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X-37 FLIGHT DEMONSTRATOR PROJECT: CAPABILITIES FOR FUTURE SPACE TRANSPORTATION SYSTEM DEVELOPMENT

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ABSTRACT

The X-37 Approach and Landing Vehicle (ALTV) is an automated (unmanned) spacecraft designed to reduce technical risk in the descent and landing phases of flight. ALTV mission requirements and Orbital Vehicle (OV) technology research and development (R&D) goals are formulated to validate and mature high-payoff ground and flight technologies such as Thermal Protection Systems (TPS). It has been more than three decades since the Space Shuttle was designed and built. Real-world hardware experience gained through the multitude of X-37 Project activities has expanded both Government and industry knowledge of the challenges involved in developing new generations of spacecraft that can fulfill the Vision for Space Exploration.

INTRODUCTION

The quest for knowledge is exemplified by astronomical study of the Sun, asteroids, and black holes, as well as voyages to the inner planets, such as Mercury and Mars, and the outer planets, such as Saturn and Jupiter. This age-old search also includes looking at Earth itself, thereby discovering ways to balance humankind's relationship with nature. Aboard the International Space Station, astronauts are learning to live and work while still close to Earth in preparation for a return to the Moon and eventual human trips to Mars.

The National Aeronautics and Space Administration (NASA) X-37 Flight Demonstrator Project has made significant contributions to that future in many ways. Developing a high-altitude flight demonstrator and advancing the readiness levels of critical enabling technologies has added immeasurable value to the aerospace knowledge base. The programmatic and technical experience gained through the X-37 Project is a valuable contribution that ultimately improves the capability to build and fly new generations of spacecraft for continued space exploration.

BACKGROUND

NASA has undergone extensive organizational transformation as a result of the tragic loss of Space Shuttle Columbia and crew in February 2003. In October 2003, the Columbia Accident Investigation Board Report made specific recommendations to NASA to retrofit the Shuttle fleet with safety upgrades, as well as encouraged the Administration to give clear strategic direction to NASA. In January 2004, the Administration presented the Vision for Space Exploration. This policy directs NASA to lead a return to the Moon in preparation for further exploration of Mars and beyond. It also instructs NASA to complete the Space Station and retire the Space Shuttle as a new exploration transportation system is developed and fielded.

NASA's Office of Exploration Systems, which includes Project Constellation in its Development Programs Division, was established in January 2004 and charged with defining both mission requirements and delivering the space transportation system needed to empower the human and robotic exploration of space. In June 2004, the Report of the President's Commission on Implementation of United States Exploration Policy was released and NASA underwent a reorganization designed to make exploration beyond low-Earth orbit (LEO) a reality. Also in June 2004, Level 0 exploration requirements were released. Goals include implementing a safe, sustained, and affordable space exploration system that will allow greater investment in the reason for space missions, namely, scientific discovery.

In the life of any project, hardware accomplishments lead to something far more valuable than the materials of which they are made. Rather, true worth comes from knowledge shared with others seeking to improve the likelihood of mission success as the Vision for Space Exploration comes increasingly closer to reality. Ultimately, the detailed data delivered and broad-based experience gained by virtue of the work completed through the X-37 Project will benefit future space development efforts such as those being conducted by Project Constellation.

DELIVERING REAL-WORLD HARDWARE DATA AND EXPERIENCE

The X-37 Project has been a partnership between multiple NASA Centers, the U.S. Air Force (USAF), and private industry. The X-37 Project consists of two development areas: (1) the Approach and Landing Vehicle design, development, and operation, and (2) Orbital Vehicle enabling technologies R&D. The ALTV development stage (Figure 1) is nearing completion, with atmospheric drop tests planned for 2005. The ALTV will demonstrate system performance in the approach and landing flight phases, as well as validate aerodynamic stability, structural integrity, and automated operations in the approach and landing environments.

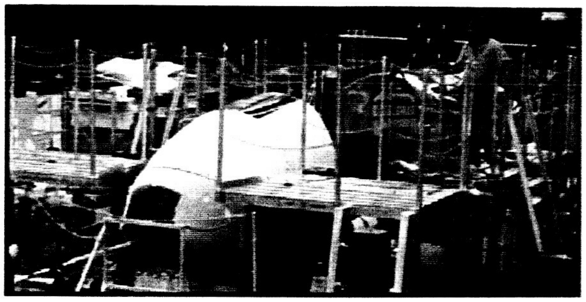

Fig. 1: Vehicle assembly.

The ALTV builds on a series of seven successful low-altitude flights in 2001 of the Air Force-owned/NASA-operated X-40A flight demonstrator (Figure 2), which improved automated guidance, navigation, and control (GN&C) and landing systems, as well as validated a streamlined operations concept.

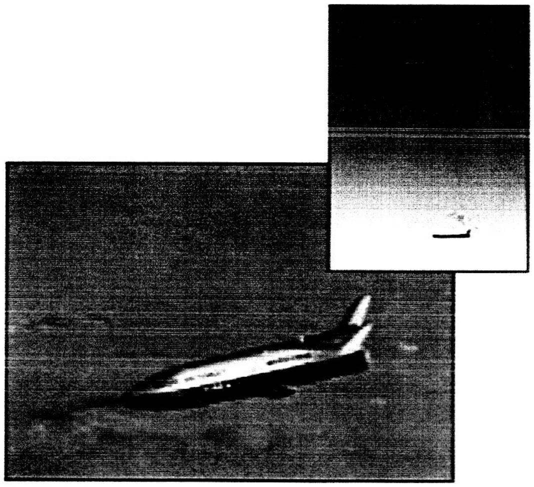

Fig. 2: Test flight of X-40A.

A new era of space exploration requires advances in basic vehicle systems and subsystems, such as those found in the ALTV, as well as innovative ways of doing business that promote greater efficiency in management, manufacturing, and operations. OV high-risk technology investments have been selected through a rigorous risk-management process to advance the state of the art in lightweight, high-performance TPS and associated Hot Structure Control Surface (HSCS) materials. These and other R&D efforts have been funded specifically to enable orbital flight.

ALTV Description and Progress

The ALTV (Figure 3) is a prototype vehicle that is 27.5-feet long with a 15-foot wingspan. It is fully automated and designed to land on a conventional runway. The flight path follows the expected reentry trajectory of an orbital vehicle. Although it is an atmospheric flight demonstrator, the ALTV includes the range of systems and subsystems representative of large-scale spacecraft and reusable launch vehicles, including a flight control system; flight computers and associated hardware and software; TPS and associated seals; command, control, and communication systems; a landing gear system; and ground and flight operations systems; among others.

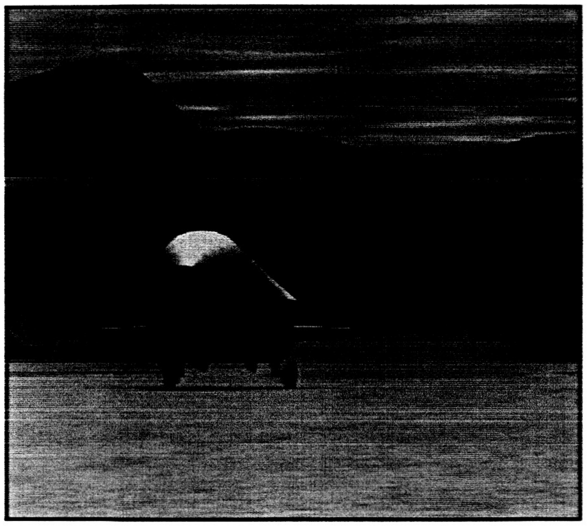

Fig. 3: ALTV landing concept.

Throughout this process, the X-37 Project has worked diligently with its prime contractor (The Boeing Company), numerous suppliers across the United States, and the USAF to fully understand and disposition numerous technical challenges. A few of the X-37 Project's many ALTV accomplishments are summarized below.

Structures and Mechanics Testing

The ALTV airframe proof test (Figure 4) was successfully completed in the June to July 2003 timeframe. During this series of tests, forces were applied to the vehicle that simulated representative flight and landing loads. The static proof test involved the execution of 16 load cases pertaining to captive carry, free flight, and landing environments that validated the airframe structural integrity in accordance with technical requirements. In addition to extensive analysis of data collected, the airframe underwent before-and-after nondestructive evaluation to ensure that no latent defects were overlooked. This was a major turning point in Project's progress, because it gave confidence that the as-designed hardware could withstand the flight stresses to which it would be subjected.

Fig. 4: ALTV in the proof-test fixture.

Likewise, qualification of mechanisms (main landing gear doors and nose wheel steering and landing gear door) and aero-control surfaces required extensive and complex testing to give confidence in vehicle form, fit, and function. Each of the moveable control surfaces (speed brake, body flaps, ruddervators, and flaperons) and subcomponents (electromechanical actuators and controllers) underwent rigorous testing to verify that performance met requirements.

The X-37 team encountered many challenging opportunities during the course of ALTV development. Control surface testing is one of numerous examples of Government and industry pulling together to understand and solve technical difficulties that naturally arise during the course of delivering prototype flight hardware.

Control surface components are rated to certain stall loads, depending on the GN&C trajectory requirements. During the course of testing, the right-hand ruddervator and actuator met the qualification unit functional testing stall loads of about 4,000 pounds in both the extended and retracted directions. However, the left-hand ruddervator flight actuator had a performance shortfall. It was returned to the supplier for troubleshooting.

Facing a significant schedule slip in delivering the control surface and component to the vehicle manufacturing plant, the X-37 Team developed a testbed that allowed control surface actuators to be tested without having to include the actual flight surfaces in the test setup. Rather, a ruddervator model that simulated the control surface's mass and inertia properties, as well as center of gravity, was used in the test fitting (Figure 5).

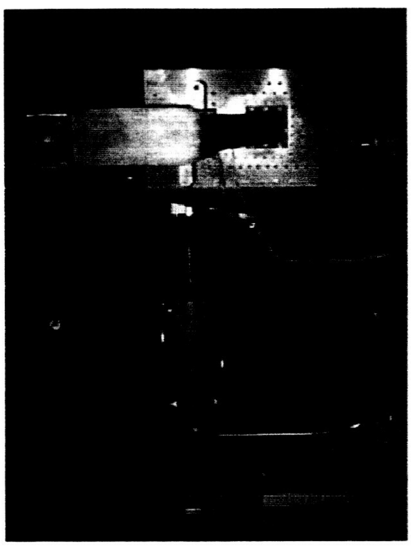

Fig. 5: Actuator in test fixture.

During the course of troubleshooting by the supplier, it was discovered that the seemingly faulty actuator had a very low cycle life, that is, had not been "broken in" as had the other units tested. The supplier subsequently completed 8 hours of cycling and testing the actuator stall-load capability. For the pre-loaded/step "hot" runs, the actuator stalled around 3720 pounds, and for "cold" runs, it stalled between 3600 and 3700 pounds. In general, higher stall loads are experienced when there is some inertia going in the unit. The supplier determined that this unit provided a worst-case stall capability of 3500 pounds. The prime contractor worked with the Project's Technical Review Board to redefine the stall requirement for both ruddervator actuators and to develop a plan to upgrade the qualification actuator to a flight unit.

This is an example of a workaround that helped in recovering from delays in delivering the control surfaces for assembly, while obtaining the functional test data needed for performance analysis. This experience proved that actual flight hardware is not needed to do early testing on actuators. These are just a few of many valuable lessons learned during the course of building and testing flight hardware.

Subsystem Checkout

Systems engineering, integration, and testing dominated the Project's ALTV development activities as the hundreds of wiring harnesses for avionics and other electrical systems were checked out individually, on the pallet, and as-installed in the vehicle. This incremental test approach process facilitates subsystem requirements verification of major components in a streamlined fashion prior to overall system verification, allows for continued assembly of the vehicle during testing, and provides better access to avionics for troubleshooting and repair.

The term "wire bird" was coined to describe the integrated testing of the avionics installed on the pallets outside the vehicle. The wire-bird configuration used mostly non-flight boxes and test cables, and enabled the team to obtain early functional data on the system's performance. The wire-bird simulations (Figure 6), conducted in the Avionics Software Integration Laboratory (ASIL), resulted in substantial risk-mitigation.

The ASIL provides for real-time simulations of systems and of the vehicle through flight using three-string avionics and active redundancy management. Located at Boeing's Huntington Beach facility, the ASIL provides verification testing ahead of the vehicle verification system tests. Avionics hardware and software data analysis helps solve problems before integration into the vehicle. Once the flight units were installed on pallets, these electronics were again checked for integrity, knowing that troubleshooting problems after installation in the

Fig. 6: Wire-bird testing.

airframe would lead to serious cost and schedule impacts. The final test series will be conducted when the pallets are integrated into the fuselage (Figure 7) to ensure that software and hardware operate as designed and that all components function properly. A mission simulation will be conducted to further verify flight readiness.

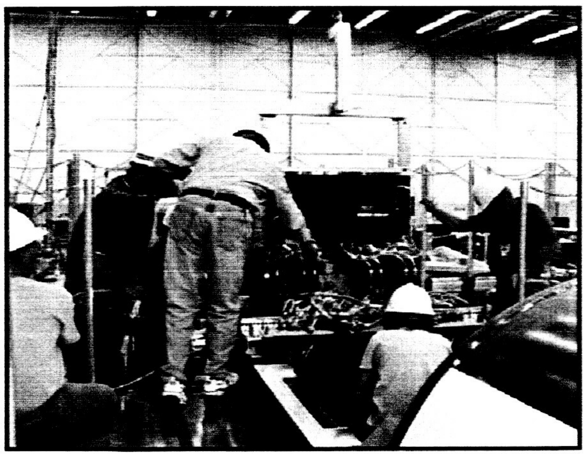

Fig. 7: Pallet installation.

Path to Flight

Current 2004 ALTV forecast milestones include final system tests and vehicle rollout. The first ALTV free flight may be conducted as early as Spring 2005. The X-37 ALTV will validate performance of the approach and landing subsystems, including the Calculated Air Data System (CADS), as well as ground and flight control operations. It will validate aerodynamic stability and structural integrity, as well as demonstrate automated operations in the approach and landing environment. The data generated and lessons learned will directly apply to future space transportation system development.

Enabling Orbital Technologies Description and Progress

Key orbital vehicle technologies are currently in development to support future spacecraft designs and mission requirements. Through the X-37 Project, investments are being made in the areas of lightweight robust materials that can withstand temperatures up to 3000 °F for wing leading edge TPS and hot structures (ruddervators and flapperons); and lightweight, long-life power sources (lithium-ion batteries) to augment solar collectors for long-duration missions. To date, TPS has been tested and selected; two advanced hot structures materials are on track for a 2004 down-selection; and lithium-ion battery work has been completed to a reasonable level of maturity. Given below are brief descriptions of TPS and HSCS risk reduction R&D for future orbital vehicle applications.

Thermal Protection Systems

Raising the technology readiness level of TPS is risk mitigation for potential application to future reusable space transportation systems. Advanced TPS will reduce weight and increase resilience to the temperature extremes spacecraft experience upon reentry to Earth's atmosphere or entry for planetary exploration. This work is managed by NASA's Ames Research Center (ARC).

A new TPS comprised of a toughened high temperature surface cap and a dissimilar low thermal conductivity base has been developed and successfully tested. Toughened Uni-piece Fibrous Reinforced Oxidation-resistant Composite (TUFROC) TPS was developed specifically for application to the leading edges or nose caps of Earth atmospheric reentry and planetary exploration entry vehicles. Both the cap and the insulator base have surface treatments applied, permitting them to survive at temperatures (i.e., aeroconvective heating) characteristic of high-speed atmospheric reentry and planetary entry. The TUFROC cap provides impact resistance and stability of the leading edge contour, while the base material provides maximum thermal protection for the vehicle structure. The exact cap and base materials are chosen along with the surface treatments for the particular application, which depends on the duration of exposure and expected temperatures.

TUFROC TPS was developed to increase the capability of a TPS with high-impact resistance to temperatures above 3000 °F. The surface treatments result in graded insulative composites capable of surviving high heating rates and large thermal gradients in the extreme aeroconvective heating environments to which spacecraft are exposed during entry and reentry. They can be tailored to make them compatible with a wide variety of different lightweight porous systems. In addition, the system includes an adjustable high temperature chemical adhesive that provides a transition along with the surface treatment and an adjustable mechanical attachment mechanism that permits the co-existence of the two parts at high temperatures. Figure 8 shows a wing leading edge test model prior to arc-jet testing in ARC facilities.

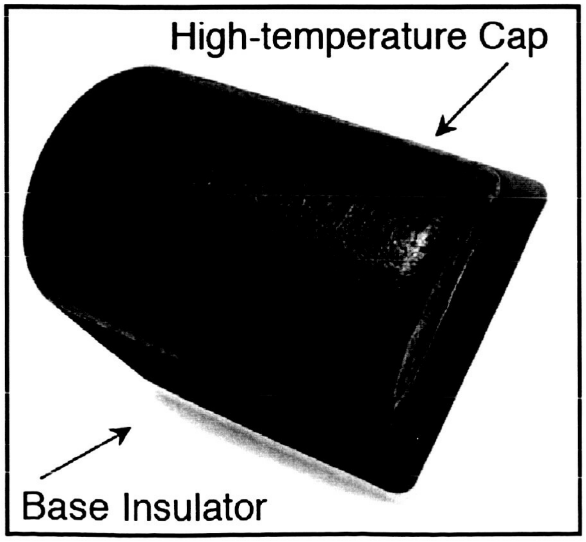

Fig. 8: Wing leading edge TUFROC model before testing.

This new technology extends the existing acreage tile technology to uses previously not attainable due to material limitations. It also permits integration of materials with largely different coefficients of thermal expansion. The parts are assembled and sintered in air. Use of a dual bond (mechanical plus ceramic) attachment scheme contributes to the integrity of the cap and insulator connection throughout the heating history (e.g., spacecraft entry and reentry flight trajectories).

Test results show that the thermal response of this unique two-part TPS is equivalent to a system using a single insulator material. Unlike conventional wing leading edge TPS (carbon, silicon carbide, hot structures, etc.), a substantial reduction in leading edge weight results because the TUFROC system consists mostly of the base (a lightweight, low thermal conductivity material).

Different versions of the system have been successfully produced and tested from 2800 °F for 10 minutes to 3600 °F for 2 minutes in aeroconvective heating environments. Figure 9 shows one version of the system being exposed in an arc-jet facility at a stagnation streamline condition of 3000 °F. In addition to providing this unique test capability, ARC broadcast a first time ever, live satellite video feed of TUFROC arc-jet testing to its partners at Boeing in Huntington Beach, CA, and at NASA's Marshall Space Flight Center.

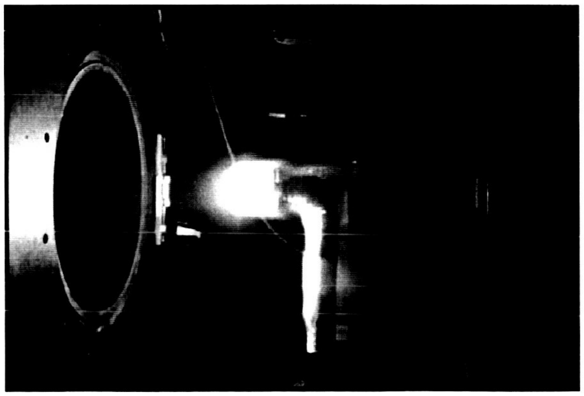

Fig. 9: TPS arc-jet testing at ARC.

Hot Structures Control Surfaces

The goal of HSCS research is to mitigate risk by qualifying the lightest possible components that meet the stringent X-37 OV weight and strength requirements, including Shuttle-type reentry environments with peak temperatures of 2800 °F. Hot structures developed to handle aeroloads at ruddervator and flapperon attachment points may lead to a new generation of robust flexible materials that will augment advanced TPS.

The relatively small size of an X-37 OV design drives the need for advanced HSCS because the vehicle's two primary aerodynamic surfaces, the flaperons and ruddervators (Figure 10), have thicknesses ranging from approximately 5 inches down to 1 inch. Traditional metallic or polymer-matrix composites covered with tile or blanket TPS materials cannot be used, as there is insufficient volume to fabricate such multi-component structures. Therefore, carbon-carbon (C-C) and carbon/silicon-carbide (C-SiC) composite HSCS structures are being developed in parallel by two teams supporting the X-37 prime contractor.

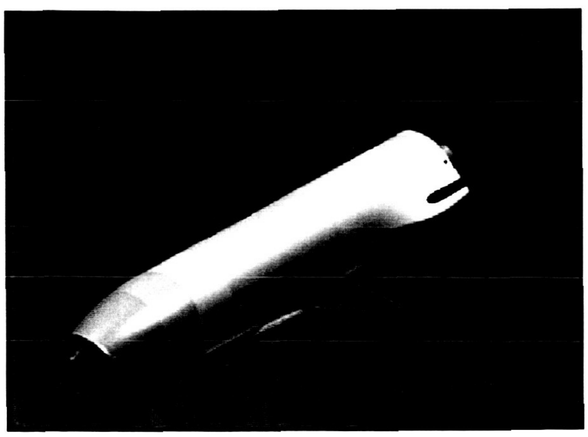

Fig. 10: OV design showing aerodynamic surfaces.

The Science Applications International Corp. (SAIC) and Carbon-Carbon Advanced Technologies, Inc. (C-CAT) team is developing the C-C HSCS, while the General Electric Energy Power Systems Composites (GE-PSC) and Materials Research and Design (MRD) team is developing the C-SiC HSCS. Both are designing, analyzing, and building coupons, samples, and engineering development units.

The SAIC/C-CAT team is using Advanced Carbon-Carbon (ACC) because its fabrication is very similar to the process used for Space Shuttle Reinforced Carbon-Carbon fabrication, including the SiC-based pack cementation conversion coating systems using with both materials. ACC was selected over RCC because it has much higher tension and compressions strengths, and because T-300 fiber is readily available, whereas RCC rayon fiber is no longer manufactured. The GE-PSC/MRD team is using a T-300 fiber-reinforced SiC matrix composite material densified by chemical vapor infiltration. The C-SiC material has an SiC-based environmental barrier coating.

Over the past year, major accomplishments have been made by both HSCS teams. C-C and C-SiC flaperon subcomponents, which are truncated full-scale versions of flight hardware, have been fabricated and are undergoing testing at the NASA Dryden Flight Research Center (Figure 11), NASA Langley Research Center, and the U.S. Air Force Research Laboratory. By the end of 2004, ruddervator subcomponents also will be delivered and tested.

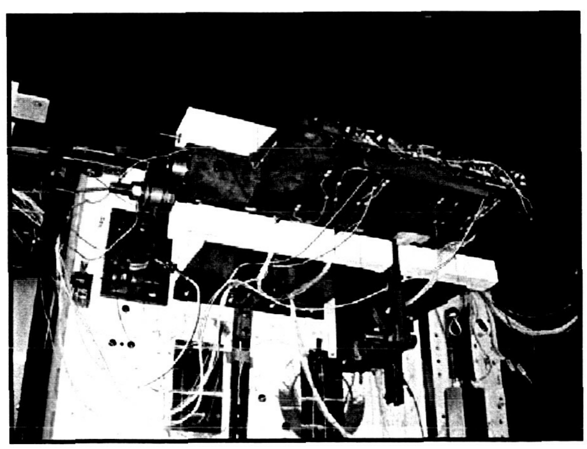

Fig. 11: Article in test fixture at DFRC.

CONCLUSION

The X-37 Project contributes capabilities for future space transportation system development. Although computer simulations and laboratory testing are useful tools to predict performance, ultimately, real-world experience yields necessary, invaluable benefits in terms of lessons learned and knowledge gained. The process of designing, building, and testing the ALTV has added substantial value by educating aerospace personnel — both business and technical, Government and industry — in the art and science of hardware development. Knowledge gained and data delivered from the ALTV experience and from the OV technologies research will be applied in support of achieving the Vision for Space Exploration.

The X-37 has provided unique opportunities for flight hardware and technology development, as well as a proving ground for both business and technical processes. Today, a new generation of engineers and aerospace professionals is engaged in the process of delivering capabilities that empower the Vision for Space Exploration. The X-37 ALTV Flight Demonstrator and OV technologies R&D validate and mature technologies through the design, building, testing, and integration phases, offering real-world flight hardware and related experience to a new generation of explorers who will continue the journey into space.

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