Design Considerations for a Commercial Crew Transportation System

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NASA's Commercial Crew Development (CCDev) initiative is providing a unique opportunity for the Boeing Company to accelerate the development of system concepts, key technologies, risk reductions, and procurement of long lead items for the CST-100 Commercial Crew Transportation System. The CST-100 is a spacecraft/system designed to affordably, reliably, and safely transfer crew from the Earth's surface to orbiting space complexes in low earth orbit, including the International Space Station and the Bigelow Space Complex. NASA's investment in CCDev, coupled with Boeing's own resources, has allowed significant progress to be made toward flying a first crewed mission by 2015.

Nomenclature

AR&D	=	Automated Rendezvous and Docking
ASIF	=	Avionics Systems Integration Facility
CCDev	=	Commercial Crew Development (Program)
CCTS	=	Commercial Crew Transportation System
COTS	=	Commercial Orbital Transportation Services
CM	=	Crew Module
CST-100	=	Commercial Space Transporter – 100
DAC	=	Design Analysis Cycle
EDS	=	Emergency Detection System
ISS	=	International Space Station
kW	=	Kilowatt
LAE	=	Launch Abort Engine
LEO	=	Low Earth Orbit
LV	=	Launch Vehicle
NASA	=	National Aeronautics and Space Administration
nm	=	Nautical Mile
PDR	=	Preliminary Design Review
RCS	=	Reaction Control System
SDR	=	System Definition Review
S&MA	=	Safety and Mission Assurance
SM	=	Service Module

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I. Introduction

Boeing is continuing to apply acquired knowledge from heritage programs and experience gained from "CCDev-1" (Commercial Crew Development Program) technology demonstrations in the on-going design considerations of the CST-100 (AIAA-2010-8841). Over the course of the last year, many design risks have been reduced or mitigated by iterative design and prototypical demonstration tests. As the program moves forward into the next phase, "CCDev-2," safety remains the priority consideration running through all design activities. Having made the selection of the Atlas V as the CST-100 launch vehicle (Figure 1), other design considerations still being traded include launch vehicle integration (e.g., mass, aero loading, thermal and acoustic issues), cost effective manufacturing and operational process flows, and the extent of capsule reusability to reduce operational costs.

The Boeing Commercial Crew Transportation System (CCTS) is designed to safely, reliably, and affordably transfer crew from the Earth's surface to space complexes in low earth orbit, including the International Space Station (ISS) and the Bigelow Space Complex. The CST-100 is a capsule-shaped vehicle that can carry a maximum of seven crew members to accommodate requirements of multiple customers. Stand-alone cargo can be substituted in lieu of crew on any given flight, allowing customers to flexibly manifest missions to meet their evolving needs. Preliminary Design Review (PDR) is on schedule for February 2012.

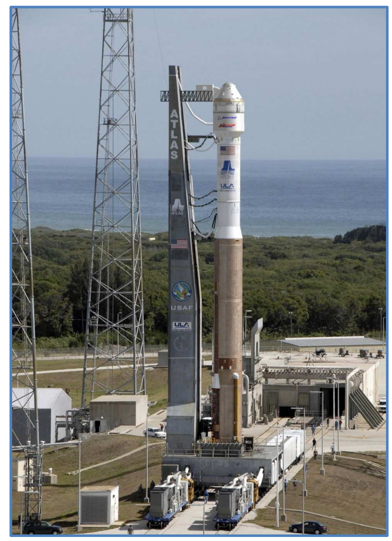

Figure 1. *Boeing's CCTS.* Launched on top of an Atlas V rocket, the CST-100 capsule safely transports crew and cargo to the International Space Station and the Bigelow Space Complex.

II. CST-100 Development

With Bigelow Aerospace and NASA as launch customers, Boeing has designed the CST-100 to meet the needs of multiple markets. Key features of the CST-100 architecture include:

- Flexible crewed vehicle that can carry a maximum of seven crew members to accommodate the broadest possible customer base
- Pusher Launch Abort System providing crew safety on a range of launch vehicles and providing additional propellant to re-boost customer platforms
- Integrated operations/crew training center to serve multiple customers needs
- Use of existing systems, hardware and software, and streamlined manufacturing techniques to lower cost and development schedule
- Lightweight design, integrated with the Atlas V launch vehicle to create a robust human-rated transportation system.

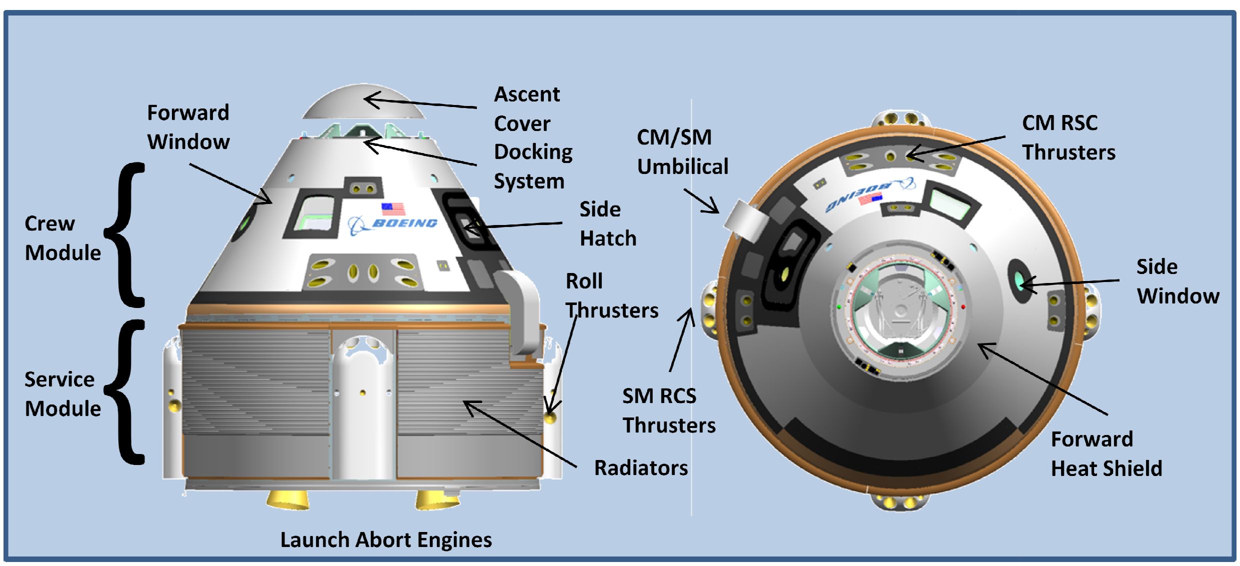

Figure 2. *CST-100 Configuration.* The CST-100, comprised of a Crew Module and a Service Module, leverages Apollo-proven aerodynamic characteristics in a design employing modern, cost effective technologies and manufacturing techniques.

Boeing's CCTS architecture is defined by four segments: Spacecraft, Operations, Launch Systems, and Ground Systems. The CST-100 (Figure 2) consists of a 4.5m diameter Crew Module (CM), with the same cone angle as the Apollo capsule, and a Service Module (SM) that interfaces with the Atlas V via a custom launch vehicle adapter.

Figure 3. *CST-100 Internal Configuration.* Up to seven crew or ancillary cargo may be carried in the CST-100 crew module in a shirt-sleeve environment. Vehicle performance is monitored by a single pilot.

The CM can be internally configured to carry up to seven crew members and empty seats replaced by customer cargo (Figure 3). The SM features an innovative integrated bi-propellant system that uses common tanks to supply hypergolic propellant for both the conventional on-orbit Reaction Control System (RCS) and pusher Launch Abort Engines (LAE). For abort, the propellants are pressurized to approximately 1000 psia feeding high thrust Pratt and Whitney Rocketdyne BANTAM-derived engines. This unique use of a common propellant storage system reduces total mass and provides additional propellant for reboost of destination space complexes or additional operational flexability. The abort system is designed to provide full ascent coverage with no abort exclusion zones, commonly referred to as "Black Zones."

The CST-100 will transport crew to LEO destinations of 250 nm altitude at 51.6° inclination for ISS, and to 225 nm at 35° inclination for the Bigelow Space Complex. The CST-100 can operate autonomously for up to 60 hours of free-flight, and is designed for Day One rendezvous with a Day Two backup opportunity. The vehicle can stay docked to a host complex for up to 210 days while provided with one kW of keep-alive power. The CST-100 utilizes Airborne Systems parachutes as an aerodynamic decelerator to accommodate land landing on ILC Dover airbags (Figure 4). System capability is provided for contingency water landings as well.

Boeing's human rating approach applies significant heritage experience in the development of the crew transportation system. It addresses all life-cycle phases and S&MA functions, and is compliant with the technical requirements of NPR-8705.2B, Human Rating Requirements for Space Systems. An Emergency Detection System (EDS) being developed by United Launch Alliance for the Atlas V will provide launch vehicle health data during ascent. Should the EDS detect an out-of-bounds condition on the Atlas V, it sends a signal to the CM initiating the launch abort sequence to safely propel the crew away from the failing rocket.

The ground segment consists of an assembly, integration, and test facility located close to the launch site, minimizing launch vehicle integration time and launch support costs. The spacecraft in-flight control center (separate from that used by the launch services provider) will be sized to handle simultaneous missions for multiple customers. Boeing will leverage existing facilities and technical experts experienced in mission design and real-time support of human space flight. An integrated operations and crew training center is being designed to serve multiple customers' needs. Returned CM capsules will be refurbished, mated with a new SM, and readied for the next flight.

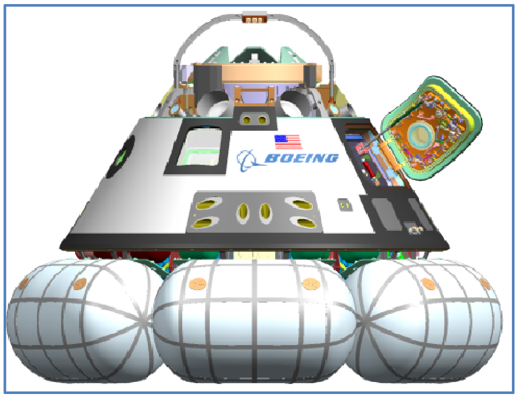

Figure 4. ***Airbags deployed for landing.*** Airborne System parachutes and ILC Dover-provided airbags decelerate the crew module for landing on dry lake beds. Contingency water landings are also possible.

III. CCDev-2 Design and Safety Review Status

Boeing employs a lean design and development approach that allows the system requirements and design to evolve simultaneously. Minimal, simplified schedules focused on products, along with high levels of accountability by project personnel, drive execution to meet key program milestones and events. Small teams of experienced subject matter experts who know their system and how it interacts with other systems are employed. Only the evolutionary advancement of technology is allowed for in this accelerated process. In this fashion, simple and flexible processes are used during the development cycle. Lean meetings geared to reviewing test and design products (i.e., as opposed to status/metrics) allow for high velocity decision making.

Within this lean approach, the iterative Design Analysis Cycles (DAC) is focused on the maturation of the CST-100 design. Figure 5 illustrates the Program Management, Technical Team, and Horizontal Integration Team activities undertaken in each DAC. To date, three such cycles have been completed, and the fourth is now underway. In each cycle a baseline is established, and a set of trade studies and analyses are identified for areas where the design is still immature, multiple solutions are evident, or system interactions require further definition. The outcomes of the fourth DAC trades will provide the baseline for the upcoming PDR in the spring of 2012.

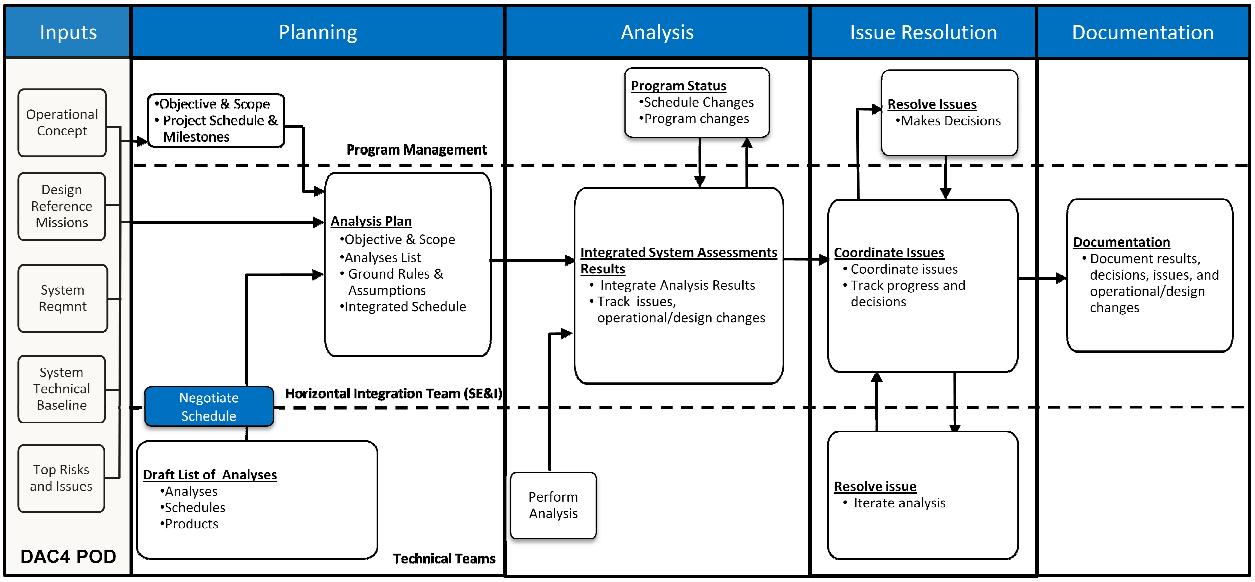

Figure 5. *Design Analysis Cycle Flow.* Programmatic, horizontally integrated, and technical team "swim lanes" illustrate the **maturation** of the baseline design through a series of subsystem or component trade studies for each design analysis cycle.

A Phase 0 Safety Review established an early program milestone to introduce independent reviewers to the CTS-100 program and related safety issues. This review, co-chaired by the Boeing Vice President of Mission Assurance, represented a checkpoint that reinforced teamwork and interactions among and between safety and design engineering personnel. Processes were exercised to ensure that the program was on track for development of PDR safety products and Phase I Safety Review, by driving early identification of issues and solutions. Baseline safety processes and current analysis of the CST-100 design were reviewed, with the focus applied to known areas needing improvement. Products of a disciplined system safety analysis process were reviewed, and disconnects and opportunities were identified in the design for resolution and incorporation in subsequent design iterations. In the end, an assessment of the design and hazard control approaches for compliance with safety and failure tolerance requirements

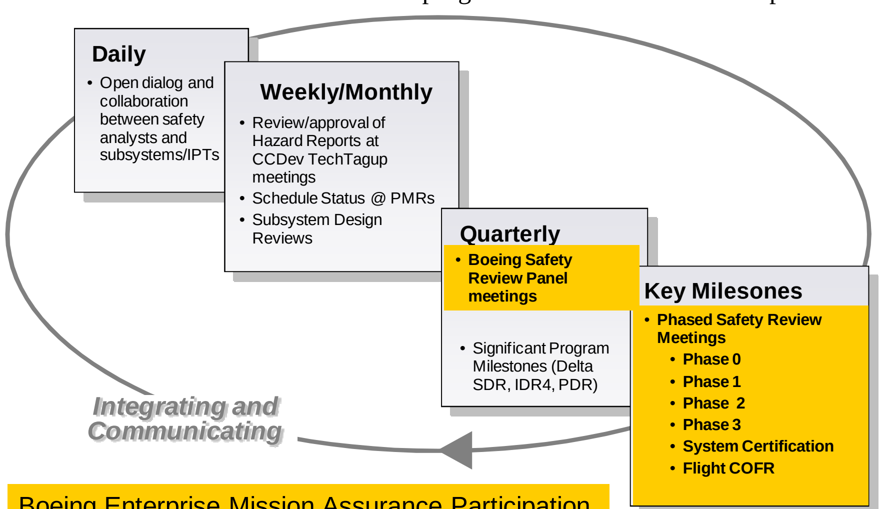

Figure 6. *Phase 0 Safety Review.* Part of the larger Enterprise Mission Assurance Program, a Phase 0 Safety Review identifies hazards and mitigations early on the design. Subsequent reviews ensure the continuity of the total system safety approach.

was provided and accepted by the governing internal safety and mission assurance board. Figure 6 illustrates how this first review fits into the larger on-going process of ensuring the safety of flight, crew, and ground personnel.

IV. CCDev-2 Risk Reduction Demonstrations

Boeing is executing a set of demonstrations to mitigate design and development risks for the CCDev-2 phase of the development program to provide focused efforts on key technologies and capabilities that require additional maturation before they can be integrated into the overall system design. CCDev-1 successfully demonstrated: Abort System Hardware; Base Heat Shield Fabrication; Avionics Software Integration Facility CST-100 performance simulation; CM Pressurized Structure Fabrication; Landing System Hardware; Life Support Air Revitalization System; Automated Rendezvous and Docking with Integrated Guidance, Navigation, and Control; and a CM Mockup.

For CCDev-2, Boeing is demonstrating: Launch Abort Engine Fabrication and Hot Fire Test; Landing Air Bag Drop Demonstration; Phase I Wind Tunnel Tests; Parachute Drop Tests; SM Propellant Tank Development Test; and LV EDS/ASIF Interface Simulation Test. A delta-System Design Review and a Phase 0 Safety Review have already been successfully completed as part of the CCDev-2 program plan.

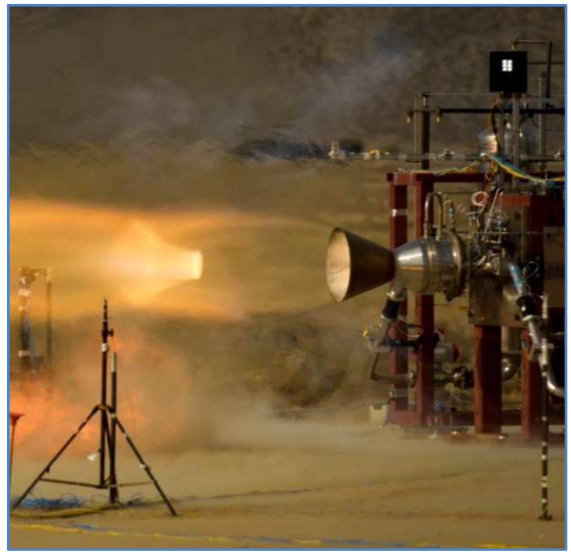

Figure 7 ***BANTAM Engine Testing.*** The BANTAM engine was tested in CCDev-1. In CCDev-2, an evolved configuration using bi-propellant fuels will be hot-fired.

Launch Abort Engine Fabrication and Hot Fire Test: The pusher launch abort system consists of four high thrust engines aft-mounted in the SM supplied by dual-use LAE/RCS fuel and oxidizer tanks. The system uses a single pressurization system for both abort and on-orbit phases for simplicity and ease of operations. The modifications being made for the CST-100 include leveraging previous work to evolve the Atlas II sustainer engine for low cost manufacturing and incorporating ablative nozzle technology similar to that used in Rocketdyne Lance engines.

This hardware demonstration (CCDev-1 configuration shown in Figure 7) utilizes a 58,000 lbf class engine previously built under the BANTAM demonstrator program and operated using hypergolic propellants. CCDev-2 testing will demonstrate engine start transients, performance, and combustion stability using bi-propellant fuels. The goal of this test is to verify design changes being made to the engine to reduce weight and improve start and overall performance characteristics.

Figure 8. ***Mobile Air Bag Drop Platform.*** A mobile drop-test rig mounted on a flatbed truck, allows for the testing of the airbag landing system at planned landing sites with simulated wind velocities.

Landing Air Bag Drop Demonstration: On dry lake beds near Las Vegas, Boeing and Bigelow Aerospace are performing drop tests using a CM boilerplate test article and reusable landing air bags from ILC Dover. Executed off the back end of Bigelow's mobile drop rig, a semi-towed 18-wheeler flatbed truck platform (Figure 8), landing performance is capable of being tested at up to 32 ft/s vertical and 50 ft/s horizontal velocities onto representative landing surfaces.

Phase I Wind Tunnel Tests: The launch stack configuration (Figure 9), consisting of the Atlas V, a launch vehicle adapter, the SM, and the CM represents a unique aerodynamic configuration never before flown. As a result, Boeing has developed a test matrix,

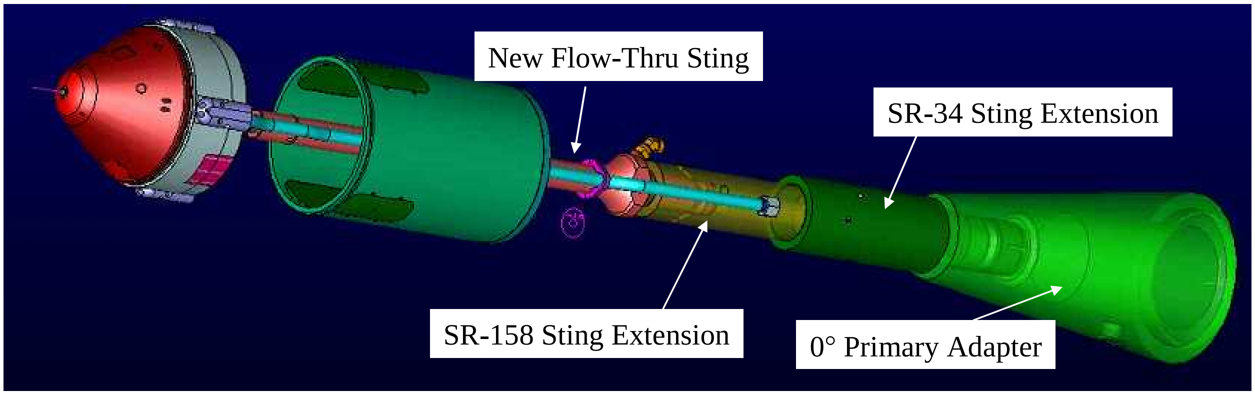

Figure 9. *CM/SM/Launch Vehicle Adapter Stack.* Wind tunnel tests of the launch stack will capture aerodynamic loads and acoustics data designers need to assess vehicle performance.

fabricated a test model, and is performing ascent wind tunnel tests to provide data to correlate computational fluid dynamics-derived forces and moments on the integrated CM/SM/LV stack for nominal ascent and abort cases.

Parachute Drop Tests: Airborne Systems is fabricating parachutes and performing drop tests of the CM parachute deployment and deceleration system from underneath a helicopter over a dry lake bed using a boilerplate test pallet. Tests will validate forward heat shield deployment, riser routing, parachute deployment, and bucket handle deployment to achieve the desired hang angle for land landings. Additional airbag landing loads data will also be collected during these tests under real world conditions.

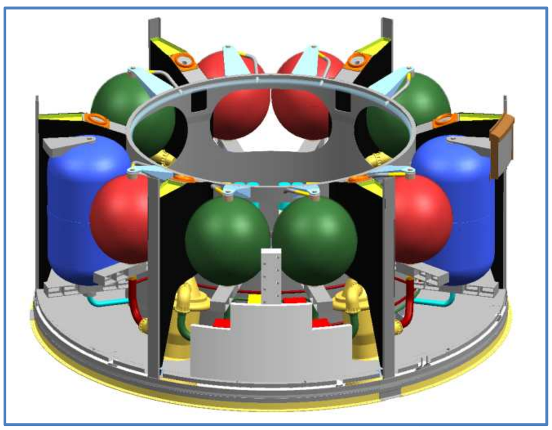

Figure 10. *SM Tank Configuration.* Internal configuration of the SM propellant tank and pressurization systems.

SM Propellant Tank Development Test: Boeing and ARDE are fabricating and performing expulsion testing of a diaphragm propellant tanks. Figure 10 shows the internal configuration of the high-reliability SM propulsion system. Propellant for both the LAE and on-orbit maneuvering thrusters is stored in the SM. Propellant tanks based on an existing satellite tank design but resized for the CST-100 operational requirements will be tested at the higher operating pressures required for abort to verify tank expulsion characteristics.

Launch Vehicle EDS/ASIF Demonstration Test: Continuing the series of tests started under CCDev-1, Boeing's Avionics Systems Integration facility (ASIF) will be linked to the Atlas V Emergency Detection System (EDS), to simulate a variety of abort conditions and spacecraft responses to Atlas V initiated aborts. Algorithms, timing, and crew interfaces and displays will be exercised during the test series.

V. Conclusion

With the CCDev Program, NASA set a goal of developing system concepts, key technologies, and capabilities that could ultimately be used in a commercial human space transportation system. Since the CCDev contract award in February 2010, Boeing has made significant progress on long lead capabilities, technologies, and risk mitigation tasks. In cooperation with Bigelow Aerospace, several significant technology and manufacturing demonstrations have been conducted. During the CCDev-2 program phase, Boeing is continuing the development of the CST-100 and will achieve the PDR milestone in February 2012. Because of the NASA CCDev Program, the CST-100 has made marked progress towards becoming an operational system to safely and reliably carry crews to destinations in low earth orbit.

Acknowledgments

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