Reflections on the Origin and Early History of the Applied Physics Laboratory

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The Laboratory Today

Established thirty-four years ago, the Applied Physics Laboratory (APL) is one of the youngest divisions of The Johns Hopkins University (JHU) whose centennial we are celebrating in 1976. From its very inception, that University has been a leader in the discovery of new knowledge and its application to the needs of society. This is attested to by its worldwide reputation in the fields of advanced education, medicine, public health, and international studies. The desire to make significant contributions to public welfare has been the dominant motivation that has brought and held together APL's staff. The primary mission of the Laboratory is the application of advanced science and technology to the enhancement of the security of the United States of America and the conduct of basic research and engineering in fields where its competence and facilities may make especially favorable contributions to problems of general interest to society. These fields now include space exploration, navigation, environmental studies, biomedical engineering, civil air control, transportation, fire research, and the development of sources of energy.

The activities of the Laboratory are focused in a complex of buildings in rural Howard County, Maryland, near Scaggsville (Fig. 1), but it maintains branches in Port Hueneme, Cali-

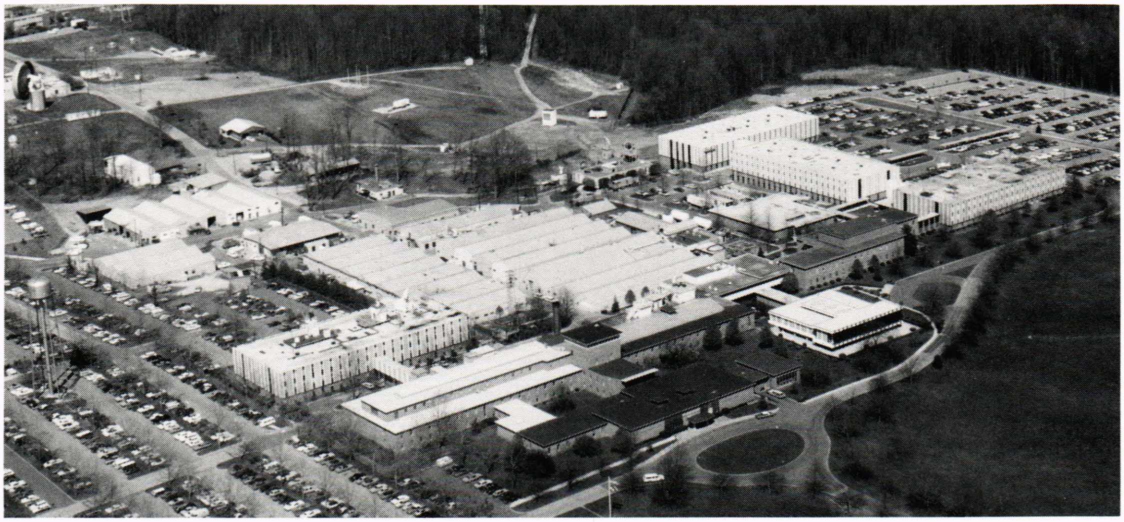

Fig. 1—Aerial view of the Headquarters of the Applied Physics Laboratory, April 1976.

fornia; Green River, Utah; White Sands, New Mexico; Wallops Island, Virginia; Princeton, New Jersey; Pomona, California; Heidelberg, Germany; Cape Canaveral, Florida; and in Silver Spring, Maryland. (The Laboratory relinquished the building at 8621 Georgia Avenue, Silver Spring, after 24 years of occupancy, from April 1942 to June 1976.) Its ideas are implemented and extended by a network of associate contractors reaching from coast to coast. There are approximately 2400 people on the staff of APL, a number that has varied by no more than four percent over the past fourteen years in accordance with a self-imposed policy adopted in 1962. Of these, 1250 are professional scientists and engineers, 170 holding doctors degrees and 450 having masters degrees. Thirty members of the professional staff have been with the Laboratory more than thirty years, 263 between twenty and thirty years, and 753 between ten and twenty years. This represents an aggregate of more than 160 man-centuries of corporate experience in guided missiles, satellites, and related fields of science and engineering. Although it is only comparatively recently that the Laboratory has devoted a significant part of its effort to biomedical engineering, its total experience in that field already exceeds one and one-half man-centuries.

On the academic side of the Laboratory, individuals and small groups in the Research Center and in the Space Physics and Instrumentation Group of the Space Department carry out fundamental research investigations whose results are published in scientific journals. The Laboratory has been host to a number of visiting fellows from this country and abroad who have desired to take part in certain research programs. It has also sponsored the thesis work for a considerable number of graduate students.

The Library, containing about 40,000 volumes, is always open to the staff and to visitors. It has close relations, including loan privileges, with all the main libraries in the Baltimore-Washington area and, indeed, initiated and now participates in the maintenance of an up-to-date index of the journal holdings in most of the special libraries in this area.

The JHU Evening College Center at APL, whose faculty is drawn from members of the APL staff, offers five curricula leading to Master of Science degrees in Electrical Engineering, Numerical Science, Applied Physics, Space Technology, and Computer Science for the benefit of the APL staff and the employees of neighboring organizations. About 400 individuals take these courses annually, 25% being younger members of the APL staff. Over the past eight years approximately 70% of all the Master of Science degrees in technical subjects awarded by the University have been earned by candidates from the APL branch of the Evening College. Another less obvious, but very important, phase of the Laboratory's work has been the education of the staff of associate contractors in new concepts and techniques in the design and control of missiles, satellites, and other devices it has developed.

The Laboratory's work is supported almost entirely by funds from agencies of the Federal Government: the Navy, Army, and Transportation Departments; the National Institutes of Health; and the National Aeronautics and Space Administration. For historical reasons that will become apparent later, by far the greatest amount of this support, over 80%, comes from the Navy which has provided the equipment and furnishings of APL and whose requirements have first call on the Laboratory's efforts under an agreement signed by representatives of the Navy and the University in 1968. The title to all the land and the buildings at Howard County is held by the University. Such is a thumbnail sketch of the Applied Physics Laboratory as it is today.

The Historian's Task

In addressing myself to the main object of this paper, I soon found out that the condensation of thirty-four years of intense activity into 32 pages of faithful narrative that might interest, instruct, and not bore a general audience is a well-nigh impossible task. An account of the history of APL cannot be exhaustive without being exhausting. Furthermore, experience has convinced me of the truth of the words of Horace, *"Brevis esse laboro, obscurus fio."*[1]

For the real story of APL, as of many other organizations and enterprises, is shaped by the values of people strongly influenced by the times in which they find themselves, by their common goals, by strong personalities that lead them to these goals, and especially by the attitudes,

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[1] From *Ars Poetica,* freely translated. "When I struggle to be brief, I become unintelligible."

thoughts, and actions of all individuals who have taken part in the life of the organization. The resultant is a complex and intricate tapestry of personalities, facilities, decisions, and events through which the historian must trace coherent and characteristic elements that portray significant movements in true perspective, avoiding lengthy catalogues of names, dates, and events, interesting as those might be to sophisticated and involved readers. The tapestry on which the experience of APL has been woven day by day and year by year is a most complicated and intricate one. Many hundreds of individuals have made significant contributions to its design; many hundreds more have added lesser, but essential, threads to its texture. Indeed, of the thousands of individuals who have worked at APL, it is hard to find many whose participation in its life and work can be called negligible. Even to list the names with a single sentence about the work of each of these people would occupy this entire paper and have the completeness and general interest of a telephone directory.

Any faithful history must maintain a proper balance of foresight and hindsight. That reputedly 20-20 vision called "hindsight" can be treacherous. It can lead the chronicler to write of past events not as they really occurred, but as it would have been nice for them to have occurred. It can degenerate into second guessing—the refuge of the critic who, himself having avoided hard decisions, takes pleasure in magnifying the mistakes of those who took the responsibility. To preserve this balance, the historian must try to resuscitate the spirit of the times in which decisions and actions were taken that molded the movements he desires to describe and to do so without passing judgment.

The programs and projects on which APL's efforts have been focused have proliferated in breadth, depth, and scope in a rational progression. The development of a single component of a shell, the VT fuze, led to the development, care, and nurture of a family of guided missiles, each an assembly of many components. This led to involvement to a greater or lesser degree in the development and evaluation of complete systems operating under water, on the surface, in the air, and in space—all assemblies of many more components. The history of this progression cannot really be set forth intelligently without a detailed description of the technological problems that were encountered and solved—a very long story. Therefore, this relatively short paper is limited to reflections on the external and internal factors which, by influencing the administrative and technological education of the Laboratory, brought about the movements that underlie its history. The narrative is illustrated by pictures of the buildings and other facilities used by APL. They are symbols of the bases or homes where the products of the minds and hands of people were generated, symbols of the social and political climate in which people worked, and reminders of successes and failures.

The Post-Depression Euphoria

Figure 2 shows a picture of the Cyclotron Building at the Department of Terrestrial Magnetism (DTM) of the Carnegie Institution of Washington. It was built in 1938 to extend the Department's work on high-energy physics. (Incidentally, it was the DTM that first repeated and verified in the United States the experiment on uranium fission of Hahn and Strassmann. Those were the halcyon days for most of us in this country. The memory of a "war to end wars" was fading in the distance. We were on the way to recovery from a severe economic depression. "Happy days were here again," and most of us were making the most of them immersed in our own interests—mine was research in physical chemistry—only dimly aware of the ominous changes taking place in Europe.

In 1937 a committee established by the National Research Council to advise on "Scientific

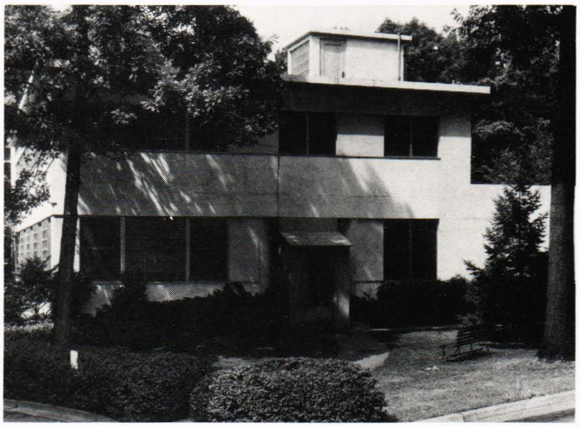

Fig. 2—Cyclotron Building, Department of Terrestrial Magnetism, Carnegie Institution of Washington, in 1940, when it became the birthplace of an interdisciplinary team of scientists and engineers developing a practical radio-proximity fuze.

Aids to Learning" brought together periodically in Washington a number of highly competent scientists and engineers among whom were Frank Kewett, James B. Conant, Richard C. Tolman, K. T. Compton, and Vannevar Bush, then President of the Carnegie Institution. After each meeting, they discussed their concern about the trend in international affairs, particularly the rising power of Hitler. In early 1940, their worry became acute. They were concerned that an extensive war was imminent, that it would be a highly technical struggle, that sooner or later the United States would be drawn into it in some way, that we were in no way prepared, and that the current military system, Navy and Army, would never fully produce the new instrumentalities that would be needed and that were possible in the state of science as it then existed. Here and there in the Army and the Navy there were brilliant, generally young, far-sighted officers who realized the dire need for new weapons and equipment, who had sound ideas on how they might be developed, but who were powerless to act because of lack of high-level interest and financial support brought about by the prevailing euphoria. In arsenals throughout the country, built in World War I to develop and supply new weapons and equipment and now supported practically on a caretaker basis, there were a few perceptive "voices crying in the wilderness," brilliant and knowledgeable people living in technological isolation. Even the medical and dental services associated with the Army and the Navy had fallen so low in competence as to be the scorn of their professional colleagues in civil life.

The Foundation Is Laid

Into this atmosphere was born the National Defense Research Committee (NDRC) for which Bush obtained the proper government authority, thanks to his acquaintance with men like Oscar Cox and Harry Hopkins, who had the ear of President Roosevelt and the know-how to "get things done" in Washington. An order signed by members of the Council for Defense on June 27, 1940 established the NDRC and specified as members the President of the National Academy of Sciences, the Commissioner of Patents, representatives from the Navy and Army, and persons to be nominated by Bush: Conant, Compton, and Tolman. Each member was given responsibility for a division of the Committee's operations, and authority to establish sections dealing with specific problems and to seek the cooperation of the keenest scientists and engineers in the universities and in the scientific and industrial institutions throughout the country. The response to their requests for assistance was amazing.

I should emphasize that a concept fundamental to the whole policy of the NDRC and later of the Office of Scientific Research and Development (OSRD) was that of *partnership of military men and civilians* in the development of equipment to support the Armed Services. Partnership is a relation between equals as opposed to the traditional master-servant or buyer-supplier relationship. Decisions concerning the planning and execution of military operations belonged to the Services who knew that business; decisions concerning the potential and conduct of technological developments belonged to the knowledgeable civilian agencies. The gray area of the requirements for and the potentials of military technology was the subject of dialogue between equals.

Among those responding to the call of the NDRC was a group in the DTM consisting of Merle A. Tuve, L. R. Hafstad, Richard B. Roberts, and their assistants, who interrupted their research in high-energy atomic physics to look for a problem in national defense to which they could contribute. They found one: the development of a *practical* radio proximity fuze, namely a fuze that would set off a shell or a bomb as it passed sufficiently close to an aircraft to do enough damage to neutralize the aircraft. The idea of a radio proximity fuze[2] itself was not new, *but the concept of how to reduce the idea to practice* was new and seemed to have a 10% chance of being successful. Bush supported it. Dr. Tuve was made head of Section T ("T" standing for Tuve) in Tolman's Division of Armor and Ordnance in NDRC, and was allotted funds to proceed. The operations started in August 1940 in the Cyclotron Building at the DTM whither Tuve and his colleagues brought a selection of the most brilliant and ingenious men from universities, research institutions, and industry who essentially donated their services. Furthermore, a special mission from Great Britain, which was already deeply involved

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[2] Later this type of fuze was called a variable time (VT) fuze to distinguish it from the fixed time fuze whose effectiveness depended on the gunner's ability to estimate the time the shell would take to travel from the muzzle of the gun to the target aircraft, a quantity extremely difficult to estimate with effective precision.

in the war with Germany, disclosed to Tuve and his group their work on proximity fuzes, especially the use of light beams as the detonating link. Thus began an era of international cooperation.

The interest and support of the Navy grew rapidly. Enemy aircraft were realized to be the greatest menace to our surface Navy at that time. Indeed, it was strongly maintained by writers in the press and elsewhere that the day of the battleship was over. The proximity fuze promised perhaps the greatest improvement then possible for increasing the effectiveness of the Navy antiaircraft guns. Young Navy officers joined with the scientists and engineers of Section T. The group soon realized that the development of proximity fuzes was part of a much larger problem, namely the defense of the Fleet against aircraft attack.

The first practical radio proximity fuze was in course of development in October 1940. By the time that the action at Pearl Harbor (December 7, 1941), followed a few days later by the sinking of the *Prince of Wales* and the *Repulse* by Japanese fliers, had demonstrated the devastating power of aircraft against ships of the line, the work of Section T had progressed to a point where the power and practicality of the radio proximity fuze were virtually assured. The Navy renewed pressure on NDRC to expedite the work to the utmost.

Tuve insisted that Section T must be expanded and given larger quarters than were available at DTM if the job were to be done. The OSRD, a branch of the Executive Office, which now comprised NDRC and its medical counterpart, the Committee on Medical Research, concluded a management contract with The Johns Hopkins University[3] as of March 10, 1942 and the contract with the Carnegie Institution was phased out. The Navy transferred $2,000,000 to OSRD for expansion of the work under the new contract. Commander W. S. Parsons was appointed special assistant to Bush, in overall charge of the Section T activities. Tuve continued as Chairman of the Section and Director of the Laboratory, Hafstad as Vice Chairman, and a young Baltimore banker and Trustee of the University, D. Luke Hopkins, became, on a voluntary basis, the authorized representative of the University to supervise all the administrative and business aspects of the new contract. Through his efforts, a garage building, known as the Wolfe Building, and surrounding ground were acquired in Silver Spring, Maryland (Fig. 3), and were converted and expanded as the need arose. The Wolfe Building was occupied in May 1942.[4]

The potential of the new proximity fuze was so great that the danger to our own forces from the information falling into enemy hands was a source of grave concern. Extensive precautions to avoid leaks were in effect. Only those whose talents and skills were needed to devise and make successfully the many component parts were privy to information, and even that was limited. However, the number of people not only at APL but in some fifty associated universities and industrial organizations reached into the thousands as the work progressed. Despite these and many other administrative difficulties, their efforts matured rapidly. In January 1943, the cruiser *Helena,* using radio-proximity-fuzed shells, brought down attacking Japanese aircraft. The Russians found out all they needed to know about the atomic bomb to make one of their own, but both the Russians and the Germans seem to have been completely ignorant of proximity fuze development in this country and were taken completely by surprise when it came into devastating action in the Battle of the Bulge.

I dwell on these early days of APL because they saw the establishment of a pattern of operation and management that has had a profound influence on the history of the Laboratory ever since. Fascinating as may be the story of the many technical problems that had to be met and solved, of the failures, successes, serendipitous accidents, and administrative frustrations, space forces me to

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[3] This was not the first formal contact of The Johns Hopkins University with the development of proximity fuzes. In November 1940, a Section T Associate Contract under the NDRC was negotiated with the University covering research and development by the Physics Department pertaining to radio proximity fuzes under the direction of Prof. J. A. Bearden who, indeed, played a very influential part in events leading up to the prime contract between the University and the OSRD sponsoring the newly formed Applied Physics Laboratory. In the winter of 1942–43, Dr. Bearden's group was named the Radiation Laboratory at John Hopkins, which later became a component of the Institute for Cooperative Research. This group took over the additional responsibility of investigating countermeasures to jam or prematurely activate VT fuzes. The associate contract with APL continued until September 1961, its scope being extended to cover basic research in flame spectroscopy and aerodynamics as well as proximity fuzes.

[4] Although there has been discussion from time to time about the appropriate date used to mark anniversaries of the founding of APL, custom and consensus now determine March 10, 1942, the date of signing the contract between the OSRD and the University, as the date from which anniversaries of the founding of APL are calculated.

Fig. 3—The Wolfe Building, a garage on Georgia Avenue in Silver Spring, Maryland, the first home of the Applied Physics Laboratory, in early 1942.

leave it to others[5,6,7,8] and to summarize here some of the outstanding elements of this overall pattern. Let me list these elements.

(1) *Partnership*—The principle of Navy-civilian partnership was established and practiced effectively. Both the Navy and APL agreed upon a clear-cut objective. Funds from the Navy were provided through the OSRD, under whom the Laboratory had complete authority for the research, development, engineering, and testing program.[9]

(2) *Decentralization of Effort with Centralized Direction*—Instead of building at APL a large organization and facility capable of handling all the development and engineering work, Tuve and company made a point of using specialized skills and facilities wherever they existed by having contracts placed with industrial and scientific organizations to apply their experience, specialized capabilities, and facilities to specific component parts of the overall system. Thus, for example, National Carbon developed appropriate batteries for the fuze; Sylvania, RCA, Sonotone, and others developed small rugged tubes; the Universities of Michigan and Virginia contributed the brains of their physics departments; and the New Mexico School of Mines provided a test facility in the desert for studying the action of the fuze against mocked-up targets.

However, the direction of the overall project was centralized in the Applied Physics Laboratory, where the system was defined and where all components and assemblies were specified and examined for adherence to specifications. Technical direction by "men with dirty hands" rather than by men in office chairs was emphasized. The staff members were active workers in some field of science or engineering. Many engineers left responsible positions in their organizations to work out the problems and take the results home for implementation. All new ideas or modifications were tested at APL. The training of inexperienced workers for production-line operations was

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[5] J. P. Baxter, 3rd, *Scientists Against Time*, M.I.T. Press, Cambridge, Mass., 1946 (especially pp. 221–239).

[6] J. C. Boyce (Ed.), *New Weapons for Air Warfare*, Little, Brown and Co., Boston, Mass., 1947 (especially Chapters X through XIV, by J. A. Hynek).

[7] M. R. Kelley, "Capsule History of APL," *APL News*, November 1952.

[8] Two manuscripts in the APL Archives provide additional information about APL's history: "They Never Knew What Hit Them," by R. B. Baldwin (provides a detailed account for the period 1940 to 1944); "University-Industry-Military—In War and Peace," by E. A. Fitzpatrick.

[9] The strong participation of Section T (APL) in the Navy's production contracts for supplying VT fuzes was a continual source of concern to Dr. Bush since this activity appeared to lie outside the charter of OSRD, which called for research and development. Indeed, it was suggested that APL should be divorced from production or placed directly under Navy contract (May 1943). Neither course was looked on favorably by Dr. Tuve and his colleagues. They were convinced that development did not end until its products were demonstrated to give the best available performance in the situations in which they were destined to be used. Control of production was essential to success of the development. On the other hand the value of the partnership relationship with the Navy, made effective by the OSRD contractual relationship, was too valuable an asset to be lost. It is interesting to note that in November 1943 the Navy requested that no change be made in the contractual relationship. When, a year later, the APL contract was taken over by the Navy, this partnership concept was preserved as far as was legally possible in what became known as a "Section T type contract."

studied by installing a prototype line manned by women including housewives and high-school girls. These women developed remarkable expertise in the assembly of prototype fuzes for large-scale testing.

The central laboratory maintained a group to test and evaluate performance of the fuzes, both on the bench and in the field, a most valuable and really sophisticated operation whose importance cannot be overestimated, since a useful development is not by any means completed until its product performs satisfactorily in the environment in which it has to be used. Some of the industrial engineers knew this; the scientists had to learn it.

(3) *Interdisciplinary Communications*—Gathered together at DTM, and subsequently at APL, were large numbers of scientists, mostly from the physical sciences departments in universities; experienced practical engineers, skilled in reducing ideas to practice, mostly from industry; and enthusiastic officers and men from the Army and the Navy. These groups worked closely together and came to understand each others' languages and *modi operandi*. The bridging of the cultural gap between thinkers and doers was a major achievement. There grew up a mutual respect, confidence, pleasure in the exchange of technical ideas, and even admiration. This tradition is still very much alive at APL; unfortunately it is not as universal elsewhere as it might be.

(4) *Operations Analysis and Assessment*—The dialogue between the military operators and the civilian developers concerning military requirements and weapons effectiveness was made clearer and more exact by the development of systematic studies of the type now called "operations research." Mathematicians and physicists studied theoretically and experimentally the military operations in which the fuze was to be used to assess its potential effectiveness in the light of estimates of the enemy's technological and operational advances. The results were fed back to developers so that they could produce fuzes that would be more effective under realistic combat conditions.

Birth of the Bumblebee

Competition for technological ascendancy either in war or peace is a never-ending struggle between two or more parties. One party may resign, or be forced to resign, from the struggle with the certainty of its own ruin, but in doing so it only makes the attainment of technological ascendancy easier for the parties that have the will to continue the fight. This distillate of human experience, namely that technological ascendancy is only relative, was soon realized with the successful introduction of the radio proximity fuze into Navy and, later, Army operations.

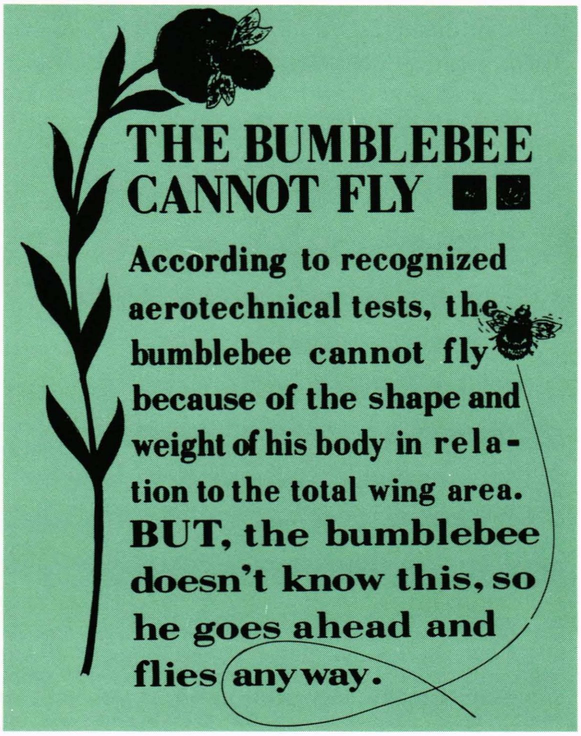
Makers and users of military aircraft had not been idle. Faster and more maneuverable planes were available and the pilots exploited this potential. As a result, the defending gunner found it impossible to place a shell in a trajectory that would meet that of the aircraft some seconds later unless he was assisted by a device that tracked the target and predicted its future position. To supply part of this requirement, APL developed a compact radar-controlled gunfire predictor system to be used in conjunction with the secondary batteries on warships to add to the accurate antiaircraft fire power of the radar-controlled primary batteries. The Mark 57 Gunfire Control System was installed on ships in late 1944.

However, it was becoming clear that something brand new must be developed, if a favorable balance was to be maintained between the attacking power of developing aircraft and aircraft tactics, and the defensive power of Naval ships. In July 1944, the Navy Bureau of Ordnance (BuOrd) requested APL to make a study of the future requirements of Naval antiaircraft defense and try to find out what that something new might be. The results of an extensive and intensive investigation by APL and its associated universities, notably the University of Virginia, were reported to BuOrd in November 1944, suggesting that a supersonic, rocket-launched, ramjet-propelled, radar-guided missile was the "something new" that might solve the emerging operational problems.

When a shell leaves the muzzle of a gun, its path in space is uniquely determined on the basis of information concerning the position and motion of the target aircraft at the time of firing. On the other hand, a guided missile can obtain more up-to-date information during its flight to the target and can change its course accordingly. The increasing ranges, speeds, and maneuverability of attacking aircraft made it mandatory for defensive weapons to acquire and act on this more up-to-date information.

In late November 1944, BuOrd, after careful study and consultation, signified its agreement with this conclusion and authorized APL to go ahead with exploration of the basic and applied research fundamental to the development of a guided missile. The program was what would now be called a "high risk" one; indeed, today it would be completely turned down by the authorities in the Pentagon. No rockets to launch such a vehicle existed; the theory of the ramjet propulsion engine had been enunciated by René Lorin in 1913, but no working supersonic model had ever been made. Theory or practice concerning the control or even the aerodynamics of supersonic aircraft was in a most elementary state, and mechanisms for deriving from a radar beam the information necessary for the guidance of a missile were nonexistent. The code name "Bumblebee" given to the program reflected the spirit of optimism of workers and sponsors alike. It was inspired by a *jeu d'esprit* whose authorship is unknown (Fig. 4).

On December 1, 1944, the Department of the Navy and The Johns Hopkins University signed a contract, NOrd 7386, that transferred the sponsorship and financial support of APL from OSRD directly to the Navy. The transfer of the sponsorship for APL from OSRD to the Navy had been under discussion for some time and had aroused considerable apprehension that a direct contract with the Navy might destroy, or at least weaken, the partnership existing between the Navy and the OSRD-sponsored APL. This concern was given great attention in the contract negotiations; the resulting document, which defined the Laboratory's obligation in terms of broad Tasks, went as far toward perpetuating the Navy-APL partnership principle that existed under the OSRD as was legally possible. Task F[10], which covered the Bumblebee Program, did not call for production of a specific hardware item but for a program of research and development in all areas leading to a useful missile to be defined as the work progressed. Tasks assigned to industrial and university contractors by the Navy to work on matters related to Bumblebee contained clauses to the effect that the investigations covered by the appropriate Tasks in these contracts would be performed in accordance with instructions issued by the Director of APL or his authorized representative.


THE BUMBLEBEE CANNOT FLY ■■

According to recognized aerotechnical tests, the bumblebee cannot fly because of the shape and weight of his body in relation to the total wing area. BUT, the bumblebee doesn't know this, so he goes ahead and flies anyway.

Fig. 4—The origin of the name "Bumblebee."

With characteristic energy, Tuve, Hafstad, Roberts, Porter, Hopkins, and their associates embarked on the new Task. Groups, each responsible for exploration in the pertinent fields of science and technology, were organized from the existing staff. Where necessary, new scientists and engineers were brought in to supplement their knowledge and expertise (Fig. 5). The fields of interest included jet-engine development, supersonic aerodynamics, automatic control, guidance intelligence systems, telemetry, and laboratory and field testing. Associate contracts were negotiated with nine universities and twelve industrial companies to carry out basic research, development, engineering, and fabrication in fields where they had an established, or potential, competence.

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[10] "A comprehensive research and development program . . . embracing all technical activities necessary to the development of one or more types of rocket-launched, jet-propelled, guided antiaircraft missiles. The desired performance characteristics are to be defined in consultation with the Bureau of Ordnance as the work progresses, in accordance with the objective of obtaining a weapon of useful military characteristics in the shortest feasible time.

"This program shall include pertinent basic research, investigations and experiments, and the design, fabrication, and testing of such missiles, their component parts, and supplementary equipment. Alternative modes of promising technical approach are to be pressed either singly or simultaneously, as deemed most effective. The work shall include cooperation and joint activity, as may be feasible, with those groups in the Armed Services and other agencies, which are actively concerned with the development, testing, producing, and use of either similar or related missiles for the United States Government. The work also may include, on request of the Bureau of Ordnance, supervision and guidance of the technnical work under other Navy contracts which may be assigned work related to this Task."

(Letter from Rear Admiral G. F. Hussey, Chief, BuOrd, to APL, dated January 11, 1945.)

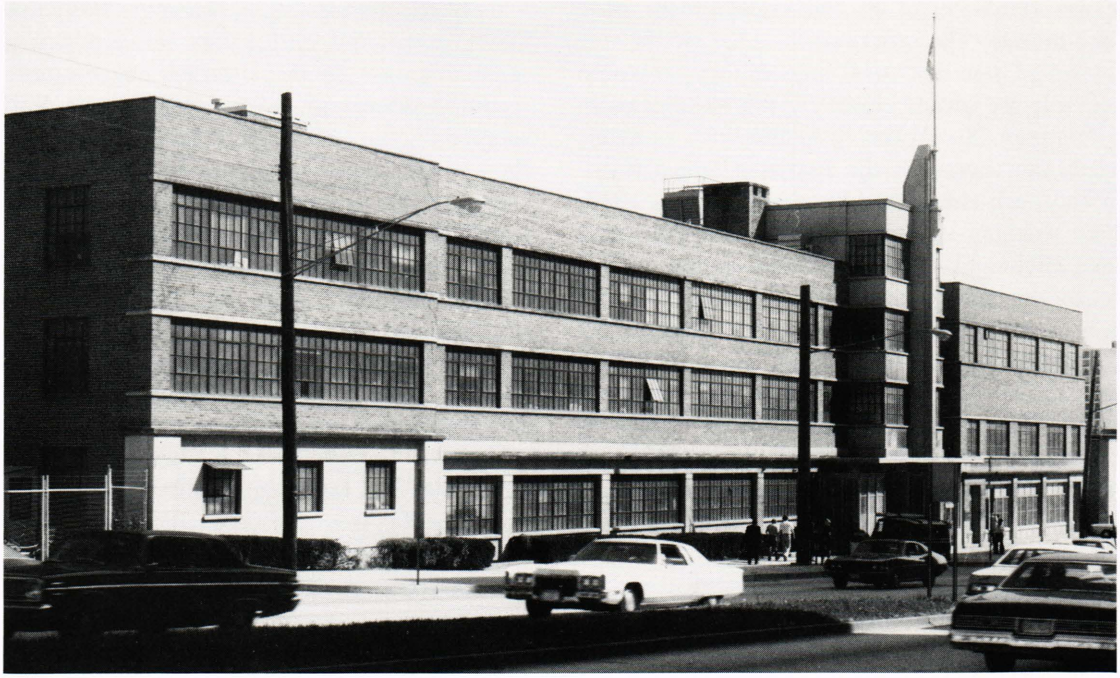

Fig. 5—The Applied Physics Laboratory, 8621 Georgia Avenue, Silver Spring, as in late 1944; the birthplace of Bumblebee. This complex of offices, laboratories and shops, owned by the Navy and constructed by additions to the Wolfe Building (Fig. 3), was a major site of the Laboratory's activities for over 30 years. It was finally relinquished on June 30, 1976.

In order to focus the research and development on pertinent problems, the staff at APL mobilized all existing knowledge and skills to design and construct working models of critical components on a scale large enough to be tested under realistic operating conditions. For this, new facilities were needed. Ground and buildings used by an obsolete Navy radio school, situated about one mile north of the Laboratory on Georgia Avenue, were acquired early in 1945 (Fig. 6) and an engine testing laboratory (Fig. 7), furnished with a large air supply from old compressors, formerly used in the construction of the Shasta Dam, was added. This facility, called the Forest Grove Station, served the Laboratory for more than twenty years.

In Daingerfield, Texas, a high-pressure air generator capable of supplying air for testing full-scale ramjet engines and operating a large supersonic wind tunnel was found to be available, since the Lone Star Steel Company for whom it had been constructed did not require it for their current operations. The Consolidated Vultee Aircraft Corporation (later Convair and now a division of General Dynamics) accepted an associate contract to build and operate under the direction of APL a full-scale ramjet-engine test facility, the first of its kind. The facility was to supply air for prototype engines at speeds of Mach 2 to 4, through nozzles with exit diameters variable from 24 to 32 inches. There was also constructed and operated a supersonic wind tunnel with a 19- by 27.5-inch test

Fig. 6—The Main Building at the Forest Grove Station, 9000 Georgia Avenue, Silver Spring, associated with major engineering activities in the Bumblebee Program including telemetry, supersonic aerodynamics, environmental tests, fabrication of the sectionalized Terrier, and location of central machine and electronic shops. Occupied in 1945, it was relinquished in 1962.

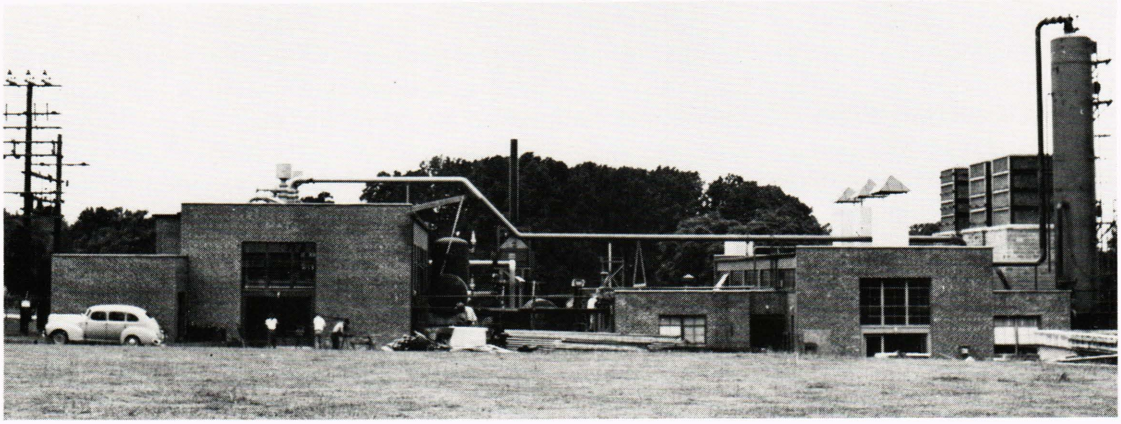

Fig. 7—The Burner Laboratory at the Forest Grove Station. Here the first supersonic ramjet engines to give excess of thrust over drag, the six-inch-diameter Cobras, were developed and tested. It was the center of combustion research and of experimental investigations of ideas for the design of ramjet components to give improved performance over wide ranges of Mach numbers and altitude.

section that would provide air velocities of Mach 1.25 to 2.8. The facility, which came into operation in mid 1946 and later became known as the Ordnance Aerophysics Laboratory (Fig. 8), served the Bumblebee Program and many others sponsored by the various Services for twenty-five years and pioneered many important advances in supersonic aerodynamics and in the design of missile configurations and of jet engines.

A tract of ground among the sand dunes at Island Beach, New Jersey, was taken over as a facility for flight testing six-inch-diameter ramjet engines.

Before the end of 1945, the Bumblebee Program was in full swing. Most of the right questions had been formulated and the staff of APL, together with the staffs of a large family of associate contractors, were busy trying to find the answers. Important facilities were under construction and in preliminary operation. One crucial question had been answered, namely that a supersonic ramjet was a practical engine. René Lorin's theoretical predictions of 1913 were experimentally proved when a small-scale ramjet, fired from Island Beach on October 19, 1945, developed sufficient thrust over drag so that it accelerated; furthermore, it sent a record of the performance of its components back to the ground over telemetry channels. A practical guided missile was coming into sight but was still a considerable distance in the future.

A Commitment Is Kept

On August 9, 1945, the end of the war with Japan brought to a close the active hostilities of World War II and, with it, some problems for the University and the Laboratory. Rapid demobilization of the war effort and return to the peacetime status of the late 1930's was the popular mood at that time. Should the Laboratory and its family of university and industrial contractors disband, the staff returning to the universities and industries whence they came? Many on the staff favored the course of liquidation; indeed, many senior people who had been on some kind of leave of absence did return to their previous bases of employment. However, most of the staff, especially the younger members, felt very strongly that the Laboratory had made a commitment to the Navy to carry the Bumblebee Program through to a satisfactory conclusion and that that commitment must be hon-

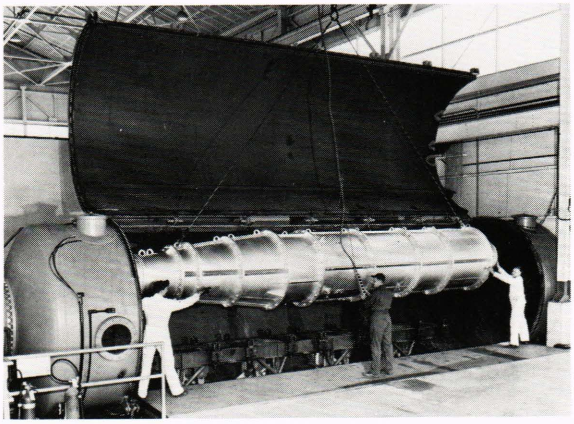

Fig. 8—The test cell at the Ordnance Aerophysics Laboratory, Daingerfield, Texas, used to investigate the performance of full-scale ramjets under different Mach numbers and altitudes.

ored. The technical promise was overwhelming, the investment in money and brains was already significant, and it was not at all clear that the end of hostilities meant the advent of a peace that would enable the United States in general, and the Navy in particular, to lower its guard. The University was faced with the decision as to whether or not it should continue to carry the responsibility for operating the Applied Physics Laboratory under contract with the Government to develop Naval weapons systems. The Secretary of the Navy, Mr. Forrestal, wrote President Bowman urgently requesting that the University continue the operation of the Laboratory and the extremely promising work it was doing for the Navy in providing systems that would certainly become necessary components of its combat capability. Largely due to this letter and to other representations from high officials, and as a result of a strong desire to support the staff of the Laboratory in honoring commitments in the name of the University, the President and Board of Trustees of the University agreed, with some reservations, to continue the operations under contract NOrd 7386 as a public service consistent with its traditions and charter. The Bumblebee project continued apace.

The Post World War Period

Although the Laboratory experienced administrational stresses during the transition from wartime to peacetime regimes, the Bumblebee Program continued with only slightly abated momentum. The scientific scope of the Laboratory's work actually increased although the efforts on the Gun Director and VT fuzes fell to quite a low level. On the Laboratory's initiative, most of the fuze development and the people associated with it were transferred to the Naval Ordnance Laboratory, White Oak, Maryland. Only a small amount of research on new and more sophisticated proximity fuzes remained at APL.

Fundamental Research and Development: The Research Center

During all the arguments concerning the future of APL that took place in 1945 and 1946, all parties were in complete agreement on one thesis, namely that if APL were to be a viable scientific and engineering organization in the post-war era and, indeed, if it were to be worthy of the sponsorship of the University, it must earmark a significant fraction of its effort for fundamental scientific research investigations leading to the understanding of nature. As early as January 1946, a program to study the physics of the upper atmosphere was initiated by Dr. Tuve and placed under the leadership of Dr. J. A. Van Allen. A golden opportunity for these studies had arisen. The Army had acquired a number of V-2 rockets captured from the Germans. In the course of an engineering study of these devices, it proposed to make a series of flight tests at White Sands Proving Ground, New Mexico. Warhead space was made available for scientific studies of the upper atmosphere since the rockets could reach altitudes (approximately 75 miles) hitherto unattainable. The Laboratory was allotted space on a number of these rockets and promptly devised instruments for examining the nature and distribution of cosmic rays, the ultraviolet spectrum of the sun, and other phenomena that, because of the disturbing effects of the lower atmosphere, could not be observed in their pristine state from the surface of the earth or even from balloons. On April 16, 1946, the first V-2, carrying counters for recording cosmic ray intensity, was launched at White Sands. During the next four years, the Laboratory participated in the launching of nine V-2 rockets, all of which flew successfully, reaching maximum altitudes ranging from 50 to 114 miles. Among the interesting results was a series of motion pictures of the earth from a height of 65 miles, probably the first ever taken.

Recognizing that the supply of V-2 rockets would be exhausted long before the scientific problems in near space were even explored, the Laboratory and associate contractors, notably the Aerojet Engineering Corporation and the Douglas Aircraft Corporation, designed and built with strong Navy support a simple, relatively small rocket called the "Aerobee." This rocket could be launched from ships as well as from the fixed site at White Sands and, therefore, permitted observers to study the upper atmosphere from different latitudes and longitudes. The development of the Aerobee was authorized on May 17, 1946, the contract calling for the design, test, and fabrication of twenty rockets capable of carrying a payload of 150 pounds to about 375,000 feet. The first successful flight demonstrating these characteristics originated at White Sands on May 3, 1948[11]. On March 17, 1949, an Aerobee carrying

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[11] See L. W. Fraser, "High Altitude Research at the Applied Physics Laboratory," APL Bumblebee Report No. 153, May 1951.

instruments to measure cosmic ray distribution and characteristics of the earth's magnetic field was launched from the deck of the USS *Norton Sound* at the geomagnetic equator off the coast of Peru. Aerobee flights provided new information concerning the distribution of ozone[12] and other molecules in the stratosphere, the variations of the earth's magnetic field, both with altitude and with geomagnetic latitude, and more details about cosmic rays.

In accordance with a policy adopted in 1948, the Laboratory's pioneering researches in upper-atmosphere physics were brought to a conclusion in 1951, shortly after the supply of Aerobees was exhausted, only to revive on an even larger scale eight years later when satellites replaced rockets as the principal vehicles of exploration.

Although the exploration of physics within and from the upper atmosphere was the first program in fundamental research initiated at APL, it was soon followed by others, including investigations in mass spectrometry, ionization potentials, flame spectroscopy, low-temperature spectroscopy, and cosmology. To establish a base for this academic work, an informal Research Board was set up by Dr. Hafstad in April 1947. When the Laboratory became a regular Division of the University, a less informal organization, the Research Center, was established. Dr. F. T. McClure was its first Chairman, a position he held for twenty-five years.

The Navy recognized the value of the Research Center and authorized the Laboratory to allocate a small fraction of the Bumblebee budget to support its self-generated researches. Although the Research Center has remained relatively small in size, its budget never exceeding 8% of the total Laboratory budget, its output and its influence have been great. Over the course of the years, about a thousand papers by Research Center members have appeared in first class journals; it has been the host to research fellows from around the world; it has been a strong link between the Laboratory and the world of scientific research; and it has sponsored and arranged weekly colloquia that have brought to APL leaders in all fields of learning. For many years, the Research Center organized and sponsored ad hoc Task Research Groups to attack difficult problems arising in missile technology and to explore new ideas leading to developments of wide potential interest. Both the satellite navigation and the biomedical engineering programs came out of the Research Center.

Emerging Guided Missile Technology

Within a year or two after they were started in 1945, experimental investigations showed that the critical "high risk" problems associated with a rocket-launched, ramjet-propelled, supersonic, radar-guided missile could have practical solutions. However, it was becoming very apparent that in all pertinent fields of technology a host of scientific and engineering problems were arising that had to be solved before practical, reliable missiles of established performance could be built. To focus a broadly based segment of experience and judgment on missile problems, a number of "Bumblebee Technical Panels" were organized in 1946 in the areas of Launching (A. Kossiakoff, Chairman); Propulsion (including combustion) (W. H. Goss and J. E. Cook, Co-Chairmen); Aerodynamics (Supersonic) (R. P. Peterson and, later, A. R. Eaton, Chairmen); Guidance and Control (D. T. Sigley and, later, R. B. Kershner, Chairmen); Composite Design (H. H. Porter, Chairman); and Warhead and Fuze (H. S. Morton, Chairman). The Propulsion Panel actually consisted of two groups, one of which was concerned with the general technology of air-breathing engines and the other, WCOP (the Working Committee on Propulsion), with the detailed problems arising from day-to-day development of Bumblebee engines. These groups were chaired, respectively, by Cook and Goss. The Aerodynamics Panel was the first to be organized. Very early in the Bumblebee Program, it issued a "Handbook of Supersonic Aerodynamics," a small volume that included most of what was then known about the subject[13].

The membership of these panels consisted

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[12] The measurements of the quantity and distribution of ozone in the stratosphere made in Aerobee A-14, June 23, 1949, and A-20, January 25, 1951, represent the first quantitative experimental data on this subject although the presence of ozone was known from theoretical considerations. At that time, ozone in the stratosphere was a matter of purely academic interest. It is now a matter of widespread public interest and even political importance. It is interesting to note that the experimental methods developed and tested by J. J. Hopfield and H. E. Clearman in 1949 are those used today in monitoring ozone in the stratosphere by satellites.

[13] Between October 1945 and February 1946, the Laboratory sponsored four symposia to examine the current knowledge in fields pertinent to the Bumblebee Program. The papers given by authorities in each field have been preserved in the following APL/Bumblebee reports (BB): "Ram Jets," BB-24, "Aerodynamics," BB-29, "Guidance and Launching," BB-37, and "Telemetering," BB-42 (symposium held at Princeton University). The idea of a Handbook of

of working scientists and engineers from APL and all the concerned Associate Contractors. Meetings were held periodically in different places, and the technical problems were fully and frankly discussed. The solutions to many important problems stemmed from these meetings, which also carried on most effectively the interdisciplinary dialogue between scientists and engineers. Naval officers knowledgeable in the field of operations also participated in the discussion. After a few years, representatives of other agencies developing guided missiles for the Armed Services eagerly accepted invitations to Bumblebee Panel meetings. Their participation in the free exchange of experience gave the panel meetings a national and, indeed, international reputation. The educational value of these panels cannot be overestimated. In 1945, the staffs of APL and its Associate Contractors were amateurs in a new field; by 1950 they were professionals.

The development of a practical, effective Bumblebee missile centered around laboratory and flight experiments with test vehicles, each designed to investigate one segment of the complex technology involved in a complete missile. The validity of a design was established when the detailed flight performance of the vehicle and its components agreed completely with that predicted by theoretical and experimental laboratory studies. Determination of flight performance stimulated an extensive development in telemetry—the construction of instruments to measure the performance of components and convert the readings into signals that could be transmitted to earth by radio links from the flying vehicle. The Telemetering Forum, composed of engineers from numerous nationwide agencies, in which APL engineers took a leading part, brought together the rapidly growing experience in telemetry and was instrumental in standardizing telemetry components and techniques.

Three series of test vehicles were studied: (a) launching test vehicles (LTV's) for examining the performance of large-scale solid-fuel rockets (the propellant charge of 2000 pounds being heavier by a factor of more than ten than those used in previous rockets); (b) burner test vehicles for investigating the flight behavior of 18-inch-diameter ramjet engines; and (c) supersonic test vehicles (STV's)[14] that were quite complex and heavily instrumented to permit in-flight studies of the strength of supersonic airframes, of their response to the motion of steering surfaces, and of the reaction time of control systems and devices to receive guidance signals from a radar and convert them into prompt and unequivocal steering orders. These vehicles at once highlighted problems that had not, or could not have, been predicted from laboratory studies. Most were engineering problems having to do with design and strength, but some were fundamental, among which may be mentioned the "reverse roll problem."

Bumblebee missiles were designed to be roll stabilized in flight, i.e., their steering depended on their not rotating about their long axis in the direction of flight. Any rotation was detected by a gyro and a signal was sent to aerodynamic surfaces that caused them to rotate to a direction that neutralized the twist and gave roll stability. Vehicles showed that in a certain range of supersonic speeds they responded in the opposite way to that predicted and the commanded motion of the wings actually speeded up the rotating movement instead of stopping it. An empirical method for fixing this defect was rapidly devised, but it took months, even years, of study led by A. R. Eaton to track down and explain the fundamental cause of the phenomenon and give a satisfactory solution. An interesting chapter in the history of supersonic aerodynamics!

In the Laboratory, simulators were designed to produce forces equivalent to those acting on the missile in flight. With these devices, the responses of the missiles' guidance and control systems to a wide spectrum of flight regimes could be measured quantitatively and adjustments made that were equivalent to those that would have been obtained only by a large number of flight tests. At first, analog computers were employed in the simulators. Later on, the rapidly developing high-speed digital computer technology came into service. Actually, the wind tunnel itself was probably the earliest aerodynamics simulator.

Supersonic Aerodynamics was proposed at the Aerodynamics Symposium by R. B. Roberts. Over the years, this Handbook grew to be a six-volume work known as the "Handbook of Supersonic Aerodynamics," NAVORD Report 1488. It is available from the National Technical Information Service (NTIS).

[14] To avoid complications expected in supersonic flight, beam riding guidance was first studied in a subsonic vehicle called the Control Test Vehicle (CTV). Although this type of guidance was first demonstrated in the CTV, the potential of the vehicle was very limited and its lifetime correspondingly short.

A Branch of the Bumblebee Stem

After many missteps and failures, a supersonic test vehicle (STV-3) was designed and flown. It was launched by a large solid-fuel rocket, and its speed in flight was sustained by a smaller solid-fuel rocket. The responses of STV-3 to guidance and control signals were very close to those predicted. It weighed 1000 pounds less than the prototype ramjet-propelled missile, but its range and warhead capacity were considerably smaller. Nevertheless, in the late spring of 1948, the Navy agreed that, with minor modifications, the test vehicle could be converted into a useful short-range antiaircraft missile for use on intermediate-sized ships. The Laboratory accepted the responsibility for converting this test vehicle into a prototype missile. In December of that year, following the suggestion of R. B. Kershner, who was then in charge of the development, the new missile was officially named "Terrier," the initial letter "T" standing for Section T.

Since it was expected that Terrier would be available for tactical deployment considerably before "Talos," the name subsequently given to the ramjet-propelled vehicle, and could cover the shorter-range missile requirement, plans were made to exploit the capabilities of the ramjet engine and to extend the target range of Talos to 50 miles or more with a more sophisticated guidance system appropriate to the longer range, an objective that was finally achieved and even surpassed.

The Era of the Korean War

On June 24, 1950, the army of North Korea invaded South Korea. President Truman decided promptly that the United States would send military aid to South Korea, an action approved by the United Nations and one in which the United States was joined by fifteen other member nations. The involvement of all our Armed Forces in that struggle became considerable and support of their activities affected all connected directly or indirectly with the Department of Defense, APL being no exception.

Since the months succeeding the outbreak of the Korean war saw events that had a great influence on the history of APL and the education of its staff, it is pertinent to summarize the status of its technical work at that time. All the crucial problems envisioned in 1945 had been solved: solid-fuel rockets powerful enough to launch full-scale test vehicles to supersonic speeds and to sustain those speeds were available and reliable; the ramjet engine's performance was realized in a practical airframe; control systems rapid and powerful enough to steer missiles in supersonic flight had been designed and tested by simulators in the laboratory and telemetered flight tests; vehicles were able to receive information from radar beams accurate enough to guide them to moving air targets; and airframes strong enough to withstand the stresses of maneuver in supersonic flight and capable of accommodating all the components had been designed and tested. Warheads and fuzes were in sight. Of great importance for the use of antiaircraft missiles aboard Navy ships had been the demonstrations that full-scale missiles could be fired in the proper direction from "zero-length launchers," elevatable and rotatable structures on which the missile is supported by guide rails approximately six inches long, in comparison with the then-current launching devices that carried guide rails supported on structures 10 to 20 feet long. A Navy radar (Mark 25 Mod 6) was in the first stages of modification for the injection of signals into its target-tracking beam to guide beam-riding missiles. That equipment was being readied for installation at the Naval Ordnance Test Station (NOTS), California, for guidance of missiles over a land range, and on the USS *Norton Sound* for guidance of missiles at sea.

In the field of composite design, the knowledge and experience of APL and its contractors—especially Consolidated Vultee Aircraft Corporation (CVAC) and Bendix Pacific for Terrier, and Bendix South Bend and McDonnell Aircraft Corporation, St. Louis, for Talos—had been incorporated into the design engineering and construction of experimental prototype missiles. CVAC, San Diego, was under contract with the Navy to produce in small lots missiles made, inspected, and tested under factory conditions for tactical trials over land and sea. Following the original pattern of the Laboratory, it was considered wise to run the late development and early production programs in parallel rather than in series. Provision was made for incorporating, in each successive lot of missiles, improvements in components and subassemblies as they emerged from the development programs.

Another program that occupied some of the Laboratory's efforts at the time applied the aerodynamics and propulsion techniques being developed for Talos to the design of a long-range (400 miles) cruise missile called "Triton." The program explored the use of characteristics of the earth's magnetic field for mid-course guidance and radar map-matching for mid-course and, more especially, terminal guidance. The information developed in the program proved to be of great value in later years. However, the Triton project terminated when the accuracy potential of the ballistic missile was realized. It was replaced by Polaris.

Another development program examined the potential of an entirely spherical missile, powered by a solid-fuel propellant, stabilized in roll, pitch, and yaw, and steered by suitably placed on-and-off nozzles that emitted some of the propellant gas. It received guidance signals from an operator on the ground, either through a wire or a radio link. It was proven to have great potential both on land and at sea but was never used in service.

Programs of fundamental research in high-altitude physics, spectroscopy, flame propagation, the origin and evolution of the universe, supersonic and hypersonic aerodynamics, chemical kinetics, and nuclear magnetic resonance had resulted in the publication of approximately 100 papers in scientific journals. A determined effort was also underway to develop a satisfactory understanding of the phenomena of high-speed combustion in ramjets.

Early in 1952, a group was organized in the Research Center to study the properties of transistors and their applications in sophisticated electronic circuits. These revolutionary devices were just emerging from the Bell Telephone Laboratories where they had been discovered. The group not only studied transistors and their applications, but also spread the knowledge through the Laboratory by lecture courses, practical demonstrations, and the publication of a handbook. As a result of that activity, the Laboratory was able to apply transistors to electronic subassemblies in various guided missiles and reap the benefits of decreased volume and weight and increased reliability. In 1957, the Talos homing system was completely transistorized.

Problems of Complexity

Two major problem areas to which the Laboratory for one reason or another had been unable to give proper attention loomed on the horizon. Both may be classed as "problems of complexity" rather than "problems of principle."

The first arose in the basic approach to the design of missiles suitable for large-scale production and testing. It was assumed that the techniques currently used in manufacturing and testing airplanes were applicable to the production of guided missiles. In practice then current, the subsystem components were fitted as conveniently as possible into an airframe and were connected electrically or mechanically as the assembly proceeded. The whole system was then tested, suitable adjustments were made, and mistakes were corrected so that all components worked together within proper tolerances to achieve the performance objective set up for the whole missile. However, even a simple missile system is so complicated in the number and interactions of its components that it is virtually impossible to detect flaws in construction or to make adjustments with certainty by testing the whole assembly. The assumption that missiles could be successfully produced using aircraft techniques was fallacious.

The second problem of complexity may be called one of overall systems engineering. For our purpose, we may think of a system as an assembly of elements designed to fulfill a certain purpose, each element being capable of generating and receiving information pertinent to that purpose. The successful operation of a system depends on two main factors: the capacity of each element to perform reliably and accurately the functions assigned to it, and the timeliness and accuracy with which information is passed from one element to another. In any well-designed system, such as the human body, there are both direct communication links that transmit instructions from outside and feedback links that convey information about the action that has resulted from the instructions. A missile itself is a small system, designed with the foregoing principles in mind. However, it is part of a much larger system whose purpose is to destroy or deter aircraft attacking Navy ships. Information about the approach of aircraft and estimates of their intent are developed by one component, the early warning radar. This information is passed to fire-control radars that start to track the target and point the missile launcher in the right direction. At the proper time, the missile is fired, taken under control by the radar, and furnished with information that guides it to its target. The system also contains men who must evaluate and pass on information, maintain all equipment in a state of readiness, and make decisions for action.

When you realize that the various elements of the system (each in itself a system of some complexity) were designed and furnished by different agencies of the Navy, that the training of the human component was accomplished by still another, and that the whole system must operate in minutes or even in seconds, you will recognize that the success of the whole system depends on much more than the performance of the missile. Problems arising from the complexity and heterogeneity of the whole system were to assume gigantic proportions when an accelerated program to build and deploy guided-missile ships was mounted by the Navy.

On October 25, 1950, K. T. Keller, President of the Chrysler Corporation, was appointed Director of Guided Missiles by the Secretary of Defense. His purview included all of the many U.S. guided missile developments under the sponsorship of the Navy, the Army, and the Air Force. His responsibility was to accelerate the production and the deployment of guided missiles by all the Services. He was given authority over the allocation of funds to carry out this responsibility. Keller was an outspoken man of dynamic personality, with years of experience in engineering and production at all levels behind him; his entry into the Department of Defense was like a combination of earthquake and typhoon. He, and the able staff he acquired, inspected in detail every guided-missile program and selected three as candidates for acceleration into large-scale production. Among these candidates was Terrier.

This decision had traumatic consequences for the Navy, which was responsible for the procurement and acceptance of the missiles; for the contractor, Convair, which was responsible for their production, testing, and acceptability; and for APL, which was responsible to the Navy for their performance and for advice concerning methods of testing and acceptance. In accordance with Keller's instructions, a contract was negotiated with Convair for the construction of an engineering and production facility capable of turning out some 1000 missiles a month. Ground at Pomona, California, was broken for this plant (Fig. 9) in August 1951, and production began in the spring of 1953. In the interim, the Convair plant in San Diego intensified its efforts to develop production and testing techniques that would provide missiles aceptable to the Navy and that could be transferred to the larger-scale operations of the new plant. Many frustrations were being encountered. Although some Terriers that finally passed acceptance tests and were given very special preflight tests (under APL observation) performed excellently against airborne targets, many of the factory products failed acceptance tests time and time again and others that passed developed severe and fundamental troubles in flight.

Fig. 9—The plant for engineering and large-scale production of Terrier missiles, built and operated by Consolidated Vultee Aircraft Corporation at Pomona, California.

In April 1952, the Laboratory assigned a few engineers to work in San Diego with the Convair engineers on the production and testing problems; a month later it enlarged this effort to a "Terrier Emergency Group," which was responsible for concentrating on the roll-control system and the power supply, two particular trouble spots. In November 1952, the production troubles became so urgent as a result of the combination of the acceptance difficulties and the new roll-stabilization problems, among others, that a "Terrier Task Group" was formed by the Bureau of Ordnance in response to Mr. Keller's urging. It was headed by Commander Boyle as representative of the Chief of the Bureau and by Dr. Kossiakoff as representative of the Director of APL. The group was stationed at the Convair plants, first at San Diego and later at Pomona.

In the meantime, the Laboratory continued its in-house investigation of a number of the components and subassemblies used in production. The education of the Laboratory in engineering and other production problems was approaching an advanced stage. The problems encountered in production suggested strongly that a fundamentally new design principle was needed; classical airplane production techniques were inadequate.

The new design concept technique, proposed and promoted by Dr. Kossiakoff and his colleagues, and based on the principle of interchangeable sectionalization, is now fundamental to good missile engineering. The various functions that a missile must perform, e.g., propulsion, roll control, receipt of intelligence, generation of steering signals, and power transmission to steering surfaces, are analyzed, and each mechanism needed to implement them is built as a discrete package whose geometry, inputs, and outputs can be specified in *quantitative, readily measurable terms* so that when properly made, all work together as a system. With this technique, each package can be tested separately within defined tolerance limits and under the environmental conditions (temperature changes, accelerations, vibrations, shock, etc.) it is expected to encounter in handling, storage, and use.

When a number of packages of the same type pass the tests, any one may be used; they are interchangeable. The same principles and practices are also applied to assemblies of the components that make up a package. They are specified in such a way that their outputs may be described quantitatively in terms of their inputs and, therefore, they can be tested for adherence to specifications before they are assembled into a package. The principle is really the elementary one that mistakes are better avoided or corrected early rather than later in any enterprise. The Navy was very much interested in this approach to the fabrication of guided missiles. It asked that the Laboratory undertake an engineering Task under the contract to fabricate a dozen Terrier missiles according to this principle using subassemblies and packages made by the Laboratory and by different contractors according to rigid specifications issued by APL. This engineering Task was accepted by the Laboratory in July 1953 with administrative reluctance but with technical enthusiasm and was carried out by a special engineering group headed by R. O. Larson and R. T. Ellis.

The various packages proved to be interchangeable, showing that the principle was valid. The missiles so produced gave a 90% score in flight tests and the Task cost half a million dollars less than had been estimated. The special Task was finished in the fall of 1954. The educational experience gained by the Laboratory in this project was invaluable as was proved some years later when it entered the field of space exploration and use by near-earth satellites.

By the end of 1953, a steady but not copious stream of Terrier missiles from the Convair plant at Pomona was being delivered to the Navy for flight tests at the NOTS Inyokern Land Range and for sea tests from the experimental ship USS *Norton Sound*, AVM-1, and the battleship USS *Mississippi*, EAG-128, which, after a period in an assist phase from the Bureau of Ordnance, became a unit of the Navy's Operational and Development Force (OPDEVFOR). The factory-produced missiles showed notable improvement in reliability and performance; by mid-1954, 67% of those fired by OPDEVFOR achieved their objective successfully. Involvement with the semitactical installations for storage, handling, firing, and guiding missiles on the *Mississippi* gave APL its first inkling that the overall guided-missile-ship system, men and machines, might present problems far more complex than any encountered in proximity fuzes or in the missiles themselves.

On November 1, 1955, the cruiser USS *Boston*, carrying Terrier missiles, was recommissioned as CAG-1, the first combatant guided-missile ship in the world (Fig. 10). This marked the culmination of the first phase of the Terrier Program.

The Main Bumblebee Stem

Involvement in Terrier production and engineering design problems interfered only slightly

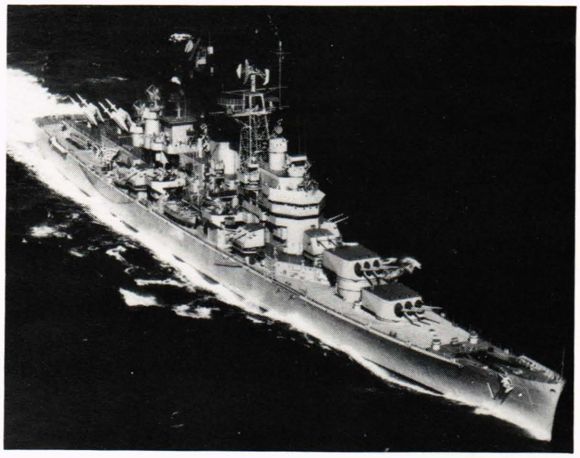

Fig. 10—USS *Boston*, CAG 1, the first guided-missile warship in the world, equipped with Terrier Missile Systems.

with the other research and development programs at APL. In particular, the Talos Missile Division, under the leadership of Dr. W. H. Goss, attacked vigorously all the problems connected with the revised objectives of extending greatly the effective range and altitude performance of Talos. After demonstrations of the feasibility of the various elements of the missile, e.g., the ramjet engine, control and steering at supersonic speed, beam-riding mid-course guidance, and radar-interferometer homing for terminal guidance[15], the years from 1948 to 1951 were spent in exploring the various engineering choices for practical implementation, both in the laboratory and in flight experiments with two series of ramjet-propelled complete test vehicles. For example, two combustor designs proposed and tested by different associate contractors were studied seriously and tested under a wide variety of conditions at the Ordnance Aerophysics Laboratory. A design combining the better features of both was then decided upon.

During the first half of 1951, data were at hand for formulating general specifications for the prototype Talos missile, its length and diameter being determined primarily by the size of ramjet engine required to give the thrust needed to achieve the range and altitude performance objectives, and by the weight of the warhead. The planform, beam-riding guidance and control systems were based largely on the experience gained with Terrier and previous test vehicles.

In June 1951, the general specifications were turned over to the Bendix Aviation Corporation, Products Division (South Bend, Indiana), the Associate Contractor who had built and tested pre-prototype ramjet beam riders and had designed and fabricated the fuel-control system that was so important in preserving the stability of combustion in the Talos engine through wide variations of external conditions, pressure (altitude), etc., and in maintaining the velocity of the missile within design limits. Bendix took over the responsibility of prime contractor to the Navy for the assembly, test, and delivery of prototype missiles. They awarded a subcontract to the McDonnell Aircraft Corporation, St. Louis[16], for the fabrication of the airframe and integral ramjet engine. The first missile produced by Bendix was fired as a propulsion test vehicle on October 28, 1952. It met all the flight objectives with complete success.

At the same time, a Talos *System* was designed, complete with radars to detect and to track airborne targets, with computers, and with display systems to interpret and transmit information to command and control personnel for evaluation and thence to missile launchers for action. Emphasis was placed on the use of existing Navy equipment with only simple engineering modifications. The first system was designed for ground-based use at the White Sands Proving Ground, where it began operations in December 1953 and was later called the "Desert Ship." Learning from the experience with Terrier, the developers of Talos planned and implemented through contractors simple "go/no-go" test equipment to determine the adherence of the missile to performance specifications for inspection at the factory or in the field.

The next three years saw the continuation of research and development related to Talos and its system: research to understand the various complicated aerodynamic, physical, chemical, dynamic, and cybernetic phenomena involved in system operations, and development to solve problems or initiate improvements indicated by studies of the quantitative performance of the prototype missiles and their components. For example, researches by the Propulsion Group under Dr. W. H. Avery (later Head of the Aerodynamics Division of APL) and by the group at Esso Laboratories, directed by Dr. J. P. Longwell, led to an understanding of the effects of mixing of air and fuel, heat release, mass flow, flame spreading, etc. on the combustion of fuels in ramjets[17]. In the field of aerodynamics, the overall efficiency of the engine was greatly improved by modifications to the configuration of the inlet resulting from experiments conducted during the latter half of 1953 at the Ordnance Aerophysics Laboratory by

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[15] Fundamental experimental investigations of the radar-interferometer homing system were made by the Defense Research Laboratory of the University of Texas. Because its geometry fitted well with the geometry of the front-end air intake of a ramjet missile, the homing system was incorporated in the design of the Talos prototype.

[16] Later, December 1952, McDonnell Aircraft Corporation became an Associate Contractor to the Applied Physics Laboratory. It is now (1976) known as McDonnell Douglas Corporation.

[17] An interesting account of ramjets and their history was published by W. H. Avery, *Jet Propulsion*, **25**, No. 11, November 1955, 604–614.

the Propulsion Group and Associate Contractors.

Studies of the dynamics of the prototype missile airframe and the control and guidance systems, both in laboratory and in flight tests, suggested a number of innovations that would radically improve the performance of the missile. Among these may be mentioned the introduction of sensitivity feedback in the steering control system, whereby a programmer monitored the aerodynamic effectiveness of a given wing deflection by comparing the acceleration achieved with that demanded and adjusted gains accordingly; and a stable-platform phase-follow-up system that corrected the signals coming in from the interferometer homing sensor for motion of the missile itself and vastly improved the accuracy of the terminal guidance system.

In the field of ordnance, an entirely new design of high-explosive warhead, that ejected a solid ring of steel rod rather than a shower of fragments, was shown to be extremely effective against the current generation of "tough" military aircraft and was developed for use on the regular Talos missile. A special version of Talos adapted to carry a highly effective warhead and completely controlled with extreme safety precautions from the ground was designed, built, and flight-tested first on December 15, 1953.

The flight tests of the prototype Talos missiles revealed many failures of components that prevented or degraded achievement of objectives. The few failures that proved to be systematic were easily avoided by minor redesign. The many that were random were corrected by stringent quality control, by introduction of the Terrier System of interchangeable functional packaging, and, most importantly, by long and difficult investigations to determine the nature of the vibrations set up in the missile and its components by supersonic flight through the air and by the noise of its engine. Discrepancies in mechanical engineering rather than in electrical engineering were found to be the main culprits. Tracking down the causes of flight failures and devising methods for the elimination of their effects was a strenuous but rewarding educational experience.

On January 8, 1955, the Naval Industrial Reserve Ordnance Plant, operated by the Bendix Aviation Corporation, Products Division, Mishawaka, Indiana, was dedicated and opened for the production of Talos missiles for the Navy. At that plant all control and guidance equipment was fabricated and assembled into the integral ramjet airframes from the subcontractor, McDonnell Aircraft Corporation; the whole missile was then tested and delivered to the Navy. The first production missiles were delivered late in 1955.

From the very start of the Bumblebee Program, the Laboratory, in concert with many other agencies, pursued extensive and intensive studies to assess the abilities of the proposed missile to solve tactical problems likely to rise in military operations, especially the defense of ships against modern aircraft attack. As developments proceeded and data on the performance of Terrier and Talos became more quantitative, the assessment studies became more and more significant. Indeed, they served a dual purpose: first they gave the military operators reliable information on which to base strategic and tactical planning; second, and perhaps more important, they revealed to the developers areas of tactical importance where the potential capabilities of the missiles were quite inadequate and inspired work to eliminate or drastically reduce these inadequacies. An example was the effectiveness of missiles against very-low-flying attacking aircraft, which inspired the use of continuous-wave radar homing guidance in both missiles.

In late 1952, the Laboratory began a study to assess the capabilities of Talos, based on the known performance of its prototype, to defend cities or other important land-based installations against air raids. The results of these studies were recognized by the Navy and the Air Force to be so promising that funds were allocated for the development and demonstration of a Talos land-based system. On December 12, 1956, the Navy, on behalf of the Air Force, who then had primary cognizance over continental defense, entered into a contract with the Moorestown Division, Radio Corporation of America (RCA), for the engineering and construction of a land-based system, referred to as the "Talos Defense Unit" (TDU). RCA had long been an Associate Contractor and had developed for Bumblebee a monopulse tracking and guidance radar whose reliability and performance were never surpassed. An up-to-date system was designed and built at White Sands Proving Ground. It embodied early warning, tracking, and guidance-control radars based on the design of the Bumblebee radars mentioned above; fully automated equipment for periodically testing the readiness of all parts of the system, including the missiles and the automatic machinery for launching them; and a very effective system of information display for command and control. On December 13, 1957, a Talos launched from and controlled by the TDU scored a direct hit on a drone target. During 1958, many firings against a variety of sophisticated airborne targets proved the effectiveness and reliability of the TDU. The installation was accepted by the Navy in September 1957 and cognizance for further development and tests was turned over to the Army, which by this time had taken over responsibility for the system from the Air Force. Although intensive studies showed that the TDU certainly had a limited capability against intercontinental missiles, the rise of the threat of ballistic missile raids and the decline in the possibility of raids by conventional bombers lessened interest in the TDU and the project was terminated in 1959.

In the years following 1955, research and development efforts paid off in modifications to the basic design of the Talos missile, which resulted in its envelope of effective performance being extended to 100 miles in range and 70,000 feet in altitude. Its cruising speed was approximately Mach 2.5. On May 28, 1958, the recommissioning of the USS *Galveston*, CLG-3, as a guided missile cruiser (Fig. 11) marked the introduction of the Talos System into the Combatant Fleet. Thirteen years after the start of this "high risk" program of research and development, the Talos System with a performance capability undreamed of in 1945 became an active instrument in implementing the power of the United States Navy.

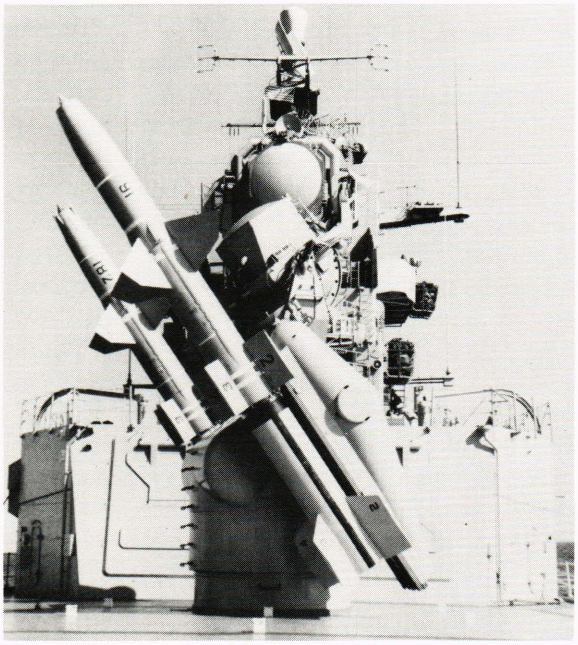

Fig. 11—Talos missiles on the USS *Galveston*, CLG-3.

The story of evolving missile technology at APL is not complete without mention of Tartar. On March 23, 1951, at the request of the Navy, the Laboratory began a study of a surface-to-air missile system suitable for deployment on small ships such as destroyer escorts, a requirement that inspired a number of development and engineering innovations that later found application in other missiles such as Terrier. Among these innovations was a combined missile storage magazine and automatic launcher somewhat larger than a 5-inch gun turret, a dual-thrust rocket engine that first boosted the missile to full speed and then maintained that speed for the proper time, and a complete new planform with low-aspect-ratio surfaces called dorsal fins that proved ideal at supersonic speeds. All steering and roll-control orders were implemented by movable tail fins that were folded during storage and erected automatically on the launcher; guidance signals were derived from a homing system that picked up radar reflections from the target. The missile was given the code name "Tartar." S. Kongelbeck and his group of engineers played a leading role in implementing these engineering innovations, which raised very sophisticated problems in the dynamics of automatic machinery. The development was completed successfully under the direction of T. W. Sheppard in 1959, and the Tartar missile system was first deployed on a combatant ship, the USS *Adams*, DDG-2, which was commissioned on September 10, 1960.

The Search for Stability

The official opening of Building One in Howard County (Fig. 12) on October 16, 1954 marked the end of one phase of the life of the Laboratory as well as the beginning of another. Building One symbolizes a culmination in a search for stability, a problem whose many factors had demanded considerable attention for more than eight years.

It has always been recognized by all concerned that the stability of the Laboratory in terms of continuity of effort is something the staff must earn unremittingly by the technical competence, imagination, practical skill, and determination it

Fig. 12—Building 1 at Howard County, the first University-owned home of APL, dedicated October 16, 1954.

devotes to well-thought-out objectives leading to devices and services of real use to Government agencies. There are no substitutes for excellence of performance and utility of product. However, human beings cannot do their best in an atmosphere of uneasiness and uncalculated risks that may lead to catastrophe; thinkers and doers like to feel that they "belong" to an empathic organization having under its control material assets and facilities that enable them to implement their ideas and skills. For want of a better term, I use the word "stability" to denote the state of an environment in which the upward and downward flow of loyalties and visibility of material resources foster constructive thought and action.

Late in 1945, despite an ephemeral climate of rapid transition from wartime to peacetime activity, the University undertook to continue the sponsorship of APL in support of its commitments to the Navy to develop shipborne antiaircraft guided missiles. The responsibilities associated with this commitment were by no means trivial. From the financial point of view, the budget of APL was comparable with that of all the rest of the University. The University was responsible for the prudent and legal expenditures associated with this budget and, to an increasing degree, for the support of the large staff of professional people. The contract, which involved annual expenditures of some $10 million, was subject to termination on thirty days notice. Furthermore, there was a growing feeling in some quarters that the development and engineering of guided missiles for the Armed Services was not an appropriate activity of a university in peacetime and therefore might be subject to popular criticism.

Joint Operation

In order to minimize the risks, financial and otherwise, the University, with full concurrence of the Navy (BuOrd), invited an industrial concern, the Kellex Corporation, to share with it the responsibilities involved in the operation of APL. Although never precisely defined, the division of effort was roughly as follows. The Manager of the Laboratory, the Director of Research, and the "scientific" staff were employees of the University, reporting to the President and responsible for all programs related to Contract NOrd 7386, basic research, applied research and development, and the technical direction of the work of all Associate Contractors. The Kellex Corporation, under a separate contract with the Navy, would be responsible for all "engineering" activities, for certain developments initiated by Kellex, for technical support (shops, etc.), for the supporting staff and business operations, and for the custodianship of buildings and other facilities. A joint committee called the Subcommittee of the Board of Trustees Committee on Cooperative Research, consisting of members of the Board of Trustees of JHU and corporate officers of Kellex, with D. Luke Hopkins as Chairman, was appointed to oversee the whole operation. Under this joint operation, the "scientific" staff was expected eventually to approach but not to exceed 100. The "gradual transition" called for by this arrangement started in June 1946 and began a phase in the University's search for stability for APL.

The Institute for Cooperative Research

Such problems concerning the exact relationship with the University as academic titles and tenure began to worry some members of the scientific staff of APL. These were thought by Dr. Hafstad and Dr. Bowman to be serious enough so that steps were taken early in 1946 to explore the establishment of an Institute for Cooperative Research (ICR) in the University, one object of which was to form a link between the University and the APL staff, another being to provide a focus for all research projects sponsored by external agencies in any School of the University. The overall objective of the establishment of ICR was to recognize the mutual advantages, demonstrated in wartime, to industry, to the Government, and to the University, of cooperative research enterprises and to provide a mechanism for promoting them throughout the University. Note that this was long before NIH and NSF were in business.

To assume cognizance of all contract research in the University, ICR was activated on April 16, 1947, with the appointment of Dr. Hafstad as its Director. He continued as Director of Research at APL.

The action was taken after a year of meetings and deliberations by the Advisory Board for Cooperative Research consisting of members of the faculties of the School of Higher Studies, the Engineering School, the Medical School, the School of Hygiene, and APL. This board proposed that ICR be established as a Division of the University with faculty appointments of Professor, Associate Professor, Research Physicist, Research Chemist, and Research Engineer, Assistant Professor, Instructor, and Associate. Some 20 members of the staff of APL were recommended for and given one or another of these titles.

Furthermore, it was the obvious intent of the Advisory Board that ICR, as a Division of the University, should have laboratory facilities of its own, either on or off campus, where its faculty could conduct investigations of their own choosing supported by grants or contracts. APL was considered such a facility.

During the pre-establishment deliberations of this Advisory Board, grave doubts were arising in several quarters concerning the place and function of APL in ICR. The prospect of a faculty committee, the Advisory Board of ICR, coming between APL and the President and Trustees with implied faculty control of the operation was not regarded favorably by either the Kellex Corporation or the University side of APL. The precise relationships between APL and ICR were never defined; hence, except for some academic titles, the place of the members of the scientific staff of APL and their tenure in the University were also undefined in June 1947, by which time ICR was operating (and still operates) as an office dealing with the purely contractual and administrative functions concerned with the externally supported research conducted by the various departments. The establishment of ICR and the studies leading to it constituted a positive step forward in the search for the stability of APL, both by the University and the "scientific" staff of the Laboratory. It interested a wide cross section of the JHU faculty in cooperative research in general and in APL in particular. It resulted in a positive statement of University policy regarding the appropriateness and value of cooperative research. It offered the "scientific" staff of APL, the University remnant in the joint operation, a University base through which, among other things, University-owned facilities could be acquired. And it paved the way for the final reorganization that occurred about a year later.

The Laurel Land

Late in 1945 a destabilizing problem emerged at the Forest Grove Laboratory when neighbors complained that the noise from the Burner Laboratory created a nuisance, a complaint that resulted in political action. Matters became so serious that the management of the Laboratory and the Navy agreed that operations at the Burner Laboratory should stop by the end of 1946. Since the facilities at the Burner Laboratory were absolutely essential to the development of an engine for the Bumblebee missiles, it was decided to acquire land in an isolated and secluded area to which the facilities at the Forest Grove Station could be transferred.

In the summer of 1946, negotiations were in progress to acquire a 93-acre parcel of land between Laurel and Greenbelt, Prince Georges County, Maryland, fronting on Old Gunpowder Road (sometimes called Bladensburg or Powder Mill Road). The total cost of $14,700 was financed from the Laboratory Contingency Fund (Special University Reserve No. 2). This tract of land had all the desirable characteristics of seclusion and zoning restrictions, together with easy access to plentiful supplies of water and electric power[18]. Its only drawback was the distance, 11 miles from 8621 Georgia Avenue, Silver Spring.

However, the Burner Laboratory was never moved to the "Laurel land." A successful program of soundproofing satisfied the neighbors. In addition, zoning difficulties that stood in the way of plans by the company owning the land for a lucrative use of the site induced the company to encourage the Navy to renew the lease and to continue all the Laboratory operations at that site.

Although the risk of the loss of the Burner Laboratory at Forest Grove never really disappeared, it was December 1962 before the facility was dismantled, operations at the Propulsion Laboratory in Howard County having begun in September 1961.

However, the Laurel land proved to be a good investment in a number of ways. In late 1947 and early 1948, the site was used for radiation experiments. A high-temperature and materials laboratory was planned not only for burner investigations but also to investigate materials problems associated with the applications of nuclear energy. Finally in 1951, the University ownership of the land facilitated decisions by all parties concerned about the future home of APL.

Divisional Status

A great step in the Laboratory's search for stability was taken on March 26, 1948 when the University decided to dissolve the partnership with the Kellex Corporation and incorporate APL into the University structure as a Division reporting directly to the President. Early in 1947, it was becoming apparent that certain fundamental conflicts, especially in the field of technical policies, were arising because of incompatibility between the aspirations of the scientific staff and the management of the Kellex Corporation. On June 13, 1947, Mr. Haylor, the Manager of APL, resigned, feeling his position untenable; a few weeks later Dr. Hafstad requested leave of absence to take over the Secretaryship of the Joint Research and Development Board in the Department of Defense. R. E. Gibson was appointed Acting Director on July 1, 1947. A few months earlier, in a Laboratory reorganization, the Research Council, representing the University-sponsored "scientific" staff of APL, had been set up with Dr. Hafstad as Chairman and Dr. Kossiakoff as Secretary. In August 1947, this Council was made responsible for initiating and formulating recommendations concerning long-range technical planning for the Laboratory. (See *APL News*, August 1947.)

The efforts of the Research Council not only strengthened and extended the research program of APL, but also crystallized and communicated to the University the aspirations of the research scientists and engineers concerning the management environment in which they could work successfully with Associate Contractors to bring to fruition the Laboratory's commitments to the Navy.

On April 12, 1948, as the result of the meeting of the Trustees Committee held March 26, 1948, the University announced that initial steps leading toward definite separation of the joint responsibilities of The Johns Hopkins University and the Kellex Corporation in the operation of the Applied Physics Laboratory would be taken at once. On May 11, policies and mechanisms for effecting this reorganization were promulgated.

A joint reorganization committee consisting of representatives of the University, the Kellex Corporation, and the Navy worked out the details of the division of responsibility. As a result, the Kellex engineering and special development tasks were transferred to a new organization, the "Kellex Silver Spring Laboratory," which later became part of the Vitro Corporation and still (1976) collaborates with APL.

The Advisory Board

Each major Division of the University has an Advisory Board. Although they differ in composition and methods of selection, each advises the President and the Board of Trustees concerning the health and problems of the Division, particularly in matters affecting the Division's interaction with the University as a whole, and makes recommendations for faculty appointments and for major changes in the Division's operation.

On April 17, 1948, representatives of APL met with the President and with P. Stuart Macaulay,

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[18] An account of the "Laurel land" and related negotiations is given in a letter from H. M. Haylor, Manager of APL, to Isaiah Bowman, President, JHU, dated October 24, 1946. It is interesting to note that the land was recommended to be purchased as a field station for the ICR.

Provost of the University, to discuss the formation of an Advisory Board for APL. Following the unanimously accepted suggestion of Mr. Macaulay, the President decided to appoint an Interim Advisory Board for APL and asked the Laboratory for nominations for membership. The nominations received the approval of the President and the Trustees at the end of May. The chief functions of the Interim Board were to study current University practice, and special features of the APL organization, and to recommend an Advisory Board structure and method of selection appropriate to the Laboratory.

At a meeting on November 2, 1948, the Interim Advisory Board made two recommendations. The first was that there be created in APL a staff category called the "Principal Professional Staff," roughly parallel in constitution and status to Professors and Associate Professors in other Divisions of the University. Its membership would be exclusively eligible for election to the Advisory Board and would be drawn from leaders in research, development, engineering, and administration in the Laboratory. Nominations to the Principal Staff would be made by the Director, recommended by the Advisory Board, approved and appointed by the President. The second recommendation was that the Advisory Board for APL be composed of the President of the University, the Provost, and the Director of the Laboratory as *ex officio* members, the Assistant Directors, the Chairman of the Research Center, designated Task Supervisors, two members of the Principal Professional Staff elected by the Advisory Board itself, four members of the Principal Staff elected by the whole Senior Staff, and one member (later changed to two) from other Divisions of the University.

Both recommendations were approved by the President and the Trustees. The first twenty members of the Principal Professional Staff, nominated by the Interim Board, were appointed by the President as of December 28, 1948.

The first meeting of the Advisory Board for APL, constituted according to the procedures outlined above, was on January 28, 1949 under the chairmanship of D. W. Bronk, the new President of the University. APL was now truly a Division of The Johns Hopkins University.

The Trustees Committee for the Applied Physics Laboratory

As soon as it was decided that the University would assume full responsibility for the operation of APL, the President asked the University representatives on the Subcommittee of the Board of Trustees Committee on Cooperative Research (see page 22) to constitute a Trustees Committee for the Applied Physics Laboratory under the Chairmanship of D. Luke Hopkins. The chief function of this Committee was to supply the Trustees with first-hand information concerning the status of APL and to recommend action appropriate to the Board on matters affecting the Laboratory. From the outset, high-ranking officials and officers of the Navy have been invited to attend all the Committee meetings, giving them an opportunity to appraise the Laboratory's work. Frictions arising between the Laboratory and the Navy or other sponsors thus receive the Trustees' attention and resolution before they become serious. The Chairmen of this Committee in the order of incumbency have been D. Luke Hopkins, Robert W. Williams, Stuart S. Janney, F. H. Fitzgerald Dunning, and William Purnell Hall.

Stabilization Fund

The stability of any organization depends on its having money in the bank to take care of emergencies that might otherwise drive it to bankruptcy.

The contracts, the first with OSRD and the second with the Navy, under which the Laboratory operated during the first 25 years of its existence, provided that all costs, both direct and indirect, were reimbursible as direct costs allowable under the contract when supported by financial vouchers subject to Government audit[19].

Under both contracts, the Government provided the University with funds to cover expenses recognized as necessary for the operation of the Laboratory, but not reimbursible under the contract. Under the OSRD contract, a "lump sum in lieu of fee" was paid to the University to cover expenses of a nonreimbursible character, costs disallowed in Government auditing, and the overhead expense of University administration under the contract. Under the Navy contract, a similar arrangement was made with a fourth item added, namely a contingency fund to provide for an

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[19] For internal management purposes, the Laboratory kept separate accounts for costs (salaries, wages, material, etc.) directly associated with the research and development work and for indirect costs (administrative and custodial services) in order to determine a figure comparable to the "overhead" computed according to industrial audit standards and regulations.

orderly redeployment of the staff in the event of termination of the contract. It should be noted that, under the OSRD contract, many Laboratory staff members were on leave from other organizations to which they might return. All members understood that upon cessation of hostilities, it was extremely probable that OSRD and their employment at APL would terminate. Under the Navy contract, the future of the Laboratory became more indefinite, bringing home to all concerned the necessity of a contingency fund to protect the staff to some extent in case the contract were terminated.

In 1948, when the University resumed complete responsibility for the operation of APL, the Navy and the University both felt it desirable to avoid possible questions of the legality of "lump sum" payments and to adopt a negotiated fee system, payable under the newly enacted Armed Forces Procurement Act. Since January 1, 1948, a fixed fee has been negotiated with each annual extension of the contract.

It was agreed by all parties that the proceeds of the "lump sum" or fee payments belonged to the University and could be used without Government audit in management and other expenses connected with the operation of APL. In 1948, the University (mostly through the efforts of D. Luke Hopkins) formally created a Stabilization and Contingency Fund for APL into which accumulations from "lump sum" and "fee" payments could be deposited and held to stabilize the employment of the staff. In recognition of the justification of this Fund, the Navy Contracting Officers have taken into account the requirements of the Fund in annual negotiations concerning the magnitude of a reasonable fixed fee.

The Howard County Site

In 1950, it became apparent that a shortage of laboratory and office space was seriously limiting the capacity of APL to carry out technical work desired by the Navy and to handle anticipated increased demands arising from the Korean War. For example, the staff of APL increased from 674 in December 1942, to 868 in December 1951, and to 1142 by the time the first Howard County building was accepted. The problem was alleviated, but not solved, by renting additional space in Silver Spring.

At a meeting of the Trustees Committee, attended by the Chief of the Bureau of Ordnance on October 3, 1950, the matter of constructing a new building for APL on the Laurel land owned by the University was seriously discussed as a more permanent solution of the space problem. At that time, a Government policy was being stressed of decentralizing essential activities in the Washington area. The location of the Laurel site was far enough from Washington to accord with that policy. As a result of a suggestion made by the Chief of the Bureau of Ordnance at the next meeting on January 24, 1951, a joint Navy-APL ad hoc committee was organized to study in depth the space requirements of the Laboratory in the light of its current and potential work load and to explore various plans for meeting these requirements. The report of the committee confirmed the need for more space and recommended the construction of a new building of approximately 100,000 square feet on the Laurel land as the preferable way of supplying the extra space needed.

At a special meeting on May 3, 1951 attended by Messrs. Bronk, Macaulay, Hopkins, Gibson, and Curry, it was decided to take immediate steps to develop the information necessary for decisions concerning a new building by arranging for an architectural study of a building to supply the Laboratory's needs at the Laurel site and to explore means of financing and amortizing the cost thereof. At its meeting on October 10, 1951, the Trustees Committee voted unanimously to recommend to the Board of Trustees that APL take steps to build a laboratory on the Laurel property at a cost of $1.8 million, financed by $400,000 from the APL Stabilization Fund and a bank loan of $1.4 million negotiated without recourse to the University's assets.

Securing a bank loan on its own credit proved to be a difficult job for the Laboratory. However, through the good offices of T. S. Nichols, a member of the Trustees Committee, a loan authorization was obtained from the Reconstruction Finance Corporation under Section 502 of the Defense Production Act of 1950, based on the understanding that the Navy would issue a 15-year amortization agreement that would be payable as an allowable charge under the contract, which it did. Under this authorization, the Riggs National Bank granted a loan of $1.4 million. In return for the amortization agreement, the University gave the Navy an option to buy the building at any time for the unamortized amount of the loan.

As the efforts of the architects (Voorhees, Walker, Foley, and Smith, of New York) to design a building that would be optimally suited to the Laboratory's needs at a price within the budget proceeded to the final stages, it became apparent that some additional land would have to be procured to round off the Laurel site. Owners of the adjoining land were unwilling to sell this extension to the University largely because of the valuable deposits of sand and gravel that underlay the terrain. In view of this difficulty and of the undesirability of placing a permanent building in an area surrounded by gravel pits, the Laboratory began a search for a new site reasonably close to Silver Spring and between Silver Spring and Baltimore to facilitate traffic between APL and the University. A highly suitable tract of land for sale was found in Howard County west of Route 29 on the north side of Gorman, later renamed Johns Hopkins, Road. The price was very reasonable. The architects were certain that the building they had designed for the Laurel site could be placed on the Howard County land without additional cost. Purchase of the land[20] with monies from the Stabilization Fund was approved by the Trustees Committee at its meeting on January 31, 1952. Use of the new site was also approved by the Navy and by agencies associated with the bank loan. Ground was broken on February 24, 1953 with the unceremonial snort of a bulldozer. The building was ready for occupancy in September 1954 and was formally dedicated at a ceremony on October 16, 1954, followed by a "Family Day" Open House complete with exhibits. In the meantime, the Laurel land had been sold to the Contee Sand and Gravel Company for $36,332.25, or 2½ times its original cost to the University.

Epilogue

This essay should be regarded as an outline of and a comment on the various chapters that might comprise the first volumes of the History of APL. It traces the education of the Laboratory in a branch of systems engineering that focuses research and development—and reduction to practice in a remarkable number and variety of disciplines—on the design and construction of high-speed, automatic devices that must live and function with precision in rugged and even hostile environments. Those years were exciting ones; the field was new—on the forefront of the art and of the science. The objectives were almost, but not quite, out of reach. The opportunities for "firsts" were almost unlimited. Each flight test was the culmination of months of studies in the laboratory or the office and of labor in the workshop. The results were awaited in a tense atmosphere of expectation comparable with that preceding the outcome of the Derby or the seventh game of a World Series.

Paradoxically, we learned most from our failures. The conviction that behind seemingly mysterious effects lay rational causes spurred on efforts to determine those causes and to devise ways to eliminate the unwanted effects. The successes lifted the spirits not only of those immediately concerned but of the whole Laboratory, restoring confidence and renewing determination. Nobody who lived through the day of a successful flight test will ever forget the experience. Over the years there were many such days of which two or three may be recalled: March 6, 1951, when the first experimental prototype ramjet-propelled missile ever to be guided by a radar beam demonstrated achievement of all of the original objectives; a similar successful demonstration that occurred two days later; and May 16, 1952, when two Terriers launched within two hours each destroyed an F6F drone target on the range at the Naval Ordnance Test Station, Inyokern, California.

The deployment of Bumblebee missiles on warships marks, somewhat arbitrarily, the end of this narrative. It also marks the beginning of exciting new undertakings in research and engineering that triggered the period of the most rapid growth in the Laboratory's history. In the decade 1955 to 1965, the permanent staff doubled in size; office and laboratory space increased by a factor of two and a half; and new facilities were added, including a modern Propulsion Laboratory (1961), the Typhon Radar Building (1961), the Microelectronics Laboratory (1959), the Computing Center (1961), the Fleet Systems Radar Building (1963), and a new Library Building with classrooms (1963). The expansion in scope of the Laboratory's work during this decade and beyond

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[20] The land originally purchased in Howard County consisted of four parcels: the Wessel farm, 126.9 acres; the Moore farm, 76.9 acres; the Wolff farm, 20.4 acres; and another Wolff farm, 80.0 acres—a total of 304.2 acres. The total price amounted to $100,412, an average of $330 per acre.

arose logically from experience gained in the Bumblebee Program. Although the expansion must form the subject of the second set of volumes of the History of APL, some hints of the contents may be given here.

The deployment of missiles on ships imposed some restraints on further development of the missiles, but left plenty of room for the incorporation of improvements suggested by (a) the increasing knowledge of supersonic aerodynamics, guidance, control, and propulsion at high speeds; (b) newly developed devices such as transistors and integrated circuits for compact and reliable electronics; and (c) the application of transistors and, subsequently, integrated circuits to produce compact, reliable, and sophisticated electronics. In cooperation with the prime contractors, General Dynamics and Bendix Aviation Corporation, notable improvements were made, tested, and incorporated in the missiles produced for the Navy.

Increasing experience in the tactical performance of missile systems brought the realization that the *certainty* and the *rapidity* of the generation and transmission of information by the various components (search radars, tracking radars, computers, etc.) so necessary to the successful operation of any system were inadequate. Furthermore, the reliability and means of testing such systems left much to be desired. The Laboratory became deeply involved in both long- and short-term solutions for this cluster of problems.

The long-term solution was based on a thorough study in late 1957 of the necessary characteristics of future Fleet air-defense systems. The study led to a sizable program of experimental research and development leading to a complete, advanced guided-missile system involving a computer-controlled combined search and tracking radar and high-speed missiles to take advantage of the system's capability of providing rapid and certain tactical data. The facility built for this work is shown in Fig. 13.

The search for short-term solutions rose to an urgent pitch in 1962 when unhealthy symptoms in all parts of the man-machine systems deployed on increasing numbers of combat ships involved the Laboratory deeply in the diagnosis and cure of malfunctions in all components of the systems. A new building, the Radar Systems Building (Fig. 14), was erected on which current Navy radars were mounted for operation, study, and demonstration of necessary modifications to supplement the shipboard activities of many members of the staff.

On November 15, 1957, a group was established to consider how best the Laboratory could respond to a request by the Special Projects Office of the Navy for active participation in the development of the Navy's strategic deterrent system, the submarine-launched Polaris missile. The first project undertaken in response to this request was a relatively obvious one, namely the application of the store of experience gained in the test and evaluation of missile systems to the devising of methods and instrumentation for measuring quantitatively those properties of the Polaris system and its components that determined the performance, reliability, readiness, and accuracy of the system as a whole. Experiments were designed so that the measurements could immediately be reduced by computers into terms readily interpretable by engineers and military men (Fig. 15).

The results of this work gave military planners a more accurate basis for assessing the combat effectiveness of the Polaris system than had ever been available for any weapon system. They also showed exactly where new ideas or hardware were needed to eliminate weaknesses or were desirable to bring about significant improvements. Some of these improvements were explored experimentally at APL and implemented by industrial contractors.

The second project was not at all an obvious one, being based on a scientific "breakthrough" originating in the minds and experiments of

Fig. 13—The Propulsion Laboratory, March 1976.

Fig. 14—The Radar Systems Building (now the Systems Evaluation Building) at Howard County symbolizes the Laboratory's effort to improve the reliability and performance of guided-missile systems deployed on Naval ships.

members of the Research Center. A sophisticated analysis of the Doppler shift in the frequency of radio signals received from the Russian satellite Sputnik I (October 4, 1957) showed that the orbit parameters of the satellite could be determined with reasonable accuracy from observations at *one* station on the earth's surface, together with a knowledge of the earth's gravitational field[21]. The inverse proposition that, from observations of the Doppler shift in the frequency of radio waves emitted from a constant-frequency oscillator on a satellite whose orbital parameters were well-known, an observer could determine his own position with fairly high precision, gave the theoretical basis for a global, all-weather navigation system. Although its application seemed to be universal, the proposed navigation system, to which the name "Transit" was given[22], was especially acceptable to the navigator of a Polaris submarine since it required only a short exposure of a very simple antenna above the surface of the sea to provide the readings necessary to determine latitude and longitude with precision, data essential to the effective performance of the Polaris system.

At the Navy's urgent request, the Advanced

Fig. 15—The Typhon Building at Howard County, built in 1960. It symbolizes the first stage of APL's investigations of a complete missile system in which a computer-controlled radar provided timely and complete information for the guidance of missiles to an indefinite number of airborne targets under realistic tactical conditions.

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[21] W. H. Guier and G. C. Weiffenbach, "Theoretical Analysis of Doppler Signals from Earth Satellites," *Nature* **181**, No. 4622, 1958, 1525–1526.

[22] Over the years the name "Transit" has met with oscillating approval and disapproval in official circles; indeed, at one time its use was banned, ostensibly for security reasons. However, recognition of its appropriate brevity has persisted, and now (1976) the terms "Transit," "Navy Satellite Navigation System," and "Satellite Doppler Navigation System" are used interchangeably.

Research Projects Agency (ARPA) of the Department of Defense funded the Transit project from December 15, 1958 to May 9, 1960 when it was turned over to Navy management as a going concern. In December 1958, the Space Division of the Laboratory was established under the leadership of Dr. R. B. Kershner to assume responsibility for the complete system. The Division carried out development and engineering both to design and build reliable instrumented satellites and to design and build simple receiving equipment and locate it in tracking stations at suitable sites throughout the world linked to APL through a communication network. It also conducted research to explore more fully the satellites' operational environment: the gravitational field sensed by satellites; the effects of solar radiation and cosmic rays on the satellites and their components; refraction of radio waves by the ionosphere and the troposphere; and geomagnetic phenomena. The Division also studied mathematical methods for simplifying the massive computation operations needed to interpret the Doppler shift data obtained at the various receiving stations. Satellites Transit 1B (1960 Gamma II), which was launched April 13, 1960, and Transit 2A (1960 Eta), which was put into orbit a few months later, demonstrated without doubt the validity of the basic principles, the adequacy of the instrumentation and, above all, a degree of precision in the determination of orbit parameters that exceeded the most sanguine expectations. Not only was it then certain that Doppler tracking data could provide precise navigation data, it was also apparent that these satellites could increase by orders of magnitude quantitative knowledge of the earth's gravitation and magnetic fields and the distribution of high-energy particles and electromagnetic radiation in time and space. NASA joined with the Navy in support of the Laboratory's space program, particularly in the development of "scientific satellites."

The Transit Satellite Navigation System was declared operational in the fall of 1966 and was turned over to the Navy for use somewhat less than five years after the project started. Within the next few years, the Transit Navigation System became recognized as a powerful tool by all those who for military, scientific, or economic reasons required rapid and precise determination of their position (Fig. 16). It found increasing use by Naval ships of all kinds and by merchant ships, surveyors, ocean research ships, and fishing boats.

Fig. 16—The Injection Station epitomizes the Transit program. Through the 60-foot-diameter radio telescope, a special computer supplies data to the memory of the satellite. The same telescope is used to track satellites and receive signals of scientific interest from the sun and other regions of space.

The Philosophy of APL

"Philosophy is the guide to life" says the motto of a great academic fraternity. Conversely we may say that the life of an institution gives a clue to its philosophy. Indeed, the direction in which APL has grown reflects a pattern of pragmatic beliefs and practices that constitutes its philosophy. These practices and beliefs include the following:

The Challenge of Systems Problems—Interesting and compelling problems worthy of the best that men and women can give come from the outside world, from the needs and aspirations of humanity. Such problems have an urgency that sharpens the ability of scientists and engineers to generate technical solutions based on the most up-to-date resources of science and engineering. In general, these are systems problems that call for assemblies of elements designed to accomplish a predetermined purpose, interdisciplinary problems involving the close cooperation of the specialist and the generalist.

User-Developer Partnership—The Laboratory was founded on the basis of a genuine partnership with the Navy, the implications of which are detailed in the early part of this paper. The cultivation and maintenance of real partnership with the users of its developments has been a cardinal point in the Laboratory's philosophy.

Associate Contractor Partnership—To provide the wide range of talents and skills necessary to deal with all phases of systems problems from basic research to production, the Laboratory has relied on close collaboration with universities and industrial organizations, first through the mechanism of associate contracts and later of subcontracts. Uninhibited dialogue and personal contact have been essential features of this cooperation, whether the financial arrangements with the contractor are made directly with the Government (associate contracts) or directly with the Laboratory (subcontracts), and its spirit has very often been one of partnership rather than merely a business arrangement.

Centralized Technical Responsibility—Regardless of what cooperative relations exist, the Laboratory has assumed responsibility for the soundness of the technical objectives to be reached in the reduction of the systems concept to practice, for the coordination of the various efforts, and for the reliability and performance of the final systems. Policies and resources needed to implement these responsibilities include the following:

Flexible "Hands-on Approach." Since nobody can predict the specific areas of science and engineering from which enlightened solutions to externally generated systems problems may come, a consistent philosophy has implied certain characteristics of the staff responsible for technical direction. Although specialists in certain fields of science digging deeply into narrow fields have added to the intellectual and practical resources of the Laboratory, most staff members have demonstrated a capacity and a will to extend their professional expertise, within reasonable limits, to meet the demands of new systems problems by acquiring first-hand knowledge and experience in the pertinent specialties of science and engineering. Technical direction by people having first-hand knowledge of the detailed as well as the general problems in any development has persisted since the days of the Cyclotron Building.

Experimental Exploration of Advanced Technical Objectives. To be viable and up-to-date when completed, a system must be conceived in terms of advanced technical objectives whose feasibility may be uncertain. The experimental exploration of the validity of these objectives has been found by APL to be perhaps the most economical in time and effort and has become a part of its technical philosophy. For example, the ramjet engine only became a valid technical objective when simple experimental test vehicles developed excess thrust over drag. These same vehicles brought to light practical problems whose solutions were needed to attain the technical objective of using that engine in a supersonic missile. Many years later, the Transit 1B—a relatively simple satellite—confirmed experimentally the principle of a Doppler navigation system and at the same time brought to light the scientific and engineering problems that had to be solved in achieving a practical system.

Progressive Approach to "Perfection." The original Bumblebee task called for research and development leading to the general objective of a supersonic guided missile, but deferred specification of the end product pending experimental exploration to uncover the real potentialities inherent in the technology. The results exceeded the most sanguine expectations, as later happened in the case of the Transit system. Both resulted from progressive improvement based on experimentally derived knowledge—from simpler experimental models being used as stepping stones to the more sophisticated. The continuing scrutiny of technical objectives in the light of real, rather than imagined, operational requirements by the user has been an important feature of the user-developer partnership in making realistic the policy of progressive improvements.

By synthesizing these unwritten practices and policies which run like dominant threads through the tapestry of APL's history, we can catch a glimpse of the philosophy that has guided its growth. Perhaps the term "Pragmatic Humanism" best epitomizes what APL is all about.

PUBLICATIONS

Compilation of principal recently published books and technical articles written by APL staff members.

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R. A. Farrell and R. L. McCally, "On Corneal Transparency and Its Loss with Swelling," *J. Opt. Soc. Am.* **66**, No. 4, Apr. 1976, 342.

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J. D. Randall, "Finite Difference Solution of the Inverse Heat Conduction Problem and Ablation," *Proceedings of the 1976 Heat Transfer & Fluid Mechanics Institute*, Stanford University Press, 1976.

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E. T. Sarris and S. M. Krimigis (APL) and T. P. Armstrong (Univ. of Kansas), "Observations of Magnetospheric Bursts of High Energy Protons and Electrons at $\sim$ 35 R_e with IMP-7," *J. Geophys. Res.* **81**, No. 13, May 1976, 2341.

V. G. Sigillito, "A Priori Inequalities and the Dirichlet Problem for a Pseudo-Paraboloid Equation," *SIAM J. Math. Anal.* **7**, No. 2, Apr. 1976, 222.

V. G. Sigillito, "A Priori Inequalities and Approximate Solution of the First Boundary Value Problem for $\Delta^2 u = f$," *SIAM J. Num. Anal.* **13**, No. 2, Apr. 1976, 251.

M. Sugiura (Goddard Space Flight Center) and T. A. Potemra (APL), "Net Field-Aligned Currents Observed by TRIAD," *J. Geophys. Res.* **81**, No. 13, May 1976, 2155.

PATENTS

J. L. Abita, J. G. Bebee—*Method for Resist Coating of a Glass Substrate*, No. 3,951,659

C. T. Pardoe—*Telemetry Synchronizer*, No. 3,953,674

D. W. Rabenhorst—*Multi-Ring Filament Rotor*, No. 3,964,341

HONORS AND AWARDS

Dr. Vivian O'Brien, a Research Center physicist, has been elected a Fellow of the American Physical Society.

Russell A. Rollin, senior staff engineer in F4D group, was the general chairman of the 14th Symposium on Infrared Countermeasures held at the Naval Surface Weapons Center White Oak Laboratory on May 26–27, 1976.

Mary Schaefer, Space Department Senior Editor, has been named a Fellow of the Society for Technical Communications, of which she is a past president.