improvement in dexterity, comfort, and durability.[88]

As he prepared to retire in 1962, David Clark, the man, gave a percentage of the David Clark Company to the College of the Holy Cross in Worcester. Holy Cross is the oldest Roman Catholic college in New England and one of the oldest in the United States. Finally, to raise capital for the company before he left, Clark sold his remaining share to Munsingwear, to which he had already sold a major interest. The sale to Munsingwear had little effect on the operations of the company, other than providing a needed boost in capital. By 1965, Munsingwear had acquired the Holy Cross portion of the company also.[89]

In 1975, Clark's successor as president, John E. Flagg, along with company Treasurer Darald Libby and a few senior managers, bought David Clark Company back from Munsingwear. Ownership has remained within the company ever since, with a combination of senior management and employee stock ownership plans. As of 2009, David Clark Company was a 100-percent-employee-owned business. The employees

Excepting the X-15 program, this was the standard operational configuration of the A/P22S-2 suit with a parachute and a seat kit that held the suit support systems and emergency oxygen. The X-15 used a back kit instead of a seat kit. Note the spurs on the back of the boots that were used to lock the pilot's feet in the ejection seat to keep his legs from flailing as he left the airplane.

Courtesy of the David Clark Company, Inc.

believe the significance of this ownership heritage is that each successive generation of owners has come from within the company and chosen to perpetuate the continuous advancement of pressure-suit-related technologies that David Clark initiated during the 1940s. Executive Vice President Jack Bassick opined that, "each generation of owners-managers has remained interested and in touch with the company throughout their entire lifetimes. We are presently transitioning from the third to the fourth generation of senior management, with my (third) generation being the last one to have known Dave personally."[90] It has obviously worked well since David Clark Company has been the primary (and, often, only) supplier of pressure suits in the United States.

In February 1963, the ADC conducted an operational evaluation using A/P22S-2 suits in a two-seat Convair F-106B Delta Dart interceptor. Ten flights were conducted from 10 different USAF bases that totaled about 23 hours of flight time, all flown by Maj. Edward W. Kenny and Capt. Robert I. Platenberg. Both pilots had limited experience in the MC-3 and MC-4 partial-pressure suits prior to the evaluation. In general, the pilots found the A/P22S-2 comfortable, but both complained about the lack of ventilation in the gloves and reported that their hands perspired excessively. Unusually, the pilots took matters into their own hands, literally, and each purchased a pair of nylon insert gloves that they wore under the pressure gloves. They reported that this substantially eliminated the perspiration problem. The pilots indicated that the faceplate defogging system worked very well, even at Duluth AFB and Loring AFB, where the temperature was well below zero. They made one landing at the Colorado Air National Guard Base at Buckley Field, CO, expressly to determine what difficulties would be encountered landing at a base with no facilities or experience with pressure suits. According to the pilots, "no major problems were evidenced."[91]

In general, the pilots found no substantial faults with the A/P22S-2 during their whirlwind tour. Excepting the perspiration issue with the gloves, the list of complaints was small. For instance, the helmet had to be fitted carefully to avoid discomfort, the knife pocket on the left leg restricted stick movement and should be moved, care had to be taken when reaching for some controls since the wrist rings might accidently actuate the wrong control, and the visor did not adequately eliminate glare on the radar scope. During the 10 flights, the crew spent between 3 hours, 30 minutes and 12 hours, 15 minutes in the suits every day without major complaint. Overall, the evaluation concluded that "aircrews can wear the A/P22S-2 with the minimum amount of discomfort, accomplish the assigned mission, and still be afforded the protection that the full-pressure suit will provide."[92] Nevertheless, the ADC wanted several modifications.

In response, on March 1, 1963, the USAF awarded the David Clark Company a contract to develop the improved A/P22S-2A version of the full-pressure suit. Joe Ruseckas began working on the new suit on April 4, 1963, and delivered an improved helmet visor to the USAF on January 13,1964, with the rest of the suit following 10 days later. The A/P22S-2A differed from earlier versions by having a larger helmet that included commercial radio equipment compatible with the AIC-10A standard and rearranged pressurization and oxygen controls. Improved gloves used different materials and eliminated the slide fasteners in favor of two adjustment straps. The outer layer now had a black leather palm and fingers and an aluminized-nylon back and wrist. The coverall incorporated a B.F. Goodrich pressure-sealing slide fastener in the crotch area that served as a relief opening. The knife pocket was relocated based on numerous pilot comments about it restricting control stick movement, the helmet ring and latch were sturdier, and the wrist-attach rings were redesigned to be simpler and more reliable. The resulting suit was slightly heavier than the standard A/P22S-2—20.12 pounds compared to 19.95 pounds. This was a little deceptive since the coverall was almost 2 pounds lighter than the earlier version, but the helmet was 2 pounds heavier. Testing and evaluation of the A/P22S-2A determined that the new suit "shows some improvement" but that "further improvements are required to make the outfit more operationally acceptable."[93] There is no record that this version of the suit entered production or was issued to operational squadrons.

As late as July 1963, the Tactical Air Command (TAC) was still evaluating the relative merits of the A/P22S-2 and the A/P22S-3 (Navy-Goodrich Mark IV). In addition to the two American full-pressure suits, the tests also compared the RAF jerkin pressure vest that only covered the torso and crotch. The jerkin was donned through a sliding fastener running from the center of the neck down to the front of the left leg. It was possible to don the jerkin in a few seconds, versus the 5 minutes it took to get into either of the full-pressure suits. The jerkin used a blue-gray Terylene outer fabric and a blue-gray nylon inner layer. Between the two fabric layers was a textured rubberized silk bladder that completely inflated the jerkin except for a small portion of the buttock and the small of the back. The jerkin had to be used with a pressure-breathing oxygen mask and was worn over a standard G-suit.[94]

Joe Ruseckas and Robert R. "Bob" Banks from David Clark Company witnessed some of the tests and were surprised about the inclusion of the Navy suit since they believed the USAF had already eliminated that suit from contention a year earlier. The purpose of this particular test was to determine which suit would be best suited for use in the new McDonnell F/RF-4C Phantom II, in particular, how much infrastructure was required to support full-pressure suit operations. The Navy was already using the Mark IV suit in the F-4B version of the aircraft. The test order pointed out that while the Navy generally operated from established shore bases or well-equipped aircraft carriers, and the ADC operated from bases in the continental United States, the TAC routinely operated from austere bases in other countries.[95]

Col. Frank K. "Pete" Everest and Capt. Stanley G. Sprague flew the tests from the 4453rd Combat Crew Training Squadron at MacDill AFB, FL on July 16–17, 1963. Since the USAF F-4C was not yet available, the tests used one of the 47 Navy F-4Bs operated by the 4453rd. Like most early F-4Bs, these aircraft were equipped to use the Mark IV pressure suit but were easily adapted to use the A/P22S-2. The test determined that the A/P22S-2 better suited the USAF requirements than the Navy or RAF garments, but it also resulted in a rather long list of relatively minor changes that could improve the A/P22S-2.[96]

The search for an improved suit continued, and in August 1964, the David Clark Company began developing the A/P22S-2A (Mod 1) suit. The first article was delivered

David Clark Company fabricated special versions of the A/P22S-2 for the NASA and Air Force lifting body programs. This is NASA test pilot William H. Dana standing in front of the HL-10 lifting body on one of the dry lakes at Edwards AFB, CA. Note the portable air-conditioning unit attached to the suit to keep Dana cool in the High Desert.

NASA

Bill Dana being interviewed following the last flight of the X-24B lifting body on September 23, 1975. The David Clark Company had agreed to supply NASA with white A/P-22S-2 pressure suits and black boots for the lifting body pilots. At his fitting, Dana found his suit had white boots, which he opined were not sufficiently masculine for a test pilot. "I might as well wear pink boots," he said, a comment that was not lost on the David Clark technicians. When Dana's suit was delivered, it came with standard black boots. However, the David Clark technicians, remembering the earlier comment, also provided a second pair—pink with adhesive flower decals. To his credit, Dana wore the boots on his next HL-10 flight and again during his final X-24B flight. Great test pilots have a sense of humor, even at their own expense.

NASA

to the USAF in May 1965. The suit used a monolithic, conductive-coated visor that was similar to the one used during the X-15 program, and the visor and sunshade knobs were reworked to provide better tactile feedback when moved. The top back of the helmet contained an exhaust valve developed for the Navy Mark IV suit, and a new suit controller, developed by Firewel for the Mark IV, was mounted on the right-front center of the coverall. Improved gloves had white leather palms and fingers, and the index finger outseam was moved to the back of the finger to provide a better sense of feel. The inside of the gloves were lined from the wrist to the base of the thumb and fingers with a chloroprene-coated

Air Force pilots assigned to the lifting body programs also wore the custom white A/P22S-2 suits with black boots. From left are Maj. Jerauld R. Gentry, Maj. Peter C. Hoag, John A. Manke, and William H. Dana. Note the Air Force pilots have an Air Force Flight Test Center (AFFTC) patch on their suits, while the NASA pilots have a NASA "meatball."

NASA

ripstop nylon liner to distribute ventilation air. The wrist ring was modified with a rotating bearing to provide more mobility. The material in the outer layer was changed to provide better mobility, and the pockets were moved to the front of the legs so they did not interfere with the control stick or other items in the cockpit.[97]

Air Force evaluation of the A/P22S-2A (Mod 1) did not show any marked improvement over the earlier suits. In particular, the results showed no particular difference in the efficiency of the ventilation system. Surprisingly, in some tests, the (Mod 1) suit appeared to inhibit mobility more than the standard suit. The new gloves, and a similar change to the socks, were not particularly successful and were "not considered practical at this time."[98] The rotating wrist bearing would find use on the special A/P22S-2 suits (S935) fabricated for the NASA lifting-body program but would otherwise have to wait until the much later S1034 to be included on a standardized USAF full-pressure suit. Like the A/P22S-2A before it, the (Mod 1) suit did not enter production.

Production of the A/P22S-2 continued, albeit at rates far below the original estimates. Although the USAF designation did not change, the David Clark Company model numbers changed frequently and included: S906 (X-15), S926, S931, S934, S935 (NASA lifting bodies), S940 (X-15), S963, S971, S998 (X-15), S1016, and S1027 (X-15). The S935 featured a different method to exhaust pressurization air to make it compatible with the lifting bodies, and it used the rotating wrist ring originally developed for the (Mod 1) suit. The custom-fitted X-15 suits used a thicker visor and a different visor-heat system, as well as a back kit instead of a seat kit so they could be used with the X-15 ejection seat. The final S1027 suits fabricated at the end of the X-15 program were custom fitted for NASA test

The vast majority (163 of 199) of flights of the hypersonic North American X-15 research airplane used A/P22S-2s instead of the original MC-2 suits. The pilots found the newer suit to be much more comfortable. Interestingly, even pilots that complained about restricted mobility when the suit was on the ground seldom mentioned it when they were faced with using it in flight. Adrenalin is a wonderful thing. Note the "mission marks" on the back of the life-support van. Unlike the standardized A/P22S-2, the X-15 suits were custom tailored for each pilot.

NASA

pilots William H. Dana and John A. Manke, and for Air Force pilots Maj. Michael J. Adams and Maj. William J. "Pete" Knight.[99]

On November 22, 1968, an F-104C crashed near Mojave while on a training mission, killing Maj. Kermit L. Haderlie, a student from the USAF Aerospace Research Pilots School (ARPS) at Edwards. For students at the ARPS, the zoom climb was a rehearsal for possible future spaceflight. The pilots always wore A/P22S-2 suits since the Mach 2 climb continued until the General Electric J79 engine flamed out, which deprived the cockpit of pressurization. The Air Force accident board determined that a "design deficiency" in the suit wrist ring allowed an "inadvertent disconnection" of Haderlie's glove while he was at altitude.[100]

Air Force suit-donning procedures originally required the glove-locking ring to be taped over to increase the force required to move the sliding lock and thus reduce the possibility of an inadvertent unlocking. Oddly, in the spring of 1968, taping was removed from the donning procedure. On his fatal flight, Haderlie reported his pressure suit inflated as expected while passing through 50,000 feet. However, as he reached 63,000 feet, Haderlie reported "I lost my glove," and the Starfighter began tumbling.[101] The accident report indicates the F-104 reached 69,400 feet before it began an inverted dive toward the desert. At the time of the accident, the USAF had more than 400 A/P22S-2 suits in inventory.

Because of the impending 60-month service-life expiration of the A/P22S-2 assemblies, in early 1967 the Air Force had initiated a program to develop an improved suit. Joe Ruseckas and the rest of the David Clark Company went back to the drawing board. By this time, David Clark Company was well into the development of the spacesuits for Gemini and Dyna-Soar and had gained considerable experience with the "special projects" (Lockheed A-12 and SR-71 Blackbird) suits. Ruseckas felt it "desirous to investigate these for possible incorporation."[102] The designers at David Clark Company conducted numerous experiments and came up with a variety of improvements for a suit that the USAF subsequently designated A/P-22S-4.

A/P22S-3—A NAVY SUIT FOR THE AIR FORCE

The Air Force decision not to field the MC-2 in great numbers and to develop the A/P22S-2 suit delayed the introduction of a full-pressure suit to operational units. The ADC, in particular, was not happy about this turn of events, so in May 1960, the USAF procured a small number of the Goodrich Mark IV full-pressure suits developed for the Navy. The suits were procured by the Navy under contract N383(MIS)165773 and designated A/P22S-3 in USAF service. It appears that Goodrich manufactured all A/P22S-3 suits and that no Arrowhead suits were used by the Air Force. The first eight Air Force suit technicians from the 4756th Physiological Training Flight at Tyndall AFB, FL, arrived at the Goodrich plan in Akron in early May 1960 for indoctrination.[103]

The A/P22S-3 suit was generally similar to the Mark IV except for different communication and oxygen hose connectors, a different suit regulator, and a short hose pigtail attached to the suit to reach the USAF aircraft connectors. In addition, the standard Mark IV helmet was painted white with a USAF wing decal (instead of being gold with a Navy decal), and the restraint layer was international orange instead of olive drab. Since the suits were being procured primarily for the ADC, the A/P22S-3 did not include the normal G-suit connections (the Mark IV used a standard G-suit under the full-pressure suit).[104]

Despite the late-1961 evaluation that concluded that the A/P22S-2 was the preferred suit, the ADC conducted another evaluation in mid-1962. This "Comparative Test of Aircrew Pressure Suits" evaluated the David Clark A/P22S-2 and the Goodrich A/P22S-3 full-pressure suits alongside the CSU-4/P and CSU-5P partial-pressure suits.[105]

The ADC selected the 325th Fighter Interceptor Squadron at Truax AFB near Madison, WI, to conduct the evaluation. Six pilots from the squadron each wore all four suits during day and night high-altitude missions using Convair F-102 Delta Dagger interceptors. Ultimately, the squadron flew 60 daytime sorties and 27 night sorties for a total of 124 hours and 55 minutes of flight time. Of these flights, 24 were flown with the suits unpressurized and 63 with the cockpit pressurization "dumped" so the suits would pressurize for at least part of the mission. In all, 24 sorties were flown with the A/P22S-2, 19 with the A/P22S-3, 20 with the CSU-4/P, and 24 with the CSU-5/P. The pilots evaluated the suits in a readyroom environment that simulated 5-minute alerts lasting up to 6.5 hours. The suits were also evaluated during cockpit alerts that lasted up to 2 hours, although the pilots did not wear gloves or helmets while in the cockpit. During these

Not much remains of the Air Force's A/P22S-3 suit program, which was a slightly modified Goodrich-Navy Mark IV. Like many contemporary pressure suit gloves, the A/P22S-2 glove used leather on the palm to provide better feeling for the pilot. However, the glove fared poorly during Air Force cold-weather evaluations.

Courtesy of the David Clark Company, Inc.

tests, the pilots rated each suit as satisfactory (S) or unsatisfactory (U) in 10 categories. The results are shown in the accompanying table; note that not every pilot rated every suit.

The evaluators noted that although suit donning was not an evaluation category, every pilot commented on the merits of the A/P22S-2, which could be donned unassisted in about 5 minutes. The pilots were also unanimous in praising the relative comfort of the A/P22S-2 and confirmed they could reach all of the controls and circuit breakers in the F-102, although it was not possible to see the left and right aft circuitbreaker panels.[106]

Given the excellent reputation of the Goodrich Mark IV suit in Navy service, it is interesting to note its rather dismal showing in the USAF evaluation. Part of this might be attributed to the suits not fitting properly at first, mostly because of a lack of experience from the suit technicians assigned to assist the pilots. The ratings tended to improve toward the end of the test after everybody had become more familiar with the suits, but the overall comfort and mobility ratings of the A/P22S-3 never matched that of the A/P22S-2. The pilots also did not appreciate the tight fit of the Navy suit and reported that it was difficult to don.

Because the pilots were used to wearing partial-pressure suits, the CSU-4/P fared well in the evaluation, with all of the pilots feeling it provided excellent comfort and mobility, even when pressurized at 55,000 feet. Nevertheless, the pilots felt that the suit was difficult to don, and they disliked that the suit would partially inflate when the wearer took a deep breath.

The CSU-5/P fared less well, primarily because the pilots felt it was too bulky (the result of the anti-exposure features integrated into the suit, rather than added over it as with the CSU-4/P). The evaluators noted that a near accident caused by the CSU-5/P, when

Table 5—Pilot Evaluations of Pressure Suits

	A/P22S-2		A/P22S-3		CSU-4/P		CSU-5/P	
Category	S	U	S	U	S	U	S	U
Aerial Comfort	42	—	4	28	33	1	38	2
Ventilation	42	—	28	2	34	—	37	3
Mobility	42	—	3	29	34	—	40	—
Aircraft Control	42	—	23	9	34	—	40	—
Weapons System Control	42	—	19	9	31	3	39	1
Vision	42	—	32	—	33	1	40	—
Communication	42	—	33	—	34	—	40	—
Flight Safety	42	—	32	—	34	—	39	1
Ground Comfort	12	—	—	12	12	—	3	9
Ground Mobility	12	—	—	12	12	—	11	1
Total	*360*	—	*171*	*101*	*291*	*5*	*327*	*17*
Overall Rating	100		63				95	

Source: Capt. Norman R. Smedes, 4750th Test Squadron, Tyndall AFB, FL, "Comparative Test of Aircrew Pressure Suits," Project ADC/734AD/60-11, April 1, 1961.

a pilot on final approach lowered his landing gear and inadvertently caught the suit-to-glove bladder hose on the throttle, shutting down the engine. Despite the precarious situation—1,000 feet above ground level, landing gear down, and only 220 knots—the pilot executed a successful air start and landed normally. The evaluators recommended the two partial-pressure suits be modified to cover the wrist hoses to prevent similar accidents in the future.[107]

Each suit was also tested at the All-Weather Climatic Laboratory at Eglin AFB, FL. This large facility is able to reproduce just about any imaginable weather condition, from well below zero to over 100 °F. The pilots entered the chamber equipped with only those items they would likely have after an ejection. For all tests, a flight surgeon observed the pilots to ensure they did not endanger themselves. The results of these tests were enlightening.[108]

The chamber was initially chilled to –5 °F and lowered 5 degrees per hour until it reached –25 °F. The wind, generated by a large fan, blew between 5 and 30 mph, and there was 4 feet of snow on the floor. The pilot wearing the A/P22S-2 suit had to leave after 2 hours and 30 minutes, complaining of a backache. The flight surgeon determined his backache was the result of a too-short suit, so the pilot donned a larger suit and returned to the chamber. He participated with the others in building a snow shelter, and the pilot exited the chamber after 5 hours and 20 minutes, indicating he could have remained for an indefinite time. The pilot wearing the A/P22S-3 suit also worked on the shelter, but he left the room after 2 hours and 15 minutes complaining of extremely cold hands and feet. His legs and knees were also cold, and his neck ring was frozen, preventing his helmet from rotating. He donned a second set of long underwear and returned to the chamber for an addition 2 hours and 40 minutes but still complained of being cold. For an hour, he wore a "combi suit" (a walk-around sleeping bag) and booties, which seemed to provide adequate warmth. The total time in the chamber was 4 hours and 55 minutes.

The pilot wearing the CSU-4/P also wore a CWU-4/P anti-exposure suit and wool mittens from his survival kit. He left the chamber after 3 hours and 20 minutes to relieve himself. Thirty minutes after returning to the chamber, he complained of extremely cold hands and feet. After donning a second set of long underwear and socks, he remained in the chamber for another 1 hour and 15 minutes. At the end of the test, after 5 hours and 5 minutes in the cold chamber, he was cold but otherwise mobile and healthy.

The CSU-5/P was intended for water survivability. The pilot worked on the shelter and left the chamber after 4 hours and 10 minutes to relieve himself. He was in good condition except for coldness around the neck ring, caused by an improper helmet adjustment that allowed condensation from the faceplate to drain into the neck seal. After the helmet was adjusted, the pilot returned to the chamber for a total of 5 hours and 45 minutes.

Cold-water tests were conducted in Lake Superior at Duluth, MN, where the air temperature varied from 10 to 21 ºF, the water temperature was 33 ºF, and wind blew from 10 to 18 knots. The subjects jumped into the lake from a 10-foot height wearing inflated LPU-2/P underarm life preservers. Each pilot was supposed to remain in the water for 15 minutes and then board a one-man life raft. Once again, a flight surgeon observed the pilots and took periodic oral temperature readings.

The pilot wearing the A/P22S-2 suit remained in the water for 15 minutes, boarded the raft for 1 hour and 15 minutes, and then returned to the water for 15 minutes before terminating the test. He displayed no outward symptoms of exposure during or after the test but did complain of being cold. After leaving the water, he could walk with ease and his overall condition and demeanor appeared normal. The A/P22S-3 suit provided substantially similar results, not surprising given the premium the Navy placed on cold-water survival during its development.

After only 1 minute in the water, the pilot wearing the CSU-4/P and CWU-4/P became extremely cold, and after 15 minutes, he had considerable difficulty boarding the raft because his legs were numb. He looked extremely cold and was shivering after 15 minutes in the raft but indicated he was okay. Ten minutes later, he began to shiver violently and the flight surgeon terminated the test. The pilot's legs were so numb he had to be helped from the raft, and his oral temperature had dropped to 94 ºF.

The CSU-5/P fared no better. After only a minute in the water, the pilot became very cold and climbed into the raft without significant difficulty. However, 10 minutes later, he became extremely cold and the flight surgeon terminated the test. The pilot's oral temperature was 95 ºF, but he was in relatively good condition compared to the subject in the CSU-4/P.

The tests clearly showed the advantage of the full-pressure suits to protect the wearer against a harsh environment. Neither of the partial-pressure suits was truly useable for more than an hour, even when equipped with an anti-exposure cover. The two full-pressure suits, on the other hand, were demonstrably satisfactory for 5 to 6 hours, and possibly much longer.

In the end, the evaluation recommended that if a pressure suit was to be made standard equipment, that the A/P22S-2 should be selected. The report also contained a list of recommended modifications for the suit. The glare and reflection on the visor needed to be reduced, and the visor should be operable with one hand. In addition, the face-seal adjustment should be made independent of the earphone adjustment. On the suit itself, a small altimeter should be installed on the left thigh (it was, on some versions) and the suit controller should be made smaller. The flight surgeon also commented that each suit should come with two pairs of waffle-weave long underwear, as well as two pairs of cotton long underwear. The evaluators believed the F-102 should be modified with additional oxygen storage, a better ventilation unit, and a larger radarscope hood to accommodate the full-pressure suit helmet, and they also believed that each squadron should receive sufficient portable ventilation units and suit-tester units.[109]

The Air Force ultimately standardized on the David Clark A/P22S-2 full-pressure suit, and the Goodrich suit had a remarkably short USAF career. It could not be determined from available documentation exactly how many Goodrich suits were purchased or if they were ever issued to operational squadrons.

A/P22S-4 AND A/P22S-6—EVOLVING THE CONCEPT

During January 1967, the USAF awarded David Clark Company a contract to modify the final A/P22S-2A (Mod 1) development suit into a prototype A/P22S-4 suit.[110] The company developed the A/P22S-4 under the sponsorship of the 6570th Aerospace Medical Research Laboratory and Systems Engineering Group at Wight-Patterson AFB.

The A/P22S-4 was the result of the ADC's desires to improve the A/P22S-2. The first results were the A/P22S-2A and A/P22S-2A (Mod 1) suits, but, ultimately, they did not provide sufficient improvement to justify production. After the (Mod 1) effort, Joe Ruseckas and David Clark Company went back to basic research to determine the best method of improving the earlier suits. The advances developed during this research were incorporated into the Gemini and Dyna-Soar spacesuit efforts.[111]

Although pilots almost universally praised the A/P22S-2 for being easy to don and doff in comparison to other pressure suits, everybody realized it needed to be made easier if it was going to routinely meet the ADC's 5-minute alert requirement. For the new suit, Ruseckas eliminated the U-entry of the A/P22S-2 and used a 37-inch pressure-sealing slide fastener that started at the front crotch and extended up the back parallel with the spine to a point 12 inches below the neck ring. This dictated major revisions to the gas container and restraint coverall. The resulting rear-entry closure was similar in many respects to the opening developed for the David Clark Company Gemini spacesuits.

Moving the main entry to the back allowed the gas container to be shaped to better fit the chest, waist, and hips. The closer-fitting garment allowed easier movements by the wearer when pressurized. Molded flanges were incorporated for the wrist rings, making it easier to replace the hardware when needed. The upper torso on the A/P22S-2, except for the shoulders and parts of the chest, had been made from marquisette, which somewhat limited the mobility of the wearer. For the A/P22S-4, the upper torso was constructed entirely from Link-Net, which also allowed the layer to be adjusted to fit the wearer easier than the marquisette garment. Previously, the major deterrent from using a vertical rear-entry closure was sizing limitations around the waist and hips. The use of Link-Net largely solved these problems, and the restraint layer included adjustment laces on the forearms, waist, and each side of both legs. A takeup panel around the waist and hips extended up and around the main entry at the back and allowed adjustments without disrupting the slide fastener. This capability was a major advance over the A/P22S-2, for which torso adjustments were limited. By now, David Clark Company had figured out how to machine-make Link-Net, whereas previously, it had been entirely hand woven. It also had become obvious that the expected procurement of "thousands" of pressure suits was hopelessly optimistic, so expanding the use of Link-Net was not a major cost driver.

The exterior cover was also changed significantly, mostly to conform to the rear entry and to improve mobility. Pocket locations, a seemingly trivial thing that was the source of many comments from pilots, were changed. The calf pockets were moved to the front of the leg to allow easier access by a seated pilot and the knife pocket was moved to the outside of the left thigh so as not to interfere with control-stick movements. There was also a cigarette pocket with pencil slots on the left sleeve. Most of these changes had been incorporated on the A/P22S-2A or (Mod 1) suits.[112]

An improved neck ring was similar to the one developed for the Gemini suit. On the A/P22S-2, it was necessary to position the helmet, seat it in the ring around the entire circumference, hold it in place, and then secure its locking ring. The improved neck ring replaced the locking balls with stainless steel latch dogs that held the helmet securing in place while the pilot rotated the locking ring.[113]

The gloves, always an object of criticism from the pilots, used softer leather but were otherwise unchanged. The full-pressure gloves had a dipped neoprene bladder covered by Nomex fabric, leather, and Link-Net. Straps on the back of the gloves provided for personal adjustments and palm restraints. The gloves attached to the suit at a nonrotating wrist disconnect.[114]

After production of the A/P22S-4 and A/P22S-6 suits began, David Clark Company developed a double latch for the lock on the glove disconnect that required a more intentional and deliberate action to unlock prior to glove removal. The new latches required that two fingers be used to depress them prior to sliding the lock into the open position and then rotating the disconnect ring to the unlocked position. This was in response to numerous incidents concerning the glove disconnect. This same wrist ring would be used on the A/P22S-4, A/P22S-6/6A, S901J, S1010, S1030, and S1031. It was not until the S1034 and S1035 that David Clark Company adopted a new ring using a rotating bearing. Interestingly, the rotating bearing idea, first seen on the A/P22S-2A (Mod 1), had been around for a while, and David Clark Company used it on special A/P22S-2 suits for the NASA lifting body program and the Gemini spacesuits and S901H special projects suit.[115]

The helmet consisted of a molded fiberglass shell, a cushion assembly that came in five sizes, a movable visor and independently movable sunshade, a neoprene-coated-fabric face barrier, an anti-suffocation valve, and a communications system. Oxygen was supplied through a rear helmet entry, via plumbing to the oral-nasal cavity. Exhaled gases were vented through a valve in the face barrier where they were routed with ventilating air back to the suit and eventually exhausted through the suit controller. Two different electrically heated acrylic visors were available: a laminated visor that used a wire grid, and a gold-coated conductive version. The aneroid-operated pressure-demand regulator delivered breathing oxygen to the breathing area of the helmet and automatically delivered makeup pressure to the suit in the event of pressure loss.

The helmet holddown assembly consisted of an endless-loop stainless steel cable that passed through metal guides on each side of the helmet disconnect ring. The cable also fed through nylon pulleys on the front and back of the suit. The front pulley was attached to an adjustable holddown latch used for helmet height adjustment.[116]

By mid 1966, when a service test quantity of A/P22S-4 suits became available, the ADC had largely abandoned using full-pressure suits, regardless of its drive to create the new suit. Despite an apparent lack of interest, on March 8, 1967, the ADC published Required Operational Capability (ROC) ADC-9-67 for a "Physiological Protection Garment." After a rather brief evaluation, the ADC concluded that the A/P22S-4 suit did not satisfy the ROC requirements.

It is possible the Royal Australian Air Force used A/P22S-4 suits in its F-111C fighter-bombers. The United States did not use pressure suits in its F-111, although some test flights did. Here is General Dynamics test pilot Val Prahl in an A/P22S-2 getting ready for a flight in an early F-111A. Note the U-shaped entry zipper and the leather knife pocket on the front of the left thigh.

Courtesy of Lockheed Martin Aeronautics

The A/P22S-4 (S1023) was available in the standard eight sizes, based on nude height and weight. Seven sizes of restraint boots and four sizes of flocked boots were available. The standardized A/P22S-4 ensemble consisted of the HGK-19/P22S-4 helmet, orange CSK-8/P22S-4 coveralls, and HAK-10/P22S-4 gloves.[117] Apparently, David Clark Company produced only 17 A/P22S-4 suits for the USAF, significantly fewer than the number of A/P22S-6/6A suits that were fabricated. In addition, David Clark Company made a few sage-green A/P22S-4 suits for the Royal Australian Air Force, although exactly what airplane they were used in is unclear.[118]

Despite its considerable investment, much like the Navy, the Air Force quickly lost interest in the concept of an operational full-pressure suit. By 1965, the Strategic Air Command had decided that low-level bombing was the way of the future and began modifying the B-52 for nap-of-earth (very low altitude) penetrations, essentially eliminating the need for pressure suits in strategic bombers. The ADC was seldom flying zoom intercepts, and its pilots did not like any of the pressure suits they had evaluated. As Jewel Melvin later noted, "Fighter pilots were accustomed to being relatively unencumbered to fly the airplane. They yearned for the scarf and goggles days and the suit took them in the opposite direction."[119] The TAC was too occupied with the build-up in Southeast Asia to be concerned with high-altitude flight. Ironically, besides the Air Force Flight Test Center and NASA, the major user of the A/P22S-2 was the Military Airlift Command (MAC), specifically, the 58th Weather Reconnaissance Squadron (WRS) that flew the General Dynamics WB-57F high-altitude reconnaissance aircraft. This, of course, ignores the other user of full-pressure suits: the CIA.

With the future of a standardized full-pressure suit now in doubt, on October 25–26, 1967, the Aeronautical Systems Command held a conference with the MAC.[120] The B-57F program began when the Air Force sought an aircraft with better performance than the RB-57D, which had been procured as an interim reconnaissance aircraft pending the development of the U-2. Because General Dynamics was responsible for contract maintenance on the RB-57Ds, the USAF asked the company to develop what became the RB-57F. The prototype made its first flight on June 23, 1963, using a new wing that spanned more than 122 feet—some 14 feet more than the RB-57D and nearly double that of the original B-57B. General Dynamics replaced the Wright J65 turbojets with Pratt & Whitney TF33 turbofans that provided twice the thrust. The empennage was also altered to provide sufficient stability and control at altitudes up to 80,000 feet. Eventually, General Dynamics modified 14 B-57 airframes into F-models.[121] At some point, the USAF changed the RB-57F designation to WB-57F to reflect the weather-centric mission of the airplane.

The 58th WRS at Kirtland AFB, NM, received its first airplane in 1964 and deployed around the world to sample the upper atmosphere for evidence of nuclear weapons tests. Structural problems in 1972 forced the retirement of nine of the WB-57Fs, and the other five received new wings. Despite the major modifications to the wings, the 58th WRS retired its last WB-57F on July 1, 1974. NASA operated a single airplane (63-13501, NASA 925) from 1968 until 1982 when it was retired to the Pima Air and Space Museum in Tucson, AZ. In 1972, NASA received one of the airplanes (63-13503, NASA 926) the 58th WRS was retiring and based it at Ellington Field near Houston. During 1974, NASA brought a second airplane (63-13298, NASA 928) out of retirement. These aircraft are still operational in 2010 and routinely conduct scientific research at altitudes in excess of 60,000 feet.[122]

During the summer of 1967, Military Airlift Command (MAC) pilots had conducted six WB-57F flights wearing S901J special projects suits for a total of almost 38 hours of flight time. In general, the pilots greatly preferred the J-suit to the normal A/P22S-2. In addition to these flights, pilots also spent about 30 flight hours using J-suit gloves with the standard A/P22S-2 suits. For instance, Maj. Theodore

Like the A/P22S-4 before it, the A/P22S-6 switched from the U-shaped entry zipper used on the A/P22S-2 to a rear entry. Previously, Joe Ruseckas and the designers at David Clark Company had found a vertical rear zipper created sizing problems around the waist and hips. Switching from the marquisette fabric used in the A/P22S-2 to Link-Net for the entire upper torso solved this problem. Here, the suit is pressurized to 3.5 psi, its normal operating pressure.

Courtesy of the David Clark Company, Inc.

A. Jenson, a command pilot with 5,784 total hours, including 552 in pressure suits, thought the J-suit was better fitting, although he found it was somewhat harder to don and doff. He believed the J-suit was more comfortable both pressurized and unpressurized, and that the soft foam helmet liner eliminated much of the head discomfort with the A/P22S-2. Helmet and glove ventilation were "markedly superior" in the J-suit, as was wrist mobility.[123]

At the time of the October 1967 pressure-suit conference, David Clark Company was under contract for the development and fabrication of the A/P22S-4 suit. Joe Ruseckas explained that the major differences between the A/P22S-4 then under development and the 901J special projects suit evaluated by MAC were the exterior cover, the oxygen system, the pressure-sealing zipper, and the range of sizes. One of the outcomes of the conference was a revision of the David Clark Company contract to reconfigure the A/P22S-4 suit per MAC requirements, instead of ADC requirements.

The resulting suit was designated A/P22S-6 (S1024). The suit was substantially similar to the A/P22S-4 (S1023) except for minor changes that made it more similar to the special projects suit (S901J). These changes included using a softer helmet liner, relocating the external communication leads to the right side of the helmet, incorporating a fire-resistant outer layer, adding a redundant pressure-sealing zipper, and deleting the built-in life preserver. The S-4 was manufactured in the standard 8-size height-weight tariff, while the S-6 was made to the old David Clark 12-size scheme, largely to satisfy the MAC.

During April 1968, the USAF awarded a contract to the David Clark Company to fabricate 72 A/P22S-6 suits. The contract was later amended to provide 72 additional suits.[124] During 1970, the WB-57F crews completed an operational suitability questionnaire for the A/P22S-6, and the results showed the crews preferred the A/P22S-6 to other pressure suits (mostly the A/P22S-2) they had used. Since

The U.S. Air Force does not use pressure suits in its McDonnell Douglas (Boeing) F-15 Eagle fighters. However, the Israeli Defense Forces used the A/P22S-6 full-pressure suit in some of its aircraft for undetermined reasons.

U.S. Air Force

One concern with the pressure suit is the relative clearance of the pilot's shoulders with the sides of the airplane during ejection. These photos show the relative roominess of the rear cockpit (left) of NASA's WB-57F aircraft compared to the front. Each of these pilots is wearing an A/P22S-6 pressure suit. Note that the back-seater has his clear visor down while his tinted visor is still up.

NASA

most had never used a special projects suit, it is unknown if they would have preferred the S901 suit.[125]

The standardized A/P22S-6 ensemble consisted of the HGK-19/P22S-4 helmet, CSK-9/P22S-6 coveralls, and HAK-10/P22S-4 gloves. Note that only the coveralls were different from the A/P22S-4. The last production quantity of A/P22S-6 outfits included shipping containers that were 30 by 12 by 15 inches, approximately 4 inches longer than the containers used by all previous suits. This additional length was requested by the MAC crewmembers to facilitate carrying leather flight boots in the container.[126] David Clark Company also provided 16 A/P22S-6 suits to the Israeli Defense Forces for use in its Peace Jack F-4E(S) and F-15A/Bs.

Despite having talked about pressure suits for a decade, by 1970 the USAF was still struggling with integrating their use into the cockpit of the few aircraft that still needed them. In particular, the General Dynamics WB-57F, Lockheed F-104 Starfighter, and Convair F-106 Delta Dart had cockpits that seemed too small to permit the efficient use of full-pressure suits, despite the fact that the aircraft had accommodated the suits for years. During 1970, the USAF conducted an evaluation to determine the effects of wearing the A/P22S-2 and A/P22S-6 in these aircraft. This included evaluating each suit in the cockpit, both unpressurized and pressurized, as well as conducting anthropometric measurements to study the mobility and reach of crewmembers in the suits.[127]

The concern can be illustrated by noting that the width between canopy sills in the front cockpit of the F-104 was only 26.5 inches, while the width in the F-106 was 27.7 inches and the B-57 was 29.9 inches. An extra-large A/P22S-6, when inflated, measured 27.4 inches across the shoulders, while a medium suit measured 24.85 inches. This made a successful ejection from an F-104 unlikely and cast doubt on the F-106 and B-57. For instance, an extra-large A/P22S-2 would clear the canopy sills in the front position of a B-57 when an ejection seat was raised under a 1-G situation on the ground. But when the suit was inflated to 3 psi, the elbows frequently got stuck under the canopy sill, which during a real ejection at 15-G, would have resulted in tearing the suit or serious injury to the pilot. The back seats of all the aircraft were somewhat wider than the front seat and presented less of an issue, particularly in the B-57.[128]

The evaluation concluded that a pilot sitting in the front seat of the F-104 and F-106 could see and reach all of the instruments and controls with little difficulty. The pilot's knees and legs were in a good position for ejection, but the helmet was too far from the headrest and the arms and shoulders would likely contact the canopy sills. The evaluators stressed that prior to their first flight wearing a pressure suit in a specific aircraft type, each crewmember and an observer should carefully determine if the crewmember could reach all the controls and assume a safe ejection position. This should be done with the suit unpressurized and pressurized. The report concluded that the pilot "should use the outfit operationally in the aircraft only if he and a qualified observer or observers are confident that the above tasks and ejection from the aircraft can be performed in a satisfactory manner."[129]

During July 1970, the San Antonio Air Materiel Area at Kelly AFB, TX called a conference to review improvements to be incorporated into a small production batch of full-pressure suits being procured in 1971. For the most part, the changes to the A/P22S-6A were incremental improvements over the A/P22S-6. The most significant was the addition of a urine-collection system to allow crewmembers to relieve themselves in flight without opening the suit. The urine-collection system, for men only, consisted of an inner hose connected to an external catheter, a release valve, and an external hose attached to a storage bag mounted on the aircraft. The other major change was a stationary hold-down cable guide located near the top of the pressure-sealing slide fastener that replaced the back helmet hold-down pulley. To improve reliability and maintainability, and to increase comfort, the neoprene-flocked boot and nylon-restraint boot were replaced with a neoprene coated oxford nylon boot in four sizes. In addition, the face seal was modified for additional comfort, the torque for the helmet disconnect was reduced, and the leg adjustment cords were modified to prevent breakage. Minor changes included a redesigned oxygen valve, the addition of a pencil pocket that attached with Velcro, elbow patches, different thigh pockets, a new helmet liner cushion, and a revised microphone bracket. The most obvious change was that the outer cover was changed from two-ply sage-green, herringbone-weave Nomex to one-ply international-orange, high-temperature, nylon-twill cloth, and all zippers were changed from dark oxide to bright brass.[130]

The standardized A/P22S-6A (S1024A and, later, S1024B) High Altitude Flying Outfit ensemble included the HGK-19/P22S-4 helmet, CSK-9A/P22S-6 coveralls, and HAK-10/P22S-4 gloves. Note that only the coverall was different from the A/P2S-4 or A/P22S-6. The A/P22S-6A consisted of (from the wearer out) long underwear, comfort liner with integrated vent ducts and antiblock devices, gas container, restraint layer, and the exterior cover. The comfort liner was made of smooth nylon fabric that facilitated donning and doffing, and it reduced friction with the gas container. A series of snap fasteners and fastener tape integrated the comfort liner with the gas container. The vent duct assembly was a network of channels that brought cooling air to the head, torso, hands, and feet. Stainless steel springs in the channels kept them from collapsing as the suit moved. The vent inlet was located on the front-left side of the suit torso.[131]

The A/P22S-6A introduced a variety of changes to earlier suits that improved comfort and serviceability. One major change was a stationary holddown-cable guide located near the top of the pressure-sealing slide fastener that replaced the back helmet holddown pulley in the helmet holddown system. A pulley was still used in front to provide the necessary adjustments.

Courtesy of the David Clark Company, Inc.

The neoprene-coated nylon gas container extended over most of the torso, arms, and legs but not the hands or feet. Combination bladder-restraint boots were attached to the gas container at the calves. A rear-entry pressure-sealing closure extended from the crotch to the upper mid-back. Sizing panels, or cords, on the restraint assembly at the waist, chest, upper and lower arms, legs, and back allowed personal adjustments. The pressure controller was an aneroid-operated device that controlled suit pressure and acted as the outlet valve to discharge vent air. The controller was calibrated to maintain suit pressure at 175 ± 7 mm Hg (3.5 psi, 35,000 feet).

The helmet disconnect ring incorporated a sealed bearing that permitted helmet and head rotation. Vent air passed through a neck-ring ventilation plenum and entered the helmet interior through two slots in the disconnect ring. The helmet holddown consisted of a stainless steel cable that passed through a nylon pulley on the front of the suit and a metal cable guide on each side of neck ring. The cable was secured at the rear of the suit via a retainer assembly that locked the ends of the cable.

Ultimately, David Clark Company produced 80 A/P22S-6A suits. The A/P22S-6 and A/P22S-6A were used in the General Dynamics WB-57F, Convair F-102 Delta Dagger, Lockheed NF-104A Starfighter, Convair F-106 Delta Dart, North American XB-70A Valkyrie, and McDonnell Douglas F-4 Phantom II.[132]

In addition, at least one USAF F-15A received the necessary modifications to use the A/P22S-6 full-pressure suit. Beginning on January 16, 1975, three Air Force pilots and a modified F-15A (72-119) made an assault on the world-class time-to-climb records for aircraft powered by jet engines.

Streak Eagle *pilots (from left) Maj. Willard R. "Mac" MacFarlane, Maj. Roger J. Smith, and Maj. David W. Peterson pose in front of their modified McDonnell Douglas F-15 Eagle. Smith and Peterson wore David Clark A/P22S-6 full-pressure suit on their high-altitude record-setting flights.*

National Museum of the United States Air Force Collection

The three pilots—Maj. Roger J. Smith, Maj. Willard R. "Mac" MacFarlane, and Maj. David W. Peterson—were all members of the F-15 Joint Test Force at Edwards. Pete Garrison, a McDonnell Douglas test pilot, was instrumental in the development of the flight profiles used for the record flights.

On April 1, 1974, the Air Force awarded McDonnell Douglas a $2.1 million dollar contract to modify an early F-15A to support the record attempt. All non-mission critical systems were deleted, including the flap and speed brake actuators, cannon and ammunition-handling equipment, radar and fire-control systems, noncritical cockpit displays and radios, one of the generators, the utility hydraulic system, and, of course, the 50 pounds of paint (hence the *Streak Eagle* name). Significant additions included a revised oxygen system, support equipment for the A/P22S-6, extra batteries, a pitot boom with alpha and beta vanes, an over-the-shoulder video camera, a battery-powered radio, sensitive accelerometers, a standby attitude gyro, a large very-high frequency (VHF) antenna under the canopy behind the pilot, and a special "hold-down" device in place of the tail hook.

All of this effort resulted in saving approximately 1,800 pounds. When weighed in preparation for a 30,000 meter run (on test flight no. 37), 72-0119 weighed 36,799 pounds. For the record attempts, the aircraft was physically held down to the runway while the pilot applied full power. The record runs were accomplished at Grand Forks AFB, ND, where the cold atmospheric conditions were ideal. Six different record flights were flown, and margins of between 15 and 33 percent were achieved over the previous records. Peterson and Smith used A/P22S-6 suits for all flights 15,000 meters and higher.

A highly modified MiG-25 (E-266) later recaptured several of the higher altitude records and set one to 35,000 meters (nearly 22 miles). All of the records have since been broken by the P-42 prototype for the Sukhoi Su-27. There was consideration given to further modifying *Streak Eagle*, including using more powerful production engines, and making another attempt, but this never materialized. *Streak Eagle* was turned over to the Air Force Museum where it is currently in storage.[133]

By 1978, the A/P22S-6 suits were reaching the end of their service lives. The USAF intended to replace the suit with the new High Altitude Protective Outfit, but funds were not available to complete development. In addition, the need for full-pressure suits in the regular Air Force had seemingly disappeared. A limited number of the suits had their service lives extended to support the NASA WB-57F effort and other small needs from NASA and USAF programs.[134]

Streak Eagle *takes off at Grand Forks AFB on one of its record-setting flights. Roger Smith took the airplane to 98,425 feet in 207.80 seconds, although the record has since been broken by a modified MiG-25.*

National Archives College Park Collection

BOYLE'S LAW SUIT

During the late 1960s, a team at the Air Force School of Aerospace Medicine at Brooks AFB developed a different type of pressure suit as part of Project 7164 "Aerospace Protective Technology." The team included Lt. Col. Frederick R. Ritzinger, Maj. Jefferson C. Davis, and MSgt. Henry B. Whitmore with major contributions by Maj. Joseph Boyle III.[135]

Table 6—Streak Eagle Time to Climb Records						
Altitude (meters)	Altitude (feet)	Date	Pilot	Old record (seconds)	Goal (seconds)	Actual (seconds)
3,000	9,843	Jan 16, 1975	Smith	34.50	27.00	27.57
6,000	19,685	Jan 16, 1975	Macfarlane	48.80	38.60	39.33
9,000	29,527	Jan 16, 1975	Macfarlane	61.70	47.90	48.86
12,000	39,370	Jan 16, 1975	Macfarlane	77.10	58.00	59.38
15,000	49,212	Jan 16, 1975	Peterson	114.50	73.70	77.02
20,000	65,616	Jan 19, 1975	Smith	169.80	126.10	122.94
25,000	82,020	Jan 26, 1975	Peterson	192.60	163.70	161.02
30,000	98,425	Feb 01, 1975	Smith	243.90	206.90	207.80

The researchers believed that, "None of the operational pressure suits in the USAF inventory is compatible with present or future USAF mission requirements. Present pressure suits are bulky and complicated. All current partial or full-pressure suits are uncomfortable during long-term unpressurized wear. These inadequacies have led to the rejection of pressure suits by high altitude fighter pilots and to the astronauts removing their pressure suits during extended orbital flights. They have also led to promotion of a so-called shirt-sleeve environment, even for military missions in which cabin depressurization may be encountered at any time by enemy action."[136] These criticisms may have been extreme since there were other, perfectly valid reasons for some of the actions cited, but there was no question that pressure suits were complicated and generally uncomfortable devices.

The A/P22S-6 suits have had long lives with the NASA WB-57F program at Ellington Field, TX. Unlike their sexier silver cousins at the Flight Research Center, the WB-57F suits are standard international orange with orange gloves and black boots. There was some consideration to using S1035 suits from the Space Shuttle after that program ended in 2011, but this would have required a major reconfiguration of either the suits or the airplanes and was rejected as uneconomical. Note the portable air-conditioner connected to the suit.

NASA

The Boyle's Law Suit consisted of a loosely fitted restraint coverall made from a permeable fabric with multiple collapsible closed cells filled with a predetermined amount of gas. A neck seal provided closure between the suit and helmet. The essential theory was that as the ambient pressure outside the suit fell, the gas in the closed cells expanded, applying mechanical counter-pressure to the skin. The cells were independent and a leak in one did not seriously degrade the operation of the suit. On the ground, the cells occupied about a quarter of the space between the body and the restraint coverall, leaving a half-inch void that provided comfort for the wearer. Even at a pressure altitude of 27,000 feet, the expanding cells did not completely fill this void, leaving the suit somewhat loose. At higher altitudes, the restraint coverall forced the cell's expansion against the skin. The individual cells were tailored to specific parts of the body to ensure that the suit did not "bulk up" too much as the cells expanded.

Chamber tests up to 70,000 feet were generally successful, although despite the tailoring of individual cells, the suit did not provide uniform pressure on all parts of the body. The chamber tests, some of which lasted an hour, showed this was of little consequence and was a reasonable price to pay for reduced bulk.[137] Although an interesting concept, there was little reason to switch from the existing pressure suits and the concept languished.

PHAFO—THE STILLBORN HIGH-ALTITUDE FLYING OUTFIT

In 1974, the USAF initiated the High Altitude Flying Outfit (HAFO) program to develop a pressure suit suitable for use in the new McDonnell Douglas F-15 Eagle. The F-15 had its origin in the mid-1960s, when the aircraft industry was invited to study requirements for an advanced tactical fighter to replace the McDonnell Douglas F-4 Phantom II as the primary fighter in service with the USAF. The aircraft needed to be capable of establishing air superiority against all projected threats in the post-1975 period. Without compromising the primary air-to-air combat role, the aircraft was to be capable of performing a secondary air-to-ground mission and needed a top speed in excess of Mach 2.5 at altitudes above 60,000 feet. The Tactical Air Command, the intended user of the F-15, believed that a new full-pressure suit was needed for the air superiority mission.

The USAF circulated a draft Required Operational Capability (ROC) document among the user commands for comment. Eventually, the combined efforts of the Aeronautical Systems Division, the School of Aviation Medicine, and the Air Logistics Command apparently convinced the TAC that its desired capabilities were too far in advance of the state of the art. The ROC was never formalized, and the installation of full-pressure-suit systems was eliminated from production USAF F-15s.[138]

On the other hand, at least some of the F-15A/Bs delivered to Israel had the capability to use pressure suits, and David Clark Company supplied 18 A/P22S-6 suits to the Israeli Defense Forces (IDF). In addition, the USAF had loaned the IDF some earlier A/P22S-2 suits for use in its McDonnell Douglas F-4 Phantom IIs, most likely the modified Peace Jack variants operated as reconnaissance aircraft. The IDF returned the suits to David Clark Company for depot-level maintenance a couple of times but did not replace them when they reached the end of their service lives.[139]

The HAFO program did not progress further until June 1976, when the pressure suit depot notified the Aeronautical Systems Division that the A/P22S-6 full-pressure suits were going through their last permissible overhaul. This would carry the inventory through 1983, at which time there would be no more pressure suits available unless new A/P22S-6 suits were purchased or a new suit was developed. In response, the Aeronautical Systems Division decided to purchase new state-of-the-art suits based on the experience gained from the A/P22S series, the special projects suits used by the U-2 and SR-71, and the various NASA manned space programs. In reaching this decision, the Aeronautical Systems Division noted that although previous suits had provided the required physiological protection, "the users have not been the most satisfied group of people in the USAF."[140]

The USAF wanted an altitude suit that also protected against water immersion, chemical and biological agents, penetration and impacts, windblast, open flames, and explosive decompression. In addition, the ensemble needed to provide protection against reflections and glare; allow the pilot to eat, drink, and pass urine; and be compatible with the standard USAF G-suit. The requirements indicated the suit should not balloon (grow in size) more than the A/P22S-2 and have communication performance better than the A/P22S-6. The suit needed to withstand an overpressure of 7.0 psi and fit the 5th to 95th percentile of pilots. Perhaps the most interesting requirement was to "be esthetically appealing to crewmembers."[141]

The USAF awarded contracts to ILC Dover (F33657-77-C-0667) and David Clark Company (F33657-77-C-0668) for design studies and the fabrication of Prototype High-Altitude Flying Outfit (PHAFO) suits. ILC Dover proposed to develop a full-pressure suit while David Clark Company proposed a partial-pressure suit.

The suit delivered by ILC included was a 5.0-psi full-pressure garment complete with convoluted joints and a continuous cable restraint system at the shoulders based on the Apollo suit design. The garment used a single-layer butyl-coated Kevlar-Nomex gas container, and the pilot donned it through an extruded, two-part, "tobacco pouch" pressure-sealing slide fastener at the waist. The top and bottom of the suit were separable to allow mix-and-match sizing. A lower-torso buckle assembly, upper-torso buckle assembly, and a torso-adjust strap created a block-and-tackle system extending from the shoulder to the lower abdominal area. This allowed the torso to be foreshortened, modifying the contour and relieving some of the load on the slide fastener. The neck ring included a bearing to allow head rotation, and a neck seal separated the helmet from the suit. A suit-mounted demand regulator provided breathing oxygen directly to the helmet. Exhaled breathing air was exhausted into the suit through an expansion valve in the neck seal. The detachable gloves used a neoprene-dipped nylon pressure-retention layer that was similar to the NASA Apollo gloves. A heavier neoprene-dipped nylon-restraint layer covered all portions except the fingers. A gimbal ring attached at the wrist provided mobility. Standard flight boots covered the feet.[142]

The ILC suit included a Kevlar-graphite-fiberglass, hard-shell, semi-conformal helmet that had a movable visor and integral communications equipment. The helmet used a ring-bearing disconnect to attach to the suit. The helmet included an anti-suffocation valve that opened with each breath to supply ambient air if the oxygen supply was cut off. The material was chemical- and biological-agent resistant. Flat patterning of the joints at the neck, elbows, hips, knees, and ankles contoured the suit to the cockpit and provided decent mobility. A standard G-suit was worn under the pressure suit, and a cooling vest was available. An anti-exposure garment was worn under the pressure suit, as was a urine-collection system.[143]

David Clark Company delivered its PHAFO on September 13, 1978. The suit consisted of a coverall, communications carrier and oxygen mask, nonconformal helmet, and a retainer assembly with parachute harness and floatation gear. The suit was a modular ensemble that could be used with optional sunshades or polarized lead zirconium titanate (PLZT) flashblindness-protection devices, chemical/biological filters, a G-suit, or a urine-collection system.[144] Standard flight boots provided adequate foot protection for limited periods, and MG-1 gloves (as used on the MC-3A and MC-4) were modified to work with the new suit.[145]

The David Clark Company design philosophy was to create a self-donned ensemble that required substantially fewer special support considerations than previous pressure suits. The coverall assembly consisted of upper and

The David Clark Company PHAFO was evaluated by Jack Bassick, during water tests in a local swimming pool during 1979. The suit consisted of a coverall, non-conformal helmet, and a retainer assembly with parachute harness and floatation gear. The exterior of the suit was made of high-temperature Fypro™ material and the gold color was a compromise between its fire retarding capabilities and the need to reflect some solar radiation to keep the suit cool.

Courtesy of the David Clark Company, Inc.

lower modules that could be interchanged between certain sizes to increase the fitting flexibility within the standard eight-size tariff. Designers selected a double-walled bladder configuration that eliminated the need for a pressure-sealing closure and simplified the design. A review of historical data showed that the pressure zipper was one of the most maintenance- (and failure-) intensive items on most pressure suits. The effectiveness of the double-walled bladder had been shown on the CSU-4/P.[146]

The designers considered the ease of donning the suit while wearing the standard G-suit. David Clark Company investigated several configurations but rejected most as overly complicated or too difficult. In the end, it selected a concept similar to the A/P22S-2. With the upper and lower modules connected to each other, the need for pilots to start a separating fastener or make gas connections was

The anatomy of a modern partial-pressure suit. The David Clark Company Prototype High Altitude Flying Outfit (PHAFO) consisted of several modular components that made the suit easy to fabricate and service.

Courtesy of the David Clark Company, Inc.

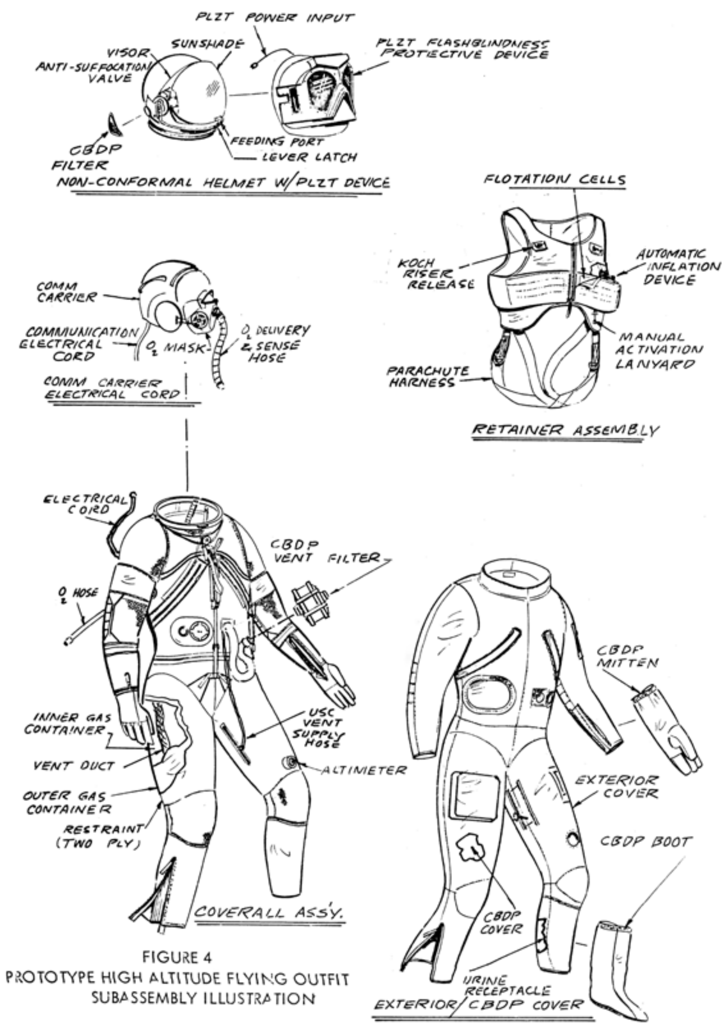


FIGURE 4
PROTOTYPE HIGH ALTITUDE FLYING OUTFIT
SUBASSEMBLY ILLUSTRATION

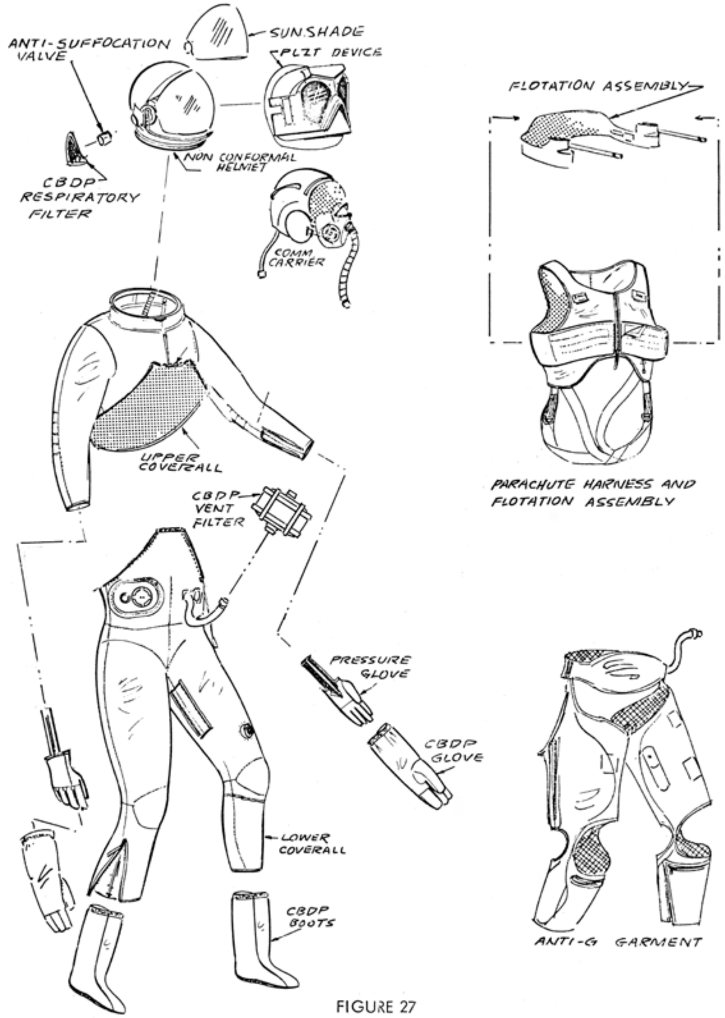


FIGURE 27
PHAFO MODULAR
SUBSYSTEMS

eliminated. The modules could be separated by undoing some laces and a few screws, but this was normally performed by technicians, not pilots. The bladders used urethane-coated nylon, and a butyl layer provided chemical and biological protection. Link-Net was used extensively in the shoulders, arms, and legs to increase mobility. An integrated parachute harness and dual flotation cells were worn over the outer layer of the suit. A nonconformal, dome-type helmet with a two-ply visor and hinge-mounted sunshade was provided. The pressure controls were generally similar to those used on late-model A/P22S-6A full-pressure suits.[147]

The exterior of the suit was made of high-temperature Fypro™ material.[148] Fypro is produced through a process in which DuPont Nomex is saturated with an aqueous solution and put in an autoclave to increase its oxygen index under heat and pressure. The fire-retardant characteristics of Fypro are directly related to its level of processing and the resultant color of the material. The darker the color, the more fire retarding it is. Green Nomex becomes dark brown Fypro while white Nomex becomes dark gold. The color of a pressure suit is an interesting, and emotional, quandary. The search-and-rescue people want orange in snow or white in jungle areas. Physiologists want a color that keeps the aviator cool. Pilots want something that looks good. The gold color selected for the PHAFO was a compromise between its fire-retarding capabilities and the need to reflect solar radiation to keep the suit cool.[149]

Both of the prototype HAFO suits weighed more than the 37.4-pound A/P22S-6; the ILC Dover suit weighed 39.6 pounds, and the David Clark Company suit weighed 39.4 pounds (45.3 pounds if all the optional chemical filters and PLZT goggles were included).[150]

Each contractor tested its suit against the USAF requirements prior to delivery. The ILC Dover suit did not meet the required donning time, primarily because of the entry pressure fastener and the time required to operate it. In addition, the anti-suffocation valve was too small, and the suit did not float well. The David Clark Company suit showed distortion in the visor; donning required the use of a mirror (or extensive practice) although it could be completed within the allocated time; and the suit ballooned more than the specification allowed. The Aeronautical Systems Division conducted extensive tests on both suits after they were delivered to Wright-Patterson AFB. On April 10–11, 1979, a USAF assessment team met to discuss the test results with the group concluding neither prototype offered sufficient improvement over the A/P22S-6 suit to warrant further development.[151]

Given the relatively limited need for pressure suits within the regular Air Force (i.e., not the "special projects" U-2 and SR-71), the USAF concluded that the existing A/P22S series of pressure suits could be overhauled and refurbished to meet the requirements.

7: Special Project Suits

The Air Force designations for pressure suits never made much sense to anybody outside the industry and possibly, not much to those even directly involved. The Central Intelligence Agency (CIA) never worried much about designations and simply used the David Clark Company model numbers when referring to pressure suits. Eventually the Air Force came to the same conclusion. Unfortunately, the David Clark model numbers are only marginally better. The ubiquitous "Sxxx" designations are used by the full range of David Clark Company personal-protection equipment, so pressure-suit model numbers are scattered among other numbers for "Air Police Boots" and "Valve, Heart." In addition, the company has frequently assigned multiple model numbers to the same basic configuration or, conversely, used the same model number for several different configurations. It is one of the consequences of a small company fabricating a handmade, custom-fitted product for a trusting customer. Despite the sometimes apparent randomness as viewed from the outside, it all seems to work just fine and has served the Air Force, CIA, and NASA well for over 50 years.

S901 AND S970—SUITS FOR OXCART

The early 1950s were a period of rapid technological advance for United States military aviation. In February 1953, Chance-Vought delivered the last piston-powered fighter (a Vought F4U Corsair). Three months later, North American delivered the YF-100 Super Sabre, the first fighter capable of supersonic speeds in level flight. There were five publicly known air arms: the Air Force, the Army, the Coast Guard, the Marine Corps, and the Navy. There was soon to be a sixth, unknown to all but a few.

In March 1953, the CIA issued a specification for a new reconnaissance aircraft capable of an altitude of 70,000 feet and a range of 1,750 miles. The agency believed that the high operational ceiling would enable the aircraft to penetrate Soviet airspace at subsonic speeds with relative immunity from interception. The requirement eventually resulted in the development of the Lockheed U-2, possibly the most famous secret aircraft ever built. The U-2 became operational in June 1956 and remained an invaluable intelligence-gathering asset for almost 4 years, until May 1, 1960, when Francis Gary Powers was shot down

A line of Lockheed A-12s at the test facility on Groom Lake, NV. The second airplane in line is the only two-seat A-12. At this point in their careers, the aircraft were in their natural titanium finish except for the composite chines and the rudders on some aircraft.

Courtesy of Lockheed Martin Aeronautics

near Sverdlovsk, Soviet Union. However, even as the CIA tested and began using the U-2 over the Soviet Union, it was obvious that a faster and higher flying aircraft would be needed to stay ahead of the burgeoning surface-to-air missile threat.

In 1956, the CIA appointed Richard M. Bissell, Jr. (1910–1994), who had been program manager for the U-2, to oversee the development of an advanced reconnaissance aircraft. Bissell realized the development and production of such an aircraft would be exceedingly expensive, and there was a great deal of skepticism about whether the project could succeed at all. To secure the necessary funds, Bissell needed the support of the most believable experts he could find. Accordingly, Bissell put together a panel chaired by Edwin M. Land (1909–1991), a respected American scientist and cofounder of the Polaroid Corporation. Between 1957 and 1959, this panel met six times, usually in Land's office in Cambridge, MA.

The requirements for the new reconnaissance airplane were quietly floated to a small number of aircraft manufacturers. At the Lockheed Skunk Works, Kelly Johnson began designing an aircraft that would cruise at Mach 3.0 and altitudes above 90,000 feet. On July 23, 1958, he presented this concept to Land's advisory panel, which expressed interest in the approach. Two months later, after reviewing a proposal from Convair and yet another Lockheed design, the Land panel concluded it would be feasible to build an aircraft whose speed and altitude would make radar tracking difficult and interception impossible. The panel's findings had precisely the impact Bissell wanted. Based on Land's recommendation, President Dwight D. Eisenhower approved $100 million to develop and manufacture 12 aircraft.

On August 20, 1959 (1 month before the first flight of the North American X-15 research airplane) Lockheed and Convair submitted proposals to a joint Air Force and CIA selection committee. The two aircraft were similar in performance and the Lockheed design was selected based mainly on cost. Ironically, at the end of August 1959, the fastest air-breathing aircraft ever built was given the code name Oxcart.

According to the specifications, Oxcart was to fly at Mach 3.2 (2,375 mph: 2,064 knots, or 3,484 feet per second, making it somewhat faster than a 0.30 rifle bullet), have a range of 4,120 nautical miles, and reach altitudes of 84,500 to 97,500 feet. The new aircraft would be five times faster than the U-2 and would fly almost 3 miles higher. By mid-January 1960, various changes had evolved the Lockheed design number to A-12, the 12th iteration of what Kelly Johnson had named Archangel. Afterward, Johnson noted in the Archangel project log: "We have no performance margins left; so this project, instead of being 10 times as hard as anything we have done, is 12 times as hard. This matches the design number and is obviously right."[1] Johnson had a wry sense of humor.

The original Lockheed proposal included using a version of the U-2 partial-pressure suit. However, heat radiated from the 400 °F windshields would drive cockpit temperatures above 100 °F during Mach 3 cruise. Even Johnson admitted this, "would require that the pilot be provided with some sort of a cooling and ventilation garment."[2] Fortunately, now Brig. Gen. Donald D. Flickinger was providing an independent assessment of pilot protection for Richard Bissell. After his service on the U-2 program, Flickinger was the CIA's "go-to guy" when it came to physiology for much of the early Blackbird era. Jack Bates and Bruce Bassett were the USAF program physiologists, defining the requirements and qualifications, as well as monitoring the flightcrews. Because of the prolonged time at high altitude and the extreme heat in the cockpit, Flickinger believed the pilots of the A-12 needed a full-pressure suit similar to the one being developed for the X-15 program.

As Lockheed developed the A-12, it became necessary to involve other contractors to supply specialized parts. Lockheed selected Firewel to build the oxygen system and

Left: The parts that made up an S901 helmet are laid-out for display. Note how the microphone is attached to the face seal.

Below: David Clark Company used a mockup of the A-12 parachute pack to test with the S901 full-pressure suit interface.

Courtesy of the David Clark Company, Inc.

supply the protective garment for the pilots. Firewel subcontracted to the David Clark Company for a pressure suit, although at the time it was not clear exactly what form it would take. In early 1960, Lockheed held a predevelopment conference attended by Joe Ruseckas from David Clark Company and a representative from Firewel. Having seen how uncomfortable the partial-pressure suit was in the U-2, and based on advice from Flickinger, the CIA wanted a full-pressure suit for the A-12. Kelly Johnson would have none of that, believing the suit was too heavy and his airplane did not need one. After a heated discussion, Ruseckas got up to leave, but the CIA representative calmed everybody down and made it clear that a full-pressure suit had just become a firm requirement. Somewhat later, the CIA contracted directly with David Clark Company for the pressure suits (although

Firewel still was the prime contractor for the oxygen system, suit pressure controllers, and breathing regulators). On OXCART, everybody had a codename, and David Clark Company's was "Northeast Manufacturing."[3]

The pressure suit needed to provide altitude protection and thermal insulation during cruise, and it needed to protect the pilot against heat and windblast during ejection. However, the last requirement was not really as bad as one would expect. Although OXCART cruised at a high Mach number, because of the extreme altitude, this corresponded to only 175 knots equivalent airspeed. In fact, the maximum equivalent airspeed, at any altitude, was only 400 knots. Windblast and deceleration effects at these velocities were relatively low, and aerodynamic heating of the pilot during ejection was not a serious problem. At 100,000 feet altitude and Mach 3.2, deceleration of an ejection seat from cruise speed to terminal velocity would take 52 seconds. The initial 10 seconds of this deceleration was the

The S901 series of suit evolved separately, but simultaneously, from the A/P22S series of suits David Clark Company was making for the "normal" Air Force. Nevertheless, there was a bleed over of ideas between the projects since the same few designers were working both. The S901 series was generally a more form-fitting suit and the aluminized HT-1 exterior covers made them look more futuristic than the sage-green or orange covers used by the other suits. Note the white boots. This is the prototype S901 suit with an A-12 ejection seat in April 1961.

Courtesy of the David Clark Company, Inc.

Joe Ruseckas in the third S901 (S901-3) suit in July 1962. This shows the U-entry feature that Ruseckas believed would make the suit easier to don and doff. The zipper starts on one shoulder, runs down and across the back, then up onto the other shoulder. This type of closure would be adapted to the A/P22S-2, but most David Clark full-pressure suits would later use a simpler rear-entry zipper. The aluminized HT-1 exterior cover has been removed for these photos.

Courtesy of the David Clark Company, Inc.

critical period for aerodynamic heating. After that, the ejected pilot had slowed to approximately Mach 2.3, with a corresponding reduction in temperature.[4]

The CIA also asked Flickinger to draw up the criteria for pilot selection, with advice from Kelly Johnson and CIA Headquarters. Pilots had to be qualified in the latest high performance fighters and be emotionally stable and well-motivated. They were to be between 25 and 40 years of age, and the size of the A-12 cockpit dictated they be under 6 feet tall and less than 175 pounds. Air Force personnel files were screened for possible candidates who were called for interviews without disclosing for what project they were being considered. The requisite psychological assessments and physical examinations eliminated many candidates, but eventually a list of 16 potential pilots was assembled. This group underwent further security and medical scrutiny by the CIA. Those who remained were approached to take employment with the CIA on a highly classified project involving a very advanced aircraft. In November 1961, commitments were obtained from five pilots, and arrangements were made with the Air Force to effect appropriate transfers and assignments to cover their training and to lay the basis for their transition from military to civilian status. Compensation and insurance arrangements were similar to those for the U-2 pilots.

The CIA ordered the first Oxcart suit on March 7, 1960, tailored for Capt. Harry Collins, the guinea pig who tested the S901 before "production" suits were ordered. Since the participant names were closely held, David Clark Company referred to Collins as Subject 1, roughly the same routine it had used during the original U-2 program. In addition to altitude chamber and thermal tests, Collins made several parachute jumps to verify the suit worked outside the airplane. Joe Ruseckas generally flew in the C-130 with

Collins to make certain the suit was ready for the jump. The suit, sans occupant, was also tested on the North Base rocket sled track at Edwards AFB.[5]

The original S901 "Flying Outfit, Full-pressure, High Altitude, Multi-Layer" suit for Oxcart included an outer layer made from aluminized HT-1 (an aromatic polyamide fiber created by DuPont for use at high temperatures and later named Nomex), a double-latch Protection, Inc. neck ring, and a single pressure-sealing slide fastener.[6] All Blackbird suits used a U-entry until the S970 and S901J, which used rear entry. A biomedical instrumentation pad was located on the back.

Eventually, Collins and the physiologists were satisfied and the USAF ordered a second suit on June 28, 1962. This one was made for Louis W. "Lou" Schalk, Jr. (Subject 2), the Lockheed test pilot who became the first to fly the A-12. This S901A was similar to the S901 except it used a single-latch neck ring instead of the original double-latch neck ring. The suit used a lot of insulation under the aluminized HT-1 cover, but Schalk felt the suit was too bulky, so later suits (including Schalk's second) deleted most of the insulation.[7]

The S901B featured a biomedical fitting instead of a pad and was custom made for Subject 3, but nobody remembers who that was or why the suit was made. Like the original S901, this suit used a double-latch neck ring.[8] The suit apparently never flew.

The S901C used a single-latch neck ring and included a double slide fastener: one regular and one pressure-sealing. This suit was custom made for Ed Markum, another USAF parachutist who helped qualify the suits.[9]

The S901D switched from Protection, Inc. neck rings to Air-Lock neck rings and featured revised communications equipment and forearm disconnects. The first two suits were custom made for William C. "Bill" Park, Jr., and Lou Schalk (who, for unremembered reasons, became Subject 6 for this suit).[10]

The S901E was a heavily revised suit that evolved from the earlier models and was the first to be called a "Pilots Protective Assembly." The restraint layer switched from marquisette to Link-Net with a sage-green oxford-nylon-restraint cover. Sizing panels were added to the ends of the sleeves and legs for personal-fitting adjustments. The exterior cover continued to use aluminized HT-1 fabric (Nomex) and now included an integral flotation bladder. New altimeter and bioinstrumentation ports were used. A watch pocket was added to the left glove, thigh and calf pockets were added to the legs, and a knife pocket was added to the inside of the left thigh. Joe Ruseckas added a hidden inner pocket to the inside of the right leg to hide contingency money and papers in the event the pilot was forced to abandon the airplane. The visor used a gold coating as the conductor for the electrical defogging system, and pilots frequently complained of being able to "count the pores" on their faces because

David Clark fabricated the S901C for Ed Markum, another parachutist that helped qualify the suit. Harry Collins, the original parachutist, is standing next to Markum holding binoculars, on December 19, 1963. Note the parachute is still attached to Markum.

Courtesy of the David Clark Company, Inc.

The Lockheed YF-12A was undoubtedly the most advanced interceptor ever built by the United States and was capable of Mach 3 at altitudes exceeding 80,000 feet. The aircraft was equipped with a long-range radar and three Hughes AIM-47 Falcon missiles with nuclear warheads. Weapons systems tests proved remarkably successful, and after the YF-12 program was cancelled, the radar and missiles formed the basis of the system used on the Grumman F-14 Tomcat.

National Museum of the United States Air Force Collection

Before the YF-12 interceptor program was cancelled, the Air Force used one of the aircraft to set several Fédération Aéronautique Internationale (FAI) Class C-1 Group 3 (turbojet-powered landplanes) records on May 1, 1965. In one of these, Maj. Walter F. Daniel (pilot) and Capt. James P. Cooney flew 1,688 mph over a 1,000-kilometer closed course. All of the pilots wore S901F suits during the flights. At right, Daniel is congratulated by Clarence R. "Kelly" Johnson, the chief designer at the Lockheed Skunk Works.

National Archives College Park Collection

layer, and a restraint cover. The aluminized HT-1 exterior cover completely covered the suit to provide protection against windblast and heat. The exterior coverall was donned separately using a center-front slide fastener and included an integral floatation system. The helmet used a face seal that isolated the breathing space from the suit. The plexiglass visor included an electrically conductive gold coating for defogging, and a dual pneumatic seal inflated automatically when it was lowered. The gloves used a neoprene bladder with a Link-Net restraint layer and featured leather palm and finger surfaces. The back of the fingers was an aluminized oxford-nylon material, and the knuckles were Helenca (a fabric with a one-way stretch). The remainder of the glove was aluminized HT-1 fabric. The gloves were attached to the suit sleeves by a mechanical metal ring that did not use bearings.[15]

David Clark Company fabricated the suit in 12 sizes: small, medium, large, and extra large, with short, regular, and long versions of each. The YF-12A cockpits were somewhat larger than the A-12, and the S910F suits fit pilots ranging from 125 to 224 pounds and from 63 inches to 76 inches tall. Laces were provided to adjust the length of the legs and sleeves. Gloves were available in 12 sizes, the boots were available in 7 sizes, and the helmet was supplied with the 3 sizes of crown pads.

The aircraft normally provided ventilation air for the suit, which was only pressurized in an emergency. If the cabin altitude exceeded 35,000 feet, the primary suit-pressure control system maintained a pressure of 178 ±7 mm Hg (between 34,500 and 36,000 feet) or, if that should fail, 167 ± 7 mm Hg (35,000 to 37,000 feet) with the secondary system. A


Lockheed test pilot William C. "Bill" Park, Jr. in the S970-5-3 suit without an exterior cover. The rear-entry zipper extended from the shoulder blades to the front of the crotch. Note the extensive use of Link-Net for the restraint layer, similar to the X-15 suits.

Courtesy of the David Clark Company, Inc.

press-to-test button for each system pressurized the suit to 2.25 psi. A back kit contained the emergency oxygen supply, and an anti-suffocation feature was built into the left-hand helmet bearing that deflated the visor seal about 50 seconds after oxygen depletion. A DN-500-U portable vent kit and a DN-500-I portable oxygen kit could be connected to the suit for ground use.[16]

The suit operating manual contained a caution: "Under no circumstances will the suit be worn in flight with the main entry slide fastener unlocked or the relief slide fastener open. Glove disconnects must be locked and sealed. The helmet must be locked to the suit disconnect ring with the visor in the closed and locked position."[17]

The S901G was generally similar to the S901F but was custom fitted instead of coming in 12 standard sizes. Because they were custom fitted, the adjustment laces on the arms and legs were omitted. This suit also appears to have been oriented toward the YF-12A program, probably for a pilot that did not fit well into the 12 standard sizes.

The S901H was the primary production suit for Oxcart, but it was a major departure from previous S901 suits. The majority of the hardware (neck and wrist rings, pressurization controls, etc.) was similar to the S901F, but the basic softgoods (gas container and restraint layer) came from the S971, which was an A/P22S-2 suit. Nevertheless, Joe Ruseckas and the designers at David Clark Company made some major changes for this application.[18]

Instead of the U-entry used on the A/P22S-2 and all previous Oxcart suits, the S901H used a pressure-sealing zipper installed vertically in a straight line from a point on the upper back approximately between the shoulder blades, down and under the buttocks, and terminating in the front approximately waist high. The vertical zipper allowed a better-fitting garment, and an expanded use of Link-Net over the entire torso greatly improved mobility.[19] The Link-Net leg design had adjustable cords on the inner and outer seams in place of laces on the calf. Vent ducts extended to each extremity, and the vent system was attached to the inner liner instead of the gas container. The rear helmet holddown pulley was fixed instead of being adjustable. This suit came in the standard 12 sizes.[20]

The first S901Hs, produced in 1965, used an outer layer made of aluminized HT-1 with no separate exterior cover. However, Oxcart pilots had long complained the aluminized

The A-12s were eventually painted overall black, like their later SR-71 cousins. The A-12 proved to be a remarkable aircraft and was the fastest of the Lockheed Blackbirds. Political considerations, and the fact that the Air Force SR-71 carried a more diverse reconnaissance suite, led to the early retirement of the A-12.

Courtesy of Lockheed Martin Aeronautics

suit created undesirable reflections around the cockpit. In response, David Clark Company developed a white Dacron outer layer for later S901Hs, but the Dacron was not fireproof so it was backed with HT-1 fabric, adding some bulk to the suit.[21]

A late modification for the S901H added a urine-collection system. This consisted of a pair of underwear drawers with pile fastener tape fitted to a circular opening in front, a latex-rubber external catheter that mated with the fastener tape on the drawers, and a hose-and-valve arrangement that connected the duct to an external repository. This same arrangement would be used on the S901J, A/P22S-6A, and most later suit designs.[22]

David Clark Company lists the S970 as a modification of the S901G, but it seems to have more in common with the S901H. It used a rear-entry zipper instead of a U-entry and the outer layer was aluminized HT-1 with an integrated floatation garment. No separate exterior coverall was required.[23]

The first A-12, known as Article 121 (USAF serial number 60-6924), was assembled and checked out in Burbank during January and February 1962. Since it could not be flown to Groom Lake, the aircraft was partially disassembled and put on a special trailer. Lockheed made appropriate arrangements with the police and local officials to safely transport the aircraft without disclosing exactly what was in the odd-shaped container. The entire fuselage, minus wings, departed Burbank on February 26, 1962, and arrived at the test location 2 days later.[24]

On April 26, 1962, Lockheed test pilot Lou Schalk took the A-12 for an unofficial first flight, flying less than 2 miles at an altitude of about 20 feet. This unexpected event occurred during a high-speed taxi run when the aircraft began a series of oscillations as the nose wheel lifted off the ground. Schalk immediately added power and lifted the aircraft into the air, regaining control. Once he managed to stop the oscillations, Schalk set the A-12 safely back onto the lakebed. Kelly Johnson noted that this "…was obviously a day for the A-12, in that 2 × 6 = 12."[25] The "official" first flight took place on April 30, 1962, witnessed by a number of CIA and USAF representatives. With Schalk again at the controls, Article 121 took off at 170 knots and climbed to 30,000 feet, achieving a top speed of 340 knots during the 59-minute flight. On May 2, 1962, during its second test flight, the aircraft broke the sound barrier, reaching Mach 1.1 for a few minutes.

Initially, the A-12 had a design top speed of Mach 3.2 (2,064 knots), a maximum altitude of 87,000 feet, and a range of 3,600 nautical miles. This was later raised to Mach 3.29 and 90,000 feet. Nevertheless, the airplanes were initially restricted to Mach 2.35, at first because of the limited thrust of the interim Pratt & Whitney J75 engines (the definitive Pratt & Whitney J58s were not yet ready), then because of inlet issues and unacceptable engine airstart capabilities.

The first OXCART accident, in Article 123 (60-6926), took place on May 24, 1963, near Wendover, UT. CIA project pilot Ken Collins remembered:

> I was flying a subsonic J58 engine test flight at 25,000 feet altitude with Jack Weeks as the F-101 chase pilot. In my turn back to base, we ran into heavy clouds and rain. Trying to get above the weather, I climbed up to 30,000 feet, but was still in the heavy clouds. I waved Weeks off, because of the dense clouds and turbulence since The F-101 was prone to pitch-ups in slow flight. All cockpit instrument readings appeared to be normal, but the flight controls were slow responding. Rechecking all the instruments, I saw the altimeter beginning to rapidly 'wind' down, as did the airspeed indicator. Having no visual references in the clouds, I was uncertain of my true altitude and airspeed; the flight instruments were unreliable. Within seconds, the airspeed decreased to 102 KIAS. Then the A-12 stalled and pitched up and over into an unrecoverable flat inverted spin. Having no positive idea of my real altitude, I choose to eject from the inverted aircraft.[26]

Because this had been a "low and slow" evaluation flight, Collins was not wearing his S901 pressure suit, but instead he wore a normal flight suit and helmet. Fortunately, Collins survived the ejection little the worse for the experience. The subsequent investigation determined that a flaw in the pitot system was the root cause of the accident. Jack Bassick and Bob Banks at David Clark Company remember that many low-and-slow flights were made without pressure suits, as were most flights in the two-seat *Titanium Goose* trainer (60-6927). Collins remembers that "after the trainer check out, the object was to become familiar and comfortable in the pressure suit, therefore; the pressure suits were always used." But he hastens to add, "nothing is 'always.' "[27]

Based on a series of modifications, the allowable speed of the A-12 was raised to Mach 2.8 in July 1964 and to Mach 3.0 in March 1965. It was not until August 1965 when electronic inlet controls began to be installed that operational aircraft were cleared to Mach 3.2. Aircraft also needed structural modifications to fuselage station 715 (the wing join) before being allowed to exceed Mach 3.0. Between the first flight in April 1962 and March 24, 1965, the fleet accumulated only 15 hours above Mach 3, all by Lockheed flight-test aircraft. The first operational aircraft flown by a project pilot to exceed Mach 3.0 was Article 128 (60-6931) on March 25, 1965, but it would be several months before this became routine.[28]

During the fall of 1965, the OXCART fleet began to carefully venture up to Mach 3.0, with an average of 1.28 hours at Mach 3.0 per aircraft to validate operational systems. In January 1966, flight activity was substantially curtailed during the investigation of the December 28, 1965 accident of Article 126 (60-6929). This aircraft crashed shortly after takeoff because Lockheed wired the yaw and pitch gyros in the stability-augmentation system incorrectly, and the aircraft became uncontrollable. The project pilot, Mele Vojvodich, was wearing his S901 suit and ejected successfully.[29]

By the spring of 1966, the operational aircraft and project pilots again began to fly, spending an average of 45 minutes per sortie at Mach 3.0. In a September 1966 document, the CIA reported that the fleet of 10 airplanes (7 operational A-12s, the two-seat *Titanium Goose* trainer, and 2 flight-test aircraft) had

The M-21/D-21 combination demonstrated the significant difficulties of separating two vehicles at high Mach numbers and were intended to provide an unpiloted reconnaissance capability over China and the Soviet Union. The M-21 was a two-man version of the CIA A-12 reconnaissance aircraft and carried the D-21 drone to its Mach 3 launch conditions.

Courtesy of Lockheed Martin Aeronautics

accumulated 2,078 flights for a total time of 3,186 hours and 39 minutes. Of these, 485 flights had been at or above Mach 3 for a total of 244 hours and 39 minutes; 264 of these flights were by operational aircraft, the remainder by flight-test aircraft. Pilots had used the S901 pressure suits on 1,480 of the 2,078 flights. During this period, no sorties were cancelled or aborted because of issues with the S901 suits, although two missions were cancelled due to cockpit-pressurization-system problems.[30]

By 1968, one Mach 3.3 flight had lasted 3.5 hours, and the longest Oxcart flight was 7.6 hours (with aerial refueling). There had been 2,670 total flights, of which 1,751 used S901 pressure suits. Between August 26, 1965, and December 31, 1967, a period that included operational Black Shield flights over Vietnam, the pressure suit worked on 692 sorties of 693 attempted wearing the suit. Pilots wearing S901 suits had experienced three ejections. Bill Park and Mele Vojvodich survived, but Walt Ray was killed when a seat malfunction precluded man-seat separation after ejection.[31]

When originally conceived, the primary mission for Oxcart was to overfly the Soviet Union. After Francis Gary Powers and his U-2 were shot down on May 1, 1960, the rules changed. One of the many concessions made by President Eisenhower for the release of Powers was the immediate cessation of all manned overflights. The word “manned” was carefully stipulated because of the possibilities envisioned for future Corona reconnaissance satellites. However, since the satellites were still several years away from operations, the CIA decided that a drone also fell outside the “manned” category.

The drone had to be simple, relatively lightweight, and able to fly Mach 3 at 90,000 feet, and it had to have a low radar cross section and be compatible with systems and techniques already developed for Oxcart. Because of the complexities of turbojet power and its associated intakes, the J58 was quickly discarded in favor of a Marquardt RJ43 ramjet borrowed from the IM-99 BOMARC surface-to-air missile. Since ramjet engines do not function at low speeds, a modified A-12 was selected as a platform that would carry the drone to Mach 3 and then release it. The CIA called the drone Tagboard, and it was originally known within Skunk Works as the Q-12. As work progressed, however, it was given the D-21 designation (D for daughter), while its two-seat Blackbird carrier aircraft was called the M-21 (M for mother).

The two M-21s (Article 134, 60-6940 and Article 135, 60-6941) were purpose built, not modified, A-12s, although there were remarkably few differences. A dorsal-mounted pylon carried the D-21, but aerodynamic considerations resulted in the pylon being shorter than Kelly Johnson desired. This dictated that the M-21 “push over” during launch, instead of flying straight and level as originally intended, a concession later regretted. In addition, the aft fuselage of the M-21 was strengthened around the pylon attach points. Unlike the original A-12s, the M-21 carried a back-seater known as the Launch Control Officer (LCO) who used a periscope to monitor the drone. Only 6 inches of clearance existed between the wingtips of the D-21 and the top of the M-21’s vertical stabilizers.

The first captive-carry flight, with Lockheed test pilot Bill Park in the front cockpit and no LCO, took place on December 22, 1964, coincidently the same day that the first SR-71 made its maiden flight. The basic flight-test program lasted just over a year. The first successful launch occurred on March 5, 1966, with the D-21 (503) having only 25 percent of its design fuel load. The second D-21 (506) launch carried a 50 percent fuel load on April 27, and the first launch with a fully fueled D-21 (505) occurred on June 16. The full fuel load allowed the D-21 to fly nearly 1,600 miles while making eight programmed turns and maneuvers. The flight-test effort then stood down to digest what had been learned.

The mated combination was not as straightforward as it might appear. The weight of the

Top, right: An M-21 approaching a tanker to refuel before launching the D-21. There were only 6 inches of clearance between the D-21 wingtips and the top of the M-21's vertical stabilizers.

Bottom, right: The M-21/D-21 program ended tragically on July 30, 1966, when the D-21 impacted the M-21 after launch. Bill Park and Ray Torrick successfully ejected, but Torrick drowned when his pressure suit took on water after he landed in the ocean. The project was immediately cancelled, although Lockheed modified the surviving drones to be launched from B-52 motherships. Four operational D-21B missions over China took place under the codename of Senior Bowl *between November 9, 1969, and March 20, 1971, to photograph the Lop Nor nuclear test site.*

Courtesy of Lockheed Martin Aeronautics

D-21 significantly slowed the acceleration of the Blackbird. To be at the correct speed and altitude over the designated Pt. Mugu launch area, the M-21 had to begin its speed run over Albuquerque, NM. Once the Marquardt ramjet in the D-21 was running at full power, the pilot flew the M-21 in a 0.9-G downward arc to assist in separation. Fuel reserves were minimal when the M-21 reached the launch point, and an in-flight refueling was made immediately after the drone was launched (or immediately after the decision was made not to launch it).

Bill Park did not believe that a sustained 0.9-G downward arc could be maintained under the pressure of an operational mission. To determine how critical it was to maintain exactly 0.9-G, a scheduled July 30, 1966, full-fuel launch (using Article 135 and 504) attempted separation in level flight. For the first 2–3 seconds of the drone launch, everything went normally. Unfortunately, the drone was not able to penetrate the Mach 3 shock wave coming off the mothership. The D-21 just cleared the M-21's rudders when it encountered the shock wave, bounced off, rolled 45 degrees to the left, and impacted the Blackbird where the forward fuselage attached to the wing root. The M-21 tumbled out of control and into the Pacific. Bill Park and Ray Torrick successfully ejected, but Torrick drowned when his pressure suit took on water. Some reports attribute this to Torrick prematurely opening his visor, but informed sources have stated that the buoyancy of the David Clark suits makes this unlikely. Others have speculated that shrapnel from the wreckage tore his suit as he ejected. Regardless, Kelly Johnson and the CIA promptly cancelled Tagboard.

This accident provided the impetus for David Clark Company to add an automatic flotation-inflation device to later special projects suits. David Clark Company also redesigned the suit's integrated flotation garment to provide higher floatation and a more vertical orientation in the water. In addition, the company designed a new, easier-to-board life raft, which was approved by the program in June 1967. Training was given to the project pilots using the new raft in Lake Mead during June 1967.[32]

Almost a decade elapsed between when the concept for the Oxcart aircraft was first examined and the first A-12 being operationally deployed. Then, after only 29 operational missions, the most advanced air-breathing aircraft ever built was retired. The abandonment of the Oxcart did not result from any particular shortcomings of the aircraft but lay in fiscal pressures and competition between the reconnaissance programs of the CIA and the Air Force. Oxcart was replaced by the heavier and somewhat slower SR-71.

All A-12 aircraft at Groom Lake and the forward operating base at Kadena AB, Okinawa, Japan, were ordered flown to the Lockheed facility in Palmdale. Unfortunately, on June 4, 1968, Article 129 (60-6932) was lost during a functional checkflight out of Kadena to test a replacement engine. The aircraft disappeared 520 miles east of Manila; search and rescue crews never found a trace of the plane or its pilot, Jack W. Weeks. Several days later, the last two aircraft from Kadena joined the other six aircraft in Palmdale for storage. Article 131 (60-6937) made the last A-12 flight from the Nevada test site to Palmdale on June 21, 1968.

The dozen single-seat A-12s had accumulated slightly over 3,727 hours of flight time during 2,189 flights. The lone two-seat trainer added another 1,076 hours in 614 flights. Of the 13 aircraft, 5 single-seat A-12s were written off in accidents, but no A-12s were lost to enemy action.

In 1972, the CIA floated a proposal to revive Oxcart for surveillance flights over North Vietnam. When the Oxcart program was cancelled, the surviving A-12s had been placed in flyable storage in Palmdale, along with a complete "regeneration" package that included the operating procedures, mission directives, checklists, and names of qualified personnel. The package included sufficient spare parts and aerospace ground equipment to reconstitute five operational aircraft and support them for 90 days. During this time, the CIA would award the appropriate contracts to provide longer-term support.[33]

The CIA intended to conduct flight training at Beale AFB so the effort could share the airspace already allocated to SR-71 operations. The agency expected to have one pilot and one aircraft operationally capable within 45 days of the order to proceed. Operational missions would be flown from Kadena and require 200–250 personnel. The only major modification was to switch to SR-71 ejection seats and S901J pressure suits since the Oxcart seat was "unsatisfactory" and the Oxcart pressure suits were no longer available.[34]

The revived Oxcart never happened and the aircraft remained in storage until they were dispersed to museums in 1991.

S-100—HYBRID SUIT FOR THE ORIGINAL U-2

In early 1970, officials at Lockheed asked Joe Ruseckas if he could improve the

The David Clark Company S-100 developed for the U-2C aircraft that were still in service during the 1970s. Although it had been demonstrated that the A/P22S-2 family of suits would work in the early U-2s, the Air Force was reluctant to invest in the necessary modifications. This led Joe Ruseckas to adopt an A/P22S-6 full-pressure helmet to a capstan partial-pressure suit, replacing the USAF MA-2 style helmet that was no longer supportable.

Courtesy of the David Clark Company, Inc.

partial-pressure suit used by the first-generation U-2s. Although flight tests had concluded that a full-pressure suit would physically fit in the cockpit, the USAF was hesitant to make the required changes to the airplane. Ruseckas agreed that a better partial-pressure suit could be created. Contrary to popular reports, the resultant S-100 suit was not so much a modification of the MC-3A partial-pressure suit as an entirely new suit based on the MC-3A design and hardware. Ruseckas decided that much of the discomfort experienced by the pilots on long flights was more the result of the MC-2 helmet, rather than the suit itself. Therefore, he decided to mate a full-pressure helmet from the A/P22S-6 with a new partial-pressure suit. Because of the neck ring required for the full-pressure helmet, the David Clark Company softgoods expert, Ed Dubois, developed patterns for a rear-entry suit instead of the shoulder entry of most partial-pressure suits. The novel integration of the A/P22S-6 helmet with a partial-pressure

The radical concept behind the S-100 partial-pressure suit was the use of a full-pressure helmet. The novel integration of the A/P22S-6 helmet with a partial-pressure suit provided considerable improvement in early-model U-2 pilot comfort and mobility along with a commensurate reduction in stress and fatigue. Like many full-pressure helmets, the S-100 helmet used a face seal to contain the oral-nasal breathing compartment, while the suit used a neck seal to contain the breathing bladder inner wall. The use of a conventional full-pressure suit neck-ring and bearing greatly improved pressurized mobility.

Courtesy of the David Clark Company, Inc.

suit provided considerable improvement in pilot comfort and mobility along with a commensurate reduction in stress and fatigue.[35]

Ruseckas took the prototype S-100 to Tyndall AFB where USAF physiological training officer Paul Roberts ran the altitude chamber. Ruseckas did a chamber check to 60,000 feet, followed by Roberts. The new helmet demonstrably improved comfort, and after further qualification tests, David Clark Company started fabricating S-100 suits for the USAF and NASA (the CIA having long departed from the scene).[36] Note the S-100 model-number uses a dash (unlike most David Clark Company model numbers) and is far outside the normal model number sequence.

The helmet was essentially identical to the one used on the A/P22S-6 and consisted of a

Except for the neck seal and full-pressure helmet, the S-100 looked much like a partial-pressure suit. Large capstans ran up the legs and arms, and there were lace-adjustment panels on the chest and shoulders. Note the NASA U-2C (ER-1) behind NASA pilot Jim Barnes in the background. The S-100 was used by the Air Force and NASA until they each retired their early-model U-2s

NASA

fiberglass shell fitted with a movable visor and independent sunshade, an oxygen system, an anti-suffocation valve, a takeup adjustment mechanism, cushion assembly, and communications. The molded fiberglass shell contained channels that distributed vent air around the head. A spray bar around the inner edge of the visor opening delivered breathing oxygen and kept the visor from fogging. A face seal separated the helmet breathing space from the rest of the helmet. The spring-loaded exhalation valve passed exhaled air from the breathing space to the pressure-suit breathing-bladder assembly. An anti-suffocation valve was mounted on the left side of the helmet and opened to the atmosphere if the oxygen supply was depleted. A drinking and feeding port was located at the lower-right front of the helmet. The helmet used two different electrically heated visors, one with a gold coating and one with a laminated grid for defogging.[37]

The suit consisted of a coverall with a restraint assembly, a capstan assembly, and a breathing

Much like the MC-3 and MC-4 before it, the S-100 featured an exterior cover that could be worn to protect it against snagging on items in the cockpit. The exterior cover also had extra pockets and large Velcro pads on the thighs to mount checklists and other materials.

NASA

bladder that was worn directly over a set of long underwear. The capstan and breathing-bladder assemblies provided sufficient protection up to 80,000 feet. Interdigitizing tapes around the capstans extended down the back and along the sides of the arms and legs to provide counter-pressure. Slide fasteners located in the center of the back, wrists, and ankles facilitated donning, and laces along the arms, legs, chest, and back allowed individual size adjustments. Adjustable breaklines at the waist and groin allowed the pressure bladders to crease at those locations to facilitate standing and sitting. The breathing bladder wrapped completely around the torso and incorporated a neck seal on the inner wall and a neck ring on the outer wall. A perforated inner liner at the front and back of the bladder permitted vent air to flow around the wearer. The capstans and pressure bladders were fabricated from coated nylon cloth.

The breathing bladder used the standard full-pressure suit dual-system controller, however the controller was rescheduled to maintain 155 mm Hg (38,000 feet) instead of the

NASA used the U-2C as an Earth resources aircraft at the Ames Research Center in California. Here the airplane is posed with a variety of payloads it could carry during its research missions.

NASA

175 ± 7 mm Hg (35,000 feet) protection of the contemporary Blackbird full-pressure suits. The S-100 helmet included a single-system breathing regulator from the A/P22S-6. The suit and gloves were available in the standard 12 sizes, and there were 4 sizes of helmet cushions.

The partial-pressure gloves were made from Nomex with soft black suede leather palms, and an elastic cuff. Lacings on the back of the hand allowed personal adjustments. A slide fastener, extending from the top of the cuff to the palm, allowed donning. A bladder assembly extended from the wrist to the top of the fingernails on the backside of the hand.

The separate Nomex exterior cover included slide fasteners in the front, and at the wrists, and at the lower legs and were available in several colors, including sage green and international orange. Snap tabs at the waist and wrists allowed limited adjustments. The cover had a pocket on each lower leg, a leather-lined knife pocket on the inside of the right leg, and a pocket with pencil accommodations on the upper right sleeve.[38]

Operational U-2C flights began using the S-100 in early 1972, and Air Force and NASA pilots used the suits until the first-generation aircraft were finally retired in 1989. David Clark Company fabricated 142 S-100 suits.[39]

S901J—INITIAL SUIT FOR SENIOR CROWN

In December 1962, 8 months after the first flight of the Oxcart, the USAF ordered six reconnaissance versions of the Blackbird as a rider to the CIA A-12 contract. Internally Lockheed referred to the new aircraft as the R-12, a reconfigured A-12 that was slightly longer and heavier to accommodate different reconnaissance systems and a second crew-member. The extra weight, and some additional drag from a reconfigured nose, resulted in a slightly slower maximum speed and a lower operating ceiling. By mid-March 1964, the manufacture of the six R-12s was well under way.

In August 1963, the USAF initiated its own procurement (not through the CIA) of 25 additional aircraft under the Senior Crown contract, for a total of 31 Air Force aircraft. The existence of this variant of the Blackbird family became public on July 24, 1964, during a speech by President Lyndon B. Johnson: "I would like to announce the successful development of a major new strategic manned aircraft system, which will be employed by the Strategic Air Command. This system employs the new SR-71 aircraft, and provides a long-range advanced strategic reconnaissance plane for military use, capable of worldwide reconnaissance for military operations. The Joint Chiefs of Staff, when reviewing the RS-70, emphasized the importance of the strategic reconnaissance mission. The SR-71 aircraft reconnaissance system is the most advanced in the world. The aircraft will fly at more than three times the speed of sound. It will operate at altitudes in excess of 80,000 feet."[40]

Contrary to the popular belief, the President did not misread his speech when referring

The Lockheed SR-71 "Blackbird" became the Air Force's primary user of full-pressure suits. Designed by Kelly Johnson at the Skunk Works, the two-seat SR-71 was capable of cruising at Mach 3 and 80,000 feet. Surprisingly, this was somewhat slower and lower than its CIA A-12 cousin.

Courtesy of Lockheed Martin Aeronautics

The SR-71 used a much more advanced ejection seat than the earlier A-12 operated by the CIA, necessitating a new pressure suit. In response, David Clark Company developed the S901J, which quickly became popular among pilots and eventually contributed ideas and concepts into the mainstream (nonblack-world) pressure suit business.

Tony R. Landis

to the aircraft as the SR-71. It was standard practice in those days to have an official White House stenographer taking a shorthand verbatim transcript of what the President said, to be used later for the official press release. In all three places where President Johnson said "RS-71," the stenographer heard incorrectly and inserted "SR-71."[41] The stenographer's copy became the official press release that was passed out to the 315 people in attendance at the State Department that day.

At the end of October 1964, the first Senior Crown aircraft was ready to begin the overland journey followed by all Blackbirds. However, unlike the A-12 and YF-12s before it, the journey would lead to new Lockheed facilities located at Air Force Plant 42 in Palmdale, CA, only 50 miles from Burbank. All the earlier aircraft had gone to Groom Lake for their first flights, but the SR-71 would fly from Plant 42, which is officially known as the Air Force Production Flight Test Facility. On December 22, 1964, Lockheed test pilot Bob Gilliland took the first SR-71

Like most operational Air Force aircraft, the SR-71 had a seat kit that contained emergency supplies in case the pilot needed to eject. Included in the seat kit were a life raft, dehydrated food, a radio, dye marker, a knife, medical supplies, and suntan lotion.

NASA

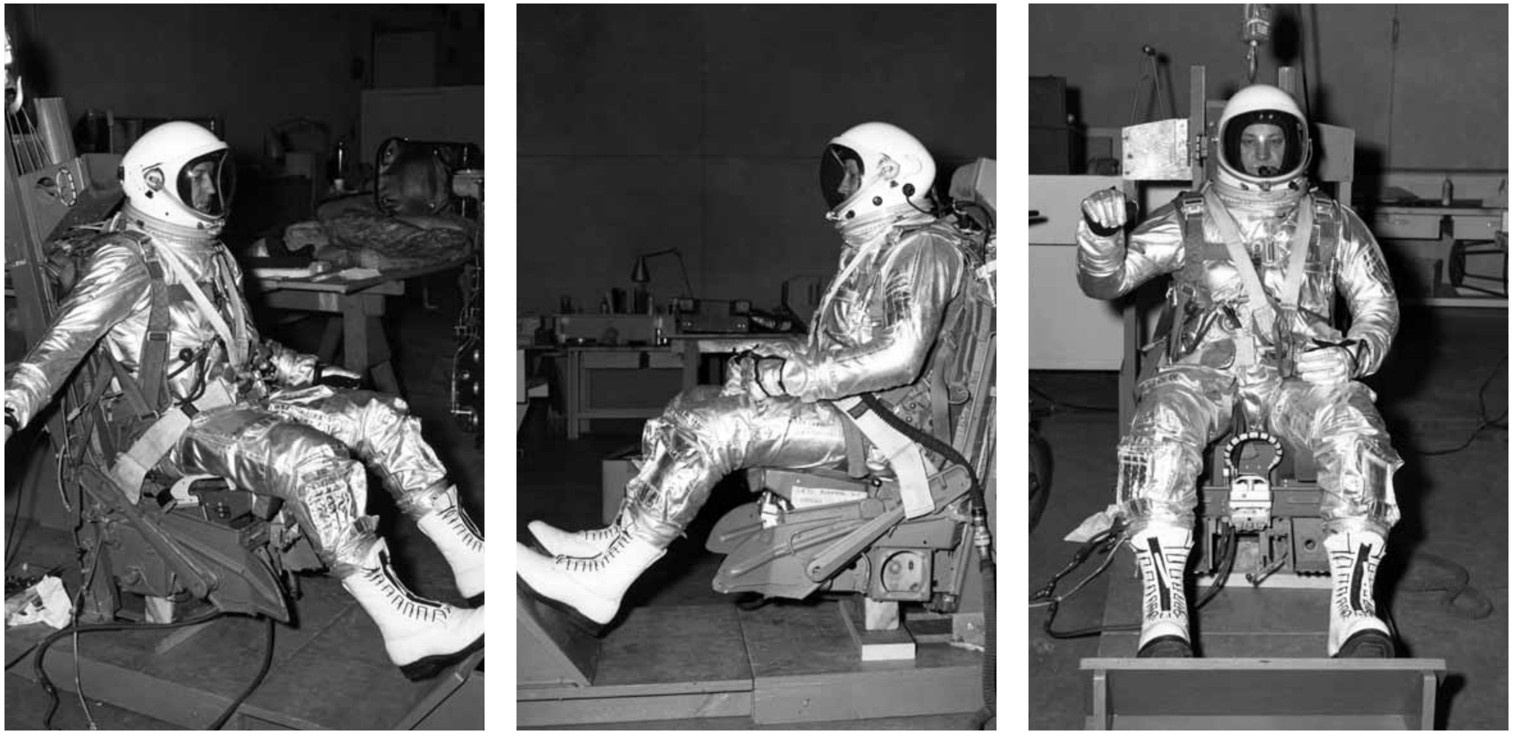
(61-7950) on its maiden flight. (As a safety precaution, the back seat was empty.) Coincidently, on the same day, 150 miles to the northeast, the M-21 mothership was making its first flight from Groom Lake.

In early 1965, the growing SR-71 fleet was moved to nearby Edwards. The first six SR-71s were allocated to flight-test and, along with the three YF-12s already stationed there, a total of nine Blackbirds were operated by the newly activated YF-12/SR-71 Test Force. The first of two SR-71B trainers (61-7956) made its maiden flight on November 18, 1965, and, after a brief time at Edwards, became the first SR-71 to be delivered to the 9th Strategic Reconnaissance Wing at Beale AFB, CA, on January 7, 1966.

On February 8, 1965, Joe Ruseckas at David Clark Company sent the Senior Crown program office a technical proposal for a new suit to support the SR-71. The Air Force finalized the purchase specification on November 29, 1966. Interestingly, the specification was only 47 pages long and never once mentioned the program name or aircraft type.[42]

Because of differences in the ejection seats (the A-12 used a nonstabilized seat while the SR-71 used a much more sophisticated stabilized seat) and oxygen systems, the A-12 and SR-71 could not use the same pressure suits. David Clark Company developed an entirely new S901J Pilots Protective Assembly (PPA) for the SR-71. The Senior Crown program office continued to use the "GN" prefix originally assigned by Oxcart to "Northeast Manufacturing" (the David Clark Company) for its part numbers, and therefore, the S-901J suits were part number GN-S901J.[43]

The S901J was based on the late-model S901H used on the A-12 but incorporated new requirements and lessons learned from the older program. Perhaps the most noticeable difference was that the aircraft oxygen hoses no longer attached directly to the controller on the abdomen. Instead, two hoses ran from the aircraft to the right rear corner of the seat kit, which included an emergency oxygen supply. Dual-seat kit hoses with quick-disconnects in turn connected to helmet hoses integrated



A David Clark Company S901J suit with the original sliver exterior cover. S901J suits were later retrofitted with white, then brown exterior covers in an attempt to reduce cockpit instrument washout from sunlight reflecting off the suit.

Courtesy of the David Clark Company, Inc.

into the center rear of the helmet. The neck ring was based on the design developed for the Gemini spacesuit and included a pass-through for helmet ventilation. The sealed bearing was integrated on the suit side rather than the helmet side of the neck-ring disconnect.[44]

The sage-green, oxford-nylon cloth inner-comfort liner was attached using Velcro and could be easily detached for cleaning. The ventilation duct assembly consisted of a network of channels fabricated of neoprene bladder cloth. The channels contained a series of stainless steel springs enclosed in a nylon mesh to provide paths for cooling air and three anti-block assemblies covered the relief valves and suit pressure controller opening. The coated ripstop nylon fabric gas container included a pressure-sealing slide fastener that extended from the center back, through the crotch, and terminated in front just below the waist. Restraint bladder boots, designed to incorporate both bladder and restraint features, were cemented to the gas container above the ankles. These were made of coated nylon-oxford cloth, with cuffs made from Dacron and Nomex.[45]

The Link-Net restraint assembly had takeup laces located at each wrist for individual

The S901J suit included a fully integrated parachute harness, an automatic water-activated flotation system, urine collection system, and an optional inflatable thermal protective garment.

Courtesy of the David Clark Company, Inc.

length adjustment. Takeup panels, located at the top of the pressure-sealing slide fastener and around the waist, allowed vertical trunk adjustment. Takeup cords at the inseams and outseams allowed leg-length adjustments. The restraint assembly was stitched to the gas container at the pressure-sealing slide fastener, and molded reinforcement rings attached to the Link-Net were cemented to the gas container at the hardware openings. A nylon cloth-restraint cover between the exterior cover and the restraint assembly prevented the parachute harness from damaging the Link-Net. The suit used the same urine collection system introduced via modification on the S901H.

The white Nomex exterior cover provided thermal and physical protection for the restraint assembly and gas container. Openings allowed the parachute harness straps and other hardware to pass-through the exterior cover. The cover included box-type pockets on each thigh and calf, a knife pocket on the inside of the left thigh, and pencil pockets on the lower right leg and upper left sleeve. In

NASA test pilot Don Mallick poses with the second Lockheed YF-12A (60-6935) in his S901J full-pressure suit. Note the silver gloves used with the otherwise all-white suit and boots. The white exterior cover was developed in response to pilot complaints about reflections from the aluminized exterior covers used by many earlier S901-series suits.

NASA

This S970 helmet has a PPG glass visor with an integrated heating element. Initially, the designers at David Clark Company used an acrylic visor on the S901J helmet as a way to reduce weight. However, various operational considerations drove the Air Force to require glass visors for the front-seater, although the reconnaissance-systems operator in the back seat could (and usually did) wear an acrylic visor.

Courtesy of the David Clark Company, Inc.

addition, a manifold pocket was located over the controller opening, a hose-excess pocket on the upper-center back, and a holddown-strap pocket on the upper left chest. Slide fasteners attached the exterior cover at the collar, gloves, restraint bladder boots, and torso harness liner.[46]

A parachute harness was integrated with the exterior cover, as was a floatation system located outside the harness, except for an area at the top of the shoulder. The floats were laced to the exterior cover around the neck area and passed under the arms and into pockets on the front of the exterior cover. A carbon dioxide cylinder and lanyard were attached to the inner left side and an oral inflation tube to the outer left side.[47]

The palm area and inner sides of the glove fingers were made from black-dyed chrome-tanned sheepskin leather. Initially, the remainder of the outer glove was made from

Table 7—Comparison of USAF Full-Pressure Suits Available in 1967			
	A/P22S-2	**A/P22S-4/6**	**S901J**
Contruction	Bladder, Link-Net, and exterior cover	Bladder, Link-Net, and exterior cover	Bladder, Link-Net, and exterior cover plus separate outer garment
Entry Zipper	U-Entry	Rear Entry	Rear Entry with reinforcing zipper
Ventilation	Torso, arms and legs	Extended to head	Extended to hands and head
Sizing	Eight	Eight	Twelve
Helmet	No drinking port	Drinking port with mechanical seal	Drinking port with mechanical seal
	Circumferential spray bar	Interrupted spray bar	Circumferential spray bar
	Fixed microphone	Adjustable microphone	Adjustable microphone
	Warning-type anti-suffocation device	Warning-type anti-suffocation device	No warning
Floatation Gear	External	Built-in	External
Inner Suit	Fixed	Removable	Removable
Source: Kent W. Gillespie and John R. Hochwalt, "The Design Requirements, Description, and Functional Operation of the A/P22S-4 and A/P22S-6 High-altitude, Flying Suits," ASD-TR-70-58, April 1971.			

aluminized Nomex, but this changed over the years to the same white Nomex used on the exterior cover. A hinged palm restraint ran through a nylon sleeve in the palm area to prevent ballooning. Flocked neoprene inner booties were restrained by sage-green nylon-oxford-cloth booties. White leather outer boots were worn over the pressure booties; the white color was selected to help reflect radiated heat. A slide fastener was used to expedite boot donning and doffing, while laces across the instep allowed personal sizing.[48]

Other changes included using nickel instead of cadmium-plated hardware, as in previous S901 suits, due to cadmium's deleterious effect on the titanium used to manufacture the SR-71. Somewhat confusingly, the A-12 and YF-12A used identical titanium construction. The suit conformed to the standard 12-size tariff, with socks now available in 6 sizes. The coverall and gloves weighed 14 pounds, the exterior cover and harness 10 pounds, and the helmet 7 pounds, for a total of 31 pounds.[49]

A new dual suit controller was designed for the S901J that was smaller and lighter than the one used on the S901H. The new controller still used two separate aneroids, either of which could operate the suit independently of the other. The primary aneroid was set to an absolute pressure of 175 ± 7 mm Hg and the secondary aneroid was set at 165 ± 7 mm Hg. This new controller used an elegant design that did not require an external pilot (oxygen) pressure source as with prior controllers, but rather used suit (bleed) pressure for the necessary pressure control. This design has been very successful and remains in use for Air Force and NASA pressure suits as of 2011. Two relief valves, located on the outside of each hip of the coverall, were set at 4.5 ± 0.5 psi.[50]

On September 13, 1974, the Air Force used an SR-71 (61-7972) to set a speed record from London to Los Angeles (2 weeks earlier, the same aircraft had set a record from New York to London). The flightcrew was Capt. Harold "Buck" Adams (pilot) and Maj. William C. "Bill" Machorek, both wearing S901J full-pressure suits. The total time for the record flight was 3 hours, 47 minutes and 36 seconds. Adams and Machorek had covered nearly 5,463 miles at an average speed of 1,435.587 mph.

U.S. Air Force

It appears the S901J suit came in colors other than white. Here is NASA test pilot Thomas C. McMurtry and flight-test engineer Vic Horton after McMurtry's first flight in the YF-12A, on December 14, 1977.

NASA

The S901J helmet was less complicated than the A/P22S-2 helmet. For instance, the previous pneumatic seal around the visor was replaced with a Gemini-style static seal that was activated mechanically via a visor-closing bailer bar. Designers moved the face seal farther forward to provide maximum headroom in the helmet and decrease the volume of the breathing space. The face seal consisted of a neoprene-coated fabric, a neoprene face seal, and a malleable aluminum frame. The microphone was mounted on the helmet shell with an external adjusting knob located front left, under the visor opening.[51]

The S901J helmet shell was based upon the original S901 shell with minor changes to accommodate new pressure controls and a compression sealed visor assembly. This replaced the pneumatic seal used on the earlier S901 helmets. A subsequent need for increased internal headroom for some crewmembers resulted in the development of a "bumped out" S901J helmet, where the back section of the helmet shell was enlarged.[52]

David Clark Company molded the helmet from a mixture of milled fiberglass, epoxy

The difference between the original U-2s (such as the NASA U-2C in the foreground) and the later big-wing U-2Rs (NASA ER-2s) is readily apparent. The U-2R was a much larger aircraft with a roomier cockpit that finally allowed the pilots to wear full-pressure suits.

NASA

The U-2R eventually grew large "super pods" on each wing to house additional sensors and equipment. Forty-five years after its first flight, the U-2 is still a valuable national asset. Over the years, the aircraft has received a turbofan engine and a glass cockpit, becoming the U-2S.

Courtesy of Lockheed Martin Aeronautics

resin, hardener, and fiberglass cloth that was heat cured at 150 °F for 60 minutes. After the shell cooled, holes were drilled for wiring and hardware, and a metal disconnect ring was attached to the bottom of the shell. A molded silicone-rubber gasket was bonded around the visor periphery to form an airtight seal when the visor was down and locked. A black neoprene spray bar was bonded around the interior of the face opening. A series of holes in the spray bar discharged oxygen to keep the visor defogged. A drinking port with a spring-action door was located offcenter to the right. The helmet liner, available in four sizes instead of three, was a molded neoprene foam material called nopcofoam with a deerskin covering.[53] An oxygen-pressure-piloted anti-suffocation valve located on the left side of the helmet just above the neck ring opened automatically if the suit lost its oxygen-pressure source. However, many pilots did not like the J-suit anti-suffocation valve since it provided no warning of complete loss of oxygen pressure.[54]

Originally, the helmet used a gold-coated acrylic visor. After an in-flight accident that implicated visor reflections, PPG developed an anti-reflective-coated laminated glass visor with heating filament wires between the layers of glass for defogging. Subsequently, the SR-71 flight manual required the front-seater to wear a glass visor, but the back-seater generally wore an acrylic visor; they were interchangeable.[55]

The helmet holddown system consisted of an endless stainless steel cable that passed through a nylon pulley in front, metal cable guides on either side of the helmet disconnect ring, and through a nylon pulley in the back. A strap adjustment assembly in the front pulley allowed the pilot to control the amount of helmet rise.[56]

Each suit came with a helmet bag and a 30-by-12-by-14-inch suitcase equipped with a Yale padlock. Over the course of several years beginning in 1966, David Clark Company fabricated 148 S910J suits for Senior Crown.

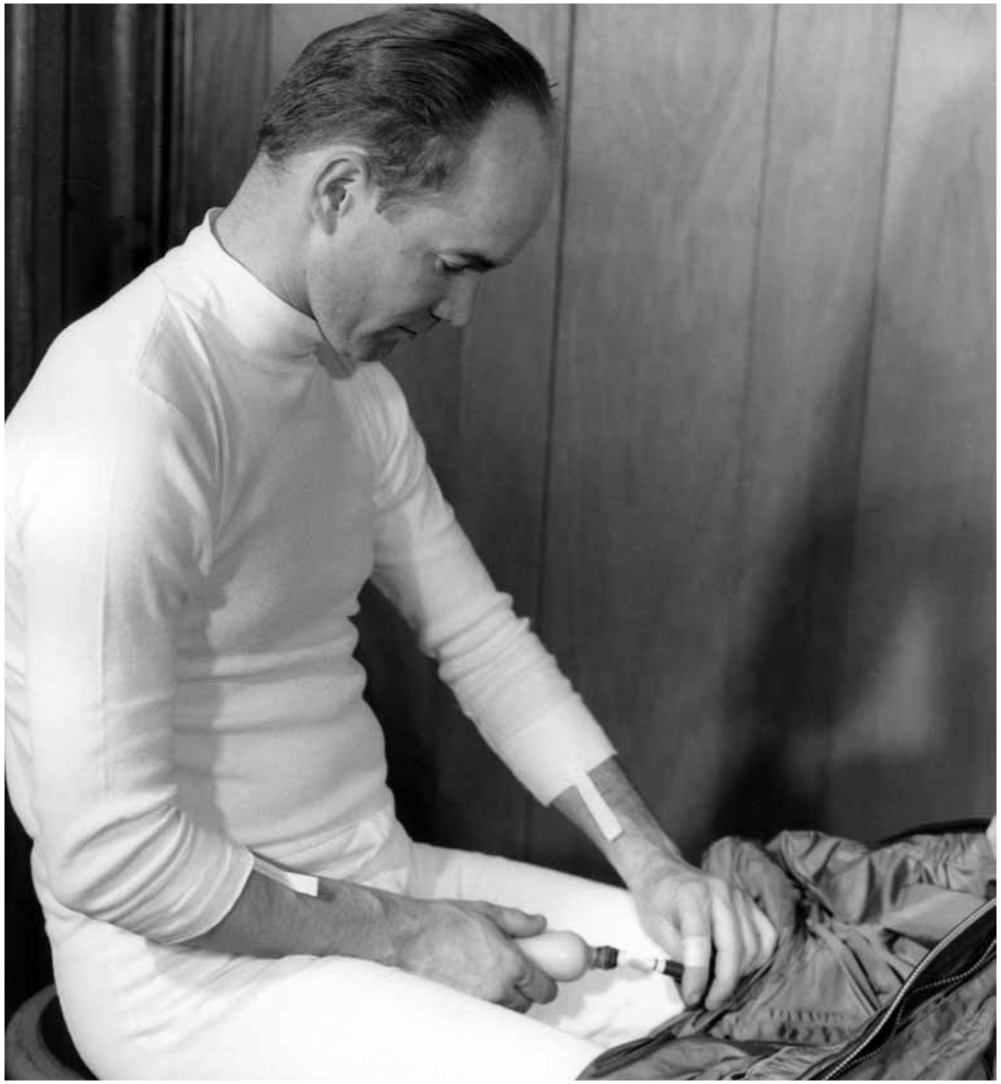
Although the first common suit that could officially be used in both the SR-71 and U-2R did not come until the S1031C in 1989, it appears that pilots at Lockheed Skunk Works wore modified S901Js on U-2R test flights beginning sometime before 1968. The primary modification was a minor change to the lower end of the helmet oxygen hoses and a tee block that mated the aircraft, seat kit, and helmet oxygen hoses. A similar modification was performed on a limited number of S1030 helmets to allow their evaluation in the U-2R.[57]

S1010—A SUIT FOR THE DRAGON LADY

Over the years, Kelly Johnson had been tinkering with advanced U-2 versions, beginning in September 1963 with a modified U-2C sometimes referred to as the U-2L ("L" probably stood for "long" or "lengthened" instead of being an official designation). Two further years of refinement resulted in the Lockheed Model CL-351, and in August 1966, the Air Force awarded Skunk Works a contract to begin development of the U-2R, with the "R" meaning "redesigned" or "revised"; however, this time the designation became official.

As finally built, the U-2R was a completely new airplane, sharing nothing but its general configuration with the first-generation airplanes. The U-2R was almost 40 percent larger than the original U-2, with a 23-foot increase in wingspan. To the pilots, perhaps the most welcomed change was a larger cockpit. The U-2R pilots enjoyed the luxury of a full-pressure suit and a zero-zero ejection seat. Kelly Johnson and his design team placed significant emphasis on increasing range and endurance since the first-generation U-2 suffered from an inherent fuel-capacity limitation and its endurance rarely exceeded 9 hours. Although in-flight refueling was added to a few early U-2s, the aircraft's range was marginal for many missions. The U-2R carried considerably more fuel and missions in excess of 14 hours became possible, but it was rarely flown due to the physiological limitations of the pilot, even with the new full-pressure suits.

On May 25, 1967, personnel from the CIA, David Clark Company, Firewel, Lockheed,

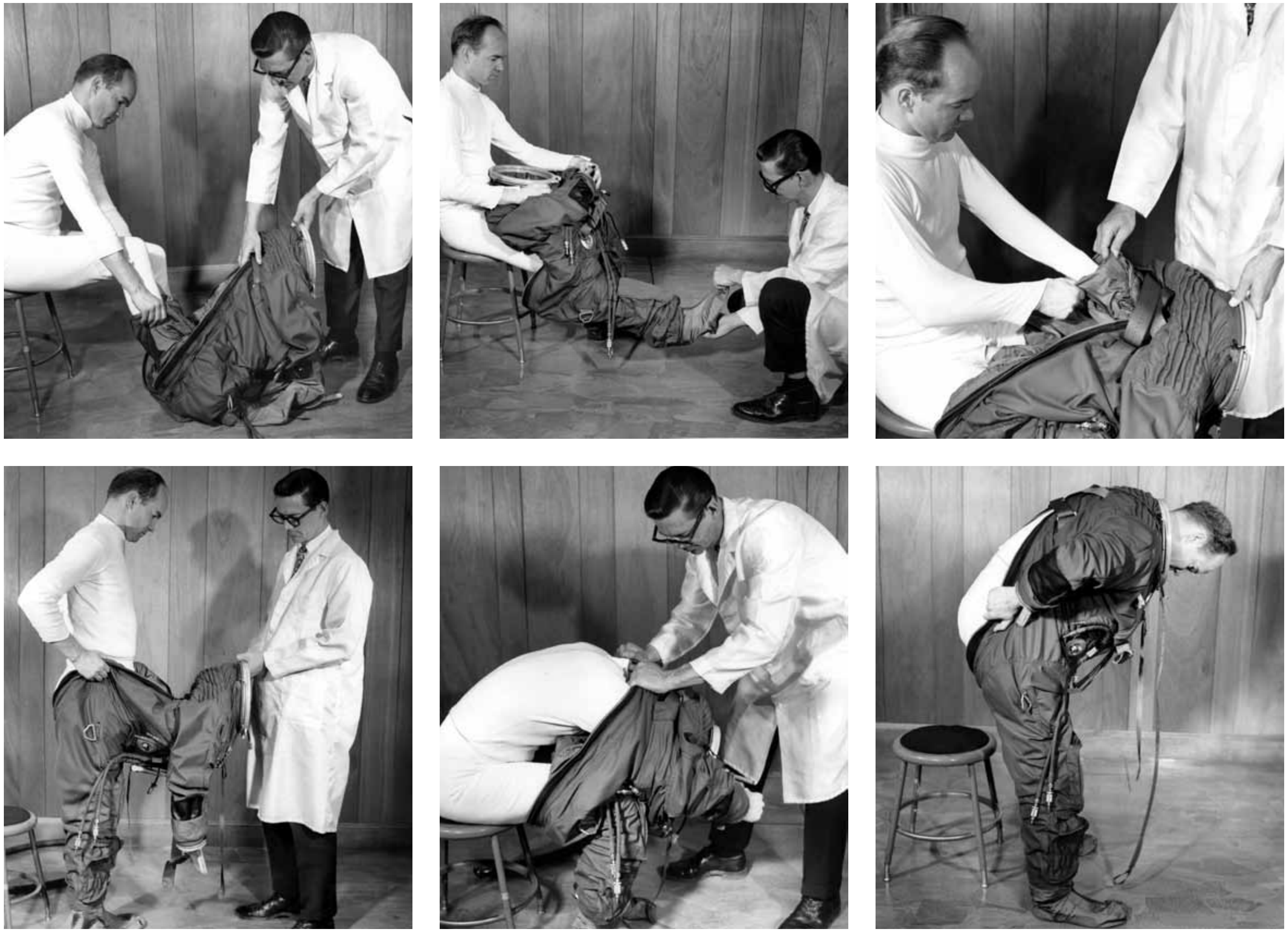


David Clark Company introduced a urine-collection system as a modification to the S901H and used the same system on many later suits. The urine-collection system, for men only, consisted of an inner hose connected to an external catheter, a release valve, and an external hose attached to a storage bag mounted on the aircraft.

Courtesy of the David Clark Company, Inc.

and USAF met in Burbank to discuss the final configuration of the U-2R cockpit, pressurization system, escape system, seat kit, parachute, and pressure suit. A design review of the new David Clark Company S1010 PPA was held in Worcester in June 1967, and a review of the aerospace ground equipment and test fixtures was held at Firewel in Buffalo later that month. The company began fabricating a prototype suit in July. The first S1010 suit was not ready for flight-test until September, so in the interim, several OXCART S901 suits were modified to work in the U-2R for Lockheed test pilots. Lockheed test pilot Bill Park, who had previously flown the A-12, made the first U-2R flight using Article 051 (N803X, 68-10329) on August 28, 1967, from the CIA facility at North Base on the edge of Edwards AFB.[58]

In general, the S1010 was similar to the S901J but with oxygen and electrical connections tailored for the cockpit of the U-2R. The suit included a fully integrated parachute harness, an automatic water-activated flotation



Above and photos on page 336: Donning the S1010 was not as difficult as one might expect, but it was a complicated procedure and generally went much better with an experienced suit technician assisting. The process begins with the wearer putting his feet in the pressure booties, raising the suit to the thighs, then putting the head and shoulders into the suit. The final steps were donning boots, attaching the helmet, and putting on the gloves.

Courtesy of the David Clark Company, Inc.

system, and an optional inflatable thermal protective garment. Given the long-duration missions of the U-2R, Joe Ruseckas and Ed Dubois at David Clark Company developed a urine-collection system for the S1010, and the company subsequently retrofitted this system to numerous other pressure suit models.[59]

An entirely new, third-generation helmet was designed for the S1010, and the David Clark Company designers made every attempt to reduce head-borne weight to minimize pilot stress and fatigue during long missions. They accomplished this by removing the breathing regulator and oxygen supply system from the helmet and relocating it in the coverall. In addition, the coverall helmet-disconnect bearing assembly was integrated with the helmet via a soft neck section at the base of the helmet shell so that the weight of the neck ring would not be head borne. They also enlarged and reshaped the S1010 helmet shell to increase headroom, relative to the S901J.[60]

The coverall and gloves weighed 14 pounds, the exterior cover and harness 10 pounds, and the helmet 7 pounds, for a total of 31 pounds. The entire suit, minus helmet, could be folded into a 2.7-cubic-foot package. The coverall and gloves were custom tailored for each U-2R pilot, while the helmet came in one size with five interior cushion sizes. David Clark Company also fabricated custom S1010 suits for Republic of China Air Force (RoCAF) pilots that flew the U-2R for the CIA from 1969 until 1974. Project pilots began showing up in Worcester during late 1967 to be measured and fitted for the new suits.[61]

David Clark Company fabricated custom suits for Republic of China Air Force (RoCAF) pilots that flew the U-2R from 1969 until 1974. The Chinese pilots were generally smaller than their American counterparts.

Courtesy of Clarence J. P. Fu Collection

The Air Force also procured two variants of the S1010. The S1010A had the breathing-oxygen regulator, communications gear, parachute harness, and flotation device mounted integrally. The S1010B moved the regulator and communications gear back to the helmet while the parachute and floatation gear formed part of a separate harness worn over the suit. In all, David Clark Company produced 151 S1010 suits of the various models.[62]

During 1978, David Clark Company began designing a new helmet to replace the S1010 units when they reached the end of their services lives in 1981. The primary goal was to minimize helmet-induced stress and fatigue. Designers explored a nonconformal dome helmet that completely eliminated head-borne weight and provided freedom of head movement within the helmet without the rotational torque (neck stress) associated with conformal helmets. Designated S1010D (D for dome; there were no A-C helmets), this nonconformal helmet used a large moveable visor (a considerable challenge given the need for highly reliable sealing under pressure) that provided excellent visibility. The pilot wore a skullcap communications carrier with a microphone and earphones. The prototype S1010D helmet was fully qualified, and completed

The S1010B featured a harness-and-flotation system integrated into a vest that was worn over the pressure suit. Other differences from the S1010 were the location of the neck mobility joint to the suit side of the helmet-to-suit neck-ring disconnect and the routing of the oxygen and communication umbilicals directly into the helmet.

Courtesy of the David Clark Company, Inc.

The S1010 helmet moved the face seal further forward to reduce the volume of the breathing space and allow more of the head to be ventilated with suit gas. The major change was using a bailer bar to mechanically compress a static visor seal instead of the complicated pneumatic seal used on earlier S901 helmets. A similar technique had been used on the Gemini spacesuits.

Courtesy of the David Clark Company, Inc.

The S1010 helmet was designed to minimize head-borne weight by placing a softgoods section at the bottom of the helmet shell to offload the nexk ring weight. The designers also placed the breathing regulator and oxygen system in the coveralls. Oxygen was released into the helmet via a plenum in the neck ring. Further streamlining was accomplished by routing the communications cord internally as shown here. The S1010 helmet hold-down was generally similar to the S901 and A/P22S series suits. An endless stainless steel cable that passed through a nylon pulley in front, metal cable guides on either side of the helmet disconnect ring, and through a nylon pulley in the back. A strap adjustment assembly in the front pulley allowed the pilot to control the amount of helmet rise.

Courtesy of the David Clark Company, Inc.

operational test and evaluation (OT&E) in a U-2R, albeit with mixed results. The prototype helmet-support system consisted of foam pads of varying thickness integrated under the coverall neck ring to support the helmet on the shoulders at the desired height location. Pilots complained this was unsatisfactory because it interfered with the parachute riser and shoulder harness and provided inadequate fore-aft stability. Consequently, the USAF decided to use a variant of the S1030 helmet (subsequently dubbed the S1031) on the new U-2R PPAs when they replaced the S1010 beginning in 1981.[63]

S1030—IMPROVED SENIOR CROWN SUITS

In 1977, David Clark Company developed the S1030 PPA as a replacement for the S901J used in the SR-71. This rear-entry suit introduced several innovative features, including compression-sealed hardware (eliminating adhesives), a thermal-protection garment integral with the gas container, and a modular (field-removable) gas container made from heat-sealable, urethane-coated nylon taffeta fabric. The designers created a separate retainer assembly to contain an integrated parachute harness and a fully redundant, automatic flotation system that had improved cold-temperature performance and water-activated inflation devices. The S1030 also included the drinking port and urine-collection system

The S1030 supported female pilots like NASA's Marta Bohn-Meyer, in front of an SR-71B (61-7956/NASA 831) on February 27, 1992. Bohn-Meyer was the chief engineer at the Dryden Flight Research Center until she was killed while practicing for the 2005 U.S. National Aerobatic Championships when the Giles 300 aerobatic aircraft she was piloting crashed in Yukon, OK. The cause of the crash was deemed the catastrophic failure of the front hinge of the canopy, which apparently incapacitated her.

NASA

that had been added to the S901H via retrofit. The S1030 coverall came in the 12 standard sizes, with 8 sizes of bladder boots, 12 sizes of gloves, and a single helmet size with 3 cushion sizes.[64] Each suit cost approximately $30,000 and lasted 10–12 years. The suits were typically inspected every 90 days, or 150 hours, and overhauled every 5 years.[65]

David Clark Company developed a new helmet that featured greater headroom, a positively vented cushion assembly, a drop-in breathing regulator, and improved head impact protection. The designers also reduced the weight of the oxygen system weight and eliminated legacy on-off valves by using a novel regulator sensing line shut-off valve keyed to the visor position via a rotating visor pivot pin. Other novel features included a modular drinking port, modular anti-suffocation valve, a more reliable takeup assembly, a more maintainable visor sealing and locking

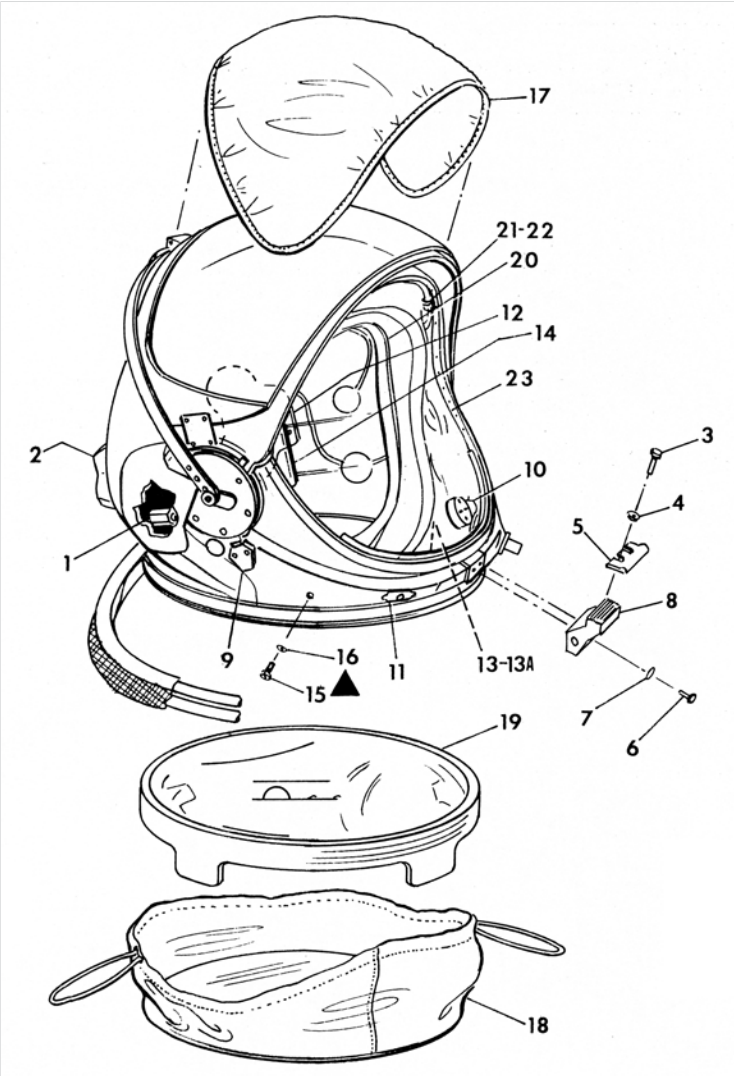
NASA research pilot Ed Schneider prepares for his first SR-71 flight on October 18, 1994, wearing his S1030 suit.

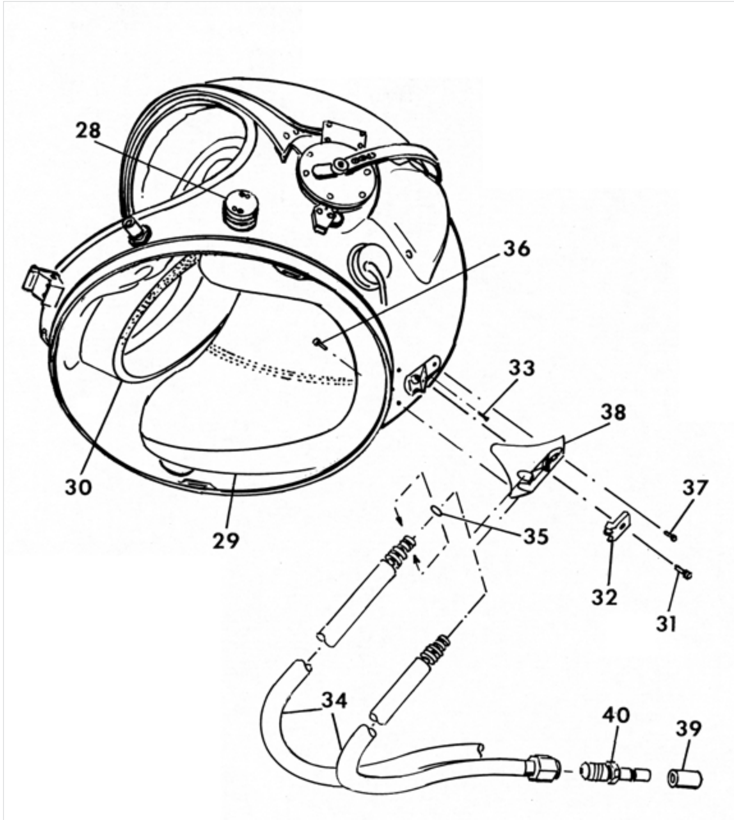
NASA

mechanism, integrated lower-torque (thrust) bearing, and an improved (amplified) noise-canceling microphone and flat cable electrical harness integrated to the interior surface of the helmet shell. The prototype S1030 helmet was fully qualified and completed its OT&E during flight tests in an SR-71. Despite generally positive evaluations, the USAF decided to revert to the bumped-out S901J helmet shell for the production S1030 helmet, albeit with the improved on-off valve, a larger drinking port, and a modular anti-suffocation valve.[66]

The complete S1030 ensemble consisted of six layers including long underwear, comfort liner, ventilation layer, double-walled gas container, restraint layer, and a Fypro-fabric exterior cover that was the gold-orange color referred to as "old gold." However, at least one suit was fabricated in a medium-blue color.

The S1030 began replacing the S901J in late 1978 and remained active until 1996 when it was replaced by the S1034, although by that time the SR-71 had been retired from USAF service and the only three flyable airplanes were operated by NASA. David Clark Company produced 115 S1030 suits.[67]



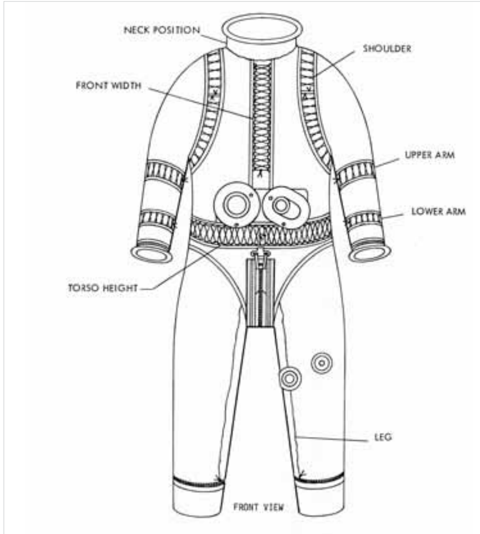


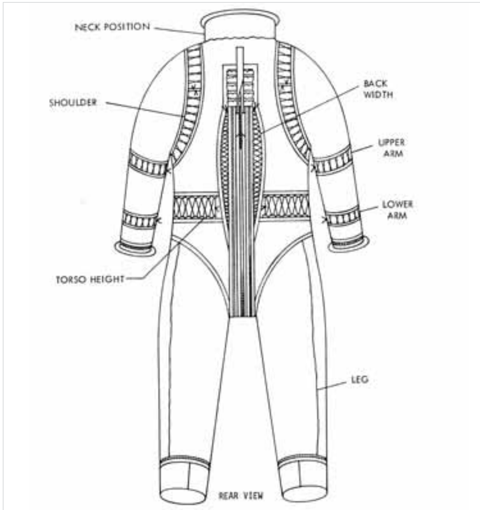
Although the new S1030 helmet was generally well received by the pilots, the Air Force decided to replace it with the bumped-out version for the S901J helmet for production suits. Some of the more significant items include (1) oxygen-system valve, (2) helmet-pad adjustment knob, (10) microphone, (17) visor, (18) helmet bag, (23) oxygen spray bar, (29) cushion assembly, (30) face seal, and (34) hose assembly.

Courtesy of the David Clark Company, Inc.

Officially, all S1030 suits were "old gold" Fypro, but there was at least one medium-blue suit. This is Lt. Col. Joseph T. "J.T." Vida (left, in the blue suit) and Bredette C. "B.C." Thomas, Jr. at Norton AFB, CA, on November 16, 1986.

Tony R. Landis





The adjustments on the restraint layer of the S1030 were generally similar to other modern full-pressure suits using laces to tighten or loosen a fabric panel underneath.

Courtesy of the David Clark Company, Inc.

On its last flight, on March 6, 1990, Lt. Col. Raymond E. "Ed" Yielding and Lt. Col. Joseph T. "J.T." Vida set three world speed records in SR-71A (61-7972). One of these involved flying 1,998 miles from Los Angeles to Washington, DC, in 1 hour, 4 minutes, and 20 seconds, averaging 2,144.83 mph. At the flight's conclusion, they landed at Washington-Dulles International Airport and turned the airplane over to the Smithsonian's National Air and Space Museum.

Courtesy of Lockheed Martin Aeronautics

The S1031 replaced the S1010 for all U-2R operators during the early 1980s. For all intents, the suit was a variant of the S1030 developed for the SR-71 with the major changes being the necessary interfaces to mate with the airplane.

Courtesy of the David Clark Company, Inc.

The S1031 floatation device kept the pilot mostly vertical in the water, ensuring that water did not enter the anti-suffocation valve on the helmet. David Clark Company spent considerable effort to make the suits as safe as possible following an over-water ejection; the memory of Ray Torrick drowning after ejecting from a Lockheed M-21 in 1966 is still fresh.

Courtesy of the David Clark Company, Inc.

Below and photos on page 347: It was possible to self-don the S1031, but having assistance made the process much easier. Like all rear-entry suits, the process began by inserting one's feet through the legs into the booties, pulling the suit up to the thighs, inserting the arms followed by the head and shoulders, then standing up and arranging the suit correctly on the torso. The rear zipper can be closed using a long lanyard, but suit technicians are usually present to ensure everything is aligned properly. Boots come next. After the suit is properly donned, the parachute harness is added. The helmet and gloves are next, flowed by pressure integrity testing in the physiological support area. The suited pilot then heads to the aircraft.

Courtesy of the David Clark Company, Inc.

Various views of the S1031 helmet. The face seal is as far forward as possible to minimize the breathing space in front of the pilot. The oxygen hoses attach to the back of the helmet where they do not interfere with the pilot's vision or movement. Note the bailer bar that provides mechanical pressure against the visor to ensure a tight seal.

Courtesy of the David Clark Company, Inc.

S1031—IMPROVED DRAGON LADY SUITS

In 1981, David Clark Company developed the S1031 PPA as a replacement for the S1010 used in the U-2R. The resulting suit was nearly identical to the S1030 developed for the SR-71 except for different oxygen and electrical interfaces dictated by the aircraft. These interfaces precluded using a single type of suit in the two aircraft. In addition, special care was taken to limit the bulk on the front of the chest to minimize interference with the steering-wheel-type control column used in the U-2R. Like the S1030, the suit came in the standard 12 sizes and weighed approximately 35 pounds.[68] The S1031 helmet was identical to the S901J-based production S1030 helmet except that it did not have oxygen system on-off valves (not required in the U-2R) and did not have an externally adjustable microphone bracket (never present on the S1010 helmet). The S1031 used the same "old gold" Fypro color as the S1030.[69]

The S1031 replaced the S1010 in service beginning in late 1982 and remained active until 1996 when it was replaced by the S1034. The suit was used by the USAF in the U-2R, U-2S, and TR-1, and it was used by NASA in the ER-2. A midproduction running change in the S1031 suit deleted the pocket on the left thigh. After a few suits were produced, a Velcro pad was added on the left thigh—same as had always been on the right thigh. David Clark Company fabricated 231 S1031 suits.[70]

In 1984, David Clark Company began investigating improved helmets in anticipation of the need to replace the S1030/S1031 helmet in the late 1980s. This study examined three different concepts: a lightweight version of the S1030/S1031 helmet, an improved version of the S1010D nonconformal helmet, and a "soft" clamshell Sokol-type helmet. The company fabricated engineering models of each concept, with the lightweight S1030/S1031 helmet, designated S1030L/S1031L, ultimately being selected. It is noteworthy that the nonconformal helmet improvements made as a part of this effort, principally in helmet support and stability, eventually benefited NASA when it became part of the S1032 Launch Entry Suit and, later, with the S1035 Advanced Crew Escape Suit.[71]

S1031C—COMMON SUIT

David Clark Company developed the S1031C PPA in 1989 as a common replacement for the S1030 and S1031 PPAs for use in the SR-71 and U-2R. Developing a common suit for use in aircraft with different interfaces was accomplished by designing a parachute-harness/retainer assembly and urine-collection system that was reconfigurable in the field for use in either aircraft; this was accomplished by selecting either the S1030 or S1031 helmet for use with S1031C coveralls. Additionally, the S1031 retainer assembly was standardized for use with the S1031C PPA because of its lower frontal bulk (compared to S1030). Thus, the S1031C PPA was a hybrid S1030/S1031 system based largely upon mid-1970s (S1030) pressure-suit technology.[72]

All previous urine-collection systems had passed fluid to storage containers mounted on the aircraft, a concept that complicated aircraft maintenance and posed some risks if a spill occurred. David Clark Company designed several configurations of internal urine-collection systems that were flight-tested using S1031 suits. However, none were considered satisfactory, mostly due to leakage. Although David Clark Company designers still thought it possible to develop an acceptable internal-collection system, its increased complexity, and the limited internal (coverall) storage volume appeared to offset the advantages to be gained. For the time being, at least, aircraft-mounted urine storage would continue.[73]

The S1031C began replacing S1030 and S1031 suits in 1991, and David Clark Company fabricated 60 S1031C suits.[74]

The Air Force uses "crew vans" similar to the NASA astronaut van. This pilot is wearing an S1034 in preparation for a U-2R mission in July 2004. The pilot gets to ride in the lounge chair, while the accompanying suit technicians ride on the bench to the left.

U.S. Air Force

Table 8—S1034 Requirements Classification

Category	Requirement	
I	1. Comfort (unpressurized) 2. Visibility 3. Mobility (upressurized) 4. Tactility–Dexterity 5. Oxygen Breathing System 6. Communications	7. Aircraft Compatibility 8. Thermal (hot-cold) Protection 9. Glare Protection 10. Pockets 11. Ease of Donning and Doffing 12. Aesthetics
II	1. Drinking and feeding 2. Urine Collection 3. Valsalva 4. Altitude Protection 5. Mobility (pressurized) 6. Comfort (pressurized)	7. Leakage (pressurized) 8. Structural Integrity 9. Maintainability 10. High and Low Temperature Storage 11. Durability 12. 5th to 95th Percentile Sizing
III	1. Ejection G Forces 2. Parachute Compatibility 3. Survival Kit Compatibility 4. Wind Loading Protection 5. Flotation Provision 6. Water Immersion Protection 7. Impact and Penetration Protection	8. Anti-Suffocation Protection 9. Open Flame Protection 10. Laser/Flashblindness Protection 11. Explosive Decompression Protection 12. Chemical Biological Defense Protection

Source: "S1034 Pilots Protective Assembly, Development & Qualification Final Report," David Clark report DCR-3124-00, February 28, 1992.

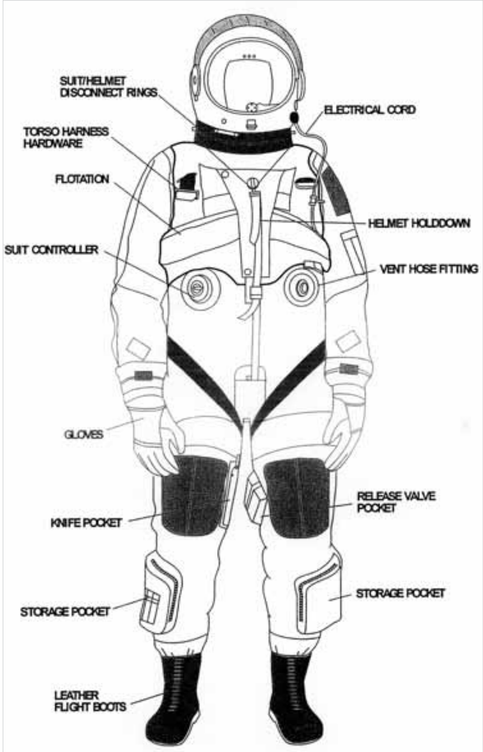
S1034—IMPROVED COMMON SUIT

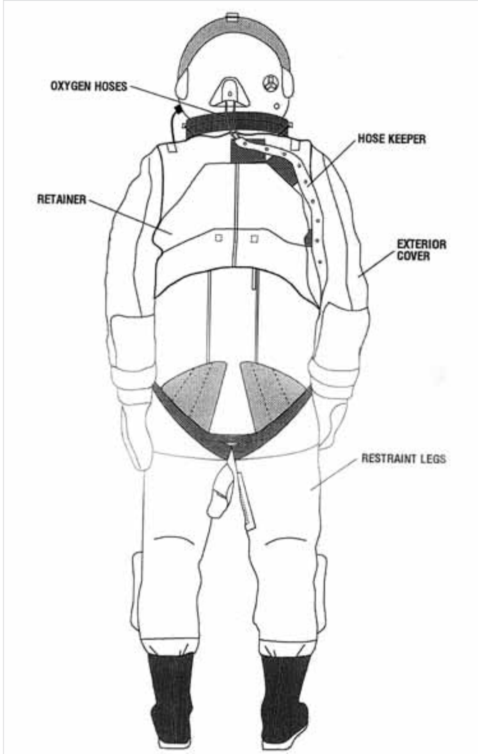
In late 1987, David Clark Company began developing a new suit to replace the S1030 and S1031. This was a year before the company began developing the S1031C common suit. The goal was to develop a common suit that reduced crewmember stress and fatigue, with a secondary goal of reducing ground support and maintenance requirements. Unlike all previous suits, which had been obvious evolutions of the original A/P22S-2 and S901, what became the S1034 was largely a clean-sheet design, although it ended up looking and acting very much like an evolutionary suit.[75]

Designers began by categorizing the known requirements based on years of crewmember and maintainer experience with pressure suits. Requirements were placed into one of three general categories: Category I directly affected performance on every mission; Category II occurred frequently but not on every mission; and Category III occurred infrequently and usually only under emergency conditions. The relative order of individual requirements within each category was more subjective, with the designers basing the ranking primarily on previous experience. David Clark Company designers recognized that all of the requirements were valid, and the ranking was simply a method to prioritize their implementation.

None of these requirements was new, and all had been addressed, to varying degrees, by previous generations of pressure suits. For the most part, comments from crewmembers regarding the S1030 and S1031 series suits had been overwhelmingly positive. In the 30 years since the MC-2 full-pressure suit was introduced for the X-15, David Clark Company had largely eliminated the problems concerning comfort and mobility that had plagued suit development since Wiley Post. Nevertheless, wearing a full-pressure suit still induced pilot stress and fatigue, and maintaining the suits was somewhat labor-intensive. The designers felt that a new generation of materials might offer significant improvements and took the opportunity to reevaluate their entire approach to pressure suits. According to Jack Bassick, the director of research and development at David Clark Company at the time:

> A clean slate approach was used in the requirements-design trade study process, wherein each PPA requirement was carefully reconsidered and revalidated prior to being accommodated. Additionally, the relative importance of each requirement to the mission was weighed to ensure that low priority requirements did not exert a disproportionate amount of adverse influence on high priority requirements. Numerous mock-ups were fabricated for test and evaluation of various concepts throughout the requirements-design trade study process. Concepts considered ranged from full to partial-pressure coveralls, from single to multiple layer coveralls and from soft, non-conformal, fixed visor helmets to rigid, conformal, movable visor helmets.[76]





The S1034 is not much different visually than the suits it replaced, but modern materials allowed David Clark Company to make it much more comfortable and sustainable.

Courtesy of the David Clark Company, Inc.

The conceptual design that emerged from the evaluation, however, was not terribly different from what had come before. By this time, the S1031C common suit was well along in development and, perhaps not surprisingly, the designers concluded that the S1031C concept offered the best approach. Nevertheless, the designers identified several developments that might reduce stress and fatigue, including a lightweight helmet, breathable-gas-container materials, low-torque bearings, and a better glove-disconnect design.[77]

During 1989, designers at David Clark Company fabricated an engineering model that used Gore-Tex fabric for the gas container.[78] This breathable material allowed a lightweight garment that was more

During the 1950s, unfortunate human subjects wore pressure suits during cold-water evaluations. By the 1990s, researchers had turned to instrumented brass anthropomorphic dummies for such tedious and potentially dangerous tasks. This is the dummy used for the S1034 cold-water evaluations.

Courtesy of the David Clark Company, Inc.

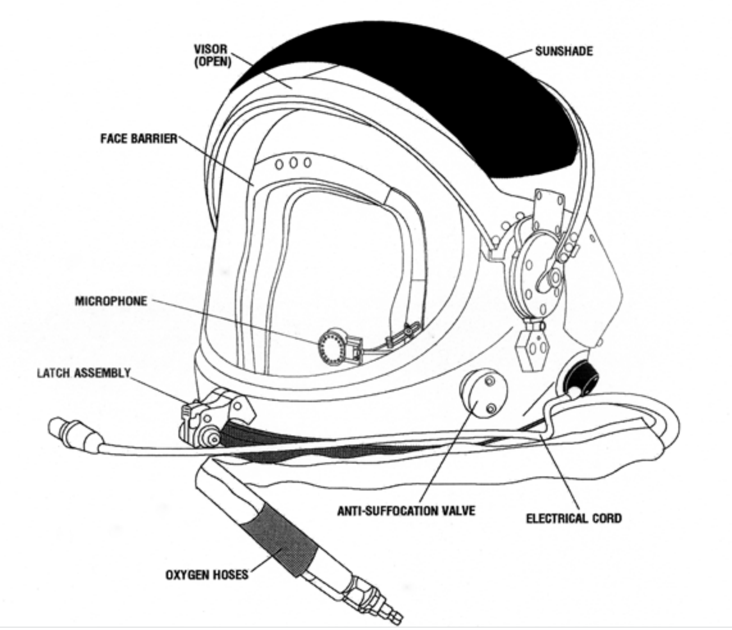
comfortable, less bulky, easier to don and doff, and far simpler than the S1030/S1031 gas container. In this context, "breathable" refers to the ability of the fabric to allow perspiration to pass in the form of water vapor while retaining air pressure. The breathable gas container allowed David Clark Company to minimize the amount of vent ducting within the suit. After a great deal of experimentation, designers chose a three-ply material: a nylon taffeta fabric for the outer ply; a Gore-Tex membrane for the waterproof, pressure-retaining, breathable inner ply; and a nylon tricot fabric for the inner ply. Laboratory testing of the material showed its durability and launderability was comparable to the urethane-coated nylon taffeta fabric used for the S1030/S1031 gas container and that reliability, maintainability, and repair should be similar. Subjective evaluations indicated that it was more pliable with a better "hand" and should provide better comfort.[79]

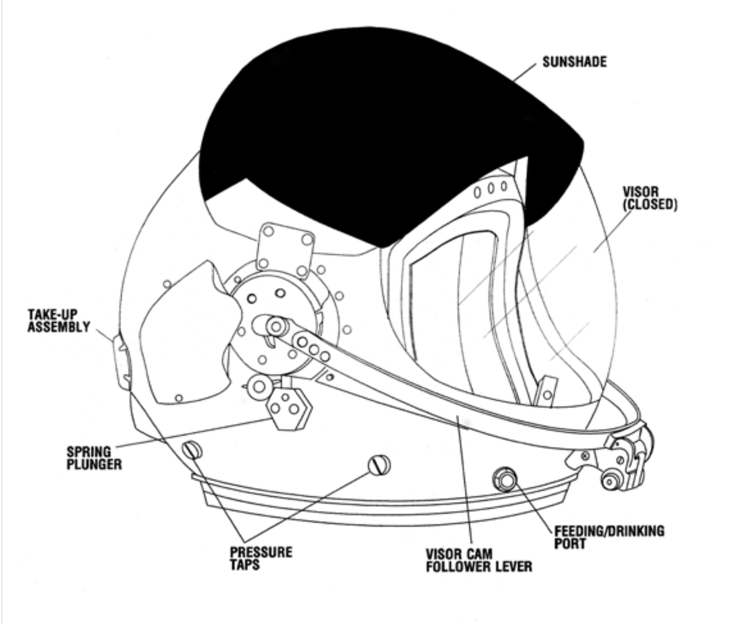
The use of Gore-Tex allowed the designers to greatly simplify production, especially of the legs. Typically, full-pressure suits incorporated at least four layers including an inner comfort liner, gas container, restraint layer, and exterior cover that primarily provides flame and abrasion protection. In the design of the S1034 legs, the restraint layer and exterior cover were incorporated into a single layer of high-temperature woven fabric. Additionally, the S1034 vent ducts were incorporated directly to the gas container via integral channels that distributed vent air throughout the coverall, including the hands and legs.[80]

The designers selected a YKK (Yoshida Kogyō Kabushikigaisha, or Yoshida Manufacturing Corporation) pressure-sealing closure after the source for the legacy B.F. Goodrich closure vanished. Engineers closely monitored the performance of the new closure, first introduced on late S1031 suits, during extensive flight-test and operational evaluation with the S1031 and found it to be satisfactory. The YKK closure functioned both as a pressure sealing and restraint (structural) closure, thereby eliminating the need for two, independently operated slide fasteners.[81]

Surprisingly, the designers also eliminated Link-Net from the restraint layer on the legs, choosing instead to combine the restraint and exterior cover functions into a single layer of Nomex fabric that was shaped to provide adequate knee mobility and comfort. The S1031 torso and arm restraint and exterior cover designs remained largely unchanged, still making extensive use of Link-Net for comfort and mobility.[82]

During the 1980s, David Clark Company had developed the S1031L lightweight helmet, and it had already been through





The S1034 helmet is an evolutionary design based on the S1031L lightweight helmet designed several years earlier for the S1031 suit. Modern materials allowed an improved two-ply visor to be added to the design, along with smaller oxygen hoses and microphone.

Courtesy of the David Clark Company, Inc.

extensive flight-test and operational evaluation. The unit was functionally identical to the S1031 helmet but was fabricated of lighter materials. This helmet was used for the engineering model S1034, although David Clark Company developed a new two-ply heated visor that used an inner ply of polycarbonate to resist internal shattering and an outer ply of acrylic to provide scratch resistance. Additionally, they modified the helmet with smaller-diameter oxygen hoses and a lighter, smaller-profile microphone. Designers selected a modified version of the standard PPA helmet holddown system that used a sized cable and a simplified rear-anchor bracket.

During the development of the S1034, the David Clark Company designers conducted a detailed review of alternate full-pressure glove designs and determined that it would be possible to improve comfort and mobility. This was based, at least partly, on a glove developed under a NASA-sponsored 8.3 psi glove program that consisted of an all-Link-Net restraint and a separate outer cover. However, that design was considerably more complex and expensive to manufacture. Given the limited benefits and significant costs, David Clark Company decided to stay with a modified version of the S1031 glove.

The prototype S1034 gloves offered improved comfort, mobility, and dexterity by using a combination of flat and tucked patterning. Designers replaced the leather and nylon palm of the S1031 glove with a single layer of Nomex embossed with silicone for improved gripping and wear protection. They also

Lt. Col. Charles P. "Chuck" Wilson in the blue prototype S1034 in Taif, Saudi Arabia. One of the U-2S aircraft assigned to the 4402nd Reconnaissance Squadron (Provisional) is behind the pilots. The other pilots are wearing S1031C suits.

Courtesy of Charles P. Wilson

introduced a new glove disconnect for the S1034 that featured the improved locking mechanism and low-torque bearings from the NASA 8.3 psi glove program. At the same time, better machining capability and the new locking mechanism allowed designers to increase the inside diameter so that it was easier to pass the hand through while maintaining the same outside diameter. This was especially important given the limited cockpit volume of the U-2R.[83]

An improved flotation system consisted of dual low-bulk flotation cells fitted with automatic water-activated inflators. This system provided about half-again as much water-displacement volume as the S1031, with less stowed bulk, reducing the potential for U-2R control column interference. The greater displacement volume also resulted in a much higher floating position, thus keeping the helmet further out of the water.

Several pilots evaluated the engineering model S1034 and found it lighter, less bulky, more comfortable, easier to don and doff, and more mobile than the S1030/S1031. In addition, it appeared to be easier to maintain. Based on the positive results of this limited evaluation, in late 1989, the USAF authorized a full-scale development and qualification program.[84]

Having substantially improved the interior layers of the S1034, the David Clark Company designers conducted a search for new exterior cover materials based on flammability, strength, color, colorfastness, and durability. Flammability was a major concern since the exterior cover was the primary protection against open flame. The evaluation led designers to select two off-the-shelf Nomex fabrics. While other materials, such as Fypro or PBI (polybenzimidazole) offer superior flame protection, Nomex provided acceptable overall performance coupled with widespread availability and lower costs.[85]

Color is, almost by definition, a subjective choice. Since 1977, the S1030/S1031 had used "old gold" Fypro based on its combination of solar heat reflection, visible light reflection, and aesthetics. However, search

A mixture of colors. When they fabricated the royal-blue suit, they did not have any blue Velcro so the suit used standard sage-green patches. Also note the "old gold" gloves.

Courtesy of Charles P. Wilson

and rescue (SAR) personnel identified tan as the best color from a SAR perspective given worldwide operations. David Clark Company also identified blue as a possible alternate, based primarily upon its aesthetics and desirability by USAF pilots.[86]

Nomex is available from DuPont in a range of weaves, weights, and colors. Natural Nomex is white, and DuPont creates several other colors through a producer dyeing process that results in a colorfast fabric. However, in 1990, the only colors available from DuPont were natural, green, and blue. Solution dyeing, where natural Nomex is dyed, almost always by third parties, provides a wider variety of colors but generally lacks colorfastness, especially when exposed to the high-intensity ultraviolet light present above 50,000 feet.

Below: The S1034 may be the last full-pressure suit fabricated in the United States. The only aircraft that currently require the use of pressure suits on a routine basis are the U-2 (and its ER-2 cousin) and the WB-57Fs. The Government expects to phase both of these aircraft types out of service over the next decade. The retirement of Space Shuttle during 2011 eliminated the only other routine user of pressure suits.

NASA

Lt. Col. Delewis "Dee" Porter wearing the third prototype S1034 suit at the U-2 test base in Palmdale, CA, during June 1991. Technicians noted the tan Nomex exterior cover soiled easily, and Porter found minor issues with the revised parachute harness, but overall everybody thought the garment was a significant improvement over previous pressure suits.

Courtesy of the David Clark Company, Inc.

Nevertheless, David Clark Company ultimately selected a solution-dyed gold Nomex that was available in different weaves and weights. They chose a 5.5-ounces-per-square-yard poplin weave for the upper coverall exterior cover and a 5.9-ounces-per-square-yard gabardine weave for the leg restraint-exterior cover. As an alternate, the designers selected an off-the-shelf, solution-dyed, royal-blue Nomex in a 6-ounces-per-square-yard gabardine weave. This fabric was a bit heavier than necessary for the upper coverall exterior cover and resulted in a slightly heavier garment.

The S1031 pocket configuration was selected for the S1034, although eliminating the exposure garment allowed the designers to remove the oral-inflation hose pocket from the left thigh. As it did with the S1031, David Clark Company placed a large piece of Velcro on the right thigh for optional use, and beginning with the third S1034 suit, did the same on the left thigh.

Life support technician Jim Sokolik (left) assists Dee Porter in his S1034 suit into a NASA ER-2 (809) during January 2000. The ER-2 and the NASA DC-8 were based north of the Arctic Circle in Kiruna, Sweden, to study ozone depletion as part of Project SOLVE. Scientists had observed unusually low levels of ozone over the Arctic during previous winters, raising concerns that ozone depletion there could become more widespread, as with the Antarctic ozone hole. The NASA-sponsored international mission took place between November 1999 and March 2000.

NASA

David Clark Company designers used a slightly modified version of the S1031 urine-collection system in the S1034. The modifications included the addition of self-sealing, quick-disconnect connectors at the internal hose interface that reduced urine spillage during the disconnect-doffing process and eliminated the need for a separate safety clip.[87]

The S1034 urine-collection system supports both male and female wearers. It consists of an internal hose that connects with an external catheter or collector and an external release valve that connects to a urine receptacle mounted on the aircraft. The release valve is located in a pocket on the inside of the left leg. The male urine-collection system consists of underwear drawers and briefs that are modified with a circular opening at the front for integration with the urine duct. A female urine-collection system consists of a collector assembly worn in conjunction with a support brief and female underwear drawers. These are modified with a slot-shaped opening at the front to integrate with the urine-collection system.[88]

The female collector (which is used only once) was originally purchased from a Government-approved source at a cost of several hundred dollars per unit. During 2000, after several months of research, Ed Dubois, on his own initiative, purchased several off-the-shelf incontinence products from a local drug store at a cost of several dollars per unit. Minor modifications allowed the product to interface with the urine-collection system in the S1034 suit. Dubois' wife tested the prototypes at home and, ultimately, a workable solution was found at an extremely reasonable cost.[89]

Designers considered several approaches for the S1034 helmet holddown assembly, including an automatic pressure-compensating design that eliminated the need to manually readjust the holddown upon pressurization. In the end, the designers believed that the benefits were not worth the additional complexity and cost. Instead, David Clark Company modified the S1031 design to make it somewhat simpler and lighter by replacing the adjustable length holddown cable with sized cables, eliminating any excess cable protrusions and the keeper sleeve at the rear. This allowed the use of a simple, low profile rear-cable anchor. The cables come in four sizes corresponding to the four basic pressure-suit sizes (small, medium, large, and extra large). The proper size cable is installed during the initial coverall fitting, with no subsequent adjustments required. The holddown assembly is capable of controlling helmet rise at operating pressures up to 5.0 psi.[90]

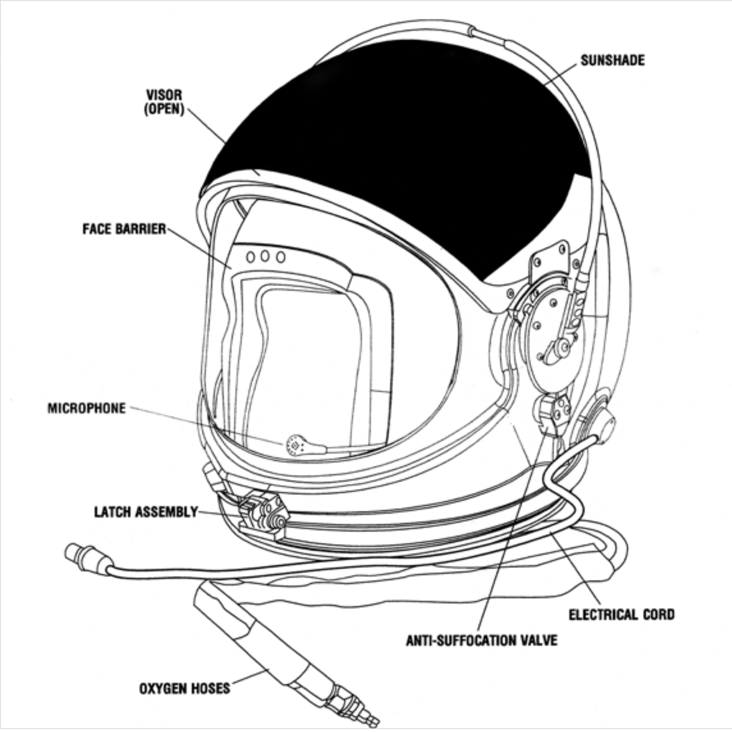
David Clark Company selected the standard dual-system pressure controller, first used on the S901J, based upon its redundant design, crewmember familiarity, satisfactory performance, pressure-schedule flexibility, and availability. David Clark Company designed the S1034 to be operated at 5.0 psi if the need arises, although 3.5 psi is the standard operating pressure. Prior study and preliminary testing showed the existing dual suit controller can be rescheduled to provide 5.0 psi, and the suit itself can withstand the pressure. However, a significant amount of mobility would be lost because of the higher pressure.[91]

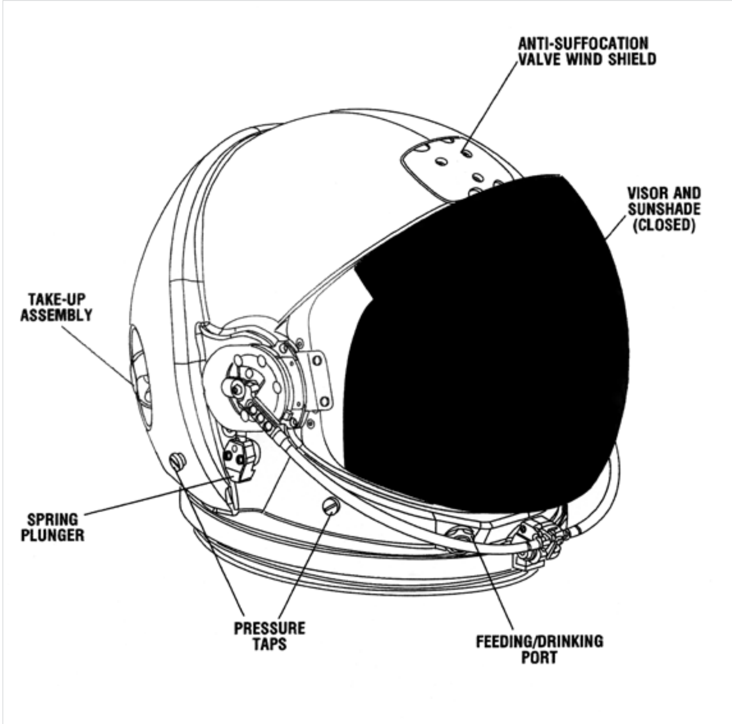
The helmet includes a modular drinking port at a slightly different location that provides, "an optimum angle for probe insertion into the mouth."[92] The port also has a new seal that is easier to replace. A low-profile M-169 microphone replaces the M-101 used on the S1030/S1031 helmets. Although the standard S1034 (and later S1034E) helmet provides a normal sunshade, laser and flashblindness-protection visors are also available.

David Clark Company fabricated three S1034 prototype suits for qualification testing. A size large-regular destructive-test unit (suit 001) and one medium-long flight-test suit (003) were fabricated with tan Nomex exterior covers. The second flight-test suit (002), in large-long, used a "Carolyn blue" Nomex exterior cover. The two flight-test suits were made for Lt. Col. Delewis "Dee" Porter and Lt. Col. Kenneth Sasine from the U-2R flight-test detachment at the Lockheed Skunk Works facility at Plant 42 in Palmdale, CA.[93]

The first suit (003) and helmet (103) arrived at Palmdale on June 20, 1991. This was Porter's suit and he made the first flight of an S1034 in a U-2 and eventually logged 145 flight hours wearing the garment. Technicians in Palmdale quickly found that the tan Nomex exterior cover soiled easily, but they did not attempt to clean it during the evaluation. Porter experienced some problems with the new parachute harness and floatation retainer assembly, and he complained of discomfort from the parachute harness across the buttocks. This was addressed by David Clark Company with a redesigned retainer assembly, but the parachute harness discomfort remained.[94]

Ken Sasine's suit (002) and helmet (102) arrived in Palmdale on June 27, 1991. Sasine ultimately used the suit for 158 flight hours during the evaluation, and the blue exterior





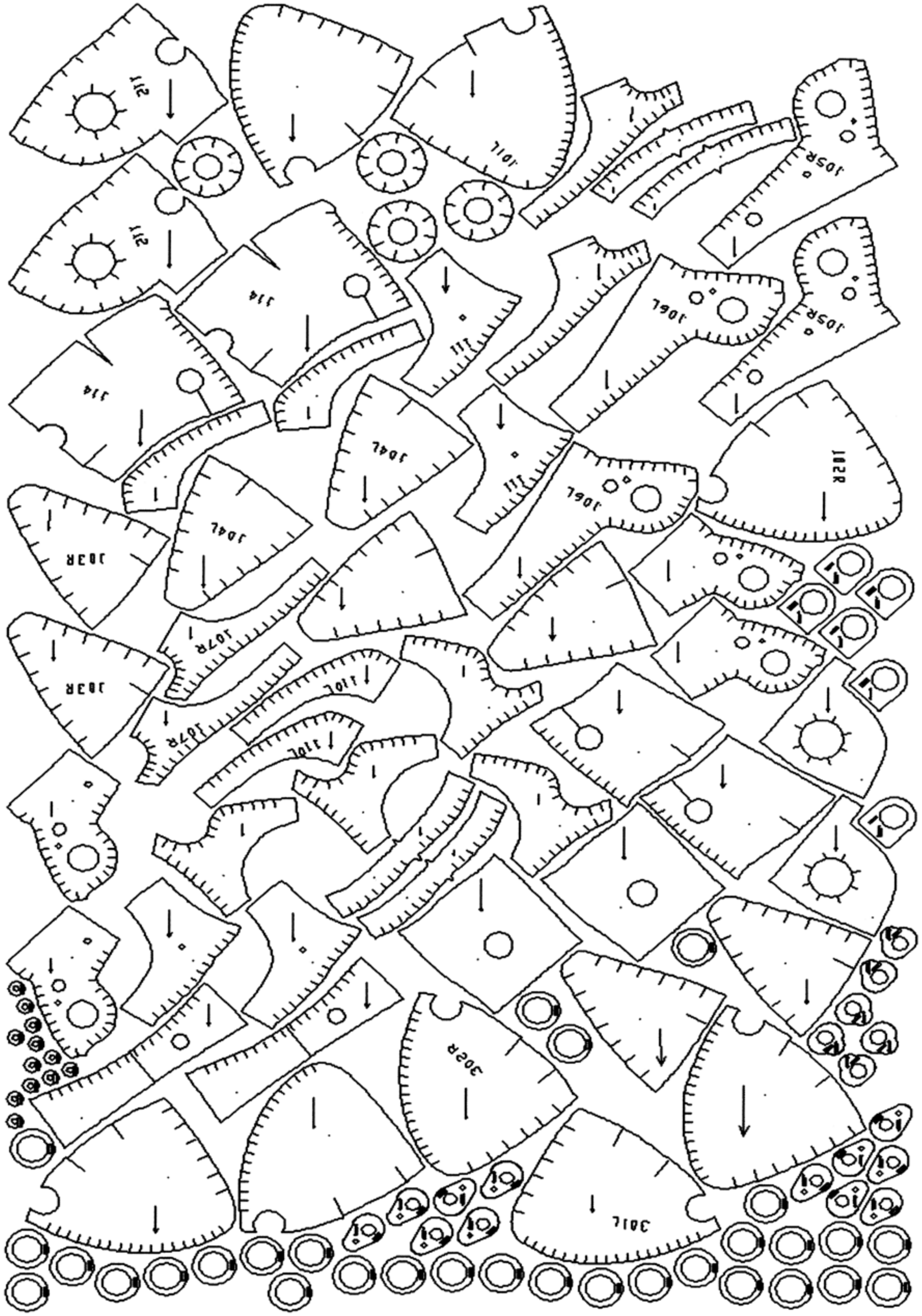
The S1034E is the latest full-pressure suit helmet from David Clark Company. The "E" suffix was added to reflect the entire helmet was designed using an electronic 3-D modeling system. There were no S1034B–D versions, and the suit itself continues to be an S1034 (no suffix).

Courtesy of the David Clark Company, Inc.

cover did not soil as easily as the tan on the other suit. Sasine complained of grainy and distorted optics causing eyestrain and headaches. Technicians replaced the helmet visor with a standard acrylic visor, and the hybrid acrylic-polycarbonate visor was returned to David Clark Company for evaluation.

Both pilots were impressed with the S1034 suits, remarking they were more comfortable and provided better mobility than previous suits. They also liked the improved ventilation and the low-torque neck ring and glove disconnects. Technicians performed two periodic inspections on the suits during the evaluation with no discrepancies found and no maintenance required. The preparation time prior to a flight was cut by a third, mostly because the pressure sealing/restraint fastener did not need to be lubricated every time the suit was donned. In fact, the closure required lubrication only once during the evaluation.[95]

Nevertheless, Porter and Sasine recommended several minor changes. These included moving the breathing regulator manifold pass-through closer to the helmet shell to provide more internal headroom, moving the leg-length adjustments to the exterior of the garment to allow easier sizing adjustments, and



Fabricating a helmet is a complicated endeavor, as shown by the number of different fiberglass patterns required for the S1034E. Each helmet is largely handmade, due partially to the low production volume and the critically of the helmet to the pilot's well being.

Courtesy of the David Clark Company, Inc.

reinstalling the S1031-style "butt pads" to the parachute harness to eliminate the discomfort experienced by Porter.[96] Based on these results, David Clark Company began finalizing the design of the production S1034 suit. Designers also switched the exterior cover to a gold Nomex material, although some tan suits have also been fabricated.

All previous full-pressure suit sizing had been based upon USAF anthropometric data published in 1959. While developing the S1034, David Clark Company studied all available anthropometric data, including the latest available for female USAF flying personnel, to determine if the standard 12 sizes were still satisfactory. In the end, David Clark Company and the USAF agreed that these still accommodated the greatest percentage of USAF flying personnel, including females.[97]

The S1034 is available in 12 sizes, the retainer in 4 sizes, the gloves in 12 sizes, and the restraint boots in 5 sizes. The suit can also be custom fitted if needed for a particular pilot or application. Both the S1034 and S1034E helmets come in a single size with five cushion sizes. The coverall and gloves weigh 12.5 pounds, the retainer weighs 7.5 pounds, and the S1034 helmet weighs 6.5 pounds. The suit (minus helmet) folds into a 2.7-cubic-foot suitcase.

The S1034 began replacing the S1031 in the U-2R in 1996 and in the NASA ER-2 in 1997. Sometime later, the suit began replacing A/P22S-6 suits used by the NASA WB-57F program at Ellington Field, although NASA continues to use A/P22S-6 helmets with its S1034 suits. The A/P22S-6 helmet has a single-system oxygen regulator (matching the WB-57F), while the S1034 helmet has a dual-system regulator (matching the U-2). By June 2010, David Clark Company had fabricated 314 S1034 suits for the Air Force and NASA.[98] Like its predecessors, the S1034 requires an overhaul every 6.5 years. The suits are returned to the David Clark Company for refurbishment, a process that generally takes 30 to 60 days.

Not long after the S1034 entered service, designers at David Clark Company began investigating new helmet designs that might offer yet lighter weight and improved performance. This became more formal in June 1999, and during 2002, the company developed an engineering model of the next-generation helmet. David Clark Company provided this helmet to the U-2S (an updated U-2R) operations community for its initial assessment, which was favorable except for a concern about the helmet's overall height with the visor lever in the straight-up position (visor opening and closing swing radius).[99]

The initial S1034 helmets would begin reaching the end of their service lives in June 2006, so in early 2003, the USAF approved a development program to finalize the configuration of the new helmet. A preliminary design review was held on June 17, 2003, and engineering development of the newly designated S1034E helmet commenced immediately thereafter. The "E" suffix was added to reflect the entire helmet was designed using an electronic 3-D modeling system and there were no S1034B-D versions, and the suit itself continues to be an S1034 (no suffix).

The S1034E helmet is slightly larger than the original S1034 "oversize" helmet to accommodate the largest heads and an optional impact liner, and it weighs approximately 1 pound more than the standard helmet. The S1034E includes a thinner face seal for improved comfort, an optional integrated impact liner, and a comfort cushion cover that uses a "phase change" material to moderate extreme temperature swings. The S1034E also features a redesigned anti-suffocation valve mounted on top of the helmet to lessen the possibility of water entry and to improve the pilot's ability to breath under zero-oxygen-pressure conditions.[100]

In January 2005, prototype S1034E helmets were ready for operational evaluation in the U-2 to verify cockpit compatibility. Lockheed and USAF test pilots operating from Site 2 at Plant 42 in Palmdale conducted six evaluation flights—three in a single-seat U-2S and three in a two-seat TU-2S trainer—between August 22 and October 18, 2005. Of the trainer evaluations, two were conducted in the forward cockpit and one in the aft cockpit.[101]

The pilots had various minor comments, including concern over some slight distortion in the visor that was traced to raw-material sources. Overall, the pilots confirmed that the S1034E was a suitable replacement for the S1034 helmet. David Clark Company began building production S1034E helmets in 2006 to replace the earlier helmets as they reached the end of their service lives.

Sidebar: The Shrinking Industrial Base

At the height of the Cold War, the United States industrial base was the envy of the world. There were a dozen aircraft manufacturers, a half-dozen engine manufacturers, and a large base of specialized companies that developed avionics, landing gear, and weapons. Nevertheless, the number of high-altitude protective-clothing manufacturers has always been small.

Although a fair number of companies manufactured G-suits during World War II and the immediate postwar years, there were only two with extensive development experience: Berger Brothers and David Clark Company. These same two companies largely took the lead on partial-pressure suits.

The development of full-pressure suits began during World War II with a half-dozen companies but ended abruptly when the Army cancelled the effort. Surprisingly, when the effort picked up again after the war, there were almost as many companies involved, and eventually Arrowhead, Berger Brothers, David Clark Company, Goodrich, ILC Dover, Space Age Control, and U.S. Rubber all developed full-pressure suits for the Air Force, Navy, or NASA. After winning the Apollo suit competition, ILC Dover decided to specialize in true spacesuits, and except for an occasional prototype, left the aviation pressure suit business.

But as the luster wore off the full-pressure suit concept, and the anticipated "thousands" of suits fell to a few hundred, interest faded. For most of the Cold War, David Clark Company fabricated all of the full-pressure suits for the CIA and USAF, while Goodrich manufactured suits for the Navy. A series of events that included the Navy deciding to abandon their operational suits (and NASA hiring their chief engineer) eventually drove Goodrich out of the business. This left David Clark Company as the sole supplier of full-pressure suits in the United States. This became so obvious to everybody that the Air Force stopped assigning military designations to the suits, simply using the David Clark model numbers instead.

Eliminating competition is never good, particularly when Government contracting and taxpayer money is concerned. However, if it has to happen—and the pressure suit market became so small it could not support multiple manufacturers—then having David Clark Company as the sole supplier was the best possible answer. David Clark Company is a small, employee-owned business and has proven many times over the years that it is willing to do what is best for its programs, regardless of contractual or funding limitations. Jack Bassick, a long-time employee and retired executive vice president, once wrote, "DCC continues to take seriously its self-imposed responsibility, initially promulgated by Mr. David Clark in the 1940s, to preserve and develop further this national capability as best we can."[102]

It has become increasingly difficult to maintain even a single company as an industrial base for full-pressure suits (a similar problem confronts the spacesuit business, but that is beyond the scope of this book). Throughout the last two decades of the 20th century, multiple programs required full-pressure suits: the SR-71 (Senior Crown), U-2 (Senior Year), and Space Shuttle. In 1999, the Air Force and NASA finally retired the SR-71, leaving only two programs. In 2011, NASA retired the Space Shuttle. Although most people consider it unlikely, the Air Force has announced the U-2 will be retired in 2012, replaced by a fleet of unmanned aerial vehicles.

As of 2010, the U.S aviation pressure suit sustaining-engineering function is funded almost entirely through the Senior Year (U-2) program office, which is part of the 576th Aircraft Sustainment Squadron, 330th Aircraft Sustainment Wing, at Robins AFB, GA. Management at the David Clark Company has been pointing out for a number of years that their support staff is only "one deep," meaning that only a single skilled person is available for certain critical tasks. Funding shortfalls within DoD have trickled down to the industrial base that supports the U-2, including David Clark Company. The lack of funding has several detrimental effects, most critically the inability to purchase long-lead materials and replace vanishing vendors have resulted in a reduced inventory of operationally ready U-2 suits.

Sustaining engineering capability also diminishes with reduced funding. For the past 50 years, having a continuing sustaining engineering activity at David Clark Company (and Berger Brothers when they were still in the business) has allowed the Nation to respond rapidly to unforeseen needs in high-altitude protective equipment. A classic example is the timely creation of the S1032 Launch Entry Suit for the Space Shuttle Program in response to the 1986 Challenger accident. Without an existing industrial base, this suit could not have been brought on line in a timely manner, with adverse impacts to what was one of America's most visible technical achievements. This sustaining-engineering funding also allowed the development of the S1034 Pilots Protective Assembly, S1034E helmet, and coincidentally, the Space Shuttle S1035 Advanced Crew Escape Suit that is a variant of the S1034.

Reduced funding also makes it difficult to retain critical skills. For pressure suits, this is especially true of the softgoods disciplines, such as pattern design and grading, cutting, stitching, cementing, sealing, and Link-Net fabrication—skills that are no longer promoted in schools and need to be learned on the job.

This is not to say that all industrial bases are worth saving. Technology marches on, and some industries are simply no longer required. There were once thriving businesses dedicated to making typewriters, IBM punch card machines, and floppy disk drives; but those businesses are no more, and, honestly, nobody misses them. The same will soon be true for incandescent light bulbs and cathode ray tubes, as newer, better technologies replace those items. Sometimes, it is simply time to move on.

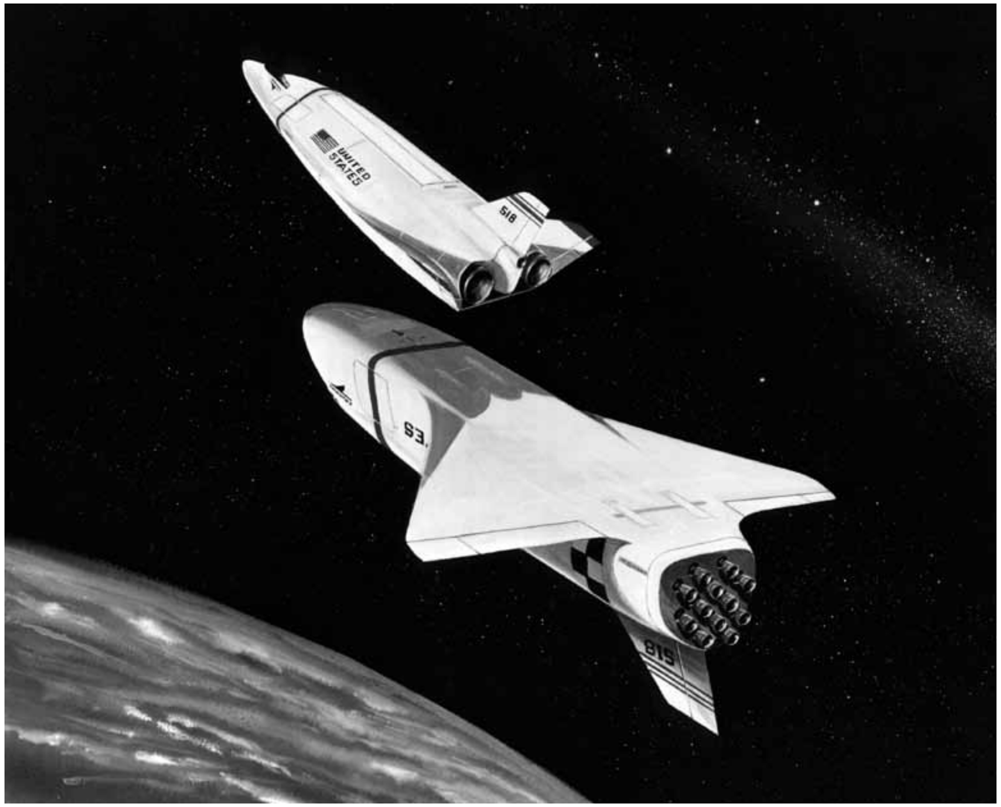
Perhaps this is true of pressure suits. However, as with many highly specialized capabilities, once the pressure suit (and spacesuit) industrial base disappears, it will be very difficult to reconstitute. All of this bodes ill if the United States again finds itself in the position of needing high-altitude protective clothing for some, as yet unimagined purpose. The Nation needs to make a conscious decision regarding this capability, not just ignore it until it goes away.

8

8: Space Shuttle Pressure Suits

President Richard M. Nixon formally announced the Space Shuttle Program on January 5, 1972. Space shuttle was different from all spacecraft that had come before. Instead of the disposable capsules used by Mercury, Gemini, and Apollo, the new vehicle had wings and was reusable. NASA and the Air Force had ambitious plans that included a flight rate of one per week from launch sites in Florida and California. For the first time, non-professional astronauts would fly into space to perform experiments, service satellites, and deploy and retrieve payloads.[1]

NASA liked to talk about "airline-like" operations without the fanfare and preparation that accompanied the earlier programs. Designers envisioned a shirtsleeve environment for the occupants, eliminating the need for pressure suits, although spacesuits would still be required for extravehicular activities (EVA), such as servicing satellites and building the eventual space station. All potential emergencies during ascent were covered by "intact abort" scenarios in which the orbiter flew to a recovery site and landed, eliminating the need for any personal-protection devices, such as ejection seats or pressure suits. For emergencies on orbit, NASA investigated concepts such as "rescue balls" in which crewmembers cocooned themselves in inflatable enclosures, and the crew from another space shuttle pushed them



Most early shuttle concepts showed a fully reusable, two-stage vehicle. At the time, NASA and its contractors were enthralled with the idea that somehow, the space shuttle would operate much as a commercial airliner, and there were no immediate plans to use pressure suits, except for extravehicular activities (EVA).

NASA

Prior to the first space shuttle mission, NASA investigated the concept of a "rescue ball" that an astronaut could take refuge in. Astronauts could carry the balls from the stricken vehicle to a nearby rescue vehicle. The concept was investigated again after the Challenger accident in 1986.

NASA

the short distance between the stricken vehicle and the rescue ship. It appears that the prospect of an emergency during entry, despite the red-hot temperatures as the vehicle slowed from 17,500 mph to landing speed, was simply dismissed as improbable.

ISSA AND EIS—STILLBORN SPACE SHUTTLE SUITS

By late 1970, NASA was 2 years into the formal space shuttle study cycle and was beginning to better define details, such as the need for pressure suits. Although the orbiter would have a shirtsleeve environment, pressure suits would still be needed if the cabin depressurized due to a leak or systems failure. To define exactly why an astronaut would need a suit, engineers at the Manned Spacecraft Center (MSC, later renamed the Lyndon B. Johnson Space Center, or JSC) conducted an internal study of possible pressure suit requirements. To further investigate the type of suit needed to counter these emergencies, the MSC funded Space Age Control, Inc. and the

International Latex Corporation—the primary spacesuit contractor on Apollo—to develop prototypes of representative pressure suits.

On October 1, 1970, MSC awarded an 18-month contract to Space Age Control in Palmdale, CA, for the fabrication of two Intravehicular Space Suit Assembly (ISSA) prototypes. Space Age Control had been established in 1968 to design, develop, and manufacture pilot-protection devices for space-based and high-performance aircraft test programs. In 1970, NASA awarded the company a contract to produce precision, small-format position transducers for aircraft flight-control testing. The success of this effort led to the development of a complete line of position transducers that were used by more than 900 customers in 20 industries around the world.[2]

The NASA contract called for developing a flexible, comfortable pressure suit capable of operating at 5 psi (versus 3.5 psi for most aviation pressure suits) that weighed less than 12 pounds. The Space Shuttle Program wanted a pressure suit that would satisfy the requirements of launch, vehicle transfer, entry, pressurized and unpressurized cabin operation, and possible emergency operations. The effort was divided into three phases. Phase A included configuration analysis and detailed design, Phase B fabricated a prototype based on the Phase A design, and Phase C fabricated a second prototype based on the results of testing the first suit. Space Age delivered the Phase C suit to MSC on March 9, 1972.[3]

One of the primary concerns of any pressure suit designer is shoulder mobility, and by 1970, the only mostly satisfactory arrangement was the one developed by David Clark Company using Link-Net. Since this was proprietary technology, Space Age Control wanted to find another solution. In the past, designers of soft- and hard-suit shoulder joints had tried pleated convolutes, molded convolutes, rotating bearings, ball and socket fittings, rolling convolutes, mechanical hinges, and stovepipe sections in an attempt to provide mobility. None of these had attained the nude range of shoulder motion in all planes, although Link-Net had come closest. Space Age investigated two designs: a preshaped sewn convolute and a single-axis random convolute.

The preshaped joint consisted of two cone frustums sewn together at the shoulder joint using convolutes that were 7.0 inches inside diameter and 8.80 inches outside diameter. Space Age discovered that a difficulty with this type of joint was designing a restraint system that had low friction when sliding through the turnarounds. Numerous systems were tested, and Dacron cord and stainless steel turnarounds proved the most promising. Space Age fitted its Phase B suit with a sewn convolute shoulder joint. The problems that surfaced during testing were frictional wear of the restraint slip cords and noise as the cords slid through the turnarounds. In addition, the bulk of the joint made it impossible to meet the 23-inch shoulder measurement specified in the contract.

As an alternative, Space Age investigated a single-axis, random convolute joint. This joint had a restricted range of motion in the transverse plane (adduction-abduction) but excellent torque characteristics in the lateral medial plane. It also solved the frictional wear and noise problems and fit within the required shoulder width. This joint was formed by restraint cords located on each side of a cylinder of nylon restraint material that was gathered by pleating along the restraint line. A restraint cord was stitched over the pleats to hold them in place. Space Age installed this shoulder on the Phase B suit, and other than the expected lack of motion in the transverse plane, it was more comfortable, had a better arms-down profile, had lower torque, and was cycled 5,000 times without failure. Space Age selected this design for the Phase C suit.

To eliminate an adjustable frontal tiedown system for sitting or standing configurations, the Space Age designers incorporated a waist gusset. The first design consisted of nylon pass-throughs and nylon cord similar to the takeup used on NASA pressure boots. This design exhibited adequate strength, but the positive locking of the cord ends was bulky, and it was difficult to open the gusset due to the close tolerance necessary between the nylon pass-throughs when closed.

The second design used a Talon eight-chain brass zipper on nylon tape. Structurally, either of the designs was adequate, but the second design required less room to install on the suit and Space Age used the eight-chain zipper for the Phase C suit. The takeup along the torso centerline was 5.5 inches, which allowed full standing with no encumbrance with the zipper opened and foreshortened the frontal section sufficiently when closed to maintain the correct helmet position at 5 psi.

The preliminary Space Age head covering used a full-hemisphere visor bonded to the basic pressure garment. The Phase B helmet, with a diameter of 12 inches, was considerably larger than necessary and presented a storage problem. The Phase C helmet was reduced to 10.25 inches wide and 12 inches deep.

Space Age investigated two glove-disconnect designs. The first approach was a metal disconnect, designed so the outer housing functioned as a spring clamp. Although having safety features that appeared complex, the designs operation was simple, requiring only opposing forces from the thumb and forefinger to open when the suit was unpressurized. Before donning the suit, the wearer moved the latch to the closed position, depressed the latch lock pin, and moved the latch outward to the armed position. Engagement of the suit-glove connector automatically brought the connector to the lock-lock position. Space Age used this system in the Phase B and Phase C suits.

Space Age also investigated a soft-roll seal-glove disconnect to further reduce weight and increase comfort. This disconnect consisted of a neoprene tube on both the glove and suit. The suit seal was folded upward over the forearm and the glove seal was pulled over the suit seal. The seal ends were then rolled or folded downward to create the seal, similar to the original waist seal on the David Clark MC-2 suit. This design proved comfortable and reliable at the required suit pressures, but it increased donning time, required greater dexterity for donning, and increased leakage.

Space Age fabricated the gas bladders for both suits from neoprene-coated nylon ripstop fabric covered by a nylon restraint layer. The Phase B suit, including gloves, communications carrier, and bioinstrumentation connector, weighed 13 pounds and 3 ounces. The basic Phase C suit was over a pound lighter, but the gloves were somewhat heavier, resulting in a total weight of 12 pounds and 1.5 ounces, very slightly over the requirement. Space Age noted it could reduce the weight of the Phase C if the pockets were eliminated but decided

During the definition phase for the Space Shuttle, engineers expected the crew to operate in a shirtsleeve environment throughout the mission. Eventually the program acknowledged that pressure suits would still be needed if the cabin depressurized due to a leak or systems failure. In 1970, NASA awarded contracts for the development of a lightweight, Intravehicular Space Suit Assembly (ISSA) that could be stored in lockers in the crew compartment. One of these contracts went to Space Age Controls in Palmdale, CA. This Phase C suit used a smaller helmet than the earlier Phase B suit.

Courtesy Space Age Control, Inc.

the pockets were functional and elected to keep them.[4]

During predelivery testing, Space Age pressurized the Phase C suit to 5 psi for 15 minutes, with a leak rate of 240 cc per minute, within the specification. The suit was then pressurized to 8 psi for 15 minutes and returned to 5 psi with the leak rate still 240 cc per minute. Several subjects demonstrated the suit could be self donned with relative ease. A subject dressed in long underwear could take the suit out of its storage container, don it, and attach the gloves in 6 minutes. If the gloves were already mated to the wrist rings, the time was reduced to 3 minutes and 5 seconds. In all cases, the suit could be doffed in less than a minute. Mobility was satisfactory, although the shoulder did not meet the range-of-motion requirements. Space Age believed it had a revised shoulder—consisting of two single-axis joints offset 90 degrees to each other and joined by a low-profile rigid-bearing coupler—that would satisfy the requirement. Ultimately, Space Age concluded:

> Significant advances were accomplished in manufacturing a lightweight, comfortable, highly articulate full-pressure suit that is capable of withstanding a pressure differential of 5 psi. Of major importance is the simple elbow and knee joints that exhibit very low torque and excellent neutral range of motion. No cable restraints or metal turnarounds were required on the suit to maintain stability or structural integrity. There is a need for substantial improvement in glove disconnects for this type of suit to meet the requirements of rapid donning. If it is decided that a flexible, stowable visor is required for future suits, additional design effort is required to provide a better material than the vinyl used for these suits. The shoulder joints resulting from this program do not meet the operational requirements of a flight vehicle due to the limited transverse-motion capability. It is our opinion that a shoulder joint, using the basic single-axis design, can be developed using a slip ring turnaround separating 2 single-axis joints, or a slip ring at the armhole opening and 2 single-axis joints (offset 90 degrees) separated by a fixed load-carrying ring and perhaps an upper arm bearing. In order to prevent over-design of a shoulder joint, detail cockpit motion envelope requirements should be stipulated prior to design effort.[5]

A 1970 ILC advertisement boasted, “The ability to move is the secret that keeps ILC ahead of its competition and the ISSA Suit (Intravehicular Space Suit Assembly) is real proof of that fact. Hardware speaks louder than words.”[6] The hardware being referred to was a company-funded 1969–70 prototype of a lightweight “Briefcase Suit” that offered compact stowage. ILC considered the suit’s technology mature since many of its ideas, and even some of its components, were directly traceable to the Apollo A7L spacesuits.

MSC awarded the second contract for a prototype ISSA to International Latex Corporation in Dover, DE (ILC Dover), on October 8, 1970. By this time, Dixie Rinehart, John Ratermanis, Al Kenneway, George Matthews, and George Durney in the Soft Goods Engineering Group at ILC had already completed the design using corporate funding. The

As required, the ILC Dover ISSA concept fit into a small suitcase; the storage space could be halved if the suit was vacuum packed. Oddly, engineers at ILC had already investigated the idea of a suitcase spacesuit as part of a company-funded study during 1969–70.

Courtesy of the International Latex Corporation

In an emergency, an astronaut could quickly self don the ILC ISSA suit. Although called an IVA suit, it could be used for limited EVA activities if needed (mostly meaning an ability to move from a damaged orbiter to a rescue vehicle).

Courtesy of the International Latex Corporation

Considering the suit could be stored in a 0.5-cubic-foot suitcase, it looked very bulky in use. Like its Space Age Control counterpart, this suit was pressurized to 5 psi instead of the normal 3.5 psi but was still fairly flexible.

Courtesy of the International Latex Corporation

designers largely based their ISSA largely on the Briefcase Suit developed earlier that year. The Phase B prototype weighed 10.2 pounds, including the suit, two arm bearings, gloves, boots, and soft helmet with integral visor. The garment measured 22.75 inches across the shoulders and 16.75 inches across the knees. The suit could be stored in a volume of 0.5 cubic foot, which could be reduced to 0.22 cubic foot if the garment was vacuum packed. The pressurized mobility was equal to or greater than the Apollo suit, and the unpressurized mobility was somewhat greater. ILC fabricated a second suit that featured a flat-pattern mobility system aimed at further reducing storage volume and cost and improving mobility. The Phase C suit was delivered to MSC in May 1971.[7]

NASA researchers and astronauts at MSC evaluated the Space Age and ILC suits for several months, but no record of the results could be located. In any case, neither suit would be produced or flown.

As the ISSA suits were being evaluated, external events caused NASA to reconsider its position concerning pressure suits in the space shuttle during ascent and entry. On June 30, 1971, the Soyuz 11 spacecraft prepared to enter the atmosphere after a 2-week visit with the Salyut 1 space station. Unknown to the crew or ground controllers, a ventilation valve between the orbital module and the descent module failed during retrofire. Somewhere above 100 miles altitude, as the descent module entered the atmosphere, the failed valve opened, allowing the vehicle to depressurize. As built, the three-man Soyuz was not large enough to accommodate a crew wearing pressure suits, and the crew of Soyuz 11—Vladislav Nikolayevich Volkov, Georgiy Timofeyevich Dobrovolskiy, and Viktor Ivanovich Patsayev—died from asphyxiation within seconds. After the accident, the Soviets redesigned the Soyuz spacecraft to accommodate only two crewmembers, this time wearing spacesuits. It would not be until the introduction of the Soyuz T variant in 1980 that the capsule accommodated three crewmembers in spacesuits.[8]

The concern went beyond the need for pressure suits, but it also included what type of pressure suit would be most useful. Aviation pressure suits, and the ISSA prototype from ILC Dover, typically operate at about 3.5 psi, using pure oxygen as a breathing gas (the Space Age ISSA prototype operated at 5.0 psi). NASA physiologists worried this might not be sufficient pressure to save a crew in a Soyuz-type accident since there would be no time to prebreathe pure oxygen to prevent decompression sickness. Researchers were beginning to think that a high-pressure suit, perhaps using as much as 8 psi, would be necessary to protect the crew. At the same time, physiologists began wondering if there was a better way to conduct EVA—the limited experience on Gemini and Apollo had not answered many questions, and NASA expected many thousands of EVA hours would be needed to construct the eventual Space Station.

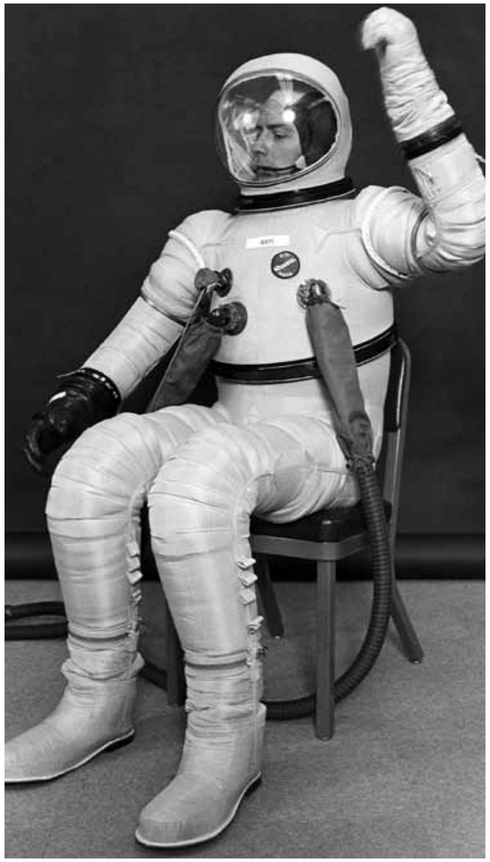
To validate its proposed requirements, NASA embarked on a yearlong effort to study intra-vehicular activity (IVA) and EVA tasks, guidelines, and constraints, as well as to develop requirements for pressure suits, mobility aids, and emergency intervehicular transfer support.[9] To support the effort, on March 14, 1972, NASA awarded a contract to the Hamilton Standard Division of United Aircraft Corporation and 2 weeks later awarded a contract to the Vought Systems Division of LTV Aerospace and its subcontractors Convair, ILC Dover, and Rockwell International.[10] Hamilton Standard concentrated on the environmental and life-support system aspects of the issue, while the Vought team defined the suits themselves. The Hamilton Standard and Vought studies concentrated on the EVA aspects of the program since that was the larger unknown. Nevertheless, the effort examined what sort of protection the crew and passengers would need in the event of a cabin pressurization failure or a systems failure that forced the vehicle to remain on orbit awaiting rescue.[11]

Vought subcontracted much of the actual suit study to ILC Dover, which delivered its report to Vought in December 1972. The requirements for an IVA suit, as seen by ILC, included allowing the commander and pilot to control the orbiter during entry and landing, allowing the crew to assist EVA crewmen into the orbiter in the event of an airlock failure, and performing limited contingency EVAs in the event of an emergency (i.e., transfer to a rescue vehicle). Oddly, given they had already designed the ISSA prototype under a different contract, the engineers at ILC initially believed these requirements could be met by using the existing Apollo A7LB suits. It soon became obvious this was not the case.[12]

After a great deal of study regarding the possible scenarios that would force a crew to don suits, ILC validated NASA's concerns and selected an 8 psi operating pressure since this eliminated the need to prebreathe pure oxygen. The suit would have a proof pressure of 16 psi and a burst pressure of 20 psi, providing an adequate margin of safety. Having decided upon this high-pressure suit, ILC evaluated the A7LB suit and determined the mobility of the shoulder, hip, and waist joints became impractical above 6 psi. The ILC engineers believed they understood the problems and could fabricate joints that would provide acceptable mobility at the higher pressures. However, the gloves seemed to present an unsolvable problem. Fortunately, researchers at the NASA Ames Research

Center were already working with several contractors to develop gloves that would operate at 8 psi, so ILC did not dwell on the issue. In addition, ILC determined that the leakage rates of the A7L series suits made them unacceptable for use as emergency garments.[13]

ILC pointed out that an 8-psi suit would have a larger stowage volume than lower pressure suits, although making a two-piece suit that separated at the waist, with a detachable helmet and gloves, could lower these requirements somewhat. The report investigated ventilation, cooling, and pressurization requirements, as well as donning-and-doffing considerations. The engineers also presented a detailed evaluation on the required impact, thermal, and radiation protection.[14] Vought expanded the ILC report considerably before delivering to NASA in April 1973. The final recommendation was for a new IVA suit that used incremental sizing (like aviation pressure suits, and unlike the custom-fitted A7LB suits), a hard waist connector for donning and doffing, and a soft helmet. A thermal overcoat could provide short-term impact and thermal and radiation protection for contingency EVAs. A simplified version of the suit that provided less mobility by deleting the bearings at the shoulders, neck, elbows, and wrists could suffice for passengers that needed life support but had no duties other than staying alive.[15]



The ILC Dover Emergency Intravehicular Suit (EIS) operated at 8 psi to support reasonably rapid decompression from a 14.7-psi cabin pressure without risk of decompression sickness. The entire suit, except for the waist disconnect ring, was fabricated of flexible materials, including the helmet and face shield.

Courtesy of the International Latex Corporation

Hamilton Standard came to generally the same conclusions as Vought-ILC regarding IVA requirements. However, Hamilton Standard did not attempt to design a pressure suit, concentrating instead on its area of specialty: the environmental and life-support systems. Nevertheless, its report recommended a lightweight suit that could be donned quickly in the event of the loss of cabin pressure. Unrealistically, the study determined that a trained crewmember should be able to don and activate a pressure suit within 1 minute. Each suit should

ILC Dover evaluated the EIS prototype using a side-stick controller being proposed by the North American Aviation Space Shuttle team. Like the ISSA concept, the EIS would only be used in an emergency, but pilots would still be required to fly and land the vehicle.

Courtesy of the International Latex Corporation

include a portable breathing system capable of supporting the crewmember for 1 hour, and onboard systems should be capable of supporting all 10 crewmembers for 10 hours for mission aborts and 96 hours while awaiting on-orbit rescue.[16]

While those studies were ongoing (and perhaps one reason ILC did not bid on the studies as a prime), in 1972 NASA awarded ILC a contract to fabricate an emergency IVA prototype that looked a lot like the suit concept it provided to Vought for its report. The Emergency Intravehicular Suit (EIS) operated at 8 psi to support reasonably rapid decompression from a 14.7-psi cabin pressure without risk of decompression sickness. The 21-pound EIS was entirely soft, except for a circular waist entry disconnect, helmet disconnect, and arm bearings. Tailoring was by laced and zipper takeups on the restraint garments. The fabric helmet used an integral acrylic bubble.[17]

All of the suit manufacturers pointed out the need for better gloves. In response, the NASA Ames Research Center awarded contracts to, at least, David Clark Company, ILC Dover, Space Age Control, and the Aerotherm Division of Acurex Corporation in Mountain View, CA. Some of these contracts directed research toward gloves that could satisfactorily operate at 5 psi, while others investigated 8-psi gloves. Most of this research was oriented toward EVA gloves, but some was applicable to an IVA suit as well.

For instance, William Elkins headed a 7-month effort at Aerotherm that included developing a new layup technique for a miniconvolute joint system and evaluating its effectiveness at 8 psi pressure. Eventually, he proved the joints could safely withstand 100,000 cycles. The final Aerotherm glove used a 3-ply layup of marquisette cloth and neoprene that resulted in a

NASA astronaut Robert L. "Crip" Crippen in the cockpit of Columbia (OV-102) on October 10, 1980, prior to the launch of STS-1. Note the modified Lockheed SR-71 ejection seat and Crip's David Clark Company S1030A full-pressure Ejection Escape Suit. Columbia was the only space-rated Orbiter to use ejection seats, and they were only active for the four orbital flight test (OFT) missions (although they were physically installed until after STS-9).

NASA

0.017-inch thick glove. The miniconvolute joints were inlaid only on the back side of the fingers, leaving a smooth front surface that presented more feel and was less vulnerable to snagging. The palm area was reinforced with a stainless steel and Nomex cloth. Subsequent phases of the effort, completed at the end of 1974, concentrated exclusively on EVA requirements.[18]

As the Space Shuttle morphed through its development phase, NASA continued to emphasize the relative safety of airline-type operations. In addition, cost and schedule were becoming major concerns, and NASA returned to its original concept of a shirtsleeve environment for the Space Shuttle.

S1030A—EJECTION ESCAPE SYSTEM (EES) SUITS

Long prior to the first flight of Columbia (OV-102), NASA engineers decided that the Space Shuttle would not have an escape system. Simulations showed that the Space Shuttle system was safe, and in the unlikely event that something did go wrong, the best option was an "intact abort" where the orbiter separated from the stack and flew to a conventional runway landing at some predetermined location. This philosophy was similar to that used for airliners, which do not provide parachutes or ejection seats for passengers or crew. However, NASA was well aware that the test flights posed an unreasonable danger to the two-person crew and took steps to mitigate the risks.

The crews for the eight Approach and Landing Test flights that used Enterprise (OV-101) at Edwards AFB during 1977 did not use pressure suits since the maximum altitude of the flights was just over 30,000 feet. However, they did sit on modified SR-71 ejection seats. These seats were the highest performance ejection seats in the operational inventory at that time (the hypersonic X-15 research

The David Clark Company S1030A was a derivative of the S1030 suits used on the Air Force SR-71 program. Most of the hardware was identical to the S1030 and, in fact, was borrowed from the Air Force. However, the softgoods were an all-new design to meet Space Shuttle Program requirements.

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airplane had used higher performance seats, but the program had been out of business for a decade, and the seats were unavailable and overly complex in any case).[19]

After Enterprise proved the orbiter could glide to a controllable landing, the next step was to test an orbiter in space. There would be no unmanned test flights, and John W. Young and Robert L. "Crip" Crippen became the first crew to fly a new vehicle on its maiden space flight. Between April 1981 and July 1982, Columbia (OV-102) conducted four Orbital Flight Tests (OFT). Like Enterprise, Columbia was equipped with modified SR-71 ejection seats for its two pilots. Each crewmember wore David Clark Company S1030A full-pressure suits. These were variants of the Air Force S1030 Pilots Protective Assembly used by SR-71 crews and provided proven protection up to Mach 2.7 and 80,000 feet.[20]

Separately, on November 15, 1976, NASA awarded David Clark Company (DCC) a $98,171 contract to develop an Anti-G Suit (AGS) for the OFT flights. James O. Schlosser at JSC was the contract monitor, and Jack Bassick was the David Clark Company project engineer. Although the ascent acceleration was relatively benign, the entry environment was less well understood, so acceleration protection might be needed. NASA expected to use the AGS to apply counter-pressure to the abdomen, thigh, and calves. The crewmembers wore the 3-pound AGS under the

Ejection Escape Suit (EES) and donned it through slide fasteners on each leg and the side of the abdomen. Heat-sealed urethane bladders were covered with an oxford-nylon restraint that had lace adjustments at the waist, thighs, and lower legs. An Anti-G Control Valve (AGCV) was integrated on the left thigh of the full-pressure suit, and a relief valve vented the bladders if the pressure exceeded 3.0 psig. The AGCV was manually adjustable to provide between 0 and 2.5 psi. The AGCV was designed to automatically vent the AGS when the full-pressure suit pressurized and shut off in the event of a continuous flow (e.g., a leak in the AGS). Carleton Controls provided the AGCV.[21]

NASA issued David Clark Company a second contract on August 7, 1978, to develop the S1030A full-pressure suits. Joe Ruseckas at David Clark Company originally estimated the development effort and fabrication of a dozen suits would cost $325,845, not including the Government-furnished hardware that would come from the SR-71 program. Eventually, largely because of constantly changing requirements as the Space Shuttle Program matured, the 13 suits cost $578,304, exclusive of the hardware supplied by the USAF. NASA called the S1030A an EES.[22]

Contrary to most reports, the dozen S1030As were not "modifications" of Air Force S1030 suits but were new suits fabricated expressly for the Space Shuttle Program. They were derivatives of the S1030 design, using most of the same hardware and manufacturing techniques. However, although the softgoods were based on S1030 experience, they were necessarily different to support the addition of the AGS and biomedical instrumentation port and to increase the proof-pressure requirements.

The S1030A consisted of a pressure suit, helmet, gloves, exterior cover, AGS, and biomedical instrumentation system. The breathing space was separated from the rest

Table 9—S1030A Ejection Escape Suits

Serial Number	Size	Color	Astronaut	Mission
001	Large-Long	Gold Fypro	Certification Suit	—
002	Medium-Regular	Dark Gold PBI	John W. Young	STS-1
003	Medium-Regular	Dark Gold PBI	Robert L. "Crip" Crippen	STS-1
004	Medium-Long	Dark Gold PBI	Joe H. Engle	STS-2
005	Medium-Regular	Dark Gold PBI	Richard H. Truly	STS-3
006	Large-Long	Dark Gold PBI	Jack R. Lousma	STS-3
007	Medium-Regular	Gold Fypro	Fred W. Haise, Jr.	—
008	Large-Regular	Gold Fypro	Vance D. Brand	—
009	Medium-Long	Dark Gold PBI	Charles Gordon "Gordo" Fullerton	STS-3
010	Short-Long	Dark Gold PBI	Thomas K. "Ken" Mattingly	STS-4
011	Large-Regular	Gold Fypro	Paul J. Weitz	—
012	Medium-Long	Dark Gold PBI	Henry W. "Hank" Hartsfield, Jr.	STS-4
013	Large-Long	Gold Fypro	Robert F. Overmyer	—

Source: NASA S1030A Ejection Escape Suit (EES), a serial number list supplied by David Clark Company.

The STS-003 crew, Jack R. Lousma (left) and C. Gordon Fullerton, show off their S1030A suits on January 20, 1982. These were both dark gold PBI suits.

NASA

of the suit by a face seal. A dual-demand breathing regulator mounted in the helmet automatically delivered breathing oxygen when the wearer lowered the helmet visor. The ventilation connector was located on the lower left of the torso and the AGCV was located on the left thigh.[23]

Another difference was that NASA wanted the helmet microphones to always be "hot" so that the pilots did not have to key a transmit switch when they talked and all events could be recorded on the ground. As anybody who has listened to conversations with people using breathing devices on a "hot mic" can attest, it is very distracting when the wearer inhales. David Clark Company solved this by installing microphone cutout switches in the S1030A helmet. These switches were tied to the oxygen regulator such that every time the pilot inhaled, the switches muted the microphone.[24]

The proof pressure requirements for Space Shuttle differed somewhat from the SR-71. On the Blackbird (and U-2R), the cockpit was nominally pressurized to the equivalent of 35,000 feet during routine operations, meaning there was about 3.5 psi pressure on the suit. If the cockpit explosively depressurized, the suit-pressure controller closed and the suit immediately inflated to 3.5 psi, so there was little pressure transient. In the orbiter, the cabin was maintained at 14.7 psi. If the cabin explosively depressurized and the suits inflated to 3.5 psi, there was an 11.7-psi transient, and NASA wanted to verify the suit could tolerate the stress. No problems were noted during the tests.

On October 27, 1978, James V. Correale, the chief of the Crew Systems Division at JSC, wrote to Lt. Col. Calvin E. Greer in the SR-71 Program Office at Norton AFB, CA, requesting 13 sets of S1030 hardware be supplied to David Clark Company to facilitate the manufacture of the EES suits. This hardware included pressure controls, neck rings, wrist rings, ventilation fittings, helmets, and miscellaneous fittings. This transfer of SR-71 hardware had been previously coordinated with Tom Bowen from the Physiological Support Division at Beale AFB. Greer concurred with the request on November 17, and the Air Force released the hardware shortly thereafter.[25]

David Clark Company fabricated the suits during March 1979 in five sizes to fit the 12 astronauts assigned to the OFT flights. Interestingly, five of the suits used gold Fypro covers and eights used functionally identical dark-gold Polybenzimidazole (PBI) covers.[26]

As seen before the first flight, NASA expected the OFT to consist of six missions, but political expedience later dictated they would end after the fourth mission, despite not fulfilling all of their original objectives. Since the operational flights would have more than two crewmembers, the ejection seats in Columbia were deactivated after STS-4, although they would not be physically removed until a modification period that took place following STS-9. Five of the S1030A suits were sent to Beale AFB, where the PSD recovered the hardware for use on standard S1030 PPAs. NASA removed the USAF hardware from the remainder of the suits and they were subsequently scrapped, as were the ejection seats.[27]

LEH—LAUNCH ENTRY HELMET

NASA believed that all of the crew should have "equal access" to escape; therefore, if the astronauts on the middeck could not have ejection seats, then nobody would. It was a contentious argument in the astronaut office but one that ultimately concluded there would be no escape provisions for the operational flights.[28]

Beginning with STS-5, the first "operational" mission, Space Shuttle crews wore tailored "NASA blue" flight suits, an AGS, and a derivative of an off-the-shelf helmet during launch and entry. The AGS was a cutaway suit made by the David Clark Company based on the standardized USAF G-suit and was generally similar to the AGS used under the S1030A suits during the OFT.[29]

The Launch Entry Helmet (LEH) was donned via an unusual "clamshell" hinging mechanism that divided the helmet into joinable fore-and-aft, semi-hemispherical sections. The flight suit and helmet were supplemented by an inflatable life vest, harness assembly, jump boots, and gloves. The entire ensemble weighed about 21.2 pounds. The LEH helmet was distantly related to the AOH-1 (Aviator Oxygen Helmet) developed by Protection, Inc. for the Navy. The integrated oxygen breathing and bump-protection helmet provided a breathing space using a face seal instead of using a conventional oronasal mask. The aft portion of the helmet was open to ambient air. The resulting helmet, perhaps unsurprisingly, looked much like a full-pressure suit helmet, but it was not.[30]

The AOH-1 led to the Air Force HGU-15/P helmet developed during the early 1960s for pilots of the Convair F-106 Delta Dart interceptor as an alternative to wearing full-pressure suits. The Air Force wanted the helmet to provide head protection during high-speed ejections and have an integrated pressure-breathing mask, along with visors that protected against severe sunlight at high altitudes and flashes from the nuclear-tipped Falcon missiles. The Air Force purchased

A Shuttle crew wearing the standard flight suits and LEH helmets in a simulator at the Johnson Space Center. Each orbiter had eight connections that supplied 100-psi oxygen for the LEH regulators and Anti-G Suits. At this point, there was no intent to wear pressure suits in the orbiter.

NASA

Reportedly, the chief of the astronaut office, John W. Young, thought the initial all-white LEHs were too plain and requested Gentex to develop a more suitable paint scheme. All of the production helmets used pearlescent white paint with red and blue stripes and both the NASA "worm" and "meatball" logos. The ratchet knob on the right side of the helmet allowed the wearer to adjust the face seal.

Courtesy of Gentex Corp.

16 HGU-15/P helmets from Protection, Inc. for operational evaluation using Lockheed F-104 Starfighters and Republic F-105 Thunderchiefs at George AFB, CA. The pilots quickly complained that the faceplate visor severely limited peripheral vision and that, at 8 pounds, the helmet was too heavy. The Air Force discontinued the project in early 1964.[31]

The design was revived in 1968 when the Navy purchased more than 700 similar HGU-20/P helmets and issued them to fighter squadrons for operational testing. By this time, Gentex Corporation had purchased Protection, Inc. The Navy pilots had many of the same complaints as their Air Force counterparts and the Navy quickly withdrew the helmet from use.[32] Despite its failure as

As late as 2010, some LEH helmets were still being used during training exercises with S1032/S1035 suits, where they adequately simulated the weight and mass of a full-pressure helmet. These were undoubtedly some of the last items that still used the NASA logotype (worm) that was retired from official use in 1992.

NASA

a military helmet, the clamshell design has been used in many nonaviation applications, most notably for chemical protection suits.

During the late 1970s, NASA physiologists decided a clamshell helmet was a reasonable compromise between a shirtsleeve environment and a pressure suit. Given the short time before Space Shuttle flights were scheduled to begin and the limited funding available, James O. Schlosser at JSC sought an existing design upon which to base the helmet. Enter the HGU-20. Gentex took the basic HGU-20 concept and modified it to meet NASA specifications. This included using nickel instead of cadmium-plated hardware, adding a second microphone, and adding a microphone-breathing cutout. Gentex developed a new oxygen regulator to meet the NASA flow characteristics, a constantly changing target since NASA kept revising the specification. To improve comfort, new take-up reels, using a ratchet knob on the right side of the helmet, kept the face seal tight against the wearer. The neoprene face seal was adjustable for various face sizes and shapes, although some astronauts still needed to be custom fitted. Similarly, a variety of cushion pads were provided for inside the helmet, but several astronauts needed custom pads to achieve the desired comfort and protection. Three sizes of back shells were available: small, regular, and extra large.[33]

Given that the astronauts did not wear any counter-pressure clothing, the LEH could not function as a pressure-breathing mask (at least not under any meaningful pressure) and since there were no contingency plans to bail out of the orbiter (and indeed, no parachutes), the helmet did not provide windblast protection. In reality, the only protection the helmet provided was against ambient noise during ascent, incidental bumping of the head against the inside of the crew module, and possible smoke in the cockpit.

Gentex began fabricating LEH helmets in early 1981 and delivered about 20 helmets per year through 1985. An order for an additional 20 was in place prior to the Challenger accident, and Gentex delivered 10 helmets from this order before terminating production. The initial batch of helmets were standard USAF white, but John W. Young, the chief of the astronaut office (and commander of STS-1), did not believe the appearance of the helmet properly represented NASA. Subsequent helmets were painted pearlescent white with red and blue stripes and strategically placed NASA logos. Reportedly, Gentex manufactured a pink LEH for an unidentified female astronaut, although it was never worn for an actual mission (if at all).[34]

Each orbiter was equipped with eight oxygen outlets (four on the flight deck and four on the middeck) that supplied 100-psi for the LEH regulators and AGS. After NASA replaced the LEH helmets with the S1032 LES and, later, the S1035 ACES ensembles, the controllers remained labeled "LEH". In addition to working with the later pressure suits, the control panels could be used with the emergency "Quick-Don Mask" assemblies that were carried aboard the orbiter for emergency use during on-orbit operations and for EVA prebreathing.[35] As late as 2011, some LEH helmets were still being used during training exercises, where they adequately simulated the weight and mass of a full-pressure suit helmet.

S1032—LAUNCH ENTRY SUITS (LES)

A cold morning dawned in central Florida on January 28, 1986, as a crew of seven boarded the Challenger (OV-099) for the first flight from the newly completed Launch Complex 39B at the Kennedy Space Center. The program was picking up momentum; this was the 25th Space Shuttle launch and the eleventh in the past 12 months. A significant amount of ice had accumulated on the launch pad overnight, creating considerable concern for the ground operations team, which delayed launch several hours to allow the ice to melt. At 11:15, the team gave a "go" for launch despite the ambient air temperature being only 36 ºF measured at ground level approximately 1,000 feet from the vehicle. This was 15 degrees colder than any previous Space Shuttle launch.

The final flight of Challenger began at 11:38:00.010, Eastern Standard Time. Seventy-three seconds later, the Flight Dynamic Officer in the Mission Control Room in Houston announced, "… RSO [the USAF range safety officer] reports the vehicle has exploded."[36] Francis R. Scobee, Michael J. Smith, Judith A. Resnik, Ellison S. Onizuka, Ronald E. McNair, Gregory B. Jarvis, and Sharon Christa McAuliffe were killed.

President Ronald Reagan established a Presidential Commission chaired by former Secretary of State William P. Rogers to investigate the accident. The 14-person commission included such notables as Neil A. Armstrong; 1965 Nobel Laureate in physics Richard P. Feynman; and the first U.S. woman astronaut, Sally K. Ride. The commission released its report on June 6, 1986.

> The consensus of the Commission and participating investigative agencies is that the loss of the Space Shuttle Challenger was caused by a failure in the joint between the two lower segments of the right Solid Rocket Motor. The specific failure was the destruction of the seals that are intended to prevent hot gases from leaking through the joint during the propellant burn of the rocket motor. The evidence assembled by the Commission indicates that no other element of the Space Shuttle system contributed to this failure.
>
> During the period of the flight when the Solid Rocket Boosters are thrusting, there are no survivable abort options. There was nothing that either the crew or the ground controllers could have done to avert the catastrophe.[37]

The commission issued recommendations to fix the Solid Rocket Boosters and to change the engineering and management culture surrounding the human space flight enterprise. The commission also issued several ancillary recommendations, including ones to improve launch-abort and crew-escape options. "The Shuttle program management considered first-stage abort options and crew escape options several times during the history of the program, but because of limited utility, technical infeasibility, or program cost and schedule, no systems were implemented. The Commission recommends that NASA: Make all efforts to provide a crew-escape system for use during controlled gliding flight."[38]

In a report attached to a July 14, 1986, letter from NASA Administrator James Fletcher to President Reagan, NASA provided the status of implementing the recommendations of the Rogers Commission of interest to this history work.

> On April 7, 1986, NASA initiated a Shuttle Crew Egress and Escape review. The scope of this analysis includes egress and escape capabilities from launch through landing and will provide analyses, concepts, feasibility assessments, cost, and schedules for pad abort, bailout, ejection systems, water landings, and powered flight separation… Crew escape and launch abort studies will be complete on October 1, 1986, with an implementation decision in December 1986.[39]

The egress and escape review conducted an extensive, if quick, study of available options.

The harness assembly worn over the S1032 also contained sleeves on each side of the back for the emergency oxygen cylinders and across the front for the floatation device. Note the "green apple" that activated the emergency oxygen.

NASA

Various proposals for ejection seats, separable capsules, and escape pods were evaluated and rejected based on performance, schedule, or budget. In the end, two options were evaluated in detail: a tractor rocket-extraction system and a telescopic escape pole. In both cases, the astronauts would use personal parachutes to bail out of the orbiter. Engineers considered both methods useful only below 230 mph and 20,000 feet during controlled gliding flight. The tractor rocket system used small rockets attached to individual parachutes that could be fired from the crew-access hatch to propel crewmembers clear of the orbiter. The telescopic escape pole used a spring-loaded pole that extended 9.8 feet downward from the crew-access hatch to guide crewmembers away from the orbiter and under the left wing.[40]

The parachute itself attached the harness assembly at four locations. Note the D-ring on the left shoulder strap (right in photo). The black object on each strap is a SEAWARS device that automatically released the parachute upon immersion in saltwater.

NASA

William A. Chandler, crew system escape manager at JSC, noted that although both systems provided adequate escape clearance for the crew, the slide-pole system was safer and more cost effective over the life of the orbiters. This system was not meant as a means of escape in a Challenger-type scenario, as it assumed that the orbiter was in a recoverable mode and could be safely maneuvered to a stable, subsonic glide with minimum sink rate.[41] The escape system was installed in the remaining orbiters during the standdown between 1986 and 1988. These modifications allowed crewmembers to equalize the pressure in the crew module with the outside atmosphere, pyrotechnically jettison the side hatch, and bail out from the middeck after manually deploying the escape pole. One by one, each crewmember would attach a lanyard hook assembly that surrounded the deployed escape pole to their parachute harness and egress through the side hatch opening. Attached to the escape pole, the crewmember would slide down the pole and off the end on a trajectory that took them away from the fuselage and below the left wing. Changes were also made to the orbiter flight control software to provide an automatic-mode that established a stable gliding flight for crew bailout.[42]

This escape system was tested on a USAF Lockheed C-141B Starlifter during the spring of 1988. The modifications to Discovery (OV-103) were completed on April 15, 1988, and the system was operational in time for the launch of STS-26R, the first flight after Challenger. The escape pole, as well as an inflatable escape slide for use during ground evacuations, was subsequently installed on Columbia (OV-102) and Atlantis (OV-104) before their return to flight and were production features on Endeavour (OV-105).[43]

As part of the new escape system, NASA physiologists determined the crewmembers

A mixture of S1032 suit colors in the simulator at the Johnson Space Center during 1988. The initial prototype and first 10 suits used dark-blue exterior covers and the last 38 suits used orange covers. NASA also bought two spare orange covers. Astronauts used the dark-blue suits only for training and they never flew.

NASA

needed a pressure suit to provide personal protection during emergencies. Initially, NASA called the ensemble the Crew Protective System (CPS), then the Crew Altitude Protective System (CAPS), before settling on the Launch Entry Suit (LES) nomenclature. On February 11, 1987, the Lockheed Engineering and Management Services Company, the prime contractor for flight crew equipment (FCE) issued a $300,000 subcontract to the David Clark Company for the development of a single prototype.[44]

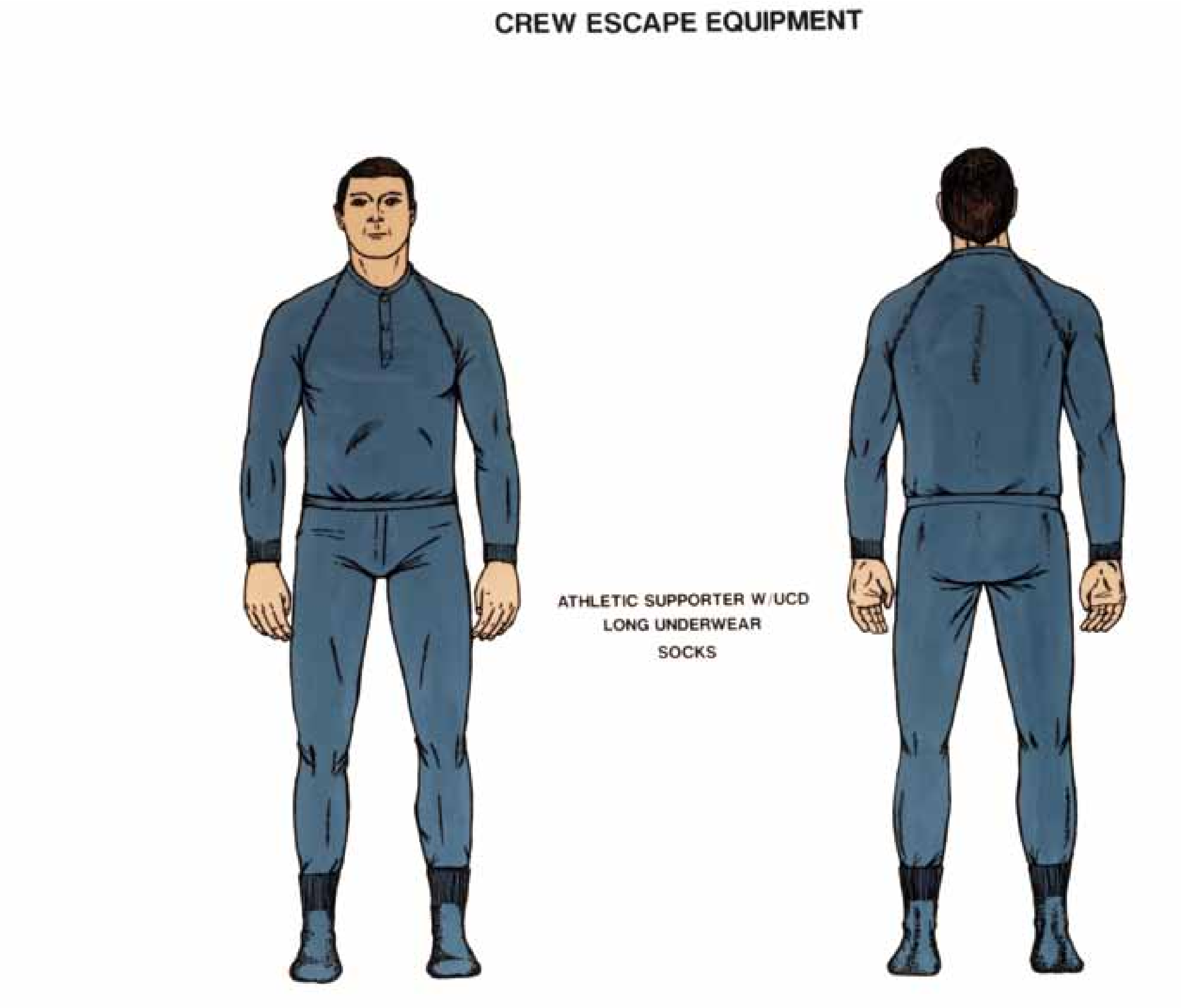
A team of NASA, David Clark, and Lockheed researchers evaluated various pressure suits before deciding to adopt something similar to the High-Altitude Protective Outfit used at the NASA Dryden Flight Research Center. The ensemble offered a reasonable combination of comfort and protection and could be available in a short time. Contrary to most reports, the suit was not a variant of the CSU-4/P partial-pressure suit, although the bladder system used in the LES was generally similar. Most of the other major components had been developed, qualified, and flown previously as part of various aircrew protective systems. Thus, the development effort was largely one of integrating the components with each other and with the orbiter.[45]

The designers selected a nonconformal (dome) helmet since it virtually eliminated head-borne weight, was comfortable, and provided a wide field of view. The helmet provided a complete head and neck enclosure with no direct body contact above the shoulders. A large, moveable pressure visor provided good forward and peripheral vision. Side and rearward visibility was accomplished by manually rotating the helmet using a bearing on the neck ring. The helmet traced its origins to the S1010D nonconformal helmet developed in 1978 under USAF sponsorship. A single prototype of the S1010D accumulated more than 1,400 hours in the U-2R before being rejected in favor of a conformal helmet based on the S1030 design. David Clark Company addressed the original complaints of inadequate fore-aft stability by installing adjustable wire supports under the helmet disconnect ring.[46]

The neck ring had a latch that secured the helmet to the suit. Sliding the latch halves together moved six latch-dogs to secure the helmet on the neck ring. Sliding them apart retracted the dogs, allowing the helmet to be removed from the neck ring. Two independently operating polycarbonate and acrylic visors provided a clear pressure visor and a dark sunshield. The crewmember closed and locked the pressure visor by pulling the visor and the bailer bar down into the locked position. To open the pressure visor, a latch on the bailer bar lock had to be pushed down and two buttons on either side of the lock pressed. This allowed the bailer bar to unlock, after which the visor could be opened. The helmet had to be attached to the neck ring and the pressure visor closed and locked to pressurize the suit.[47]

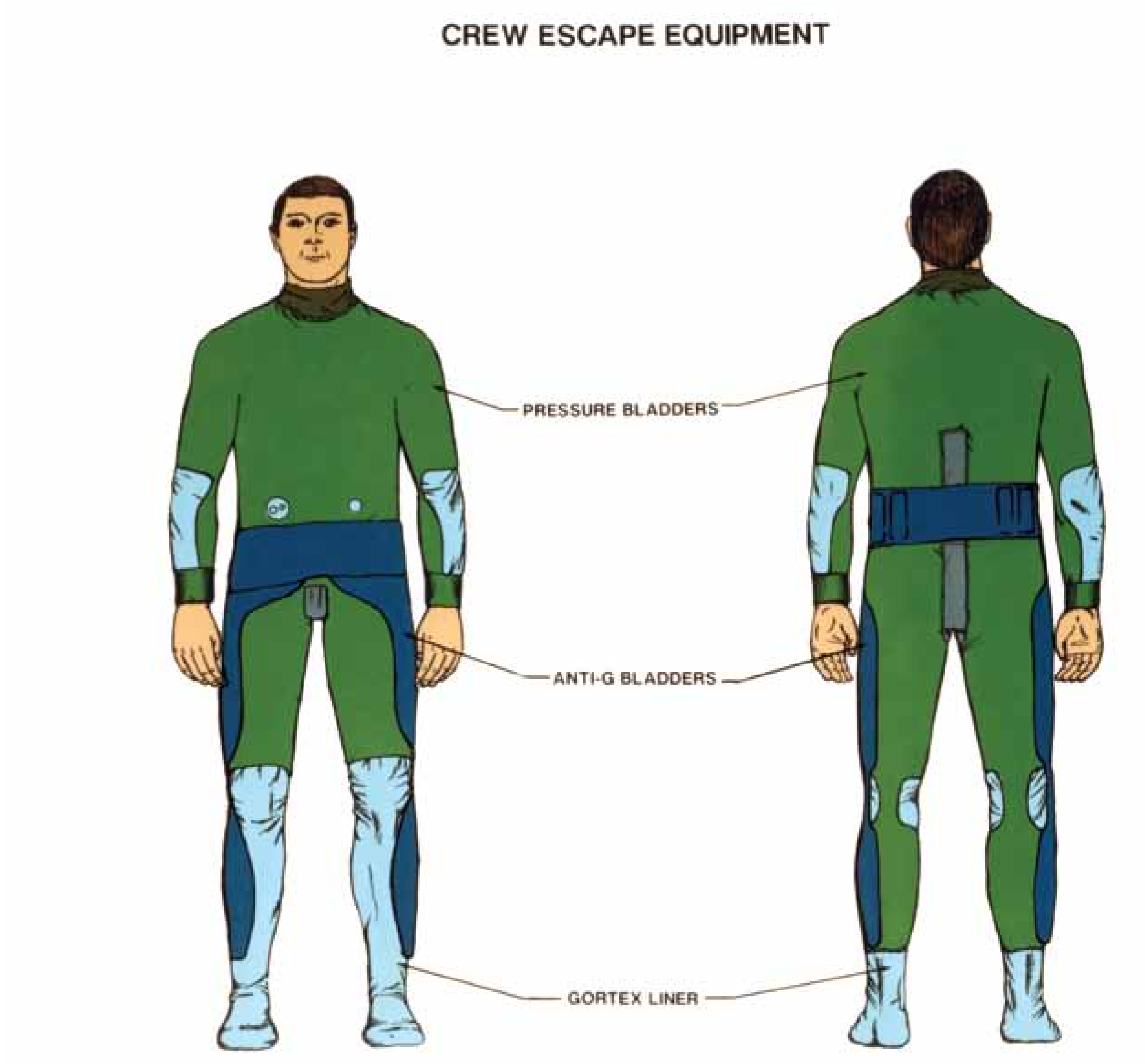
Dual earphones and a flexible boom-mounted microphone were installed on a lightweight fabric "Snoopy Cap" communications carrier worn under the helmet. (A second microphone was added to the second production batch of suits.) Like the S1030A and LEH helmets before it, a pressure switch between the oxygen-delivery system and communication circuitry muted the microphone during inhalation. The comm carrier included head buffeting-protection padding and a large mesh area at the top to minimize heat buildup. The communications cable passed through the lower left side of the helmet and connected to a headset interface unit, which in turn connected to the orbiter communications system.[48]

The first LES prototype used a relatively simple torso counter-pressure garment designed to interface with the helmet via the disconnect bearing assembly and with a lower-body counter-pressure garment similar to a cutaway G-suit, except it contained two separate bladders: one for altitude protection and one for acceleration protection. The ensemble included counter-pressure sleeves and standard partial-pressure gloves to provide physiological protection comparable to the CSU-4/P partial-pressure suit. David Clark Company



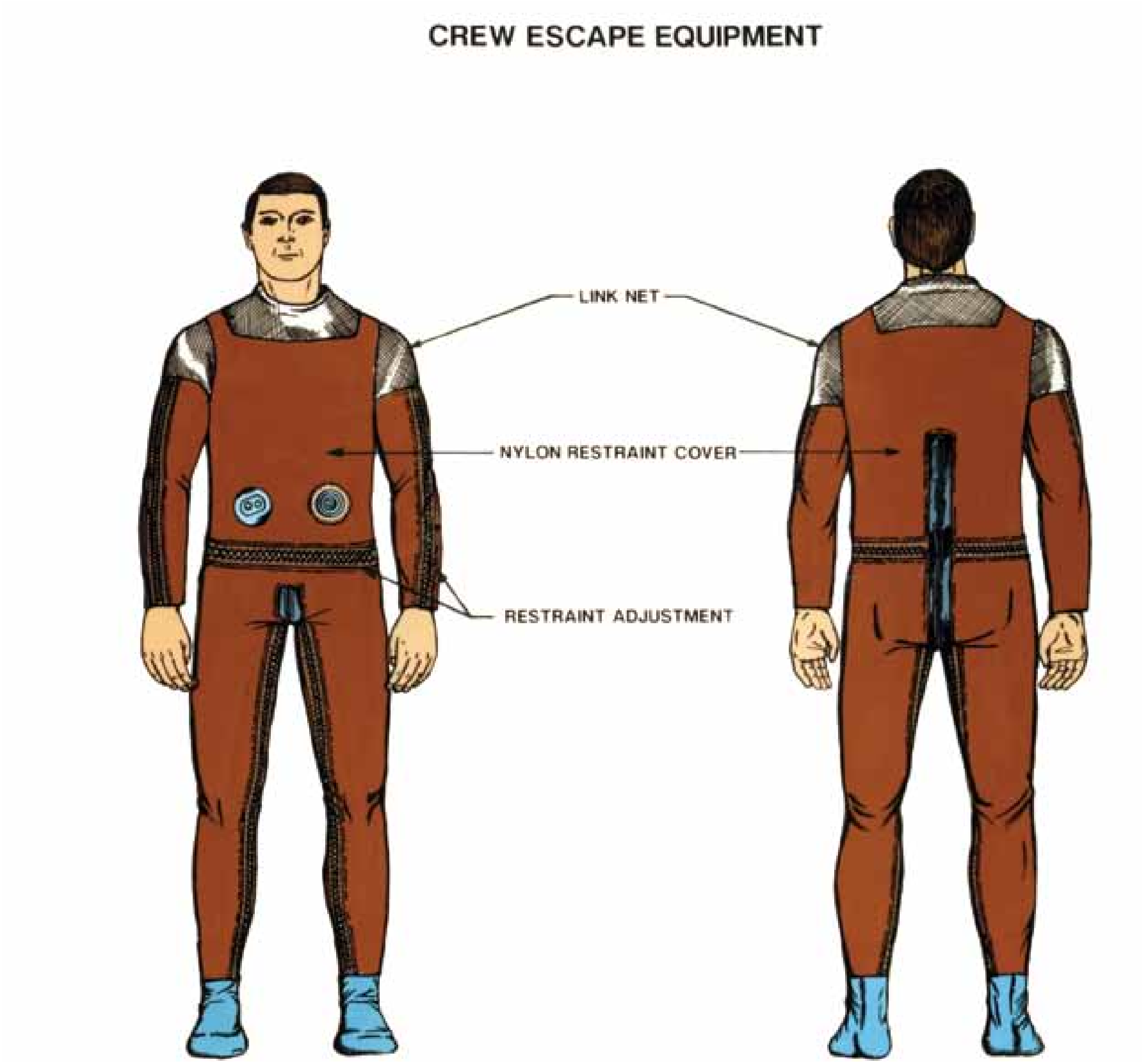
The following illustrations show the various layers of the S1032 Launch Entry Suit (LES). The layer closest to the wearer was a set of long underwear and socks. For men, this included an athletic supporter and urine-collection device.

NASA



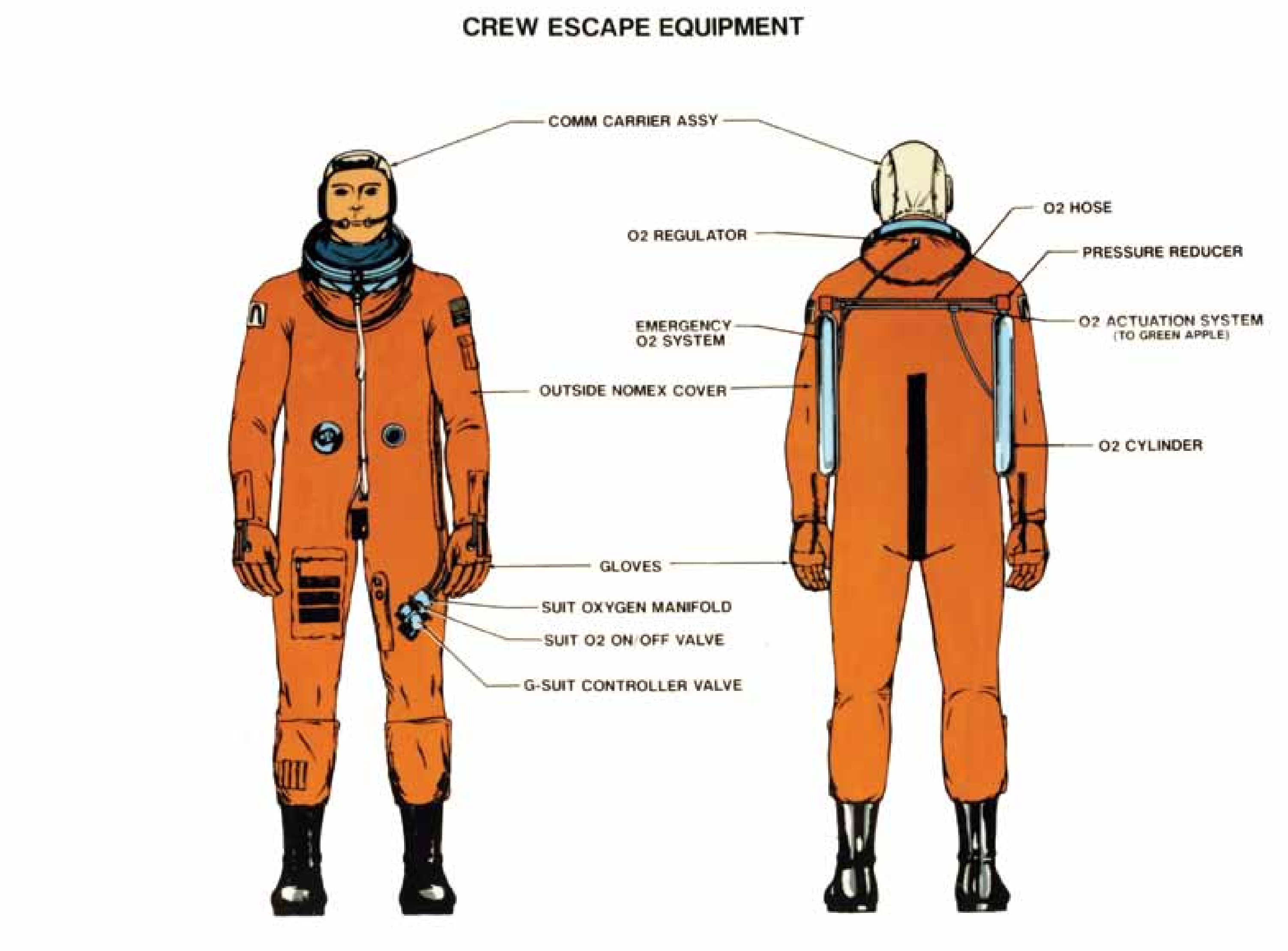
The counter-pressure garment contained the bladders that provided altitude protection if needed. This layer also included unpressurized Gore-Tex fabric sections that protected the wearer against cold-water immersion and allowed ventilation air to circulate within the suit. The dark-blue areas illustrate the cutaway G-suit.

NASA



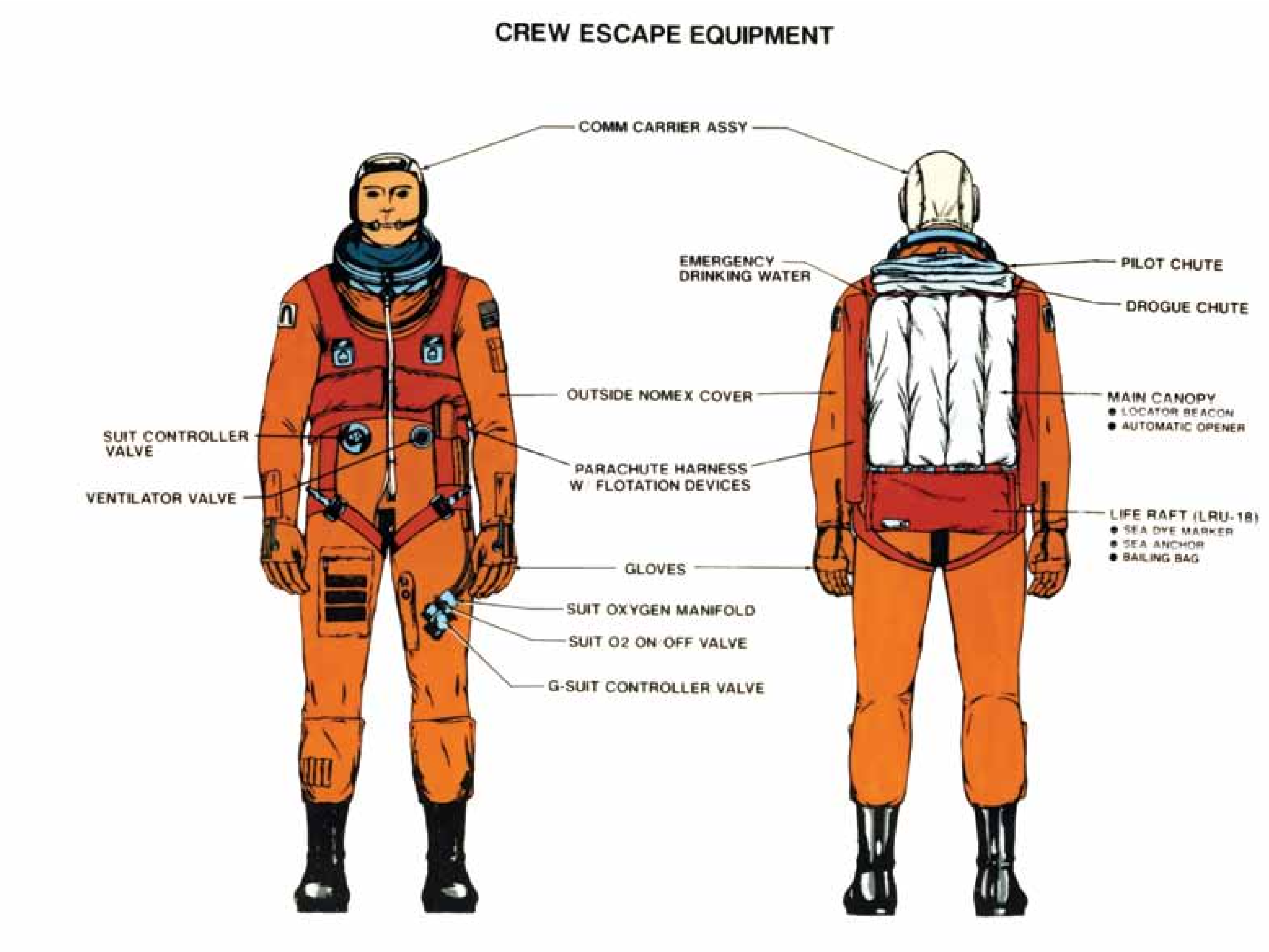
The restraint layer was a relatively unyielding garment that allowed the counter-pressure garment to press inward toward the wearer when inflated. As with all pressure suits, the trick was to make the restraint layer unyielding to internal pressure but still provide sufficient mobility for the wearer to accomplish their tasks. Note the use of Link-Net around the shoulders to increase flexibility.

NASA



The outer cover is what most people think of when they consider pressure suits, although the suit is perfectly capable of operating without it. Early LES suits used dark-blue Nomex covers while all operational suits used orange Nomex for enhanced visibility during search and rescue operations. Note the emergency oxygen cylinders suspended from the shoulders.

NASA

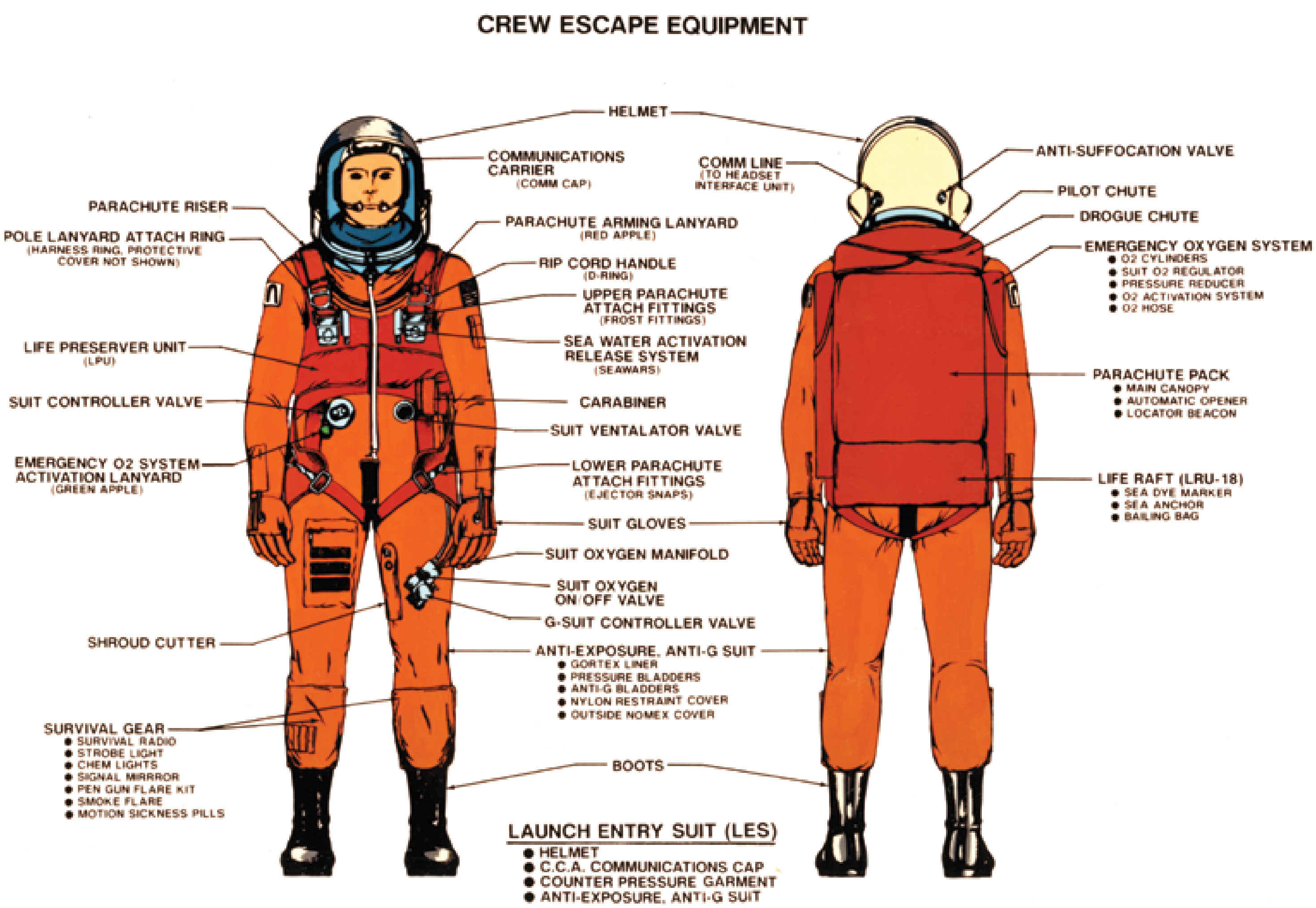


Next came the parachute harness, floatation devices, and various other supplies. Note that the communications carrier assembly is separate from the helmet.

NASA

The final items included the helmet and gloves. Note the location of the "green apple" that was used to initiate the flow of emergency oxygen, the knife pocket on the inside of the left thigh, and the ripcord D-ring handle.

NASA



delivered the first prototype to the Johnson Space Center on June 2, 1987.[49]

The original specification for the CAPS did not include cold-water immersion protection. However, David Clark Company engineers soon learned that NASA intended to provide water-immersion protection through a separate over-garment. This would greatly complicate the donning and doffing process on orbit, so David Clark Company unilaterally decided to incorporate immersion protection into the basic ensemble. As originally conceived, the S1032 was a simple modular design that covered only the portions of the body required for emergency hypobaric protection, thereby minimizing heat loading. The addition of immersion protection required completely covering the body with water-impermeable materials, resulting in considerable metabolic heat loading. To minimize heating and its associated perspiration, David Clark Company integrated breathable Gore-Tex fabric with the pressure bladders to form a watertight coverall with an integral ventilation system. The vent system consisted of an inlet on the left front of the coverall torso, airtight vent ducts routed through the torso pressure bladder to several outlets in the inner bladder wall, and check valves to allow vent air to channel through the pressure bladder for exhaust via the pressure controller. Although complicating the garment itself, the integration of immersion protection within the S1032 nonetheless resulted in a simplified system from a crewmember standpoint.

A modified S1030 full-pressure suit controller was located on the right side of the chest (left in the photo) and the ventilator valve was located on the left side. Because the S1032 was only a partial-pressure suit, the control aneroid was rescheduled to maintain only 2.8 psi instead of the 3.5 psi used by the S1030 (and S1030A).

NASA

For the legs, the G-suit and altitude-protection bladders used the same restraint layer. This

Despite being a partial-pressure suit, the S1032 looked very much the part of a full-pressure suit. In front, the parachute harness is clearly visible, as is the emergency flotation-device housing around the chest. At the back, the parachute is flanked by an emergency oxygen cylinder on each side.

NASA

design theoretically provided greater acceleration protection than the standard military cutaway G-suit since it provided contiguous coverage through the knee, hip, and groin areas and had slightly greater bladder area coverage, similar to the recent full-coverage G-suit employed in fighter aircraft. The G-suit was only used during entry.

David Clark Company selected the standard S1030 full-pressure suit dual system controller for the S1032. However, given the partial-pressure suit application, the control aneroid was rescheduled to maintain a minimum absolute pressure of 2.8 psi, instead of the 3.5 psi used by the S1030. The harness assembly contained a torso harness, an enhanced life preserver unit, a freshwater-pouch assembly, an emergency rescue package that contained flares and a knife, and a two-bottle emergency oxygen supply that provided 10 minutes of life support.

The first production S1032 suit was delivered to NASA on February 8, 1988. Researchers at the USAF School of Aerospace Medicine conducted altitude chamber tests and concluded that the S1032 provided acceptable protection at 100,000 feet. Cold-water tests at the Naval Air Development Center showed the suit provided more than 3 hours of protection for subjects immersed in 40 ºF water.[50]

Lockheed issued three separate purchase orders to the David Clark Company for S1032 suits. The first, on September 4, 1987, was for six suits to support system certification training and STS-26R crew training. David Clark Company fabricated these suits using dark-blue Nomex exterior covers, same as the prototype. Each suit cost $84,180. David Clark commenced deliveries on February 8 and completed them on February 25, 1988.[51]

The second purchase order was issued on November 11, 1987, for 10 suits at a cost of $84,180 each. The order was modified on April 14, 1988 to add a second microphone to each suit and to change the configuration of the leg pockets to more closely match the S1030A. Six of these suits were fabricated using orange Nomex covers for enhance visibility during search and rescue operations.

Dual earphones and a flexible boom-mounted microphone were installed on a lightweight fabric "Snoopy Cap" communications carrier worn under the helmet. The communications cable passed through the lower left side of the helmet and connected to a headset interface unit, which in turn connected to the orbiter communications system. Here, the white cable is tucked into a pocket on the exterior cover.

NASA

The other four used dark-blue exterior covers. David Clark Company delivered the first suit on March 4, 1988, and the last on September 9, 1988.[52]

The last production order was issued on August 18, 1988, for 32 suits at a cost of $88,769 each. All of these included dual microphones and orange Nomex outer covers. These suits were provided in six additional sizes (small regular, small long, large short, and extra-large short, regular and long). Lockheed also ordered two extra orange exterior covers for $3,372 each. The first suit was delivered on October 28, 1988, and the last on April 24, 1990.[53]

Although David Clark Company developed patterns for the standard 12 sizes, only 10 different sizes were ultimately delivered.[54]

The flotation system initially used with the LES was an Air Force model used by T-38 aircrews. However, during cold-water immersion tests, subjects assumed a horizontal position in the water that allowed the aspiration of water through the anti-suffocation valve located on the back of the LES helmet; this both exacerbated thermal stress and increased the risk of drowning. Subsequently, NASA adopted a modified Navy flotation system that worked reasonably well but used a makeshift interface with the LES. Water inflow through the anti-suffocation valve continued to be a problem, despite the approximate 45-degree angle relative to the water surface assumed by floating subjects. Eventually, DDC designers suggested using the flotation system used by SR-71 crews that placed subjects in a relatively upright position (i.e., approximately perpendicular to the water surface).[55]

During 1990, David Clark Company added a biomedical instrumentation port (BIP) to the LES suits. Informally called a "hole-in-the-suit," this port on the right thigh could accommodate biomedical instrumentation as needed. A blank plug covered the port when not in use. In 1992, David Clark Company modified the LES neck seal by adding

In 1988, before the return-to-flight of STS-26R, NASA astronaut and flight surgeon Jim Bagian conducted a mobility study that compared the original shirtsleeve/LEH environment with the then-new S1032. Here Bagian demonstrates that the LES allowed reaching behind him while wearing the emergency oxygen cylinders and parachute pack.

NASA

pull-tabs and Velcro to improve ventilation to the head and neck during prelaunch and post-landing when the crew was sitting in the seat for extended periods.[56]

Before the return-to-flight of STS-26R in 1988, NASA astronaut and flight surgeon James P. Bagian conducted a study of the mobility of the original LEH shirtsleeve ensemble and the then-new LES garment. Primarily, Bagian and researcher Lauren W. Schafer from Lockheed Engineering & Sciences Company,[57] were interested in how the different ensembles affected the ability of the crew to reach various controls in the orbiter. Seven veteran astronauts and four airmen volunteers were tested on the human centrifuge at the USAF School of Aerospace Medicine at Brooks AFB to find the answer. The subjects were strapped into a seat that mimicked the launch orientation of the orbiter and instructed to conduct a series of “reach sweeps” that were measured by researchers using high-speed video. Each sweep began with the hand on the knee, reached

Bagian in the vertical middeck simulator at JSC. Note the "green apple" that initiates the flow of emergency oxygen. The outermost orange tubes across the chest was the floatation device (life vest). Note how cramped the seating arrangement is, with the middeck lockers only a couple of feet away.

NASA

directly forward, sweeping back toward the aft wall of the gondola, to a position over the head, and finally back to the knee. Tests were conducted at 1-G (gondola sitting still) and at +3-Gz, about the maximum reached during a Space Shuttle ascent.[58]

All of the subjects practiced the sweeps multiple times to familiarize themselves with the action and encumbrances of both types of suits. Bagian commented, "The changes in forward reach were qualitatively what had been expected based on anecdotal reports."[59] On the average, the subjects experienced a 1.45-inch reduction in forward reach at +3-Gz versus 1-G for both suits. This was not as great a reduction as the researchers expected. The study also found that the forward reach in the LES was 2.40 inches less than in the LEH at each acceleration level. Bagian concluded that, "the reduction in forward reach capability of 13 percent was inherently due to the change in required crew equipment."[60] Interestingly, right overhead reach was found to be 2.00 inches (8 percent) greater than the left for both suits at each acceleration level.

Robert R. "Bob" Banks from the David Clark Company (DCC) models the prototype S1035 full-pressure suit on April 20, 1990. Based largely on the success of the Air Force S1034 development effort, this prototype was used for the initial comparisons with the existing S1032 suits. Note the DCC patch on the right chest.

Courtesy of the David Clark Company, Inc.

Since the garments were symmetrical, Bagian attributed the difference to the parachute harness worn over each ensemble. Although not part of the study, each subject reported that the field of view provided by the LES helmet was substantially greater than the LEH.

Bagian, who has long been one of the most vocal proponents of the need to provide better protective equipment for Space Shuttle crewmembers, concluded, "Although the LES permitted less forward and overhead reach capability than its predecessor, the LEH, the observed reductions are offset by the expanded crew escape and survival potential provided by this new suit."[61]

In 1990, David Clark Company completed the development and qualification of the Air Force S1034 Pilots Protective Assembly full-pressure suit. At the time, NASA was looking to procure additional LES ensembles and this presented an opportunity to reconsider the benefits of partial versus full-pressure suits. David Clark Company fabricated a prototype S1035 full-pressure ensemble for NASA in 1990, based largely on the S1034 design. The new suit was considerably lighter, less bulky, cooler, and more comfortable than the S1032, used the same helmet and pressure controls as the S1032, and provided better physiological protection and more mobility. The prototype evolved into the S1035 Advanced Crew Escape Suit (ACES).[62]

David Clark Company configured the exterior cover of the S1035 identically to the S1032, and the two are largely indistinguishable without careful examination. This might explain why NASA public affairs continued to refer to LES suits until the end of the program, ignoring the ACES designation entirely. The easiest way to tell the suits apart at a glance is to see how the gloves are connected; if they use a wrist ring, it is an S1035. This is the STS-129 crew during the terminal countdown demonstration test (TCDT) emergency egress training.

NASA

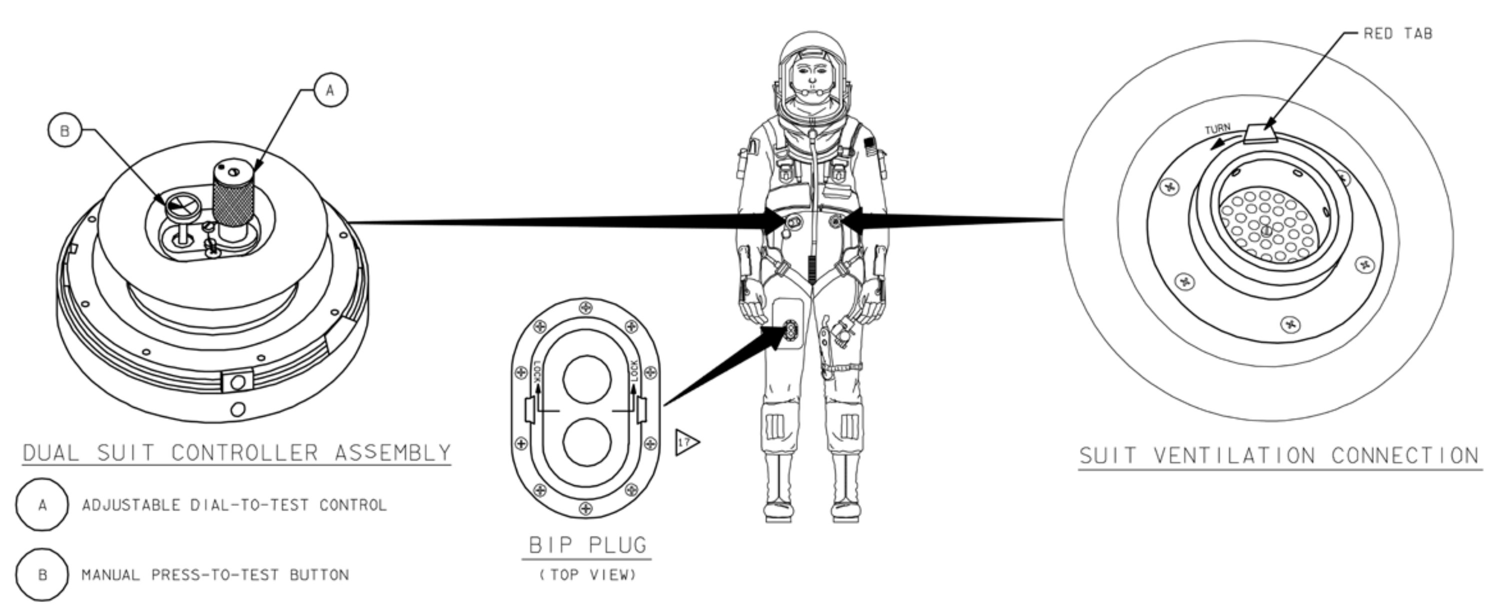
The LES supported 42 Space Shuttle missions, beginning with STS-26R in September 1988 and ending with STS-98 on February 7, 2001. The dark-blue LES ensembles never flew in space, being relegated to training purposes. NASA continued to use the suits for some training until the end of the program in 2011, long after the LES was retired from flight duties.

S1035—ADVANCED CREW ESCAPE SUIT (ACES)

The prototype S1035 fabricated by David Clark Company in 1990 heavily leveraged the technologies developed for the USAF S1034 Pilots Protective Assembly. Since the existing S1032 partial-pressure suits were nearing the end of the service lives, the S1035 provided NASA a low-risk path to upgrade to a full-pressure suit. Lockheed engineers compared

This illustration shows the location of the dual suit controller, ventilation connection, and the bioinstrumentation pass-through. All of this hardware was identical to (and mostly salvaged from) the earlier S1032 suits.

NASA



Bioinstrumentation Pass-Thru (BIP)

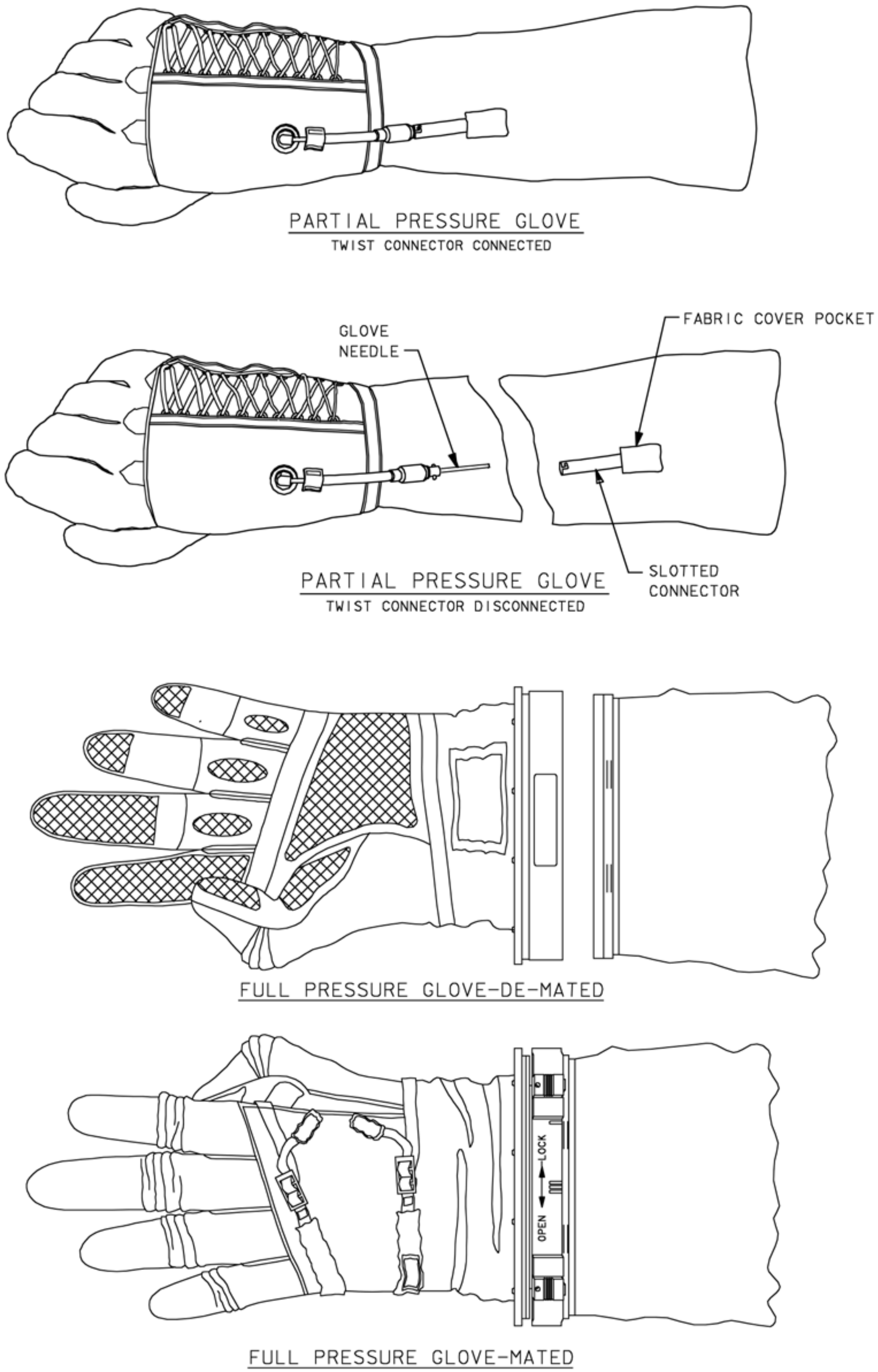
the prototype S1035 to the S1032 LES in regards to reach and treadmill performance and found no significant differences. Favorable crew evaluations of the prototype S1035 led to full-scale development in 1992.[63]

David Clark Company began production of the S1035 Advanced Crew Escape Suit (ACES) in February 1993 and delivered the first article to NASA in May 1994. In a switch from the usual scenario, the S1035 entered production and operational service before the S1034 from which it was derived.[64]

As a cost savings, David Clark Company removed significant hardware from the S1032 suits and reused it on the S1035 suits. This included the dual-system suit controllers, neck rings, neck seal, relief valves, helmets, helmet holddown hardware, and the oxygen manifold behind the neck ring. The suit controllers, oxygen-breathing regulators, exhalation valves, and relief valves were rescheduled to operate at 3.5 psi for ACES instead of the 2.8 psi used in the LES.[65] To minimize training requirements, the exterior coverall was configured identical to the last S1032s and used the same biomedical instrumentation pass-through. Because of this, the pocket configuration on the S1035 differs from the S1034.[66]

Several of the material/configuration changes that David Clark Company adopted to satisfy other design objectives resulted in a marked improvement in the comfort of the ACES compared to the LES. Particularly, this included the use of a breathable gas-container material and the elimination of a separate restraint layer in the legs. The S1034 glove also provided better comfort and mobility. This glove used a bladder assembly fabricated from breathable materials in the wrist, palm, and backhand areas to reduce thermal load. It also used an outer restraint with a combination of flat and tucked patterning to reduce the torque needed to flexion-extension of the hand joints in both pressurized and unpressurized modes. In addition, new wrist disconnects incorporated low-torque bearings to minimize the forces associated with repeated rotations of the wrist. Standard, commercial-off-the-shelf Rocky 911 boots were worn over ACES pressure-bladder booties.[67]

The design and construction of the S1034 and S1035 were essentially identical, although there were differences in the integration of accessories due to differing modes of crew escape and mission objectives. Visible differences between the two suits included the suit controller and vent connector being closer together on the S10135 because NASA used a Mustang parachute harness instead of a standard USAF unit. Less noticeable was that the S1035 did not use an inner comfort liner, a vent system, or a urine-collection system.



Launch and Entry Suit Gloves

A comparison of the S1032 partial-pressure suit glove and the S1035 full-pressure suit glove. Like most partial-pressure gloves, the S1032 glove was not directly attached to the suit except through the ventilation tube, while the full-pressure glove used a lock-ring that tightly secured it to the suit.

Courtesy of the David Clark Company, Inc.

Table 10—S1034 Requirements Classification		
Component	**USAF S1034 PPA**	**NASA S1035 ACES**
Helmet	Conformal helmet with face seal, integrated anti-suffocation valve, breathing regulator, exhalation valves, food and liquid intake pass-through, integrated and self-contained communication	Dome (nonconformal) helmet, larger neck ring, integrated anti-suffocation valve, and communication connection. (Communication provided as a separate communication carrier assembly.)
Coverall	Outside Nomex cover, Link-Net restraint, Gore-Tex bladder/ exposure layer and inner comfort liner.	Identical to S1034 except no inner comfort liner and coverall provisions for oxygen pass-through and G-suit oxygen manifold. NASA system used an integrated neck seal because of dome helmet use.
Hardware	Neckring and glove disconnects with low-torque bearings, vent inlet fitting and duct system, helmet holddown system.	Identical hardware components with the addition of a G-suit pressure controller/ oxygen manifold, biomedical pass-through and dome helmet-support springs.
Pressure Controls	Dual suit-controller assembly, oxygen-breathing regulator located in helmet, suit relief valve, exhalation valves located in helmet.	Identical except oxygen-breathing regulator (single system) was located in the suit and exhalation valves were located in the suit neck seal.
Gloves	Full-pressure suit glove with wrist disconnects.	Identical

Source: Phil Landis and Phil Hooper, "Assessment of the S1035 Advanced Crew Escape Suit for Use in the Space Launch Initiative program," Lockheed Martin Space Operations report LMSEAT-34099, January 16, 2003.

Various pieces of crew-worn equipment include an S1035 ACES, along with its harness assembly and AGS (left), a diaper, the communications carrier and helmet, boots, and cold-weather over-gloves.

NASA

In addition, the S1035 had provisions to use an Anti-G Suit (AGS) under the pressure suit during entry.[68] The AGS was fabricated from Nomex and nylon with counter-pressure bladders configured generally similar to the standard USAF "5 bladder" cutaway G-suit. Lacing on the waist and legs allowed some customization for fit. The AGS was pressurized with suit oxygen and the connection to the orbiter was through a self-sealing connector that permitted the crewmember to wear the S1035 by itself (standard launch configuration),

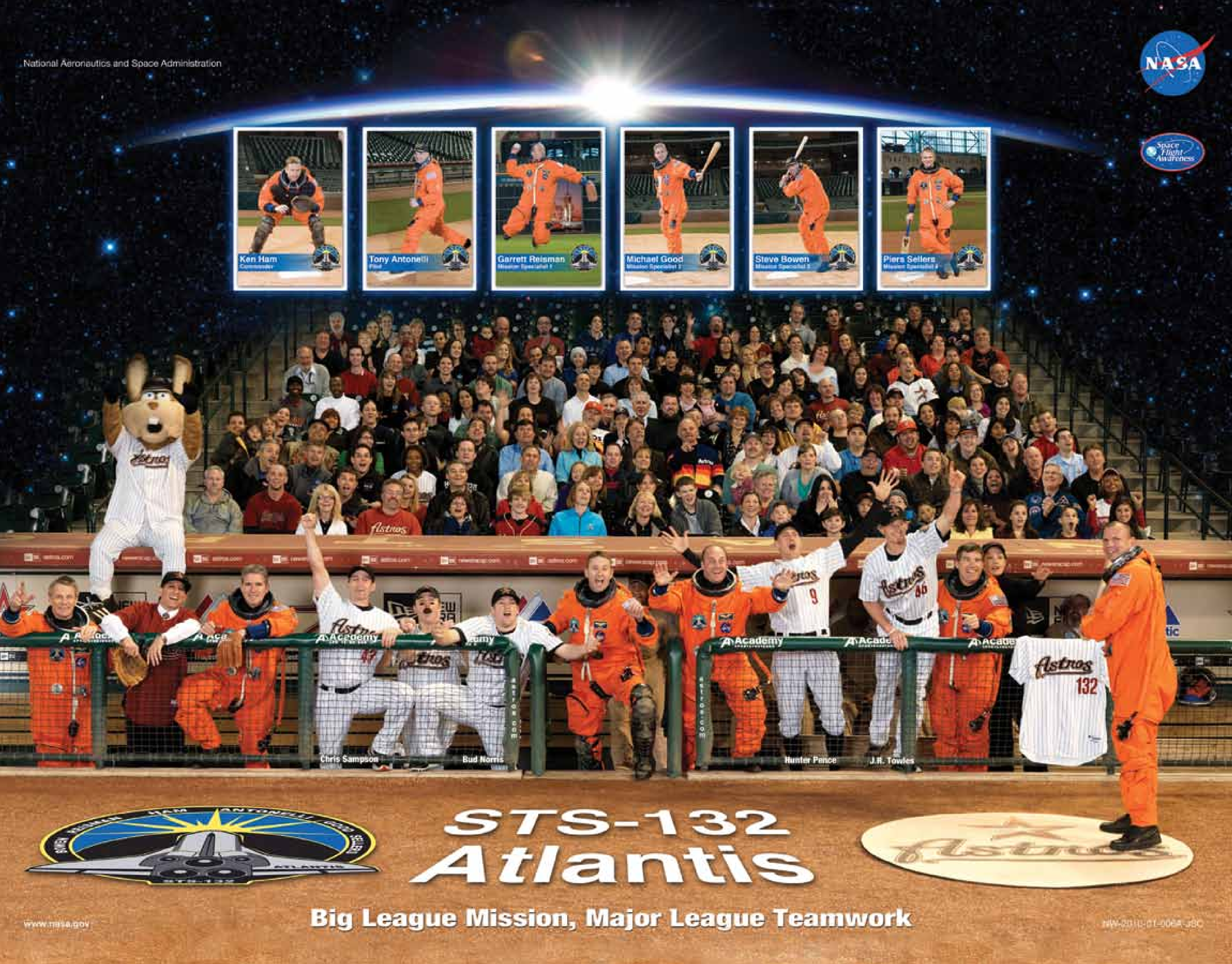
Above: From the back, the S1035 shows its long vertical rear-entry zipper and the harness assembly with side pockets that held emergency oxygen cylinders. Note the booties sticking out of the legs of the S1035; these were permanently connected to the gas container inside the suit.

Right: The crew of STS-95 show off their ACES full-pressure suits. This was a highly publicized mission due to former Mercury astronaut and U.S. Senator John H. Glenn, Jr.'s return to space for his second space flight, at age 77. Re-creating a famous Mercury Seven pose are (left to right, front): Steven K. Robinson, Curtis L. Brown, John H. Glenn, and Scott E. Parazynski; (left to right, back): Pedro Duque (ESA), Chiaki Mukai (NASDA), and Steven W. Lindsey.

NASA

the S1035 with the AGS (standard entry configuration), or the AGS by itself without the pressure suit.[69]

In the SR-71 and U-2, the pilot wore all of his equipment when he entered the aircraft and sat on an ejection seat. Astronauts, on the other hand, wore only their pressure suits when they entered the orbiter and sat on lightweight crew seats. The USAF parachute system was contained within the seat along with a survival kit, whereas the Space Shuttle system used a stand-alone parachute positioned in the orbiter seat backs and


National Aeronautics and Space Administration
NASA
Space Flight Awareness
Ken Ham
Commander
Tony Antonelli
Pilot
Garrett Reisman
Mission Specialist 1
Michael Good
Steve Bowen
Piers Sellers
Chris Sampson
Bud Norris
Hunter Pence
J.R. Towles
132
STS-132
Atlantis
Big League Mission, Major League Teamwork
www.nasa.gov

Not really intended as a demonstration of the flexibility of the S1035 suit, the STS-132 Space Flight Awareness photos at Minute Maid Park in Houston on February 11, 2010, nevertheless provided some insight. The crew horsed around in training versions of the suit, pretending to play baseball and cricket, and generally having fun.

NASA

Table 11—Space Shuttle Crewmember Protection by Mission								
Mission	Date	CDR	PLT	MS1	MS2	MS3	MS4	MS5
STS-1 through STS-4	—	S1030A	S1030A	—	—	—	—	—
STS-5 through STS-33	—	LEH	LEH	LEH	LEH	(LEH)	(LEH)	(LEH)
STS-26R through STS-65	—	LES	LES	LES	LES	(LES)	(LES)	(LES)
STS-64	Sep 9, 1994	LES	LES	ACES	LES	ACES	LES	—
STS-68	Sep 30, 1994	ACES	ACES	LES	LES	LES	LES	—
STS-66	Nov 3, 1994	LES	LES	LES	LES	LES	LES	—
STS-63	Feb 3, 1995	ACES	ACES	ACES	ACES	LES	LES	—
STS-67	Mar 2, 1995	LES	LES	LES	LES	LES	LES	LES
STS-71	Jun 27, 1995	ACES	ACES	ACES	ACES	LES	LES	LES
STS-70	Jul 13, 1995	ACES	LES	LES	ACES	LES	—	—
STS-69	Sep 7, 1995	LES	ACES	LES	ACES	LES	—	—
STS-73	Oct 20, 1995	LES	ACES	LES	ACES	ACES	LES	LES
STS-74	Nov 12, 1995	ACES	ACES	LES	LES	ACES	—	—
STS-72	Jan 11, 1996	LES	LES	ACES	LES	LES	ACES	—
STS-75	Feb 22, 1996	LES	ACES	LES	ACES	LES	ACES	LES
STS-76	Mar 22, 1996	ACES	ACES	LES	LES	LES	LES	LES
STS-77	May 19, 1996	LES	LES	LES	LES	LES	LES	LES
STS-78	Jun 20, 1996	LES	ACES	LES	ACES	LES	LES	LES
STS-79	Sep 16, 1996	ACES	ACES	LES	LES	LES	LES	LES
STS-80	Nov 19, 1996	LES	LES	LES	LES	LES	—	—
STS-81	Jan 12, 1997	LES	LES	LES	LES	LES	LES	LES

Table 12—Space Shuttle Crewmember Protection by Mission (continued)								
Mission	Date	CDR	PLT	MS1	MS2	MS3	MS4	MS5
STS-82	Feb 11, 1997	LES	ACES	ACES	ACES	ACES	LES	ACES
STS-83	Apr 4, 1997	ACES	ACES	ACES	ACES	ACES	LES	LES
STS-84	May 15, 1997	ACES	ACES	ACES	ACES	ACES	ACES	ACES
STS-94	Jul 1, 1997	ACES	ACES	ACES	ACES	ACES	LES	LES
STS-85	Aug 7, 1997	ACES	ACES	ACES	ACES	ACES	LES	—
STS-86	Sep 25, 1997	ACES	ACES	ACES	ACES	ACES	ACES	ACES
STS-87	Nov 19, 1997	ACES	ACES	ACES	ACES	ACES	LES	—
STS-89	Jan 22, 1998	ACES	ACES	ACES	ACES	LES	ACES	ACES
STS-90	Apr 17, 1998	ACES	ACES	ACES	ACES	ACES	LES	LES
STS-91	Jun 2, 1998	ACES	ACES	ACES	ACES	ACES	ACES	ACES
STS-95	Oct 25, 1998	ACES	ACES	ACES	ACES	ACES	ACES	ACES
STS-88	Dec 4, 1998	ACES	ACES	ACES	LES	ACES	ACES	—
STS-96	May 27, 1999	ACES	ACES	ACES	ACES	ACES	ACES	ACES
STS-93	Jul 23, 1999	ACES	ACES	ACES	ACES	ACES	—	—
STS-103	Dec 19, 1999	ACES	ACES	ACES	ACES	ACES	ACES	ACES
STS-99	Feb 11, 2000	ACES	ACES	ACES	ACES	ACES	ACES	—
STS-101	May 19, 2000	ACES	ACES	ACES	ACES	ACES	ACES	ACES
STS-106	Sep 8, 2000	ACES	ACES	ACES	ACES	ACES	ACES	ACES
STS-92	Oct 11, 2000	ACES	ACES	ACES	ACES	ACES	ACES	ACES
STS-97	Nov 30, 2000	ACES	ACES	ACES	ACES	ACES	—	—
STS-98	Feb 7, 2001	ACES	ACES	ACES	ACES	ACES	—	—
STS-102 through STS-135	—	ACES	ACES	ACES	ACES	(ACES)	(ACES)	(ACES)
Source: Bruce W. Sauser (NASA/JSC), Carlton F. "TC" Thomas (USA/JSC), and Ronald C. Woods (NASA/KSC).								

Seven S1035 suits await their crew prior to the last flight of Columbia, STS-107.

Courtesy of the David Clark Company, Inc.

connected to the harness assembly after orbiter ingress. Both parachute systems were based upon a pilot, drogue, and reefed main-canopy system. When these systems were initiated, a pilot chute deployed a drogue chute that provided speed and orientation stabilization until reaching 14,000-feet altitude, at which time the main-canopy deployed (in the case of the U-2R and SR-71, this occurred at pilot-seat separation). The SR-71 main canopy parachute was 35-feet in diameter, compared to 28 feet in the U-2R and 26 feet in the Space Shuttle.[70]

Breathing oxygen came from the orbiter supply, the emergency oxygen system (EOS) at each seat, or from carry-around bottles that allowed crewmembers to move about the crew module. The ACES breathing regulator delivered 100 percent oxygen to the helmet at slightly above suit pressure. This resulted in oxygen-enriched air being exhaled into the crew module. Over time, this increased the oxygen concentration in the crew module, creating the potential for fire. Therefore, the amount of time that crewmembers had their visors down and were breathing 100 percent oxygen was operationally limited except, of course, during emergencies.[71]

The EOS was located within the parachute pack and consisted of two 3,000-psi oxygen bottles (381 liters total) with regulators that reduced the pressure to 70 psi. A common manifold delivered 70-psi oxygen from both bottles to a hose that connected to the ACES oxygen manifold. Pulling the "green apple" knob on the right side of the harness activated the system.

Crewmembers wore various garments under the ACES and G-suit for comfort. These included a liquid-cooling garment, thermal underwear, wool socks, and a diaper (unlike the S1034, the S1035 did not include a urine-collection system). The liquid cooling garment consisted of thermal underwear, shirt, and trousers with tubes sewn into the fabric. A thermoelectric liquid-cooling unit or

Lockheed test pilot William A. "Bill" Weaver in front of an SR-71 wearing a David Clark Company S901 suit adapted for use with the SR-71A. On 25 January 1966, Weaver survived after his SR-71A (61-7952) broke up at Mach 3 and 75,000 feet. (See story on the following page.)

Courtesy of Lockheed Martin Aeronautics

individual-cooling unit pumped chilled water through a network of tubing in the liquid-cooling garment to cool the crewmember. The water supply and return lines were fed through a plug located on the right thigh of the ACES.[72]

Like the LEH and LES before it, the ACES was supported by the orbiter oxygen system with four connections on the flight deck and four on the middeck. The middeck connections each had a tee that supported two connections, for eight available connections in all on the middeck. Each of these 12 connections could support an ACES or a Quick-Don Mask (QDM) assembly that was used for on-orbit contingency operations.[73]

As it had for the S1034 PPA, David Clark Company examined all available anthropometric data to determine if the existing 12-size tariff was still valid for the S1035. The conclusion was the same as it had been for the S1034, namely that the 12 sizes provided an adequate fit from the 5th to the 95th percentile of expected wearers, including females.

However, the increased range of sizes for personnel in the Space Shuttle and International Space Station (ISS) programs led to the addition of an extra-small category and a small regular modified subcategory. David Clark Company ultimately fabricated 62 S1035 suits for the Space Shuttle Program.[74]

There were proposals to give the S1035 suits to the NASA WB-57F operation at nearby Ellington Field after the Space Shuttle retired in 2011. The engineers at David Clark Company pointed out that it would be costly to modify the S1035s to work with the WB-57Fs since the suits were considerably different than the S1034 PPAs used by the WB-57F crews. Although much of the hardware could be salvaged from the S1035s and used to build new S1034s, actually converting the S1035s would have been prohibitively expensive.[75]

COMPARING COLUMBIA TO AN SR-71 BREAKUP

As part of the investigation into the Columbia accident during STS-107 in 2003, the Spacecraft Crew Survival Integrated Investigation Team compared the breakup of Columbia to a similar breakup of an SR-71A (61-7952) on January 25, 1966. The Blackbird suffered a structural failure during a high-speed turn and broke apart at approximately Mach 3 and 75,000 feet. This translates to approximately 400 knots equivalent air speed (KEAS). Lockheed pilot William A. "Bill" Weaver was thrown clear of the wreckage and blacked out during the accident but recovered and landed safely. James T. "Jim" Zwayer in the back seat apparently broke his neck as his helmet hit the Mach 3 slipstream and did not survive. While three other crewmembers lost their lives in the A-12 and M-21 programs, Zwayer was the only fatality in an SR-71.[76]

Although seemingly dissimilar, the two accidents shared some common traits. For instance, in both accidents, crewmembers were involuntarily separated from the vehicle when the seat restraints failed. The S901J pressure suits worn by the SR-71 crew were a distant relative of the S1035 pressure suits worn by the Columbia crew but provided essentially similar protection. Most importantly, from an investigation perspective, the dynamic pressure when the Columbia crew module broke up was approximately 405 pounds per square foot (psf), and the dynamic pressure at SR-71 breakup was roughly 398 psf, a difference of less than 2 percent.

However, there are also notable differences between the two accidents. Bill Weaver's S901 suit pressurized automatically, as designed, when the cockpit depressurized due to the aircraft breakup. The pilot attributed his survival to the pressurized suit, which protected him from the low-pressure and low-oxygen environment, as well as the aerodynamic forces experienced when he separated from the aircraft (and ejection seat). The Columbia suits did not pressurize because the astronauts had not lowered their visors to activate the suit oxygen system and three crewmembers had not donned gloves, required actions for the suit to pressurize. In addition, although the Columbia crewmembers were exposed to a similar dynamic-pressure environment as the SR-71 crewmembers, the thermal environment was much more severe during the STS-107 breakup and is believed to have been nonsurvivable.

In the Space Shuttle orbiter, the crew module is a separate, pressurized compartment housed within the forward fuselage. There are two levels in the crew module: the flight deck on top and the middeck below (there is also an uninhabited equipment compartment below the middeck). Aerodynamic analysis indicates that the Columbia forward fuselage failed at approximately 400 KEAS, exposing the crew module that then failed due to the combined effects of the high accelerations, aerodynamic forces, and thermal loads. The crew module depressurized 6 seconds after the forward fuselage broke apart, although the flight deck retained structural integrity longer than the middeck. The reduced drag of the crew module, once it separated from the forward fuselage, allowed it to accelerate to 560 KEAS during its fall before it disintegrated.[77]

David Clark Company designed the ACES to maintain structural integrity and pressure response when exposed to a 560-KEAS windblast. Because NASA certified the S1035 based on its similarity to the S1034, it was not subjected to windblast tests for certification.[78] However, as part of its certification process, in 1990, the USAF conducted two tests of the S1034 in a 600-KEAS windblast. For the USAF test, the suit contained a mannequin and was properly restrained in an ejection seat with the visor down and locked. During the first test (suit unpressurized), the sunshield separated from the helmet and a life preserver inflation tube separated from the life preserver unit. During the second test (suit at 2.99 psi), both calf pockets were forced open. No other relevant anomalies were observed in either test, and the Air Force certified the suit based on the results.[79]

In the USAF windblast test configuration, the helmet visors were lowered, whereas debris evidence indicates the Columbia helmet visors were up. With the helmet visor up, the helmet cavity presents a high-drag configuration that could contribute to a mechanical failure of the suit/helmet interface.[80]

The investigation team decided it did not have enough data about either accident or about the suit-certification process to come to any particular conclusions. There is little doubt, however, that not wearing a pressure suit properly has an adverse effect on the amount of protection it can provide. Nevertheless, even if the Columbia astronauts had been wearing the suit correctly, and the suits had protected the astronauts sufficiently to save them from the initial breakup, it is unclear how they would have survived the rest of the accident. Ultimately, the investigators issued several recommendations to improve future pressure suits.

ENDNOTES

Endnotes

PREFACE

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CHAPTER 1

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16 Robert Boyle, *New experiments physico-mechanical, touching the spring of the air, and its effects, (made, for the most part, in a new pneumatical engine)* (Oxford, Printed by H. Hall for Theodore Robinson, 1660).

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22 Phil Landis and Phil Hooper, "Assessment of the S1035 Advanced Crew Escape Suit for Use in the Space Launch Initiative Program," Lockheed Martin Space Operations Report LMSEAT-34099, January 16, 2003.

23 Donn A. Byrnes and Kenneth D. Hurley, *Blackbird Rising: Birth of an Aviation Legend* (Los Lunas, NM: Sage Mesa Publications, 1999).

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33 Donn A. Byrnes and Kenneth D. Hurley, *Blackbird Rising: Birth of an Aviation Legend* (Los Lunas, NM: Sage Mesa Publications, 1999).

CHAPTER 2

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3 Fred M. Sample, Patent 1,272,537 for a "Suit for Aviators," July 16, 1918. Sample applied for the patent on March 20, 1917.

4 Lloyd Mallan, *Suiting Up For Space: The Evolution of the Space Suit* (New York: The John Day Company, 1971).

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6 Name and title confirmed by Gail Fithian, Government Documents Department, Boston Public Library, via email, April 20, 2009. This was confirmed by Mr. John J. Devine, Jr., Reference Librarian, Boston Public Library in an email on April 21, 2009, "In both the 1933 and 1935 Officials and Employees of the City of Boston and County of Suffolk (we were lacking 1934) there is a Timothy Leary, M.D., listed as an employee of Suffolk County as Medical Examiner for the Southern Division. He was first employed by the County in 1908 and assumed his position on the 18th of March 1931."

7 *Suiting Up For Space: The Evolution of the Space Suit*.

8 A.E. Boycott, G. C. C. Damant, and J. S. Haldane, "Prevention of compressed air illness," *The Journal of Hygiene*, Vol. 8, 1908. Haldane led an interesting life, and among other things, developed the first gas mask in response to German attacks during World War I. He also determined the regulation of breathing, discovered the Haldane effect in hemoglobin, and founded *The Journal of Hygiene*.

9 *Suiting Up For Space: The Evolution of the Space Suit*.

10 Davis had a long history with Siebe & Gorman, having worked for the company since he was 11 years old.

11 Siebe Gorman & Company Ltd was a British company that advertised itself as "Submarine Engineers." The partnership of Siebe and Gorman was established in 1868 when Augustus Siebe retired from the manufacturing business. By that time, he had produced hundreds of diving suits and helmets. Henry Siebe, second son of Augustus, and his son-in-law William Augustus Gorman established the company as Siebe & Gorman in 1870. Henry Siebe died in 1887 and William Gorman died in 1904. In 1905, the Vickers Family reformed the company as Siebe Gorman & Company, Limited.

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14 *Suiting Up For Space: The Evolution of the Space Suit*.

15 Ibid.

16 The lineage of the United States Air Force is: August 1, 1907–July 18, 1914, Aeronautical Division, U.S. Signal Corps; July 18, 1914–May 20, 1918, Aviation Section, U.S. Signal Corps; May 20, 1918–May 24, 1918, Division of Military Aeronautics; May 24, 1918–July 2, 1926, U.S. Army Air Service; July 2, 1926–June 20, 1941, U.S. Army Air Corps; June 20, 1941–September 18, 1947, U.S. Army Air Forces (The Air Corps became a subordinate element of the USAAF, and no longer an administrative organization, on June 20, 1941. It continued to exist as a combat arm of the Army (similar to Infantry) until disestablished by Congress with the creation of the U.S. Air Force in 1947.); September 18, 1947–Present, United States Air Force.

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26 "Wiley Post," located at *http://en.wikipedia.org/wiki/Wiley_Post*; "Post and Settle Win Flying Prizes; Gain Harmon International Trophies for 1933 for World and Stratosphere Flights," *New York Times*, April 22, 1934.

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36 *Suiting Up For Space: The Evolution of the Space Suit*.

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51 *Wiley Post, His Winnie Mae, and the World's First Pressure Suit*.

52 *Wiley Post, His Winnie Mae, and the World's First Pressure Suit*; *Physiological Protection of the CSU-4/P High Altitude Pressure Suit*.

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CHAPTER 3

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[29] Edwin G. Vail and Richard G. Willis, "Pilot Protection for the X-15 Airplane," a paper in the *1958 Research Airplane Committee Report*.

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[31] "Pilot Protection for the X-15 Airplane;" email, William Ayrey, ILC Dover to Dennis R. Jenkins, February 4, 2010.

[32] "Development of a Full-pressure Suit System," David Clark Company, ASD Technical Report 61-116, May 1961. The contract number was AF33(616)-3903.

[33] Ibid.

[34] Comments from Ed Dubois at David Clark Company on a draft version of this manuscript, June 2010.

[35] "Development of a Full-Pressure Suit System."

[36] A. Scott Crossfield, *Always Another Dawn: The Story of a Rocket Test Pilot* (Cleveland, OH: World Publishing Co., 1960), quote on p. 239.

[37] "Pilot Protection for the X-15 Airplane."

[38] "Development of a Full-Pressure Suit System." At rest, the human hand tends to be in a semi-closed position as the muscles relax. The kangaroo leather boots eventually gave way to standard Hyde Athletic Shoe Company Model Z100 flying boots that were modified to interface with the pressure suit.

[39] "Development of a Full-Pressure Suit System;" conversation with Joe Ruseckas at David Clark Company, March 2009 and February 2010.

[40] "Development of a Full-Pressure Suit System."

[41] "Development of a Full-pressure Suit System." Between September 18 and November 26, the S794-3C suit spent 66 hours and 40 minutes pressurized without failure at David Clark Company, Firewel Company, North American, and Wright Field.

[42] "Development of a Full-Pressure Suit System."

[43] Ibid.

[44] X-15 WSPO Weekly Activity Report, October 30, 1957; "Full-Pressure Suit Assembly," Physiology Branch, Aero Medical Laboratory, WADC, 1 January 1958; memorandum, G. Kitzes, Assistant Chief, Physiology Branch, Aero Medical Laboratory, WADC, to Chief, Fighter Aircraft Division, ARDC, subject: Status of MC-2 Full-Pressure Altitude Suits for the X-15 Research Aircraft, April 10, 1958.

[45] Interview of Capt. Jerry E. Schaub X-15 WSPO, Director of Systems Management, ARDC, May 28, 1959, by Robert S. Houston, History Branch, WADC. Written transcript in the files at the AFMC History Office. X-15 WSPO Weekly Activity Report, May 2, 1958.

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[48] Memorandum, Lt. Jerry E. Schaub, X-15 WSPO, to Chief, Aero Medical Laboratory, WADC, August 19, 1958, subject: X-15 Full-pressure Suit Program. In the files at the AFMC History Office; X-15 WSPO Weekly Activity Report, September 5, 1958, and November 7, 1958; Lt. Col. Burt Rowen, "Human-Factors Support of the X-15 Program," *Air University Quarterly Review,* Air War College, Vol. X, No. 4, Winter 1958-59.

[49] R.G. Bartlett, Jr., "A Study of CO_2 Build-Up With a Neck Seal Substituted for the Face Seal in the Full-pressure Suit Helmet," *Aerospace Medicine*, January 1963.

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[53] Vail and Willis, "Pilot Protection for the X-15 Airplane."

[54] Ibid. How the MC-2 was pressurized in the X-15 was slightly different than MC-2 suits used in other aircraft.

55 X-15 WSPO Weekly Activity Report, November 21 and December 5, 1958, and January 9, January 30, and April 3, 1959; memorandum, Col. F. A. Holm to Chief, Programs and Evaluations Office, ARDC Inspector General, February 13, 1958. In the files at the AFMC History Office; "Biomedical Monitoring of the X-15 Program."

56 Minutes of Meeting, X-15 Human Factors Subcommittee, December 30, 1960.

57 "Biomedical Aspects of the X-15 Program, 1959-1964."

58 Joseph A. Ruseckas, "Development of Flying Outfit, Full-Pressure, High Altitude, Type A/P22S-2," Technical Documentary Report No. ASD-TR-61-469, March 1962. This was contract AF33(600)-36525.

59 Ibid.

60 Ibid; conversation with Joe Ruseckas at David Clark Company, February 2010.

61 "Development of Flying Outfit, Full-pressure, High Altitude, Type A/P22S-2."

62 Email from Jewel M. Melvin, Air Force Materiel Command, 576 ACSS, Robins AFB, February 17, 2010.

63 Letter, Maj. Robert C. Roth, Chief Life Support Systems Branch, to Distribution, Subject: Full-pressure Suit Systems Management, not dated but approximately June 1970; conversation with Jack Bassick at David Clark Company, March 16, 2009.

64 Letter, Maj. Robert C. Roth, Chief Life Support Systems Branch, to Distribution, Subject: Full-Pressure Suit Systems Management, not dated but approximately June 1970.

65 Email from Jewel M. Melvin, Air Force Materiel Command, 576 ACSS, Robins AFB, February 17, 2010.

66 Emails from Jewel M. Melvin, Air Force Materiel Command, 576 ACSS, Robins AFB, February 17, 2010, and February 23, 2010.

67 Ibid; conversation with Joe Ruseckas at David Clark Company, February 2010. David Clark Company still has the original Mark II helmet they used as a model.

68 "Development of Flying Outfit, Full-Pressure, High Altitude, Type A/P22S-2."

69 Ibid. Weatherbar was a commercially available material manufactured by Duplan of Canada, Ltd. David Clark Company used Hunter Yellow and Indian Orange.

70 X-15 Status Reports, Paul F. Bikle/FRC to H. Brown/NASA Headquarters, July 15, 1960; July 29, 1960; and April 3, 1961. In the files at the DFRC History Office; Lt. Col. Burt Rowen, Maj. Ralph N. Richardson, and Garrison P. Layton, Jr., "Bioastronautics Support of the X-15 Program," a paper in the *Research Airplane Committee Report on the Conference on the Progress of the X-15 Project*, A Compilation of the Papers presented at the Flight Research Center, 20-21 November 1961. A slightly expanded version of this paper was subsequently republished as AFFTC Technical Report FTC-TDR-61-61, "Bioastronautics Support of the X-15 Program," December 1961.

71 Kent W. Gillespie, "Outfit, Flying, Full-Pressure, High Altitude, Type A/P22S-2," AFSC Functional Evaluation Report No. ASNRSE-61-1, June 2, 1961.

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73 Ibid.

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76 "Outfit, Flying, Full-pressure, High Altitude, Type A/P22S-2;" "Development of Flying Outfit, Full-Pressure, High Altitude, Type A/P22S-2."

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82 Capt. Budd F. Knapp, "A/P22S-2 Full-Pressure Suit Evaluation in the U-2," Air Force Flight Test Center, 1962.

83 Ibid.

84 Ibid.

85 Ibid.

86 Kent W. Gillespie, "Comparative Evaluation of USAF Standard A/P22S-2 and Improved A/P22S-2A High Altitude, Full-Pressure Flying Outfits," Technical Report SEG-TR-65-9, April 1965.

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88 "Comparative Evaluation of USAF Standard A/P22S-2 and Improved A/P22S-2A High Altitude, Full-Pressure Flying Outfits."

89 Conversation with Jack Bassick at David Clark Company, March 16, 2009, and email from Jack Bassick on February 23, 2010.

90 Ibid.

91 Maj. Edward W. Kenny and Capt. Robert I. Platenberg, "Operational Report on the High Altitude, Full-Pressure Flying Outfit A/P22S-2," February 25, 1963.

92 Ibid.

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94 Supplemental Test Order, High Altitude and Supersonic Personal Protective Equipment, TAC Test No. 63-31A, not dated.

95 Ibid; Letter, Joe Ruseckas to John Flagg, Subject: TAC Test No. 63-31A Trip Report, MacDill AFB, FL, July 16–17, 1963.

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97 Kent W. Gillespie, "Comparative Evaluation of USAF Standard A/P22S-2 and Improved A/P22S-2A High Altitude, Full-Pressure Flying Outfits: Supplement 1, A/P22S-2A (Mod 1)," Technical Report SEG-TR-65-9, Supplement 1, April 1966.

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101 Ibid.

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104 E-mail from Dennis Gilliam, pressure suit historian, to Dennis R. Jenkins, February 23, 2010.

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109 Ibid.

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112 Ibid.; "The Design Requirements, Description, and Functional Operation of the A/P22S-4 and A/P22S-6 High Altitude, Flying Suits."

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[116] Kent W. Gillespie and John R. Hochwalt, "The Design Requirements, Description, and Functional Operation of the A/P22S-4 and A/P22S-6 High Altitude, Flying Suits," ASD-TR-70-58, April 1971.

[117] Ibid.

[118] Conversation with Bob Banks and Ed Dubois at David Clark Company, February 2010; Production numbers provided by Bob Banks and Ed Dubois at David Clark Company, May 2010. It is likely the suits were used in the McDonnell Douglas F-4E Phantom IIs operated by the RAAF while awaiting delivery of their General Dynamics F-111Cs (most Reports indicate the F-111Cs, like most F-111s except the D-models, were not equipped for full-pressure suits).

[119] E-mail from Jewel M. Melvin, Air Force Materiel Command, 576 ACSS, Robins AFB, February 17, 2010; "The Design Requirements, Description, and Functional Operation of the A/P22S-4 and A/P22S-6 High Altitude, Flying Suits."

[120] "The Design Requirements, Description, and Functional Operation of the A/P22S-4 and A/P22S-6 High Altitude, Flying Suits."

[121] "A Brief History of the B-57 Canberra," located at h*ttp://jsc-aircraft-ops.jsc.nasa.gov/wb57/history.html*.

[122] Ibid.

[123] "The Design Requirements, Description, and Functional Operation of the A/P22S-4 and A/P22S-6 High Altitude, Flying Suits."

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[125] Ibid. The contract was F33657-68C-0833.

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[127] Reymond H. Middleton, Milton Alexander, and Kent W. Gillespie, "Cockpit Compatibility Studies Conducted with Aircrewmembers Wearing High Altitude Flying Outfits in B-57D, B-57F, F-104A, F-104B, F-106A, and F-106B Aircraft," Report ASD-TR-70-25, December 1970.

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141 Ibid.

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144 “Prototype High Altitude Flying Outfit,” David Clark Company Technical Report DCC-263-TNR, December 12, 1978.

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146 “Prototype High Altitude Flying Outfit.”

147 “Prototype High Altitude Flying Outfit;” “Prototype High Altitude Flying Outfit—Phase I.”

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151 Ibid.

CHAPTER 7

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24 The test location was, of course, Groom Lake in southwest Nevada, some 83 miles north-northwest of Las Vegas. The base lies within the Nevada Test and Training Range and was originally marked on most aeronautical charts as Restricted Area 51. Other names used for the facility include Dreamland, Paradise Ranch, The Ranch, Home Base, Watertown Strip, and most recently Homey Airport.

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27 E-mail, Ken Collins to Dennis R. Jenkins, February 23, 2010; conversations with Jack Bassick and Bob Banks at David Clark Company, February 2010.

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31 "OXCART A-12 Aircraft Experience Data and Systems Reliability," CIA Directorate of Science & Technology, Office of Special Activities, Report BYE-8725-68, January 15, 1968; comments by Jack Bassick to a draft copy of this manuscript. Bill Park had the distinction of ejecting from 2 Blackbirds, A-12 Article 133 (60-6939) on July 9, 1964, and M-21 Article 135 (60-6941) on July 30, 1966. In addition to these ejections wearing suits, Ken Collins had ejected from Article 123 without a suit, and Bill Park and Ray Torrick had ejected from the M-21, with Torrick drowning after landing.

32 Brig. Gen. Paul N. Bacalis, "Program Progress Report," April 1, 1967–June 30, 1967, document BYE-2511-67, July 31, 1967.

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34 Ibid.

35 Conversation with Jack Bassick at David Clark Company, March 16, 2009 and Joe Ruseckas at David Clark Company, February 2010.

36 Ibid.

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42 Joe Ruseckas, "Technical Proposal for the S901J Pilots Protective Assembly," February 8, 1965; "Purchase Specification: Pilots Protective Assembly GN-S901J," November 29, 1966.

43 Conversations with Jack Bassick and Bob Banks at the David Clark Company, February 2010.

44 Joe Ruseckas, "Technical Proposal for the S901J Pilots Protective Assembly," February 8, 1965; David Clark Company model number listing provided by Jack Bassick.

45 "Operations and Maintenance Instructions with Illustrated Parts Breakdown: S901J Pilots Protective Assembly," technical manual TM14P3-GN:S901J:6-2.

46 Ibid. The "hose-excess" pocket is where suit technicians secure any extra length of oxygen hose to keep it from becoming entangled in the cockpit environment.

47 Ibid.

48 "Purchase Specification: Pilots Protective Assembly GN-S901J," November 29, 1966; comments from Jack Bassick on a draft version of this manuscript.

49 David Clark Company model number listing provided by Jack Bassick; Kent W. Gillespie and John R. Hochwalt, "The Design Requirements, Description, and Functional Operation of the A/P22S-4 and A/P22S-6 High Altitude, Flying Suits," ASD-TR-70-58, April 1971.

50 "Operations and Maintenance Instructions with Illustrated Parts Breakdown: S901J Pilots Protective Assembly;" "Purchase Specification: Pilots Protective Assembly GN-S901J," November 29, 1966; comments from Jack Bassick on a draft version of this manuscript.

51 "Technical Proposal for the S901J Pilots Protective Assembly;" "The Design Requirements, Description, and Functional Operation of the A/P22S-4 and A/P22S-6 High Altitude, Flying Suits."

52 "S1034E PPA Helmet Engineering Development and Qualification: Final Report," David Clark Company Report DCR-3453, October 2006.

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54 "Purchase Specification: Pilots Protective Assembly GN-S901J."

55 "Operations and Maintenance Instructions with Illustrated Parts Breakdown: S901J Pilots Protective Assembly." Pittsburgh Plate Glass Company (PPG) has long been a leader in the development of glass and paints.

56 "Purchase Specification: Pilots Protective Assembly GN-S901J."

57 OEP-23, Attachment 2, U-2R Addendum. Not dated; email, Malcom V. "Mike" Todd to Dennis R. Jenkins, February 18, 2010.

58 Brig. Gen. Paul N. Bacalis, "Program Progress Report," April 1, 1967–June 30, 1967, document BYE-2511-67, July 31, 1967.

59 "S1034 Pilots Protective Assembly, Development & Qualification Final Report," David Clark Company Report DCR-3124-00, February 28, 1992.

60 "S1034E PPA Helmet Engineering Development and Qualification: Final Report," David Clark Company Report DCR-3453, October 2006.

61 "Operations and Maintenance Instructions with Illustrated Parts Breakdown: S1010A Pilots Protective Assembly," technical manual TM14P3-GNS1010A-2; Conversations with Jack Bassick, Bob Banks, and Ed Dubois at David Clark Company, February 2010.

62 Conversations with Jack Bassick, Bob Banks, and Ed Dubois at David Clark Company, February 2010; Production numbers provided by Bob Banks and Ed Dubois at David Clark Company, May 2010.

63 "S1034E PPA Helmet Engineering Development and Qualification: Final Report."

64 "S1034 Pilots Protective Assembly, Development & Qualification Final Report," David Clark Company Report DCR-3124-00, February 28, 1992; "Operations and Maintenance Instructions with Illustrated Parts breakdown, Pilots Protective Assembly, GNS1030," technical manual TM14P3-GN:S1030-2, May 1, 1979.

65 Donn A. Byrnes and Kenneth D. Hurley, *Blackbird Rising: Birth of an Aviation Legend* (Los Lunas, NM: Sage Mesa Publications, 1999).

66 "S1034E PPA Helmet Engineering Development and Qualification: Final Report."

67 Production numbers provided by Bob Banks and Ed Dubois at David Clark Company, May 2010.

68 "S1034 Pilots Protective Assembly, Development & Qualification Final Report."

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71 "S1034E PPA Helmet Engineering Development and Qualification: Final Report."

72 "S1034 Pilots Protective Assembly, Development & Qualification Final Report."

73 "S1034 Pilots Protective Assembly, Development & Qualification Final Report."

74 Production numbers provided by Bob Banks and Ed Dubois at David Clark Company, May 2010.

75 "S1034 Pilots Protective Assembly, Development & Qualification Final Report."

76 Ibid.

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78 Gore-Tex is a waterproof/breathable fabric, and a registered trademark of W.L. Gore & Associates. It was co-invented by Wilbert L. Gore (1912–1986), Rowena Taylor, and Gore's son, Robert W. Gore. Robert Gore was granted U.S. Patent 3,953,566 on April 27, 1976, for a porous form of polytetrafluoroethylene (PTFE) with a micro-structure characterized by nodes interconnected by fibrils. Robert Gore, Rowena Taylor, and Samuel Allen were granted U.S. Patent 4,194,041 on March 18, 1980, for a "waterproof laminate." For its invention, Robert W. Gore was inducted into the National Inventors Hall of Fame in 2006.

79 "S1034 Pilots Protective Assembly, Development & Qualification Final Report."

80 Daniel M. Barry and John W. Bassick, "NASA Space Shuttle Advanced Crew Escape Suit Development," SAE Technical Paper 951545, 25th International Conference on Environmental Systems, July 10–13, 1995.

81 "S1034 Pilots Protective Assembly, Development & Qualification Final Report." The term "vanishing" is standard industry terminology for vendors, often small mom-and-pop shops, that suddenly go out of business or stop making highly specialized parts.

82 "S1034 Pilots Protective Assembly, Development & Qualification Final Report."

83 Ibid comments by Jack Bassick on a draft of this manuscript.

84 "S1034 Pilots Protective Assembly, Development & Qualification Final Report." The contract was F09604-90-C-0006.

85 "S1034 Pilots Protective Assembly, Development & Qualification Final Report." PBI is used extensive in firefighters ensembles. According to the manufacturer, "PBI (polybenzimidazole) stable fiber is an organic fiber that provides thermal stability for a wide range of high temperature applications. PBI fiber will not burn in air, it does not melt or drip, and it will retain its strength and flexibility after exposure to flame." For further details, see *http://www.pbigold.com/en/applications/apparel_fireservice*.

86 "S1034 Pilots Protective Assembly, Development & Qualification Final Report."

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89 The product used by David Clark Company is Serenity by TENA, a division of Svenska Cellulosa Aktiebolaget (SCA); conversation with Jack Bassick, Bob Banks, and Ed Dubois at David Clark Company, February 2010.

90 "S1034 Pilots Protective Assembly, Development & Qualification Final Report."

91 Ibid.

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INDEX

Index

Numbers in bold indicate pages with illustrations or tables

A

A3J (A-5) Vigilante, 230
A6M Zero, 85, 94
A-7 oxygen mask, 429n108
A-8 oxygen mask (Boothby-Lovelace-Bulbulian oxygen masks), 91, 429n108
A-12 (Emerson) demand regulators, 123, 124
A-12 reconnaissance aircraft (Oxcart) accidents in, 312, 315–16, 410
  Article 121, 311
  Article 123, 312, 460n31
  Article 126, 312
  Article 128, 312
  Article 129, 316
  Article 133, 460n31
  black painted surfaces, **311**
  code names, 302, 304, 324
  Convair design, 302
  cost of development and manufacturing of aircraft, 302
  cost of suits for, 308
  David Clark Company suits for, 279
  design and development of, 302
  ejection seats, **304**, 314, 316, 324
  ejections from, 304–5, **304**, 312, 314, 460n31
  engines, 312
  first flight, 311
  fleet size, 312
  Flickinger role in, 153
  Groom Lake, transport to, 311
  Groom Lake testing, **301**, 311, 316, 460n24
  Land panel and development of, 302
  Lockheed design, 302
  loss of aircraft, 316
  low and slow evaluation flight, 312
  M-21 aircraft, ejections from, 315–16, 346, 460n31
  M-21 Article 134, 314
  M-21 Article 135, 314, 315–16, 460n31
  M-21/D-21 aircraft/drone combination, **313**, 314–16, **315**
  M-21 test flight, 324
  North Vietnam operations, revival for, 316
  number of flights and flight time, 314, 316
  operational flights, 312, 314, 316
  oxygen masks, systems, and supply, 302–4
  parachute pack, **303**
  physiological effects and risks, 302
  pilot compensation and insurance arangements, 305
  pilot selection, 305
  R-12 aircraft, reconfiguration as, 322
  range and capabilities, 302, 304–5, 311–12
  regeneration package and return to operations, 316
  retirement and storage of, 311, 316
  S901H as production suit, 310–11
  S901/S901J suit use, 312, 314, 316
  S901 suit development for, 302–6, **303**, **304**, **305**, 308–11, **309**, **310**, 312, 314
  speed of, 302, 311–12
  SR-71 as replacement for, 316
  suit performance requirements, vi, 302, 303–5
  test flights, 311–12, 323
  titanium construction and finish, **301**, 329
  Titanium Goose trainer, 312
  U-2 aircraft compared to, 302
  See also YF-12A/AF-12 interceptor aircraft
A-13 pressure-breathing mask, 123–24, 127, 130, 132
A-14A regulators, 124
A-14 oxygen masks, 57, 91, 429n108
A-24/SDB-3A Dauntless, 103
A-28 Hudson, 68
Abbott, Ira H., 205
abdominal support
  anti-G straining maneuvers, x, 73–74, 94, 113–14, 115
  G-suits, x
  Hook Maneuver, 113
  Poppen Belt, 81, **82**

Abel, Rudolf (Vilyam Genrikhovich Fisher), 156
acceleration
  blood pressure and, 43, 73
  centrifuge for study of effects, 74–80, **75**, 77, **78**, **79**
  fighter aircraft, air combat maneuvers, and, 113–14
  G-loads (Gz) and, 43, 72–74, **72**, 80–83, **81**, 424n10
  lateral (Gy), **72**, 73
  measures of, 72–73
  physiological effects and risks, 72–74, **72**, 80–83, **81**, 425n15
  research on effects, 80–83
  transverse (Gx), **72**, 73
  vision and, 43, 73, 80, **81**, 425n15
Acurex Corporation, Aerotherm Division, 373–74
Adam, Maurice James, 41, 419n80
Adam Aircraft A700 prototype, 464n93
Adams, Harold "Buck," **330**
Adams, Michael J., 278
ADC. *See* Air Defense Command (ADC)
Advanced Crew Escape Suits. *See* S1035 Advanced Crew Escape Suit (ACES)
Advanced Technology Anti-G Suit (ATAGS), 112–13, 116–18, 119
aeromedical and physiological research, 41–43, 81, 89–92
Aero Medical Equipment Laboratory (AMEL), 206, 209
Aero Medical Laboratory, Wright Field
  Acceleration Unit, 77
  Benson and research at, 43
  counter-pressure clothing, research on, 124
  CSU-2/P suits, 165–67
  CSU-4/P suits, 169, 171
  face seals versus neck seals, 258–59
  full-pressure suit development, 216, 237, 239–41
  funding for suits, 258
  G-suit development, 95, 97
  latex rubber suit testing, 242–43
  Lovelace research at, 91
  MB-1 suit development and testing, 141, 144, 145, 146
  MC-2 suit testing, **252**, 253–56, 453n41
  MC-3 suit development, 147–48
  Mercury program suits, research on, 233
  Model H suit testing, 240–41
  name of, 425n24, 437n20
  Omni-Environment Suit testing, 184, 237, 239
  pressure-breathing masks, development of, 123–24
  pressure-breathing research, 122, 123, 124
  pressure-suit research, 45, 49, 50–51, 52, 53–54, 56, 68
  sizing of flying suits, 134, 136
  T-1 suit testing, 136
  test subjects, 145
  USAF suits, development of, 216
  USC laboratory, relationship with, 125
  X-15 program suits, 244–46
  XMC-2-DC suit testing, **248**, **249**, 252–53
Aeromedical Museum, Brooks Air Force Base, 417n37
Aeromedical Research Unit, Wright Field, 43, 97, 425n24
Aero Medical Unit, Mayo Clinic, 90–91, 437n20
Aeronautical Systems Command, 286
Aeronautical Systems Division, Wright-Patterson Air Force Base, 262, 266, 267, 295–96, 299
Aerospace Medical Division, 425n24
Aerospace Medical Laboratory, 425n24
Aerospace Medical Research Laboratory and Systems Engineering Group, 6570th, 283
Aerospace Protective Technology project (Project 7164), 293–95
Aerospace Research Pilots School (Test Pilot School), 265, 278
Aerotec Company, 217
Aerotech Industry Corporation, 110
Aerotherm Division, Acurex Corporation, 373
aether, 16, 413n6
AF-12 interceptor. *See* YF-12A/AF-12 interceptor aircraft
AFFTC. *See* Air Force Flight Test Center (AFFTC)
AIC-10 communications system, 139, 228, 274
AIM-47 (GAR-9/GAR-X) Falcon missiles, **307**, 308, 378
air, weight of, 16, 17
air-conditioning equipment
  conditioned air supply equipment (CASE), 224, 226
  crew vans, **349**
  portable, 225–26, **225**, **275**, **294**
  RAAF air-conditioned vans, 84
  readyrooms, air-conditioned, 224, 226
  suiting-up van, **227**
  TAC Trucks, 226
aircraft
  advances in and pressure suit requirements, 121, 237, **238**, 239, 243
  artificial horizon instruments, 80–81
  cockpits, pressurized, 121, 259, 377–78
  manufacturers of, 362
  piston-powered aircraft, 142, 237, 301
  pressurized cabin, first, 237
  prohibition of jumping from, 26
  Round One X-planes, 244
  Round Two X-planes, 244
  standardization of suit designs for, 105–6, 109–10, 135, 258
  See also engines
aircraft carriers
  conditioned air supply equipment (CASE) for readyroom, 224

dressing rooms, 225
Forestall-class carriers, 224–25
readyrooms to accommodate pressure suits, 224
Aircraft Sustainment Squadron, 576th, 330th Aircraft Sustainment Wing, 363
Air Defense Command (ADC)
A/P22S-2 suit testing and use, 272, 273–74, 279–83, **281**
A/P22S-3 suit testing and use, 272, 279–82, **281**
A/P22S-4 suit testing, 284
bases of, 274
CSU-4/P suit testing and use, 171, 279–82, **281**
CSU-5/P suit testing and use, 279–82, **281**
full-pressure suit use, 264, 284, 286
interceptor aircraft, 146, 147, **147**, 239–40, **239**
MB-1 suits, 146–47
MB-2 suits, 147
MC-3/3A suits, 156, 240
MC-4/4A suits, 240
Physiological Training Unit, 264
pressure suit requirements, 239–40
S-2 suits, 147
Air Force, U.S. (USAF)
Advanced Technology Anti-G Suit (ATAGS), 112–13, 116–18, 119
air missions, 301
A/P22S-2 suit use, 262
contracts for G-suits, 108–9
creation of, 416n16
crew vans, **349**
depot for suit maintenance, testing, and logistical support, 264
designation system for suits, 262, 362, 430n123
Excelsior, Project, 162–65, **163**, **164**, 269
full-pressure suits, comparison of, **329**
full-pressure suit use, 286, 293, 362
G-suits, postwar, 109–10
HGU-15/P helmet use, 378, 380
Libelle G-Multiplus G-suit testing, 115
Life Support Special Project Office (LSPRO), 265
lineage of, 416n16
MANHIGH, Project, 161–62, 165
Mark IV pressure suit testing, 274
Military Assistance Program, 161
partial-pressure suits, development of, 205
patches on pilot's suits, **277**
pilot protective clothing, conference on, 103
pressure suit development, 68, 205, 216, 237, 239–41
pressure suit requirements, 240, 289, 293, 294, 299
reconnaissance programs, competition between, 316
S-100 partial-pressure suit use, 318, 319, 322
School of Aerospace Medicine. *See* School of Aerospace Medicine (Air Force)
sizing of flying suits, 134, 136, 360
SR-71 aircraft, transfer of, 155
standardized full-pressure suits, 277, 282–83
Stargazer, Project, 165, **166**
Tactical Life Support System program, 112
U-2 aircraft pilots, 153
windblast evaluation of suits, 411
X-1 rocket plane program, ix
X-15 program, ix
See also Army/Army Air Corps, U.S.
Air Force Aerospace Medical Research Laboratory, 425n24
Air Force Flight Test Center (AFFTC)
CSU-4/P partial-pressure suit, 171
depot for suit maintenance, testing, and logistical support, 265
F-16/PBG G-suit development, 110
full-pressure suit use, 264
patches on pilots' suits, **277**
Yeager, pressure suit use by, 134
Air Force Museum, 293
Air Force Production Flight Test Facility (Air Force Plant 42), 323–24, 358–59, 361
Air Launched Sounding Rocket (ALSOR), **229**
Air-Lock neck rings, 306
Air Logistics Command, 295
air races, 28, 29, 72
Air Research and Development Command, 147, 153, 156, 216, 239
airsickness, 43
A.J. Sawyer Company, 225
Akerman, John D.
BABM suits, 46–47, **48**, 51–52, **51**, 53, 55, **59**, 62–63, **64**, 179
counter-pressure vest development, 123
education and career, 46
Model 7 full-pressure suit, 179–81, **179**, **180**
pressure suit development, 46, 51
Type 7 pressure suit, 50–51
Alexander, Milton, 158, 167
Allen, Edmund T. "Eddie," 46, 97
Allen, James T., 464n93
Allen, Peter, 86
Allen, Samuel, 463n78
Allen, Shannon, 126
Allison Division, General Motors, 140–41
All-Weather Climatic Laboratory, Eglin Air Force Base, 281–82

ALSOR (Air Launched Sounding Rocket), **229**
altitude
  aeromedical and physiological research, 41–43
  aircraft performance increases and, 237, 238, 239
  air pressure and weight and, 17
  Armstrong Line, xi, 22, 75
  atmospheric data by, **19**
  atmospheric pressure and, 20
  engine performance and, 142, 237
  oxygen, altitude, and physiological impairment, 20, 21, 22–23, 41–43, 122
  oxygen requirements for consciousness, 21
  partial pressure of gases and, 21
  pressure breathing for altitude (PBA), 113
  speed of flight and, 29
  suit performance requirements, vi
  temperature and, 18, 19, 20, 23, 25
  time of useful consciousness and, 19, 22
altitude chambers
  BABM suit testing, 56, **59**
  Brooks AFB, 112
  Douglas Aircraft, **199**, **200**, 201–2, 204, 211
  Harvard University, 75
  Mayo Clinic chamber, 51–52, 55, 181
  McDonnell Aircraft Company, **225**
  Medical Research Laboratory/School of Aviation Medicine, 42
  NACEL chamber, 179
  Navy chamber, 61, 63, 66
  Post pressure suit testing, 28, 31, 33–34
  Ridge pressure suit testing, 27
  USC chamber, 128
  Wright Field chamber, 28, 31, 57, **61**, 68, 124, 155, 17n37
Altitude Protective Garment (APG), 173–74
altitude suits, ix
AMAL (Aviation Medical Acceleration Laboratory) 230–31
AMEL (Aero Medical Equipment Laboratory), 206, 209
Ames Research Center, 154, **321**, 371–72, 373
AN/ASG-18 fire control system, 308
Andonian, Harry, 271
anesthesia apparatus, development of, 91
Angel, 150, 459n1. *See also* U-2 spy plane "Dragon Lady"
animal research, 128
Antietam, 232
Anti-G Control Valve (AGCV), 376
anti-G straining maneuvers, x, 73–74, 94, 113–14, 115
anti-G suits. *See* G-suits/anti-G suits
anti-suffocation feature, xii, 267, 299, 310, 319, 334, 361, 395
Antonelli, Tony, **404**
AOH-1 (Aviator Oxygen Helmet), 378
A/P22P-16 COMBAT EDGE ensemble, 114
A/P22S-1 full-pressure suit, 262
A/P22S-2 full-pressure suit
  ADC testing and use, 272, 273–74, 279–83, **281**
  Air Force suits, comparison of, **329**
  A/P22S-2A (Mod 1) version, 274, 276–77, 283, 284
  A/P22S-2A version, 274, 277, 283, 284
  approval of by USAF, 267
  back kits, 273, 277
  biomedical data collection, 268
  boots, 263, 266, **273**, **276**, **277**
  colors of exterior covers, **276**, **277**, 454n69
  comfort of, 272, 273, **278**, 280
  communications, 274
  custom fitting of, 277–78
  designation system for suits, 262
  development and specifications, **140**, 173, 262–63, 266–67, **268**
  distribution and use of, **140**, 262, 270–71, 277–78, 282–83
  donning and doffing, 268, 271, 272, 278–79, 280, 283
  ensemble components, 268, **268**
  exterior covers, 263, 267, **276**, 277, **277**, 454n69
  F-102 testing and use, **271**, 279–81, **281**, 283
  F-104/104B testing and use, 289–90
  F-106/F-106B testing and use, 267, **271**, 272, 273–74, 289–90
  fabrics and materials, 263, 267, 454n69
  face seals, 259, 266, 268, 269, 283
  gloves, 263, 266, 267, 268, 269, 272, 273, 274, 276–77, 278–79, 280
  Haderlie accident, 278–79
  helmets, 263, 266, 267, 268, 269, 272, 274
  improvements to design, 268
  interceptor aircraft use, **271**, 272, 273–74
  Israeli Defense Forces use, 295
  lifting body program use, **275**, **276**, 277, **277**
  Link-Net fabric use, 263, 269
  MAC/WB-57F pilots' evaluation of, 286–87
  model numbers of suits, 277
  neck ring, 263
  number of suits produced, 270–71, 279
  oxygen masks, systems, and supply, 266, 271, 272
  parachutes, **271**, **273**
  restraint layer, 263, 266, 269
  rocket-sled evaluations, 267
  rotating wrist bearings, 277, 456n68
  S906 suits, 268–69, 277

S926/S926A suits, 268, 277
S931 suit, 272
S931 suits, 277
S934 suits, 277
S935 suit, 277
S935 suits, 277
S940 suits, 268–69, 277
S963 suits, 277
S971 suits, 277, 310
S998 suits, 277
S1027 suits, 277–78
S1034 suit, 277
seat kits, **271**, **273**, 277
service-life expiration, 279
sizing of, 268–69
suit controllers, **268**, 272, 276, 283
TAC testing and use of, 274
testing of, 266–67
U-2 program use, 271–72, 317
underwear, 263, 283
ventilation garments, 263
visors, 266, 269, 276, 277, 283
WB-57F program testing and use, 286, 287, 289–90
weight of, 266, 274
wrist rings, 277
X-15 program suits, 267, 268–69, 273, 277–78, **278**
zippers and fasteners, 173, 263, 266, **266**, 267, 268, **268**, 269, 272, 274, 283, **285**, **305**
A/P22S-3 full-pressure suit
ADC testing and use, 272, 279–82, **281**
depot for maintenance, testing, and logistical support, 264
designation system for suits, 262
development and specifications, 279
gloves, **280**
Goodrich as manufacturer, 279
modified Mark IV pressure suits, 233, 272, 279, 280, **280**
neck ring, 282
TAC use, 274
underwear, 282
A/P22S-4 full-pressure suit
Air Force suits, comparison of, **329**
color of, 286
designation system for suits, 262
development and specifications, 279, 283, 287
distribution and use of, 284, 286
ensemble components, 286
exterior covers, 284
gloves, 284, 286
helmets, 284, 286
Link-Net fabric, 283, 284
neck ring, 284
number of suits produced, 286
oxygen masks, systems, and supply, 284
pocket locations, 284
restraint layer, 283–84
S901J suit compared to, 287
sizing of, 287
wrist rings, 278–79, 283, 284
zippers and fasteners, 283
A/P22S-6/6A full-pressure suit
Air Force suits, comparison of, **329**
A/P22S-6A version, 290–91, **291**
boots, 289, 290, **294**
colors of, 290, **294**
comfort liner, 290
designation system for suits, 262
development and specifications, 173, 287, 290–91
distribution and use of, 291–93, **292**
ensemble components, 289, 290
exterior covers, 290
F-15/F-15A/F-15B testing and use, 176, 291–93, **292**
F-102 use, 291
F-104/104B testing and use, 289–90, 291
F-106/F-106B testing and use, 289–90, 291
face seals, 290
gloves, 289, 290, **294**
helmets, 289, 290, **291**, 317–19, **318**, **319**, 361
Israeli Defense Forces use, **288**, 289, 295
MAC requirements, 287
number of suits produced, 286, 287, 291, 457n124
oxygen masks and systems, 290, 361
replacement of, 361
replacement of for USAF use, 295, 299
S901J suit, similarities to, 287
service-life expiration, 295
shipping containers, 289
sizing of, 287
suit controllers, 291
testing of, 176
underwear, 290
urine-collection system, 290, 311
visors, **289**
WB-57F program testing and use, 287, 289–90, **289**, 291, 293, **294**
wrist rings, 284
XB-70/XB-70A use, 291
A/P22S designation system, 262
APG (Altitude Protective Garment), 173–74
Apollo program
A7L/A7LB suit, 369, 371, 372

capsule for, 365
centrifuge for pilot training, **78**, 80
gloves, 296
ILC suits, **232**, 246, 296, 362, 367, 369, 371, 372
Approach and Landing Test flights, 374–75
Aquatone project, 150. *See also* U-2 spy plane "Dragon Lady"
Archangel, 302, 459n1. *See also* A-12 reconnaissance aircraft (Oxcart)
Area 51 (Restricted Area 51), vii, 150, 460n24
argon, **18**
Aristotle, 15, 16, 413n4
Arlauskas, Rose, 103, 242
Armstrong, Harry George
animal research by, 128
British high-altitude flights, survey of, 45
education and career of, 42, 74–75
physiological effects and risks, research on, 42–43, 74–75
protective equipment, development and testing of, 45, 57, 75, 77, 81
recognition for contributions of, 90
Armstrong, Neil A., 259, **260**, 382
Armstrong Line, xi, 22, 75
Army Air Service, U.S.
Clark-Dreyer Oxygen System, 41–42
operational period for, 416n16
Ridge pressure suit, 27–28
Army/Army Air Corps, U.S.
air missions, 301
BABM suits, 46–47, **48**, 49–50, **49**, 51–52, **51**, 53, 55, 56, **58**, **59**
Bell pressure suit, 46
Berger Brothers G-suit use, 94, 95, 431n132
cost of pressure suits, **44**, 45, 47, 49, 52, 57
David Clark cutaway suit use, 105, 106
designation system for suits, 44, 430n123
G-2 G-suit, 104
Goodrich suits, 43–44, 45–46, 47, 51, 52–53, 54, 56–57, 60, 68
Goodyear suits, 43, 44, 47, 52–55, 60, 68, 420n102
G-suit development, 43–44
MX projects.
See MX research and development projects
National Carbon Company suits, 44, 50–51
operational period for, 416n16
Post pressure suit, 31–32, 43
pressure suit development, 237, 362
pressure suit development, coordination of research for, 52–53
pressure suit development, failure of, 68, 69
pressure suit requirements, 44
U.S. Rubber suits, 43–45, 49, 52–53, 54, 420n90
Army Signal Corps Medical Research Laboratory, 31, 41–42. *See also* School of Aviation Medicine (Army)
Arnold, Henry H. "Hap," 45
ARO Corporation/ARO Equipment Company, 124, 154
around-the-world flights, 29, 416n25
Arrowhead Products Division, Federal-Mogul-Bower
Arrowhead AE-83 suit (Mark IV suits), **227**, 230–31, 279
Garment, Upper Hollywood (GUH), 227
garment, upper stratosphere (GUS) Mark III suit, 222, 226–27
pressure suit development by, 362
Arterial Occlusion Suit (AOS), 100, 101–2, **101**, 103
artificial horizon instruments, 80–81
ATAGS (Advanced Technology Anti-G Suit), 112–13, 116–18, 119
Atlantis (OV-104), 384
Atlantis Warrior program, 114
atmosphere
altitude and atmospheric data, **19**
atmospheric pressure, 16–17, 19, 20–22
definition of, 18
percentages of atmospheric gases, **18**
purpose of, 18
Strato-Lab project to study, 231–33
structure of, 18–20
Austin, F.H., Jr., 224
Australia
G-suit development, x, 89
MacRobertson Race, 29, 33, 417n28, 418n43
University of Sydney centrifuge, 75, **75**, 84
See also Royal Australian Air Force (RAAF)
Australian National Health and Medical Research Council, 75
Autoflug GmbH, 115
Autoflug Libelle GmbH, 115
Aviation Medical Acceleration Laboratory (AMAL), 230–31
aviator bends (decompression sickness), xi, 21, 22, 23, 26, 132, 141
Aviator Oxygen Helmet (AOH-1), 378
Avro (A.V. Roe of Canada, Ltd.), 141

B

B-8 goggles, 127, 130
B-12 constant-flow oxygen mask, 62
B-17/B-17E/B-17F Flying Fortress
BABM suit design for, 46

BABM suit testing, 47
physiological research flight, 427n58
pressure-breathing-mask research, 124
pressure suit development for, 46, 47
range, capabilities, and pressure suit requirements, **55**
XH suit testing, 54, 55–56, 57, 60
B-29 Superfortress
B-29 (P2B-1S) carrier aircraft, 198, **202**, 206, 209
pressurized cabin, 237
range, capabilities, and pressure suit requirements, 47
reconnaissance missions, 149
Tupolev Tu-4 bomber aircraft, 146–47
B-36 bombers
bends incident, 141
crews as test subjects, 145
descent rates, 135, 144
emergency descent incident, 141
Featherweight program and MC-1 suit, 141–42, 144–46, **144**, 239, 440n89
partial-pressure suit use, 135
range, capabilities, and pressure suit requirements, 135, 141, **142**, 142, 144, 237
RB-36 reconnaissance aircraft, 149, **149**
S-2 partial-pressure suit use, **136**, 141–42, 144
B-45 aircraft, 149
B-49 bombers, 135
B-50 aircraft, 149
B-52 Stratofortress
mothership for drone launches, 315
nap-of-earth/low-altitude missions, 286
NB-52 carrier aircraft, 261
pressure suit development for, 216, 240–41
range, capabilities, and pressure suit requirements, 142, 147–48, **148**, 239
shirtsleeve environments, 156
B-57/RB-57 Canberra, 149, 155, 156, 171, 286. *See also* WB-57F aircraft
B-58 Hustler bombers
CSU-4/P partial-pressure suit, 171
escape (ejection) capsule, 156, 213
Goodrich suit testing, 216
pressure suit development for, 216
range, capabilities, and pressure suit requirements, 147–48, **148**, 156, **213**, 239
shirtsleeve environments, 156, 210
XB-58 cockpit mockup, 210, **212**, 216, 240
B-70 bomber, **238**
BABM suits
BABM-3 suit, 47
BABM-5 suit, 51, 55
BABM-7 suit, 51–52
BABM-8/8a suits, 52, 55
BABM-9 suit, 52, 53
BABM-18 suit, **64**, **65**
delivery of to Army, 56, 58
development of, 46–47, 179
fabrics and materials, 62, 68
helmets, 46, 47, 49–50, **49**, 52, **58**, 62, **64**, **65**
Navy testing, 62–63
neck ring, 52, 62
photos of, **48**, **49**, **51**, **58**, **59**, **64**, **65**
back kits
A/P22S-2 full-pressure suit, 273, 277
configurations and purpose, **201**, **203**, 219, **256**, 448n74
Mark III suit, 222
MC-2 suits, **256**, 258, **259**, 262
Model 7 Omni-Environment Suit, **201**, 256
Model 11 suit, **203**
Model 13 suit, 209
S901 full-pressure suit, 310
seat kit use instead of, 258
weight of, 209
X-15 seat kits versus back kits for suits, **256**, 258, **273**, 277
Bagian, James P. "Jim," 396–98, **396**
bailer bar, 331, **339**, **348**, 386
Bailey, Clyde, **131**
Bailey, Kenneth, 103
bailouts. *See* ejections/bailouts
Bald Eagle project, 149
Baldes, Edward J. "E.J."
Cornelius control valve, development of, 102
education and career, 91
G-protection clothing testing, 98–99, 100, 103
Mayo Aero Medical Unit, 90
Mayo centrifuge, 76, 77, 91, 98–99, 126
Baliani, Giovanni Batista, 16
ball-bearing joints, 37, 39, 56, 192–94, **193**, 196, **197**, 205, 206, **207**, 209–10
balloon flights
aeromedical and physiological research, 41
Excelsior, Project, 162–65, **163**, **164**, 269
MANHIGH, Project, 161–62, 165
Piccard flights, 26
Ridge and Haldane-Davis stratosphere flying suit, 27, 28, 30, 40
rocket sled flights, 162
Spanish suit design for, 39–40
Stargazer, Project, 165, **166**
Strato-Lab project, 231–33
Wise and discovery of jetstream, 29

Balloon Hangar centrifuge, 43, 74, 75, 77
Banks, Robert R. "Bob," 274, 312, **398**, 457n118
Banting, Frederick Grant, 76, 86–88, 426n30, 427n67
Barach, Alvan L., 123
Barnes, Jim, **319**
Barnicki, Roger J., 173, 174, 175, 176, 264
barometer, 16–17
Bassett, Bruce, 302
Bassick, Jack
  Anti-G Suit development, 375
  David Clark Company business operations and ethics, 362–63
  David Clark Company career, vii
  David Clark Company ownership and employee-ownership heritage, vii, 273
  low and slow flights, pressure suit use during, 312
  on NASA role in pressure suit development, ix
  PHAFO suit testing, **297**
  rotating bearings, use of, 456n68
  S1034 suit development, 351
Battle aircraft, 87
Bauer, Louis H., 80, 426n44
Baumgartner, Felix, 165
Bazett, Henry C., 123, 124, 127, 174, 175
BDM slide fasteners, 173, 443n161
Beale Air Force Base
  A-12 flight training, 316
  Physiological Support Division, 265, 378
  SR-71 for 9th Strategic Reconnaissance Wing, 324
Beaupre, Francis, 162
Beaupre Multi-Stage Parachute system, 162–65, **163**, **164**
Beeckman, Isaac, 16
Bell Aircraft
  BABM suits, 46–47, 49–50, 51–52, **51**, 53, 56, **58**, **59**, 179. *See also* BABM suits
  pressure suit development and testing, 46, 68
  T-1 and S-2 suit use, 141
Bell Model 67 aircraft, 149–50
bellows and convoluted joints, 45, 51, **51**, 56–57, **57**, 195–96, **197**, **203**, 205, 210, 246
Bell P-39/P-39D Airacobra, 46, **51**, 52
Bell P-59A Airacomet, 107
Bell X-2 aircraft, **138**, 205, 244
Bell X-16 aircraft, 149–50
Bell XS-1 (X-1) aircraft. *See* XS-1 (X-1) rocket-powered aircraft
Bendix Aviation Corporation, Eclipse-Pioneer Division, 198, 202
bends, xi, 21, 22, 23, 26, 132, 141
Benson, Otis O., Jr., 43, 97, 98, 99
Bercovitz, Mr., 443n161
Berger, Darwin Spencer, 92, 105
Berger, George Wendell, 92
Berger, Spencer Merriam, 92, 105
Berger Brothers
  blackout sequence for dive bombing maneuvers, 81
  bladders, 92, 93, **94**, 94, 95, 106
  contracts for G-suits, cancellation of, 106
  CSU-2/P partial-pressure suit, 159, 165–67, 171
  custom fitting of suits, 136, 144
  G-1 suit, 93–95, **95**, 103–4, 431n132
  G-2 suit, 94, 95, 431n132
  G-3 cutaway suits, 105–6
  G-3 suit, 431n132
  gloves, manufacture of, 158
  G-suits, 83, 84, 86, 88, 92–95, **93**, **94**, 97, 99, 100
  Henry Suit, manufacture of, 136
  Mayo Clinic testing of suits, 92–93, 94, 103, 105
  MC-3/3A suits, 156, 157–58
  pneumatic socks, 166–67
  pressure suit development and manufacturing, 362, 363
  pressurizing valves on suits, 95, **95**, 97
  sizing of flying suits, 94, 136, 158, 167
  subsidiaries of, 92
  vacuum pumps to pressurize suits, 93, 95, 102
Berliner-Joyce P-16 aircraft, 42
Bert, Paul, 41
Berti, Gasparo, 16
Best, Charles H., 426n30, 427n67
B.F. Goodrich Company
  advances in suit design and development, 68
  A/P22S-3 full-pressure suit. *See* A/P22S-3 full-pressure suit
  archives of, ix
  Army, pressure suit development for, 43–44, 45–46, 47, 51, 52–53, 54, 56–57, 60, 68
  boots, 47, 51, **218**
  Colley and suit development by, ix, 44, 215. *See also* Colley, Russell S.
  color of pressure garments, 222
  cost of pressure suits, 44, 45, 57
  counter-pressure vests, development of, 123
  de-icing boot development, 32–33
  exhaust-valve system, **226**
  fabrics and materials for suits, 44, 45, 51, 56, 69, **210–11**, 215, 219
  full-pressure suits, development of, 240, 362
  gloves, 217

helmets, 51, **210–11**, **212**, **214**, 217–19, **218**, 222–23, 235
joint designs, 215
Mark I (Model S) suit, 215, **216**, 218–20
Mark II suit, **218**, 220–22, 223, 266, 454n67
Mark III/III-LW suit, **218**, **219**, **221**, 222–27
Mark IV suit. *See* Mark IV pressure suit
Mercury program suits, 233, **234**, 235
Model H suit, **210–11**, **212**, 215–16, 240–41
Model L suit, **214**, 217
Model M suit, 217
Model N suit, 217
Model Q suit, 217
Model R suit, 217–18
Model S (Mark I) suit, 215, **216**, 218–20
movie and magazine features about suits, 68–69, 227
MX-117 project suits, 52, 195, 237
NACEL evaluation of suits, 215–16, 224
Navy, pressure suit testing by, 61–62, 64, 68
oxygen masks and systems, **214**, 216–17, 219, 221, 222–23
Post pressure suit development, 30, 32, 33–34, 417n35
pressure suit development, coordination of research for, 52–53
pressure suit development by, ix, 184
quick fix suits, **234**, 235
spacesuits, full-pressure suits as, 217
suit controllers, 217
Type 3 "Strato-Suit," **44**, 420n89
Type 5/5E "Strato-Suit," **44**, 45–46, 47, 61–62, **62**, **63**
Type 6/6A/6B "Strato-Suit," **44**, 47, 57
Type 8/8A pressure suit, **44**, 47
ventilation, 222, **226**
XH-1/XH-1C pressure suit, **44**, 51, **51**, 54, 56
XH-5 pressure suit (tomato-worm suit), **44**, 56–57, **57**, 60, **60**, **61**, 68, 195
XH-6/XH-6B pressure suit, **44**, 54, 56, **56**
zippers and fasteners, 172–73, 274, 352

Bill Jack helmets, 157, 263

biomedical data collection
A/P22S-2 full-pressure suit, 268
Mayo Clinic centrifuge, 76
MC-2 full-pressure suit, 260
S901 full-pressure suit, 306
S1030A Ejection Escape System suits, 376
S1032 Launch Entry Suit, 395, **400**

Bissell, Richard M., Jr., 302

Blackbird reconnaissance aircraft. *See* SR-71 Blackbird aircraft

Black Shield operations, 314

bladders
air- and gas-filled G-suit bladders, x, 88, 93–94, **94**, 95, **95**
Arterial Occlusion Suit, **101**
Berger Brothers suits, 92, 93, 94, **94**, 95, 106
capstans compared to, 127
COMBAT EDGE, 113, 114
Cornelius control valve, 102, **102**
CSU-4/P partial-pressure suit, 169–70, **170**, **172**, 386
CSU-5/P partial-pressure suit, 172–73
CSU-15/P G-suits, 109
David Clark suits, 99–100, **101**, **103**, 105, 105, 106, 108
G-valve for inflation, 97, 111–12, 113, 176
helmets, rubber bladder for under, **138**
Henry Suit (S-1 partial-pressure suit), 128, 133, 144
jerkin and jerkin-based ensembles, 175
manufacturing of, 93
MC-1 Featherweight suit, 144, 145–46, 154, 155
MC-3/3A partial-pressure suit, 155, **155**
pressure-breathing vest, x
Progressive Arterial Occlusion Suits, 99–100
Retrograde Inflation Anti-G Suit (RIAGS), 118, **118**
S-100 breathing bladder assembly, 319–20
S1032 Launch Entry Suit (LES), **388**
Straightaway garment, 97
Tactical Life Support System, 112
valve immune to variance in source pressure, 99, 101–2
valve modification for turbojet engines, 107
valves for inflation, 95, **95**, 97, 111–12, 113
water-filled G-suit bladders, x, 86–87, 88

Blake, Frank, 214, 215

BLB (Boothby-Lovelace-Bulbulian) oxygen masks, 91, 122, 429n108

blood
hypoxia, xi, 22–23, 41, 43
milking blood up from legs, G-suit design for, 99, 100
oxygenation of, x, 21
oxygen saturation, 122
pooling of in legs, x, 73, 82–83, 123
vacuum and boiling of, 22, 75

blood pressure
acceleration and, 43, 73, 92
arterial pressure, increase, 92
consciousness and, 71, 92
Crile's suit to control, 71
G-suits and abdominal support to control, x
syncope, 145–46
vacuum and boiling of blood, 22, 75

Blood-Pressure in Surgery (Crile), 71
Boeing
BABM suits, 46–47, 55, **58**, **59**, 179
See also BABM suits
pressure suit development and testing, 46, 68
Strato-Lab environmental chamber, 47, **59**
T-1 and S-2 suit use, 141
Tactical Life Support System program, 112
Boeing (McDonnell Douglas) F-15/F-15B Eagle
See F-15/F-15A/F-15B Eagle
Boeing B-17/B-17E/B-17F Flying Fortress
See B-17/B-17E/B-17F Flying Fortress
Boeing B-29 bombers. *See* B-29 Superfortress
Boeing B-52 Stratofortress. *See* B-52 Stratofortress
Boeing F-13 Superfortress, 124
Boeing P2B-1S (B-29) carrier aircraft, 198, **202**, 206, 209
Bohn-Meyer, Marta, **340**
bomber aircraft
blackout sequence for dive bombing maneuvers, **81**, 82
descent rates of, 135
nuclear mission profile, 160
sealed pressure cabins for, 42–43
shirtsleeve environments, 156, 210
Soviets, strategic bombing threat from, 146–47
strategic bombing missions, 142
See also specific aircraft
Boothby, Walter M., 46, 47, 50–51, 90, 91, 123
Boothby-Lovelace-Bulbulian (BLB) oxygen masks, 91, 122, 429n108
boots
A/P22S-2 full-pressure suit, 263, 266, **273**, **276**, **277**
A/P22S-6 full-pressure suit, 289, 290, **294**
BABM suits, **48**
colors of, **276**, **277**
General Electric suits, **67**
Goodrich suits, 47, 51, **218**
Henry Suit (S-1 partial-pressure suit), 128
Mark IV pressure suit, 230, **231**
MC-4/4A partial-pressure suit, **159**
protection provided by, xi
Rocky 911 boots, 401, 402
S901 full-pressure suit, **304**
S901J Pilots Protective Assembly, 329
S1035 Advanced Crew Escape Suit, 401, 402
spurs, **273**
U.S. Rubber suits, 47
XMC-2-DC suits, 252, 452n38
Bosee, Roland A., 209, 227
Bowen, Steve, **404**
Bowen, Tom, 378
Boyle, Joseph, III, 293
Boyle, Robert, 17–18
Boyle's Law, 17–18, 295
Boyle's Law Suit, 293–95
Brand, Vance D., **376**
Branshaw, Charles E., 68
Brauer Knitting Company A48C stretch nylon fabric, 167
B/RB-66 Destroyer, 149, 156
breathing
altitude, consciousness, and oxygen requirements, 21
anti-G straining maneuvers, 73–74, 113–14, 115
automatic suit controllers and, 216–17
COMBAT EDGE and breathing process, 113
compensated metabolism apparatus, 122
exhalation, x, 22, 121, 123
face seals versus neck seals, 258–59
full-pressure suits and breathing process, xi, 21
high-altitude flight and natural breathing process, x, 21–22
lung collapse, 123
oxygen pressure requirements for natural breathing, 20
partial-pressure suits and breathing process, xi, 21
prebreathing requirements, 43, 271, 371, 382
pressure breathing for altitude (PBA), 113
pressure breathing for G (PBG), 113
pressure breathing/positive pressure breathing (PPB), 21–22, 23, 30, 122–24
pressure breathing research at USC, 126
breathing masks. *See* oxygen masks, supply, and systems; pressure-breathing masks
Brett, George H., 45
Bridgeman, William B., 139–40, 167
Briefcase Suit, 369, **369**, 370
Bristol 138a aircraft, 41
British Aircraft Corporation TSR.2 aircraft, 174
Brock, William S. "Billy," 33
Brooks Air Force Base (AFB)/Brooks Field
Aeromedical Museum, 417n37
altitude chamber, 112
Armstrong Laboratory, testing at, 117–18, 119
human centrifuge, 112–13, 396–98
Libelle G-Multiplus G-suit testing, 115
School of Aerospace Medicine. *See* School of Aerospace Medicine (Air Force)
School of Aviation Medicine, 42, 74
TLSS testing, 112–13
training at, 42
Brown, Curtis L., **403**
BT-13A Valiant/SNV-1 trainer, 63
Buckley Field, Colorado Air National Guard Base, 273
Bulbulian, Arthur H., 47, 90, 91

Bunker Hill, 94
Bureau of Aeronautics (BuAer), 97, 189, 205–6, 216, 222, 240
Bureau of Medicine (BuMed), 240
Bureau of Weapons, 225
Burke, Arleigh A., 224
Bush, Vannevar, 89, 125
Byrd, Richard E., 55
Byrd Cloth, 55–56

C

C-1/1A/s1AM partial-pressure suits, 167–68
C-1A G-suit, 157
C-4/4A partial-pressure suit, 157, 168, **169**
C-46 Commando, 135, 153
C-130 Hercules, 305–6
C-141B Starlifter, 384
Cain, Clarence C., 136, 142
caisson disease (decompression sickness), xi, 21, 22, 23, 26, 132, 141
Canada
  crew protection for high-altitude flight, 112
  G-suit development, x, 89
  Sustained Tolerance for Increased G G-trouser, 114
  See also Royal Canadian Air Force (RCAF)
Canadian Defence and Civil Institute of Environmental Medicine (DCIEM), Tactical Life Support System program, 112
Caproni Ca.113 aircraft, 36
Caproni Ca.161 aircraft, 36
CAPS (Crew Altitude Protective System), 386, 393
capstans
  bladders compared to, 127
  concept and function of, x
  double-capstan system, 165–67
  effectiveness of, 126
  G-suits and capstan-controlled counter-pressure, x, 104, 115, 126
  Omni-Environment Suit use to control helmet lift, 188–89, **188**
  See also partial-pressure suits, capstan-operated
carbon dioxide (CO_2)
  build-up in helmet, concern about, 217
  G-suit bladder-fill material, x
  percentages of atmospheric gases, **18**
  role of in atmosphere, 20
carbon monoxide, 43
Carl, Marion E., **202**, 206, 209
Carleton Aviation/Carleton Technologies Inc./Carleton Controls, 154, 376
Carlson, Walter A., 137
Carpenter, M. Scott, **234**
Carroll, Franklin O., 68, 135
Carson, Leon D., 92, 97
CASE (conditioned air supply equipment), 224, 226
Cassidy, William B., 206, 209
cathode ray tubes, 18
Catholic Church, 15–16
Cecil Field, 98
Central Intelligence Agency (CIA)
  A-12 aircraft suit requirements, 302–5
  A-12 program pilot selection, 305
  A-12 revival for North Vietnam operations, 316
  A/P22S-2 suit use, 262
  designation system for suits, 301
  full-pressure suit use, 286, 362
  Overflight operation, 153–54
  reconnaissance aircraft missions, 301
  reconnaissance programs, competition between, 316
  S-100 partial-pressure suit use, 318
  U-2 aircraft, development of, 150
  U-2 aircraft, pilots for, 151, 153, 154–55, 337, **338**
centrifugal force
  benefits of, 74
  consciousness and, 71
  gravity, relationship to, 74
centrifuge, human
  Balloon Hangar centrifuge, 43, 74, 75, 77
  Brooks AFB/Brooks Field, 112–13, 396–98
  development of first, 43, 74
  Mayo Clinic centrifuge, 76–77, **77**, 88, 91–92, 95, 99, 100, 126, 181
  National Research Council–funded centrifuges, 76, 77, 87
  Naval Air Development Center Wheel centrifuge, **78**, 79–80, **79**
  Naval Air Station Pensacola centrifuge, 77
  operation of, 76–77
  purpose of, 74, 77, 79
  RCAF centrifuge, 51, 76
  University of Sydney centrifuge, 75, **75**, 84
  USC centrifuge, 77, 104, 126
  Wright Field centrifuges, 43, 77, 95, 126
CF-18 Hornet, 112
CH-113 balloon, 26
Challenger (OV-099), 363, 366, 382–83
Chance Vought F7U-3 Cutlass, **169**
Chandler, William A., 384
Charland, Alma, 104
China, reconnaissance missions over, 313, 315
Chisholm, John, 106
Christy, Ralph L., 182–83

Clark, David M.
College of Holy Cross, company ownership share of, 272
education and career of, 96
ethics of, 362–63
G-suit standardization, 105–6
G-valve for bladder inflation, 97
Henry, assistance to, 126
Henry Suit (S-1 partial-pressure suit), testing of, 128
Henry Suit, design of, 133
Iberall, relationship with, 242
Julia Greene, work with, 99, 103, 104, 126, 133
knitting business of, 96–97
Link-Net fabric, development of, 155, 191, 242, 441n118
Mayo Clinic centrifuge, 76
MC-3 suit, meeting about, 148–49, 153
Omni-Environment Suit, **185**
opinions about, 96, 205, 244
PAOS testing, 100
partial-pressure suits and full-pressure suit, descriptiveness of terms, x, 121
patents awarded to, 96, 97, 441n118
pressure suit development, role in, ix
retirement of, 272
Ruseckas as flight instructor, 133
See also David Clark Company
Clark, William G., 77, 126
Clark-Dreyer Oxygen System, 41–42
Cleveland Clinic, 71
closures. *See* zippers and fasteners
Coast Guard, U.S., 301
Cobham plc, 154
Code, Charles F., 76, 90–92, 99, 101, 103
College of Holy Cross, 272
Colley, Russell S.
death of, 215
de-icing boot development, 32–33
education and career choice of, 32
features of suits designed by, 45–46, **51**
helmet designs, **216**
joint designs and mobility, 44, **51**, 56–57, **57**
Mark I (Model S) suit, 215, 218–20
Mark III suit, 222
Mark IV suit, **57**, 180
Mercury program suits, 215, 235
NASA role of, 215
patents awarded to, 57, 215
Post pressure suit development, 32, 33–34, **35**, 44, 215
pressure suit development, role in, ix, 44, 215
retirement of, 215
Type 3 "Strato-Suit," 44
XH-5 pressure suit (tomato-worm suit), 45–46, 56–57, **57**
Collier Trophy, 90
Collins, Harry, 305–6, **306**
Collins, Ken, 312, 460n31
Colorado Air National Guard Base, Buckley Field, 273
Columbia (OV-102)
accident and investigation, 410–11
cockpit of, **374**
crew-escape options, modifications for, 384
ejection seats, **374**, 375, 378
Orbital Flight Tests (OFT), 375–76, 378
S1035 suits, **408**, 410–11
Combat Crew Training Squadron, 4453rd, 274
COMBAT EDGE, 112–14, 115, 116
Combined Advanced Technology Enhanced Design G-Ensemble, 112–13. *See also* COMBAT EDGE
communications
AIC-10 setup, 139, 228, 274
A/P22S-2 full-pressure suit, 274
BABM suits, 52
CSU-4/P partial-pressure suit, 170
Goodrich suits, 51, 69
K-1 helmet, 138, 139
Launch Entry Helmet, 381
M-101 microphone, 358
M-169 microphone, 358
MA-2 helmets, 139
Mark IV pressure suit, 228
MB-5 helmets, 139
MBU-24/P masks, 117
microphone cutout switches, 377, 381
Omni-Environment Suit, 186
S901 full-pressure suit, **303**, 306
S901J Pilots Protective Assembly, 331
S1010 Pilots Protective Assembly, 338, **338**, **339**
S1030A Ejection Escape System suits, 377
S1031 Pilots Protective Assembly, 348
S1032 Launch Entry Suit, 386, **391**, **392**, 394, 395, **395**
S1034 Pilots Protective Assembly, 353, **353**, 358
Snoopy Cap communications carrier, 386, **391**, **395**
compensated metabolism apparatus, 122
Compton, Karl T., 27
conditioned air supply equipment (CASE), 224, 226
consciousness
altitude and oxygen requirements for, 21
altitude and time of useful consciousness, 19, 22
anti-G straining maneuvers, x, 73–74, 94, 113–14, 115

arterial pressure to maintain, 92
blackout sequence for dive bombing maneuvers, **81**, 82
blood pressure and, 71, 92
centrifugal force and, 71
G-loads and loss of, 71–72, 80–83, **81**, 92
gravity-induced loss of consciousness (G-LOC), 71–72, 116
Contingency Altitude Protection Suit, 177
Convair
reconnaissance aircraft proposal, 302
T-1 and S-2 suit use by, 141
Convair B-36 aircraft. *See* B-36 bombers
Convair B-58 Hustler bombers. *See* B-58 Hustler bombers
Convair F-102 Delta Dagger. *See* F-102 Delta Dagger
Convair F-106 Delta Dart. *See* F-106/F-106B Delta Dart
Convair JTF-102A trainer, 267, 271
Convair RB-36 reconnaissance aircraft, 149, **149**
Converse, Selden A. "Connie," 220
convoluted and bellows joints, 45, 51, **51**, 56–57, **57**, 195–96, **197**, **203**, 205, 210, 246
cooling systems
liquid-cooling garments, 173–74, 408–9
TLSS liquid-cooling system, 114
Typhoon fighters, 114
Cooney, James P., **309**
Cooper, L. Gordon, Jr., **234**
Cornelius, Richard, 102, 107
Cornelius control valve, 102, **102**, 107
Corona reconnaissance satellites, 314
Correale, James V., 227, 378
Cotton, Frank S., 22, 83–84, 99
Cotton, Frederick J., 91
Cotton Aerodynamic Anti-G Suit, 83–85, 99
counter-pressure clothing
G-suits compared to, 126
opposition to, 124
research on and development of, 124
See also vests
Coupe d'Aviation Maritime Jacques Schneider (Schneider Trophy), 72
CPS (Crew Protective System), 386
Crew Altitude Protective System (CAPS), 386, 393
crew protection equipment. *See* pilot and crew protection equipment
Crew Protective System (CPS), 386
Crile, George W., 71, 81–82
Crippen, Robert L. "Crip," **374**, 375, **376**
Croce-Spinelli, Joseph-Eustache, 41
Crossfield, Albert Scott
collaborative suit-design efforts, v
D558 program flights, 206, 209, 244
D558 program suits, 198–99, 205–6, **205**, 210, 244
on David Clark, 96, 205, 244
in Douglas Aircraft altitude chamber, **200**
MC-2 suit testing, 253–56, **255**
pressure suit development, role in, 262, 415n1
Weldon, relationship with, 199
X-2 program suit, 205
X-3 program suit, 205
X-15 program suits, 244–46, 258, 259, 262
X-plane development, role in, 198
Crowley, John W., 205–6
CRU-73 regulator, 112
CRU-103/P regulator, 114
CSK-6/P22S-2 coveralls, 268
CSK-8/P22S-4 coveralls, 286
CSK-9A/P22-6 coveralls, 290
CSK-9/P22-6 coveralls, 289
CSU-1/P suit, 159
CSU-2/P partial-pressure suit, 158, 159, 162, 165–67, 169, 171
CSU-3/P cutaway G-suit, 170
CSU-4/P partial-pressure suit
ADC testing and use, 279–82, **281**
bladders, 169–70, **170**, **172**, 386
color of, 171
development and specifications, 162, 167, 169–73, **170**, **172**
distribution and use of, 171–72
fabrics and materials, 170, 171
helmets, 171
neck ring, **170**
S822/S822-1/S822-1A suits, 170–72
S1032 suit and, 386
sizing of, 171
underwear, 282
wrist hose, 456n107
zippers, 171
CSU-5/P partial-pressure suit, 172–73, 279–82, **281**
CSU-12/P G-suits, 109
CSU-13A/P G-suits, 109
CSU-13B/P G-suits, 110, 112, 114, 115, 116–17, 118
CSU-13/P G-suits, 109, 110
CSU-15A/P G-suits, 109
CSU-15B/P G-suit, 114, 116
CSU-15/P G-suits, 109–10
CSU-17/P counter-pressure vest, 114
CSU-20/P cutaway G-suit, 114, 117
CSU-21/P counter-pressure vest, 114, 117
CSU-22/P G-suits, 116
CSU-23/P G-suits, 116–17. *See also* Advanced Technology Anti-G Suit (ATAGS)

Curtiss C-46 Commando, 135, 153
Curtiss JN-4 Jenny biplane, 28, 80, 416n19
Curtiss P-40E Kitty-hawks, 84, **84**
cutaway suits
  Berger Brothers G-3 cutaway suits, 105–6
  Clark G-3/G-3A cutaway suits, 105–8, 106
  CSU-3/P cutaway G-suit, 170
  CSU-20/P cutaway G-suit, 114, 117
CWU-4/P immersion suit, 171
CWU-27/P flyers coveralls, 118, **119**

D

D-21/M-21 drone/aircraft combination, **313**, 314–16, **315**, 324, 346
D558 program
  D558-1 Skystreak, 196, 198
  D558-1 Skystreak record flight, 206
  D558-2 Skyrocket, 198
  D558-2 Skyrocket record flights, 139–40, **202**, 206, 209, 244
  escape (ejection) capsule, 245
  full-pressure suits for, v, ix, 196–210, **197**, **198**, **199**, **201**, **202**, **203**, **204**, **205**, 244
  P2B-1S (B-29) carrier aircraft, launch from, 198, **202**, 206, 209
  Reaction Motors XLR11 rocket engines, 209, 447n46
  value of research, 209
Dalton's Law of partial pressure, 21
Dana, William H. "Bill," 174, 175, 176, **177**, **275**, **276**, **277**, 278
Daniel, Walter F., **309**
Darwin, Charles, 74
Darwin, Erasmus, 74
David Clark Company
  A-12 program code name, 304, 324
  air-conditioning equipment, portable, 225
  Anti-G Suit (AGS) for Space Shuttle, 375–76, 378, 382
  A/P22S-2 full-pressure suit. *See* A/P22S-2 full-pressure suit
  A/P22S-4 full-pressure suit. *See* A/P22S-4 full-pressure suit
  Arterial Occlusion Suit (AOS), 100, 101–2, **101**, 103
  bladders, 99–100, **101**, **103**, 105, **105**, 106, 108
  business operations and ethics, 270, 272–73, 362–63
  C-1/1A/1AM partial-pressure suits, 167–68
  C-4/4A partial-pressure suit, 169
  College of Holy Cross, ownership share of, 272
  contracts for G-suits, 106–7, 108–9
  CSU-4/P partial-pressure suit, 169–73, **170**, **172**
  CWU-4/P immersion suit, 171
  D558 program suits, v, ix, 196–210, **197**, **198**, **199**, **201**, **202**, **203**, **204**, **205**, 244
  designation system for suits, 181, 301, 318, 362
  Dyna-Soar spacesuit contract, 270, 279
  engineering activities, 363
  EVA and IVA gloves, 373
  facility, photos of, **269**, **270**
  founding of, 25, 96
  full-pressure suits, development of, 210, 240
  G-2 suit, 95, **96**, 104, 431n132
  G-3/G-3A cutaway suits, 105–8, **106**
  G-3 G-suit, 104
  Gemini spacesuit contract, 270, 279
  gloves, manufacture of, 158
  G-suits, 84, 86, 88, 99–105, **101**, **105**
  helmets, 64
  Henry Suit, manufacture of, 132–33, 134, 135–36, 144
  jerkin-based ensemble, 177
  leg bandage, progressively-inflating, 99
  life rafts, 316
  location of, **269**, 270
  Mark II helmet as model, 266, 454n67
  Mayo Clinic, testing by, 103, 105
  MB-1 partial-pressure suit, 146
  MC-1 suit, development of, 141, 144
  MC-2 suit testing, 254, 453n41
  MC-3/3A suits, development of, 147, 148–49, 153–54
  MC-3/3A suits, manufacture of, 156, 157–58
  MC-4/4A suits, **159**
  Mercury program suits, 233, 235
  milking blood up from legs, G-suit design for, 99, 100
  Model 1 G-suit, 100
  Model 2 G-suit, 100
  Model 5 G-suit, 100
  Model 6 G-suit, 100
  Model 8 Arterial Occlusion Suit (AOS), 100, **101**
  Model 21 G-suit, 181
  Munsingwear, sale to, 272
  Omni-Environment Suit. *See* Omni-Environment Suit
  ownership of and employee-ownership heritage, vii, 96, 272–73, 362–63
  pressure suit development and manufacturing, ix, 109, 273, 362–63
  Progressive Arterial Occlusion Suits (PAOS), 99–100, **117**, 118, 119
  Prototype High Altitude Flying Outfit (PHAFO) suits, 296–99, **297**, **298**
  quality of suits produced by, 270
  RAF get-me-down suit, 175
  Retrograde Inflation Anti-G Suit (RIAGS), **117**, 118–19, **118**, **119**

S-100 suit. *See* S-100 partial-pressure suit
S612 partial-pressure suit gloves, **160**
S787 prototype suit, 159
S802 prototype suit, 159
S901 suit. *See S901 suit entries*
S970 full-pressure suit, 306, **310**, 311, **328**
S1010 suit. *See* S1010 Pilots Protective Assembly (PPA)
S1030 suit. *See* S1030 Pilots Protective Assembly (PPA)
S1031 suit. *See* S1031 Pilots Protective Assembly (PPA)
S1031C suit, 334, 349, 350, 351, **354**
S1032 suit. *See* S1032 Launch Entry Suit (LES)
S1034 suit. *See* S1034 Pilots Protective Assembly (PPA)
S1035 suit. *See* S1035 Advanced Crew Escape Suit (ACES)
Sears, Roebuck, and Co., manufacturing for, 107, 269
security inspection of, 148
sizing of flying suits, 104, 136, 156, 158, 167, 168, 268–69, 360
Straightaway garment, 96–97, 98–99
suit controllers, 217
T-1 suits, manufacture of, 136, 137–38, 439n70
undergarment manufacturing, 107
valve immune to variance in source pressure, 99, 101–2
valve modification for turbojet engines, 107
X-15 program suits, 244–62
XMC-2-DC suits, 243, 244, 246–53, **248**, **249**
Z-1 suit, 103–4
Z-2 suit, 104–5, **105**
Z-3 (G-4/G-4A) suits, 107–8, 109, 439n70
See also Clark, David M.
Davis, Jefferson C., 293
Davis, Robert H., 26–27, 28, 415n10
Davis-Monthan Air Force Base, 265
Dawbarn, Waring L. "Pete," 56
DC-8 aircraft, 357
decompression
cabin decompression, v
flameouts and protection from slow decompression, 121
physiological effects of rapid decompression, 22–23
decompression, explosive
A/P22S-2 suit testing, 267
CSU-4/P suit testing, 171
NACEL research, 217
Omni-Environment Suit testing, 202, 204
pressurized cockpits and, 377–78
protection against, 121
research on, 43
sources of, 121
TLSS testing and survival of, 112
decompression sickness (aviator bends), xi, 21, 22, 23, 26, 132, 141
Dent, Frederick R., Jr., 205
Descartes, René, 16
Détré, Georges, 37, 419n63
Diamond Alkali Company, 462n53
Diamond Shamrock Corp., 462n53
Diehl, John A., 30
diluter demand oxygen system, 43, 61, 62, 429n108
Diringshofen, Heinz von, 87
Discovery (OV-103), 384
Dive Bomber, 81, 427n50
diving suits and helmets, ix, 25, 26–27, 416n11
DN-500-I portable oxygen kit, 310
DN-500-U portable vent kit, 310
Dobrovolskiy, Georgiy Ivanovich, 371
Doelter, Dr., 443n161
Dominion Textiles, Ltd., 86
donning and doffing suits
A/P22S-2 full-pressure suit, 268, 271, 272, 278–79, 280, 283
assistance with, 33, 57, 199, **202**, 209, 225
CSU-4/P partial-pressure suit, 170, 171
CSU-5/P partial-pressure suit, 173
dressing rooms/vans, 225, 226, **227**
glove design and, 180, 217
helmet designs and, 33, 46, 173, 184, 191
loose-fitting garments, 165
PHAFO suit, 296–97, 299
S1010 Pilots Protective Assembly, **336–37**
S1031 Pilots Protective Assembly, **346–47**
time needed for, 57, 171, 187, 199, 268, 271
zippers and, **50**, 54, 87, 94, 130, 133, 155, **180**, 186, **191**, **205**, **207**
Doolittle, Jimmy, 30, 80
Douglas A-24/SDB-3A Dauntless, 103
Douglas Aircraft
altitude chamber and suit testing, **199**, **200**, 201–2, 204, 211
T-1 and S-2 suit use by, 141
Douglas B/RB-66 Destroyer, 149, 156
Douglas D558 program. *See* D558 program
Douglas F3D Skynight, 215
Douglas F4D (F-6) Skyray, 230
Douglas X-3 aircraft, 205
Douglas XF4D Skyray, **199**, **200**, 201–2, 204, 211
Dräger pressure suits, 37–39, **38**, **39**
Dräger-Werke, AG, 37–39
Dreamland, 460n24. *See also* Groom Lake
Drinker, Cecil K., 75, 81
Drinker, Philip, 75
drinking and feeding system, vi, 319, 334, 340, 341, 358

drones
B-52 motherships, launches from, 315
M-21/D-21 aircraft/drone combination, **313**, 314–16, **315**, 324, 346
reconnaissance missions with, 314, 315
Drury, Douglas R., 77, 124, 126
Drybak Outdoor Clothing Company/Drybak Corp., 109, 136
Dryden, Hugh L., 151
Dryden Flight Research Center
Altitude Protective Garment (APG), 173–74
Bohn-Meyer role at, 340
get-me-down (emergency) suits, 175–76
High Altitude Protective Outfit use, 386
jerkin and jerkin-based ensembles, 174–77, **177**, 265
Knutson role at, 155
life-support shop, 264
Physiological Support Division, support from, 265
dry suits. *See* diving suits and helmets
Dubois, Ed
A/P22S-4 suit use, 457n118
Link-Net fabric characteristics, 248
rotating bearings, use of, 456n68
S-100 suit, development of, 317
S787 prototype suit, 159
S1010 suit development, 337
urine-collection system development, 358
DuBois, Eugene F., 82, 123
Duluth Air Force Base, 273
Dunlop Rubber Co., Ltd., 85, 86, 88, 446n40
Duplan Weatherbar polyurethane-coated nylon, 267, 454n69
Duque, Pedro, **403**
Durkee Atwood Company, 180
Durney, George, 369
Durup, Paul C., 182–83
Dyna-Soar program
centrifuge for pilot training, **78**, 80
contract for spacesuits, 270, 279
spacesuit design and development, 283

E

EAGLE (Enhanced Anti-G Lower Ensemble), 116–18
Earhart, Amelia, 29
Earls Court, 71, 424n6
ears
counter-pressure device for, 133
ear-oxygen meter, 122
foam ear pads, 266
Henry suit testing and, 130, 132
Earth resource program (NASA)
Physiological Support Division, 265
Project SOLVE, 357
S-100 partial-pressure suit, **319**
S1031 Pilots Protective Assembly, 348
S1034 Pilots Protective Assembly, **355**, **357**, 361
U-2C (ER-1) aircraft, **319**, **321**
U-2R (ER-2) aircraft, **332**, 348, 355, **357**
Eastham, Jim, 308
ebullism, 22, 23
Eclipse-Pioneer Division, Bendix Aviation Corporation, 198, 202
Edwards, Edwin "Eddie," **131**
Edwards, George, 26
Edwards Air Force Base
Aerospace Research Pilots School (Test Pilot School), 265, 278
Air Force Flight Test Center. *See* Air Force Flight Test Center (AFFTC)
A/P22S-2 suit testing, 266–67, 271
COMBAT EDGE testing, 114
F-15 Joint Test Force, 293
full-pressure suits for, 210
G-suit testing at, 110
Libelle G-Multiplus G-suit testing, 115
lifting body programs, 275
MC-2 suit testing, 256–57, 257, 267
North Base, 265, 271, 305–6, 335
Physiological Support Division, 264, 265, 271
rocket-sled evaluations, 257
Space Shuttle Approach and Landing test flights, 374–75
SR-71 aircraft base, 324
Test Pilot School, 115
TLSS testing, 112
Effler, Carl F., 235
Eglin Air Force Base, All-Weather Climatic Laboratory, 281–82
Eglin Field
G-suit testing at, 95, 105
pressure suit testing at, 47, 54, 55, **55**, 56, 57, 68
Eiken, Ola, 115
Einstein, Albert, 74
Eisenhower, Dwight D., 302, 314
ejections/bailouts
A-12 aircraft, ejections from, 304–5, **304**, 312, 314, 460n31
A-12 ejection seats, **304**, 314, 316, 324
A/P22S-2 suit testing, 267, 290
escape (ejection) capsule, 156, 213, 244–45, 383
escape pole, telescopic, 383–84

from F-104/104B Starfighter, 290
from F-106/F-106B Delta Dart, 290
G-suit weight and concerns about, 94
initiation of ejections and ejection seats, 157, 167–68, **168**, 192, **194**, 211, 230–31
M-21 aircraft, ejections from, 315–16, 460n31
Mark III suits and, 223–24
mobility of suits and ejection initiation, 167–68, **168**
oxygen and power supply to suit during, xii
physiological effects and risks, 22
Space Shuttle crew-escape options, 365–66, **366**, 374, 383–84, **383**, **384**
Space Shuttle ejection seats, 365, 374–75, **374**, 378
spurs for locking to ejection seat, **273**
SR-71 ejection seats, **323**, 324, 374, 375, 403
suit performance requirements, vi
tractor rocket-extraction system, 383–84
U-2 ejection seats, 151, 334, 403
visors, power for heating after ejection, 269
from WB-57F aircraft, 290
X-15 ejection seats, 245, 258, 261, 277, 374–75
See also back kits; get-me-down (emergency) suits; seat kits
elastic bodies, 241
Elkins, William, 373
Ellington Field, 286, **294**, 361, 410
Emergency Intravehicular Suit (EIS), 371–74, **372**, **373**
emergency suits. *See* get-me-down (emergency) suits
Emerson (A-12) demand regulators, 123, 124
Endeavour (OV-105), 384
Enevoldson, Einer K., 176
engines
A-12 reconnaissance aircraft (Oxcart), 312
altitude and operation of, 142, 237
AR2-3 rocket engines, **140**
flameout during F-104C flight, 278–79
flameouts and protection from slow decompression, 121
flameouts in U-2 aircraft, 151
J31 (I-16) turbojets, 107
J33 (I-40) turbojets, 107
J47 engines, 440n89
J57 engine flameout incident, 223
J58 engines, 312, 314
J65 turbojet engines, 286
J75 engines, 312
J79 engines, 278
jet aircraft compared to piston-powered aircraft, 142
manufacturers of, 362
piston-powered aircraft, 142, 237, 301
R-4360 engines, 141, 142, 440n89
RJ43 ramjet, 314, 315
rocket engines and aircraft performance, 121
TF33 turbofan engines, 286
turbojets and aircraft performance, 121
XLR11 rocket engines, 209, 447n46
XLR99 rocket engines, 244
England. *See* Great Britain
Engle, Joe H., **376**
Enhanced Anti-G Lower Ensemble (EAGLE), 116–18
Enterprise (OV-101), 374–75
Equipment Laboratory, Wright Field, 42–43, 44
Erickson, Mervin E., 47
Ernsting, John "J.E.," 174, 175
ER program. *See* Earth resource program (NASA)
escape (ejection) capsule, 156, 213, 244–45, 383
Ethernet, 413n6
Everest, Frank K. "Pete," Jr., 133, 134, 135, **138**, 274
Ewing, Donald D., 235
Excelsior, Project, 162–65, **163**, **164**, 269
exosphere, 20
explosive decompression. *See* decompression, explosive
exposure protection. *See* temperature and exposure protection
exterior covers
A/P22S-2 full-pressure suit, 263, 267, **276**, 277, **277**, 454n69
A/P22S-4 full-pressure suit, 284
A/P22S-6 full-pressure suit, 290
flammability of fabrics, 354, 464n85
HT-1 exterior covers, **304**, 306, 309
MC-2 full-pressure suit, 260–61, **260**, **261**, 263
PBI (polybenzimidazole), 354, **376**, **377**, 378, 464n85
S-100 partial-pressure suit, **320**, 321
S901 full-pressure suit, **304**, 306, 309
S901H special projects suit, 310–11
S901J Pilots Protective Assembly, **325**, 326–28, **327**
S970 full-pressure suit, 311
S1030A Ejection Escape System (EES) suits, **376**, **377**, 378
S1030 Pilots Protective Assembly, 341
S1031 Pilots Protective Assembly, 348
S1032 Launch Entry Suit (LES), **385**, **390**, 394–95, 399
S1034 Pilots Protective Assembly, 354–56, **356**, 358
S1035 Advanced Crew Escape Suit (ACES), **399**
extravehicular activities (EVA)
EIS use, 371, 372
ISSA suit use, 370
pressure suit requirements, 371
spacesuits for, 365
study of, 371

Extreme Cold Weather Survival Clothing Outfits designation system, 262

F

F2H Banshee, 215
F3D Skynight, 215
F4D (F-6) Skyray, 230
F-4/F-4A/F-4B/RF-4C (F4H/F4H-1) Phantom II, 230, 274, 289, 291, 295, 457n118
F4U/F4U-1 Corsair, 93, **182**, 184, 187, 301
F-5 (P-38) Lightning, 95, 124, 149
F-6 (F4D) Skyray, 230
F6F/F6F-3 Hellcat, 93, 94
F7U-3 Cutlass, **169**
F8U/F8U-1 (F-8A) Crusader, 220, 223, 224, 226, 230
F11F-1 Tiger, 220
F-13 Superfortress, 124
F-14 Tomcat, 307
F-15/F-15A/F-15B Eagle
- A/P22S-6 suit testing and use, 176, 291–93, **292**
- ATAGS (CSU-22/P) suit for, 116
- cabin pressure, 176
- COMBAT EDGE testing, 114
- CSU-13B/P G-suits testing, 116
- CSU-15B/P G-suit testing, 116
- CSU-23/P G-suit testing, 116–17
- interceptor role of, 239
- Israeli Defense Forces use, **288**, 289, 295
- jerkin and jerkin-based ensembles, 175, 176, 265
- maneuverability and acceleration specifications, 111
- photo of, **111**
- Physiological Support Division, support from, 265
- pressure suit use, 288
- range, capabilities, and pressure suit requirements, 111, 295
- *Streak Eagle*, **292**, 293, **293**, **294**
- time-to-climb record flight, 291–93, **292**, **293**, **294**
- TLSS testing, 112

F-16 Combined Test Force, 110
F-16/F-16B Fighting Falcon
- ATAGS (CSU-22/P) suit for, 116
- COMBAT EDGE testing, 114
- G-protection needs for, 111
- interceptor role of, 239
- TFCS testing, 110
- TLSS testing, 112

F-16/PBG G-suits, 110
F-22 Raptor, 116
F-86D/E Sabre, 138
F-89 Scorpion, 147, 240
F-94B/C Starfire, 138, 240
F-100 fighter, 156
F-101 Voodoo, 147, 156, 239, 240, 312
F-102 Delta Dagger
- ADC use, 240, 279–81
- A/P22S-2 suit testing and use, **271**, 279–81, **281**, 283
- A/P22S-3 suit testing and use, 279–81, **281**
- A/P22S-6 suit testing and use, 291
- CSU-4/P suit testing and use, 171, 279–81, **281**
- CSU-5/P suit testing and use, 279–81, **281**
- JTF-102A, suit testing in, 267, 271
- range, capabilities, and pressure suit requirements, 147, 156, 239

F-103/XF-103 aircraft, 237, 240
F-104/104B Starfighter
- A/P22S-2 suit testing and use, 289–90
- A/P22S-6 suit testing and use, 289–90, 291
- cockpits, roominess of, 289–90
- CSU-4/P suit use, 171
- development of, 127
- ejection from, 290
- Haderlie accident, 278–79
- HGU-15/P helmet use, 380
- interceptor role of, 147, 240
- jerkin and jerkin-based ensembles, 176, 265
- JF-104A aircraft, **229**
- MC-2 suit testing, 256, 257
- NF-104A aerospace trainer, **140**, 291
- Physiological Support Division, support from, 265
- TF-104G trainer, 176
- U-2 spy plane cover story, 151
- XF-104 aircraft, 141

F-105 Thunderchiefs, 380
F-106/F-106B Delta Dart
- A/P22S-2 suit testing and use, 267, **271**, 272, 273–74, 289–90
- A/P22S-6 suit testing and use, 289–90, 291
- cockpits, roominess of, 289–90
- CSU-4/P suit use, 171
- ejection from, 290
- HGU-15/P helmet use, 378, 380
- interceptor role of, 147, **147**, **239**, 240
- range, capabilities, and pressure suit requirements, 240

F-108 Rapier, 239, 240, 308
F-111C/F-111D fighter-bombers, **285**, 457n118
F/A-18 fighter aircraft, 114, 116
fabrics and materials
- Altitude Protective Garment (APG), 174
- A/P22S-2 full-pressure suit, 263, 267, 454n69

BABM suits, 62, 68
ballooning of suits and, 189–91, **189**, **197**
Byrd Cloth, 55–56
Cotton Aerodynamic Anti-G Suit, 84, 85
CSU-2/P partial-pressure suit, 167
CSU-4/P partial-pressure suit, 170, 171
CSU-5/P partial-pressure suit, 173
Dacron slipnet fabric, 242
Duplan Weatherbar polyurethane-coated nylon, 267, 454n69
flammability of fabrics, 354, 464n85
Franks Flying Suit, 86
French pressure suits, 36
General Electric suits, 65, 68
German Dräger pressure suits, 37
German get-me-down suits, 39
Goodrich suits, 44, 45, 51, 56, 69, **210–11**, 215, 219
Goodyear suits, 47, 55–56
Gore-Tex fabric, 351–52, 393, 463n78
Helenca knit fabric, 170, 227–28, 309
Henry Suit (S-1 partial-pressure suit), 133
HT-1 fabric, 310–11
Italian pressure suits, 36
jerkin and jerkin-based ensembles, 274
latex rubber, 242–43
liquid-cooling garment, 174
Mark IV pressure suit, 227–28
marquisette, 246–47, 250, 263, 283, 287, 306, 373–74
MC-2 full-pressure suit, 246, 247–48, **247**, **248**, **250**, **251**, 252, 253, 260–61
Mercury program suits, **221**
Model 7 full-pressure suit, 180
NACEL evaluation of, 189
National Carbon Company suits, 50
nopcofoam, 334, 462n53
nylon fabric, 167
Omni-Environment Suit, 181, 189–91, **189**, 192, 195, **195**, 196, **197**, 204, 206, 210, 446n40
open-weave net fabric, 189–91, **189**, 192
polybenzimidazole (PBI), 354, **376**, **377**, 378, 464n85
Post pressure suit, 30, 33
Prototype High Altitude Flying Outfit suits, 296, **297**, 299
reflective fabric for spacesuits, **259**, 260–61, **261**
research on human perceptions about, 242
Ridge pressure suit, 26–27
S-100 partial-pressure suit, 320
S901 full-pressure suit, 159, 306, 309
S901H special projects suit, 310–11
S901J Pilots Protective Assembly, 325–26, 328–29, 334
S1030A Ejection Escape System (EES) suits, **376**, **377**, 378
S1030 Pilots Protective Assembly, 341, **343**, 352
S1031 Pilots Protective Assembly (PPA), 352
S1031 Pilots Protective Assembly, 348, 352
S1032 Launch Entry Suit (LES), **389**, **390**, 393, 394–95
S1034 Pilots Protective Assembly, 351–56, **356**, 358
Spanish pressure suits, 39
suit-induced stress and fatigue and, 351
Teflon-coated yarns and fabric, 167
Terylene fabric, 274
Trilok fabric, 173, **221**, 228, 263
U.S. Rubber suits, 44, 49
waffle-weave fabric, 196, **197**, 204, 210
XMC-2-DC suits, 246–48, **248**, 250
See also Fypro material; Link-Net fabric; Nomex fabric
face seals
A/P22S-2 full-pressure suit, 259, 266, 268, 269, 283
A/P22S-6/6A full-pressure suit, 290
neck seals versus, 258–59
S-100 partial-pressure suit, 318, 319
S901J Pilots Protective Assembly, 331
Faget, Maxime A. "Max," 233
FAI. *See* Fédération Aéronautique Internationale (FAI)
fainting in the air, 72, 73. *See also* consciousness
Fairchild reconnaissance aircraft, 149–50
Fairey Battle aircraft, 87
Falcon (AIM-47/GAR-9/GAR-X) missiles, **307**, 308, 378
Farabi, Al-, 15
fasteners. *See* zippers and fasteners
Federal Air Regulation, 414n28
Federal-Mogul-Bower. *See* Arrowhead Products Division, Federal-Mogul-Bower
Fédération Aéronautique Internationale (FAI)
Gold Medal award to Post, 29
record-setting flights, 29, 34, 36, 41, 165, 233, **309**, 418n59, 419n63, 419n78, 419n80, 464n93
feeding and drinking system, vi, 319, 334, 340, 341, 358
Ferwerda, Thomas J., 98
Feynman, Richard P., 382
fighter aircraft (pursuit airplanes)
acceleration and air combat maneuvers, 113–14
G-suits and fighter combat missions, 88
high-altitude flights by, 45
loss of consciousness by pilots, 72
pilot attitude toward pressure suits, 286, 294
supersonic aircraft, 301
See also specific aircraft
Fighter Interceptor Squadron, 325th, 279–81
fighter squadrons

VF-8 Ghost Cats, 94
VF-142 Flying Falcons, 226
Firewel Corporation
automatic suit controllers, 216–17
MC-2 suit testing, 254, 453n41
regulators, 154, 158–59, 168, 198, 202, 211, 217, 228, 302–3
S1010 suit development, 335
suit controllers, 154, 276
Fisher, Vilyam Genrikhovich (Rudolf Abel), 156
FJ-3 Fury, **168**
Flagg, John
as David Clark Company president, 272
David Clark Company role, vii
in Douglas Aircraft altitude chamber, **200**
MC-3 suit, meeting about, 148, 153
Omni-Environment Suit, **185**, **186**, **187**, **188**, **190**, **191**, **193**, **202**, 214, 215
XMC-2-DC suits, 246
Fleet 16 Finch biplane, 76, 87
Fletcher, James, 383
Flickinger, Donald D., 153, 302, 303, 305
flight suits
CWU-27/P flyers coveralls, 118, **119**
K-2B flight overalls, 171
Flint, Lawrence E., 230
flotation systems
S901J Pilots Protective Assembly, 328
S1010 Pilots Protective Assembly, 338, **338**
S1030 Pilots Protective Assembly, 339
S1031 Pilots Protective Assembly, **346**
S1032 Launch Entry Suit (LES), **391**, **392**, **394**, 395
S1034 Pilots Protective Assembly, 354
special project suits, 316
SR-71 aircrew, 395
fluorescent light tubes, 18
footwear
Omni-Environment Suit, 185–86
S-2 partial-pressure suit, **136**
See also boots; socks
Forrestal, 224
France, pressure suit development by, 36–37
Franklin Institute, 241
Franks, Wilbur R. "Bill," 76, 83, 86–88, 105, 109
Franks Flying Suit, 83, 84, 86–88, **89**, **90**, 109
Frasier, Jim, 124
Fullerton, Charles Gordon "Gordo," **376**, **377**
full-pressure suits
Air Force suits, comparison of, **329**
anti-suffocation feature, xii, 267, 299
bids for suits designs, 243–44
breathing process and, xi, 21
collaborative design efforts, v
colors of, 222, 230, 261, 299, 454n69
comfort of, 272, 273, **278**, 280, 294
concept behind and purpose of, x–xi, 121
cost of, 240
counter-pressure from, x
custom fitting of, v
for D558 program, v, ix, 196–210, **197**, **198**, **199**, **201**, **202**, **203**, **204**, **205**
depot for maintenance, testing, and logistical support, 264–65
designation system for suits, 262, 362
development and manufacturing of, 122, 205, 210, 216, 237, 240–41, 362–63
diving suits compared to, ix, 25
fabrics and materials, v
fatigue and, 237
funding for, 363
military full-pressure suits, v–vi
mobility and, xi, 30, **31**, 36, 37, 237, 267
modern-day suit development and X-15 suit, v–vi
naming of, x
Navy use of, 179
oxygen supply for, xii
Post design, v, ix, 29–35, **31**, **32**, **35**, 417n35
power supply for, xii
protection provided by, xi, xii, 22, 121, 410–11
restraint layer of, v
sizing of, 180
as spacesuits, 217, 233–35, **234**
specifications and requirements, 243
standardization of designs, 258, 262
symposium about, 216, 241, 243
weight of, 250
zippers, fasteners, and closures, 263
See also specific suits
Fulton, John F., 82–83, 123
Fulton leggings, 82–83, 87, 92
Fypro material
colors of, 299, **343**, 348
development and production of, 299, 458n148
flame protection, 354
Nomex fabric and, 299
Prototype High Altitude Flying Outfit (PHAFO) suits, **297**
S1030A EES suits, **376**, 378
S1030 suit, 341, **343**, 354
S1031 suit, 348, 354

G

G-1 G-suit, 93–95, **95**, 103–4, 431n132
G-2 G-suit, 94, 95, **96**, 104, 431n132
G-3/G-3A cutaway G-suits, 105–8, **106**
G-3 G-suit, 104, 431n132
G-4/G-4A G-suits, 107–8, 109, 136, 439n70
Gagge, A. Pharo
  compensated metabolism apparatus, 122
  Henry Suit (S-1 partial-pressure suit), design of, 133
  Henry Suit (S-1 partial-pressure suit), testing of, 128
  Henry Suit, manufacture of, 135–36
  pressure breathing research, 122, 123, 124
Galileo, 16
Galway, Wayne, 227
GAR-9/GAR-X (AIM-47) Falcon missiles, **307**, 308, 378
Garment, Upper Hollywood (GUH), 227
garment, upper stratosphere (GUS) Mark III suit, 222, 226–27
Garsaux, Paul, 36–37
gas
  Dalton's Law of partial pressure, 21
  volume and pressure of, relationship between, 17–18
gas containers, breathable, vi
Gatty, Harold, 29
Gauer, Otto, 87
Geider, H.R., 189
Geissler, Heinrich, 18
Gemini capsule, 365
Gemini program spacesuits
  contract for, 270, 279
  design and development of, 283
  neck ring, 284, 325
  rotating bearing rings, 284, 456n68
  zippers and fasteners, 283
General Dynamics (Lockheed Martin) F-16/F-16B Fighting Falcon. *See* F-16/F-16B Fighting Falcon
General Dynamics F-111C/F-111D fighter-bombers, 285, 457n118
General Dynamics WB-57F reconnaissance aircraft. *See* WB-57F aircraft
General Electric (GE)
  capstan-controlled leg pressure G-suits, x, 104, 115, 126
  fabrics and materials for suits, 65, 68
  Henry Suit, interest in producing, 132
  J31 (I-16) turbojets, 107
  J33 (I-40) turbojets, 107
  J79 engines, 278
  L-12 G-suit, 104
  M61 Vulcan 20mm cannon, 141
  Navy, pressure suit testing by, 65–66, 68
  pressure suit development by, 65, **67**
  turbojet engines, 278, 440n89
General Motors, Allison Division, 140–41
Gentex Corporation
  HGU-20/P helmet, 380–81
  Launch Entry Helmet (LEH), 378–82, **379**, **380**, **381**
  Protection, Inc., purchase of, 380
  Tactical Life Support System program, 112
Gentry, Jerauld R., **277**
George Air Force Base, 380
Germany
  Air Force Institute of Aviation Medicine, 115
  CSU-4/P suit use by, 171–72
  Dräger pressure suits, 37–39, **38**, **39**
  get-me-down suits, 37, 39, **39**
  G-suit development, x, 87, 88, 89
  Libelle G-Multiplus G-suit, 114–16
  pressure suit development by, 36, **40**
  stratosphere flying suit, concern about access to, 27
Gerschler, Jimmy, 34
get-me-down (emergency) suits
  full-pressure suits as, 121, 192
  German suits, 37, 39, **39**
  jerkin and jerkin-based ensembles, 175–77, 265, 274
  MC-3 suit as, 154, 156
  mission-completion suits compared to, 156, 192
  Omni-Environment Suit as, 181, 192
  partial-pressure suits as, xi, 121, 135, 137, 169
  purpose of, xi, 110
  T-1 suits as, 137, **137**, **143**.
    See also T-1 partial-pressure suits
  XS-1 (X-1) aircraft, suits for, 126, 133, 135
  See also Henry Suit (S-1 partial-pressure suit)
Giles 300 aerobatic aircraft, 340
Gillespie, Kent W., 169
Gilliland, Bob, 323–24
Glenn, John H., Jr., **234**, **403**
Glider Research Institute, 39
G-loads (Gz)
  acceleration and, 43, 72–74, **72**, 80–83, **81**, 424n10
  anti-G straining maneuvers, x, 73–74, 94, 113–14, 115
  fighter aircraft, air combat maneuvers, and, 113–14
  loss of consciousness and, 71–72, 80–83, **81**, 92
  pressure breathing for G (PBG), 113
  research on effects of, 43, 80–83. *See also* centrifuge, human
gloves and mittens
  Ames Research Center, development at, 371–72, 373
  A/P22S-2 full-pressure suit, 263, 266, 267, 268, 269, 272, 273, 274, 276–77, 278–79, 280
  A/P22S-3 full-pressure suit, **280**

A/P22S-4 full-pressure suit, 284, 286
A/P22S-6 full-pressure suit, 289, 290, **294**
Apollo program suits, 296
BABM suits, **48**
disconnect incident and problems, 278–79, 284
early designs, 27
Emergency Intravehicular Suit (EIS), 371–72, 373–74
EVA and IVA gloves, 373–74
General Electric suits, **67**
German pressure suits, **38**
Goodrich suits, 47, 217
HAK-3/P22S-2 gloves, 268, 269
HAK-10/P22S-4 gloves, 286, 289, 290
Henry Suit (S-1 partial-pressure suit), 128, **129**, 132
HT-1 fabric, 159
Intravehicular Space Suit Assembly (ISSA), 368, 369
Link-Net fabric use, 272
Mark IV pressure suit, **227**, 228
MC-1 Featherweight suit, 144–45
MC-2 full-pressure suit, **245**, 246, **250**, 250, 252
MC-3/3A partial-pressure suit, 158, **160**, 165
MC-4/4A partial-pressure suit, 158, **160**
MG-1 gloves, 296
Model 7 full-pressure suit, 180, **180**
Omni-Environment Suit, **182**, 183–84, **185**, 186, 187, **191**, **203**, 206, 209
protection provided by, xi
Prototype High Altitude Flying Outfit suits, 296
S-100 partial-pressure suit, 321
S612 partial-pressure suit gloves, **160**
S901 full-pressure suit, 309
S901J Pilots Protective Assembly, 287, **327**, 328–29
S1010 Pilots Protective Assembly, 337, **337**
S1032 Launch Entry Suit, 386, **401**
S1034 Pilots Protective Assembly, 353–54, 401
S1035 Advanced Crew Escape Suit, **401**
U.S. Rubber suits, 45, 47
XMC-2-DC suits, 250, 252, 452n38
XMC-2-ILC suits, **245**, 246
goggles. *See* visors and goggles
Good, Michael, **404**
Goodell, John Charles, 154
Goodlin, Chalmers H. “Slick,” 133
Goodrich. *See* B.F. Goodrich Company
Goodyear Tire & Rubber
advances in suit design and development, 68
Army, pressure suit development for, 43, 44, 47, 52–55, 60, 68, 420n102
cost of pressure suits, 47
fabrics and materials for suits, 47, 55–56
helmets, **53**, 54, **54**
MX-117 project suits, 52
Navy, pressure suit testing by, 54–55, 63–65
pressure suit development, coordination of research for, 52–53
Type 9/9A pressure suit, **44**, 47, 53–54, **53**, 420n102
XH-3/XH-3A/XH-3B pressure suit, **44**, 54–56, **54**, 60, **66**, 68
XH-9 pressure suit, **44**
zipper, development of airtight, 54
Gore, Robert W., 463n78
Gore, Wilbert L., 463n78
Gore-Tex fabric, 351–52, 393, 463n78
Gorman, William Augustus, 416n11
Graf Zeppelin (Germany), 29
Grand Forks Air Force Base, 293, **293**, **294**
Graves, Jimmy B., 173
gravity, relationship to centrifugal force, 74
gravity-induced loss of consciousness (G-LOC), 71–72, 116
Gray, Roy C., 224
Great Britain
Air Commission, request for pressure suit information by, 45
Air Ministry, interest in pressure suits by, 27, 40
fighter aircraft, high-altitude flights by, 45
Grenfell Cloth, 55
MacRobertson Race, 29, 33, 417n28, 418n43
pressure suit development by, 26–27, **27**, 36, 40–41, **41**, 415–16nn10–11
See also Royal Air Force (RAF)
green apple emergency-oxygen activator, **383**, **392**, **397**, 408
Greene, Julia, 99, 103, 104, 126, 128, 132, 133
Greer, Calvin E., 378
Greig, D’Arcy, 87
Grenfell Cloth, 55
Gressly, Donald W., 55, 60, 61–62, 63, 64, 65
Griffith, John H., **131**
Grissom, Virgil I., **234**
Groom Lake
A-12 aircraft testing, **301**, 311, 316, 323, 460n24
location of, 150, 460n24
M-21 test flight, 324
names for, 460n24
operation OVERFLIGHT, 153–54
U-2 aircraft testing and maintenance, 150, **155**, 156, 265
YF-12A/AF-12 testing, 308
Gross, Mervin E., 89

Grumman
Mark I suit for aircraft testing, 220
readyrooms, portable air-conditioned, 226
Grumman F6F/F6F-3 Hellcat, 93, 94
Grumman F11F-1 Tiger, 220
Grumman F-14 Tomcat, 307
G-suits/anti-G suits
Advanced Technology Anti-G Suit (ATAGS), 112–13, 116–18, 119
air- and gas-filled bladders, x, 88, 93–94, **94**, 95, **95**
Anti-G Suit (AGS) for Space Shuttle, 375–76, 378, 402–3, **402**
A/P22P-16 COMBAT EDGE ensemble, 114
Army Air Corps development of, 43–44
Arterial Occlusion Suit (AOS), 100, 101–2, **101**, 103
Berger Brothers cutaway suits, 105–6
Berger Brothers suits, 83, 84, 86, 88, 92–95, **93**, **94**, **95**, 97, 99, 100, 103–4
C-1A G-suit, 157
capstan-operated, x, 104, 115
COMBAT EDGE, 112–14, 115, 116
concept behind and purpose of, x, 71, 82
contracts for, 106–7, 108–9
cost of, 116
Cotton Aerodynamic Anti-G Suit, 83–85, 99
counter-pressure clothing compared to, 126
CSU-3/P cutaway G-suit, 170
CSU-12/P G-suits, 109
CSU-13A/P G-suits, 109
CSU-13B/P G-suits, 110, 112, 114, 115, 116–17, 118
CSU-13/P G-suits, 109, 110
CSU-15A/P G-suits, 109
CSU-15B/P G-suit, 114, 116
CSU-15/P G-suits, 109–10
CSU-20/P cutaway G-suit, 114, 117
CSU-22/P G-suits, 116
CSU-23/P G-suits, 116–17. *See also* Advanced Technology Anti-G Suit (ATAGS)
cutaway suits, 105–9, **106**
David Clark Company cutaway suits, 105–8, **106**
David Clark Company suits, 84, 86, 88, 95, **96**, 99–105, **101**, **105**, 107–8, 109
designation system for suits, **44**, 430n123
development of, ix, 74, 89
devices leading to development of, 80–83, **82**
effectiveness of, 106
Enhanced Anti-G Lower Ensemble, 116–18
extended-coverage G-trousers, 113, 114, 116
F-16/PBG G-suits, 110
fabrics and materials, 84, 85, 86
fighter combat missions and, 88
Franks Flying Suit, 83, 84, 86–88, **89**, **90**, 109
G-1 G-suit, 93–95, **95**, 103–4, 431n132
G-2 G-suit, 94, 95, **96**, 104, 431n132
G-3/G-3A cutaway G-suits, 105–8, **106**
G-3 G-suit, 104, 431n132
G-4/G-4A G-suits, 107–8, 109, 136, 439n70
General Electric suits, x, 65–66, 68, 104, 115, 126
German suits, x, 87, 88
Goodrich suits, 184
jerkin and jerkin-based ensembles, 174–77, **177**, 265, 274
L-12 G-suit, 104
Libelle G-Multiplus G-suit, 114–16
manufacturers of, 362
Model 1 G-suit, 100
Model 2 G-suit, 100
Model 5 G-suit, 100
Model 6 G-suit, 100
Model 8 Arterial Occlusion Suit, 100, **101**
Model 21 G-suit, 181
modern suits, characteristics of, 110–11
pilot acceptance of, 94–95, 103–5
postwar suits, 109–10
pressure suits, confusion between, ix–x
pressurizing valves, 95, **95**, 97
Progressive Arterial Occlusion Suits, 99–100, **117**, 118, 119
Pulsatile pressure suit, 98, **98**
Retrograde Inflation Anti-G Suit, **117**, 118–19, **118**, **119**
sizing of, 94, 104, 110
skin counter-pressure, methods of application of, x
Space Shuttle anti-G suit, 375–76, 382
standardization of designs, 105–6, 109–10
Tactical Flight Combat Suit, 110
Tactical Life Support System program, 111–13, 114, 160
U.S. Rubber suits, 44, 45
vacuum pumps to pressurize, 93, 95, 102
water-filled bladders, x, 86–87, 88
weight of, 88, 94, 96, 439n70
Wright Field research on, 43
XH-1 pressure suit features, 51
Z-1 suit, 103–4
Z-2 suit, 104–5, **105**
Z-3 (G-4/G-4A) suits, 107–8, 109, 222, 439n70
Guardite Strato Chamber, 128, 130, 133, 139, 145
Guericke, Otto von, 17, 414n14
GUH (Garment, Upper Hollywood), 227
Guild, Waldo, 99
Gunn, James E., 227

GUS (garment, upper stratosphere) Mark III suit, 222, 226–27
G-valves, 97, 111–12, 113, 176
G-Whiz aircraft, 103

H

Haderlie, Kermit L., 278–79
HAFO (High Altitude Flying Outfit) program, 293–99
Haise, Fred W., Jr., **376**
HAK-3/P22S-2 gloves, 268, 269
HAK-10/P22S-4 gloves, 286, 289, 290
Haldane, John Burdon Sanderson "Jack," 26
Haldane, John Scott, 25, 26–27, 28, 30, 415n8
Haldane-Davis stratosphere flying suit, 26–27, **27**, 28, 30, 40–41, **41**
Hall, F. Gregory, 77
Hall, Florence C. "F.C.," 28, 29
Hallenback, George A., 105
Ham, Ken, **404**
Hamilton Standard Division, United Aircraft Corporation, 371, 372–73
hands, swelling of, 128
Harmon Trophy, 29, 233
Harry G. Armstrong Aerospace Medical Laboratory, 117–18, 119, 425n24
Hartsfield, Henry W. "Hank," **376**
Harvard University
  aeromedical and physiological research, 42, 43, 81
  altitude chambers, 75
  sock development by, 128
Hawker Hurricane, 84, 87
Hazelhurst Field, 31, 41–42
Head, Henry, 72, 73
Heald Machine Company, 99, 101
Heim, J. William "Bill," 43, 74, 75, 81
Helenca knit fabric, 170, 227–28, 309
helium, **18**
helmets
  anti-suffocation feature, xii, 267, 299, 310, 319, 334, 361, 395
  AOH-1 (Aviator Oxygen Helmet), 378
  A/P22S-2 full-pressure suit, 263, 266, 267, 268, 269, 272, 274
  A/P22S-4 full-pressure suit, 284, 286
  A/P22S-6/6A full-pressure suit, 289, 290, **291**, 317–19, **318**, **319**, 361
  BABM suits, 46, 47, 49–50, **49**, 52, **58**, 62, **64**, **65**
  Bill Jack helmets, 157, 263
  British pressure suits, 40
  clamshell construction, 349, 378–82, **379**, **380**, **381**
  Colley-designed, **216**
  CSU-4/P partial-pressure suit, 171
  David Clark Company, 64
  drinking and feeding system, vi, 319, 334, 340, 341, 358
  early designs, 25
  faceplates and visual field, 268
  full-pressure helmets, development of, vi
  General Electric suits, **67**, 68
  German get-me-down suits, 39, **39**, 419n70
  German pressure suits, 37, **38**
  Goodrich suits, 51, **210–11**, **212**, **214**, 217–19, 222–23, 235
  Goodyear suits, **53**, 54, **54**
  handmade helmets, 360
  Henry Suit (S-1 partial-pressure suit), **129**, 130, **130**, 132, 133, **134**
  HGK-12/P22S-2 helmets, 268, 269
  HGK-19/P22S-4 helmets, 286, 289, 290
  HGU-8/P helmet, **170**, 171
  HGU-15/P helmet, 378, 380
  HGU-20/P helmet, 380–81
  HGU-55/P helmet, 113, 114
  HGU-68/P helmet, 114, 117
  holddown system, **245**, 246, **253**, 260, 263, 266, 284, 291, **291**, 358
  Intravehicular Space Suit Assembly (ISSA), 368, **368**
  K-1 helmet, **134**, **137**, 138–39, **138**, **139**, 141, 144, 145, 161
  Launch Entry Helmet (LEH), 378–82, **379**, **380**, **381**, 397, 398
  liner, nopcofoam, 334, 462n53
  Link-Net fabric for U-2 pilot helmets, v, 155
  MA-1 helmets, 139
  MA-2 helmets, 139, 154, 155, 157, **158**, **159**, 171, 317
  MA-3 helmets, 157, 171, 261–62
  Mark II suit, **218**, 266, 454n67
  Mark IV pressure suit, **216**, **227**, 228
  MB-5 helmets, 139, 144, 145, 157
  MC-1 Featherweight suit, 139, 145
  MC-2 full-pressure suit, 246, 257, 260, 261–62, 263
  MC-3/3A partial-pressure suit, 139, 155, 157
  Mercury program suits, 233, 235
  Model 7 full-pressure suit, **180**, 181
  neck seals, 258–59, **260**, 395–96
  Omni-Environment Suit, 181, **182**, 184, 187–89, **187**, **190**, 191–92, **191**, 196, **197**, **202**, **203**, 204, 206, **208**, 214, 215
  pink, 382
  plexiglass helmets, 39, **39**, 44–45, 51, **51**, 54, **54**, 184, **203**, 204, 419n70

Post design, 30, **31**, **32**, 33, 35
protection provided by, xi
Prototype High Altitude Flying Outfit (PHAFO) suits, 296
rubber bladder for under, **138**
S-2 partial-pressure suit, 138–39
S-100 partial-pressure suit, 317–19, **318**, **319**, 321
S901 full-pressure suit, **303**, 309, 310
S901J Pilots Protective Assembly, 287, 328, 331, 334, 341
S970 full-pressure suit, **328**
S1010D helmet, 386
S1010 Pilots Protective Assembly, 337, **337**, 338–39, **339**
S1030L/S1031L helmets, 349, 352–53
S1030 Pilots Protective Assembly, 334, **339**, 339, 340–41, **342**, 349
S1031 Pilots Protective Assembly, 339, **348**, 348, 349
S1032 Launch Entry Suit, 349, 382, 386, **395**, 398
S1034E helmet, **359**, **360**, 361, 363
S1034 Pilots Protective Assembly, 353, **353**, 358, 361
S1035 Advanced Crew Escape Suit, 349
Spanish pressure suits, 39
surplus, ads for and sale of, 161, **161**
T-1 partial-pressure suits, **137**, 138–39, **138**
Type 3 "Strato-Suit," 44
U.S. Rubber suits, 44–45
XH-5 pressure suit, **60**
XMC-2-ILC suits, **245**
See also face seals; neck rings; visors and goggles

Henry, James Paget "Jim"
capstan-controlled pressure, interest in, 104, 126
Clark's assistance to, 126
education and career of, 125
Julia Greene, work with, 104, 126
patents awarded to, 134, 439n59
pressure breathing research, 126
USC human centrifuge, building of and research with, 77, 126
X-1 rocket plane, get-me-down suit for, 126
Z-1 suit, testing of, 103

Henry Suit (S-1 partial-pressure suit), 125–30, **129**, **130**, 132–34, **134**, 135–36, 144, 179, 237, 437n32
Herrera Linares, Don Emilio, 39–40
HGK-12/P22S-2 helmets, 268, 269
HGK-19/P22S-4 helmets, 286, 289, 290
HGU-8/P helmet, **170**, 171
HGU-15/P helmet, 378, 380
HGU-20/P helmet, 380–81
HGU-55/P helmet, 113, 114
HGU-68/P helmet, 114, 117
H.I. Garment Company, 136
high-altitude flight
advances in suit development, vi
balloon flights. *See* balloon flights
breathing process and, x, 21–22
British fighter aircraft, 45
clothing for, ix–xii
full-pressure suits for, v
partial-pressure suits for, v
physiological risks associated with, xi, 20, 21, 22–23
pilot stress from, 43
Post flights, 29, 34–35, **36**
record-setting flights. *See* record-setting flights
TAC flights, 286

High Altitude Flying Outfit (HAFO) program, 293–99
High Altitude Protective Outfit, 386
Hilsz, Marie-Louise "Maryse," 37, 419n63
HL-10 lifting body, **275**, 276
Hoag, Peter C., **277**
Hoagland, Hudson, 97–98
Holloman Air Force Base (AFB)
Libelle G-Multiplus G-suit testing, 115
Stargazer, Project, 165, **166**

Holmes, Bradford, 124
Home Base, 460n24. *See also* Groom Lake
Homey Airport, 460n24. *See also* Groom Lake
Hood Rubber Company, 128
Hooke, Robert, 17
Hook Maneuver, 113
Hoover, Robert A., 133
Horton, Vic, **331**
HT-1 fabric, **304**, 306, 309, 310–11
Hucks, William R., 30, 417n35
Hughes AIM-47 (GAR-9/GAR-X) Falcon missiles, **307**, 308, 378
Hughes AN/ASG-18 fire control system, 308
Hughes XF-11 aircraft, 149
human factors, pressure suits and, v
human space flight, engineering and management culture surrounding, 382–83
Hurricane aircraft, 84, 87
Hyde Athletic Shoe Company Model Z100 flying boots, 452n38
hydrogen, **18**
hypoxia, xi, 22–23, 41, 43
hypoxic environment, acclimatization to, 21

I

I-16 (J31) turbojets, 107
I-40 (J33) turbojets, 107
Iberall, Arthur S., 187, 195, 198, 241–43

Idealist project, 150. *See also* U-2 spy plane "Dragon Lady"
ILC Dover. *See* International Latex Corporation (ILC/ILC Dover)
IM-99 BOMARC surface-to-air missile, 314
impact-strike protection, xii
industry and industrial base
aircraft and engine manufacturers, 362
pressure suit manufacturers, 362–63
shrinking industrial base, 362–63
skills for suit production, 363
sole source contracting, 108–9
vendors, vanishing, 363, 463n81
Ingersoll Rand, 154
Institute of Aviation Medicine, Royal Air Force, 174, 175
Institute of Aviation Medicine/No. 1 Clinical Investigation Unit, 86
insulin, 76, 86, 426n30, 427n67
interceptor aircraft
A/P22S-2 suit use, **271**, 272, 273–74
range, capabilities, and pressure suit requirements, 146, 147, **147**, 239–40, **239**, **307**
S901F suit use, 308
See also specific aircraft
International Latex Corporation (ILC/ILC Dover)
Apollo program suits, **232**, 246, 296, 362, 367, 369, 371, 372
Briefcase Suit, 369, **369**, 370
Emergency Intravehicular Suit, 371–72, **372**, 373, **373**
EVA and IVA gloves, 373
full-pressure suits, development of, 362, 367
Intravehicular Space Suit Assembly, 369–70, **369**, **370**, 371
IVA suit development, 371
MA-2 helmets, 139, 154, 155, 157, **158**, **159**, 168, 171
Mercury program suits, **232**, 233, 235
Prototype High Altitude Flying Outfit, 296, 299
SPD-117 full-pressure suit, **232**, 235
XMC-2-ILC suits, 232, 243, 244, **245**, 246, 248, 252–53
International Space Station (ISS) program, 410
intravehicular activity (IVA)
Emergency Intravehicular Suit, 371–74, **372**, **373**
Intravehicular Space Suit Assembly, 366–70, **368**, **369**, **370**
study of, 371
Intravehicular Space Suit Assembly (ISSA)
Briefcase Suit, 369, **369**, 370
gloves, 368, 369
helmets, 368, **368**
ILC suit, 369–70, **369**, **370**, 371
joint designs, 367, 369
Space Age Control suit, 366–69, **368**
weight of, 368, 370
isothermal layer, 19
Israeli Defense Forces, 175, **288**, 289
ISS (International Space Station) program, 410
Italy, 36, 89

J

J-5 Whirlwind engine, 28
J31 (I-16) turbojets, 107
J33 (I-40) turbojets, 107
J47 engines, 440n89
J58 engines, 312, 314
J65 turbojet engines, 286
J75 engines, 312
J79 engines, 278
Jacobs, Harold J. "Jake," 133
James, A.A., 86
Japan, 89
Japanese Self-Defense Air Force, 172
Jarvis, Gregory B., 382
JAS-39 Gripen, 115–16
Jedeka, Lloyd W., 127
Jenson, Theodore A., 286–87
jerkin and jerkin-based ensembles, 174–77, **177**, 265, 274
Jester, Richard, 224
jet aircraft compared to piston-powered aircraft, 142
jetstream, 29
JF-104A aircraft, **229**
J.H. Emerson Company, 123
JN-4 Jenny biplane, 28, 80, 416n19
John B. Pierce Laboratory, 122
Johnson, Clarence L. "Kelly"
A-12 aircraft program, 302, 303, 305, 311
AF-12/YF12 interceptor program, 308, **309**
Angel, 150, 459n1.
See also U-2 spy plane "Dragon Lady"
Archangel, 302, 459n1.
See also A-12 reconnaissance aircraft (Oxcart)
Blackbird reconnaissance aircraft, development of, 127, 322
F-104 fighter, development of, 127
M-21/D-21 aircraft/drone combination, 314
P-80 Shooting Star, development of, 127, **127**
sense of humor of, 302
U-2 spy plane, development of, 127, 150, 334
Winnie Mae modifications, 34

Johnson, Louis A., 28
Johnson, Lyndon B., 322–23
Johnson, Richard S., 235
Johnson Space Center (JSC)/Manned Spacecraft Center (MSC)
  anti-G suit for Space Shuttle OFT flights, 375
  ISSA suit, 366–67, 369, 370
  pressure suit requirements study, 366–67
  S1030 and S1030A suits, hardware sharing between, 378
  Space Shuttle crew-escape options, development of, 384
  Space Shuttle simulator, **379**, **385**, **397**
joint designs
  ball-bearing joints, 37, 39, 56, 192–94, **193**, 196, **197**, 205, 206, **207**, 209–10
  bellows and convoluted joints, 45, 51, **51**, 56–57, **57**, 195–96, **197**, **203**, 205, 210, 246
  German suits, 37
  Goodrich suits, 215
  ISSA, 367, 369
  Link-Net fabric and, 248, 250
  MC-2 full-pressure suit, 246
  metal joints, 44
  net-covered joints, 241–42
  Omni-Environment Suit, 192–96, **193**, **194**, **195**, **197**, 198, **198**, 199, **203**, 205, 209–10, 214
  single-axis joints, 174
  thrust bearing joints, 174, 192–94, **193**
  tomato-worm suit, 56–57, 57, 195
Joint Services Pressure Breathing Conference, 124
Jones, W.L., 227
JSC (Johnson Space Center). *See* Johnson Space Center (JSC)/Manned Spacecraft Center (MSC)
JTF-102A trainer, 267, 271

K

K-1 helmet, **134**, **137**, 138–39, **138**, **139**, 141, 144, 145, 161
K-2B flight overalls, 171
Kadena Air Force Base, 316
Kearby, John G.
  counter-pressure vests, development of, 123
  death of, 68, 179
  full-pressure suits, development of, 122
  pressure breathing research, 122
  pressure suit development, 69, 123
  pressure suit testing, 52, 53, 54, 55, 68
  as project officer for pressure suit contracts, 44, 68, 122
Kedlock, Project, 308
Kelly Air Force Base, 290
Kelly One-Piece (K.O.P.), 85–86
Kelly's Angel, 150. *See also* U-2 spy plane "Dragon Lady"
Kennedy, John F., 233
Kennedy Space Center, Launch Complex 39B, 382
Kenneway, Al, 369
Kenny, Edward W., 273
Kincheloe, Iven C., Jr., 259
King, Alice, 130, 133
Kirtland Air Force Base, 264, 286
Kittinger, Joseph W., Jr., 161, 162–65, **163**, **164**, **166**, 269
Knapp, Budd F., 271–72
Knight, William J. "Pete," 278
Knipfer, Charles, 26
Knutson, Martin A. "Marty," 154–55
Kops Brothers, 136
Krupp, Carroll P., 57
krypton, **18**

L

L-12 G-suit, 104
lace-adjustment features
  Berger Brothers suits, 92, **93**, 94
  capstan-controlled leg pressure G-suits, x, 104, 126
  Clark cutaway suits, 105
  CSU-2/P partial-pressure suit, 167
  CSU-4/P partial-pressure suit, 170
  CSU-12/P G-suits, 109
  CSU-13B/P G-suits, 105
  CSU-13/P G-suits, 109
  CSU-15/P G-suits, 109
  CSU-20/P cutaway G-suit, 114
  CSU-21/P counter-pressure vest, 114
  effectiveness of, 126
  F-16/PBG G-suits, 110
  Franks Flying Suit, 87
  G-3A suits, 106
  Henry Suit (S-1 partial-pressure suit), 127, 130, 133
  MC-3/3A partial-pressure suit, 155
  MC-4/4A partial-pressure suit, **159**
  Omni-Environment Suit, **185**, 186, 187
  Retrograde Inflation Anti-G Suit, 118
  S-100 partial-pressure suit, **319**
  S901 full-pressure suit, 309
  S901J Pilots Protective Assembly, 325–26
  S1030 Pilots Protective Assembly, **343**
  U.S. Rubber suits, 44
LaHaye, James D., 223
Laine, Mae, 28
Lambert, Edward H., 100, 114
Lamport, Harold, 53, 104, 115, 126
Lancaster Iron Works, 42
Land, Edwin M., 302

Langley Research Center, 233, 235
Lastex, 206, 446n40
lateral acceleration (Gy), **72**, 73
latex rubber suit, 242–43
Laughlin Air Force Base, 265
Launch Control Officer (LOC), 314
Launch Entry Helmet (LEH)
- color of and paint scheme, **380**, 382
- delivery schedule for, 381–82
- development and specifications, 378–82
- distribution and use of, **381**, 382, **406**
- JSC simulator training, **379**
- LEH-shirtsleeve ensemble compared to LES, 396–98, **396**

Launch Entry Suit. *See* S1032 Launch Entry Suit (LES)
Learjet, 115
Leary, Timothy, 26, 415n6
legs
- capstan-controlled G-suits and pressure on, x
- COMBAT EDGE G-trousers, 113
- Cotton Aerodynamic Anti-G Suit leggings, 85
- Fulton leggings to prevent blood pooling, 82–83, 87, 92
- pooling of blood in, x, 73, 82–83, 123
- Sustained Tolerance for Increased G G-trouser, 114

Lester, Helen, 104, 115, 126
Leverett, Sidney, 111
LeVier, Anthony W. "Tony," 151
Libby, Darald, 272
Libelle G-Multiplus G-suit, 114–16
life rafts, 316
Life Support International, Inc., 110
Life Support Special Project Office (LSPRO), 265
life-support system, 217. *See also* back kits; seat kits
Life Support Systems AG, 115
lifting body programs
- A/P22S-2 suit use, **275**, **276**, 277, **277**
- colors of suits and boots for, **276**
- Physiological Support Division, support from, 265
- rotating bearing rings on suits, 284

Linares, Don Emilio Herrera, 39–40
Lindsey, Steven W., **403**
Lines of Nonextension, 195, **198**, 241–43
Link-Net fabric
- advantages of, 250, **251**, 367
- A/P22S-2 full-pressure suit, 263, 269
- A/P22S-4 full-pressure suit, 283–84
- characteristic requirements, 248, 250
- CSU-4/P partial-pressure suit, 170, 171
- development of and patent for, 155, 191, 242, 441n118
- gloves, 272
- joint designs and, 248, 250
- MA-2 helmet modifications for U-2 pilots, v, 155
- MC-2 full-pressure suit, 159, 247–48, **247**, 250–52, **250**, 253, 257, 260, 263
- MC-4/4A partial-pressure suit, 159
- Mercury program suits, 233
- PHAFO suit, 299
- S787 prototype suit, 159
- S901 full-pressure suit, 159, 306, 309
- S901H special projects suit, 310
- S901J Pilots Protective Assembly, 325–26
- S970 full-pressure suit, **310**
- S1032 Launch Entry Suit, **389**
- S1034 Pilots Protective Assembly, 352
- shoulder section from, 159
- weaving of, 283
- X-15 suit, v
- XMC-2-DC suits, 247–48, **248**, 250, 252

Link Trainer, 192, 209, 211
Liquid Carbonic Corporation, 27
liquid-cooling garments, 173–74, 408–9
LOC (Launch Control Officer), 314
Lockheed A-12 aircraft. *See* A-12 reconnaissance aircraft (Oxcart)
Lockheed A-28 Hudson, 68
Lockheed AF-12 interceptor. *See* YF-12A/AF-12 interceptor aircraft
Lockheed C-130 Hercules, 305–6
Lockheed C-141B Starlifter, 384
Lockheed Engineering and Management Services Company/Lockheed Engineering & Sciences Company, 386, 396, 467n57
Lockheed F-94B/C Starfire, 138, 240
Lockheed F-104 Starfighter. *See* F-104/104B Starfighter
Lockheed JF-104A aircraft, **229**
Lockheed/Lockheed Skunk Works
- A-12 aircraft storage, 316
- A-12 reconnaissance aircraft design, 302
- P-80 Shooting Star development, 302
- Plant 42, Palmdale, 323–24, 358–59, 361
- pressure suits, interest in, 126–27
- T-1 and S-2 suit use by, 141
- U-2 aircraft development, 150. *See also* U-2 spy plane "Dragon Lady"
- U-2 flights and S1034 suit testing, 358–59

Lockheed Martin (General Dynamics) F-16 Fighting Falcon. *See* F-16/F-16B Fighting Falcon
Lockheed Martin F-22 Raptor, 116
Lockheed NF-104A aerospace trainer aircraft, **140**, 291
Lockheed Orion-Explorer seaplane, 35

Lockheed P-38 (F-5) Lightning, 95, 124, 149
Lockheed P-80 Shooting Star, 107, 127, 127
Lockheed R-12 aircraft, 322.
  See also SR-71 Blackbird aircraft
Lockheed TF-104G trainer aircraft, 176
Lockheed TO2/TV2/T-33B Shooting Star trainer (T-33 T-Bird trainer), 193, 209, 256–57, 445n23
Lockheed U-2 aircraft. *See* U-2 spy plane "Dragon Lady"
Lockheed Vega, v, 28–29, 33. *See also Winnie Mae*
Lockheed XC-35 aircraft, 43
Lockheed XF-104 aircraft, 141
Lockheed YF-12 aircraft.
  See YF-12A/AF-12 interceptor aircraft
Lop Nor nuclear test site, 315
Loring Air Force Base, 273
Lousma, Jack R., **376**, **377**
Lovelace, William J. Randolph "Randy," II, 47, 90, 91, 124
Lovelace Clinic, 153
LSPRO (Life Support Special Project Office), 265
LTV Aerospace, Vought Systems Division, 371, 372
lung collapse, 123
Lunier, M.J., 52
Lutz, Charles C.
  as A/P22S-2 suit project officer, 262
  as CSU-4/P suit project officer, 169
  pressure suit testing, 209, 233, 235, 239, 242–43
Lyndon B Johnson Space Center (JSC). *See* Johnson Space Center (JSC)/Manned Spacecraft Center (MSC)

M

M-21/D-21 aircraft/drone combination, **313**, 314–16, **315**, 324, 346
M61 Vulcan 20mm cannon, 141
M-101 microphone, 358
M-169 microphone, 358
MA-1 helmets, 139
MA-2 helmets, 139, 154, 155, 157, **158**, **159**, 168, 171, 317
MA-3 helmets, 157, 171, 261–62
MA-3 ventilation garment, 170
MAC (Military Airlift Command), 286–87, 289
MacFarlane, Willard R. "Mac," **292**, 293
Mach, Ernst, 74
Machorek, William C. "Bill," **330**
MacLeod, John J.R., 426n30, 427n67
MacRobertson Race, 29, 33, 417n28, 418n43
Mac Robertson Steam Confectionery Works, 29, 84, 417n27
magazine features and movies about pressure suits, 68–69, 227
Magdeburg hemispheres, 414n14
Magiotti, Raffaello, 16
Maher, Philip, 155
Mahoney, David I., 136
Maison, George L., 77, 105, 107
Mallick, Don, **327**
Manhattan Engineering Division (S-1 Section), 125
MANHIGH, Project, 161–62, 165
Manke, John A., **277**, 278
Manned Spacecraft Center (MSC)/Lyndon B Johnson Space Center (JSC)
  anti-G suit for Space Shuttle OFT flights, 375
  ISSA suit, 366–67, 369, 370
  pressure suit requirements study, 366–67
  S1030 and S1030A suits, hardware sharing between, 378
  Space Shuttle crew-escape options, development of, 384
  Space Shuttle simulator, **379**, **385**, **397**
Marine Corps, U.S., 301
Mark I (Model S) pressure suit, 215, **216**, 218–20
Mark II pressure suit, **218**, 220–22, 223, 266, 454n67
Mark III/III-LW pressure suit, **218**, **219**, **221**, 222–27
Mark IV pressure suit
  A/P22S-3 suits as modified version, 233, 272, 279, 280, **280**
  Arrowhead AE-83 suit, **227**, 230–31, 279
  boots, 230, **231**
  communications, 228
  components of, **224**
  development and specifications, **57**
  distribution and use of, **229**, 230, 233
  ejection initiation and, 230–31
  fabrics and materials, 227–28
  gloves, **227**, 228
  Goodrich suits, 227, 228, 230–31
  helmets, **216**, **227**, 228
  Mercury program, modification for, **231**, 233, **234**, 235
  neck ring, **224**, 228
  requirements for, 227
  sizing of, 228, 230
  socks, 228
  Strato-Lab project, 231–33
  suit controllers, 276
  TAC use, 274
  testing of, **225**
  underwear, 228
  ventilation, 230

visors, 228, 230
weight of, 230
zippers, 180, **216**, 228
Markum, Ed, 306, **306**
Mark V pressure suit, 233
Marquardt RJ43 ramjet, 314, 315
marquisette, 246–47, 250, 263, 283, 287, 306, 373–74
Marshall, Gerald Struan, 40
Marshall Space Flight Center, 227, **227**
Martin B-57/RB-57 Canberra, 149, 155, 156, 171, 286. *See also* WB-57F aircraft
Marvin, Lee, 227
masks. *See* oxygen masks, supply, and systems; pressure-breathing masks
Matthews, George, 369
Mattingly, Thomas K. "Ken," **376**
Maxim, Hiram Stevens, 71
Maxus Energy Corp, 462n53
Mayo, Charles Horace, 91
Mayo, William James, 91
Mayo, William Worrall, 91
Mayo Clinic
Aero Medical Unit, 90–91, 437n20
altitude chamber testing, 51–52, 55, 181
anti-G straining maneuvers, 73–74, 113
BABM suits, 46–47, **48**, 51–52, 55, **59**, 179. *See also* BABM suits
Berger Brothers suits, testing of, 92–93, 94, 103, 105
counter-pressure vests, development of, 123
David Clark suits, testing of, 103, 105
founding of, 91
Franks Flying Suit, testing of, 88
G-2 suit development, 95
General Electric G-suit, testing of, 126
G-suit research at Wright Field, 43
human centrifuge, 76–77, 77, 88, 91–92, 95, 99, 100, 126, 181
Model 7 full-pressure suit testing, 181
oximeter, development of, 122
oxygen mask development, 91
Progressive Arterial Occlusion Suits, testing of, 100, 119
Straightaway garment, testing of, 98–99
T-1 suits, testing of, 139
tire for centrifuge, 99
Mayo Medical Museum, 91
Mayo Properties Association, 91
MB-1 partial-pressure suit, 146–47
MB-2 partial-pressure suit, 147
MB-5 helmets, 139, 144, 145, 157
MBU-20/P oxygen masks, 114, 117
MBU-24/P oxygen masks, 114, 117
MC-1 Featherweight suit
bladders, 144, 145–46, 154, 155
contracts for, cancellation of, 156–57
development and specifications, 141, 144–46, **144**, 147–48, 239
distribution and use of, 156
gloves, 144–45
helmets, 139, 145
MC-3/3A development, basis for, 154
modifications to, 154
replacement of, 155
surplus suits, ads for and sale of, 161
MC-2 full-pressure suit
back kits, **256**, 258, **259**, 262
bids for suits designs, 243–44
biomedical data collection, 260
Crossfield role in development of, importance of, 262
custom fitted suits for pilots, 259–60, **260**
delivery schedule for suits, 258, 453n54
depot for maintenance, testing, and logistical support, 264
development and specifications, 232, 242, **247**, **253**
distribution and use of, 279
exterior cover, 260–61, **260**, **261**, 263
fabrics and materials, 246, 247–48, **247**, **248**, **250**, **251**, 252, 253, 260–61
face seals versus neck seals, 258–59, **260**
funding for, 258, 259
gloves, **250**
gloves and mittens, **245**, 246, 250, **250**, 252
helmets, 246, 257, 260, 261–62, 263
joint designs, 246
Link-Net fabric use, 159, 247–48, **247**, 250–52, **250**, 253, 257, 260, 263
nitrogen for pressurization, 261–62, 453n54
number of X-15 flights with, 261, 262
oxygen masks, systems, and supply, **256**, 258–59, **259**, 261–62, 453n54
pilot attitudes toward, 262
restraint layer, **247**, 248, **250**, 253
rocket-sled evaluations, **257**
S794-1 suit, 253
S794-2 suit, 253
S794-3C suit, 253–56, **254**, 453n41
S794-4 suit, 256, 257
S794-5 suit, 256–57
S794-6 suit, 257–58
S794-7 suit, 258
seat kits, 258
suit controllers, **256**

suits based on, 262
testing of, **252**, 253–57, **255**, **257**, 267, 453n41
underwear, 253
ventilation, 256
ventilation garments, 260
visors, 262
weight of, 250, 256
X-15 program use, 229, 243–62, 278
XMC-2-DC boots, 252, 452n38
XMC-2-DC suit fabrics and materials, 246–48, **248**, 250–52
XMC-2-DC suit gloves, 250, 252, 452n38
XMC-2-DC suits, 243, 244, 246–53
XMC-2-DC suit testing, **248**, **249**, 252–53
XMC-2-ILC suits, 232, 243, 244, **245**, 246, 248, 252–53
MC-3/3A partial-pressure suit
ADC use, 156, 240
A/P22S-2 suit compared to, 271–72
bladders, 155, **155**
capstans, 155, **155**
comfort of, 153, 162, 168–69
configurations of, 157–58
contracts for, 156
custom fitting of, 149, 153–54
development and specifications, 144, 145, 147–48, 153–55, **155**, 157–59, **157**, 160, 167, 239
ejection initiation, modifications for, 168
Excelsior project and MC-3A suit, 162–65, **163**, **164**
gloves, 158, **160**, 165
helmets, 139, 155, 157
lace-adjustment features, 155
MANHIGH project and MC-3A suits, 161–62, 165
as mission-completion suits, 156
S-100 design and, 317
S616 suits, 157
S621/S621L/S621R/S621LM/S621AR suits, 157
S687 suits, 157
S799 suits, 157, 158
S836 suits, 158
sizing of, 149, 156
Stargazer project and MC-3A suit, 165, **166**
success of design, 161
surplus suits, ads for and sale of, 161
testing of, 155
underwear, 162
zippers, 155, 159
MC-4/4A partial-pressure suit
ADC use, 156
development and specifications, 157–59, **158**, **159**
distribution and use of, 160
gloves, **160**
Link-Net fabric, 159
mobility, 168–69
S805 suits, 157
S814 suits, 158
sizing of, 158, 167
McAuliffe, Sharon Christa, 382
McClure, Clifton M., 161, 162
McDill Air Force Base, 274
McDonnell Aircraft Company
altitude chamber, **225**
Mercury program capsule, 233
McDonnell Douglas (Boeing) F-15/F-15B Eagle. *See* F-15/F-15A/F-15B Eagle
McDonnell Douglas Atlantis Warrior program, 114
McDonnell Douglas CF-18 Hornet, 112
McDonnell F2H Banshee, 215
McDonnell F-4/F-4A/F-4B/RF-4C (F4H/F4H-1) Phantom II, 230, 274, 289, 291, 295, 457n118
McDonnell F-101 Voodoo, 147, 156, 239, 240, 312
McEachern, James D. "J.D.," 136
McGowan, Richard J. "Dick," Jr., 204, 224
McGuire, Terence F., 154
McKay, John B. "Jack," 139, **250**, 259, **259**
McLean, Harry, 86
McMurtry, Thomas C., **331**
McNair, Ronald E., 382
Meakin, L.W., 60–62, 65
mechanical effects, 23
Medical Research Board, 41
Medical Research Laboratory, Army Signal Corps, 31, 41–42. *See also* School of Aviation Medicine (Army)
Meek, George A., 76, 87
Meidenbauer, Clifford, 154
Meidenbauer, Philip Edward "Ed," Jr., 154, 216
Melvin, Jewel M., 174, 176, 286
mercury, 16–17, 20, 21
mercury displacement pump, 18
mercury piston pump, 18
Mercury program
animal research program, 125
astronaut screening for, 153
capsule for, 233, 365
centrifuge for pilot training, **78**, **79**, 80
Colley-designed suit for, 215
fabrics and materials for suits, **221**
Goodrich suits, 233, **234**, 235
helmets, 233, 235
ILC suit, **232**, 233
Mercury Seven, **234**
quick fix suits, **234**, 235

shirtsleeve environments, 235
spacesuit for, Mark III suit as basis, 224
spacesuit for, Mark IV modification for, **231**, **234**, 235
Mertz, H.E., 35
mesopause, 20
mesosphere, 20
Messerschmitt Me 163 aircraft, 146
methane, **18**
MG-1 gloves, 296
microphone cutout switches, 377, 381
MiG-25 aircraft, 293
Military Airlift Command (MAC), 286–87, 289
Military Assistance Program, 161
Milliken, Glenn, 122
Milliken, William F., Jr., 52
Mineola Chamber, 31, 41, 42
Mine Safety Appliances Company, 123–24
Minneapolis-Honeywell Regulator Company, 52
Minnesota Mining and Manufacturing Company (3M) fabric, 210
Minute Maid Park, **404–5**
mission-completion suits, 156, 169, 192, 240
Miss Silver Town, 33
Mitchel, John Purroy, 42
Mitchel Field
Medical Research Laboratory/School of Aviation Medicine, 42
naming of, 42
training at, 42
Mitsubishi A6M Zero, 85, 94
mittens. *See gloves* and mittens
mobility
BABM suits, 52, 55, 56, **58**, 62
challenge of suit design for, xi, 69
ejection initiation and mobility of suits, 167–68, **168**
fabric to increase, 189–91, **189**
face seals versus neck seals, 258–59
full-pressure suits, xi, 30, **31**, 36, 37, 237, 267
General Electric suits, 65–66, **67**
German suits, 37, 39
Goodrich suits, 46, 47, **51**, 54, 56, **56**, 61–62
Goodyear suits, 54, **54**, 55, **60**, 64–65
joint designs and. *See* joint designs
lines of nonextension, 195, **198**
Mark III suit, 223
Omni-Environment Suit, **182**, 184, **187**, 187, 189–91, **189**, 192–96, **193**, **194**, **195**, **197**, 199, 204, 209, 214–15
partial-pressure suits, xi, 167–68, **168**, 237
requirements for, 44, 66
S1032 Launch Entry Suit (LES), 396–98, **396**
U.S. Rubber suits, **50**
Model 1 G-suit, 100
Model 1 Omni-Environment Suit, 183–84, **183**, 237
Model 2 G-suit, 100
Model 2 Omni-Environment Suit, **186**, 187–88
Model 3 Omni-Environment Suit, 187–89, **187**, **188**, 190, 192
Model 4 Omni-Environment Suit, 192
Model 4A Omni-Environment Suit, **191**, 192
Model 5 G-suit, 100
Model 5 Omni-Environment Suit, 193–95, **194**
Model 6 G-suit, 100
Model 6 Omni-Environment Suit, **195**, 196
Model 7 full-pressure suit, 179–81, **179**, **180**
Model 7 Omni-Environment Suit, **197**, 198–99, **198**, **199**, 201–2, **201**, **202**, 204, 206, 256
Model 8 Arterial Occlusion Suit (AOS), 100, **101**
Model 8 Omni-Environment Suit, **203**, 204
Model 9 Omni-Environment Suit, 204
Model 10 Omni-Environment Suit, 204
Model 11 Omni-Environment Suit, **202**, 204–5
Model 12 Omni-Environment Suit, **204**, **205**, 206, 209, 210, 244
Model 13 Omni-Environment Suit, 206, 209
Model 14 Omni-Environment Suit, 209, 239
Model 15 Omni-Environment Suit, 209
Model 16 Omni-Environment Suit, **207**, 210–11
Model 17 Omni-Environment Suit, 214
Model 18 Omni-Environment Suit, **208**, 214–15
Model 19 Omni-Environment Suit, 215
Model 21 G-suit, 181
Model H suit, **210–11**, **212**, 215–16, 240–41
Model L suit, **214**, 217
Model M suit, 217
Model N suit, 217
Model Q suit, 217
Model R suit, 217–18
Model S (Mark I) suit, 215, **216**, 218–20
Moller, Frederick D. “Fred”
CSU-2/P partial-pressure suit, 166–67, 171
G-suit development, 83, 92, 99, 107
G-suit standardization, 105–6
sizing tariff, development of, 158
Molomut, Norman, 124
Morgan, Thomas R. “Tom,” 174, 176
movie and magazine features about pressure suits, 68–69, 227
Mukai, Chiaki, **403**
Mulka, Mr., 443n161
Munsingwear, 99, 106, 272, 431n145
Murray, Arthur, 15

Mustang Survival (Mustang Sportswear, Ltd.), 110
Mutual Defense Assistance Program (MDAP), 109, 433n186
MX research and development projects
- confidential classification and security related to, 133
- general information about, 421n116, 433n174
- Project MX-117, 52, 68, 105, 179, 195, 237, 244, 421n116
- Project MX-829, 133–34, 135, 136
- Project MX-2147, 149

N

nap-of-earth/low-altitude missions, 286
National Advisory Committee on Aeronautics (NACA)
- D558 program, ix, 196, 198, 205–6
- G-suit development, 89
- U-2 aircraft, research with, 151
- X-1 rocket plane program, ix
- X-15 program, ix

National Aeronautic Association, 34
National Aeronautics and Space Administration (NASA)
- Earth resource program. *See* Earth resource program (NASA)
- full-pressure suit use, 362
- hard suits, development of, 38
- human space flight, engineering and management culture surrounding, 382–83
- IVA and EVA study, 371
- lifting body programs. *See* lifting body programs
- patches on pilot's suits, **277**
- pressure suit development, role in, ix
- Project SOLVE, 357
- S-100 partial-pressure suit use, 318, 319, 322
- Special Advisory Committee on Life Sciences, 91
- SR-71 aircraft, transfer of, 155
- U-2 aircraft, pilots for, 153
- U-2C aircraft, use of, **321**
- WB-57F program. *See* WB-57F aircraft

National Air and Space Museum, 35, 344
National Air Race Derby, 29
National Air Races, Cleveland, 28
National Bureau of Standards, 34, 187, 241
National Carbon Company
- fabrics and materials for suits, 50
- Type 7 pressure suit, **44**, 50–51
- XH-7 pressure suit, **44**

National Defense Research Committee, 125
National Oil Products Company, 462n53
National Research Council
- G-suit development, 88, 92
- human centrifuges, funding for, 76, 77, 87
- pressure breathing research, 123

NATO nations, sale of suits to, 161
Naval Air Crew Equipment Laboratory (NACEL)
- Berger Brothers suits, testing of, 94–95
- explosive decompression studies, 217
- fabric evaluation by, 189
- full-pressure suit testing, 179
- General Electric suits, testing of, **67**
- Goodrich suits, testing of, 215–16, 224
- Goodyear suits, testing of, 54–55, 60
- helmets and carbon dioxide buildup, evaluation of, 217
- Mercury program suits, research on, 233
- name change of, 430n129
- Omni-Environment Suit testing, 184, 187, 192, 199, 201, 210, 214–15
- research and research facilities at, 179

Naval Air Development Center (NADC)
- depot for suit maintenance, testing, and logistical support, 265
- MC-2 suit testing, **255**, 256
- S1032 suit testing, 394
- standardization of G-suit designs, 109–10
- Wheel centrifuge, **78**, 79–80, **79**
- X-plane program research and testing, 244

Naval Air Station (NAS) Anacostia, 98
Naval Air Station (NAS) Atlantic City, 223
Naval Air Station (NAS) Norfolk, 223
Naval Air Station (NAS) North Island, 223
Naval Air Station (NAS) Pensacola
- *Antietam*, 232
- human centrifuge at, 77
- Naval School of Aviation Medicine, 77

Naval Air Test Center Patuxent River, 224
Naval School of Aviation Medicine, 77
Navy, U.S.
- air missions, 301
- A/P22P-16 COMBAT EDGE ensemble, 114
- BABM suits, 62–63
- bases of, 274
- Berger Brothers G-suit use by, 93, 94–95
- Bureau of Aeronautics (BuAer), 97, 189, 205–6, 216, 222, 240
- D558-2 Skyrocket program, ix
- David Clark G-suit use by, 107
- designation system for suits, 430n123
- Enhanced Anti-G Lower Ensemble (EAGLE), 116–18
- full-pressure suit use, 286, 362
- General Electric pressure suits, 65–66, 68
- Goodrich suits, 61–62, 64, 68

Goodyear suits, 54–55, 63–65
G-suits, postwar, 109–10
Hook Maneuver, 113
Mark IV suit, 57, 180
Omni-Environment Suit. *See* Omni-Environment Suit
pilot protective clothing, conference on, 103
pressure suit development, 51, 216, 217, 222, 237, 239–41
pressure suit requirements, 179, 240
pressure suit testing by, 60–68
Straightaway garment, interest in, 97
T-1 and S-2 suit use by, 140
U.S. Rubber suits, 61
X-15 program, ix
Nay, Wayne W., 52, 98
NB-52 carrier aircraft, 261
NBC (nuclear, biological, chemical) protection, 111, 112
neck rings
A/P22S-2 full-pressure suit, 263
A/P22S-3 full-pressure suit, 282
A/P22S-4 full-pressure suit, 284
BABM suits, 52, 62
CSU-4/P partial-pressure suit, **170**
Gemini program spacesuits, 284, 325
Goodyear suits, 63–64
MA-1 helmets, 139
Mark III suit, 222, 223
Mark IV pressure suit, **224**, 228
S794-4 suit, 257
S901 full-pressure suit, 306
S901J Pilots Protective Assembly, 325
S1010 Pilots Protective Assembly, **338**
S1032 Launch Entry Suit (LES), 386
Type 5/5E "Strato-Suit," 61
neck seals
face seals versus, 258–59
MC-2 full-pressure suit, 258–59, **260**
S1032 Launch Entry Suit (LES), 395–96
Negroni, Carina, 36
Neiman, Jack, Jr., 223
Nemoft, A.J., 224
Némore, Jordanus de, 16, 413n6
neon, **18**
Nesbitt, Donald, 154
net-covered joints, 241–42
Nevada Test and Training Range, 460n24
New Zipper Company, 443n161
NF-104A aerospace trainer aircraft, **140**, 291
nitrogen
altitude, pressure, and, 20
decompression sickness (aviator bends), xi, 21, 22, 23, 26, 132, 141
partial pressure, 21
percentages of atmospheric gases, **18**
respiration and, 20
X-15 aircraft and suit, pressurization with, 259, 261–62, 453n54
Nixon, Richard M., 365
Nomex fabric
Anti-G Suit (AGS), 402
A/P22S-4 suit gloves, 284
A/P22S-6 full-pressure suit, 290
colors of, 299, 355–56, **355**, **356**, **390**, 394–95
CSU-13A/P G-suits, 109
CWU-27/P flyers coveralls, 118, **119**
Fypro material and, 299
HT-1 exterior covers, 304, 306, 309
Prototype High Altitude Flying Outfit suits, 296
S-100 partial-pressure suit, 321
S901J Pilots Protective Assembly, 326–28, **327**, 329
S1032 Launch Entry Suit, **390**, 394–95
S1034 Pilots Protective Assembly, 352, 354–56, **356**
Nopco Chemical Company, 462n53
nopcofoam, 334, 462n53
North American A3J (A-5) Vigilante, 230
North American Aviation
face seals versus neck seals, 258–59
MC-2 suit testing, 254, 255, 453n41
T-1 and S-2 suit use by, 141
X-15 program suits, 244–46
North American B-70 bomber, **238**
North American F-86D/E Sabre, 138
North American F-108 Rapier, 239, 240, 308
North American FJ-3 Fury, **168**
North American P-51 Mustang, 95, 106, 107, 149
North American X-15 program. *See* X-15 program
North American XB-70/XB-70A Valkyrie, vi, 237, **238**, 265, 291, 461n41
North American YF-86D aircraft, 137
North American YF-93A aircraft, 137
North American YF-100 Super Sabre, 301
North Base, Edwards Air Force Base, 265, 271, 305–6, 335
Northrop, John K. "Jack," 28
Northrop, T-1 and S-2 suit use by, 141
Northrop B-49 aircraft, 135
Northrop F-89 Scorpion, 147, 240
Norton Air Force Base, 378
nuclear, biological, chemical (NBC) protection, 111, 112
nuclear weapons tests, reconnaissance missions to detect, 286
Nuttall, H. Wendall, 222

O

Office of Scientific Research and Development (OSRD), 88, 89, 125, 126
Okinawa, 316
Olrich, Ernest L., 99
Omni-Environment Full-pressure Suit Symposium, 216, 241, 243
Omni-Environment Suit
ballooning of suits, efforts to control, 189–91, **189**, **197**
capstan to control helmet lift, 188–89, **188**
communications, 186
contracts for, 181, 196, 210
D558 program, v, ix, 196–210, **197**, **198**, **199**, **201**, **202**, **203**, **204**, **205**
development and specifications, 181
Douglas Aircraft altitude chamber testing, **199**, **200**, 201, 202, 204
Experiment A suit, 181, **182**
Experiment B suit, 181–83, **182**
Experiment C suit, 184
Experiment designators, 181
Experiment D suit, 184–87, **185**
Experiment E suit, 187
Experiment F suit, 189, 190
Experiment G suit, 189, 190
Experiment H suit, **189**, 190
Experiment J suit, 190–91
Experiment K suit, **190**, 191
Experiment L suit, 192–93
Experiment M suit, 193–94, **193**
Experiment N suit, 196
Experiment P suit, 196
fabrics and materials, 181, 189–91, **189**, 192, 195, **195**, 196, **197**, 204, 206, 210, 446n40
footwear, 185–86
funding for, 206, 210, 215
gloves and mittens, **182**, 183–84, **185**, 186, 187, **191**, **203**, 206, 209
helmets, 181, **182**, 184, 187–89, **187**, **190**, 191–92, **191**, 196, **197**, **202**, **203**, 204, 206, **208**, 214, 215
inflation points, 187
joint designs, 192–96, **193**, **194**, **195**, **197**, 198, **198**, 199, **203**, 205, 209–10, 214
lace-adjustment features, **185**, 186, 187
malfunction of, responsibility in event of, 205–6
as mission-completion suits, 192
mobility, **182**, 184, 187, **187**, 189–91, **189**, 192–96, **193**, **194**, **195**, **197**, 199, 204, 209, 214–15
Model 1 suit, 183–84, **183**, 237
Model 2 suit, **186**, 187–88
Model 3 suit, 187–89, **187**, **188**, 190, 192
Model 4A suit, **191**, 192
Model 4 suit, 192
Model 5 suit, 193–95, **194**
Model 6 suit, **195**, 196
Model 7 suit, **197**, 198–99, **198**, **199**, 201–2, **201**, **202**, 204, 206, 256
Model 8 suit, **203**, 204
Model 9 suit, 204
Model 10 suit, 204
Model 11 suit, **202**, 204–5
Model 12 suit, **204**, **205**, 206, 209, 210, 244
Model 13 suit, 206, 209
Model 14 suit, 209, 239
Model 15 suit, 209
Model 16 suit, **207**, 210–11
Model 17 suit, 214
Model 18 suit, **208**, 214–15
Model 19 suit, 215
Model designators, 181
molds for rubber parts, **203**
NACEL evaluation of, 184, 187, 192, 199, 201, 210, 214–15
oxygen masks and systems, 198, **201**, **203**, **204**, 206, **208**, 211, 215
purpose of, 181
stress testing, 184
suit controllers, 198, **201**, 202, **203**
testing of, 187, 237, 239
ventilation, 183, 187, 209, 211
zippers, fasteners, and closures, 181, 184, 185, **186**, 187, 190, 201, 205, **205**, 206, **207**, 210–11
onboard oxygen generation system (OBOGS), 111–12
Onizuka, Ellison S., 382
Orbital Flight Tests (OFT), 375–76, 378
Ord, George, 154
Orion-Explorer seaplane, 35
OSRD (Office of Scientific Research and Development), 88, 89, 125, 126
Overflight operation, 153–54
Overmyer, Robert F., **376**
Oxcart. *See* A-12 reconnaissance aircraft (Oxcart)
oximeter, 122
oximetry, 122
oxygen
altitude, consciousness, and oxygen requirements, 21, 122
altitude and physiological impairment, 20, 21, 22–23, 41–43
arterial oxygen saturation, 122
dilution of flow, elimination of, 216–17

full-pressure suit oxygen and power supply, xii
full-pressure suits and natural breathing process, xi
high-altitude flight and natural breathing process, x, 21–22
hypoxia and, xi, 22–23, 41, 43
partial pressure, 19, 21, 22–23, 25, 122
percentages of atmospheric gases, **18**
physiological effects of lack of, 20
pressure breathing, 21–22, 23, 30
pressure requirements for natural breathing, x, 20
respiration and, 20
supplemental oxygen requirements, 23, 41, 43, 414n28
oxygen masks, supply, and systems
A-7 oxygen mask, 429n108
A-8 oxygen mask, 429n108
A-12 (Emerson) demand regulators, 123, 124
A-12 aircraft, 302–4
A-14A regulators, 124
A-14 oxygen masks, 57, 91, 429n108
A/P22S-2 full-pressure suit, 266, 271, 272
A/P22S-4 full-pressure suit, 284
A/P22S-6/6A full-pressure suit, 290, 361
B-12 constant-flow mask, 62
BABM suits, **58**
Boothby-Lovelace-Bulbulian (BLB) oxygen masks, 91, 122, 429n108
Clark-Dreyer Oxygen System, 41–42
COMBAT EDGE, 113, 114
CRU-73 regulator, 112
CRU-103/P regulator, 114
demand-type systems, 121–22
diluter demand oxygen system, 43, 61, 62, 429n108
early designs, 27, 30
emergency oxygen system (EOS), 408
Firewel regulators and controllers, 154, 158–59, 168, 198, 202, 211, 216–17, 228
full-face masks, 122–23, 126
Garsaux aviation oxygen system, 36
Goodrich suits, **214**, 216–17, 219, 221, 222–23
green apple emergency-oxygen activator, **383**, **392**, **397**, 408
G-valve for oxygen regulation, 113
Henry Suit (S-1 partial-pressure suit), 127, 130, 132
jerkin and jerkin-based ensembles, 274
Launch Entry Helmet, 381
Mayo Clinic research, 91
MBU-20/P oxygen masks, 114, 117
MBU-24/P oxygen masks, 114, 117
MC-2 full-pressure suit, **256**, 258–59, **259**, 261–62
Model 7 full-pressure suit goggle-mask, **180**, 181
NGL regulator, 112
Omni-Environment Suit, 198, **201**, 202, **203**, **204**, 206, **208**, 211, 215
onboard oxygen generation system (OBOGS), 111–12
pressure-demand systems, 124
protection provided by, xi
Quick-Don Mask (QDM), 409
S901 full-pressure suit, 310
S901J Pilots Protective Assembly, 324–25, 328, 334, 461n46
S1010 Pilots Protective Assembly, 338, **338**, **339**
S1030A Ejection Escape System suits, 376–77
S1031 Pilots Protective Assembly, 348
S1032 Launch Entry Suit, **383**, **390**, **391**, **392**, 394, **396**, **397**, 408
S1034 Pilots Protective Assembly, 361
S1035 Advanced Crew Escape Suit, 400, 408, 409
Space Shuttle, **379**, 382
standard masks, 122
Wiggins oxygen regulators, 61, 62, 63
Wildhack-Linde compensated exhalation valve, 127
XH-5 pressure suit, 57
See also back kits; seat kits
ozone layer, 19–20, 357

P

P2B-1S (B-29) carrier aircraft, 198, **202**, 206, 209
P-16 aircraft, 42
P-38 (F-5) Lightning, 95, 124, 149
P-39/P-39D Airacobra, 46, **51**, 52
P-40E Kitty-hawks, 84, **84**
P-47 Thunderbolt, 56, 95
P-51 Mustang, 95, 106, **107**, 149
P-59A Airacomet, 107
P-80 Shooting Star, 107, 127, **127**
Palmer, Don, 127
PAOS (Progressive Arterial Occlusion Suits), 99–100, **117**, 118, 119
parachutes and harnesses
A/P22S-2 full-pressure suit, **271**, **273**
Beaupre Multi-Stage Parachute system, 162–65, **163**, **164**
main canopy parachutes, 408
Red Bull Stratos jump, 165
S901J suit parachute harness, 326, **326**, 328
S901 suit and A-12 parachute pack, **303**
S1010 suit parachute harness, 338, **338**
S1032 Launch Entry Suit, 383, **383**, 384, **384**, **391**, **392**, **394**
S1035 Advanced Crew Escape Suit (ACES), 401, 403, 408
Space Shuttle crew-escape options, 383, **383**, 384, **384**

Paradise Ranch, 460n24. *See also* Groom Lake
Parazynski, Scott E., **403**
Park, William C. "Bill," Jr., 306, **310**, 314, 315–16, 335, 460n31
Parker, Will D. "Billy," 34, 418n50
partial-pressure suits
  Altitude Protective Garment, 173–74
  breathing process and, xi, 21
  collaborative design efforts, v
  comfort of, 135, **144**, 148–49, 153, 162, 168–69
  concept behind and purpose of, x–xi, 121
  continuous-wear suits, 144, 156
  counter-pressure from, x–xi
  CSU-4/P suit. *See* CSU-4/P partial-pressure suit
  CSU-5/P partial-pressure suit, 172–73
  custom fitting of, 136, 144
  emergency use of, 135
  get-me-down (emergency) suits, xi, 121, 135, 137, 169
  heat fatigue and, 271
  limitations of, xi
  MB-1 partial-pressure suit, 146–47
  MB-2 partial-pressure suit, 147
  mobility and, xi, 167–68, **168**, 237
  naming of, x, 127
  protection provided by, xi, xii, 22, 121
  S787 prototype suit, 159
  sizing of, 134, 136, 144, 156, 158, 167, 168
  specifications, 126
  standardization of designs, 135
  success and durability of design, 173
  suit controllers, 154, 158–59, 168, 174
  surplus suits, ads for and sale of, **160**, 161, **161**
  U-2 program, v, xi
  weight of, 439n70
  X-1 rocket plane program, ix
partial-pressure suits, capstan-operated
  C-1/1A/1AM partial-pressure suits, 167–68
  C-4/4A (S759/S785) partial-pressure suit, 157, 168, **169**
  concept behind and purpose of, xi
  cost of, 132, 133, 134, 138
  CSU-2/P partial-pressure suit, 158, 159, 162, 165–67, 169, 171
  double-capstan system, 165–67
  end of development of, 160, 167
  G-suits compared to, 126
  Henry Suit (S-1 partial-pressure suit), 125–30, **129**, **130**, 132–34, **134**, 135–36, 144, 179, 237, 437n32
  human factors and, v
  MC-1 suit. *See* MC-1 Featherweight suit
  MC-3 suit. *See* MC-3/3A partial-pressure suit
  MC-4/4A. *See* MC-4/4A partial-pressure suit
  S-2 suit. *See* S-2 partial-pressure suit
  success and durability of early designs, v, **130**
  suit designers and aircrews, working relationship between, v
  T-1 suit. *See* T-1 partial-pressure suits
Pascal (Pa), 17, 20
Pascal, Blaise, 17
Patrick Air Force Base, 271
Patsayev, Viktor Ivanovich, 371
Paul Bert Aeromedical Center, 36
pause, 18
Payne, Dick, **131**
PBI (polybenzimidazole) exterior covers, 354, **376**, **377**, 378, 464n85
PC-7 turboprop trainer aircraft, 115
Peace Jack F-4E(S) aircraft, 289, 295
Peak, Ira F., 80
Peck, Harry, 210, 217
Penrod, Kenneth E., 182–83, **182**, 184, **185**, **186**, 187
Perier, Florin, 17
Personnel Support Apparel designation system, 262
Peters, Lowell, 30
Petersen, Forrest S., **229**, 260
Peterson, David W., **292**, 293
Pezzi, Mario, 36
Pfister, William J., 223
Phillips, Frank, 34
Phillips Petroleum Company, 34, 35, 418n50
Photographic Reconnaissance Squadron, 14th, 124
Photographic Reconnaissance Squadron, 28th, 124
photosynthesis, 20
physical elasticity, laws of, 241
physiological effects and risks
  A-12 aircraft, 302
  acceleration, 72–74, **72**, 80–83, **81**, 425n15
  aeromedical and physiological research, 41–43, 81, 89–92
  Blackbird era, monitoring during, 302
  ejections/bailouts, 22
  high-altitude flight, risks associated with, xi, 20, 21, 22–23
  oxygen, altitude, and physiological impairment, 20, 21, 22–23, 41–43, 122
  oxygen deprivation, 20
  pressure breathing, 21–22
  syncope, 145–46
Physiological Research Unit, Wright Field, 42, 74–75, 425n24
Physiological Support Divisions (PSDs), 264, 265, 271, 378

Physiological Training Unit, Tyndall Air Force Base, 264
Piccard, Auguste, 26
Pierce, Harold, 42
Pilatus PC-7 turboprop trainer aircraft, 115
pilot and crew protection equipment
designers of, vi
development of, 74–75
Equipment Laboratory research and development, 42–43
See also boots; gloves and mittens; helmets; oxygen masks, supply, and systems; pressure suits
pilots
A-12 program pilot selection, 305
attitude toward pressure suits, 262, 286, 294
crew vans, **349**
fitness and efficiency of, 41, 146
g-forces, research on effects of, 43
G-suits, acceptance of by, 94–95, 103–5
G-suits, effectiveness of, 106, **107**
high-altitude flight stress on, 43
patches on suits of, 277
physiological effects and risks. *See* physiological effects and risks
selection standards, 41
sense of humor of, 276
See also stress and fatigue
Pilots Protective Assembly. See S1010 Pilots Protective Assembly (PPA); S1030 Pilots Protective Assembly (PPA); S1031 Pilots Protective Assembly (PPA); S1031C common suit Pilots Protective Assembly (PPA); S1034 Pilots Protective Assembly (PPA)
Pima Air and Space Museum, 286
Pincus, Gregory, 98
Pinecastle Air Force Base, 132, 438n47
Pioneer Bendix Company, 124
piston-powered aircraft, 142, 237, 301
Pittsburgh Plate Glass Company (PPG) visors, **328**, 334, 462n55
Platenburg, Robert I., 273
Plato, 15
Plexiglas, 419n70
plexiglass helmets, 39, **39**, 44–45, 51, **51**, 54, **54**, 184, **203**, 204, 419n70
Plummer, Henry Stanley, 91
pneumatic lever. *See* capstans
pneumotherapy, 122
polybenzimidazole (PBI) exterior covers, 354, **376**, **377**, 378, 464n85
Poole, Forrest R., 262, 263
Poppen, John R. "Jack," 80–81, 83, 97
Poppen Belt, 81, **82**
Porter, Adrien, 76
Porter, Delewis "Dee," **356**, **357**, 358–60
Post, Wiley
altitude-record attempts, 29–30, 34–35, **36**
around-the-world flights, 29
aviation career, 28
commercial pilot license, 28
cost of pressure suit, 30, 417n35
death of, 35
high-altitude flight, prediction about, 121
loss of eye, 28
MacRobertson Race, 29, 32
pressure suit development, v, ix, 29–35, **31**, **32**, **35**, **36**, 43, 215, 417n35
Winnie Mae, 29–30, **31**, 32, 33, 34–35, **34**, **35**
Potez 506 aircraft, 36
Potez Airplane Company, 36
Power, Thomas S., 156
Powers, Francis Gary, **156**, 301–2, 314
PPG (Pittsburgh Plate Glass Company) visors, **328**, 334, 462n55
P/Q pressure-breathing mask, 175, 176, **177**
Prahl, Val, **285**
Prather, Victor A., 232–33
Pratt & Whitney
J57 engine flameout incident, 223
J58 engines, 312, 314
J75 engines, 312
R-1340 Wasp engine, 28
R-4360 engines, 141, 142, 440n89
T-1 and S-2 suit use by, 141
TF33 turbofan engines, 286
Prescott, Charles W., 75
Presidential Commission (Rogers Commission) to study Challenger accident, 382–83
pressure
altitude and, 17
atmospheric pressure, 16–17
concept of, 16
measures of, 17, 20–21
vacuum and, 16–18
vacuum pump experiment, 17, 414n14
pressure-breathing clothing. *See* counter-pressure clothing
pressure breathing for altitude (PBA), 113
pressure breathing for G (PBG), 113
pressure-breathing masks
A-13 pressure-breathing mask, 123–24, 127, 130, 132
Air Force requirements, 378
concept behind and development of, 122–24
G-suits, use with, 110
Launch Entry Helmet, limitations of, 381

Model 7 suit pressure-breathing mask, **180**, 181
P/Q pressure-breathing mask, 175, 176, **177**
XA-13 pressure-breathing mask, 123–24
pressure breathing/positive pressure breathing (PPB), 21–22, 23, 30, 122–24
pressure-breathing vests. *See vests*
pressure suits
advances in design and development, vi, ix
aircraft advancements and protection requirements from, 121, 237, **238**, 239, 243
awe associated with, 15
collaborative design efforts, v–vi
depot for maintenance, testing, and logistical support, 264–65
designation system for suits, **44**, 181, 262, 301, 318, 362, 430n123
diving suits compared to, ix, 25
early designs, 25–28, **27**
emergency incidents and evaluation of, 223
funding for, 363
future of, vi
G-suits, confusion between, ix–x
human factors and, v
inspection and maintenance of, 264–65, 340
international efforts, 35–41, **38**, **39**, **40**, **41**
manufacturers of, 362–63
mobility and, 30, **31**, 37
pilot attitude toward, 262, 286, 294
purpose of, ix, 25
similarity verification process, 468n78
spacesuits compared to, xi–xii
standardization of designs, 105–6, 109–10, 135, 258, 262
successful designs, 121
See also full-pressure suits; partial-pressure suits
Price, Bruce B., 132
Priestly, John G., 26
Progressive Arterial Occlusion Suits (PAOS), 99–100, **117**, 118, 119
Project 7164 (Aerospace Protective Technology project), 293–95
Protection Incorporated
AOH-1 (Aviator Oxygen Helmet), 378
Gentex, purchase of, 380
heated visor lens, development of, 269
HGU-15/P helmet, 378, 380
neck rings, 306
Prototype High Altitude Flying Outfit (PHAFO) suits
color of, **298**, 299
David Clark Company suits, 296–99, **297**, **298**
donning and doffing, 296–97, 299
fabrics and materials, 296, **297**, 299
gloves, 296
helmets, 296
ILC suits, 296, 299
modular ensemble, 296–99, **298**
weight of, 299
PSDs (Physiological Support Divisions), 264, 265, 271, 378
Pulsatile pressure suit, 98, **98**
Pure Oil Company, 34, **34**
pursuit airplanes. *See* fighter aircraft (pursuit airplanes)
Puy-de-Dôme experiment, 17

Q

Q-12 drone, 314. *See also* M-21/D-21 aircraft/drone combination
Quick-Don Mask (QDM), 409

R

R-12 aircraft, 322. *See also* SR-71 Blackbird aircraft
R-1340 Wasp engine, 28
radiation exposure and protection, xii, 43
Ralph E. Darling Company, 217
Ralston, William P., 127
Randall, Francis E., 123
RAND Development Corporation, 241–43
Ranger, 224, 226
Ratermanis, John, 369
Ray, Walt, 314
RB-36 reconnaissance aircraft, 149, **149**
RB-57 Canberra, 149, 155, 156, 286. *See also* WB-57F aircraft
RB-66 Destroyer, 149, 156
Reaction Motors
XLR11 rocket engines, 209, 447n46
XLR99 rocket engines, 244
readyrooms, air-conditioned, 224, 226
Reagan, Ronald, 382, 383
reconnaissance aircraft and missions
China, missions over, 313, 315
competition between reconnaissance programs, 316
development of aircraft, 149
drone use, 314, 315
manned flights, cessation of, 314
Soviet Union, missions over, xi, **149**, 153, 154, 301–2, 313, 314 *See also specific aircraft*

Reconnaissance Squadron (Provisional), 4402nd, **354**
record-setting flights
Adam Aircraft A700 prototype, 464n93
Adam flight, 41, 419n80
balloon flights, 233
competition for, 29–30, 121
criteria for, 418n59
D558 program, 139–40, **202**, 206, 209
F-15A *Streak Eagle* flight, 291–93, **292**, **293**, **294**
French flights, 36–37, 419n63
Italian flights, 36
Kittinger and Excelsior project, 162–65, **163**, **164**
MiG-25 aircraft, 293
Post flights, 29–30, 34–35, **36**
SR-71 Blackbird aircraft, **330**, 344
Sukhoi Su-27 aircraft, 293
Swain flight, 41, 419n78
time-to-climb record flight, 291–93, **292**, **293**, **294**
X-1 aircraft, 135
YF-12A interceptor aircraft, **309**
Red Bull Stratos jump, 165
Reed, Al C., 47, 52, 55, 124
Reisman, Garrett, **404**
Republic F-105 Thunderchiefs, 380
Republic of China Air Force, 153, 156, 337, **338**
Republic P-47 Thunderbolt, 56, 95
Republic XF-12 Rainbow, 149
Republic XF-103/F-103 aircraft, 237, 240
Resch, Joseph A., 53
rescue balls, 365–66, **366**
Resnick, Judith A., 382
restraint layer
A/P22S-2 full-pressure suit, 263, 266, 269
A/P22S-4 full-pressure suit, 283–84
full-pressure suits, v
MC-2 full-pressure suit, **247**, 248, **250**, 253
S901 Flying Outfit, Full-pressure, High Altitude, Multi-Layer, 306, 308
S1032 Launch Entry Suit, **389**
Restricted Area 51 (Area 51), vii, 150, 460n24
Retrograde Inflation Anti-G Suit (RIAGS), **117**, 118–19, **118**, **119**
Rhode, Richard V., 80
RIAGS (Retrograde Inflation Anti-G Suit), **117**, 118–19, **118**, **119**
Richardson, Ralph N., 271
Ride, Sally K., 382
Ridge, Mark Edward, 25–28, 30, 40
Ridley, Jackie L. "Jack," 135
Rinehart, Dixie, 369
Ring, Samuel, 27
Ritzinger, Frederick R., 293
RJ43 ramjet, 314, 315
Robertson, Ken V., 83–84
Robertson, MacPherson, 29, 417n27
Robins Air Force Base, 363
Robinson, Steven K., **403**
Rocketdyne AR2-3 rocket engines, **140**
rocket engines. *See* engines
rocket sleds
A/P22S-2 suit testing, 267
MC-2 suit testing, **257**
S901 suit testing, 306
Sonic Wind I rocket sled, 162
Rocky 911 boots, 401
Rogers, Will, 35
Rogers, William P., 382
Rogers Commission (Presidential Commission) to study Challenger accident, 382–83
Roosevelt, Franklin Delano, 28, 125
Ross, Malcolm D., 231–33
rotative couch, 74
Royal Air Force (RAF)
Berger Brothers G-suits, 88
David Clark Company G-suits, 88
Fighter Command and Battle of Britain, 83
Franks Flying Suit, 84, 87–88
Fulton leggings, testing of, 82–83, 87, 92
get-me-down (emergency) suits, 175–76
high-altitude flight, 45
Institute of Aviation Medicine, 174, 175
jerkin and jerkin-based ensembles, 174–77, **177**, 265, 274
pilot protective clothing, conference on, 103
pressure-breathing apparatus, development of, 124
T-1 and S-2 suit use by, 140
Royal Australian Air Force (RAAF)
air-conditioned van for pilots, 84
A/P22S-4 suit use, 285, 286, 457n118
Cotton Aerodynamic Anti-G Suit, 83–85
CSU-4/P suit use by, 172
Curtiss P-40E Kitty-hawks, trials with, 84, **84**
Kelly One-Piece (K.O.P.), 85–86
University of Sydney centrifuge, 75, 84
See also Australia
Royal Canadian Air Force (RCAF)
Berger Brothers G-suits, 88
Camp Borden, 87, 428n84
David Clark Company G-suits, 88, 109
Franks Flying Suit, 84, 86–88, 109

human centrifuge, 51, 76
Institute of Aviation Medicine/No. 1 Clinical Investigation Unit, 86
pilot protective clothing, conference on, 103
pressure-breathing (counter-pressure) vest and trouser use, 174
T-1 and S-2 suit use by, 140
Royal Navy Fleet Air Arm, 88
RS-70 program, 322, 461n41
RS-71 program, 322, 461n41
Ruff, Siegfried, 82, 87
Ruseckas, Joseph "Joe"
air taxi pilot role, 133
A/P22S-2 suit development, 262–63, 266–67, **268**, 269
A/P22S-2A suit version, 274
A/P22S-4 suit development, 279, 283, 287
CSU-4/P partial-pressure suit, 169, 170
CSU-5/P partial-pressure suit, 172–73
D558 program flights, **202**, 206, 209
David Clark Company role, vii, 134–35
death of, 135, 439n63
in Douglas Aircraft altitude chamber, **200**
flight instruction job, 133, 134, 135
G-suit development, 108, 109
Mark IV pressure suit testing, 274
MC-3 suit, custom fitting of, 153–54
MC-3 suit, meeting about, 148, 153
MC-4/4A suit, **159**
Omni-Environment Suit, **183**, **189**, **202**, 206, 209, 214–15
pressure suit development, role in, 415n1
retirement of, 135
S-100 suit development, 316–18
S787 prototype suit, 159
S901 suit development and testing, 303, 305–6, **305**
S901J suit development, 324
S1010 suit development, 337
S1030A suit development, 376
T-1 suits and ejection initiation, **168**
XMC-2-DC suits, 246
Rushworth, Robert A. "Bob," 260, 267
Russia. *See* Soviet Union and Russia

S

S-1 partial-pressure suit (Henry Suit), 125–30, **129**, **130**, 132–34, **134**, 135–36, 144, 179, 237, 437n32
S-1 Section (Manhattan Engineering Division), 125
S-2 partial-pressure suit
B-36 Featherweight program, 141–42, **143**, 144
contracts for, cancellation of, 156–57
development and specifications, 136, **136**, 137, 138–39, 146
distribution and use of, 140–41, 147
long underwear use with, 138, 144
MC-3/3A development, basis for, 154
sizes of, 136, 144
sleeve length, 144
weight of, 439n70
S-3 partial-pressure suit, 154. *See also* MC-3/3A partial-pressure suit
S-100 partial-pressure suit
basis for design, 317
breathing bladder assembly, 319–20
capstans, 319–20, **319**
colors of, 321
development and specifications, 316–22, **317**, **318**, **319**, **320**
distribution and use of, 318, 319, 322
exterior covers, **320**, 321
fabrics and materials, 320
face seals, 318, 319
full-pressure helmet, 317–19, **318**, **319**, 321
gloves, 321
lace-adjustment features, **319**
number of suits produced, 322
sizing of, 321
suit controllers, 320–21
testing of, 318
underwear, 320
visors, 319
zippers and fasteners, 321
S393 partial-pressure suit, 136
S518 partial-pressure suits, 167
S520 partial-pressure suits, 167–68
S612 partial-pressure suit gloves, **160**
S616 partial-pressure suits, 157
S621/S621L/S621R/S621LM/S621AR partial-pressure suits, 157
S676 partial-pressure suits, 168
S685 partial-pressure suits, 168
S687 partial-pressure suits, 157
S759 partial-pressure suit, 157, 168
S785 partial-pressure suit, 157, 168
S787 prototype suit, 159
S794-1 full-pressure suit, 253
S794-2 full-pressure suit, 253
S794-3C full-pressure suit, 253–56, **254**, 453n41
S794-4 full-pressure suit, 256, 257

S794-5 full-pressure suit, 256–57
S794-6 full-pressure suit, 257–58
S794-7 full-pressure suit, 258
S799 partial-pressure suits, 157, 158
S802 prototype suit, 159
S805 partial-pressure suits, 157
S814 partial-pressure suits, 158
S822/S822-1/S822-1A partial-pressure suits, 170–72
S830 partial-pressure suits, 168
S836 partial-pressure suits, 158
S848 partial-pressure suits, 172–73
S901 Flying Outfit, Full-pressure, High Altitude, Multi-Layer
A-12 flights, use on, 312, 314
back kits, 310
biomedical data collection, 306
boots, **304**
caution in operating manual, 310
colors of, **304**
communications, **303**, 306
cost of suits, 308
custom fitting of, 310
development and specifications, 302–6, **303**, **304**, **305**, 308–11, **309**, **310**, 312
exterior covers, **304**, 306, 309
fabrics and materials, 159, 306, 309
gloves, 309
hardware, material for, 329
helmets, **303**, 309, 310
lace-adjustment features, 309
Link-Net fabric use, 159, 306, 309
neck ring, 306
oxygen supply and systems, 310
parachute pack, **303**
pocket locations, 306, 308
restraint layer, 306, 308
S901-3 suit, **305**
sizing of, 308, 309
testing of, 305–6
U-2 flights, 334, 335
ventilation, 309–10
visors, 306, 308, 309, 310
zippers and fasteners, **305**, 306, 310
S901A full-pressure suit, 306
S901B full-pressure suit, 306
S901C full-pressure suit, 306, **306**
S901D full-pressure suit, 306
S901E full-pressure suit, 306, 308
S901F full-pressure suit, 308–10, **309**
S901G full-pressure suit, 310, 311
S901H special projects suit
exterior covers, 310–11
Link-Net fabric, 310
Oxcart production suit, 310–11
rotating bearing rings, 284
S901J suit and, 324
sizing of, 310
urine-collection system, 311, **335**, 340
zippers, 310
S901J Pilots Protective Assembly (PPA)
A-12 revival plan and use of, 316
Air Force suits, comparison of, **329**
A/P22S-4 suit compared to, 287
A/P22S-6 suit, similarities to, 287
basis for design, 324
boots, 329
colors of, **325**, **327**, **331**
communications, 331
development and specifications, 324–31, **325**, **326**, **327**, **328**, **329**, **330**, **331**, 334
exterior covers, **325**, 326–28, **327**
fabrics and materials, 325–26, 328–29, 334
face seals, 331
flotation system, 328
gloves, 287, **327**, 328–29
hardware, material for, 329
helmet liner, nopcofoam, 334, 462n53
helmets, 287, 328, 331, 334, 341
lace-adjustment features, 325–26
Link-Net fabric, 325–26
MAC/WB-57F pilots' evaluation of, 286–87
neck ring, 325
number of suits produced, 334
oxygen masks, supply, and systems, 324–25, 328, 334, 461n46
parachute harness, 326, **326**, 328
pocket locations, 326, 328, 461n46
replacement of, 339
sizing of, 329
SR-71A breakup, **409**, 410, 411
success and durability design, 323
suitcase and helmet bag, 334
suit controllers, 329
U-2 flights, 334, 335
urine-collection system, 311, 326
visors, 331
weight of, 329
wrist rings, 284
YF-12 flights, **327**, **331**
zippers and fasteners, 306, 328
S906 full-pressure suit, 268–69, 277
S926/926A full-pressure suit, 268, 277

S931 full-pressure suit, 272, 277
S934 full-pressure suit, 277
S935 full-pressure suit, 277
S940 full-pressure suit, 268–69, 277
S963 full-pressure suit, 277
S970 full-pressure suit
basis for design, 311
exterior covers, 311
helmets, **328**
Link-Net fabric, **310**
S970-5-3 suit, **310**
zippers, 306, **310**, 311
S971 full-pressure suit, 277, 310
S998 full-pressure suit, 277
S1010D helmet, 386
S1010 Pilots Protective Assembly (PPA)
communications, 338, **338**, **339**
custom fitting of, 337, **338**
development and specifications, 335–39, **336–37**, **338**, **339**
donning and doffing, **336–37**
flotation system, 338, **338**
gloves, 337, **337**
helmets, 337, **337**, 338–39, **339**
neck ring, **338**
number of suits produced, 338
oxygen masks, supply, and systems, 338, **338**, **339**
parachute harness, 338, **338**
replacement of, 349
S1010A suit, 338
S1010B suit, 338
S1010D helmet, 338–39
U-2R flights, 334–39
urine-collection system, 337
visors, 338, **339**
wrist rings, 284
S1023 full-pressure suit, 286, 287
S1024/S1024A full-pressure suit, 287, 290. *See also* A/P22S-6/6A full-pressure suit
S1027 full-pressure suit, 277–78
S1030A Ejection Escape System (EES) suits
Anti-G Control Valve (AGCV), 376
Anti-G Suit use with, 375–76, 378
biomedical data collection, 376
colors of, **376**, **377**
communications, 377
cost of, 376
development and specifications, **374**, **375**, 376–78, **377**
distribution and use of, **406**
exterior covers, **376**, **377**, 378
fabrics and materials, **376**, **377**, 378
hardware sharing with S1030 suits, 378
Orbital Flight Tests (OFT) use, 375–76, 378
oxygen masks, supply, and systems, 376–77
scrapping of, 378
sizing of, **376**, 378
Space Shuttle missions, **376**
suit controllers, 378
S1030 Pilots Protective Assembly (PPA)
colors of, 341, **343**, 354
cost of, 340
development and specifications, 339–41, **341**, **343**, **344**
ensemble components, 341
exterior covers, 341
fabrics and materials, 341, **343**, 352
female pilot use of, **340**
flotation system, 339
hardware sharing with S1030A suits, 378
helmets, 334, 339, **339**, 340–41, **342**, 349
helmets, S1030L/S1031L, 349, 352–53
inspection and maintenance of, 340
lace-adjustment features, **343**
number of suits produced, 341
replacement of, 341, 349
sizing of, 340
SR-71 flights, 334, 339–41, **340**
suit controllers, **393**, 394
U-2 flights, 334
underwear, 341
urine-collection system, 339–40
wrist rings, 284
S1031 Pilots Protective Assembly (PPA)
colors of, 348, 354
communications, 348
development and specifications, **345**, 348–49
donning and doffing, **346–47**
exterior covers, 348
fabrics and materials, 348, 352
flotation system, **346**
helmets, 339, 348, **348**, 349
helmets, S1030L/S1031L, 349, 352–53
number of suits produced, 348
oxygen masks, supply, and systems, 348
replacement of, 349, 361
as S1010 replacement, 349
sizing of, 348
U-2 flights, 345, 348
wrist rings, 284
zippers and fasteners, 352

S1031C common suit Pilots Protective Assembly (PPA), 334, 349, 350, 351, **354**
S1032 Launch Entry Suit (LES)
basis for design, 177
biomedical data collection, port for, 395, **400**
bladders, **388**
colors of, **385**, **390**, 394, 399
communications, 386, **391**, **392**, 394, 395, **395**
cost of, 394, 395
delivery schedule for suits, 394, 395
development and specifications, 363, 386–99, 387–92, 393, 394, 395, 396, 397
distribution and use of, 399, **406–7**
exterior covers, **385**, **390**, 394–95, 399
fabrics and materials, **389**, **390**, 393, 394–95
flotation system, **391**, **392**, **394**, 395
gloves, 386, **401**
green apple emergency-oxygen activator, **383**, **392**, **397**, 408
hardware from, use of on S1035 suits, 400, **400**
helmets, 349, 382, 386, **395**, 398
JSC simulator training, **385**, **397**
Launch Entry Helmet (LEH), **381**
LEH-shirtsleeve ensemble compared to, **396**, 398
Link-Net fabric, **389**
mobility, 396–98, **396**
naming of, 386
neck ring, 386
neck seals, 395–96
number of suits produced, 394
oxygen supply and systems, **383**, **390**, **391**, **392**, 394, **396**, **397**, 408
parachute and harness assembly, 383, 383, 384, **384**, **391**, **392**, **394**
restraint layer, **389**
retirement of, 399
S1035 compared to, 399–401, **399**, **401**
sizing of, 467n51
STS-26R suits, 394, 399, 467n51
suit controllers, **391**, **392**, **393**, 394, **400**
training use of (dark-blue exterior covers), **385**, 390, 394, 395, **397**, 399
underwear, **387**
urine-collection system, 387
visors, 386
S1034 Pilots Protective Assembly (PPA)
colors of, 354–56, **355**, **356**, 358
communications, 353, **353**, 358
custom fitting of, 360–61
development and specifications, 350–61, **350**, **351**, **353**, **355**, **356**, **359**, 363, 398, **398**
distribution and use of, 361, 410
Earth resource program (NASA), **355**, **357**, 361
exterior covers, 354–56, **356**, 358
fabrics and materials, 351–56, **356**, 358
flotation system, 354
gloves, 353–54, 401
hardware from S1035 suits, use of, 410
helmets, 353, **353**, 358, 361
helmets, S1034E, **359**, **360**, 361, 363
inspection and maintenance of, 361
Link-Net fabric, 352
number of suits produced, 361
oxygen masks, supply, and systems, 361
pocket locations, 356
requirements for, 350–51, **350**
rotating bearing rings, 284
rotating wrist bearings, 277
as S1030 replacement, 341
as S1031 replacement, 361
S1035, similarity to, 411, 468n78
S1035 compared to, 400, 401, **402**
S1035 development, basis for, **398**, 399
sizing of, 360–61
suit controllers, 358
U-2 flights, 349, **354**, **355**, 358–61
urine-collection system, 357–58, 408
visors, 353, **353**, 358, 359
weight of, 361
windblast evaluation, 411
zippers and fasteners, 352, 359
S1035 Advanced Crew Escape Suit (ACES)
Anti-G Suit (AGS), 402–3, **402**
boots, 401
Columbia accident and suit performance, 410–11
delivery schedule for suits, 400
development and specifications, 363, **398**, 400–403, **401**, **402**, **403**, 408–10
distribution and use of, 15, **403**, **404–7**, **408**, 410–11
emergency oxygen system (EOS), 408
exterior covers, **399**
gloves, **401**
hardware from, use of on S1034 suits, 410
hardware from S1032 suits, use of, 400, **400**
helmets, 349
Launch Entry Helmet (LEH), **381**
liquid-cooling garment, 408–9
number of suits produced, 410
oxygen supply and systems, 400, 408, 409
parachutes and harnesses, 401, 403, 408
prototype suit, 398, **398**, 399–400
rotating bearing rings, 284

S1032 compared to, 399–401, **399**, **401**
S1034, similarity to, 411, 468n78
S1034 as basis for design, 398, 399
S1034 compared to, 400, 401, **402**
sizing of, 409–10
suit controllers, **400**
underwear, 408
urine-collection system, 401, 408
WB-57F program use, **294**
windblast evaluation, 411
wrist rings, **399**
zippers and fasteners, **403**
Saab JAS-39 Gripen aircraft, 115–16
Sabo, Stephen C., 215
SAC. *See* Strategic Air Command (SAC)
Salathé, Charles-Auguste, 74
Salmon, Herman R. "Fish," **140**, 141
Salyut space station, 370
Sample, Fred M., 25, 30, 415n3
San Antonio Air Materiel Area, Kelly Air Force Base, 290
Sasine, Kenneth, 358–60, 464n93
satellites, reconnaissance, 314
Schafer, Lauren W., 396
Schalk, Louis W. "Lou," Jr., 306, 311
Schirra, Walter M., Jr., **234**
Schlosser, James O., 375, 381
Schneider, Ed, **341**
Schneider Trophy
(Coupe d'Aviation Maritime Jacques Schneider), 72
School of Aerospace Medicine (Air Force)
Benson as commandant, 97
Boyle's Law Suit, 293–95
G-suit research, 111
jerkin and jerkin-based ensemble testing, 174, 175–76
S1032 suit testing, 394, 396–98
Tactical Life Support System program, 111, 112
School of Aviation Medicine (Air Force), 153, 295, 417n37
School of Aviation Medicine (Army)
Armstrong as commandant, 75
Brooks AFB/Brooks Field, 42, 74
Mitchel Field, 42
Randolph Filed, 75
Schroeder, Harry, 94–95, 103–4
Scobee, Francis R., 382
Scott, Kenneth, 214
Scott, W.E., 60–61
Scott Air-Pak, 154
Scott Aviation, 154
SDB-3A Dauntless, 103
Seamless Rubber Company, 93
search and rescue operations, colors for, 171, 299, 354–55, 394
Sears, Roebuck, and Co., 107, 269
seat kits
advantages over back kits, 258
A/P22S-2 full-pressure suit, 277
A/P22S-2 suits, **271**, **273**
C-4/4A suits, 168
configurations and purpose, 219, 448n74
Mark III suit, 222
MC-2 suits, 258
MC-3/3A and MC-4/4A suits, 158–59, **159**
SR-71 Blackbird aircraft, **324**
X-15 seat kits versus back kits for suits, **256**, 258, **273**, 277
Sellers, Piers, **404**
Senior Bowl operations, 315
Senior Crown program, 322–24, 334, 363
Senior Year program, 363
Sessums, John W., 46
Sevareid, Eric, 153
Shamrock Oil, 462n53
Shaw, Louis Agassiz, 75
Shepard, Alan B., Jr., **234**
shirtsleeve environments
B-52 Stratofortress, 156
B-58 Hustler bombers, 156, 210
bomber aircraft, 156, 210
Mercury program, 235
Space Shuttle, **379**
Space Shuttle Program, 365, 366, 374
shoes. *See* footwear
Shook, Donald H., 57
Siebe, Augustus, 26, 416n11
Siebe, Henry, 416n11
Siebe Gorman & Company, 26–27, 40–41, **41**, 415–16nn10–11
Sierracin Corporation, 269
Silver Snoopy Award, vii
similarity verification process, 468n78
Simmons, David G., 161, 162, 165
siphon, limits of, 16
Sir Hiram Maxim's Captive Flying Machines, 71, 424n5–6
Sivel, Henri-Theodore, 41
Slayton, Donald K. "Deke," 79, **234**
Smith, Michael J., 382
Smith, Roger J., **292**, 293
Smith, Wesley L., 32–33
Smithsonian Institution, 35, 344
Snider, Lester M., 222

Snoopy Cap communications carrier, 386, **391**, **395**
SNV-1 trainer/BT-13A Valiant, 63
Snyder, Lee, 227
socks
  Henry Suit (S-1 partial-pressure suit), 128
  Mark IV pressure suit, 228
  pneumatic socks, 166–67
  pressure socks, 118, 171
Sokolik, Jim, **357**
Solid Rocket Boosters, 382–83
SOLVE, Project, 357
sonic-type aircraft
  descent rates of, 135
  pressure suits for, 135
  See also X-plane entries
Sonic Wind I rocket sled, 162
Sopwith Camel, 72
Soviet Union and Russia
  bombers, interception of, 239–40, 308
  long-range missiles, development of, 150
  partial-pressure suit development, **130**
  pressure suit development by, 36
  reconnaissance missions over, xi, **149**, 153, 154, 301–2, 313, 314
  Soyuz spacecraft, 371
  strategic bombing threat from, 146–47
  U-2 and Gary Powers, shooting down of, **156**, 301–2, 314
Soyuz 11 spacecraft and crew, 370–71
Soyuz T spacecraft, 371
Space Age Control
  Altitude Protective Garment (APG), 173–74
  establishment of, 367
  EVA and IVA gloves, 373
  full-pressure suits, development of, 362, 366–67
  Intravehicular Space Suit Assembly (ISSA), 366–69, **368**
Spacecraft Crew Survival Integrated Investigation Team, **410–11**
Space Shuttle
  accidents and investigations, 363, 366, 382–83, 410–11
  airline-like operations, 365, **365**, 374
  announcement of, 365
  Anti-G Suit (AGS), 375–76, 378, 382, 402–3, **402**
  Approach and Landing test flights, 374–75
  cockpits, pressurized, 377–78
  crew-escape options/escape system, 365–66, **366**, 374, 383–84, **383**, **384**
  ejection seats, 365, 374–75, **374**, 378
  emergencies, plans for, 365–66, 374
  escape from, equal access to, 378
  escape pole, telescopic, 383–84
  helmets for, vi
  intact abort option, 365, 374
  Intravehicular Space Suit Assembly (ISSA), 366–70, **368**, **369**, **370**
  launch-abort options, 365, 374, 383
  modifications to, 378
  number of flights, 365
  Orbital Flight Tests (OFT), 375–76, 378
  oxygen supply and systems, **379**, 382
  parachute, main canopy, 408
  pressure suit requirements, vi, 366–67, 371
  pressure suits for, ix, 363
  retirement of, 355, 363
  S1032 suit. *See* S1032 Launch Entry Suit (LES)
  S1035 suit. *See* S1035 Advanced Crew Escape Suit (ACES)
  shirtsleeve environments, 365, 366, 374, **379**
  simulator at JSC, **379**, **385**
  Solid Rocket Boosters, 382–83
  tractor rocket-extraction system, 383–84
  See also Atlantis (OV-104); Challenger (OV-099); Columbia (OV-102); Discovery (OV-103); Endeavour (OV-105); Enterprise (OV-101)
Space Shuttle missions
  STS-1, **374**, **376**, 382, **406**
  STS-1 through STS-33, **406**
  STS-2, **376**, **406**
  STS-3, **376**, **377**, **406**
  STS-4, **376**, **406**
  STS-5, 378, **406**
  STS-26R, 384, 394, 399, 467n51
  STS-26R suits, **406**
  STS-63, **406**
  STS-64, **406**
  STS-66, **406**
  STS-67, **406**
  STS-68, **406**
  STS-69, **406**
  STS-70, **406**
  STS-71, **406**
  STS-72, **406**
  STS-73, **406**
  STS-74, **406**
  STS-75, **406**
  STS-76, **406**
  STS-77, **406**
  STS-78, **406**

STS-79, **406**
STS-80, **406**
STS-81, **406**
STS-82, **407**
STS-83, **407**
STS-84, **407**
STS-85, **407**
STS-86, **407**
STS-87, **407**
STS-88, **407**
STS-89, **407**
STS-90, **407**
STS-91, **407**
STS-92, **407**
STS-93, **407**
STS-94, **407**
STS-95, **403**, **407**
STS-96, **407**
STS-97, **407**
STS-98, 399, **407**
STS-99, **407**
STS-101, **407**
STS-102 through STS-135, **407**
STS-103, **407**
STS-106, **407**
STS-107, **408**, 410–11
STS-129, **399**
STS-132, **404–5**
Space Station, 371, 410
spacesuits
development and manufacturing of, 363
for EVA, 365
full-pressure suits as, 217, 233–35, **234**
Mark III suit testing and, 223, 224
Mark IV suit modification, **231**, 233, **234**, 235
as pressure suit, 25
pressure suits compared to, xi–xii
reflective fabric for, **259**, 260–61, **261**
T-1 and S-2 suits not spacesuits, 136
T-1 suits publicized as, 140
See also Apollo program; Gemini program spacesuits; Mercury program
Spain, 36, 39–40
spatial disorientation, 43
SPD-117 full-pressure suit, **232**, 235
special project suits
David Clark Company suits, 279
flotation system, 316
full-pressure suit use, 264
S901H suit. *See* S901H special projects suit
S901J suit. *See* S901J Pilots Protective Assembly (PPA)
speed jeans, 110. *See also* CSU-13B/P G-suits
Spencer, Inc., 92
Spencer Abdominal Support Belt, 92
Spencer Ltd., 92
Spencer Supports Ltd., 92
Sperry Gyroscope, 76, 80
Spitfire aircraft
Franks Flying Suit, testing of, 87
Mk IX aircraft, 437n18
Mk V aircraft, 85, **85**
PR.XI aircraft, 124, **125**, 437n18
Spooner, David C., 104, 115, 126
Sprague, Stanley, 274
Sprengel, Hermann, 18
Sprengel pump, 18
SR-71 Blackbird aircraft
A-12 revival plan and Beale AFB airspace, 316
aircraft design and development, 127
basis for design, 322
black painted surfaces, **311**
breakup of SR-71A and suit performance, vi, **409**, 410, 411
cockpits, pressurized, 377–78
David Clark Company suits for, 279
depot for suit maintenance, testing, and logistical support, 265
designation as SR, 322–23, 461n41
Edwards AFB as base for, 324
ejection seats, **323**, 324, 374, 375, 403
first flight, 314, 323–24
fleet size, 324
flotation system for crew, 395
operational flights, delivery for, 324
as Oxcart replacement, 316
parachute, main canopy, 408
Physiological Support Division, support from, 265
pressure suit requirements, vi, 363, 403
range and capabilities, 322, **322**, **330**, 344
reconnaissance missions, 322
reconnaissance sensors and equipment, 311
record-setting flights, **330**, 344
retirement of, 363
S901J Pilots Protective Assembly, 324–31, **325**, **326**, **327**, **328**, **329**, **330**, **331**, 334, 339, **409**, 410, 411
S1030 and S1030A suits, hardware sharing between, 378
S1030 Pilots Protective Assembly, 334, 339–41, **340**
S1031C common suit Pilots Protective Assembly, 334, 349, 350, 351, **354**
seat kits, **324**
Senior Crown program, 322–24, 334, 363

SR-71B trainers, 324
test flights, 323–24
titanium construction, 329
transfer of aircraft to NASA, 155
Stanley, Robert M., 51–52
Stapp, John Paul, 77, 162, 258, 264
Stargazer, Project, 165, **166**
Stevens, J., 30
Stewart, William K., 82–83, 87, 427n58
Straightaway garment, 96–97, 98–99
Strategic Air Command (SAC)
bombing strategy, 286
CSU-4/P suits, 171
MB-5 helmet use, 139
pressure suit requirements, 142, 144, 156, 239
pressure suit use, 159–60
SR-71 aircraft use, 322
T-1 suit use, 141
Strategic Reconnaissance Wing, 9th, 324
Strato Equipment Company
BABM suits, 46, 62, 179
founding of, 179
Model 7 full-pressure suit, 179–81, **179**, **180**
Strato-Lab environmental chamber, Boeing, 47, **59**
Strato-Lab project, 231–33
stratopause, 20
stratosphere, 18–20, 29
Strato-Suit. *See* Type 3 “Strato-Suit”; Type 5/5E “Strato-Suit”; Type 6/6A/6B “Strato-Suit”
Streak Eagle, 175
Streak Eagle, **292**, 293, **293**, **294**
stress and fatigue
COMBAT EDGE and, 114
full-pressure suits and, 237
heat fatigue and partial-pressure suits, 271
high-altitude flight and, 43
partial-pressure suits with full-pressure helmets, 317–18
suit-induced, v, vi, 56, 350–51
Strughold, Hubertus, 82
suit controllers
A/P22S-2 full-pressure suit, **268**, 272, 276, 283
A/P22S-6 full-pressure suit, 291
Firewel automatic controllers, 216–17
Firewel controllers, 154, 276
Mark IV pressure suit, 276
MC-2 full-pressure suit, **256**
Omni-Environment Suit, 198, **201**, 202, **203**
partial-pressure suits, 154, 158–59, 168, 174
S-100 partial-pressure suit, 320–21
S901J Pilots Protective Assembly, 329
S1030A Ejection Escape System suits, 378
S1030 Pilots Protective Assembly, **393**, 394
S1032 Launch Entry Suit, **391**, **393**, 394, **400**
S1034 Pilots Protective Assembly, 358
S1035 Advanced Crew Escape Suit, **400**
Sukhoi Su-27 aircraft, 293
Sullivan, J.E., 206
Superior, Lake, 282
Supermarine S.6B aircraft, 72, 73
Supermarine Spitfire aircraft. *See* Spitfire aircraft
supersonic aircraft
fighter aircraft, 301
pressure suit development for, 135
surplus suits and helmets, ads for and sale, **160**, 161, **161**
Sustained Tolerance for Increased G G-trouser, 114
Swain, F.D.R. “Ferdie,” 41, **41**, 419n77–78
Sweden
Libelle G-Multiplus G-suit testing, 115–16
pressure-breathing (counter-pressure) vest and trouser use, 174
Project SOLVE, 357
Tactical Flight Combat Suit (TFCS), 110
Switzerland, 115
syncope, 145–46
Systems Research Laboratories, 118

T

T-1 partial-pressure suits
contracts for, cancellation of, 156–57
cost of, 138
development and specifications, 133, 136–41, **137**, **138**, **139**, 146, 240
distribution and use of, 140–41
long underwear use with, 138, 144
mobility of suits and ejection initiation, 167–68, **168**
S393 suit, 136
sizing of, 136, 144
sleeve length, 144
surplus suits, ads for and sale of, 161
T-1A suit, 156–57
weight of, 136, 439n70
T-33B/TO2/TV2 Shooting Star trainer (T-33 T-Bird trainer), 193, 209, 256–57, 445n23
T-38 aircraft, 395
Tabor, Richard H., **221**, 223
Tactical Air Command (TAC)
air-conditioned vehicles for pilots, 226
aircraft design and development, 146
A/P22S-2 suit testing and use, 274

A/P22S-3 suit use, 274
bases of, 274
high-altitude flight, 286
jerkin and jerkin-based ensembles, 274
MC-3/3A suits, 156
pressure suit requirements, 155–56, 295–96
Tactical Flight Combat Suit (TFCS), 110
Tactical Life Support System (TLSS) program, 111–13, 114, 160
TAC Trucks, 226
Tagboard, 314–16
Taiwan (Republic of China) Air Force, 153, 156, 337, **338**
Taylor, Rowena, 463n78
temperature and exposure protection
A-12 ejection and S901 suit, **303**, 304–5
altitude and, 18, 19, 20, 23, 25
early suit designs and protection from cold, 27
liquid-cooling garments, 173–74, 408–9
in stratosphere, 18–20
suit performance requirements, vi, xii, 240
suit performance testing, 281–82
thermal exposure, 22, 23, 42
water-immersion protection, xii, 282, 393, 394, 395
Tempier, Étienne, 15–16
Terylene fabric, 274
Test Location (The Ranch), 150. *See also* Groom Lake
Test Pilot School (Aerospace Research Pilots School), 265, 278
TF33 turbofan engines, 286
TF-104G trainer aircraft, 176
TFCS (Tactical Flight Combat Suit), 110
The Ranch (Test Location), 150, 460n24. *See also* Groom Lake
thermopause, 20
thermosphere, 20
Thomas, Bredette C. "B.C.," Jr., 343
Thompson, Robert H., 83–84
Thompson Trophy Race, 132
3M (Minnesota Mining and Manufacturing Company) fabric, 210
thrust bearing joints, 174, 192–94, 193
Thurston, Albert P., 71, 73, 424n3
Tissandier, Gaston, 41
Titanium Goose trainer, 312
TLSS (Tactical Life Support System) program, 111–13, 114, 160
TO2/TV2/T-33B Shooting Star trainer (T-33 T-Bird trainer), 193, 209, 256–57, 445n23
Todd Shipyards, 154
Toepler, August, 18
Toepler pump, 18
tomato-worm suit, 56–57, **57**, 195. *See also* XH-5 pressure suit (tomato-worm suit), B.F. Goodrich Company
torr, 17, 20
Torricelli, Evangelista, 16–17
Torricelli's Theorem, 17
Torrick, Ray, 315–16, 346, 460n31
Towle, Joe, 124
TR-1 aircraft, 348
tractor rocket-extraction system, 383–84
Transcontinental and Western Airlines (TWA), 35, 418n54
transverse acceleration (Gx), **72**, 73
Trans World Airlines, 418n54
Trilok fabric, 173, **221**, 228, 263
Tripp, Lloyd D., Jr., 118
tropopause, 18
troposphere, 18
trousers
extended-coverage G-trousers, 113, 114, 116
inflatable, 123
jerkin-based ensemble, 176
Truax Air Force Base, 279
Truly, Richard H., **376**
TSR.2 aircraft, 174
Tupolev Tu-4 bomber aircraft, 146–47
turbojet engines. *See* engines
TV2/TO2/T-33B Shooting Star trainer (T-33 T-Bird trainer), 193, 209, 256–57, 445n23
Tyndall Air Force Base, 264, 265, 279, 318
Type 1 pressure suit, United States Rubber, 44–45, **44**
Type 2 pressure suit, United States Rubber, **44**, 45
Type 3 "Strato-Suit," B.F. Goodrich Company, 43, 420n89
Type 4/4A pressure suit, United States Rubber, **44**, 49
Type 5/5E "Strato-Suit," B.F. Goodrich Company, **44**, 45–46, 47, 61–62, **62**, **63**
Type 6/6A/6B "Strato-Suit," B.F. Goodrich Company, **44**, 47, 57
Type 7 pressure suit, National Carbon Company, **44**, 50–51
Type 8/8A pressure suit, B.F. Goodrich Company, **44**, 47
Type 9/9A pressure suit, Goodyear Tire & Rubber, **44**, 47, 53–54, **53**, 420n102
Type A (altitude) suits, 45, 420n90
Type G (gravity) suits, 45, 420n90
Typhoon fighters, 114

U

U-2 spy plane "Dragon Lady"
A-12 aircraft compared to, 302
advances in suit development and, vi

A/P22S-2 full-pressure suit use, 271–72, 317
Article 341, 150
autopilot, 151
cockpits, pressurized, 377–78
construction and specifications, 151, **158**
cover stories for, 151
depot for suit maintenance, testing, and logistical support, 265
development of, 127, 149–50
ejection seats, 151, 334, 403
engine flameout issues, 151
flight characteristics, 151
in-flight refueling, 334
Groom Lake testing and maintenance, 150, **155**, 156, 265
helmet modifications with Link-Net fabric, v, 155
helmets for, vi
inventory of suits, 363
landing gear, **152**
MC-3/3A partial-pressure suit use, v, xi, 148–49, 153–55, 156, **157**, 239
NASA use of, **321**
operational flights, 322
operational period for, 301
phase-out of, 355
pilot compensation and insurance arrangements, 305
pilots for, 151, 153–55
pressure suit requirements, v, 363, 403
project names, 150
range and capabilities, 148, 151, 334
reconnaissance missions, xi, 301–2
reconnaissance sensors and equipment, **333**
retirement of, 363
S-100 partial-pressure suit use, **317**, 318, **319**, **320**
S901/S901J suit use, 334, 335
S1031 Pilots Protective Assembly, 345, 348
S1034E helmet testing, 361
S1034 Pilots Protective Assembly, 349, **355**, 358–61
Senior Year program, 363
Soviet shoot-down of, 156, 301–2, 314
suit-induced stress and fatigue, v
U-2A aircraft, 150, 151, **158**
U-2C (ER-1) aircraft, **319**, **321**
U-2C (U-2L) aircraft, **319**, **321**, **332**, 334
U-2R spy plane
cockpits, pressurized, 377–78
development of, 334
Earth resource (ER-2) aircraft (NASA), **332**, 348, 355, **357**
parachute, main canopy, 408
range, capabilities, and pressure suit requirements, **332**, **333**, 334
S1010D helmet use, 386
S1010 Pilots Protective Assembly, 334–39, **338**
S1030 helmets, 334, 339
S1031 Pilots Protective Assembly, **345**, 348–49
S1031C common suit Pilots Protective Assembly, 334, 349, 350, 351, **354**
S1034 Pilots Protective Assembly, 361
as U-2 replacement, 153
U-2S aircraft and flights, 333, 348, **354**, 361
ultraviolet radiation, 19
underwear and long underwear
A/P22S-2 suit, 263, 283
A/P22S-3 suit, 282
A/P22S-6/6A suit, 290
CSU-4/P suit, 282
jerkin and jerkin-based ensembles, 175
Mark III suit, **221**, 222
Mark IV suit, 228
MC-2 suits, 253
MC-3/3A suit, 162
Ridge suit, 27
S-2 partial-pressure suit, 138, 144
S-100 suit, 320
S901F suit, 308
S1030 suit, 341
S1032 suit, **387**
S1035 suit, 408
Strato-Suit, 69
T-1 partial-pressure suits, 138, 144
urine-collection system, 311, 357–58
United Aircraft Corporation, Hamilton Standard Division, 371, 372–73
United States
G-suit development, x
pressure suit development by, 36
Soviets, strategic bombing threat from, 146–47
United States Rubber
Army, pressure suit development for, 43–45, 49, 52–53, 54, 420n90
cost of pressure suits, 44, 45, 49
fabrics and materials for suits, 44, 49
full-pressure suits, development of, 362
G-suit development, 44, 45
helmets, 44–45
MX-117 project suits, 52
Navy, pressure suit testing by, 61
pressure suit development, coordination of research for, 52–53
Trilok fabric, 173
Type 1 pressure suit, 44–45, **44**

Type 2 pressure suit, **44**, 45
Type 4/4A pressure suit, **44**, 49
Type A (altitude) suits, 45, 420n90
Type G (gravity) suits, 45, 420n90
XH-2 pressure suit, **44**, 47, 54
XH-4 pressure suit, **44**
University of Massachusetts Medical School, 98
University of Minnesota, Department of Aeronautical Engineering, 46
University of Southern California (USC)
Aeromedical Laboratory, 125, 437n20
altitude chamber, 128
Bell XS-1 (X-1) program, pressure suite for, 126–27
counter-pressure and acceleration protective clothing, research on, 125, 437n20
General Electric G-suit, testing of, 126
Henry Suit (S-1 partial-pressure suit), 125–30, **129**, **130**, 132–34, **134**, 135–36, 179, 437n32
human centrifuge, 77, 104, 126
MX projects and security related to, 134
pressure breathing research, 126
T-1 suits, testing of, 139
Wright Field, relationship with, 125
University of Sydney centrifuge, 75, **75**, 84
urine-collection system, vi
A/P22S-6A suit, 290, 311
components of, 290, 335
S901H special projects suit, 311, **335**, 340
S901J Pilots Protective Assembly, 326
S901J special projects suit, 311
S1010 Pilots Protective Assembly, 337
S1030 Pilots Protective Assembly, 339–40
S1031C common suit Pilots Protective Assembly, 349
S1032 Launch Entry Suit (LES), 387
S1034 Pilots Protective Assembly, 357–58, 408
S1035 Advanced Crew Escape Suit, 401, 408
underwear, 311, 357–58

V

vacuum
atmospheric pressure, 16–17
blood boiling in, 22, 75
concept of, 16
definition of, 15
existence of, debate about, 15–16, 413n4
pressure and, 16–18
vacuum pumps
G-suit pressurization, 93, 95, 102
invention of and experiments with, 17, 414n14
pressurizing valves, 95, **95**
Sprengel pump, 18
Type B-2/B-3 pumps, 93
Type B-11/B-12 pumps, 95
vacuum tubes, 18
Vail, Edwin G., 233, 235, **249**
Van Orman, Ward T., 47, 54, 60, 422n120
Vega aircraft, v, 28–29, 33. *See also Winnie Mae*
ventilation
conditioned air supply equipment (CASE), 224, **226**
exhaust-valve system, 226
face seals versus neck seals, 258–59
Goodrich suits, **226**
importance of, 258
lack of in early suits, 182
Mark IV pressure suit, 230
MC-2 full-pressure suit, 256
Omni-Environment Suit, 183, 187, 209, 211
oxygen use for, 258–59
portable air-conditioning equipment, 225–26, **225**, **275**
S901 full-pressure suit, 309–10
ventilation garments
A/P22S-2 full-pressure suit, 263
CSU-4/P partial-pressure suit, 170, 171
CSU-5/P partial-pressure suit, 173
Goodrich suits, 222
MA-3 ventilation garment, 170
MC-2 full-pressure suit, 260
Versoy, Irving "Doc," 92, 106
vertigo, 43
vests
COMBAT EDGE counter-pressure vests, 113, 114
CSU-17/P counter-pressure vest, 114
CSU-21/P counter-pressure vest, 114, 117
jerkin and jerkin-based ensembles, 174–77, **177**
Model 7 full-pressure suit pressure-breathing vest, 181
pressure-breathing (counter-pressure) vests, x, xi, 110, 123, 124, 174
pressure vest/torso garment for TLSS, 112
VF-8 Ghost Cats fighter squadron, 94
VF-142 Flying Falcons fighter squadron, 226
Vida, Joseph T. "J.T.," **343**, **344**
Vietnam
Black Shield operations, 314
North Vietnam operations, A-12 revival for, 316
Vinyl Technology, Inc., 116
vision
acceleration and, 43, 73, 80, **81**, 425n15
cone cells/cone vision, 73, 425n15
visors and goggles
acrylic visors, 328, 334, 359
A/P22S-2 full-pressure suit, 266, 269, 276, 277, 283

A/P22S-6 full-pressure suit, **289**
B-8 goggles, 127, 130
bailer bar, 331, **339**, **348**, 386
faceplates and visual field, 268
fogging of visor, 219
glass visors, **328**, 334
Goodrich suits, **212**, 221
heated visors, 262, 269, 319, **328**, 353
HGU-15/P helmet, 380
HGU-68/P helmet, 117
Mark II suit, **218**
Mark IV pressure suit, 228, 230
MC-2 suits, 262
Mercury program suits, 233, 235
Model 7 full-pressure suit goggle-mask, **180**, 181
movable visors, vi
S-100 partial-pressure suit, 319
S901 full-pressure suit, 306, 308, 309, 310
S901J Pilots Protective Assembly, 331
S1010 Pilots Protective Assembly, 338, **339**
S1032 Launch Entry Suit (LES), 386
S1034 Pilots Protective Assembly, **353**, 353, 358, 359
thermal-flash-protection goggles, 112
windblast evaluation, 117, **207**
Vohden, Arthur F., 223
Vojvodich, Mele, 312, 314
Volkov, Vladislav Nikolayevich, 371
Von Braun, Wernher, **227**
Voris, Frank S., 189
Vought F4U/F4U-1 Corsair, 93, **182**, 184, 187, 301
Vought F8U/F8U-1 (F-8A) Crusader, 220, 223, 224, 226, 230
Vought Systems Division, LTV Aerospace, 371, 372
Vultee, Gerard "Jerry," 28
Vultee SNV-1 trainer/BT-13A Valiant, 63

W

WADC (Wright Air Development Center), 205, 237
Waldenburg, Louis, 122
Waldenburg apparatuses, 122
Walker, Joseph A. "Joe"
A/P22S-2 full-pressure suit, 267
MC-2 full-pressure suit, 260, **261**
T-1 partial-pressure suit, **139**, 140
X-1E flights, **139**, 140
X-15 flights, **261**, 267
Walton, Jack, **169**
Warner Brothers, 109
water
Armstrong Line, xi, 22, 75
atmospheric pressure measurement, 20
exposure protection from suits, xii, 282, 393, 394, 395
G-suit bladder-fill material, x, 86–87, 88
Waters Company X-350 Oximeter, 122
Watertown Strip, 460n24. *See also* Groom Lake
water vapor
in atmospheric layers, 19, 20
percentages of atmospheric gases, **18**
Watt, James, 74
WB-57F aircraft
A/P22S-2 suit testing and use, 286, 287, 289–90
A/P22S-6/6A suit, replacement of, 361
A/P22S-6 suit testing and use, 287, 289–90, **289**, 291, 293, **294**
cockpits, roominess of, 289–90, **289**
design and development of, 286
ejection from, 290
missions of, 286
phase-out of, 355
Physiological Support Division, 265
range, capabilities, and pressure suit requirements, 286, 355
S901J special projects suit, 286–87
S1034 Pilots Protective Assembly, 361, 410
S1035 Advanced Crew Escape Suit, 410
weapons systems, YF-12A interceptor aircraft, **307**, 308
Weather Reconnaissance Squadron (WRS), 58th, 264, 286–87
Weaver, William A. "Bill," vi, 410
Weeks, Jack W., 312, 316
Weitz, Paul J., **376**
Weldon, Harry V.
Crossfield, relationship with, 199
Omni-Environment Suit testing, 187, 189, 192, 193–95, 196, 198–99, 202, 204, 206
Werlich, John B., 181
Westover, Oscar, 27–28
White, Robert M. "Bob," 260, 267, **271**
White, Stanley C., 233
White, William C., 165, **166**
Whitmore, Henry B., 293
Wiggins oxygen regulators, 61, 62, 63
Wilder, Henry, 99
Wildhack-Linde compensated exhalation valve, 127
Willis, Richard G., 262
Wilson, Charles P. "Chuck," **354**
windblast evaluations, 117, **207**, 411
Wingfoot Corporation, 54
Winnie Mae, v, 29–30, **31**, 32, 33, 34–35, **34**, **35**
Winter, William R., 173
Wise, John, 29
Witchell, Arthur S. "Doc," **136**

W.L. Gore & Associates, 463n78
Wood, Earl H.
Clark G-suit testing, 100, 181
Mayo Clinic centrifuge testing, 91–92, 99, 181
oximeter, development of, 122
on pilots use of suits, 104
Progressive Arterial Occlusion Suits (PAOS), 118
Wright Field meeting, 101, 103
Woolams, Jack, 132
Worcester Foundation for Experimental Biology/ Worcester Foundation for Biomedical Research, 98
Wright Air Development Center (WADC), 205, 237
Wright Field
Aero Medical Laboratory. *See* Aero Medical Laboratory, Wright Field
Aeromedical Research Unit, 43, 97, 425n24
altitude chamber, 28, 31, 57, **61**, 68, 124, 155, 417n37
Arterial Occlusion Suit, testing of, 101–2
Balloon Hangar centrifuge, 43, 74, 75, 77
Beaupre Multi-Stage Parachute and Project Excelsior, 162–65, **163**, **164**
Equipment Laboratory, 42–43, 44
General Electric G-suit, testing of, 126
G-suit research at, 43, 103, 104
Guardite Strato Chamber, 128, 130, 133, 139, 145
Henry Suit (S-1 partial-pressure suit), testing of, 128, 130, 133
human centrifuge, 126
human centrifuges, 43, 77, 95
Joint Services Pressure Breathing Conference, 124
MC-1 suit, testing of, 145
MC-3 suit, testing of, 155
MX-829 project, conference about, 135
Physiological Research Unit, 42, 74–75, 425n24
pilot protective clothing, conference on, 103
pressure suit conference, 233
suit testing at, 28, 31
T-1 suits, testing of, 139
See also Wright-Patterson Air Force Base
Wright J-5 Whirlwind engine, 28
Wright J65 turbojet engines, 286
Wright-Patterson Air Force Base
Aeronautical Systems Division, 262, 266, 267, 295–96, 299
Aerospace Medical Research Laboratory and Systems Engineering Group, 6570th, 283
A/P22S-2 suit testing, 266
Atlantis Warrior program testing, 114
Dynamic Environment Simulator, **119**
G-suit development, 118
See also Wright Field
wrist rings
glove disconnect incident and problems, 278–79, 284
inadvertent control actuation with, 211, 273
latches on, 284
molded flanges for, 283
rotating bearing rings, 277, 284
S1035 Advanced Crew Escape Suit (ACES), **399**
as standard construction, 196

X

X-1 aircraft. *See* XS-1 (X-1) rocket-powered aircraft
X-2 aircraft, **138**, 205, 244, 245
X-3 aircraft, 205
X-15 program
airframe and engines, development of, 244
A/P22S-2 suit testing and use, 267, 268–69, 273, 277–78, **278**
centrifuge for pilot training, **78**, **79**, 80
delivery schedule for suits, 258
depot for suit maintenance, testing, and logistical support, 264
ejection seats, 245, 258, 261, 277, 374–75
escape (ejection) capsule, 244–45
face seals versus neck seals, 258–59
flight operations, 267
full-pressure suits for, v–vi, ix
funding for suits, 258
MC-2 full-pressure suit, 278
MC-2 suit, 229, 243–62. *See also* MC-2 full-pressure suit
mission marks on life-support van, **278**
modern-day suit development and X-15 suit, v–vi
NB-52 carrier aircraft, launch from, 261
nitrogen to pressurize cockpit and suit, 259, 261–62, 453n54
number of flights with MC-2 suits, 261, 262
oxygen supply and systems, **256**, 258–59, **259**, 261–62
performance requirements for suits, vi
seat kits versus back kits for suits, **256**, 258, **273**, 277
visors, power for heating after ejection, 269
X-1E flights and, 139
X-16 aircraft, 149–50
X-24B lifting body, **276**
XA-13 pressure-breathing mask, 123–24
XB-58 cockpit mockup, 210, **212**, 216, 240
XB-70/XB-70A Valkyrie, vi, 237, **238**, 265, 291, 461n41
XC-35 aircraft, 43

XF4D Skyray, **199**, **200**, 201–2, 204, 211
XF-11 aircraft, 149
XF-12 Rainbow, 149
XF-103/F-103 aircraft, 237, 240
XF-104 aircraft, 141
XH-1/XH-1C pressure suit, B.F. Goodrich Company, **44**, 51, **51**, 54, 56
XH-2 pressure suit, United States Rubber, **44**, 47, 54
XH-3/XH-3A/XH-3B pressure suit, Goodyear Tire & Rubber, **44**, 54–56, **54**, 60, **66**, 68
XH-4 pressure suit, United States Rubber, **44**
XH-5 pressure suit (tomato-worm suit), B.F. Goodrich Company, **44**, 56–57, **57**, 60, **60**, **61**, 68, 195
XH-6/XH-6B pressure suit, B.F. Goodrich Company, **44**, 54, 56, **56**
XH-7 pressure suit, National Carbonic, **44**
XH-8 pressure suit, **44**
XH-9 pressure suit, Goodyear Tire & Rubber, **44**
XLR11 rocket engines, 209, 447n46
XLR99 rocket engines, 244
XMC-2-DC suits, 243, 244, 246–53, **248**, **249**
XMC-2-ILC suits, 232, 243, 244, **245**, 246, 248, 252–53
X-planes, Round One, 244
X-planes, Round Two, 244
XS-1 (X-1) rocket-powered aircraft
    altitude restrictions on flights, 135
    emergency use of partial-pressure suit, 135
    hatch size, **131**, 132
    Henry Suit for, 132, 133, **134**
    photo of, **131**
    pressure suit for, v, ix, 126, 244
    record-setting flights, 135
    X-1A flight, 15
    X-1E flights, **139**, 140
    Yeager flight, 134, 135

Y

Yale University
    capstan-controlled leg pressure G-suits, x, 115, 126
    John B. Pierce Laboratory, 122
Yeager, Charles E. “Chuck,” 133, 134, 135, **140**
YF-12A/AF-12 interceptor aircraft
    cancellation of, 308
    contract for development, 308
    design and development of, 308
    Edwards AFB as base for, 324
    fleet size, proposed, 308
    Groom Lake testing, 308
    number built, 240
    Physiological Support Division, support from, 265
    range and capabilities, 240, **307**
    record-setting flights, **309**
    S901F full-pressure suit, 308–10, **309**
    S901J suit, **327**, **331**
    titanium construction, 329
    weapons systems, **307**, 308
YF-12/SR-71 Test Force, 324
YF-86D aircraft, 137
YF-93A aircraft, 137
YF-100 Super Sabre, 301
Yielding, Raymond E. “Ed,” **344**
YKK Group (Yoshida Manufacturing Corporation/ Yoshida Kogy Kabushikigaisha), 352, 443n161
Young, James O., 134
Young, John W., 375, **376**, 380, 382

Z

Z-3 (G-4/G-4A) suits, 107–8, 109, 222, 439n70
Zero aircraft, 85, 94
zippers and fasteners
    airtight zipper, development of, 54, 180
    A/P22S-2 full-pressure suit, 173, 263, 266, **266**, 267, 268, **268**, 269, 272, 274, 283, **285**, **305**
    A/P22S-4 full-pressure suit, 283
    BABM suits, 62
    Berger Brothers G-suits, 92, **93**, 94
    Cotton Aerodynamic Anti-G Suit, 85
    CSU-2/P partial-pressure suit, 167
    CSU-4/P partial-pressure suit, 171
    CSU-5/P partial-pressure suit, 172–73, 443n161
    Durkee Atwood Company zipper, 180
    Franks Flying Suit, 87, 88
    full-pressure suits, 263
    Gemini program suits, 283
    Goodrich suits, 56, 61, 69, 218
    Goodrich zippers and fasteners, 172–73, 274, 352
    Goodyear suits, **53**, 54, 63, 64
    Goodyear zippers, 54, 180
    Henry Suit (S-1 partial-pressure suit), 130, 133
    Mark IV suit, 180, **216**, 228
    MC-3/3A partial-pressure suit, 155, 159
    Model 7 full-pressure suit, **180**
    Omni-Environment Suit, 181, 184, 185, **186**, 187, 190, 201, 205, **205**, 206, **207**, 210–11
    S-100 partial-pressure suit, 321
    S901 full-pressure suit, **305**, 306, 310
    S901H special projects suit, 310
    S901J Pilots Protective Assembly, 306, 328
    S970 full-pressure suit, 306, **310**, 311

S1031 Pilots Protective Assembly, 352
S1034 Pilots Protective Assembly, 352, 359
S1035 Advanced Crew Escape Suit (ACES), **403**
Sam Browne configuration, 218
sealing slide fasteners, 172–73, 443n161
U.S. Rubber suits, 45, **50**, 61
See also lace-adjustment features
Zoot Suit, 85. *See also* Cotton Aerodynamic Anti-G Suit
Zwayer, James T. "Jim," 410

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ACKNOWLEDGEMENTS

This book would not be possible without the following design and editorial support: the design work of Lillian Gipson; the initial editing of James Schultz; and the design and editorial services of the NASA Headquarters Communication Support Services Center, specifically Christopher Yates and Benjamin Weinstein for editorial work and Tun Hla, who saw the book through the publication process.

Anybody who has watched many movies or television shows has seen them—the ubiquitous silver suits worn by pilots as they explore the unknown. They are called pressure suits, and one can trace their lineage to Wiley Post or, perhaps, a bit earlier.

There are two kinds of pressure suits: partial pressure and full pressure. David Clark, the man, once pointed out that these were not very good names, but they are the ones that stuck. In a partial-pressure suit, the counter-pressure is not as complete as in a full-pressure suit, but it is placed so that shifts in body fluids are kept within reasonable limits. On the other hand, a full-pressure suit, which is an anthropomorphic pressure vessel, creates an artificial environment for the pilot.

One type of pressure suit is not necessarily "better" than the other, and both partial pressure and full pressure suits are still in limited use around the world. Both type of suits have benefits and limitations and, by and large, pilots dislike both, even while acknowledging their necessity. For the past 60 years, they have been an indispensible part of a small fragment of the aviation world.

Although space suits, which differ from pressure suits in subtle, but important ways, have been well covered in literature, pressure suits have gone unheralded except as introductions to the space suit histories. This book is an attempt to correct that, and covers pressure suits from the beginning through the end of the Space Shuttle Program.

Legendary test pilot Capt. Iven C. Kincheloe, Jr., poses in front of a McDonnell F-101 Voodoo wearing an MC-3 partial pressure suit. Kincheloe became the first person to fly above 100,000 feet while flying the Bell X-2 using a partial pressure suit.
– Dorothy Kincheloe Collection

Another legendary test pilot, A. Scott Crossfield shows off an early David Clark Company MC-2 full-pressure suit in front of the Wright Field altitude chamber. The sign indicates the chamber was limited to 85,000 feet. Of note is the thickness of the raised entry door.
– National Archives College Park Collection

National Aeronautics and Space Administration

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300 E. Street, SW
Washington, DC 20546

www.nasa.gov

ISBN 978-0-16-090110-2
90000

NASA SP-2011-595