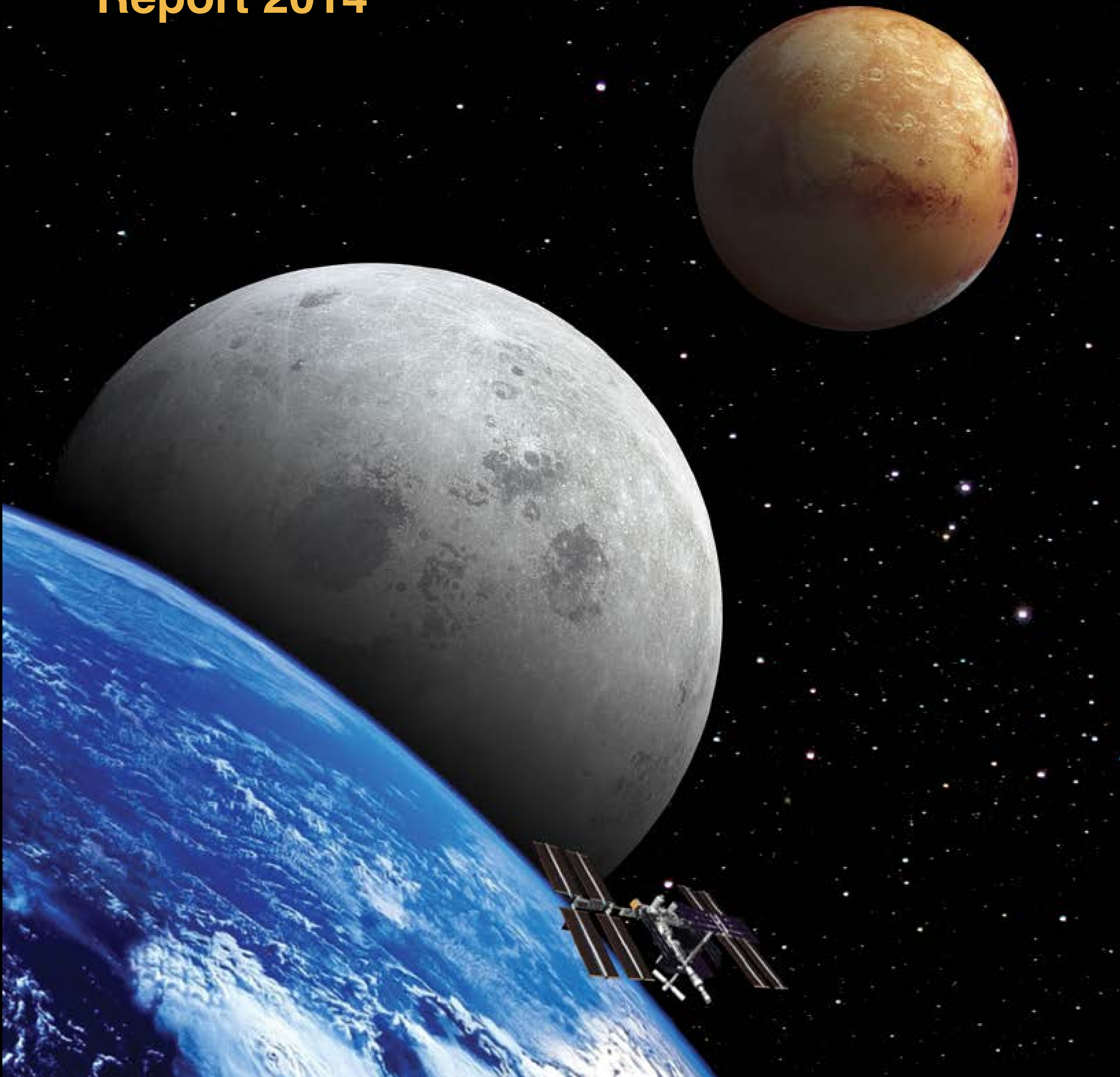
National Aeronautics and
Space Administration

NASA/TM—2015–218204

George C. Marshall Space Flight Center
Research and Technology Report 2014



NASA/TM—2015–218204

George C. Marshall Space Flight Center

Research and Technology Report 2014

A.S. Keys, M.L. Tinker, and A.D. Sivak, Compilers
Marshall Space Flight Center, Huntsville, Alabama

Acknowledgments

The point of contact and coordinator at Marshall Space Flight Center (MSFC) for this Technical Memorandum (TM) is Amy Sivak (256–544–4720). She was assisted by the MSFC Scientific and Technical Information Group, in particular Susan Burrer, Vicki Hocutt, and Mary Vaughn. The Center Chief Technologist, Andrew Keys, and the Deputy Chief Technologist, Mike Tinker, gave support, knowledge, insight, and assisted with compiling and making decisions on this TM.

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FOREWORD

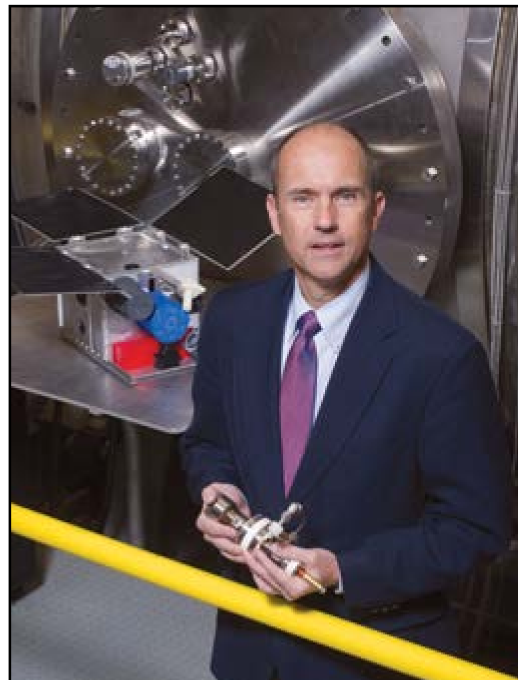
The American public widely recognizes NASA for its ability to deliver amazing missions capable of providing new knowledge about the universe around us, new understanding about the Earth on which we live, and new capabilities that serve to improve our daily lives. Many of these NASA missions would not be possible if it were not for the investments made in research advancements and technology development efforts.

The technologies developed at Marshall Space Flight Center contribute to NASA's strategic array of missions through technology development and accomplishments. They also provide all Marshall Space Flight Center employees the opportunity to gain and maintain critical skills necessary to be more innovative in solving the complex problems associated with spaceflight. The scientists, researchers, and technologists of Marshall Space Flight Center who are working these enabling technology efforts are facilitating NASA's ability to fulfill the ambitious goals of innovation, exploration, and discovery.

As you read through this report detailing Marshall Space Flight Center's technological accomplishments of 2014, I trust you will take a moment to appreciate the incredible legacy of research and technology advancements that NASA Marshall Space Flight Center provides to the nation.

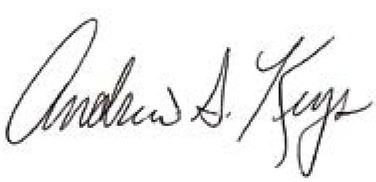
Patrick E. Scheuermann
Director
Marshall Space Flight Center

INTRODUCTION



It is my exceeding pleasure to present to you the Marshall Space Flight Center Research and Technology Report for 2014. This document showcases the wide diversity of research and technology efforts being pursued by our talented and innovative workforce. From the early stage innovations being developed as a part of the Center Innovation Fund program to the advanced technologies being investigated to enable future Space Launch System capabilities, the efforts detailed in this report strive to advance the current state of technology such that future NASA missions are enabled.

The range and diversity of the activities described herein is certainly impressive. Innovators used selective laser melting as an advanced manufacturing technology for the fabrication of turbopump impellers that could enable upper stage engine development. Engineers employed models of combustion stability within engine injector designs to improve future SLS propulsion system developments. Materials experts tested the ability of a composite cryotank to successfully store cryogenic fuels and to withstand structural loads representative of launch conditions. Technologists facilitated the launch of the first additive manufacturing printer to the International Space Station. Scientists demonstrated new methods of fabricating lightweight, high-resolution, grazing incidence optics for use in future x-ray observatories. These innovations, plus the many more described within this report, may serve to not only enhance and enable NASA's current slate of programs and projects, but could also provide the solutions required to facilitate human and robotic exploration of other solar system bodies and destinations beyond. I trust you will enjoy reviewing the Marshall research and technology accomplishments of 2014. I am greatly looking forward to what 2015 will bring!



Andrew Keys
Center Chief Technologist
Marshall Space Flight Center

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LIST OF ACRONYMS

AES	Advanced Exploration Systems
CAN	(Dual-Use Technology) Cooperative Agreement Notice
CCP	Centennial Challenges Program
CIF	Center Innovation Fund
CSDSG	Center Strategic Development Steering Group
GCD	Game Changing Development
HEOMD	Human Exploration and Operations Mission Directorate
MSFC/CMO	Marshall Space Flight Center/Center Management and Operations
SBIR	Small Business Innovation Research
SLS AD	Space Launch System Advanced Development
SMD	Science Mission Directorate
STMD	Space Technology Mission Directorate
TDM	Technology Demonstration Missions
TIP	Technology Investment Program

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Technology Programs

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Human Exploration and Operations Mission Directorate (HEOMD)

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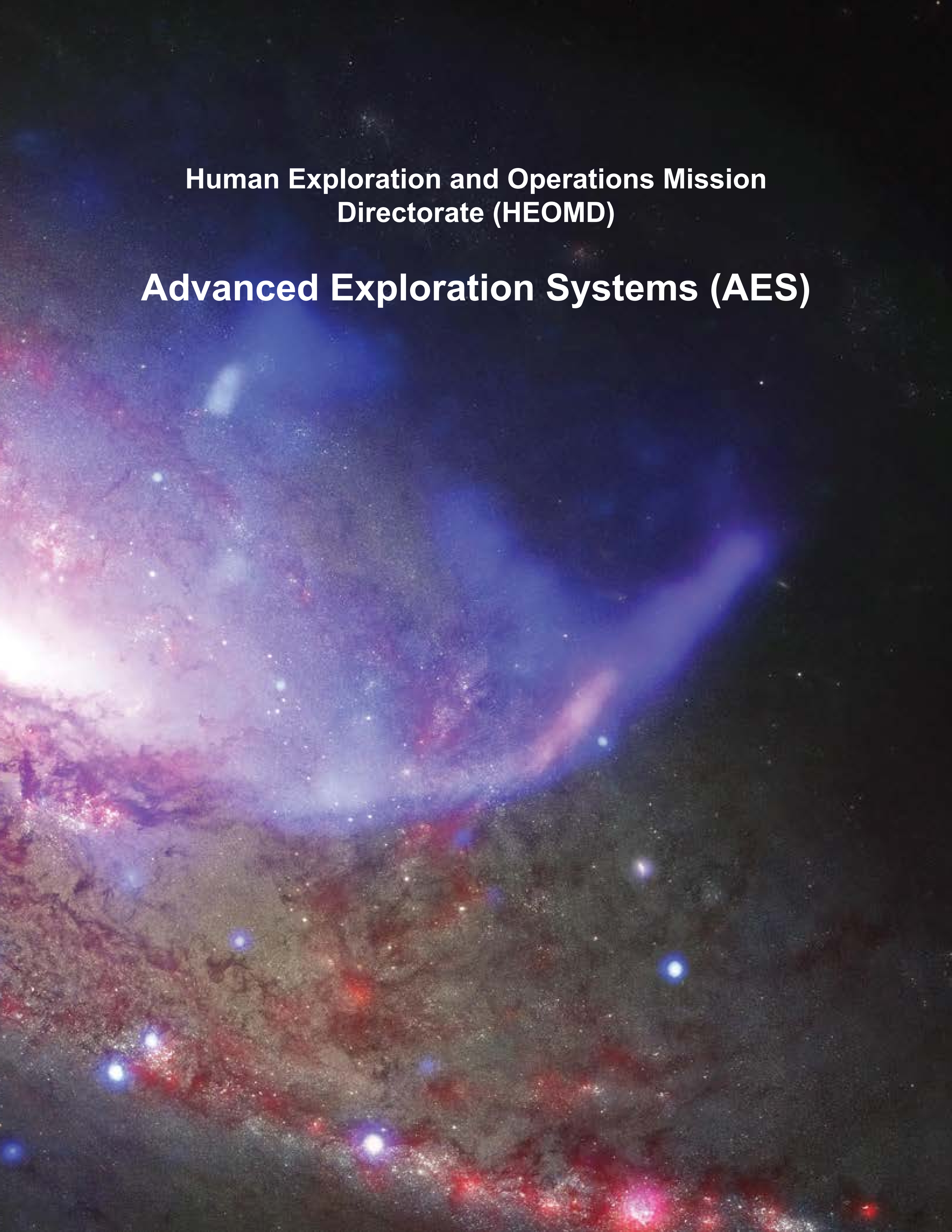
Human Exploration and Operations Mission Directorate (HEOMD)

Advanced Exploration Systems (AES)



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Lander Technologies

Project Manager(s)/Lead(s)

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Advanced Exploration Systems
Science Mission Directorate

Project Description

Since 2006 NASA has been formulating robotic missions to the lunar surface through programs and projects like the Robotic Lunar Exploration Program, Lunar Precursor Robotic Program, and International Lunar Network. All of these were led by NASA Marshall Space Flight Center (MSFC). Due to funding shortfalls, the lunar missions associated with these efforts, the designs, were not completed. From 2010 to 2013, the Robotic Lunar Lander Development Activity was funded by the Science Mission Directorate (SMD) to develop technologies that would enable and enhance robotic lunar surface missions at lower costs. In 2013, a requirements-driven, low-cost robotic lunar lander concept was developed for the Resource Prospector Mission. Beginning in 2014, The Advanced Exploration Systems funded the lander team and established the MSFC, Johnson Space Center, Applied Physics Laboratory, and the Jet Propulsion Laboratory team with MSFC leading the project. The lander concept to place a 300-kg rover on the lunar surface has been described in the New Technology Report Case Number MFS-33238-1. A low-cost lander concept for placing a robotic payload on the lunar surface is shown in figures 1 and 2. The NASA lander team has developed several lander concepts using common hardware and software to allow the lander to be configured for a specific mission need.

In addition, the team began to transition lander expertise to United States (U.S.) industry to encourage the commercialization of space, specifically the lunar surface. The Lunar Cargo Transportation and Landing by Soft Touchdown (CATALYST) initiative was started and the NASA lander team listed above is partnering with three competitively selected U.S. companies (Astrobotic, Masten Space Systems, and Moon Express) to develop, test, and operate their lunar landers.

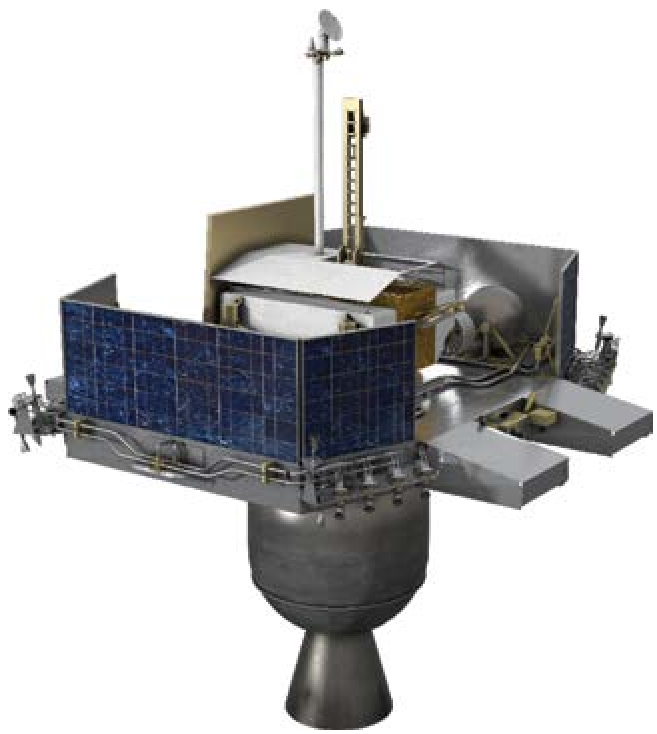

Figure 1: Lunar lander with solid rocket braking motor and rover.

Figure 2: Lunar pallet lander only.

The inspace engine (ISE100) is a 100-lbf thruster that operates using MMH and MON25 (fig.3). The SMD has funded this technology development for use on interplanetary missions (including landers) to reduce the heater requirements for propellants and to allow a high thrust to weight engine that requires low volume for packaging. The engine can operate with propellant temperatures as low as –40 ºF.

Figure 3: ISE100 fabricated in 2014.

Anticipated Benefits

Anticipated benefits of this project include low-cost lunar surface access for multiple missions which feeds forward to large Mars landers.

Potential Applications

Lunar landers specifically targeted at exploration and in situ resource utilization demonstrations, Mars landers, and interplanetary missions are potential applications.

Notable Accomplishments

Some of the notable accomplishments include the design of the low-cost robotic lunar lander with the prototype/engineering unit at the system level with flight software and simulation including a flight hardware-in-the-loop simulation. Development of subsystems and components for lunar landers with an application for science and exploration missions is also an accomplishment.

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Three-Dimensional Printing In Zero Gravity

Project Manager(s)/Lead(s)

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Advanced Exploration Systems
Space Technology Mission Directorate
Game Changing Development

Project Description

The 3D printing in zero-g (3D Print) technology demonstration project is a proof-of-concept test designed to assess the properties of melt deposition modeling additive manufacturing in the microgravity environment experienced on the International Space Station (ISS). This demonstration is the first step towards realizing a 'machine shop' in space, a critical enabling component of any deep space mission.

The 3D Print design and flight hardware (figs. 1 and 2) are products of the commercial company Made In Space, Inc., and was acquired by NASA through a Small Business Innovative Research Phase III contract. The objective is to advance the Technology Readiness Level (TRL) to a state that will support future full-scale development for an operational flight production system using plastics on the ISS.

The objectives of this technology demonstration project are to provide: (1) A detailed understanding of the critical design and operational parameters for the additive manufacturing process as affected by the microgravity environment, (2) the first demonstration of additive manufacturing in space, (3) a detailed analysis of how acrylonitrile butadiene styrene (ABS) thermoplastic resin behaves in microgravity versus Earth's gravity, (4) a comparison between additive manufacturing in Earth's gravity and in a consistent, long-term exposure to microgravity, and (5) the advancement of the TRL of additive manufacturing processes to provide risk reduction and capabilities to future flight or mission development programs.

Figure 1: 3D printer unit.

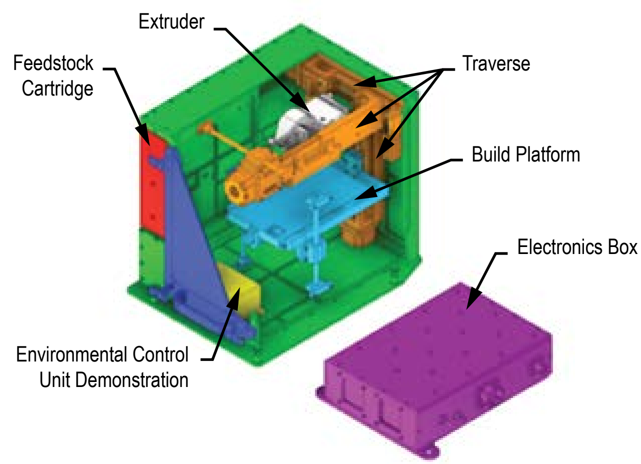

Figure 2: 3D printer components.

Anticipated Benefits

The 3D Print will demonstrate the capability of utilizing additive manufacturing technology in space. This is the first step towards realizing an additive manufacturing, print-on-demand 'machine shop' for long-duration missions and sustaining human exploration of other planets, where there is extremely limited ability and availability of Earth-based logistics support.

Figure 3: 3D printer installed in the MSG on the ISS.

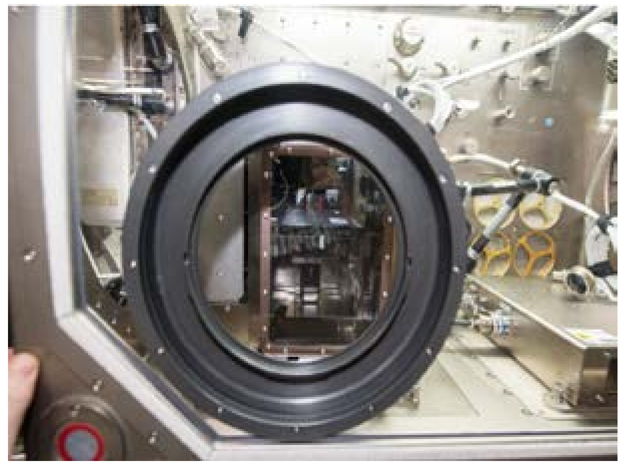

Figure 4: Closeup of 3D printer installed in the MSG.

Potential Applications

The data gathered and lessons learned from this technology demonstration will be used for the next generation of melt deposition modeling in the permanent NanoRacks Additive Manufacturing Facility (AMF) as well as for any future additive manufacturing technology NASA plans to use, such as metals or electronics in-space manufacturing, on both the ISS and deep space missions. The information obtained during the 3D Print technology demonstration will be applied to the design of the next generation of additive manufacturing technology on orbit, such as the AMF and other metallic printing devices currently in development. It is expected that additive manufacturing technology will quickly become a critical part of any mission's infrastructure.

Notable Accomplishments

The 3D Print launched on SpaceX-4 on September 21, 2014, at 1:52 a.m. ET and arrived at the ISS on September 23, 2014, at 6:52 a.m. ET.

The 3D printer, electronics box, and camera setup were successfully installed into the Microgravity Science Glovebox (MSG) on November 17, 2014 (figs. 3 and 4). A functional checkout was performed including extrusion of a calibration coupon. Additional calibration prints are planned.

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3D Print Fact Sheet, <http://www.nasa.gov/sites/default/files/files/3D_Printing-v3.pdf>, April 24, 2014.

Werkheiser, N.; et al.: "3D Printing In Zero-G ISS Technology Demonstration," Abstract, ISS Research and Development Conference, NTRS 20140000628, June 26–28, 2013.

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Clinton, R.: "The Road to Realizing In-Space Manufacturing," Presentation, National Research Council Committee on Space-Based Additive Manufacturing of Space Hardware Meeting, NTRS 20140008760, February 5–7, 2014.

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Nuclear Thermal Propulsion

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Technology Mission Directorate
Advanced Exploration Systems

Project Description

Development efforts in the United States for nuclear thermal propulsion (NTP) systems began with Project Rover (1955–1973) which completed 22 high-power rocket reactor tests. Results indicated that an NTP system with a high thrust-to-weight ratio and a specific impulse >900 s would be feasible. John F. Kennedy, in his historic special address to Congress on the importance of Space on May 25, 1961, said, “First, I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth…” This was accomplished. He also said, *“Secondly ... accelerate development of the Rover nuclear rocket. This gives promise of someday providing a means for even more exciting and ambitious exploration of space… to the very end of the solar system itself.”* The current NTP project focuses on demonstrating the affordability and viability of a fully integrated NTP system with emphasis on fuel fabrication and testing and an affordable development and qualification strategy. The goal is to enable NTP to be considered a mainstream option for supporting human Mars and other missions beyond Earth orbit.

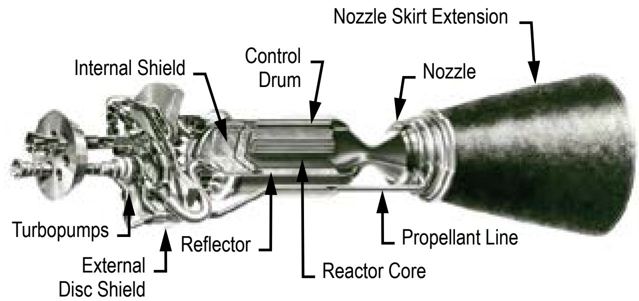

Figure 1: NTP engine schematic.

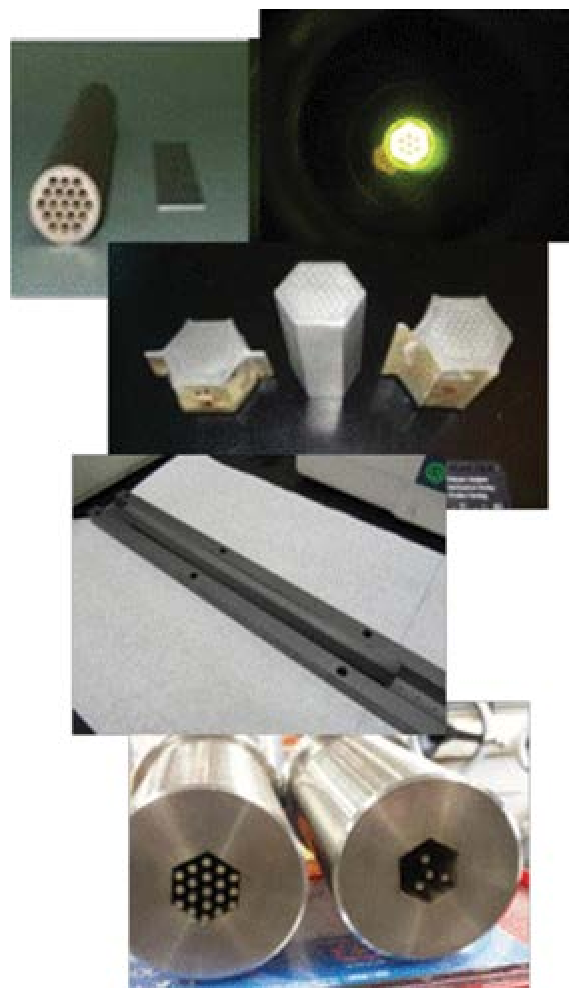

Figure 2: NTP fuel element fabrication.

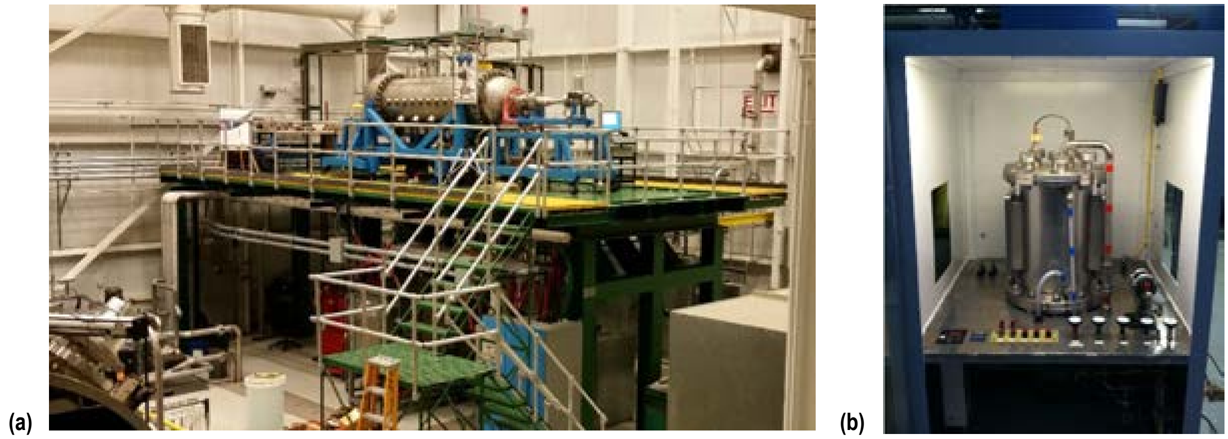

Figure 3: MSFC test facilities: (a) Nuclear Thermal Rocket Element Environmental Test System (NTREES) and (b) Compact Fuel Element Environmental Test (CFEET) System.

Anticipated Benefits

The fundamental capability of NTP is game changing for space exploration. A first generation NTP stage could provide high thrust at a specific impulse above 900 s, roughly double that of state-of-the-art chemical engines. The energy comes from fission, not chemical reactions, resulting in unlimited energy density. NTP enables the shortest trip times to Mars and beyond which exposes astronauts to less galactic radiation and zero-g time. An NTP system would require approximately four less Space Launch System (SLS) launches for a human Mars mission that saves billions of dollars. The system would result in reduced propellant mass and an increase in payload capacity.

Potential Applications

Near-term NTP systems would provide a foundation for the development of significantly more advanced, higher performance systems. The role of NTP in the development of advanced nuclear propulsion systems could be analogous to the role of the DC-3 in the development of advanced aviation. Progress made under the NTP project could help enable both advanced NTP systems and advanced Nuclear Electric Propulsion. Combined with current technologies, the vision to go beyond the Moon and to the very end of the solar system can be realized with NTP.

Notable Accomplishments

Dedicated fuel materials and processing laboratories have been brought on line at Oak Ridge National Laboratory and NASA Marshall Space Flight Center (MSFC) and are fabricating fuel elements of various materials (including the use of depleted uranium) for testing. The CFEET and NTREES test facilities have been designed and brought to operational status to perform testing on fuel element materials. This testing helps to resolve a majority of thermal hydraulic issues (including fuel endurance) while lowering cost and time needed to develop nuclear systems. Laboratories and test facilities have been licensed to handle depleted uranium for fabrication and testing. Various options are being examined for viable ground testing of an engine system. The possible use of low enriched uranium is being examined to reduce, cost, ops, testing, and diagnostics.

References

Houts, M.; Kim, T.; Emrich, J.; et al.: “Affordable Development of a Nuclear Cryogenic Propulsion Stage,” AIAA Space 2012 Conference, Pasadena, CA, September 11–13, 2012.

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Deep Space Habitat Concept Demonstrator

Project Manager(s)/Lead(s)

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Sponsoring Program(s)

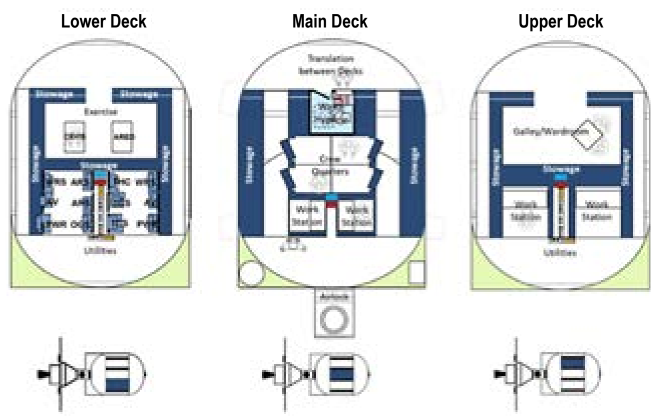
Human Exploration and Operations Mission Directorate Advance Exploration Systems, Exploration Augmentation Module Project (former AES Deep Space Habitat Project), Technology Excellence

Project Description

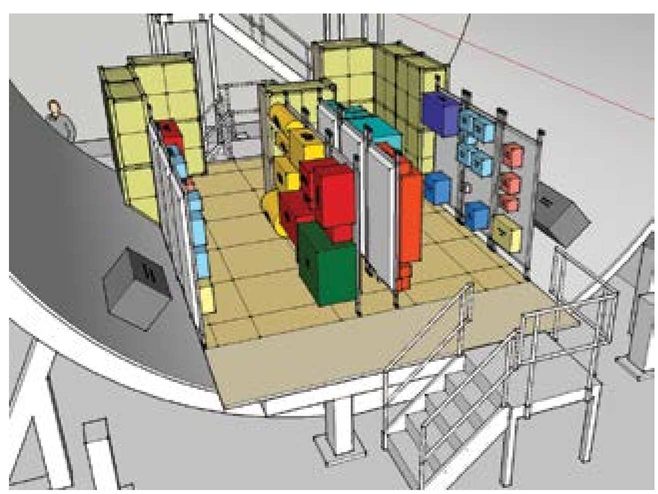
This project will develop, integrate, test, and evaluate Habitation Systems that will be utilized as technology testbeds and will advance NASA's understanding of alternative deep space mission architectures, requirements, and operations concepts. Rapid prototyping and existing hardware will be utilized to develop full-scale habitat demonstrators.

FY 2014 focused on the development of a large volume Space Launch System (SLS) class habitat (Skylab Gen 2) based on the SLS hydrogen tank components. Similar to the original Skylab, a tank section of the SLS rocket can be outfitted with a deep space habitat configuration and launched as a payload on an SLS rocket. This concept can be used to support extended stay at the Lunar Distant Retrograde Orbit to support the Asteroid Retrieval Mission and provide a habitat suitable for human missions to Mars.

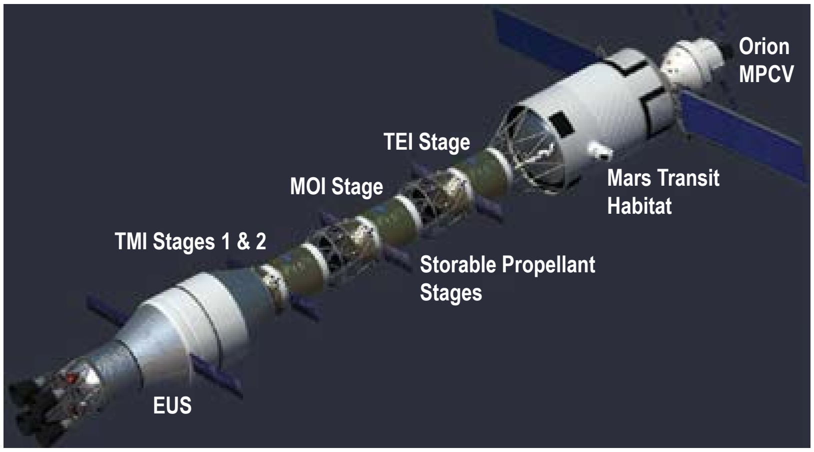
Skylab Gen 2 concept with Orion.



Skylab Gen 2 internal layout.



Utility room concept.



Mars transit concept vehicle.

Skylab Gen 2 current build.

Anticipated Benefits

The Skylab Gen 2 concept supports the SLS program by advancing the development of a future payload for launch on the SLS, utilizing SLS components as a long-duration outpost, and providing a platform for habitat and subsystem development trades while supporting NASA Marshall Space Flight Center (MSFC) interests and investments in future capabilities beyond SLS. It will provide a testbed for groups, projects, and/or other Centers to utilize for advancing Technology Readiness Levels of their designs. It also fosters collaboration and partnerships within MSFC and NASA Johnson Space Center communities focused on deep space exploration.

Potential Applications

The Skylab Gen 2 deep space habitat can serve multiple purposes. At the Lunar Distant Retrograde Orbit it can serve as a facility for deep space human research programs, asteroid resources research, and commercial and international lunar mission objectives. Due to the large size of the habitual volume, the Skylab Gen 2 concept is suitable for human Mars transit missions.

Notable Accomplishments

A trade study was performed to determine the optimized interior layout (vertical—similar to Skylab and horizontal—similar to the International Space Station). The final design will utilize the horizontal configurations, due to weight, usable volume, size variations, and other benefits identified in the trade study.

The flooring system for the concept demonstrator was designed, procured, and installed. The flooring system was designed to be versatile for ease of modifying interior layout configurations. The staircase system to access each level was procured. The interior wall building material was also procured.

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Near-Earth Asteroid Scout

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Advanced Exploration Systems

Project Description

Near-Earth asteroids (NEAs) are easily accessible objects in Earth's vicinity. As NASA continues to refine its plans to possibly explore NEAs with humans, initial reconnaissance with comparatively inexpensive robotic precursors is necessary. Obtaining and analyzing relevant data about these bodies via robotic precursors before committing a crew to visit an NEA will significantly minimize crew and mission risk, as well as maximize exploration return potential. The NASA Marshall Space Flight Center (MSFC) and NASA Jet Propulsion Laboratory are jointly developing the Near-Earth Asteroid Scout (NEAS) utilizing a low-cost CubeSat platform in response to the current needs for affordable missions with exploration science value. The mission is enabled by the use of an 85-m^2 solar sail being developed by MSFC (figs. 1 and 2).

NEAS will be a secondary payload on the Space Launch System (SLS) Exploration Mission 1 (EM-1), the first planned flight of the SLS and the second uncrewed test flight of the Orion Multi-Purpose Crew Vehicle. The NEAS flight system is based on a '6U' CubeSat form factor, with a stowed envelope slightly larger than 10 × 20 × 30 cm and a mass of <12 kg.

The solar sail propulsion system, the primary technology innovation to be flown on the spacecraft, is based on the successful NanoSail-D solar sail developed and flown by MSFC in 2010 (fig. 3). The sail system consists of four 7.3-m stainless steel booms wrapped on two spools (two overlapping booms per spool). The booms will pull the sail from its stowed volume as they deploy. The sail material will be 3 mm CP1, an aluminized polyimide.

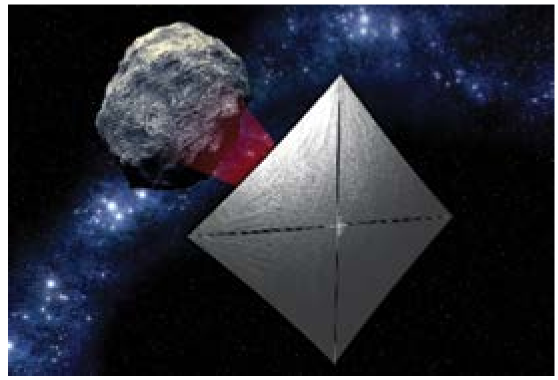

Figure 1: Artist concept of the NEAS encountering and imaging a near-Earth asteroid.

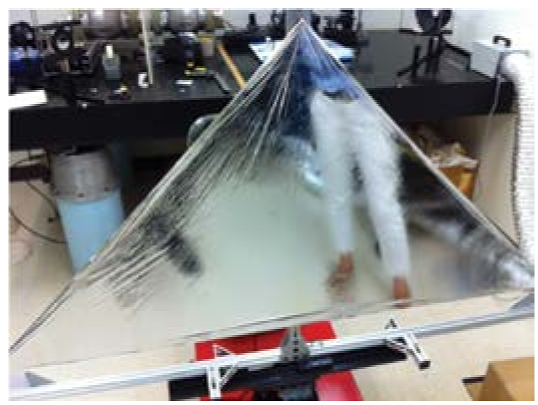

Figure 2: Reflectivity testing of the material that will be used to build the NEAS solar sail.

Figure 3: The fully deployed 10-m^2 NanoSail-D solar sail.

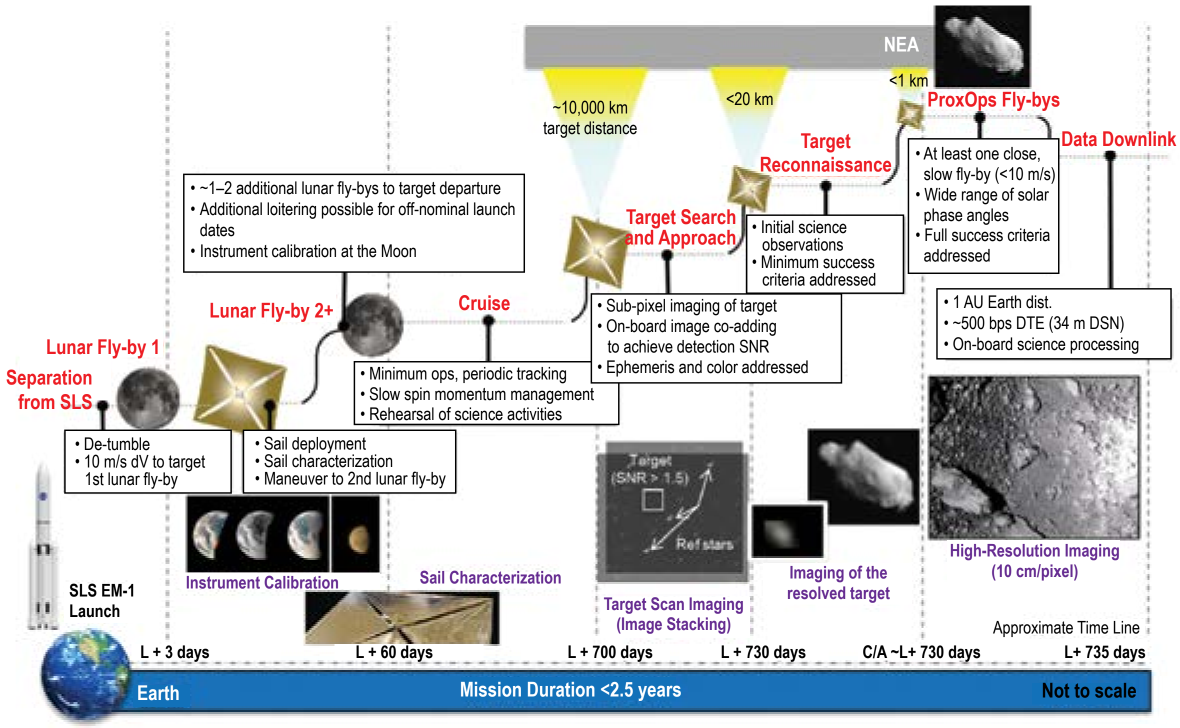

Figure 4: Summary of the concept of operations for NEAS.

Anticipated Benefits

NEAS will be a milestone for low-cost asteroid science with the exploration of the first NEA in the 1- to 100-m-size range. This class of object is poorly characterized due to the challenges that come with detecting, observing, and tracking small NEAs from Earth for extended periods of time. It has been thought that objects in the 1- to 100-m-size range are fragments of bigger objects. However, it has also been suggested that these objects could actually be rubble piles. Hence, the characterization of NEAs that are >20 m in diameter is also of great relevance to inform mitigation strategies for planetary defense. Finally, the NEAS's target still represents a relevant proxy whose characterization will help inform the planned Asteroid Redirect Mission.

Potential Applications

In developing a long-lived, deep-space capable nanosatellite bus and solar sail propulsion system, the NEAS flight system straddles the line between current interplanetary spacecraft and traditional Earth-orbiting CubeSats in terms of cost, risk, and capabilities. The NEAS solar sail propulsion system will also be used in the Advanced Exploration Systems Lunar Flashlight project that will use light reflected from the sail to search for volatiles at the lunar south pole. NEAS enables a novel way to explore near-Earth asteroids and the Moon, and paves the way for future low-cost planetary exploration.

Notable Accomplishments

NEAS successfully completed its Mission Concept Review and System Requirements Review in August 2014. Solar sail packaging was characterized, reflectivity testing was conducted, and the boom deployer system designed.

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Alhorn, D.; Casas, J.; Agasid, E.; et al.: "NanoSail-D: The Small Satellite That Could," 25th Annual AIAA/USU Conference on Small Satellites, Ogden, UT, August 8–11, 2011.

McNutt, L.; Johnson, L.; Clardy, D.; et al.: "Near-Earth Asteroid Scout," AIAA Space 2014 Conference, San Diego, CA, August 5–7, 2014.

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Lunar Flashlight

Project Manager(s)/Lead(s)

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Advanced Exploration Systems

Project Description

The Lunar Flashlight is a Jet Propulsion Laboratory project, with NASA Marshall Space Flight Center (MSFC) serving as the principal investigator and providing the solar sail propulsion system. The goal of Lunar Flashlight is to determine the presence and abundance of exposed lunar water ice within permanently shadowed regions (PSRs) at the lunar south pole, and to map its concentration at the 1–2 km scale to support future exploration and use. After being ejected in cis-lunar space by the launch vehicle, Lunar Flashlight deploys solar panels and an 85-m^2 solar sail and maneuvers into a low-energy transfer to lunar orbit. The solar sail and attitude control system work to bring the satellite into an elliptical polar orbit, spiraling down over a period of 18 months to a perilune of 30–10 km above the south pole for data collection. Lunar Flashlight uses its solar sail to shine reflected sunlight onto the lunar surface, measuring surface reflectance with a four-filter point spectrometer. The spectrometer measures water ice absorption features (1.5, 1.95 µm) and the continuum between them (1.1, 1.9 µm). The ratios of water ice bands to the continuum will provide a measure of the abundance of surface frost and its variability across PSRs. Water ice abundance will be correlated with other data from previous missions, such as the Lunar Reconnaissance Orbiter and Lunar Crater Observation and Sensing Satellite, to provide future human and robotic explorers with a map of potential resources. The mission is enabled by the use of an 85-m^2 solar sail being developed by MSFC (figs. 1 and 2).

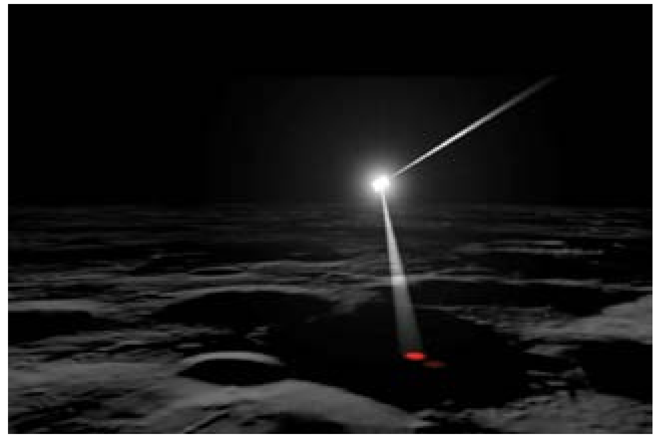

Figure 1: Artist concept of the Lunar Flashlight mission over the lunar surface.

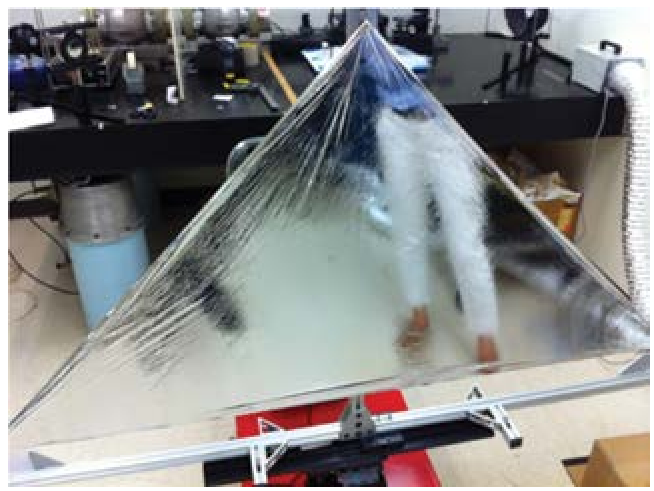

Figure 2: Reflectivity testing of the material that will be used to build the Lunar Flashlight solar sail.

Lunar Flashlight will be a secondary payload on the Space Launch System (SLS) Exploration Mission 1, the first planned flight of the SLS and the second uncrewed test flight of the Orion Multi-Purpose Crew Vehicle. The Lunar Flashlight flight system is based on a ‘6U’ CubeSat form factor, with a stowed envelope slightly larger than 10×20×30 cm and a mass of <12 kg.

The solar sail propulsion system, the primary technology innovation to be flown on the spacecraft, is based on the successful NanoSail-D solar sail developed and flown by MSFC in 2010 (fig. 3). The sail system consists of four 7.3-m stainless steel booms wrapped on two spools (two overlapping booms per spool). The booms will pull the sail from its stowed volume as they deploy. The sail material will be 3 µm CP1, an aluminized polyimide.

Figure 3: The fully deployed 10-m^2 NanoSail-D solar sail.

Anticipated Benefits

Surface water ice and other volatiles, if they exist in sufficient quantities, would be extremely useful for in situ extraction and utilization by future human and robotic missions. Understanding the composition, quantity, distribution, and form of water/H species and other volatiles associated with lunar cold traps is identified as a NASA Strategic Knowledge Gap for Human Exploration. These polar volatile deposits could also reveal important information about the delivery of water to the Earth-Moon system. The scientific exploration of the lunar polar regions was one of the key recommendations of the Planetary Science Decadal Survey.

Potential Applications

The Lunar Flashlight mission will demonstrate a low cost capability for obtaining lunar measurements. In developing a long-lived, deep-space capable nanosatellite bus and solar sail propulsion system, the Lunar Flashlight flight system straddles the line between current interplanetary spacecraft and traditional Earth-orbiting CubeSats in terms of cost, risk, and capabilities.

Notable Accomplishments

Lunar Flashlight successfully completed its Mission Concept Review and System Requirements Review in August 2014. Solar sail packaging was characterized, reflectivity testing was conducted, and the boom deployer system designed at MSFC. The mission science goals underwent a nonadvocate peer review in June 2014.

References

Alhorn, D.; Casas, J.; Agasid, E.; et al.: "NanoSail-D: The Small Satellite That Could," 25th Annual AIAA/USU Conference on Small Satellites, Ogden, UT, 2011.

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Source Contaminant Control for the Heat Melt Compactor

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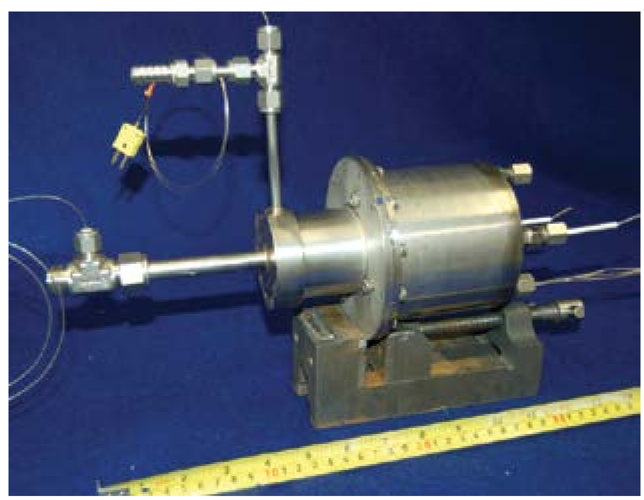
Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Advanced Exploration Systems

Project Description

The Logistics Reduction and Repurposing project includes the heat melt compactor (HMC), a device that compacts waste containing plastic into a tile that will minimize volume, and may be used as materials for radiation shielding. During the process, a small purge gas stream is directed through the HMC chamber to transport out gasses and humidity released from the process. NASA Marshall Space Flight Center is tasked with developing and delivering a contamination control system to clean the purge gas prior to exhausting it back into the cabin for crew inhalation.

HMC source contaminant control sorbent bed.



HMC source contaminant control catalytic oxidizer.

HMC original trash and final tile product.

Anticipated Benefits

Storage and reuse of waste products are needed to support deep space missions with limited resupply. The HMC is a device that compacts waste containing plastic into a tile that will minimize volume, and may be used as construction materials for radiation shielding and other applications. The contaminant control system for the exhaust will allow purge gasses to be exhausted back into the habitable volume, preserving critical atmosphere to maintain crew survivability.

Potential Applications

Potential applications are for deep space transport and orbiting habitats, as well as nonterrestrial surface habitats. The design of the contaminant control system lends itself to other in-space processes such as additive manufacturing that potentially produces air-borne contaminants.

Notable Accomplishments

The design, fabrication, and testing of a two-stage source contaminant control system for the HMC was completed. Components were delivered to NASA Ames Research Center for integration into their generation 2 HMC scheduled for demonstration in 2015.

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Atmosphere Resource Recovery and Environmental Monitoring

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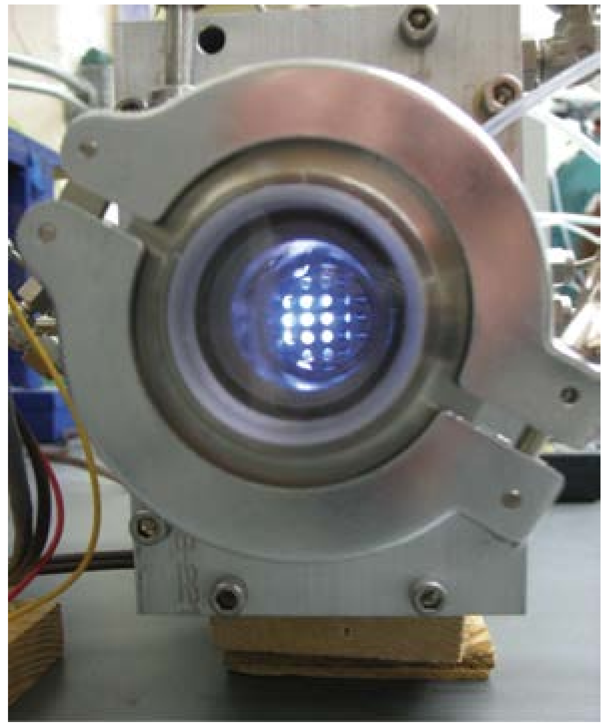
Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Advanced Exploration Systems

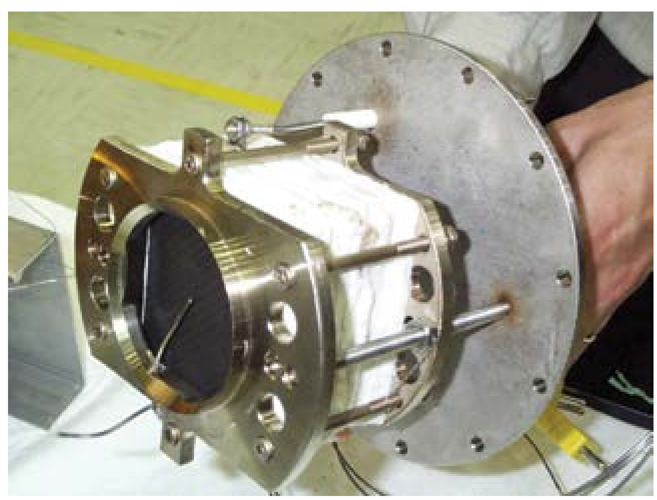
Project Description

Atmosphere Resource Recovery and Environmental Monitoring (ARREM) is a project focused on evolving existing and maturing emerging 'closed loop' atmosphere revitalization (AR) life support systems that produce clean, breathable air for crewmembers, and developing a suite of low mass, low power environmental monitors to detect and measure air- and water-borne constituents and contaminants. The objective is to improve reliability and efficiency, reduce mass and volume, and increase recovery of oxygen from carbon dioxide created by human metabolism from 43% to greater than 90%.

The technology developments under ARREM are vital to extending human space missions from low-Earth orbit like the International Space Station to destinations deeper into space such as Mars where dependency on Earth for resupply of maintenance items and critical life support elements such as water and oxygen is not possible. The primary goal of the ARREM project is to demonstrate that systems meet the more stringent performance parameters for deep space exploration and are compatible with other systems within closed loop life support through a series of integrated tests performed in an environmental test chamber capable of simulating human metabolic activities and measuring systems outputs.



Plasma pyrolysis assembly recovers hydrogen from the methane produced by the carbon dioxide reduction assembly/Sabatier, further enabling the recovery of oxygen from carbon dioxide.



Microlith® catalytic oxidizer is an ultracompact, lightweight, fast light-off catalytic reactor with resistive-heating capability for volatile organic compound trace contaminant control and other applications.

Integrated test chamber enables testing of AR technologies in an environment that simulates human metabolic activity integrated with functional AR hardware.

Anticipated Benefits

The benefit would be to improve ARREM systems, bringing them closer to meeting the figures of merit required to achieve long-duration human missions to destinations beyond low-Earth orbit such as Mars.

Potential Applications

This may potentially be used for deep space transport and orbiting habitats as well as nonterrestrial surface habitats.

Notable Accomplishments

The ARREM project completed multiple demonstration phases of integrated systems testing. The primary test objectives were to demonstrate the operation of the International Space Station-derived life support equipment in evolved configurations for the purpose of increasing reliability, reducing mass, and improving performance. The evolved configurations consisted of the oxygen generation assembly operating in an alternate configuration with improved reliability while considerably reducing mass. The carbon dioxide removal assembly operated in an alternate mode that demonstrated the capability of reducing cabin carbon dioxide levels by 40%. The trace contaminant control demonstrated an advanced configuration that used next generation catalyst configured to reduce ancillary equipment. The Trace Contamination Control system also incorporated a high flow carbon bed cartridge upstream of the condensing heat exchanger to reduce contaminant loading, including siloxanes, in water condensate to potentially relieve challenges to the water processor. The final phase of the test consisted of installing development environmental monitoring equipment developed for ARREM by the Jet Propulsion Laboratory into the E-chamber and exposing them to elevated levels of selected contaminates and comparing results to laboratory standard equipment. The monitors consisted of the tunable environmental laser spectrometer for detecting carbon monoxide, the rapid analysis self-calibrating for detecting trace gas contaminants, and the vehicle environmental monitor for detecting contaminants contained in the humidity condensate.

References

Perry, J.; Knox, J.; Parrish, K.; et al.: "Integrated Atmosphere Resource Recovery and Environmental Monitoring Technology Demonstration for Deep Space Exploration," AIAA 2012–3585, AIAA 42nd International Conference on Environmental Systems, San Diego, CA, 2012.

Roman, M.; Perry, J.; and Jan, D.: "Design, Development, Test, and Evaluation of Atmosphere Revitalization and Environmental Monitoring Systems for Long Duration Missions," AIAA 2012–5120, AIAA Space and Astronautics Forum and Exposition, Pasadena, CA, 2012.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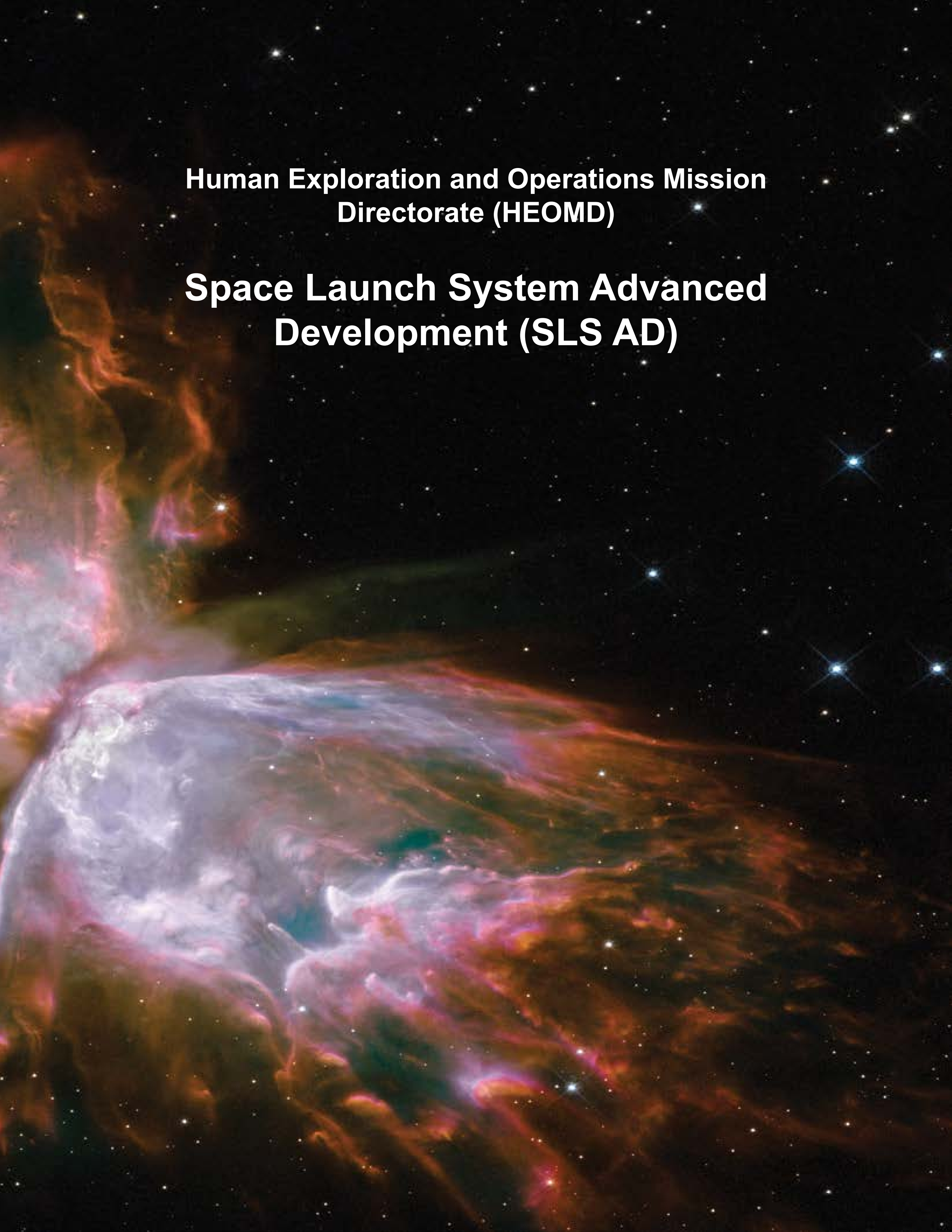
Human Exploration and Operations Mission Directorate (HEOMD)

Space Launch System Advanced Development (SLS AD)



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Advanced Booster Composite Case/ Polybenzimidazole Nitrile Butadiene Rubber Insulation Development

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

The NASA Engineering and Safety Center (NESC) was requested to examine processing sensitivities (e.g., cure temperature control/variance, debonds, density variations) of polybenzimidazole nitrile butadiene rubber (PBI-NBR) insulation, case fiber, and resin systems and to evaluate nondestructive evaluation (NDE) and damage tolerance methods/models required to support human-rated composite motor cases. The proposed use of composite motor cases in Blocks IA and II was expected to increase performance capability through optimizing operating pressure and increasing propellant mass fraction. This assessment was to support the evaluation of risk reduction for large booster component development/fabrication, NDE of low mass-to-strength ratio material structures, and solid booster propellant formulation as requested in the Space Launch System NASA Research Announcement for Advanced Booster Engineering Demonstration and/or Risk Reduction. Composite case materials and high-energy propellants represent an enabling capability in the Agency's ability to provide affordable, high-performing advanced booster concepts.

The NESC team was requested to provide an assessment of co- and multiple-cure processing of composite case and PBI-NBR insulation materials and evaluation of high-energy propellant formulations.

Notable Accomplishments

The following accomplishments were made:

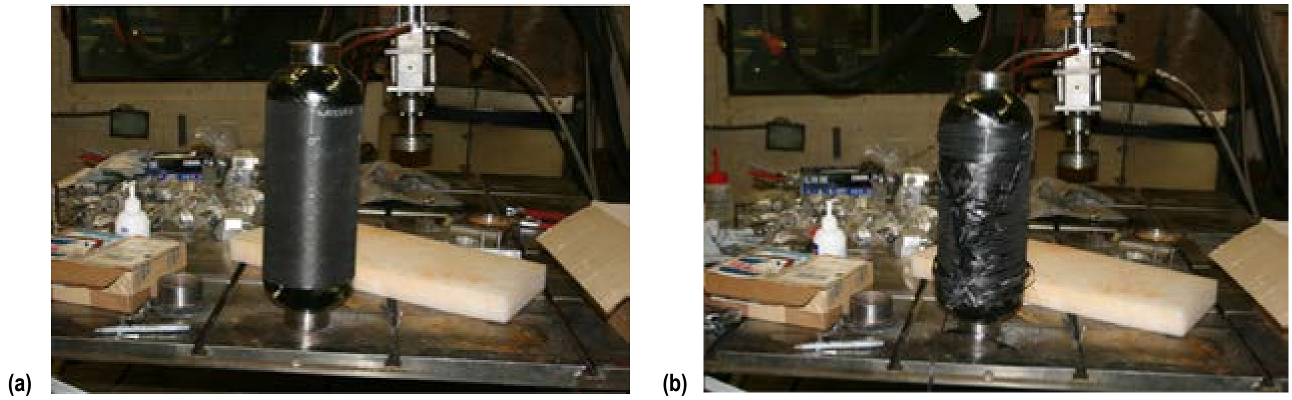
Hydroxyl terminated polybutadiene (HTPB) and hydroxyl terminated polyether (HTPE) propellant mixes were made in 1 pint, 1 gallon, and 5 gallon sizes. HTPB formulation is being worked to improve tensile properties and HTPE tensile properties were acceptable. Laboratory hazard testing and the end-of-mix viscosity testing are complete with acceptable results. The burning rates and pressure slopes are acceptable, and can be modified to meet program requirements.

Ablative liner mixes were made in 1 pint and 1 gallon sizes. The end-of-mix viscosities and tensile properties were acceptable.

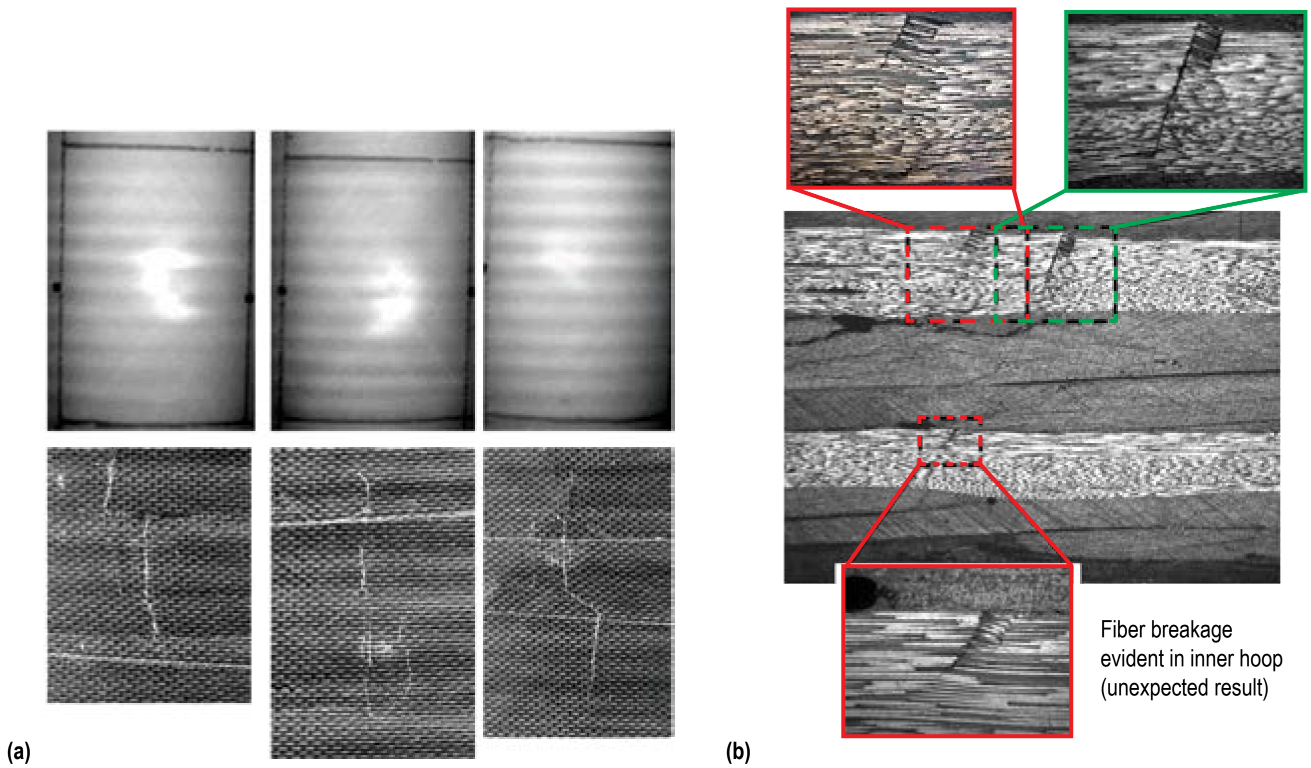
Kevlar®-filled ethylene propylene diene monomer was down-selected as insulation for bondline evaluations. Accelerated aging of HTPE propellant and its bondline specimens has commenced.

Forty-five bottles were manufactured and NDEs completed for the following: Eight test bottles each and one defect standard each for (1) prepreg co-cured and (2) prepreg multiple-cured in an oven; (3) wet wound and co-cured, (4) wet wound and multiple-cured in an oven, and (5) prepreg co-cured in an autoclave.

Impact trials were conducted to determine the lower bound on detectable damage via NDE. Burst testing of bottles was performed to evaluate possible differences in the structural capability of different processing methods. Comparison in burst pressures of the pristine co-cured and pristine multiple-cured bottles do not reveal a visible difference in burst strength.



Burst testing (a) before burst and (b) after burst (failure in hoop).



Damage to the bottle due to impact energy: (a) Flash thermography detected the impact damage from an impact energy of 3.2 ft-lb. Visual damage was also present on the exterior of the bottle and (b) photomicroscopy shows fiber damage is evident with an impact energy of 3.3 ft-lb.

The NDE techniques that were evaluated include the infrared flash thermography (IRT), proven to be an excellent method for finding indications; radiography, which has been successful in finding inserts in defect standards; and computed tomography, which is unable to find inserts in defect standards or indications found by IRT but has been excellent in detecting thickness and density changes.

References

Crumbly, C.M.; Bickley, F.P.; and Hueter, U.: "Space Launch System Spacecraft/Payloads Integration and Evolution Office Advanced Development FY 2014 Annual Report," NASA/TM—2015–218201, NASA Marshall Space Flight Center, Huntsville, AL, January 2015.

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Q4 Titanium 6-4 Material Properties Development

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

This task involves development and characterization of selective laser melting (SLM) parameters for additive manufacturing of titanium-6%aluminum-4%vanadium (Ti-6Al-4V or Ti64). SLM is a relatively new manufacturing technology that fabricates complex metal components by fusing thin layers of powder with a high-powered laser beam, utilizing a 3D computer design to direct the energy and form the shape without traditional tools, dies, or molds. There are several metal SLM technologies and materials on the market today, and various efforts to quantify the mechanical properties, however, nothing consolidated or formal to date. Meanwhile, SLM material fatigue properties of Ti64 are currently highly sought after by NASA propulsion designers for rotating turbomachinery components.

The primary objective of this task is to utilize NASA Marshall Space Flight Center's (MSFC's) existing SLM equipment (fig. 1) and knowledge base with other metal alloys to generate a reduced design allowables database of expected properties for SLM Ti64 parts. Unlike Inconel 625, Ti64 has never been used in MSFC's Concept-Laser SLM machine prior to this development effort. Therefore, we are starting with an initial build development followed by parameter optimization. Initial build development entails finding the correct general parameters, build plate materials, and build settings that yield satisfactorily dense (>99.5%) parts that will build to completion. Initial build development also entails maintaining and further honing our safety protocols around Ti-6Al-4V. As a reactive powder, it requires vigilant grounding and safety consciousness in order to expose the minimal number of operators to the least risk for the smallest amount of time.

Figure 1: SLM machine with glovebox required for Ti64.

Notable Accomplishments

The first build plate was a set of four small material test samples built on a stainless steel 90 mm × 90 mm build plate. Four samples were run at 250 W, 1,600 mm/s with varying spot sizes in an effort to quantify the melt pool size of Ti-6al-4V in the SLM. Part parameters were based on parameters successfully used at KU Leuven on a similar laser system. Three of the four samples failed to build due to peeling off the plate due to dissimilar λ. This has been corrected for by switching to Ti-6Al-4V build plates. The surviving part has been sent for sectioning and will be used to determine initial density. Parameters will be adjusted accordingly to achieve the highest density possible.

References

Crumbly, C.M.; Bickley, F.P.; and Hueter, U.: "Space Launch System Spacecraft/Payloads Integration and Evolution Office Advanced Development FY 2014 Annual Report," NASA/TM—2015–218201, NASA Marshall Space Flight Center, Huntsville, AL, January 2015.

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Testing of Selective Laser Melting Turbomachinery Applicable to Exploration Upper Stage

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

This task is to design, fabricate, and spin test to failure a Ti6-4 hydrogen turbopump impeller that was built using the selective laser melting (SLM) fabrication process (fig. 1). The impeller is sized around upper stage engine requirements. In addition to the spin burst test, material testing will be performed on coupons that are built with the impeller.

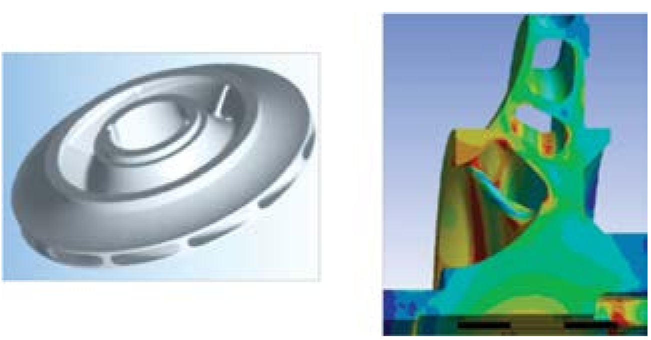

Figure 1: SLM turbopump impeller design.

Notable Accomplishments

Accomplishments for this task include the design of the impeller, SLM impeller, and material coupon fabrication, final machining (fig. 2), structured light scanning and inspection; spin burst testing, material strength data development, and data analysis. The spin test was successfully performed and operated up to 147,600 rpm, with the result that the impeller could not be failed with the equipment used.

Figure 2. SLM Ti6-4 manufactured turbopump impeller.

References

Crumbly, C.M.; Bickley, F.P.; and Hueter, U.: “Space Launch System Spacecraft/Payloads Integration and Evolution Office Advanced Development FY 2014 Annual Report,” NASA/TM—2015–218201, NASA Marshall Space Flight Center, Huntsville, AL, January 2015.

Additive Manufacturing Infrared Inspection

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

The Additive Manufacturing Infrared Inspection Task started the development of a real-time dimensional inspection technique and digital quality record for the additive manufacturing process using infrared camera imaging and processing techniques. This project will benefit additive manufacturing by providing real-time inspection of internal geometry that is not currently possible and reduce the time and cost of additive manufactured parts with automated real-time dimensional inspections which deletes post-production inspections.

Notable Accomplishments

The task successfully proved the feasibility of infrared hardware detecting an additive manufacturing process and developed custom software which created 3D geometry files of the additive manufactured part.

References

Crumbly, C.M.; Bickley, F.P.; and Hueter, U.: "Space Launch System Spacecraft/Payloads Integration and Evolution Office Advanced Development FY 2014 Annual Report," NASA/TM—2015–218201, NASA Marshall Space Flight Center, Huntsville, AL, January 2015.

Orion Delta 3D printer and manufactured part.

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Booster Interface Loads

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate Space Launch System Advanced Development, NASA Engineering & Safety Center (NESC)

Project Description

The interaction between shock waves and the wake shed from the forward booster/core attach hardware results in unsteady pressure fluctuations, which can lead to large buffeting loads on the vehicle. This task investigates whether computational tools can adequately predict these flows, and whether alternative booster nose shapes can reduce these loads. Results from wind tunnel tests will be used to validate the computations and provide design information for future Space Launch System (SLS) configurations.

The current work combines numerical simulations with wind tunnel testing to predict buffeting loads caused by the boosters. Variations in nosecone shape, similar to the Ariane 5 design (fig. 1), are being evaluated with regard to lowering the buffet loads. The task will provide design information for the mitigation of buffet loads for SLS, along with validated simulation tools to be used to assess future SLS designs.

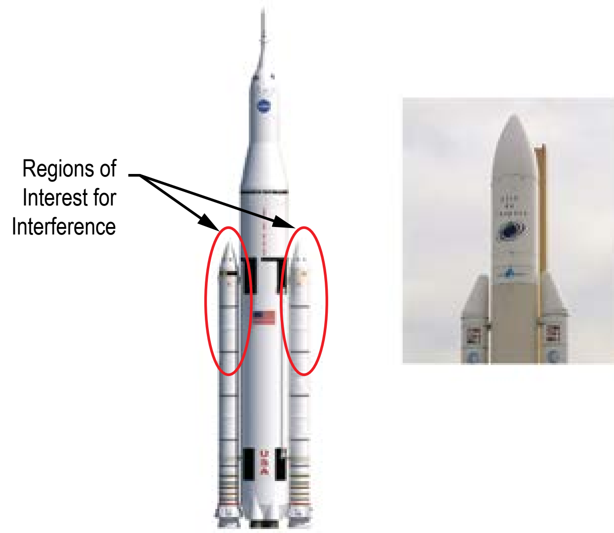

Figure 1: Booster interface loads.

Notable Accomplishments

The project has completed an initial set of computational fluid dynamics cases covering six booster nose configurations for two Mach numbers and two angles of attack. These configurations were tested in the NASA Ames 11-ft Transonic Wind Tunnel, as part of an SLS aero-acoustic test. Both computationally predicted and measured wind tunnel results indicate that substantial improvement in the booster attach region environments can be achieved (fig. 2).

While encouraging, overall root mean square (RMS) pressure levels are a relatively high-level comparison. For combined load analysis, buffet forcing functions, or integrated loads at a given longitudinal station, are needed. Accurate prediction of these buffet-forcing functions requires agreement in both magnitude and frequency.

References

Crumbly, C.M.; Bickley, F.P.; and Hueter, U.: “Space Launch System Spacecraft/Payloads Integration and Evolution Office Advanced Development FY 2014 Annual Report,” NASA/TM—2015–218201, NASA Marshall Space Flight Center, Huntsville, AL, January 2015.

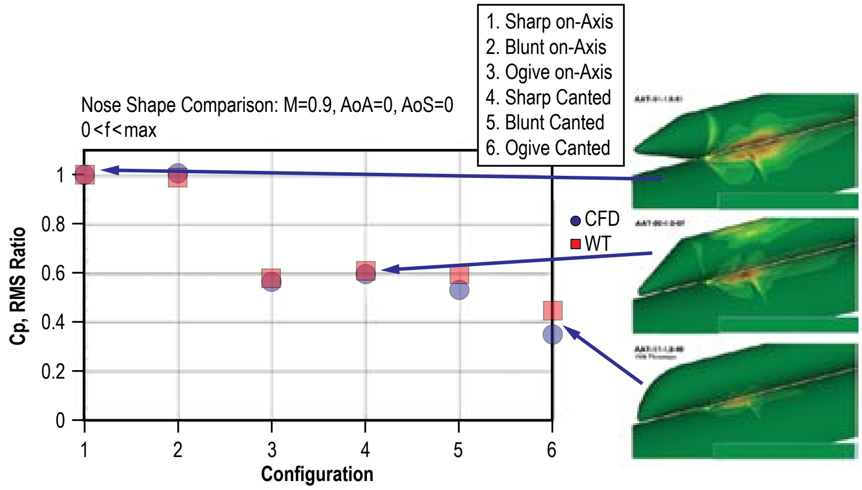

Figure 2: Area-weighted RMS pressure levels in booster attach region.

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Cryoinsulation Material Development to Mitigate Obsolescence Risk for Global Warming Potential Foams

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

Cryoinsulation foams currently being qualified for the Space Launch System (SLS) core stage are non-ozone-depleting substances (ODP) and are compliant with current environmental regulations. However, these materials contain the blowing agent HFC-245fa, a hydrofluorocarbon (HFC), which is a Global Warming Potential (GWP) substance. In August 2014, the Environmental Protection Agency (EPA) proposed a policy change to reduce or eliminate certain HFCs, including HFC-245fa, in end-use categories including foam blowing agents beginning in 2017. The policy proposes a limited exception to allow continued use of HFC and HFC-blend foam blowing agents for military or space- and aeronautics-related applications, including rigid polyurethane spray foams, but only until 2022.

The blowing agent industry and foam industry proactively began evaluating new low GWP blowing agents in 2013 for use in nonaerospace foam applications. Foams used for cryoinsulation of aerospace vehicles require unique formulations tailored specifically to meet cryogenic and aerothermal requirements. Development of low GWP foam systems will require evaluation, testing, reformulation, development, and qualification before use on a flight vehicle.

Under the Advanced Development Group initiative, the EM41 Thermal Protection System (TPS) team performed a market survey of low GWP foams as risk mitigation to proactively evaluate low GWP foams. The leading replacement blowing agents under consideration by the primary aerospace foam manufacturers are hydrofluoroolefin (HFO) molecules. However, the foam industry has not yet developed a viable way of incorporating HFO blowing agents into foam formulations. Current formulations have a very short shelf life and cannot pass building code burn tests. Ascent heating for aerospace applications is an even more severe heating environment.

Since stability issues with HFO blowing agents make them not immediately ready for aerospace applications, other low GWP blowing agents were evaluated including HFC-365mfc, pentane, carbon dioxide (CO_2), and methyl formate/Ecomate®. Figure 1 shows the insulation values of foams formulated with each blowing agent.

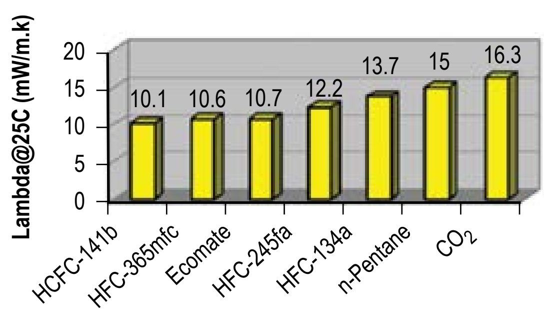

Figure 1: Insulation values of foams formulated with various blowing agents.

The table shows the ODP and GWP values for each blowing agent. Although HFC-365mfc has good insulation properties, it does not provide a significant reduction in GWP. Using pentane as a blowing agent requires class I/division I facilities and processing equipment since it is flammable. While these facilities exist in NASA Marshall Space Flight Center's (MSFC's) Building 4765, they are cost prohibitive for manufacturing facilities such as the NASA Michoud Assembly Facility (MAF). The most promising two candidates are CO_2 and methyl formate/Ecomate.

ODP and GWP values for various blowing agents.

Application	Blowing Agent	ODP	GWP
Space Shuttle External Tank	HCFC-141b	0.11	725
SLS Core Stage	HFC-245fa	0	1,030
Future Applications	HFOs	0	<25
	HFC-365mfc	0	794
	Pentane	0	<25
	Methyl Formate	0	<25
	CO_2	0	1

The company Icynene uses CO_2 as the blowing agent in a foam product named ProSeal Eco (MD-R-210). Although CO_2 is the most environmentally friendly choice, it provides poor insulation, so foam would likely have to be applied thicker, increasing the weight of the vehicle. MSFC coordinated with Icynene to obtain sprayed foam samples and liquid component samples of ProSeal Eco for testing. The company Foam Supplies Incorporated (FSI) uses methyl formate (trade name Ecomate) to formulate foam products. Methyl formate provides low GWP and foams formulated with it provide good insulation. MSFC also shared a list of required material properties with FSI so chemists at FSI can formulate a foam product with Ecomate that is specific to aerospace needs.

Anticipated Benefits

Proactive efforts to develop low GWP replacement foams would improve the affordability and reliability of the SLS core stage in future years. When the EPA begins regulating GWP materials, the current blowing agent will be subject to a phase-out period during which availability will decline, cost will increase, and NASA will be required to negotiate with the EPA for a waiver while a replacement material is sought.

Potential Applications

Applications for low GWP cryogenic foam insulation include the SLS core stage, future SLS exploration upper stages, composite cryotanks, in-space storage vessels, and commercial crew vehicles.

Forward Work

The MSFC EM41 TPS Development Team will continue to evaluate low GWP foams and blowing agents as risk mitigation. Initial in-house tests such as reactivity, density, and plug pull tension tests will provide early indications of foam performance. EM41 will remain aware of EPA policy changes and industry advances in low GWP blowing agents for foams.

References

"Transitioning to Low GWP Alternatives in Building/Construction Foams," U.S. Environmental Protection Agency, <http://www.epa.gov/ozone/downloads/EPA_HFC_ConstFoam.pdf>, February 2011.

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Hexavalent Chromium IV-Free Primer Development

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development
SLS Spacecraft Payload Integration and Evolution Element Office

Project Description

Primer materials provide corrosion protection for metal parts as well as an increased adhesion between metallic substrates and thermal protection systems (TPSs). Current primers for use in cryogenic applications contain hexavalent chromium. This hexavalent chromium provides excellent corrosion protection even in a cryogenic environment, but it is a carcinogen that requires special equipment and waste control procedures to use. The hazardous nature of hexavalent chromium makes it an obsolescence risk in the future.

This study included two phases of evaluation. Thirteen primers were initially identified as candidates and twelve of those primers were tested in phase 1. Four of the best performing candidates from phase 1 continued into phase 2 testing. Phase 1 testing consisted mostly of liquid constituent and physical property testing. Cryoflex and salt fog testing were included in phase 1 because of their importance to the overall success of a candidate material. Phase 2 consisted of physical, thermal, and mechanical properties for nominally processed and fabricated specimens.

Coating applications.

Hexavalent chromium-free primer panels.

Anticipated Benefits

Benefits of this project include identified replacement material(s) for chromate-containing primers that meet the typical demands of space launch vehicles, reduced risk of schedule and budget impacts due to potential tightening restrictions and regulations governing the use of chromate-containing primers, and identified potential technical risks and shortcomings associated with the usage of nonchromate-containing primers currently available.

Potential Applications

Primers of this type may be used on the following applications: Space Launch System elements, cryogenic pressure vessels in other launch vehicles, test articles and testing support equipment, commercial crew and commercial resupply for International Space Station support, satellite launch and support equipment, and ground support and launch support equipment.

Notable Accomplishments

All four primers tested in phase 2 performed well on thermal and mechanical tests. While none of the hexavalent chromium-free primers passed the 1,000-hr, salt-fog corrosion testing, two of the candidates had only minor defects. The top-performing primers for corrosion resistance were PRC-Desoto CF/CA 7502 with PPG Surface Pretreatment EAP-9 and Sherwin Williams CM0483787.

References

EM41-TP052, "Test Plan for SLS ADO-05 Hexavalent Chromium Free Primer for Cryogenic Applications."

EM41-TR052, "Phase 1 and 2 Test Report for SLS ADO-05 Hexavalent Chromium Free Primer for Cryogenic Applications."

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Low-Profile Diffuser

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

The propellant tanks used in liquid rockets require pressurization gases in order to maintain tank pressure while the tanks are being drained during engine operation. The pressurization gas, which is typically much warmer than the relatively cold propellants in the tank, must be introduced into the empty ullage space at the top of the tank. The purpose of the diffuser is to control the flow of the gas into the tank in order to prevent direct impingement of the gas on the liquid surface and/or the tank walls. If the diffuser did not perform those tasks, the warm gas can create excess heat transfer causing an increase in the amount of pressurization mass required.

Typical diffusers are long vertical cylinders that create a large exit area in order to minimize gas velocities. However, long vertical cylinders limit the amount of liquid that can be loaded into the tank in order not to have the liquid surface near the diffuser. A design goal for a pressurization diffuser is to create uniform flow in order to prevent jets that can impact the liquid surface and/or tank walls.

The purpose of the task was to create a diffuser design that had a lower vertical profile (in order to be able to raise the liquid surface) while still maintaining uniform flow.

Low-profile diffuser being tested without wire-cloth attached in order to validate CFD model.

Low-profile diffuser being tested with wire-cloth attached using hot-wire anemometer to measure external velocity profiles.

50 ft/s Iso-Surface

CFD model prediction of flow velocities showing the benefit of using wire-cloth.

SLS AD

Anticipated Benefits

Rocket designers are constantly trying to improve the performance of their rocket. Using a more compact diffuser such as the low-profile diffuser will allow designers to use more of the available tank volume for propellant. Increasing the amount of loaded propellant can show improvement in the amount of payload delivered to orbit.

Potential Applications

The low-profile diffuser (or variations on the concept) can be used in any liquid propellant tank in order to maximize the amount of loaded propellant. The low-profile diffuser that was designed and tested was sized for the Space Launch System core stage.

Notable Accomplishments

Computational fluids dynamics (CFD) models were used heavily during this task in order to ensure the exit flow could be made uniform in a smaller package (relative to typical diffusers). The CFD analyzed ~20 design iterations during a period of a couple of months in order to arrive at the final design. In addition, the CFD model was validated with the test data that were obtained. This gives confidence that the CFD tool can be successfully employed to analyze other diffuser designs.

Also, part of this task involved generating flow characteristics for two different weaves of wire-cloth. These data were used in the CFD model, but can also be used for analyzing pressure drop of these particular weaves of wire-cloth for other applications.

Finally, a full-size prototype was built and tested. The testing generated data used for CFD model validation.

References

Martin, M.A.: "Low Profile Diffuser Final Report for Task ADO-06," NASA Marshall Space Flight Center, Huntsville, AL, December 31, 2014

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Composite Dry Structure Cost Improvement Approach

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

This effort demonstrates that by focusing only on properties of relevance, composite interstage and shroud structures can be placed on the Space Launch System vehicle that simultaneously reduces cost, improves reliability, and maximizes performance, thus providing the Advanced Development Group with a new methodology of how to utilize composites to reduce weight for composite structures on launch vehicles. Interstage and shroud structures were chosen since both of these structures are simple in configuration and do not experience extreme environments (such as cryogenic or hot gas temperatures) and should represent a good starting point for flying composites on a 'man-rated' vehicle. They are used as an example only.

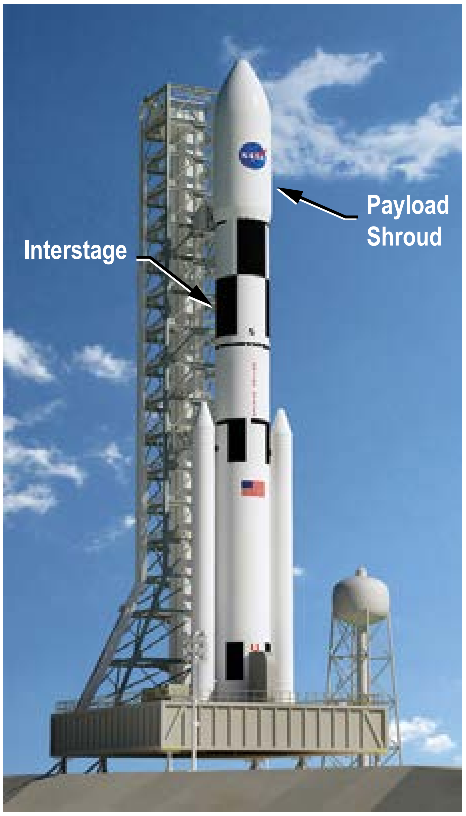
The project involves using polymer matrix composites for launch vehicle structures, and the logic and rationale behind the proposed new methodology.

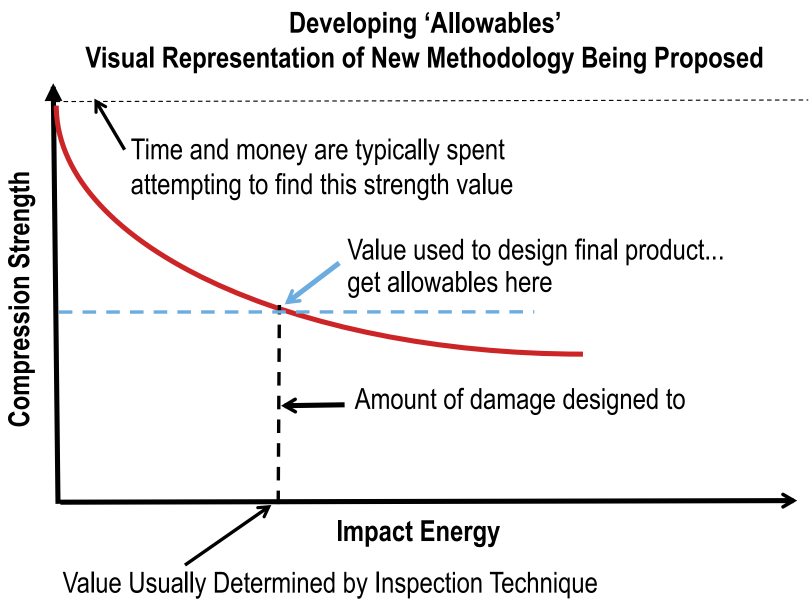
Notable Accomplishments

Notable accomplishments include rationale and remedies for the barriers in using composites: (1) Testing of lamina is not only expensive and difficult but futile since no laminate failure criteria has been shown to be valid for practical use; (2) Undamaged laminate testing is time consuming and costly. This is hard to justify as these strength numbers will probably never be used since damage must be assumed to exist in the laminate; (3) Undamaged laminate testing is more of a 'test of the test method' rather than a material property test; (4) If a structure has a dominant loading case (such as compression for an interstage structure), then characterizing other strength (such as tension) is of no practical use; (5) Costly fatigue testing is usually not necessary; (6) The statistical significance (the obtaining of which is very costly) of the multitude of undamaged test specimens is lost many times over by the time a final design number for a given piece of hardware is agreed upon; and (7) The final product will have an optimum lay-up based on undamaged properties that may not result in an optimum lay-up for damage tolerance considerations. This may contribute to design values that are either too high (poor reliability) or too low (compromised performance) being used.

References

Crumbly, C.M.; Bickley, F.P.; and Hueter, U.: "Space Launch System Spacecraft/Payloads Integration and Evolution Office Advanced Development FY 2014 Annual Report," NASA/TM—2015–218201, NASA Marshall Space Flight Center, Huntsville, AL, January 2015.


Payload
Shroud
Interstage


Developing 'Allowables'
Visual Representation of New Methodology Being Proposed
Time and money are typically spent
attempting to find this strength value
Value used to design final product...
get allowables here
Amount of damage designed to
Compression Strength
Impact Energy
Value Usually Determined by Inspection Technique

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Advanced Booster Liquid Engine Combustion Stability

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

Combustion instability is a phenomenon in liquid rocket engines caused by complex coupling between the time-varying combustion processes and the fluid dynamics in the combustor. Consequences of the large pressure oscillations associated with combustion instability often cause significant hardware damage and can be catastrophic. The current combustion stability assessment tools are limited by the level of empiricism in many inputs and embedded models. This limited predictive capability creates significant uncertainty in stability assessments. This large uncertainty then increases hardware development costs due to heavy reliance on expensive and time-consuming testing.

The objectives of this task are to advance the predictive capability of state-of-the-practice combustion stability methodologies and tools used for the Space Launch System (SLS) injector combustion stability assessment, facilitate more confident identification and characterization of combustion instabilities and efficient mitigation during SLS propulsion system development, and minimize SLS development costs and improve hardware robustness.

Notable Accomplishments

The following tasks have been accomplished: (1) Injector element design, scaling, testing, and computational fluid dynamics (CFD) simulation, including (a) element 1b—baseline element (testing is complete at both Air Force Research Laboratory (AFRL) (full-scale at 350–1,100 psia) and Purdue (subscale at 450 psia)); CFD analyses of both elements is complete; testing and CFD analysis at both scales showed an ~180 Hz chug instability; (b) element 1b4 (a redesign of element 1b to eliminate the chug instability; testing at AFRL is complete—both testing and CFD analysis indicate chug is still present, but at a considerably lower amplitude); and (c) element 1b5 (redesign of element 1b4 is being fabricated for testing at both AFRL and Purdue—CFD simulations indicate it should be stable; and (2) Demonstration of new capabilities on SLS Advanced Booster Engineering Design Risk Reduction (ABEDRR) injector, including 3D reacting flow CFD simulations of a seven-element representation of the ABEDRR injector completed (figs. 1 and 2), and data extracted from CFD simulations used to augment engineering stability assessment tools.

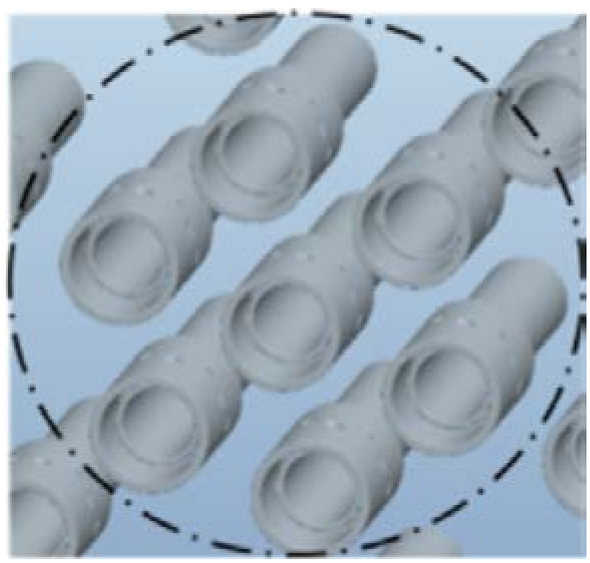

Figure 1. Seven elements from an ABEDRR injector.

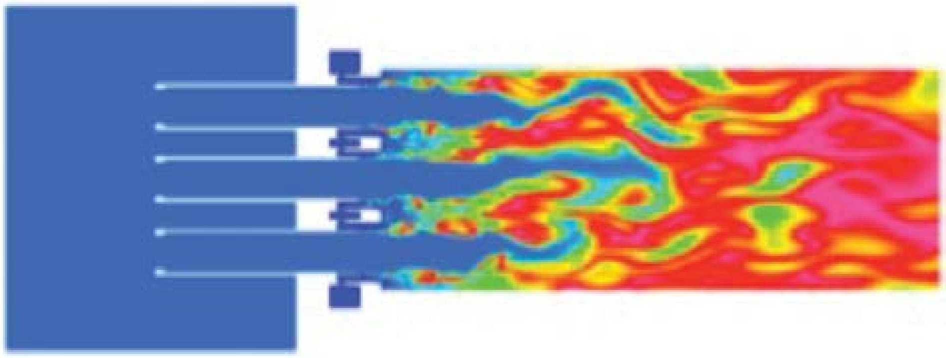

Figure 2. Two-dimensional cut of temperature field of seven-element injector.

References

Crumbly, C.M.; Bickley, F.P.; and Hueter, U.: "Space Launch System Spacecraft/Payloads Integration and Evolution Office Advanced Development FY 2014 Annual Report," NASA/TM—2015–218201, NASA Marshall Space Flight Center, Huntsville, AL, January 2015.

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Lattice Boltzmann Method for Spacecraft Propellant Slosh Simulation

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

The modeling and prediction of the behavior of fluids in microgravity continues to be a challenge in the design of spacecraft systems. In the microgravity environment, hydrodynamic regimes can be described by the nondimensional parameter of Bond number (*Bo*), characterizing the relative magnitude of the gravitational acceleration versus the capillary forces present in the liquid.

At very low Bond numbers ($Bo<10$), the hydrodynamics are dominated by the surface tension and a qualitative change in behavior is observed. Liquid-free surface interfaces become characteristically curved, and most propellants approach a near zero contact angle with solid objects (such as tank walls). The dominant time scale of the liquid dynamics increases into the tens or hundreds of seconds, and characteristic flow velocities and the Mach number are very small. In these conditions, computational fluid mechanics (CFM) approaches are required to predict the motion of the bulk fluid mass and its effect on the spacecraft when displaced from equilibrium.

The lattice Boltzmann method (LBM) has recently emerged as a promising alternative to traditional approaches to CFM. Using this approach, the continuum fluid transport phenomena, i.e., the Navier-Stokes equations, can be approximated as a solution of a discretized nonlinear difference equation based upon the kinetic theory of gases.

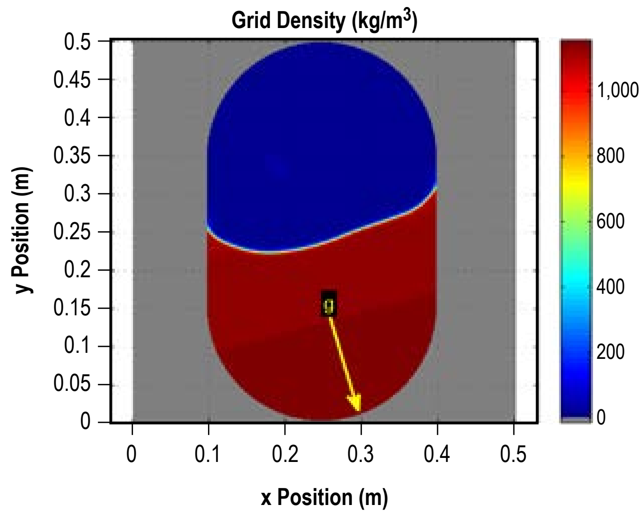

Figure 1: Fluid sloshing at $Bo=20$ (0.001 *g*).

While the LBM is typically restricted to low velocity flows, it does provide several unique advantages over traditional solvers: (1) The meshing of complex geometry is performed on a regular lattice of fluid cells, each having uniform volume in the fluid domain. As such, computations involving flux across the boundary of adjacent cells are considerably simplified; (2) The LBM has the advantage of data locality; LBM flow solvers are not required to solve a global continuity equation at each time step; and (3) The LBM is relatively simple to implement and computationally efficient.

A scalable, proof-of-concept computational approach to the simulation of propellant tank sloshing dynamics in microgravity has been developed (fig. 1). We use the lattice Boltzmann equation to approximate the behavior of two-phase, single-component isothermal flows at very low Bond numbers. Through the use of a nonideal gas equation of state and a modified multiple relaxation time collision operator,[1] the proposed method can simulate thermodynamically consistent phase transitions at temperatures and density ratios consistent with typical spacecraft cryogenic propellants; e.g., liquid oxygen. Determination of the tank forces and moments relies upon the global momentum conservation of the fluid domain, and a parametric wall-wetting model allows tuning of the free surface contact angle.

In our formulation, a pseudopotential model with a real gas equation of state is used.[2] The pseudopotential model is a diffuse interface model; i.e., the interface appears in the lattice as a density gradient over a few cells or tens of cells. This increases the required minimum lattice resolution to obtain sharp interface definition if required by the application. Disadvantages of the pseudopotential model include the interdependency of the interface thickness, the surface tension parameters, and the high interface forces required to maintain a stable interface. The latter tends to yield spurious currents, which degrade the stability. Of course, the basic Lattice Boltzmann equation is isothermal; convective effects, which can be important in cryogenic flows in zero-g, are not captured.

The computation, data processing, and visualization are implemented directly in MATLAB®. Extensive use of MATLAB's multidimensional array operators allows many of the necessary operations, such as advection, collision, and the calculation of body forces, to be accomplished without the use of nested loops. By relying on MATLAB's internally optimized matrix libraries for much of the large-scale multiplication and division operations, a considerable advantage in computational efficiency and code simplicity is realized. Verification of the multiphase LBM implementation was accomplished through comparison of numerical and theoretical results for known phenomena in surface tension dominated flows; e.g., droplet oscillation (fig. 2).

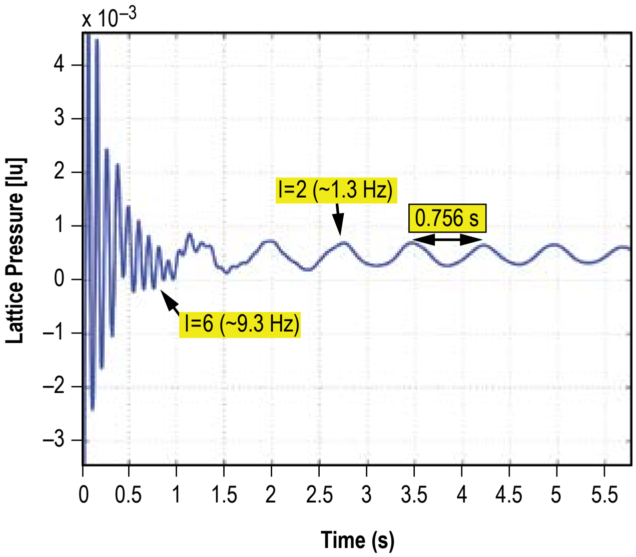

Figure 2: Analysis of oscillating droplet dynamics.

Anticipated Benefits

Rapid and accurate prediction of bulk fluid motion in spacecraft propellant tanks is crucial for analyzing the vehicle's dynamics and stability, especially during attitude control and thrusting maneuvers. In addition, the interaction of the propellant with tank hardware is particularly important in the design of propellant management devices. Since the lattice Boltzmann approach is computationally parallelizable, it may be possible to leverage emerging computing architectures to develop a fast, efficient multiphysics simulation of the coupled fluid-spacecraft dynamics.

These data can potentially reduce risk by allowing more accurate simulation predictions of an otherwise difficult-to-access flow regime.

Potential Applications

The present work was developed specifically to support analysis of the effects of propellant motion on the stability and dynamics of spacecraft, especially in the nonlinear regime and with respect to long time scales. However, the ability to model phase transitions using a real gas equation of state implies that it may be possible to directly incorporate thermal effects. In this case, the LBM may have applications to modeling and simulation of thermal management systems for cryogenic propellant storage, especially in those conditions relevant for long-duration space missions.

References

1. Lallemand, P.; and Luo, L.: "Theory of the Lattice Boltzmann Method: Dispersion, Dissipation, Isotropy, Galilean Invariance, and Stability," NASA/CR—2000–210103, NASA Langley Research Center, Institute for Computer Applications in Science and Engineering, 2000.

2. Yuan, P.; and Schafer, L.: "Equations of state in a lattice Boltzmann model," *Physics of Fluids*, Vol. 18, No. 4, p. 042101, doi: 10.1063/1.2187070, 2006.

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Hot-Fire Test of Liquid Oxygen/Hydrogen Space Launch Mission Injector Applicable to Exploration Upper Stage

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

This task is to hot-fire test an existing Space Launch Mission (SLM) injector that is applicable for all expander cycle engines being considered for the exploration upper stage. The work leverages investment made in FY 2013 that was used to additively manufacture three injectors (fig. 1) all by different vendors.

Figure 1: Manufactured LOX/H_2 injectors.

Notable Accomplishments

Accomplishments include selecting two of the injectors to use for hot-fire testing, performing nondestructive evaluation on the original SLM injectors, final machining, welding on the Rigimesh® face plate, water flow testing, fabricating the ablative chambers used to support testing, test facility buildup, writing the Test Requirements Document and successfully completing the Test Readiness Review, performing facility leak checks and blow-down testing, and hot-fire testing injectors (fig. 2).

References

Crumbly, C.M.; Bickley, F.P.; and Hueter, U.: “Space Launch System Spacecraft/Payloads Integration and Evolution Office Advanced Development FY 2014 Annual Report,” NASA/TM—2015–218201, NASA Marshall Space Flight Center, Huntsville, AL, January 2015.

Figure 2: Water flow and hot-fire testing of two LOX/H_2 SLM injectors.

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Nanoelectric Materials Laboratory Development

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate Space Launch System Advanced Development, Spacecraft/Payload Integration & Evolution/Advanced Development, Space Launch System Booster, Center Innovation Funding, Technical Excellence

Nanoelectric Materials Lab in Bldg. 4602.

Project Description

The Ultracapacitor Research and Development project is a collaborative effort between the NASA Marshall Space Flight Center's (MSFC's) ES43 Parts, Packaging, and Fabrication Branch and the EM41 Nonmetallic Materials Branch. NASA's Ultracapacitor Research is an effort to develop solid-state energy storage devices through processing of ceramic materials into printable dielectric inks, which can be formed and treated to produce solid state ultracapacitor cells capable of exceeding lithium-ion battery energy density at a fraction of the weight.

Research and development efforts into solid state ultracapacitors have highlighted a series of technical challenges such as understanding as-received nature of ceramic powders, treatment and optimization of ceramic powders, dielectric and conductor ink formulation, and firing of printed (green) ultracapacitor cells.

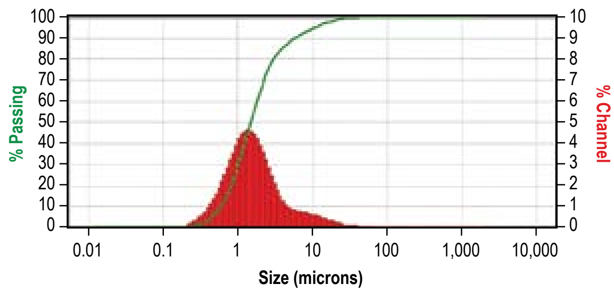
Two facilities have been continually developed since project inception: the Additive Electronics Lab in Bldg. 4487 and the Nanoelectric Materials Lab in Bldg. 4602. The Nanoelectric Materials Lab has become a unique facility at MSFC, capable of custom processing a wide range of media for additive electronics.

Vibratory mill and control system.

As research has progressed, it was discovered that additional in-house processing was necessary to achieve smaller, more uniform particle diameters.

A vibratory mill was obtained that can agitate powder and media in three directions, which has shown to be much more effective than ball milling. However, in order to understand the effects of milling, a particle size analysis system has been installed to characterize as-received and milled materials.

Continued research into the ultracapacitor technology included advanced milling and optimization of ceramic nanoparticles, fluidized bed treatment of atomic-layer deposition- (ALD-) coated ceramic particles, custom development of dielectric and conductor inks, as well as custom ink precursors such as polyvinylidene diflouride- (PVDF-) loaded vehicles. Experiments with graphene-based inks were also conducted.



Particle size analysis output—both mean and standard deviation are critical to producing high capacitance inks.

Anticipated Benefits

Solid state ultracapacitors are completely safe, posing no risk to crew, vehicle, or mission. These ultracapacitors are also capable of rapid charge and discharge, and experience no notable energy leakage. Moreover, solid state ultracapacitors will demonstrate drastic weight savings over electrochemical batteries.

Growing expertise in particle size analysis can be of great use to other research efforts, namely nuclear thermal propulsion (fuel development) and additive manufacturing (particle size has a large impact on manufactured parts).

Expanded capabilities in creating custom ink formulations opens the door to a variety of additive electronics research avenues. For example, the same capabilities can be used to research and develop electroluminescence.

Potential Applications

Potential applications include range safety batteries for the booster, core stage, and exploration stages; short-window solar energy capture for orbital satellites (CubeSats); ground-based applications are wide ranging—electric vehicles, directed energy devices, grid leveling, residential power, and hand-held electronics; and 3D circuit printing could provide tailored energy storage and integration into circuit boards.

Notable Accomplishments

A fluidized bed reactor was used to dramatically improve treatment of ALD-coated ceramic powders. Trivalent doping of perovskite ceramic nanoparticles showed a significant increase in dielectric properties, achieving capacitances in the microFarad range with 30-micron-thickness ultracapacitor devices. Vibratory milling of ceramic powders has shown dramatic decrease in particle size distribution, translating to increased density of the dielectrics and an increase in capacitance. Novel and unique dielectric inks have been developed for both high temperature with glass binders and low temperature with composite polymer-ceramics. Novel and unique conductor inks have been developed for use in ultracapacitors and 3D circuit printing.

References

Allen, L.: "Solid State Ultracapacitor to Replace Batteries," Marshall Technology Exposition, NASA Marshall Space Flight Center, Huntsville, AL, October 27, 2014.

Insulation Reformulation Development

Project Manager(s)/Lead(s)

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

The current Space Launch System (SLS) internal solid rocket motor insulation, polybenzimidazole acrylonitrile butadiene rubber (PBI-NBR), is a new insulation that replaced asbestos-based insulations found in Space Shuttle heritage solid rocket boosters. PBI-NBR has some outstanding characteristics such as an excellent thermal erosion resistance, low thermal conductivity, and low density.

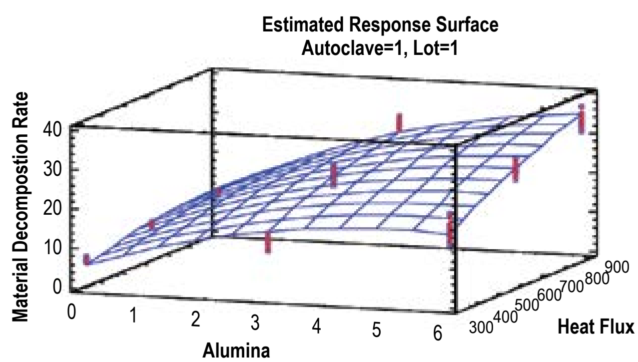
PBI-NBR also has some significant challenges associated with its use: Air entrainment/entrapment during manufacture and lay-up/cure and low mechanical properties such as tensile strength, modulus, and fracture toughness.

This technology development attempted to overcome these challenges by testing various reformulated versions of booster insulation. The results suggest the SLS program should continue to investigate material alternatives for potential block upgrades or use an entirely new, more advanced booster.

The experimental design was composed of a logic path that performs iterative formulation and testing in order to maximize the effort. A lab mixing baseline was developed and documented for the Rubber Laboratory in Bldg. 4602/Room 1178.

Rubber Lab mixer and control system.

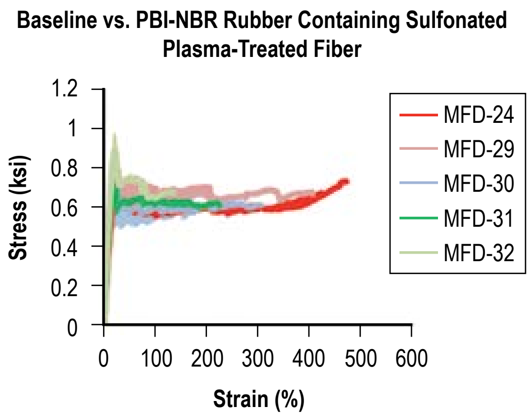
Rubber Lab mill and control system.



Contour plot of thermal erosion performance.

Comparative rheology, mechanical properties (tensile and elongation in different fiber directions), specific gravity, viscosity, scorch, Shore A hardness, and erosion performance were evaluated.

Formulations tested were derived from existing formulations: PBI-NBR and SFNBR (silica-filled acrylonitrile butadiene) and adjustments were made to fiber and fiber types, fillers, and processing aids.



Stress-strain of candidate formulations.

Anticipated Benefits

Improved understanding of the polymer chemistry of the raw ingredients and their direct effect on performance properties in extreme environments (e.g., solid rocket motors) will increase the options for material selection in future programs. The optimization of material selection for advanced booster programs within the constraints of weight impacts, mechanical performance, thermal performance, and manufacturability is key to affordable production of hardware for future missions.

Potential Applications

The better understanding of performance effects of constituents within polymers used in thermal insulation has the potential for broad industry application. Expansion of the supplier base via improved performance requirements will enable cost savings on multiple programs within defense, civilian, and commercial space programs that utilize solid rocket motors. Additional work by NASA could include development and formalization of standards for formulation methodology and test requirements for qualification.

Notable Accomplishments

Two formulations were selected for evaluation in a larger production mixer (outsourced for 100-lb batches). This allows additional test specimens and a scale-up formulation to be evaluated. Most lab scale mixes (6 lb) do not scale up equally. Properties should trend in the same fashion, but will not be exactly the same values.

Forward Work

Reformulation effort continues through FY 2015. The effort will include ethylene propylene diene monomer based formulation and alternate fibers.

References

EM41-TP063 SRM Insulation Reformulation. "SLS Booster Element Proposal for Motor Internal Insulation Development Effort," June 2013.

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Aluminum 2195 T8 Gore Development for Space Launch System Core and Upper Stage

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

Gores are pie-shaped panels that are welded together to form the dome ends of rocket fuel tanks as shown in figure 1. Replacing aluminum alloy 2219 with aluminum (Al)-lithium (Li) alloy 2195 as the Space Launch System (SLS) cryogenic tank material would save enormous amounts of weight. In fact, it has been calculated that simply replacing Al 2219 gores with Al 2195 gores on the SLS core stage domes could save ~3,800 lbm. This is because the Al-Li 2195 alloy exhibits both higher mechanical properties and lower density than the SLS baseline Al 2219 alloy. Indeed, the known advantages of Al 2195 led to its use as a replacement for Al 2219 in the shuttle external tank program. The required thicknesses of Al 2195 gores for either SLS core stage tanks or upper stage tanks will depend on the specific design configurations. The required thicknesses or widths may exceed the current experience base in the manufacture of such gores by the stretch-forming process. Accordingly, the primary objective of this project was to enhance the formability of Al 2195 by optimizing the heat treatment and stretch-forming process for gore thicknesses up to 0.75 inch, which envelop the maximum expected gore thicknesses for SLS tank configurations.

Formability data and heat-treating parameters were determined prior to stretch forming the 0.525- and 0.75-inch-thick plates. The data were used in the finite element model that was developed to help guide the stretch-forming operations and to help interpret the results (fig. 2). One 0.525-inch-thick and two 0.75-inch-thick Al 2195 plates were successfully stretch formed into gores using an existing die of the Ares I contour (fig. 3). Use of the Ares I die was a significant cost savings, as an SLS die did not have to be developed and constructed. Also, the Ares I contour is more severe than the SLS contour and therefore successful stretch-forming operations demonstrated with the Ares I die can also be expected to be successful with a die of the SLS contour.

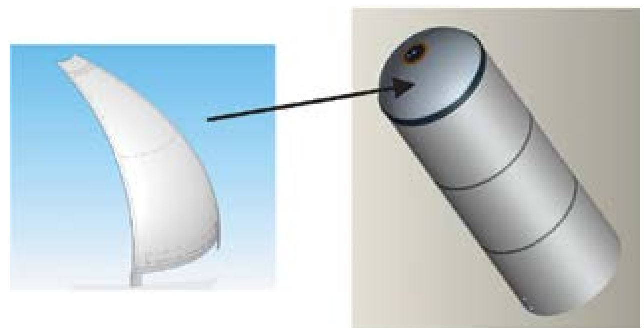

Figure 1: Gore panels are welded together to form the dome ends of SLS cryogenic tanks.

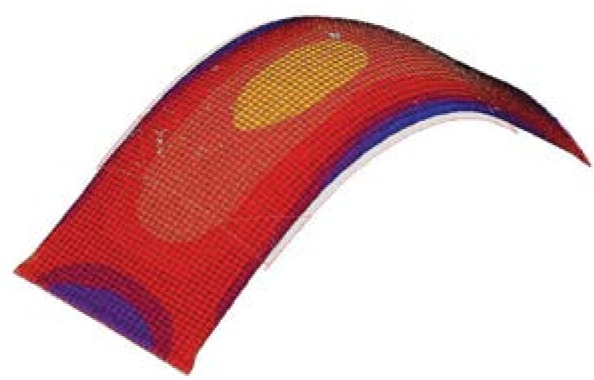

Figure 2: A finite element analysis model was used to determine the magnitude and variation of strain induced during the stretch-forming operation.

Figure 3: An aluminum panel is stretch formed into the desired contour using a die.

Mechanical testing of the 0.525- and 0.75-inch Al 2195 gores showed greater than expected tensile properties when compared to the Lockheed Martin Engineering Materials Specifications for Al 2195, STM 11-A1-LM, which was developed for the external tank program. The fracture toughness is also satisfactory and can be improved further with an optimization in the aging treatment parameters. The results of this study were very promising. All of the formability and mechanical test data gained from this program indicate that the stretch-formed 2195 gores have sufficient material properties to replace the existing Al 2219 alloy that is the current baseline for SLS flight domes.

Anticipated Benefits

Prior to this study, Al 2195 plates thicker than 0.325 inch had never been stretch formed. Therefore, it was necessary to perform formability studies on Alcoa 0.525- and 0.75-inch-thick plates to ensure that the prescribed annealing treatment indeed improved their formability. Tensile tests were performed for 0.525- and 0.75-inch-thick Al 2195 plates to compare the effects of annealing treatment on the forming range and strain hardening exponent. The annealing treatment that led to a higher forming range and strain hardening exponents was selected to anneal 0.525- and 0.75-inch Al 2195 plates prior to gore stretch forming. This annealing process was developed at NASA Marshall Space Flight Center (MSFC) and is being patented (MFS-32954-1). The NASA annealing process led to a higher strain hardening exponent and higher formability, and demonstrated that large-scale rocket domes can be reliably manufactured by the stretch-forming process with the lightweight Al-Li 2195 alloy.

Potential Applications

The intended primary applications for this technology development were SLS core and upper stage cryogenic fuel tanks. This project demonstrated that relatively thick (up to 0.75 inch) Al 2195 plates can be processed by stretch forming. Thus, any aerospace application where increased strength and weight savings are desired can take advantage of this technology.

Notable Accomplishments

All of the planned tasks for this project were successfully completed.[1] An annealing treatment that led to a higher forming range and strain hardening exponent was utilized to anneal 0.525- and 0.75-inch Al 2195 plates prior to gore stretch forming. One 0.525- and two 0.75-inch-thick plates were successfully stretch formed into gore contours and heat treated to the T8 temper (fig. 4). Mechanical testing of the gores resulted in tensile properties that exceeded the specifications for Al 2195. Finally, a detailed plan was developed for future work to enable the incorporation of Al 2195 gores into the SLS program.

Figure 4: The three completed gore panels after delivery to MSFC. Test specimens were cut from the ends of two of the gore panels for mechanical and fracture toughness testing.

References

1. Volz, M.P.; Chen, P.S.; Gorti, S.; and Salvail, P.: "Development of Aluminum-Lithium 2195 Gores by the Stretch Forming Process," National Space and Missile Materials Symposium, Huntsville, AL, June 23–26, 2014.

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Thermal Protection System Application to Composite Cryotank Technology Demonstrator

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

The EM41 Thermal Protection System (TPS) team contributed to the success of the Composite Cryotank Technology Demonstrator (CCTD) manufacturing by developing and implementing a low-cost solution to apply cryoinsulation foam on the exterior surface of the tank in the NASA Marshall Space Flight Center (MSFC) TPS Development Facility, Bldg. 4765. The TPS team used techniques developed for the small-scale composite cryotank to apply Stepanfoam S-180 polyurethane foam to the 5.5-m CCTD using a manual spray process. Manual spray foam technicians utilized lifts and scaffolding to access the barrel and dome sections of the large-scale tank in the horizontal orientation. During manufacturing, the tank was then oriented vertically, allowing access to the final barrel section for manual spray foam application. The CCTD was the largest application of manual spray foam performed to date with the S-180 polyurethane foam and required the TPS team to employ best practices for process controls on the development article.

5.5-m-diameter CCTD in vertical orientation following completion of foam application.

Manual spray foam application to barrel section of the CCTD.

CCTD in-transit on TPS transporter—foam application is complete on domes and main barrel section.

Anticipated Benefits

Following cryoinsulation foam application, the CCTD was subjected to cryogenic testing at the MSFC test area. This testing demonstrated successful foam adhesion to a composite substrate and successful performance of S-180 foam when applied manually to a large-scale tank.

Potential Applications

Manual spray foam application processes demonstrated on the CCTD can be further developed to extend to other large-scale manual spray foam applications for composite or metal cryotanks for future potential applications including composite vessels, in-space storage tanks, and launch vehicle cryotanks.

Notable Accomplishments

The TPS team worked closely with the CCTD team to reduce total schedule and cost for the project by using TPS best practices and creatively rearranging the TPS processing order for the domes and barrel to reduce scaffolding setup times and fees. The TPS team provided solution options to the CCTD project team and appropriately documented concurrence and accepted risks to progress the CCTD through the TPS application process. This was the largest manual spray application performed to date for a cryogenic vessel and was the largest composite cryotank manufactured to date that required cryoinsulation foam.

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Performance Improvement of Friction Stir Welds by Better Surface Finish

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Sponsoring Program(s)

Human Exploration and Operations Mission Directorate
Space Launch System Advanced Development

Project Description

The as-welded friction stir weld has a cross section that may act as a stress concentrator. The geometry associated with the stress concentration may reduce the weld strength and it makes the weld challenging to inspect with ultrasound. In some cases, the geometry leads to false positive nondestructive evaluation (NDE) indications and, in many cases, it requires manual blending to facilitate the inspection. This study will measure the stress concentration effect and develop an improved phased array ultrasound testing (PAUT) technique for friction stir welding.

Post-welding, the friction stir weld (FSW) tool would be fitted with an end mill that would machine the weld smooth, trimmed shaved. This would eliminate the need for manual weld preparation for ultrasonic inspections. Manual surface preparation is a hand operation that varies widely depending on the person preparing the welds. Shaving is a process that can be automated and tightly controlled.

Notable Accomplishments

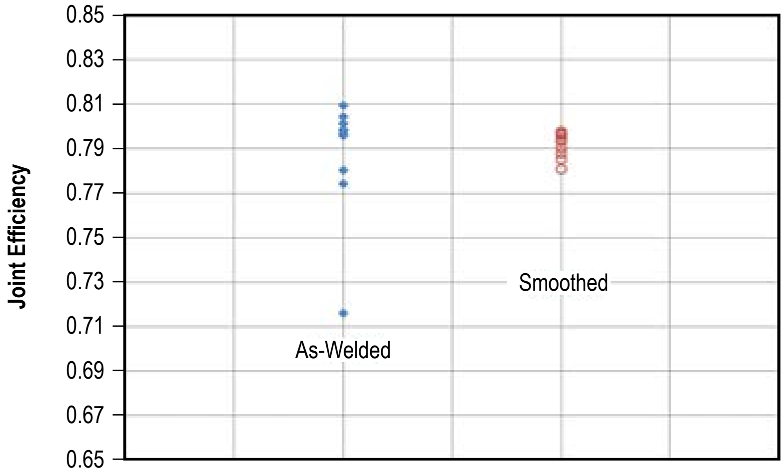
Two sets of panels will be welded with FSWs. One set will be prepared in the usual manner; the second set will be shaved by milling. These panels will be used to estimate the phased array testing detectability of defects in the surface. The defects will be electro-discharge machining (EDM) notches placed in and along the weld. Then samples will be cut from these panels and pulled in a tensile test machine to measure the strength of the shaved and unshaved panels.

The baseline self-reacting-friction stir weld (SR-FSW) panels include (a) eight baseline panels that have been welded and PAUT tested, (b) two baseline panels that have been machined into tensile specimens for room temperature, liquid nitrogen (LN_2), and liquid hydrogen (LH_2) testing; this work is complete, (c) five baseline panels that have been laid out for EDM notches; this work is complete, and (d) one EDM notched baseline panel that has been given to EM10 to measure the notches; however, they are having trouble measuring the notches. A few work-arounds are currently being assessed.

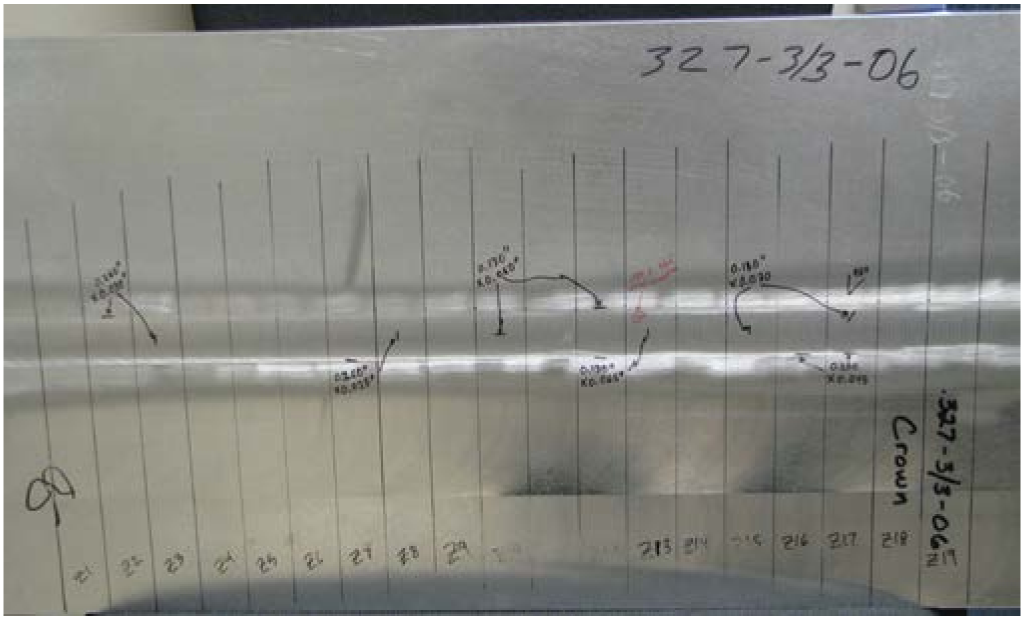
The SR-FSW panels with raised weld land (~0.025 inch) include (a) one panel with raised weld land, welded to determine the best method for machining the raised weld-land, (b) seven panels with raised weld land have been welded and PAUT inspected; these panels had a slight ridge that was not machined off and was hand sanded to remove the slight ridge, then reinspected with PAUT (five panels were identified for probability of detection inspections), (c) two panels with raised weld land have been machined into tensile specimens for room temperature, LN_2, and LH_2 testing; this work is complete, and (d) five panels with raised weld-land have been laid out for EDM notches; the work has been scheduled.

References

Crumbly, C.M.; Bickley, F.P; and Hueter, U.: “Space Launch System Spacecraft/Payloads Integration and Evolution Office Advanced Development FY 2014 Annual Report,” NASA/TM—2015–218201, NASA Marshall Space Flight Center, Huntsville, AL, January 2015.



Joint efficiency of welded panels at room temperature.



Welded panel.

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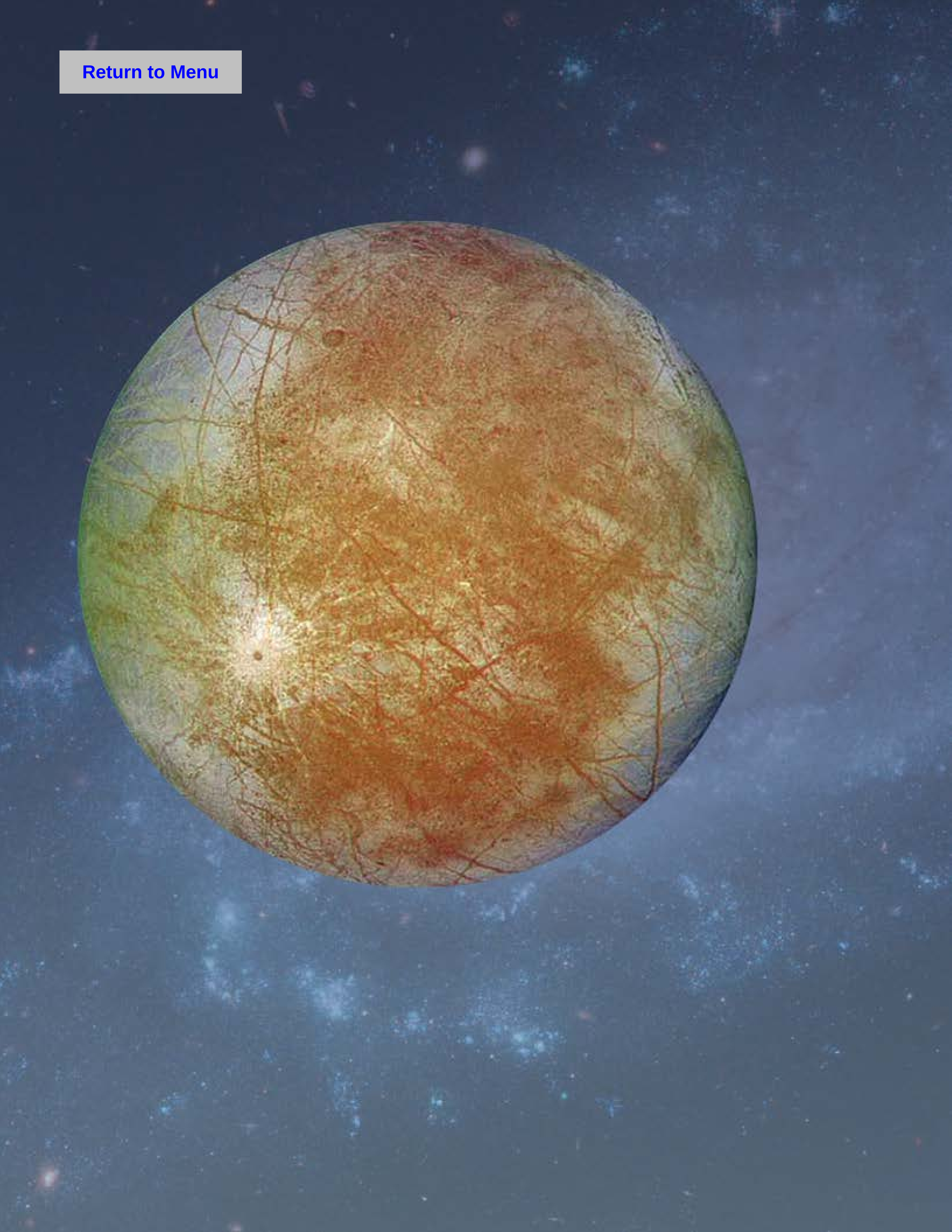

Science Mission Directorate (SMD)

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Advanced UVOIR Mirror Technology Development for Very Large Space Telescopes

Project Manager(s)/Lead(s)

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Sponsoring Program(s)

Science Mission Directorate
Cosmic Origins Program

Project Description

The Advanced Mirror Technology Development (AMTD) project is in phase 2 of a multiyear effort, initiated in FY 2012. This effort is to mature, by at least a half Technology Readiness Level step, the critical technologies required to enable 4 m or larger ultraviolet, optical, and infrared (UVOIR) space telescope primary mirror assemblies for both general astrophysics and ultra-high contrast observations of exoplanets. AMTD continues to achieve all of its goals and has accomplished all of its milestones to date. This has been achieved by assembling an outstanding team from academia, industry, and government with extensive expertise in astrophysics and exoplanet characterization, and in the design/manufacture of monolithic and segmented space telescopes; by deriving engineering specifications for advanced normal-incidence mirror systems needed to make the required science measurements; and by defining and prioritizing the most important technical problems to be solved. Our results have been presented to the CoPAG and Mirror Tech Days 2013, and proceedings papers of the 2013 and 2014 SPIE Optics & Photonics Symposia have been published.

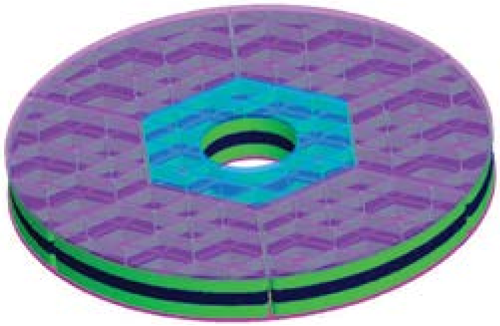
Key technology areas being pursued in phase 2 include large-aperture, low-areal density, high-stiffness mirror substrates; a support system; and integrated model validation.

Fine-scale actuator.

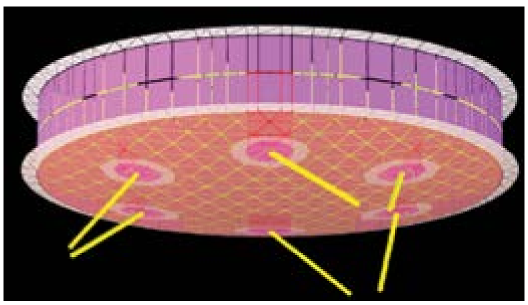
Actuator performance.

Property	Performance
Mass	0.313 kg
Axial Stiffness	40.9 N/μm
Test Range	14.1 μm
Resolution	6.6 nm (noise limited result; expected is 0.8 nm)
Accuracy	1.1 μm

MOR specimens in abrasive waterjet cutting.



Preliminary design for 1.5-m mirror.



Modeling tool with kinematic support mechanisms.

Anticipated Benefits

This project seeks to mature interlinked critical technologies such that 4 m or larger UVOIR mirrors could be produced by 2018 so that a viable mission can be considered by the 2020 Decadal Review. Because the future cannot be predicted, technologies that can enable either monolithic or segmented architectures are being pursued.

Potential Applications

This technology will be used in mirrors and its support structure for spacecraft and suborbital missions.

Notable Accomplishments

In FY 2013/2014, AMTD partner Exelis designed, built, and characterized the 'fine' stage of a low mass, two-stage actuator which could be used to co-phase mirror segments to the required tolerance. This effort is now complete and will not be continued in phase 2.

In FY 2013, Exelis tested the core-to-core low temperature fusion (LTF) bond strength using 12 modulus of rupture (MOR) test articles. Additional MOR testing was performed on 50 samples in FY 2014. The resulting Weibull 99% survival strength value was determined to be 50% above the most conservative design allowables used for margin of safety calculations at the core to plate LTF bond. The data on the 50 samples ranged from 60% to 250% above this design allowable.

The modeling tool is continually being developed in Visual Basic for ANSYS finite element modeling. This tool allows the rapid creation and analysis of detailed mirror designs. In FY 2013/2014 the ability to design a mirror support and integrate that support to the mirror substrate via kinematic and hexapod mechanisms was added. The result is a tool capable of rapidly designing complete mirror systems and transferring a high-resolution mesh to various mechanical and thermal analysis tools. Currently, exercising this tool by developing point designs for thermal and mechanical analysis is being done. For the duration of the effort, refining the tool and optimizing candidate point designs will be continued. Also in FY 2014, Exelis started designing a 1.5-m-diameter, 200-mm mirror to be fabricated via the deep core technology. The purpose of this mirror is to demonstrate lateral scalability of the process.

AMTD partner Goddard Space Flight Center continues to develop a suite of MATLAB® based tools for using structural-thermal-optical performance and jitter integrated models to calculate optical path length difference maps and line-of-sight errors. The AMTD project incorporated direct integration to transform the optical path difference to a point spread function (PSF) and between PSF to modulation transfer function.

References

Stahl, H.; Postman, M.; Mosier, G.; et al.: "AMTD: update of engineering specifications derived from science requirements for future UVOIR space telescopes," *Proc. SPIE*. 9143, doi: 10.1117/12.2054766, June 22–27, 2014.

Stahl, P.; Postman, M.; Abplanalp, L.; et al.: "Advanced mirror technology development (AMTD) project: 2.5 year status," SPIE Space Telescopes & Instrumentation Symposia, Montreal, Canada, June 22–27, 2014.

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Mars Ascent Vehicle—First Stage Motor

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Sponsoring Program(s)

Science Mission Directorate
Mars Exploration Program

Project Description

This project is development effort of a first stage solid motor based on a two-stage solid motor Mars Ascent Vehicle (MAV) design for the robotic Mars Sample Return (MSR) mission (fig. 1). The MSR MAV has been studied for decades and multiple concepts have been shown to meet the mission objectives as posed.[1] However, there remains significant uncertainty with the MAV requirements. The sample container and sample cache itself is immature. Additionally, MAV-specific requirements ranging from full three-axis controlled and strict communication requirements to minimal capability concepts are still under consideration. Given the maturity of the overall mission requirements, the MAV has been limited to a large number of parametric analyses and paper studies.

Recently, a Jet Propulsion Laboratory study highlighted the flexibility of a two-stage solid motor concept. The MAV itself is driven by the constraints of the Entry, Decent, and Landing (EDL) system. Within the EDL constraints, there is a range of MAV options ranging in complexity from simple spun upper stage options to higher capability three-axis controlled solutions. There are also options to trade the ratio of mission ΔV between the first and second stage. Finally, sensitivity studies also indicated that solid motors with a high percentage of off-load flexability only had minor impact on the total system mass over a single point design optimized motor. This flexibility in the first stage motor has allowed NASA to mature the design of the motor beyond parametric analyses and start to address known design challenges of the motor.

Figure 1: Two-stage solid motor MAV concept design.

The project included system design trades for case materials, grain design, nozzle options, actuators, etc. In addition to the ATK effort, the NASA Marshall Space Flight Center (MSFC) team also included igniter design support, igniter modeling plume analysis, thermal analysis, thermal-structural analysis, nozzle design, nozzle modeling, motor ballistics, combustion instability assessment, etc. A concept design for the first stage motor is shown in figure 2. Figure 3 illustrates some of the ignition gas dynamics.

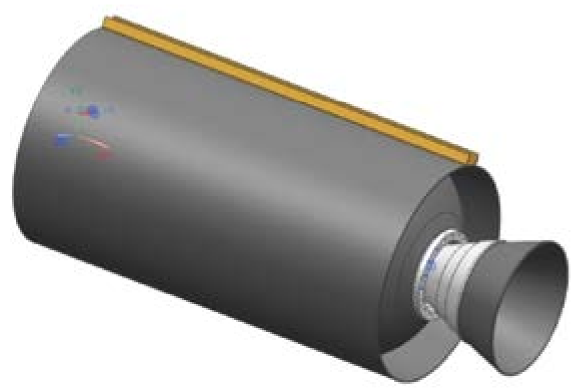

Figure 2: First stage solid motor concept design.

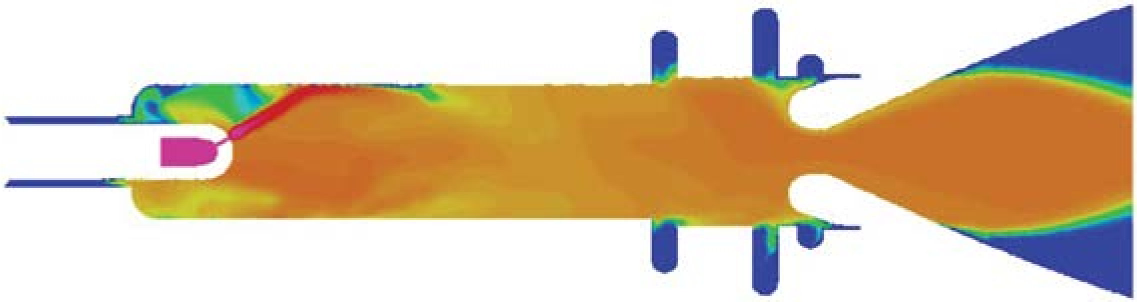

Figure 3: MSFC ignition gas dynamics modeling image.

Anticipated Benefits

The benefits of the first stage motor work included significant progress towards an engineering solution to the MAV propulsion. The MAV has been studied for decades and is listed in the Planetary Sciences Division Decadal Survey as one of the highest priority technology investments and has a high perceived risk.[2] This project is the highest fidelity design of a MAV propulsion system ever completed and provides the first preliminary analysis of a potential path forward. If successful, the MAV propulsion system development may evolve into an engineering development project rather than a higher risk technology development effort.

Potential Applications

The application for the first stage MAV motor is specific to the MSR MAV.

Notable Accomplishments

This project will complete three design and analysis cycles of preliminary design fidelity to identify a first stage solid motor solution that meets all requirements of the MAV. The project includes all thermal, mechanical, ballistics, etc. modeling of the integrated motor assembly and operation. The project also included both contractor and NASA independent validation of preliminary design and analyses. The project confirms a feasible approach to meet the objectives of the MAV first stage motor.

References

1. Dankanich, J.W.; and Klein, E.: “Mars Ascent Vehicle Development Status,” IEEE AC Paper No. 1471, 2012 IEEE Aerospace Conference, Big Sky, MT, March 3–10, 2012.

2. Squyres, S.; et al.: “Vision and Voyages for Planetary Science in the Decade 2013–2022,” NASA Research Council of the National Academies Final Report, 2011.

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Mars Ascent Vehicle—Propellant Aging

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Sponsoring Program(s)

Science Mission Directorate
In-Space Propulsion Technology Program, Mars Exploration Program

Project Description

This project is to develop and test a new propellant formulation specifically for the Mars Ascent Vehicle (MAV) for the robotic Mars Sample Return mission. The project was initiated under the Planetary Sciences Division In-Space Propulsion Technology (ISPT) program and is continuing under the Mars Exploration Program.

The two-stage, solid motor-based MAV has been the leading MAV solution for more than a decade. Additional studies show promise for alternative technologies including hybrid and bipropellant options, but the solid motor design has significant propellant density advantages well suited for physical constraints imposed while using the SkyCrane descent stage. The solid motor concept has lower specific impulse (I_{sp}) than alternatives, but if the first stage and payload remain sufficiently small, the two-stage solid MAV represents a potential low risk approach to meet the mission needs.

As the need date for the MAV slips, opportunities exist to advance technology with high on-ramp potential. The baseline propellant for the MAV is currently the carboxyl terminated polybutadiene (CTPB) based formulation TP-H-3062 due to its advantageous low temperature mechanical properties and flight heritage. However, the flight heritage is limited and outside the environments, the MAV must endure.

The ISPT program competed a propellant formulation project with industry and selected ATK to develop a new propellant formulation specifically for the MAV application. Working with ATK, a large number of propellant formulations were assessed to either increase performance of a CTPB propellant or improve the low temperature mechanical properties of a hydroxyl terminated polybutadiene (HTPB) propellant. Both propellants demonstrated potential to increase performance over heritage options, but an HTPB propellant formulation, TP-H-3544, was selected for production and testing. The test plan includes propellant aging first at high vacuum conditions, representative of the Mars transit, followed by an additional year at simulated Mars surface conditions. The actual Mars surface environment is based on the igloo design, actively maintains the propellant at or above –40 °C, 95% carbon dioxide at Mars surface pressure. The NASA Marshall Space Flight Center (MSFC) Mars environment test facility is shown in figure 1 and located in the East Test area of Redstone Arsenal due to storage of live propellants. The facility consists of a vacuum chamber placed inside a large freezer unit. The facility includes pressure and temperature monitoring equipment in addition to a vacuum quality monitoring system spectrometer to record any outgassing products.

The propellant aging test removed and shipped the first set of samples in the summer of 2014. The results showed <0.1% mass loss in all samples, a sign of vacuum compatibility. The initial mechanical property testing did not reach all of the project's stretch goals, but the mechanical properties of TP-H-3062 and TP-H-3544 are nearly identical while the new propellant has both higher I_{sp} and higher density. Currently, the new propellant is showing positive margins to all requirements and represents an increase in performance over the heritage system. Additionally, the new propellant formulation is the only propellant tested to the relevant environments with significant testing. Note: The project did include control samples at ATK and also one CTPB propellant block. The internal volume after the first samples were removed is shown in figure 2.

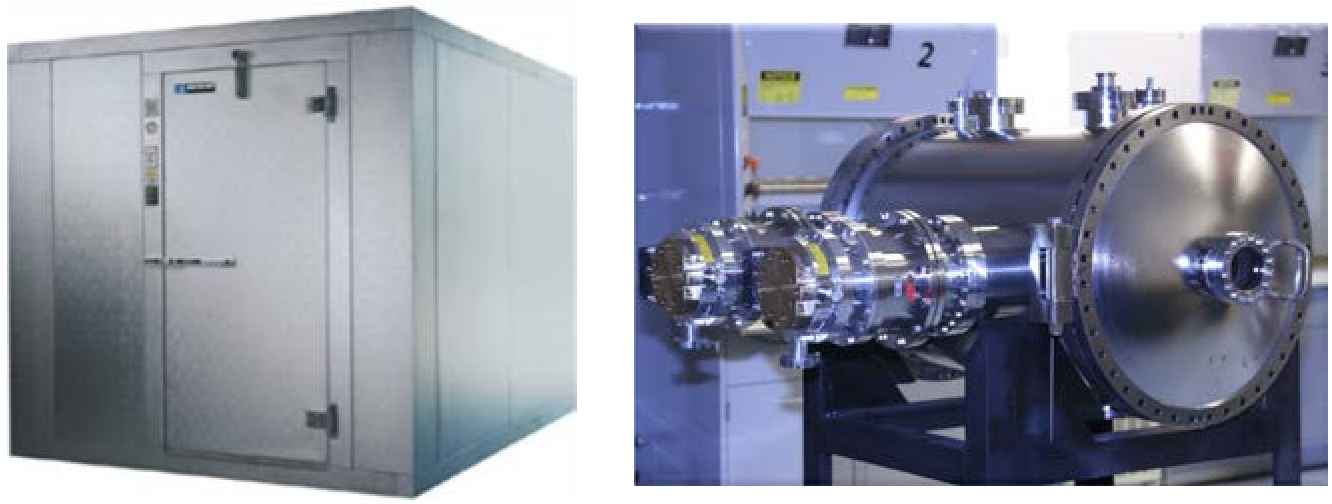

Figure 1: Propellant blocks in the MSFC Mars simulation facility.

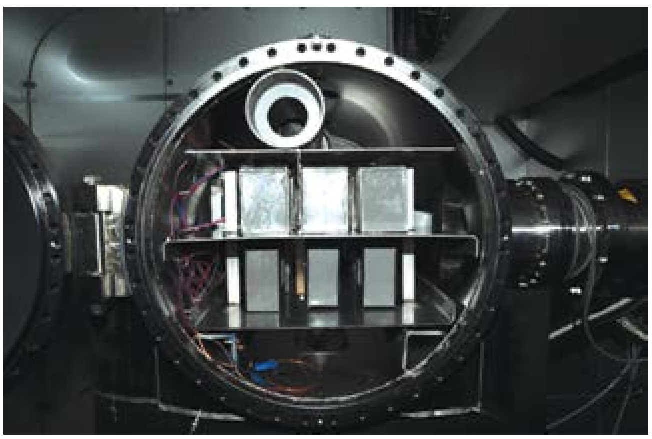

Figure 2: Internal view of the MAV propellant test facility.

Anticipated Benefits

The benefits of the new propellant formulation include high margins for mechanical performance of the propellant, increased I_{sp} over alternative heritage options, and an overall increase in total impulse of a volume-constrained MAV motor.

Potential Applications

The project's application goals are very focused for the robotic sample return MAV. However, a higher performance solid motor propellant with expanded operating environments is also of interest to non-NASA solid motor applications.

Notable Accomplishments

This project has completed a large number of propellant formulation trades and developed a database of propellant formulation options and characterized sensitivities for I_{sp}, burn rate, strain and maximum stress, etc. The project has also completed the first of three phases of propellant aging, validating vacuum compatibility of the new propellant formulation.

References

Dankanich, J.W.; and Klein, E.: "Mars Ascent Vehicle Development Status," IEEE AC Paper No. 1471, 2012 IEEE Aerospace Conference, Big Sky, MT, March 3–10, 2012.

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Space Technology Mission Directorate (STMD)

Space Technology Mission Directorate (STMD)

Technology Demonstration Missions (TDM)

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Technology Demonstration Missions

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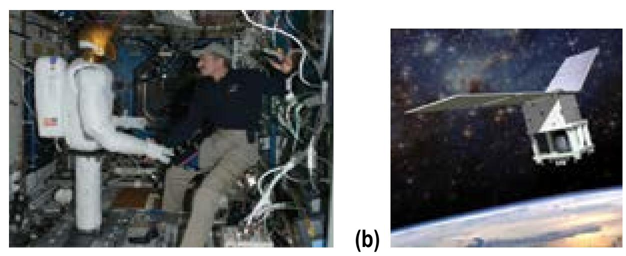
Sponsoring Program(s)

Space Technology Missions Directorate
Technology Demonstration Missions

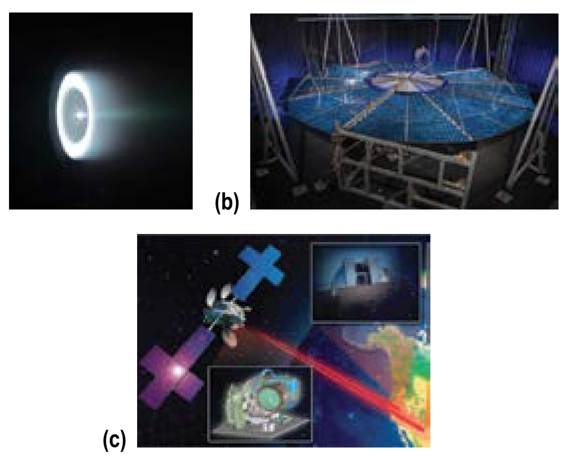
Project Description

Technology Demonstration Missions (TDM) is in its third year of execution, being initiated in 2010 and baselined in January of 2012. There are 11 projects that NASA Marshall Space Flight Center (MSFC) has contributed to or led:

(1) Evolvable Cryogenics (eCryo): Cyrogenic Propellant Storage and Transfer Engineering Development Unit (EDU), a proof of manufacturability effort, used to enhance knowledge and technology related to handling cryogenic propellants, specifically liquid hydrogen.
(2) Composites for Exploration Upper Stage (CEUS): Design, build, test, and address flight certification of a large composite shell suitable for the second stage of the Space Launch System (SLS).
(3) Deep Space Atomic Clock (DSAC): Spaceflight to demo small, low-mass atomic clock that can provide unprecedented stability for deep space navigation.
(4) Green Propellant Infusion Mission (GPIM): Demo of high-performance, green propellant propulsion system suitable for Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA)-class spacecraft.
(5) Human Exploration Telerobotics (HET): Demonstrating how telerobotics, remote control of a variety of robotic systems, can take routine, highly repetitive, dangerous or long-duration tasks out of human hands.
(6) Laser Communication Relay Demo (LCRD): Demo to advance optical communications technology toward infusion into deep space and near Earth operational systems, while growing the capabilities of industry sources.
(7) Low Density Supersonic Decelerator (LDSD): Demo new supersonic inflatable decelerator and parachute technologies to enable Mars landings of larger payloads with greater precision at a wider range of altitudes.
(8) Mars Science Laboratory (MSL) Entry Descent & Landing Instrumentation (MEDLI): Demo of embedded sensors embedded in the MSL heat shield, designed to record the heat and atmospheric pressure experienced during the spacecraft's high-speed, hot entry in the Martian atmosphere.
(9) Solar Electric Propulsion (SEP): 50-kW class spacecraft that uses flexible blanket solar arrays for power generation and an electric propulsion system that delivers payload from low-Earth orbit to higher orbits.
(10) Solar Sail Demonstration (SSD): Demo to validate sail deployment techniques for solar sails that are propelled by the pressure of sunlight.
(11) Terrestrial HIAD Orbit Reentry (THOR): Demo of a 3.7-m Hypersonic Inflatable Aerodynamic Decelerator (HIAD) entry vehicle to test second generation aerothermal performance and modeling.



Human Exploration Telerobotics (a) and Green Propellant Infusion Mission (b)



Solar Electric Propulsion (a) and (b) and Laser Communication Relay Decelerator Demo (c)

LDSD technologies and test capabilities.

Anticipated Benefits

TDM bridges the gap between advanced technologies and flight-qualified systems. Demonstrated technologies can be used in scheduled and future missions. Demonstrations give a wide range of data to be used to improve future technologies and define the ability of the hardware for future uses, making human spaceflight safer and flights more successful.

Potential Applications

TDM technologies can enable new missions or enhance existing ones.

Notable Accomplishments

2014 was an extremely successful year for TDM projects. There were 11 projects that had accomplishments involving MSFC:

(1) CEUS: A successful key design point-A (KDP-A) was completed for this project.

(2) DSAC: A successful KDP-C was completed. Repeatable manufacturing of the ion trap tube was demonstrated and multiple ion trap tubes in a closed loop configuration was operated successfully. Also, a completed Surrey Flight Services agreement was accomplished for this project.

(3) eCryo: A successful CPST KDP-B was completed as well as a successful eCryo KDP-A. The LOX Zero Boil-off test was successfully completed and a Zero Boil-off Industry Workshop was conducted. The project also completed testing of the EDU tank at MSFC.

(4) GPIM: This project had a very successful Critical Design Review. Testing of a 1 N engineering model thruster was completed which exceeded the 10,000 cycles for the L-1 requirement. Fabrication and integration of a 22 N engineering model thruster was completed and the integration of the BCP-100 spacecraft bus has started.

(5) HET: R2 climbing legs and torso upgrade parts for the International Space Station (ISS) were delivered, which launched April 2014. A new Smartphone was delivered to the ISS for integration into the Smart SPHERES, launched July 2014.

(6) LCRD: A successful Preliminary Design Review was conducted in 2014, with 95% of Flight Modem EEE parts ordered.

(7) LDSD: A Systems Integration Review was conducted. A successful supersonic test flight was conducted, and a parachute and supersonic inflatable aerodynamic decelerators development tests were conducted at China Lake.

(8) MEDLI: Turbulent flow duct arcjet testing was completed at NASA Ames Research Center and the draft of a NASA Technical Memorandum was delivered.

(9) SEP: Ambient and hot/cold thermal vacuum deployment testing of MegaFlex and ROSA (Roll Our Solar Array) solar arrays was completed. The fabrication and integration of a 12.5-kW class Hall Thruster and integration and test of a 300 V power processing unit was completed.

(10) SSD: Manual deployment of a full-size sail quadrant was completed for this project.

(11) THOR: This project was initiated in 2014 and TIG has conducted a review of proposed L1 requirements.

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Cryogenic Propellant Storage and Transfer Engineering Development Unit Hydrogen Tank

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Sponsoring Program(s)

Space Technology Mission Directorate
Technology Demonstration Missions

Project Description

The Cryogenic Propellant Storage and Transfer (CPST) project has been a long-running program in the Space Technology Mission Directorate to enhance the knowledge and technology related to handling cryogenic propellants, specifically liquid hydrogen. This particular effort, the CPST engineering development unit (EDU), was a proof of manufacturability effort in support of a flight article. The EDU was built to find and overcome issues related to manufacturability and collect data to anchor the thermal models for use on the flight design.

The EDU is a 1,000-gallon, flight-like, liquid hydrogen storage tank with built-in features, such as four tank fill level sensors, channel-based liquid acquisition devices (LADs), a thermodynamic vent system, and a comprehensive insulation/heat intercept system. (See fig. 1 for its 'as tested' configuration.) The tank body is comprised of 2219 thin-wall aluminum with about an inch of spray-on foam insulation (SOFI). The SOFI is only useful in atmospheric conditions and is in fact required in the presence of any gas other than helium in order to prevent damaging 'liquid air.' Over the SOFI is a 60-layer insulation blanket that is only effective in a vacuum to intercept heat in the form of radiation from entering the tank. The EDU was tested in a large vacuum chamber on site at NASA Marshall Space Flight Center, test stand 300 (fig. 2). The EDU was filled in a simulated launch environment (gaseous nitrogen) and then subjected to vacuum conditions to simulate launch

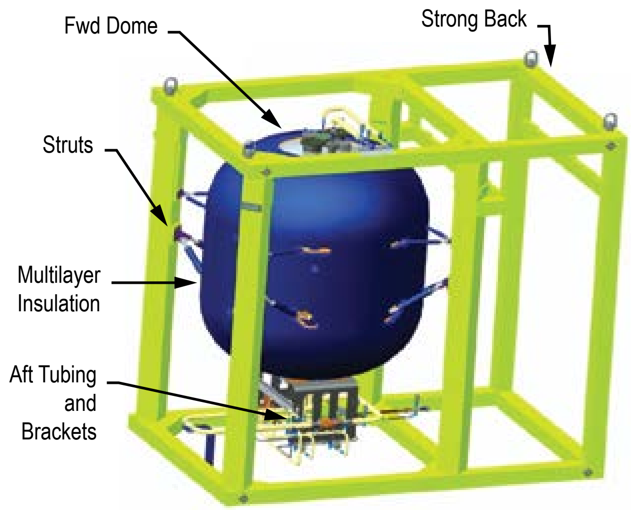

Figure 1: EDU tank.

Figure 2: Tank in vacuum chamber.

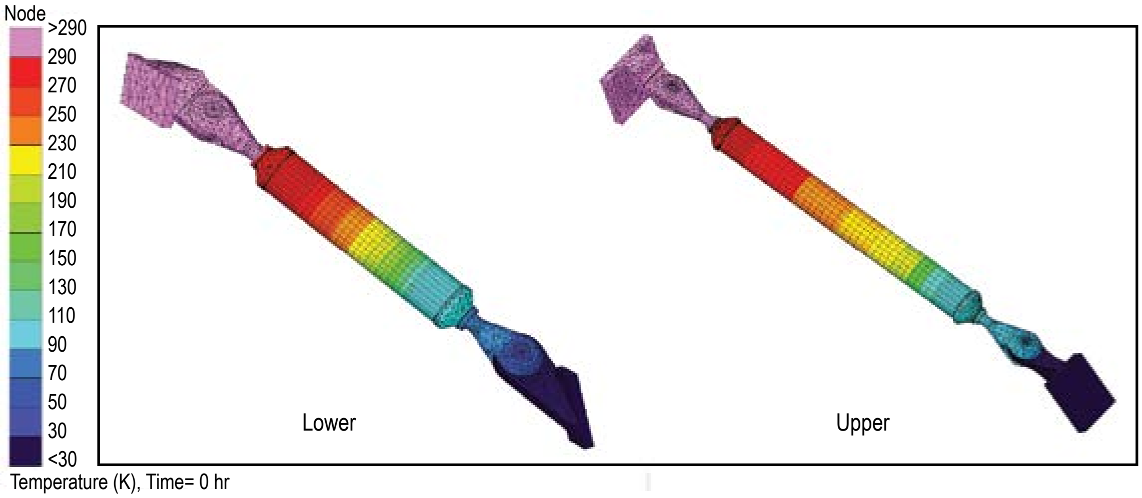

Figure 3: Thermal analysis of tank struts.

and space flight. The testing was conducted in June 2014 and was successful.

The testing was a 20-day test to determine the boil-off rate for the system at the launch pad conditions and the on-orbit conditions. The testing also was to gather data on the pressurization system for the EDU. There were two ways to pressurize the tank, one diffuser at the top (in the ullage or dry conditions) and a submerged diffuser in the bottom of the tank. Several pressure tests were conducted at different pressure levels and fill levels. (See fig. 3 for thermal analysis of tank struts.)

One other technology that was tested was the LADs. The LADs are a way to collect fuel without collecting gases. Since LADs work better in low gravity conditions, the only method to test them is to see how long they can support a column of liquid. We were able to support a column of liquid for 61 minutes during the testing. There was an ice blockage that prevented full testing of the thermodynamic vent system, but all other systems performed well. There is more testing planned for FY 2016 using the EDU and test stand 300.

Anticipated Benefits

A body of data now exists to refine thermal models with a flight-like tank and data set. EDU has also provided a better understanding of the physics of submerged pressurization.

Potential Applications

Potential applications include improved manufacturing techniques for propellant tanks and improved thermal modeling of cryogenic systems.

Notable Accomplishments

Notable accomplishments include the creation of manufacturing techniques to construct LADs, support struts, and shaping SOFI; supported a column of liquid in a LAD for 61 minutes; and proved that the radio frequency measuring gauge was accurate to within 1.5% of all other methods.

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Space Technology Mission Directorate (STMD)

Centennial Challenges Program (CCP)

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Centennial Challenges Program

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Sponsoring Program(s)

Centennial Challenges Program
Space Technology Mission Directorate

Project Description

NASA's Centennial Challenges Program was initiated in 2005 to directly engage the public in the process of advanced technology development. The program offers incentive prizes to generate revolutionary solutions to problems of interest to NASA and the nation. The program seeks innovations from diverse and nontraditional sources. Competitors are not supported by government funding and awards are only made to successful teams when the challenges are met.

In keeping with the spirit of the Wright Brothers and other American innovators, the Centennial Challenge prizes are offered to independent inventors including small businesses, student groups, and individuals. These independent inventors are sought to generate innovative solutions for technical problems of interest to NASA and the nation and to provide them with the opportunity to stimulate or create new business ventures.

The core of Centennial Challenges: opportunity, innovation, and communication.

The West Virginia University Mountaineers took home a Level 1 prize for $5,000 at the 2014 Sample Return Robot Challenge. They and one other team have also earned the right to attempt Level 2 at the 2015 event, with a potential prize purse of $1.5 million.

The Cube Quest Challenge offers up to a $5 million prize purse for communication with a CubeSat near or beyond the Moon.

Anticipated Benefits

Centennial Challenges advance technologies that are currently technology barriers for NASA to achieve its future goals. Challenges conducted address current topics on NASA's technology roadmap that are also beneficial to other technology sectors here on Earth.

Competing teams have a unique opportunity to leverage their ideas whether they win prize money or not. Through the visibility of the challenges, all participants gain the opportunity to be seen by and network with other industries who may be searching for similar solutions, as well as to interact with each other, media outlets, and with the public at outreach events.

Potential Applications

Much of the technology developed through these competitions has been adopted by the agency, academia, and/or the commercial sector and infused into their respective industries for use and continued advancement. It is the hope and goal of the program that solutions discovered via challenges will continue to grow and benefit others in areas outside of each challenge.

Notable Accomplishments

In 2014, the program completed the third running of the Sample Return Robot Challenge, an autonomous rover competition held at Worcester Polytechnic Institute in Worcester, MA. Seventeen teams competed in the two-level challenge for a $1.5 million prize purse. The West Virginia University Mountaineers completed Level 1, winning $5,000 and the opportunity to attempt Level 2 for the remaining prize money in 2015. The challenge will be competed again in June 2015.

Also this year, two new challenges were announced and opened for registration. The Mars Ascent Vehicle (MAV) Challenge <www.nasa.gov/mavprize> is helping to advance the technology to return samples from a planetary surface. The challenge focuses on getting the samples from the surface to orbit for collection and return to Earth. The MAV Challenge requires highly reliable and autonomous sample insertion into the rocket, launch from the surface, and deployment of the sample container. Innovative technology from this competition may be considered in future planning for a planetary exploration mission. Centennial Challenges is partnering with the NASA Student Launch to conduct this challenge in parallel with the Student Launch competition.

Also, the new Cube Quest Challenge <www.nasa.gov/cubequest> opened for registration in November. Cube Quest offers a total of $5 million to teams that meet the challenge objectives of designing, building, and delivering flight-qualified, small satellites capable of advanced operations near and beyond the Moon.

Cube Quest teams will have the opportunity to compete for a secondary payload spot on the first integrated mission of NASA's Orion spacecraft, and the Agency's Space Launch System (SLS) rocket.

The competition includes three stages: Ground Tournaments, Deep Space Derby, and Lunar Derby. All teams may compete in any one of the four Ground Tournaments. Teams that rate high on mission safety and probability of success will receive incremental awards. The Ground Tournaments will be held every 4 to 6 months, leading to an opportunity to earn a spot on the first integrated flight of Orion and SLS.

References

Visit <www.nasa.gov/winit> for more information on the program, upcoming and past challenges.

Space Technology Mission Directorate (STMD)

Game Changing Development (GCD)

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Bosch Reactor Development for High Percentage Oxygen Recovery From Carbon Dioxide

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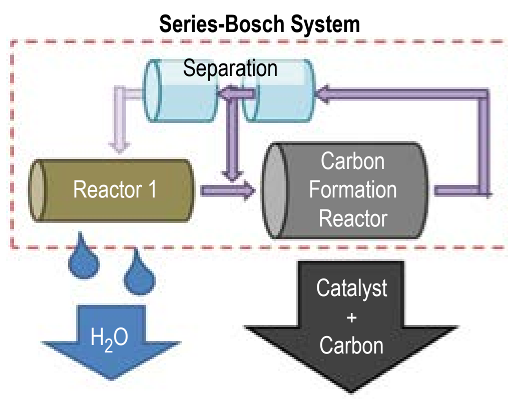
Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development

Project Description

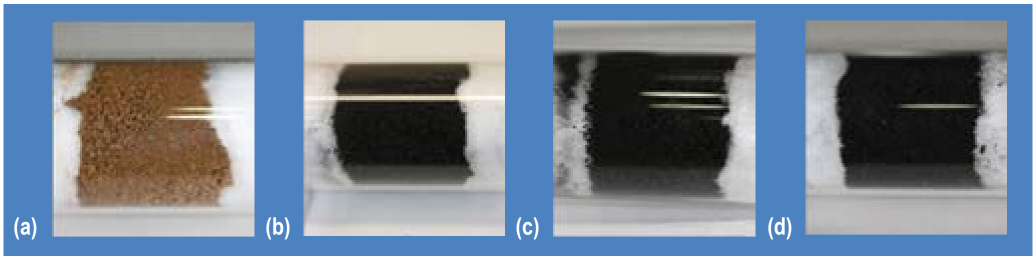
This next Generation Life Support Project entails the development and demonstration of Bosch reaction technologies to improve oxygen recovery from metabolically generated oxygen and/or space environments. A primary focus was placed on alternate carbon formation reactor concepts to improve useful catalyst life for space vehicle applications, and make use of in situ catalyst resources for nonterrestrial surface missions. Current state-of-the-art oxygen recovery systems onboard the International Space Station are able to effectively recover approximately 45% of the oxygen consumed by humans and exhausted in the form of carbon dioxide (CO_2). Excess CO_2 is vented overboard and the oxygen contained in the molecules is lost.

For long-duration missions beyond the reaches of Earth for resupply, it will be necessary to recover greater amounts of constituents such as oxygen that are necessary for sustaining life. Bosch technologies theoretically recover 100% of the oxygen from CO_2, producing pure carbon as the sole waste product. Challenges with this technology revolve around the carbon product fouling catalyst materials, drastically limiting catalyst life. This project successfully demonstrated techniques to extend catalyst surface area exposure times to improve catalyst life for vehicle applications, and demonstrated the use of martian and lunar regolith as viable catalyst materials for surface missions. The Bosch process generates carbon nanotube formation within the regolith, which has been shown to improve mechanical properties of building materials. Production of bricks from post reaction regolith for building and radiation shielding applications were also explored.



Series Bosch reaction, reacts hydrogen with CO_2 to produce recover oxygen by producing water.

Lunar regolith sintered brick.



Carbon formed on martian regolith used as catalyst in Bosch reaction: After (a) zero hours, (b) 1 hour, (c) 4 hours, and (d) 16 hours.

Anticipated Benefits

The Bosch reactor is capable of recovering 100% of the oxygen from metabolically generated CO_2. This has the potential to significantly close the loop of regenerable life support system architecture, reducing the reliance on consumables that must otherwise be transported on long-duration human missions beyond the reach of Earth for resupply. Additionally, the use of regolith materials as Bosch catalysts on surfaces such as Mars offers the potential for unlimited oxygen supply to maintain life and support other oxygen-consuming systems.

Potential Applications

A potential application may be long-duration human space missions including both vehicle and surface habitats.

Notable Accomplishments

Notable accomplishments include demonstrating the ability to extend the length of traditional catalyst materials by separating Bosch into two distinct reactions, thereby minimizing the amount of catalyst exposed to carbon formation; demonstrating techniques to significantly improve the life of traditional metal catalyst materials by tumbling and/or systematically adding catalyst in a continuous reaction process; and successfully demonstrating the use of both martian and lunar regolith as catalyst materials for in situ resource utilization.

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Soldier-Warfighter Operationally Responsive Deployer for Space

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Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development
Human Exploration and Operations Mission Directorate
Advanced Exploration Systems

Project Description

The Soldier-Warfighter Operationally Responsive Deployer for Space (SWORDS) project was a joint project between the U.S. Army Space & Missile Defense Command (SMDC) and NASA. The effort, lead by SMDC, was intended to develop a three-stage liquid bipropellant (liquid oxygen/liquid methane), pressure-fed launch vehicle capable of inserting a payload of at least 25 kg to a 750-km circular orbit. The vehicle design was driven by low cost instead of high performance. SWORDS leveraged commercial industry standards to utilize standard hardware and technologies over customized unique aerospace designs. SWORDS identified broadly based global industries that have achieved adequate levels of quality control and reliability in their products and then designed around their expertise and business motivations.

The SMDC effort was primarily funded from the Joint Capability Technology Development Program from the Office of the Secretary of Defense.

NASA provided primarily full-time-equivalent support for various design analysis. These analyses were in areas of aerodynamic modeling and database development, stage and fairing separation analyses, nozzle designs via computational fluid dynamics (CFD), vehicle performance independent assessment, buffet estimates, loads and dynamics analyses, aerothermal analyses, venting and purge analysis, liftoff and ascent aeroacoustics, mass properties, and ground systems and operations development. NASA also provided testing support in the form of wind tunnel test and engine testing at NASA Marshall Space Flight Center.

Model of SWORDS vehicle and assorted ground support equipment.

SWORDS engine testing at 75% power level.

Anticipated Benefits

A dedicated nanosatellite launcher can extend the miniature electronics revolution into space by enabling customers to have a launch-on-demand capability. SWORDS was intended to place nanosatellites into precise low-Earth orbits to provide capabilities both where and when they are needed. Nanosatellites will no longer have to wait months or years for piggyback rides subject to the schedule and orbital locations of other payloads. SWORDS would allow the affordable maintenance of constellations of nanosatellites in low-Earth orbit to provide communications and other services at an unprecedented low level of mission command, regardless of where customers are located.

Potential Applications

For NASA funded missions, SWORDS could provide a low cost, responsive launch capability for small satellites, for example CubeSats, for many of NASA's ongoing scientific missions.

For other government agencies, e.g., the U.S. Army, SWORDS could provide a low cost, responsive launch capability for small satellites to support the soldier in the field, and there are many other uses for other government agencies to place small, low cost satellites into orbit.

Notable Accomplishments

The SWORDS project successfully advanced several technologies needed to support a possible low cost launch vehicle, as follows: (1) The design of a multi-lobed/open-interstage vehicle has lead to increased knowledge of flow characteristics using wind tunnel and CFD analysis, (2) The advancement of engine modeling and improved test capability resulted in the successful testing of a 60,000-lbf class liquid oxygen (LOX)/methane engine. This is currently the most powerful LOX/methane engine to have been tested in the world, (3) Analysis of four-engine impingement effects for thrust differential controllability, acoustics, and plume interaction has lead to a better understanding of effects of using engine throttling for vehicle control, (4) Design and testing of a unique engine cross-section (ob-round) and asymmetric nozzle increased understanding of the efficiency losses of this type of engine design, (5) Use of low-cost commercial technology for launch vehicle avionics showed the viability of use for launch vehicle applications, and (6) The launch concept of operations developed for a 'universal' small launch system that can be used not only for a SWORDS type vehicle but also for any other small launch vehicle developed in the future.

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Fast Light Optical Gyroscopes

Project Manager(s)/Lead(s)

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Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development

Project Description

Next-generation space missions are currently constrained by existing spacecraft navigation systems which are not fully autonomous. These systems suffer from accumulated dead-reckoning errors and must therefore rely on periodic corrections provided by supplementary technologies that depend on line-of-sight signals from Earth, satellites, or other celestial bodies for absolute attitude and position determination, which can be spoofed, incorrectly identified, occluded, obscured, attenuated, or insufficiently available. These dead-reckoning errors originate in the ring laser gyros themselves, which constitute inertial measurement units.

Increasing the time for standalone spacecraft navigation therefore requires fundamental improvements in gyroscope technologies. One promising solution to enhance gyro sensitivity is to place an anomalous dispersion or fast light material inside the gyro cavity. The fast light essentially provides a positive feedback to the gyro response, resulting in a larger measured beat frequency for a given rotation rate as shown in figure 1. Game Changing Development has been investing in this idea through the Fast Light Optical Gyros (FLOG) project, a collaborative effort which began in FY 2013 between NASA Marshall Space Flight Center (MSFC), the U.S. Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC), and Northwestern University. MSFC and AMRDEC are working on the development of a passive FLOG (PFLOG), while Northwestern is developing an active FLOG (AFLOG). The project has demonstrated new benchmarks in the state of the art for scale factor sensitivity enhancement. Recent results show cavity scale factor enhancements of ~100 for passive cavities.

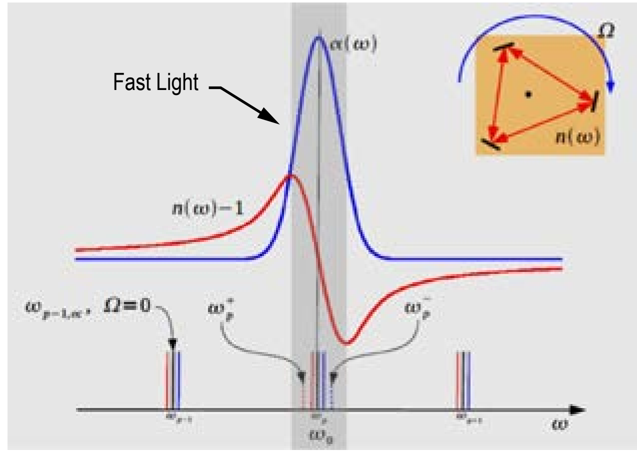

Figure 1: Illustration of how the response of a gyroscope is enhanced by fast light. The cavity modes are split by the rotation of the gyro. In the fast light region, the refractive index $n(\omega)$ decreases with frequency, which pushes on the modes and further increases the splitting.

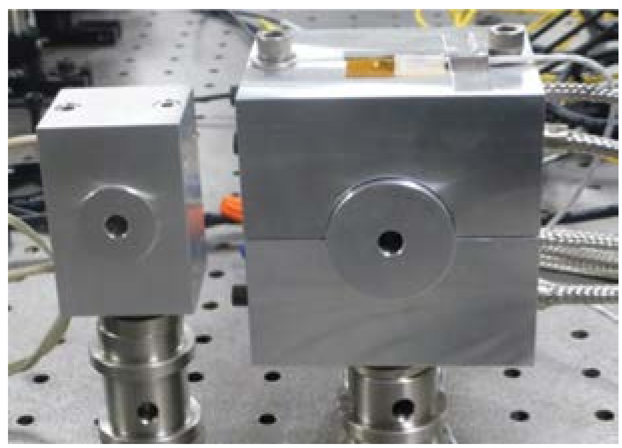

Figure 2: Temperature-stabilized atomic-vapor oven for tuning the PFLOG sensitivity: left—miniaturized version 2.0 and right—version 1.0.

Anticipated Benefits

FLOG addresses a critical need for navigation technologies that can meet the complexities of next-generation space missions, which will involve a diverse set of navigational challenges that cannot be supported with current methods. The development of onboard autonomous navigation technologies is critical to meeting these challenges, which range from cooperative flight to rendezvous with asteroids and other small bodies. FLOG is an entirely onboard technology that does not rely on the reception of signals external to the spacecraft, extending the time for standalone navigation and reducing the need for updates from startrackers.

Potential Applications

In addition to the benefits for navigation, the improvements in gyro sensitivity open up new science possibilities such as ground-based measurements of the general relativity Lense-Thirring frame dragging effect, tabletop gravitational wave detection, and enhancement of the sensitivity-bandwidth product for interferometric gravitational wave detectors under development by the Laser Interferometric Gravitational-wave Observatory project. The increase in sensitivity can also be traded off against system size which could benefit other applications that place a premium on compactness such as pointing and tracking, high bandwidth satellite and interplanetary laser communications, vehicle motion compensation for synthetic aperture radar, automatic rendezvous and docking systems, and rover/lander localization in non-GPS environments.

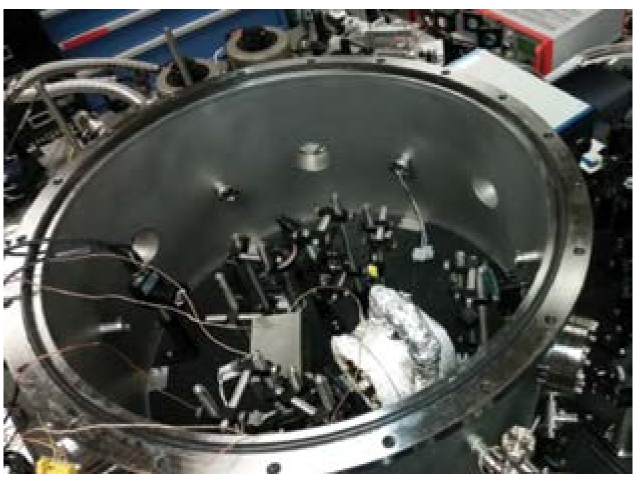

Figure 3: AFLOG custom vacuum enclosure containing shared-cavity, dead-band-free DPAL gyroscope.

Notable Accomplishments

PFLOG accomplishments for FY 2014 include the following: (1) Invented improved method for measuring cavity scale factor which substantially reduces the effect of cavity noise without the need for a hardened cavity, (2) Miniaturized and tested a compact, rugged, inexpensive, and frequency-stable laser source leveraged from the Army as low noise input to PFLOG, (3) Constructed a temperature-controlled atomic vapor oven (fig. 2) to tune to an optimal fast light condition (first demonstration of temperature tuning to control the sensitivity of an optical cavity, first demonstrated scale factor enhancement in a ring cavity using atoms, and largest cavity scale factor enhancement measured in any system), (4) Demonstrated narrow atomic resonances in high finesse cavity output by velocity selective optical pumping, (5) Achieved first scale factor enhancement in high finesse cavity by polarization mode coupling, and (6) Developed an error model to determine the effect of temperature/mechanical fluctuations on a gyro sensitivity enhancement.

AFLOG accomplishments for FY 2014 include the following: (1) Eliminated beat-note noise in a previously constructed dead-band-free, shared-cavity, diode-pumped alkali laser (DPAL) ring laser gyro by placing it in a custom vacuum enclosure (fig. 3), (2) Constructed and demonstrated the operation of a dual-pumped Raman ring laser as an alternative AFLOG design that could be easier to miniaturize, and consume less power, (3) Invented and implemented a method for stabilizing the Raman probe laser of the superluminal DPAL to an absolute frequency by locking it to a serendipitous resonance in Rb87 to make the AFLOG function in a more robust manner, (4) Invented a design for overlapping bidirectional self-biased AFLOG with no gain competition or lock-in, by using dual isotope cells with different Raman pumps, (5) Significant progress on miniaturization was made: building custom compact diode laser controllers, and compact offset phase locked laser boxes to replace all AOMs and tapered amplifiers. A single high-power DBR laser for pumping to replace bulky pump lasers is being implemented.

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Adjustable Grazing-Incidence X-ray Optics

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Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development

Project Description

With its unique subarcsecond imaging performance, NASA's Chandra X-ray Observatory[1] illustrates the importance of fine angular resolution for x-ray astronomy. Indeed, the future of x-ray astronomy relies upon x-ray telescopes with comparable angular resolution but larger aperture areas. Combined with the special requirements of nested grazing-incidence optics, mass, and envelope constraints of space-borne telescopes render such advances technologically and programmatically challenging.[2]

The goal of this technology research is to enable the cost-effective fabrication of large-area, lightweight grazing-incidence x-ray optics with subarcsecond resolution. Toward this end, the project is developing active x-ray optics[3,4] using slumped-glass mirrors with thin-film piezoelectric arrays (fig. 1) for correction of intrinsic or mount-induced distortions (fig. 2).[5]

Partnering institutions for this project are the Smithsonian Astrophysical Observatory (SAO), the Pennsylvania State University (PSU), and NASA Marshall Space Flight Center (MSFC). SAO is responsible for overall direction, mirror substrates, metrology,[6] and analyses; PSU, for development of thin-film piezoelectric arrays;[7–9] and MSFC, for coating studies, additional metrology, and x-ray testing (fig. 3).

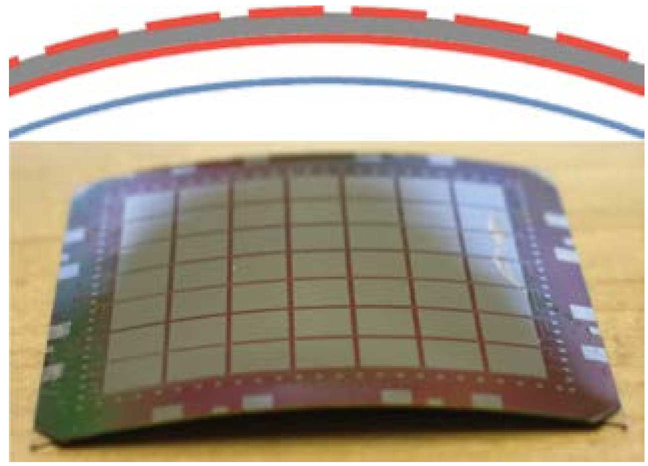

Figure 1: Grazing-incidence conical mirror segment with a backside piezoelectric array for active figure correction through voltage-controlled bimorph deformation. The drawing (top) shows—in cross section from inner concave surface outward—a thin-film optical coating (blue), the slumped-glass substrate (clear), a thin-film ground electrode (red), a thin-film piezoelectric layer (gray), and a thin-film pixilated electrode (red). The photo (bottom) displays a fabricated active mirror segment, with a 7×7 array of 1 cm square electrodes.

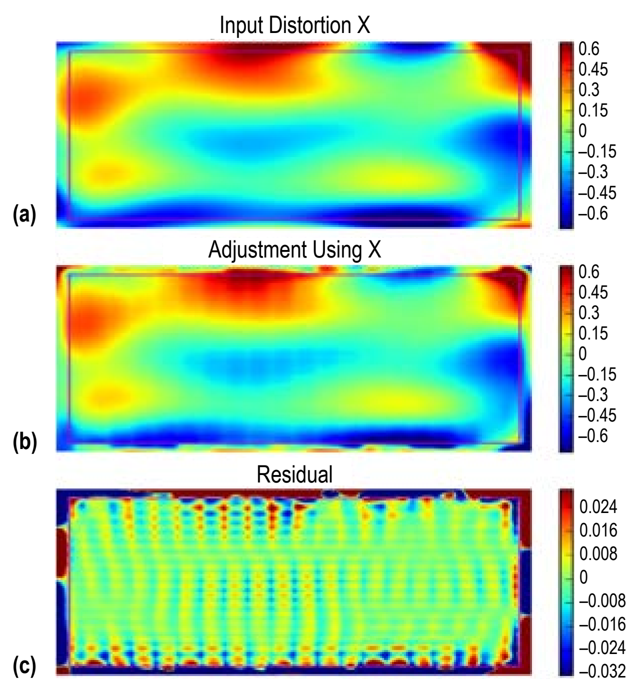

Figure 2: Simulated figure error maps for a segmented mirror, showing (a) initial error with respect to the prescribed mirror figure, (b) applied corrective adjustment, and (c) residual figure error after applied correction.

Figure 3: MSFC capabilities supporting the development of adjustable grazing-incidence optics: (a) Coating chamber, used for developing controlled-stress sputtered deposits; (b) a vertical long-trace profilometer, one of multiple metrology instruments for charcterizing x-ray mirror surfaces; and (c) the 3-m-diameter (vacuum) instrument chamber at MSFC's 100-m-long X-ray Test Facility.

Anticipated Benefits

The primary anticipated benefit is the active correction of grazing-incidence x-ray optics for space applications. This technology is equally applicable to normal-incidence optics, although existing adaptive-optics technologies are adequate in situations where mass or envelope is not an issue.

Potential Applications

The potential applications of active x-ray optics are large-area, lightweight x-ray telescopes and beam-focusing x-ray mirrors for synchrotron light sources and for x-ray free-electron lasers, although alternative technologies are suitable for ground-based applications. In addition, there are potential spinoff applications for underlying thin-film technologies being developed to enable adjustable lightweight mirrors.

Notable Accomplishments

PSU has made significant progress in developing thin-film pixilated piezoelectric devices—over 90% yield[9] in active pixels, on-device thin-film transistors[7] (for row-column addressing) and strain gauges (to monitor deformations), and use of anisotropic conductive films[7] (to simplify electrical connections). MSFC has developed an in situ stress monitor to help accurately control coating stress during deposition.

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Altitude Compensating Nozzle

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Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development

Project Description

The dual-bell nozzle (fig. 1) is an altitude-compensating nozzle that has an inner contour consisting of two overlapped bells. At low altitudes, the dual-bell nozzle operates in mode 1, only utilizing the smaller, first bell of the nozzle. In mode 1, the nozzle flow separates from the wall at the inflection point between the two bell contours. As the vehicle reaches higher altitudes, the dual-bell nozzle flow transitions to mode 2, to flow full into the second, larger bell. This dual-mode operation allows near optimal expansion at two altitudes, enabling a higher mission average specific impulse (I_{sp}) relative to that of a conventional, single-bell nozzle. Dual-bell nozzles have been studied analytically and subscale nozzle tests have been completed.[1] This higher mission averaged I_{sp} can provide up to a 5% increase[2] in payload to orbit for existing launch vehicles. The next important step for the dual-bell nozzle is to confirm its potential in a relevant flight environment. Toward this end, NASA Marshall Space Flight Center (MSFC) and Armstrong Flight Research Center (AFRC) have been working to develop a subscale, hot-fire, dual-bell nozzle test article for flight testing on AFRC's F15-D flight test bed (figs. 2 and 3). Flight test data demonstrating a dual-bell ability to control the mode transition and result in a sufficient increase in a rocket's mission averaged I_{sp} should help convince the launch service providers that the dual-bell nozzle would provide a return on the required investment to bring a dual-bell into flight operation. The Game Changing Department provided 0.2 FTE to ER42 for this effort in 2014.

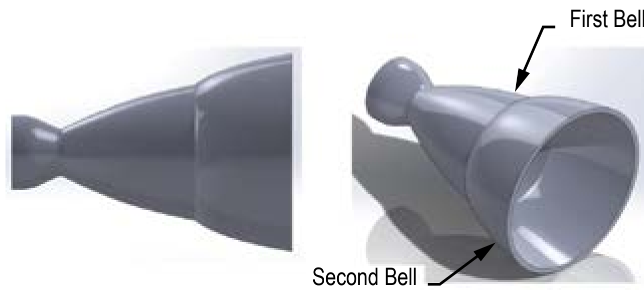

Figure 1: Front and isometric view of a dual-bell nozzle.

Figure 2: F-15 with the PFTF.

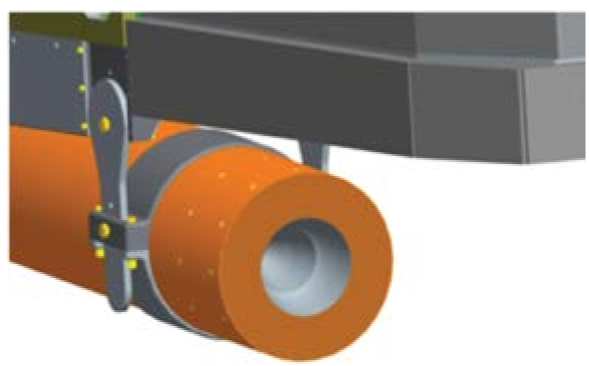

Figure 3: Aft end view of the PFTF with dual-bell installed.

Anticipated Benefits

The benefit of the larger dual-bell, multiyear task will be a dual-bell nozzle design that is capable of being controlled to the degree that launch vehicle systems require. Launch vehicle guidance, navigation, and control (GN&C) requires exacting and direct control over the thrust performance of rocket engines. Dual-bell nozzles in their simplest form, just the two bell contours, would likely not produce sufficiently predictable thrust versus altitude because the transition from mode 1 to mode 2 will be affected by the variation of vehicle base pressure, among other things. This multiyear task will develop methods to enable explicit control over the mode transition, thereby providing the launch vehicle GN&C the necessary control over the rocket engine's delivered thrust.

Potential Applications

A dual-bell nozzle, in theory, would provide benefit for rocket-powered vehicles, such as launch vehicles, that experience large changes in ambient pressure. In addition, dual-bell nozzles can be used for weapons systems that have high thrust requirements for launch, requiring high main chamber pressure, but then need efficient propulsion at much lower chamber pressures while loitering.

Notable Accomplishments

With the 0.2 FTE provided by the Game Changing Project, Mr. Ruf was able to continue working with his AFRC counterparts to size the dual-bell nozzle flight test article and develop an approach to create the large changes in nozzle pressure ratios. A short summary of the 2014 work completed is provided here. A fuller description of the 2014 work can be found in an AIAA paper[3] and a companion NASA TM.[4] First, a representative Space Transportation System trajectory was used to explain how a dual-bell could be integrated into a launch vehicle system and where the I_{sp} benefits were gained. The expected methods for controlling the mode transition during ascent were explained. The first flight test article's (a cold flow test article) throat diameter was sized via a trades study on mass flow rates, thrust derived, and test run time. The objective was to size the test article to enable testing at both the MSFC Nozzle Test Facility (NTF) and on the F-15D flying test bed. The nozzle area ratio of the two bell nozzles were sized to fit within the NTF's altitude simulation capability and the flight envelope of the F-15D while still retaining traceability to a full-scale, dual-bell nozzle. A testing protocol for the test article's chamber pressure was then developed to simulate the changes in the nozzle pressure ratio of a launch vehicle trajectory in the 4 to 6 s of test time available on the F-15D flights. These forced nozzle pressure ratio changes on the flight test will be required to show that the dual-bell nozzle transitions can be controlled during a launch vehicle accent.

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Multi-spacecraft Autonomous Positioning System

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Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development

Project Description

As the number of spacecraft in simultaneous operation continues to grow, there is an increased dependency on ground-based navigation support. The current baseline system for deep space navigation utilizes Earth-based radiometric tracking, requiring long-duration observations to perform orbit determination and generate a state update. The age, complexity, and high utilization of the ground assets pose a risk to spacecraft navigation performance. In order to perform complex operations at large distances from Earth, such as extraterrestrial landing and proximity operations, autonomous systems are required. With increasingly complex mission operations, the need for frequent and Earth-independent navigation capabilities is further reinforced.

The Multi-spacecraft Autonomous Positioning System (MAPS) takes advantage of the growing inter-spacecraft communication network and infrastructure to allow for Earth-autonomous state measurements to enable network-based space navigation. A notional concept of operations is given in figure 1. This network is already being implemented and routinely used in Martian communications through the use of the Mars Reconnaissance Orbiter and Mars Odyssey spacecraft as relays for surface assets. The growth of this communications architecture is continued through MAVEN, and future potential commercial Mars telecom orbiters. This growing network provides an initial Mars-local capability for inter-spacecraft communication and navigation. These navigation updates are enabled by cross-communication between assets in the network, coupled with onboard navigation estimation routines to integrate packet travel time to generate ranging measurements. Inter-spacecraft communication allows for frequent state broadcasts and time updates from trusted references. The architecture is a software-based solution, enabling its implementation on a wide variety of current assets, with the operational constraints and measurement accuracy determined by onboard systems.

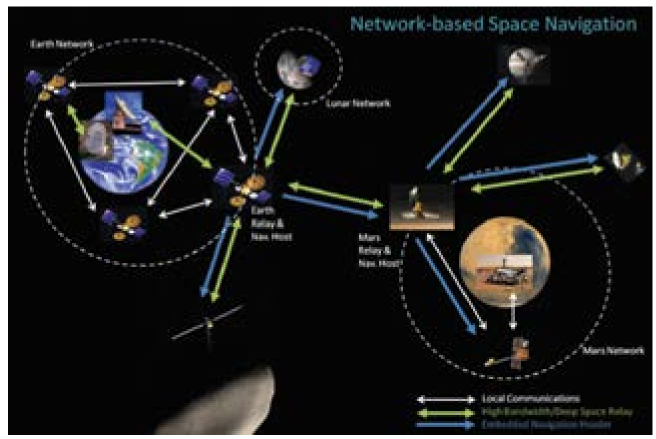

Figure 1: MAPS concept of operations.

The Martian communication network, along with deep space network support, provides an initial architecture for simulation and analysis of MAPS, providing a notional deep space implementation. This scenario is used for initial trade studies to determine capability assessments and sensitivity analysis. This architecture also serves as the mission scenario capturing the ideal initial deep space implementation of MAPS.

To support initial flight validation, a low-Earth orbit (LEO) demonstration mission concept is also being developed and analyzed. This mission scenario focuses on capturing the in-flight accuracy of the spacecraft clocks as well as in-flight packet transmission, and state estimation among a limited number of assets. To support this mission, both software and hardware simulation tools have been developed. The simulation architecture allows for analysis of link budgets and estimated performance as a function of individual asset orbits and simulated errors (such as external perturbations and timing uncertainty). To capture the effects of real hardware, a hardware-in-the-loop system is being utilized to integrate flight quality radio and clock hardware to capture receiver delays and clock uncertainty to directly model spacecraft behavior. This framework is described in figure 2.

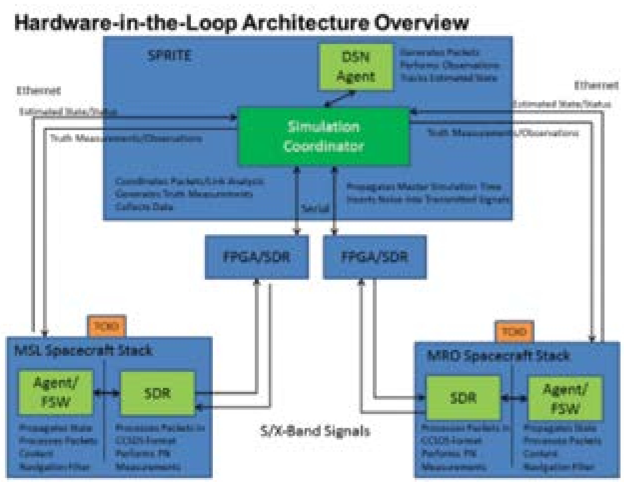

Figure 2: Simulation framework.

The capability for highly accurate timing measurements and delay modeling is enabled through the use of a truth simulation coordinator and a timing coordinator. These are both synced to high accuracy network clocks, with the timing coordinator running minimal processing to reduce any timing errors in modeling and controlling communication delays. This architecture will allow for verification and performance analysis of MAPS across a variety of mission scenarios, and provides a starting point for a full architecture simulation.

Anticipated Benefits

This technology is well suited to providing navigation capability to spacecraft participating in the communication network. By utilization of this technology, it is possible to turn every communication pass between assets into a real-time autonomous navigation pass as well, supplementing and enhancing traditional state determination methods. This reduces the reliance and load on ground-based assets while also increasing onboard state estimation capability.

Potential Applications

This architecture is designed to support in-space navigation for robotic and human missions. It can also serve as a backup navigation method for cases with limited ground support availability. As onboard clocks improve in capability and multiple spacecraft implement these algorithms, MAPS can be used as a primary navigation source. Additionally, this architecture can be used to develop high accuracy navigation references throughout our solar system, integrating with interplanetary communication relays.

Notable Accomplishments

To support mission analysis and design, an agent-based simulation tool has been developed for design space exploration, performance evaluation, and optimization of the architecture. This simulation is currently being expanded to include flight-like timing sources and radios to allow for the direct capture of hardware-based performance metrics. Current work is focused on integration with the portable hardware-in-the-loop framework to allow for detailed performance evaluation and mission analysis.

The team is also performing mission design to support a LEO technology demonstration. Initial assumptions of a CubeSat platform in LEO are being analyzed to support vehicle sizing and operations concepts. This mission concept will be the focus of the hardware-in-the loop simulation.

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Magnetogram Forecast: An All-Clear Space Weather Forecasting System

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Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development, Advance Radiation Protection Project

Project Description

Solar flares and coronal mass ejections (CMEs) are the drivers of severe space weather. Forecasting the probability of their occurrence is critical in improving space weather forecasts. The National Oceanic and Atmospheric Administration (NOAA) currently uses the McIntosh active region category system, in which each active region on the disk is assigned to one of 60 categories, and uses the historical flare rates of that category to make an initial forecast that can then be adjusted by the NOAA forecaster.

Flares and CMEs are caused by the sudden release of energy from the coronal magnetic field by magnetic reconnection. It is believed that the rate of flare and CME occurrence in an active region is correlated with the free energy of an active region. While the free energy cannot be measured directly with present observations, proxies of the free energy can instead be used to characterize the relative free energy of an active region. The Magnetogram Forecast (MAG4) (output is available at the Community Coordinated Modeling Center) was conceived and designed to be a databased, all-clear forecasting system to support the operational goals of NASA's Space Radiation Analysis Group.

The MAG4 system automatically downloads near-real-time line-of-sight Helioseismic and Magnetic Imager (HMI) magnetograms on the Solar Dynamics Observatory (SDO) satellite, identifies active regions on the solar disk, measures a free-energy proxy, and then applies forecasting curves to convert the free-energy proxy into predicted event rates for X-class flares, M- and X-class flares, CMEs, fast CMEs, and solar energetic particle events (SPEs). The forecast curves themselves are derived from a sample of 40,000 magnetograms from 1,300 active region samples, observed by the Solar and Heliospheric Observatory Michelson Doppler Imager. Figure 1 is an example of MAG4 visual output.

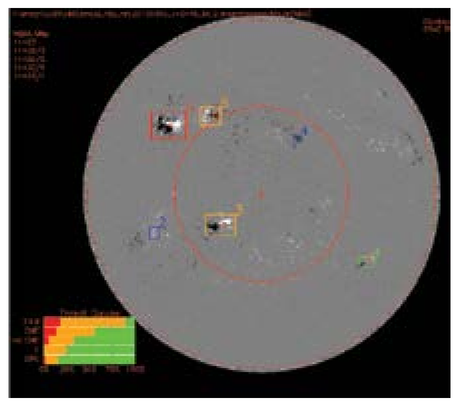

Figure 1: The graphical display of MAG4 forecast.

Each strong magnetic field area is outlined by a polygon. The polygon is color coded by threat level (green, yellow, and red, with blue showing strong magnetic field areas that do not belong to an active region). The full disk forecast with confidence levels (yellow bar) are shown graphically in the lower left. The particular date shown in figure 1 is a 'high threat day.' Figure 2 shows the same flare as seen by SDO/Atmospheric Imaging Assembly, the CME as seen by STEREO-B, and the resulting identifying SPE that the active region in the red box produced hours after the forecast. MAG4 also creates datasets that are used to further research and analysis, and to improve the forecast curves.

MAG4 free-energy proxy forecasts have been compared to forecasts using McIntosh categories, total magnetic flux, free-energy proxy, and previous flare activity. We have found that forecasts are best for active regions within 30 heliocentric degrees of disk center

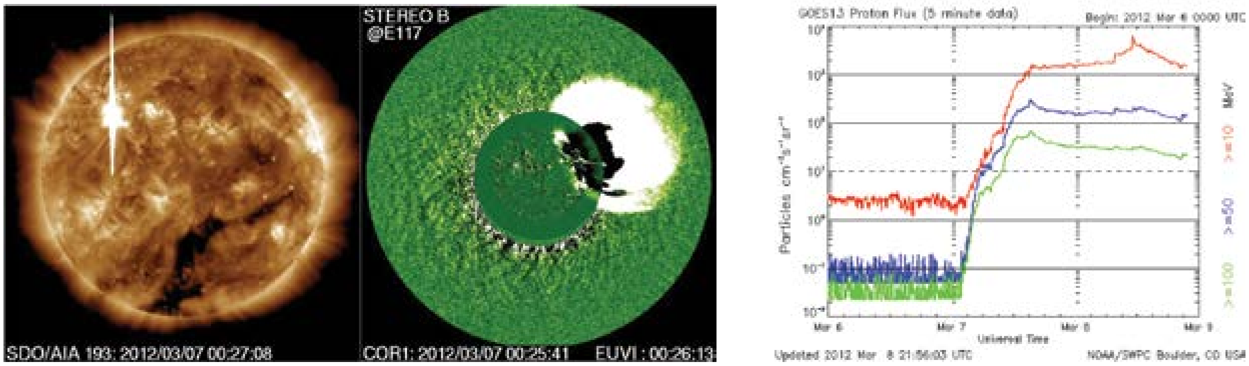

Figure 2: The flare, CME, and SPE that the upper-right active region in figure 1 produced.

when using both the free-energy proxy and previous flare activity. Figure 3 shows the difference of the Heidki Skill Score (HSS) both in standard deviations and in overall amount.

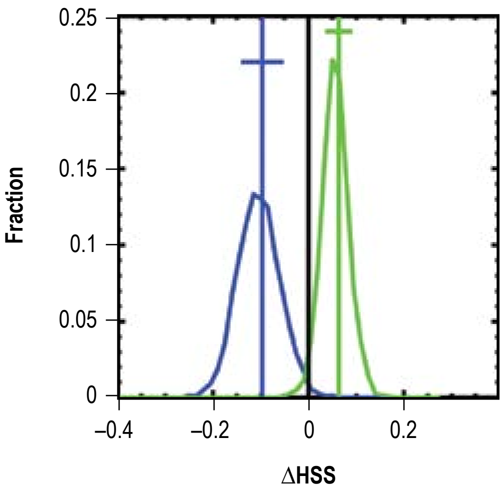

Figure 3: Plot showing clear improvement HSS in forecasts based on McIntosh system (blue relative to free-energy proxy alone), and free-energy proxy plus previous flare history (green relative to free-energy proxy alone). Each curve shows the results from 2,000 Monte Carlo runs, with the vertical bar being the average, and the horizontal bar being one standard deviation; the black line would be as good as free-energy proxy forecast only.

Anticipated Benefits

Anticipated benefits include improvements to forecasts, especially for active regions that are far from disk center. Due to projection effects, MAG4 measurements of active regions far from disk center from line-of-sight magnetograms are less accurate, and thus the forecasts are less certain that use of vector magnetograms will improve the forecasts.

Potential Applications

MAG4 can be incorporated into any operational forecasts to supplement or replace the McIntosh forecasts.

Notable Accomplishments

Forecasts based not just on the free-energy proxy but also using previous flare history were implemented in FY 2014 (Falconer, 2014). During FY 2015, the MAG4 project has begun deprojecting HMI vector magnetograms. A pilot study was conducted that indicates the possibility of far side coronal imagers measuring the total magnetic flux of far side active regions, and thus a predicted event rate.

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Composite Cryotank Technologies and Demonstration

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Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development

Project Description

NASA is exploring advanced composite materials and processes to reduce the overall cost and weight of liquid hydrogen (LH_2) cryotanks while maintaining the reliability of existing metallic designs. The fundamental goal of the composite cryotank project was to provide new and innovative technologies that enable human space exploration to destinations beyond low-Earth orbit such as the Moon, near-Earth asteroids, and Mars.

In September 2011, NASA awarded Boeing the contract to design, manufacture, and test two lightweight composite cryogenic propellant tanks.

The all-composite tanks shown in figures 1 and 2 are fabricated with an automated fiber placement machine using a prepreg system of IM7 carbon fiber/CYCOM 5320-1 epoxy resin. This is a resin system developed for out-of-autoclave applications. Switching from metallic to composite construction holds the potential to dramatically increase the performance capabilities of future space systems through a dramatic reduction in weight.

Composite Cryotank Technologies and Demonstration testing was an agency-wide effort with NASA Marshall Space Flight Center (MSFC) leading project management, manufacturing, and test; Glenn Research Center leading the materials; and Langley Research Center leading the structures effort for this project. Significant contributions from NASA loads/stress personnel contributed to the understanding of thermal/mechanical strain response while undergoing testing at cryogenic temperatures. The project finalized in September 2014.

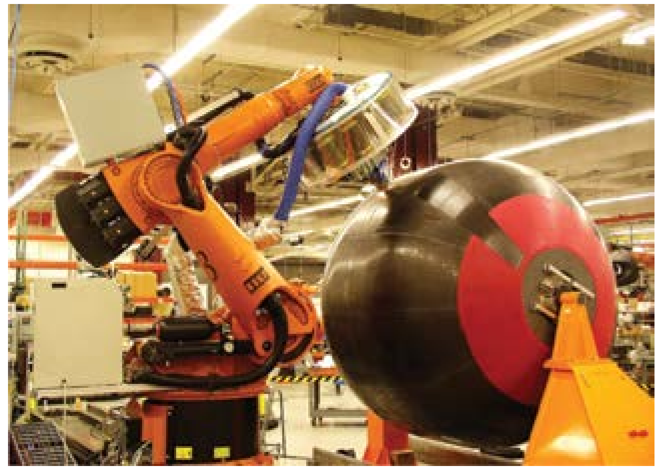

Figure 1: 8-ft- (2.4-m-) diameter, all composite tank at Boeing.

Figure 2: 18-ft- (5.5-m-) diameter, all composite tank at Boeing.

Figure 3: 5.5-m tank arrives on NASA's Super Guppy and begins testing at MSFC.

2.4-m Tank Test Summary

Built by Boeing at their Tukwila, Washington, facility, the tank arrived at NASA in late 2012. On June 25, 2013, the 2.4-m-diameter, all-composite cryogenic tank was successfully pressure tested at MSFC. The test met all requirements: stepwise fill with LH_2 (–423 °F) to 90% volume capacity followed by pressurizing the tank to 135 psig. The 2.4-m tank was then cycled through 20 pressure/vent cycles, measuring hydrogen gas permeation on the tank dome.

5.5-m Tank Test Summary

NASA's Super Guppy, a wide-bodied cargo aircraft, landed at the Redstone Army Airfield near Huntsville, Alabama, on March 26, 2014, and since then, NASA has completed a demanding series of tests inside the test stand at MSFC. Engineers added structural loads to the tank to replicate the physical stresses launch vehicles experience during flight.

In other tests, the tank successfully maintained fuels at extremely low temperatures and operated at various pressures. Engineers filled the tank with almost 30,000 gal of LH_2 chilled to –423 °F, and repeatedly cycled the pressure between 20 to 53 lb/in^2, the pressure limit set for the tests.

Anticipated Benefits

Using innovative manufacturing processes and designs, this project advanced the technologies for composite cryogenic propellant tanks at diameters suitable for future heavy-lift vehicles and other in-space applications.

Potential Applications

A potential initial target application for the composite technology is an upgrade to the upper stage of NASA's Space Launch System heavy-lift rocket.

Notable Accomplishments

The 5.5-m composite cryotank is the largest automated fiber placement, out-of-autoclave, composite LH_2 tank ever designed, manufactured, and tested.

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Advanced Near Net Shape Technology

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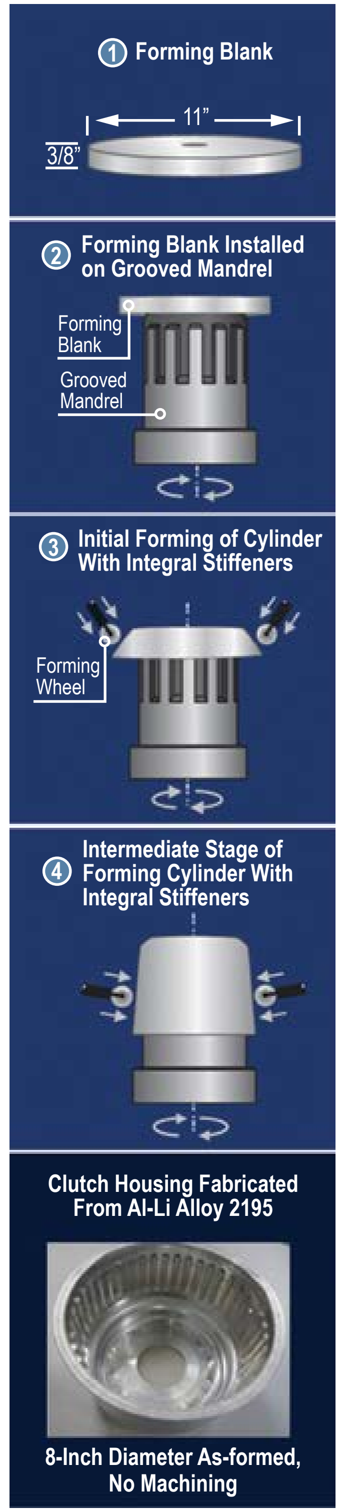
Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development

Project Description

The objective of the Advanced Near Net Shape Technology (ANNST) project is to radically improve near net shape manufacturing methods from the current Technology/Manufacturing Readiness Levels (TRL/MRL 3–4) to the point where they are viable candidates (TRL/MRL-6) for shortening the time and cost for insertion of new aluminum alloys and revolutionary manufacturing methods into the development/improvement of space structures. Conventional cyrotank manufacturing processes require fabrication of multiple pieces welded together to form a complete tank. A variety of near net shape manufacturing processes has demonstrated excellent potential for enabling single-piece construction of components such as domes, barrels, and ring frames. Utilization of such processes can dramatically reduce the extent of welding and joining needed to construct cryogenic tanks and other aerospace structures. The specific focus of this project is to successfully mature the integrally stiffened cylinder (ISC) process in which a single-piece cylinder with integral stiffeners is formed in one spin/flow forming process.

Structural launch vehicle components, like cryogenic fuel tanks (e.g., space shuttle external tank), are currently fabricated via multipiece assembly of parts produced through subtractive manufacturing techniques. Stiffened structural panels are heavily machined from thick plate, which results in excessive scrap rates. Multipiece construction requires welds to assemble the structure, which increases the risk for defects and catastrophic failures.



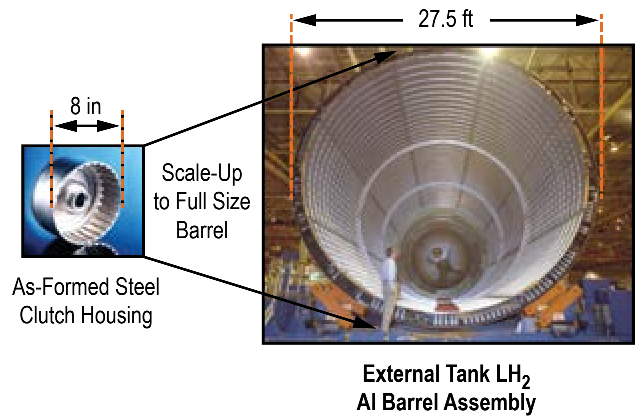
Integrally stiffened cylinder fabrication process.

Weld regions require increased material thickness to offset reduced material properties in the weld metal and require costly nondestructive evaluation inspections. For example, the previous space shuttle external tank (27.5 feet in diameter × 154 feet tall) had a material scrap rate of nearly 90%, resulting in ~$8 million per tank in wasted material and had roughly half a mile of welds. Multipiece machined and welded construction is 30$^+$-year-old technology that works but is material inefficient, expensive, and risky. There is significant room for improvement with adoption of advanced manufacturing technology, which can be applied across multiple platforms.

This project seeks to develop and adapt manufacturing technology currently used in production of small steel automotive parts to enable fabrication of single-piece stiffened metallic launch vehicle structures using aerospace grade aluminum-lithium (Al-Li) alloys. The novel ISC process will improve manufacturing efficiency and structural performance by producing single-piece stiffened barrels in one manufacturing process through combined spin- and flow-forming operations. Such a technique has never before been applied to launch vehicle structures. If successful, this will revolutionize the way integrally stiffened, metallic structures are fabricated with projected weight savings of up to 30%, cost savings of 40%, and the elimination of all longitudinal welds compared to the current state-of-the-art practice. Additional performance benefits will be realized through selective reinforcement with metal matrix composite materials incorporated into a hybrid launch vehicle structure.

Anticipated Benefits

NASA missions will benefit from the ISC process through manufacture of launch vehicle structure subelements at lower cost and with improved reliability and performance. The ISC process will greatly expand cryogenic tank barrel design space enabling greater structural performance benefits and significant mass savings.



Potential Applications

Potential applications for the ISC manufacturing technology include launch vehicle structures such as cryogenic tank barrels, dry bay structures, and payload shrouds for vehicles from sounding rockets and small satellite launchers to potentially Space Launch System scale vehicles.

Notable Accomplishments

The ANNST project has demonstrated transition of the ISC process from forming with automotive steel to an aerospace Al-Li alloy through successful fabrication of a typical automotive component. Further process optimization has shown successful increase in stiffener height from gear teeth to cryogenic tank barrel scale stiffeners.

Laboratory experiments have demonstrated the potential to selectively reinforce the stiffener's top using metal matrix composite materials. Initial testing of small-scale reinforced stiffeners showed a 30% increase in bending stiffness with only a 1% increase in mass.

GCD

Materials Genome Initiative

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Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development

Project Description

The Materials Genome Initiative (MGI) project element is a cross-Center effort that is focused on the integration of computational tools to simulate manufacturing processes and materials behavior. These computational simulations will be utilized to gain understanding of processes and materials behavior to accelerate process development and certification to more efficiently integrate new materials in existing NASA projects and to lead to the design of new materials for improved performance. This NASA effort looks to collaborate with efforts at other government agencies and universities working under the national MGI.

MGI plans to develop integrated computational/experimental/processing methodologies for accelerating discovery and insertion of materials to satisfy NASA's unique mission demands.

The challenges include validated design tools that incorporate materials properties, processes, and design requirements; and materials process control to rapidly mature emerging manufacturing methods and develop certified manufacturing processes.

The approach includes physics-based modeling to guide material design (e.g., composition, grain size, and texture); fiber layup; multiscale modeling to predict the influence of materials design on mechanical properties and durability; process modeling to determine optimal processing parameters to reliably produce as-designed material nano-/micro-structures and enable advanced manufacturing methods; and material data management to support robust material design methodology.

Capabilities provided by this technology include: (1) Develop reliable process control and certification methods for the manufacture of engine components for the Space Launch System (SLS) by selective laser manufacturing (SLM), (2) Computational tools to enable process control with a reduced reliance on trial-and-error approaches will accelerate the development cycle, (3) Simulation of the behavior of components manufactured through the SLM process will be used to inform the certification process to reduce the testing burden and the associated time and cost for future additively manufactured components, and (4) Evaluate optimal material configurations for advanced woven thermal protection systems (TPS) concepts. These highly tailorable material architectures allow for TPS to be designed for specific mission requirements. However, with this ability to tailor the material architecture creates a large design space that is impractical to explore through fabrication, as these systems are costly to build and test. Consequently, computationally assisted design is being implemented to assist the design process. Additionally, these design tools will be evaluated for use in predicting the response of these materials to operational regimes that cannot be examined in the laboratory.

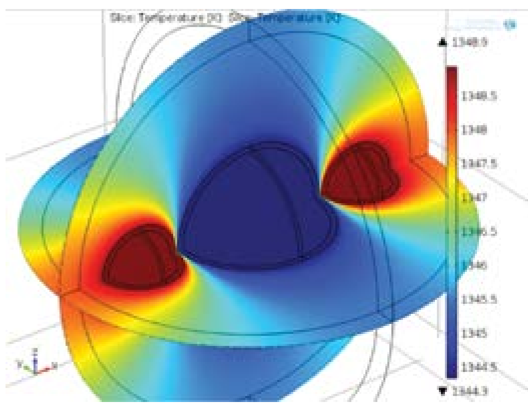
Anticipated Benefits

Synergistic efforts in multiscale modeling, information management, experimental characterization, and materials processing will accelerate design, development, and sustainment of ultra-durable material systems.

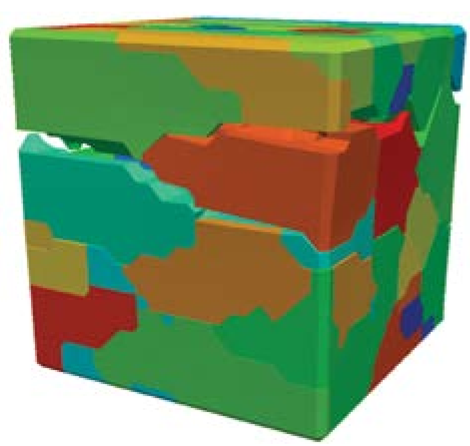
The quantitative impact includes the reduced time between discovery and technology insertion by at least half relative to current practice; shorter maturation and insertion period can translate to lower costs, greater affordability, and lower risk of failure; and integration of materials certification within a comprehensive computational approach will reduce time and cost to certify new flight hardware.

Potential Applications

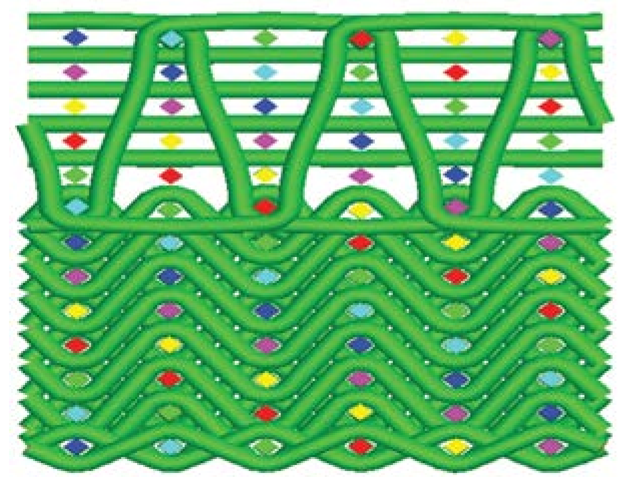
Computational materials tools will be developed in close collaboration with existing projects. These tools will be applied to improve manufacturing processes and materials performance while also reducing the cost and time to insert new materials and processes into NASA applications. For the SLS project, computational tools will focus on reducing manufacturing variability, and part certification to reduce cost and time to infuse new parts. For the conformal TPS project, trade studies for component architecture will be developed to virtually examine multiple configurations, as manufacturing multiple configurations is not financially viable to downselect potential systems.



Physics-based model of powder bed heating for selective laser melting.



Multiscale simulation utilizing aggregate dislocation behavior for crack growth in a material formed by additive manufacturing.



Hybrid weave concept of a 3D conformal TPS to be analyzed for thermomechanical behavior.

Notable Accomplishments

A near-infrared camera system has been developed and calibrated to monitor the melt pool for metallic additive manufacturing systems. Thermal maps of the melt pool and semi-solidus areas have been analyzed to develop algorithms to track and quantify the melt pool area. These algorithms have been used to create closed loop control for an additive manufacturing system to improve manufacturing quality and to demonstrate improved process reliability.

Micromechanical simulations of 2D TPS weaves have been developed to assist in initial downselect of novel woven TPS designs.

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Low Cost, Upper Stage-Class Propulsion

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Sponsoring Program(s)

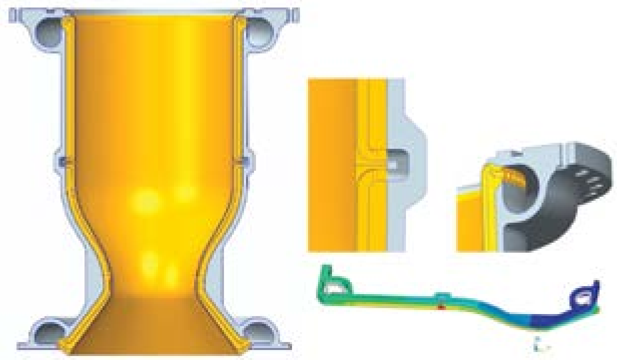
Space Technology Mission Directorate
Game Changing Development

Project Description

The low cost, upper stage-class propulsion (LCUSP) element will develop a high strength copper alloy additive manufacturing (AM) process as well as critical components for an upper stage-class propulsion system that will be demonstrated with testing.

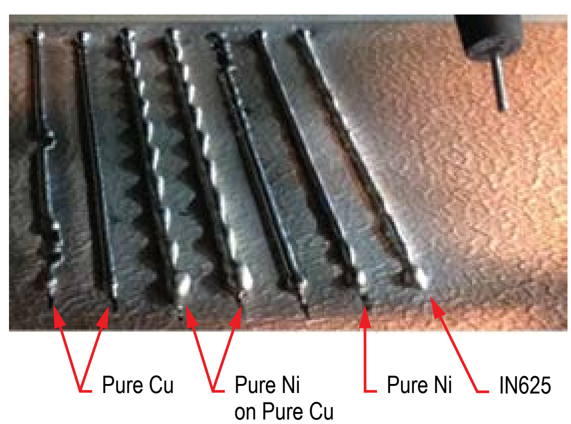
As manufacturing technologies have matured, it now appears possible to build all the major components and subsystems of an upper stage-class rocket engine for substantially less money and much faster than traditionally done. However, several enabling technologies must be developed before that can happen. This activity will address these technologies and demonstrate the concept by designing, manufacturing, and testing the critical components of a rocket engine. The processes developed and materials' property data will be transitioned to industry upon completion of the activity.

Technologies to enable the concept are AM copper alloy process development, AM post-processing finishing to minimize surface roughness, AM material deposition on existing copper alloy substrate, and materials characterization.



Chamber cross sections illustrating the copper alloy liner with built-in coolant passages and the deposited nickel alloy jacket and manifolds.

Small chamber process demonstration article printed by MSFC ER42 from copper alloy C18150.



LaRC EBF3.

Example of a previous engine component testing at MSFC's Test Stand 116. Our hardware will be tested at similar liquid hydrogen and liquid oxygen flow rates and thrust levels.

Specifically, the LCUSP project element will (1) develop materials properties and characterization for selective laser melting (SLM) manufactured GRCop, (2) develop and optimize SLM manufacturing process for a full component GRCop chamber and nozzle, (3) develop and optimize the electron beam freeform fabrication (EBF3) manufacturing process to direct deposit a nickel alloy structural jacket and manifolds onto an SLM manufactured GRCop chamber and SLM manufactured nozzle, and (4) demonstrate the process for integrating the engine system by performing a hot-fire, resistance test.

Anticipated Benefits

Existing AM equipment combined with new, enabling processes and manufacturing 'best practices' will make it possible for more companies to build high-quality rocket propulsion hardware at a lower cost and faster delivery than previously possible. These cost and schedule savings will be passed along to NASA when a new rocket engine is competed. Additive manufacturing can potentially offer an order of magnitude savings of cost and schedule for complex rocket propulsion hardware. The AM process development for copper alloy, materials characterization, and technology transfer to industry will open new competitive markets that may reach beyond the space flight industry.

Another benefit will be to provide the space industry with a new material property database and proven techniques for implementing AM in their manufacturing processes.

Potential Applications

The LCUSP element is complimentary and directly relevant to the continued development of the Space Launch System capability by pursuing affordability improvements for engines and stages.

Notable Accomplishments

NASA Marshall Space Flight Center (MSFC) is partnering with Langley Research Center (LaRC) (for the EBF3 jacket/manifold deposition,) and Glenn Research Center (for materials properties determination). A solid monolithic part with relevant feature sizes has been demonstrated. MSFC EM42 has printed a small chamber demonstration article utilizing an available nickel-silicon-bronze powder and one using copper alloy C18150, which is used in some commercial conventionally manufactured chamber applications. LaRC has completed initial successful trial depositions of Inco625 onto copper alloy.

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Space Synthetic Biology Project

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Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development

Project Description

Synthetic biology is an effort to make genetic engineering more useful by standardizing sections of genetic code. By standardizing genetic components, biological engineering will become much more similar to traditional fields of engineering, in which well-defined components and subsystems are readily available in markets. Specifications of the behavior of those components and subsystems can be used to model a system which incorporates them. Then, the behavior of the novel system can be simulated and optimized. Finally, the components and subsystems can be purchased and assembled to create the optimized system, which most often will exhibit behavior similar to that indicated by the model.

The Space Synthetic Biology project began in 2012 as a multi-Center effort. The purpose of this project was to harness Synthetic Biology principals to enable NASA's missions. A central target for application was to Environmental Control & Life Support (ECLS). Engineers from NASA Marshall Space Flight Center's (MSFC's) ECLS Systems Development Branch (ES62) were brought into the project to contribute expertise in operational ECLS systems.

Project lead scientists chose to pursue the development of bioelectrochemical technologies to spacecraft life support. Therefore, the ECLS element of the project became essentially an effort to develop a bioelectrochemical ECLS subsystem. Bioelectrochemical systems exploit the ability of many microorganisms to drive their metabolisms by direct or indirect utilization of electrical potential gradients. Whereas many microorganisms are capable of deriving the energy required for the processes of interest (such as carbon dioxide (CO_2) fixation) from sunlight, it is believed that subsystems utilizing electrotrophs will exhibit smaller mass, volume, and power requirements than those that derive their energy from sunlight.

In the first 2 years of the project, MSFC personnel conducted modeling, simulation, and conceptual design efforts to assist the project in selecting the best approaches to the application of bioelectrochemical technologies to ECLS. Figure 1 shows results of simulation of charge transport in an experimental system. Figure 2 shows one of five conceptual designs for ECLS subsystems based on bioelectrochemical reactors. Also during the first 2 years, some work was undertaken to gather fundamental data (conductivities, overpotentials) relevant to the modeling efforts.

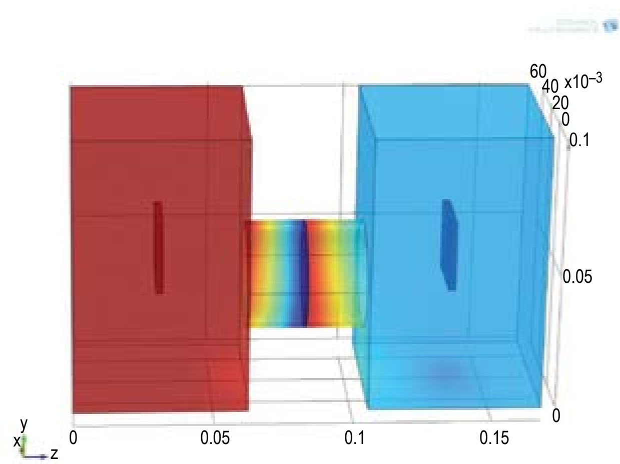

Figure 1: Results of a simulation showing proton concentration in a bioelectrochemical test cell.

In fiscal year 2014, MSFC personnel proposed to conduct development efforts on critical components of the bioelectrochemical ECLS subsystem which had not yet been investigated but which would be critical to operation of the subsystem. (All of the focus of the technical development efforts of the project to this point had been on the reactor itself.) Drawing on the conceptual design efforts of the first 2 years, MSFC identified three

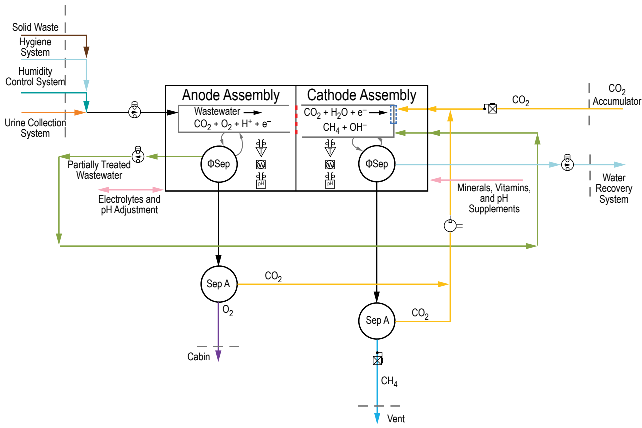

Figure 2: A process diagram of a concept design for a bioelectrochemical ECLS subsystem.

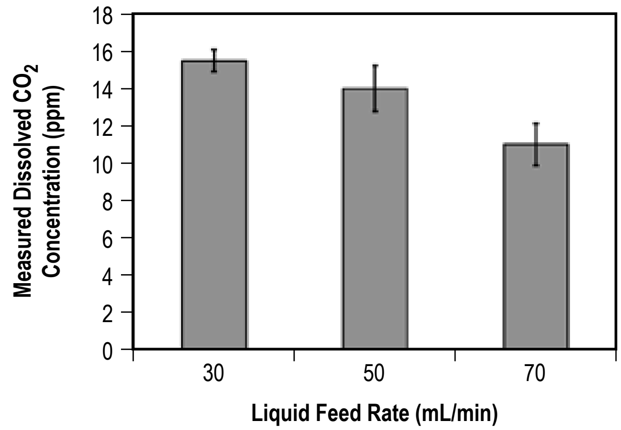

Figure 3: CO_2 injection performance results from a gas-liquid contactor.

critical components and elected to develop technologies for CO_2 injection, i.e., an efficient, microgravity-compatible method of dissolving CO_2 into the aqueous electrolyte so that the CO_2 can be reacted to useful products in the reactor.

Project personnel at MSFC proceeded to design a test system to evaluate technologies for the CO_2 injection component, and the system was assembled in the ECLS Systems Laboratory, Bldg. 4755. Considerable effort was required to a methodology for sampling and analyzing to quantify dissolved carbon. Ultimately, a procedure involving prepreparation of sealed dilution vials, sample collection via syringe, and analysis in a total organic carbon analyzer was developed. This method proved less accurate than desirable, but was sufficient to provide some degree of comparison of performance under differing conditions.

A gas-liquid contact membrane was tested by exposing an aqueous solution of known composition, at known temperature, pressure, and flow rate, to CO_2 gas at known pressure across the contactor. Gas pressure, liquid pressure, and liquid flow rate were varied between trials. Results were plotted as curves, and reported, in order to guide sizing of such a technology for CO_2 injection in a future bioelectrochemical CO_2 reduction/fixation subsystem. Some of the results are shown in figure 3.

Anticipated Benefits

The bioelectrochemical subsystem developed under the Space Synthetic Biology project is targeting an application wherein the subsystem decreases the load on the primary urine processor and CO_2 reduction subsystem, and simultaneously produces an organic precursor, which would then be utilized to manufacture a range of high-value organic products, including food, bioplastics, and pharmaceuticals.

The electrochemical modeling expertise developed and lessons learned in the early phases of the project at MSFC could benefit future development efforts for various electrochemical ECLS technologies, and the equipment, methodologies, and expertise built up may prove valuable to other subsystem development efforts relying on dissolved CO_2.

Potential Applications

Advanced ECLS development efforts within the Agency may elect to pursue development of the bioelectrochemical reactor technology for application to extended-duration, crewed missions beyond low-Earth orbit. The CO_2 injection test system may be applied to optimization of gas handling in a range of ECLS subsystems requiring handling of dissolved gases in microgravity, including algae-based air and water processors.

Notable Accomplishments

Notable accomplishments include the development and evaluation of five concept designs for ECLS subsystems based around bioelectrochemical reactors, the assembly of a test stand to evaluate CO_2 injection technologies, and reporting results of the evaluation of a gas-liquid contactor for this application.

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Programmable Ultra-Lightweight System Adaptable Radio

Project Manager(s)/Lead(s)

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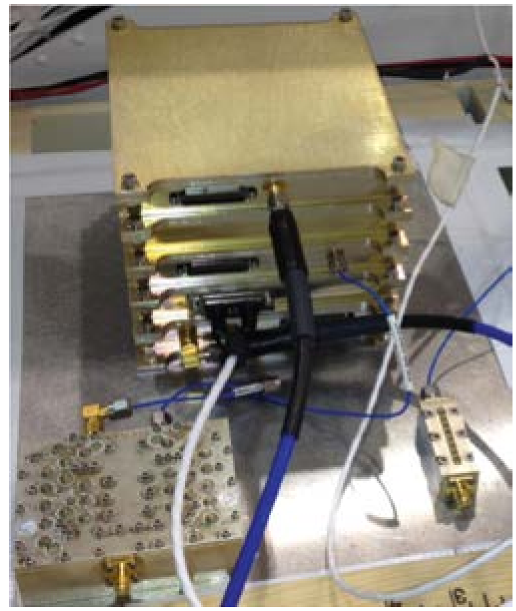
Sponsoring Program(s)

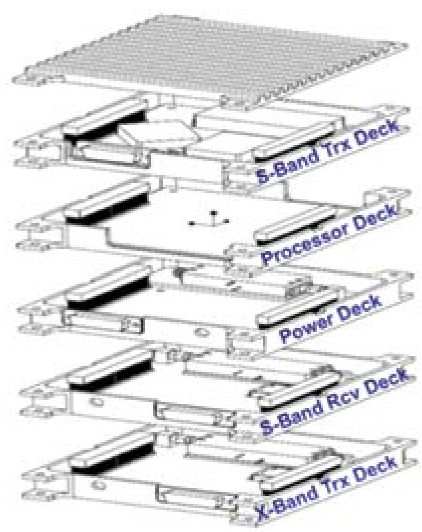
Science and Technology Mission Directorate
Game Changing Development

Project Description

The programmable ultra-lightweight system adaptable radio (PULSAR) is a NASA Marshall Space Flight Center transceiver designed for the CubeSat market, but has the potential for other markets. The PULSAR project aims to reduce size, weight, and power while increasing telemetry data rate. The current version of the PULSAR has a mass of 2.2 kg and a footprint of 10.8 cm^2. The height depends on the specific configuration. The PULSAR S-Band Communications Subsystem is an S- and X-band transponder system comprised of a receiver/detector (receiver) element, a transmitter element(s), and related power distribution, command, control, and telemetry element for operation and information interfaces. It is capable of receiving commands, encoding and transmitting telemetry, as well as providing tracking data in a manner compatible with Earth-based ground stations, near Earth network, and deep space network station resources. The software-defined radio's (SDR's) data format characteristics can be defined and reconfigured during spaceflight or prior to launch. The PULSAR team continues to evolve the SDR to improve the performance and form factor to meet the requirements that the CubeSat market space requires. One of the unique features is that the actual radio design can change (somewhat), but not require any hardware modifications due to the use of field programmable gate arrays.



PULSAR unit.



PULSAR expanded view.

PULSAR 2.2A model radios have been delivered to NASA Johnson Space Center iPASS Lab and to NASA Stennis Research Center to support an engine test. In FY 2015, PULSAR will build and fly the 2.3 model PULSAR on a Peregrine sounding rocket as a payload. In preparation for this and as part of a typical development, the 2.3 model will undergo environmental testing: thermal/vacuum, electromagnetic interference, and vibration. After the 2.3 is refined, development is expected to continue into smaller form factors and X-band reception (not just transmit).

PULSAR 2.2A as delivered for Stennis engine test support.

Anticipated Benefits

The PULSAR radio has the benefit of providing a CubeSat radio at a high data rate and a cost that is significantly lower than any other commercially available S- and X-band frequencies.

Potential Applications

Possible potential applications include CubeSats, unmanned aerial vehicles, portable ground stations for Satellite communication.

Notable Accomplishments

PULSAR has delivered two radios in calendar year 2014, designed the next evolution of the radio and is building it at this time, and has strong industry ties with GATR antennas, Miltec, and Orbital Telemetry.

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Microelectrospray Thrusters

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Sponsoring Program(s)

Space Technology Mission Directorate
Game Changing Development

Project Description

Propulsion technology is often a critical enabling technology for space missions. NASA is investing in technologies to enable high value missions with very small spacecraft, even CubeSats. However, these nanosatellites currently lack any appreciable propulsion capability. CubeSats are typically deployed and tumble or drift without any ability to transfer to higher value orbits, perform orbit maintenance, or perform de-orbit. Larger spacecraft can also benefit from high precision attitude control systems. Existing practices include reaction wheels with lifetime concerns and system level complexity. Microelectrospray thrusters will provide new propulsion capabilities to address these mission needs.

Electric propulsion is an approach to accelerate propellant to very high exhaust velocities through the use of electrical power. Typical propulsion systems are limited to the combustion energy available in the chemical bonds of the fuel and then acceleration through a converging diverging nozzle. However, electric propulsion can accelerate propellant to ten times higher velocities and therefore increase momentum transfer efficiency, or essentially, increase the fuel economy. Fuel efficiency of thrusters is proportional to the exhaust velocity and referred to as specific impulse (I_{sp}). The state-of-the-art (SOA) for CubeSats is cold gas propulsion with an I_{sp} of 50–80 s. The Space Shuttle main engine demonstrated a specific impulse of 450 s. The target I_{sp} for the Mars Exploration Program (MEP) systems is >1,500 s. This propellant efficiency can enable a 1-kg, 10-cm cube to transfer from low-Earth orbit to interplanetary space with only 200 g of propellant.

In September 2013, NASA's Game Changing Development program competitively awarded three teams with contracts to develop MEP systems from Technology Readiness Level-3 (TRL-3), experimental concept, to TRL-5, system validation in a relevant environment. The project is planned for 18 months of system development. The target objectives of the project are provided in table 1.

Table 1: MEP phase 1 project objectives.

Metric	Goal
I_{sp}	≥1,500 s
Thrust	≥100 μN
Power	≤10 W
System Efficiency	≥70%
Mass	≤100 g
Volume	≤100 cm^3
Demonstrated Life	≥200 hr
Predicted Life	≥500 hr

Due to the ambitious project goals, NASA has awarded contracts to mature three unique methods to achieve the desired goals. Some of the MEP concepts have been developed for more than a decade at the component level, but are now ready for system maturation. The three concepts include the high aspect ratio porous surface (HARPS) microthruster system, the scalable ion electrospray propulsion system (S-iEPS), and an indium microfluidic electrospray propulsion system.

The HARPS system is under development by Busek Co. The HARPS thruster is an electrospray thruster that relies on surface emission of a porous metal with a passive capillary wicking system for propellant management. The HARPS thruster is expected to provide a simple, high ΔV and low-cost solution. The HARPS thruster concept is shown in figure 1. Figure 1 includes the thruster, integrated power processing unit, and propellant reservoir.

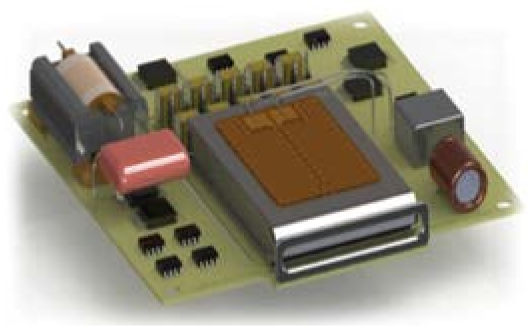

Figure 1: Busek HARPS system concept.

The S-iEPS development is led by the Massachusetts Institute of Technology (MIT). The MIT S-iEPS benefits from many years of component level development and experimentation. The S-iEPS is a microelectromechanical system based on ionic liquid emission. An electrostatic field is used to extract and accelerate both positive and negative ions from a conductive salt that remains liquid over the operational temperature range. The concept is scalable in that the thrusters can produce flat panel thrusters. Thruster pairs are used emitting the positive and negative ions to maintain charge balance. A pair of S-iEPS is shown in figure 2.

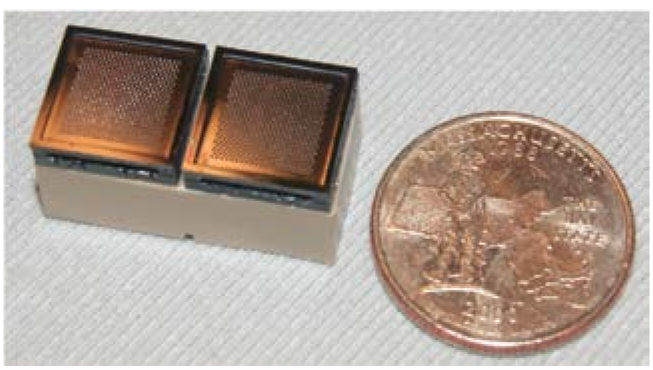

Figure 2: MIT S-iEPS thruster pair.

The Jet Propulsion Laboratory (JPL) is leading a liquid metal, indium, propellant based microfabricated thruster relying on a capillary force-driven propellant management system with no pressurization, no valves, and no moving parts. The indium thruster concept will push the limits of microfabrication techniques to produce a compact and scalable thruster. The JPL thruster is targeting 200 µN of thrust and 5,000 s I_{sp} at <10 W and 80 g. Figure 3 illustrates the JPL indium thruster concept.

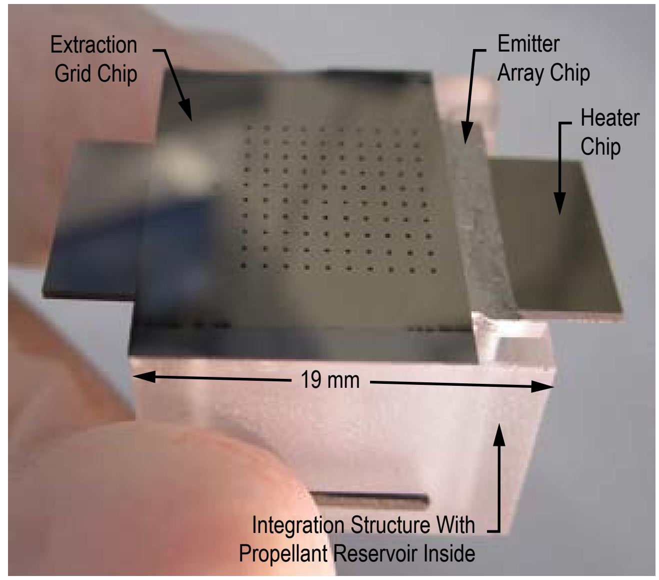

Figure 3: JPL indium thruster.

Anticipated Benefits

The benefits of MEP technology include significant improvement in low power electric propulsion efficiency, high ΔV capability for CubeSats, and high I_{sp} density over alternatives.

Potential Applications

The application targets for the MEP systems include primary propulsion for small spacecraft, attitude control, and precision propulsion for future missions.

Notable Accomplishments

This project has made significant progress to date, including integrated system testing. By summer of 2015, the project will mature the concepts to TRL-5, deliver a prototype system, and perform long-duration testing of each of the concepts.

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Space Technology Mission Directorate (STMD)

Small Business Innovation Research (SBIR)

Small Business Innovation Research and Small Business Technology Transfer Programs

Project Manager(s)/Lead(s)

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Sponsoring Program(s)

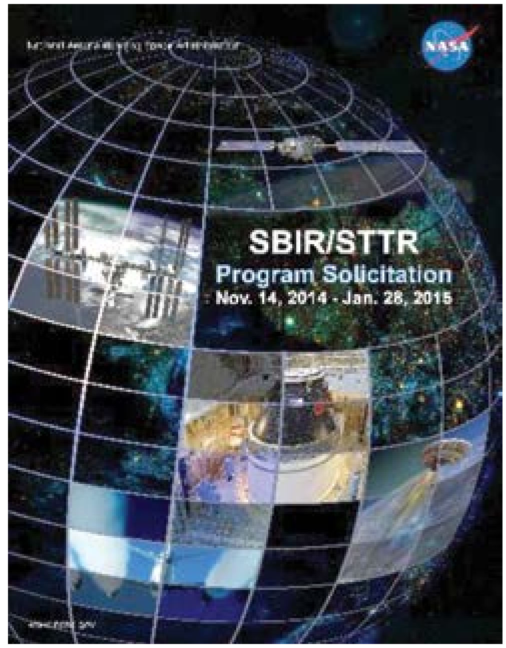
Space Technology Mission Directorate
Small Business Innovation Research/Small Business Technology Transfer Program Office

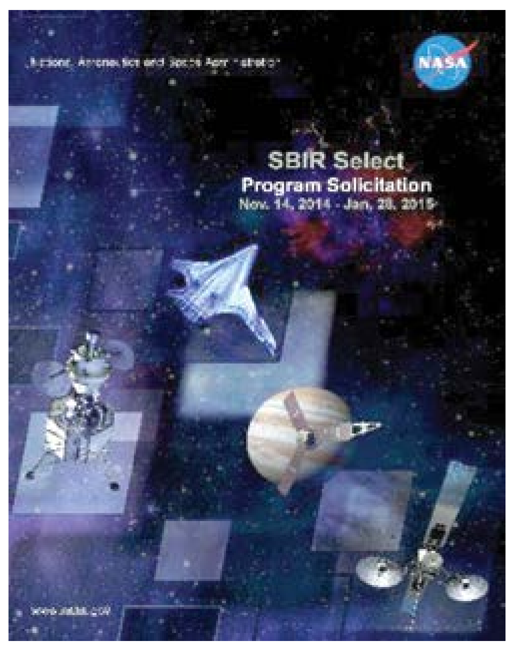
Project Description

The Small Business Innovation Research (SBIR)/Small Business Technology Transfer (STTR) programs fund the research, development, and demonstration of innovative technologies that fulfill NASA's needs as described in the annual Solicitations and have significant potential for successful commercialization. The only eligible participants are small business concern (SBC) with 500 or fewer employees or a nonprofit research institute such as a university or a research laboratory with ties to an SBC. These programs are potential sources of seed funding for the development of small business innovations.

Notable Accomplishments

The FY 2014 SBIR/STTR Solicitations (see figures for cover pages) opened for companies to submit proposals for phase I feasibility studies. For Human Exploration and Operations Mission Directorate subtopics, NASA Marshall Space Flight Center (MSFC) was lead Center on four subtopics: Nuclear Thermal Propulsion, Extreme Temperature Structures, Spacecraft Cabin Atmosphere Quality and Thermal Management, and Recycling Reclamation of 3-D Printer Plastic, and participating Center in eight subtopics.





For Science Mission Directorate (SMD), MSFC was lead Center for two subtopics: Advanced Optical Systems and Slow and Fast Light, and participating Center for 12 subtopics.

For the Space Technology Mission Directorate, MSFC was lead Center for one subtopic: Large-Scale Polymer Matrix Composites Structures, Materials and Manufacturing Processes, and participating Center on one subtopic.

For the SBIR SELECT Solicitation, MSFC was lead Center for one SMD subtopic: Advanced Technology Telescope for Balloon and Sub-Orbital Missions, and participating Center in one subtopic.

For STTR solicitation, MSFC was lead Center for two subtopics: Affordable Nano/Micro Launch Propulsion Stages and Experimental and Analytical Technologies for Additive Manufacturing, and participating Center on one subtopic.

MSFC received 32 FY 2014 phase I awards and eight phase II awards.

ZP30 developed briefing charts for SBIR/STTR technical monitor's (TM's) and contracting officer's (COR's) technical reps and conducted these briefings on May 2 and 14. The MSFC SBIR Office along with the Center New Technology Representative and NASA Shared Services Center provided valuable information to assist the TMs and CORs in the successful execution of phases I and II contracts.

MSFC awarded 32 SBIR/STTR FY 2014 phase I contracts and 10 FY 2012 phase II contracts.

MSFC awarded six phase III contracts. These contracts will continue the development of the SBIR/STTR innovation with funding from NASA programs/projects and/or external funding sources. Of these five contracts, three were funded by Space Launch Systems, two were funded by Advanced Exploration Systems, and one was funded by Technology Excellence.

Space Technology Mission Directorate (STMD)

Center Innovation Fund (CIF)

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Flexible Hybrid Battery/Pseudocapacitor

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Sponsoring Program(s)

Space Technology Mission Directorate
Center Innovation Fund

Project Description

Batteries keep devices working by utilizing high energy density, however, they can run down and take tens of minutes to hours to recharge. For rapid power delivery and recharging, high-power density devices, i.e., supercapacitors,[1] are used. The electrochemical processes which occur in batteries and supercapacitors give rise to different charge-storage properties. In lithium ion (Li+) batteries, the insertion of Li+, which enables redox reactions in bulk electrode materials, is diffusion controlled and can be slow. Supercapacitor devices, also known as electrical double-layer capacitors (EDLCs) store charge by adsorption of electrolyte ions onto the surface of electrode materials. No redox reactions are necessary, so the response to changes in potential without diffusion limitations is rapid and leads to high power.[2] However, the charge in EDLCs is confined to the surface, so the energy density is lower than that of batteries.[3]

The redox reactions in batteries store more energy per unit mass due to faradaic processes in which charge is transferred across interfaces between a battery's electrodes and the electrolyte leading to reduction and oxidation reactions (redox) of species at the interface.[4] When a battery is charged or discharged, the redox reactions change the molecular or crystalline structure of the electrodes which can often affect their stability. EDLCs show no major changes in the properties of the electrode materials during operation so can be cycled millions of times.[4]

Current in a Li-ion battery is generated when Li ions migrate from the negative electrode (anode) to the positive anode (cathode) through the electrolyte during discharge. Reversing the process results in intercalation of Li ions back into the anode and removal from the cathode to produce the charged state.

Common battery electrode materials include; $LiCoO_2$, $LiMn_2O_4$, and $LiFePO_4$ which are used as the cathode and graphite and $Li_4Ti_5O_{12}$ used for the anode.

In a supercapacitor or EDLC, a double-layer charge is developed at the interface between the electrolyte and electrodes. Thus, the larger the surface area of the electrode, the more charge that can be created. Thus, highly porous carbon is the normal selection for both EDLC electrodes. Activated carbon is commonly used due to its high specific surface area (1,000–2,000 m^2/g), however, they have a limited capacitance due to low mesoporosity (<2–50 nm) and poor electrolyte accessibility. One would therefore like a balance between mesoporosity and specific surface area in order to optimize the supercapacitor performance. Carbon nanotubes (cnts) are being actively studied as electrode materials for EDLCs. Cnts have high specific surface area, lower than activated carbons, but show a mesoporous structure providing a highly electrolyte accessible network.[5] Table 1 is a comparison between a commercial activated-carbon-based EDLC and a Li-ion battery.

Table 1: Li-ion battery versus EDLC.

Attribute	Li-Ion Battery	EDLC
Power Density (kW/L)	3	10
Energy Density (Whr/kg)	100	5
Rate Capacity X (XC)	<40	>1,800
Minimum T (°C)	0	–40
Maximum T (°C)	+40	+65
State-of-Change Excursion (%)	50	100

Electrolytes for Li-ion batteries consist of lithium salts such as $LiPF_6$ and $LiBF_4$ dissolved in an organic solvent such as ethylene carbonate or dimethyl carbonate. Electrolytes for EDLCs consists of inorganic chemicals disassociated into ions in a solvent. Typical solvents include water, propylene carbonate, tetrahydrofuran, and diethyl carbonate.

Ionic liquids, which have been studied more recently as electrolyte solutions, show great promise primarily due to the ability to tailor the properties of these liquids. There are a large number of ionic liquids available commercially.

Anticipated Benefits

If successful, the device will combine the best of Li-ion batteries and electric double-layer capacitors. Our target is 100 kW-hr/kg specific energy and 1,000 W/kg specific power. The target values are shown in the Ragone plot in figure 1. These values plus a flexible package will make for a device that is conformable to any surface area.

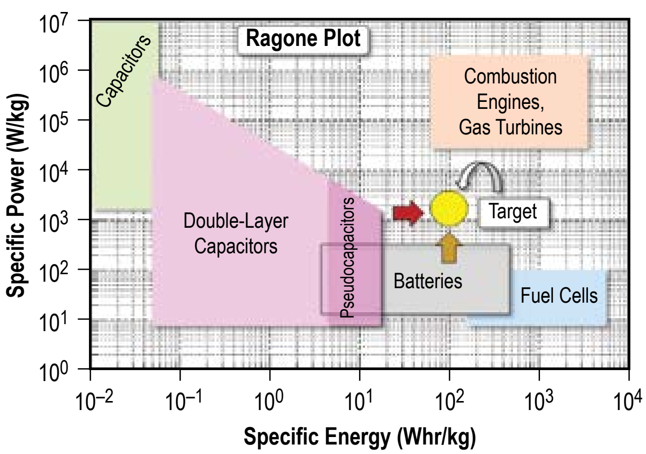

Figure 1: Ragone plot of specific power versus specific energy.

Potential Applications

Applications for NASA include power for small satellites as well as small load applications in spacecraft and habitats on the Moon and Mars. Department of Defense applications include missile systems and rolling equipment. Commercial applications include cell phones, laptops, and tablets.

Notable Accomplishments

Accomplishments include designing and constructing the electrochemical cell, measuring the electrochemical window of three ionic liquids, testing bare CNT sheets and silicon-coated CNT sheets as electrodes, and producing one NTR.

References

1. Miller, J.R.; and Simon, P.: "Electrochemical Capacitors for Energy Management," *Science,* Vol. 321, No. 5889, pp. 651–652, doi: 10.1126/science.1158736, 2008.

2. Simon, P.; Gogotsi, Y.; and Dunn, B.: "Where Do Batteries End and Supercapacitors Begin?, *Science*, Vol. 343, No. 6176, pp. 1210–1211, 2014.

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4. Abruna, H.D.; Kiya, Y.; and Henderson, J.C.: "Batteries and Electrochemical Capacitors," *Physics Today*, Vol. 61, No. 12, pp. 43–47, December 2008.

5. Lu, W.; and Hartman, R.: "Nanocomposite Electrodes for High-Performance Supercapacitors," *Phys. Chem. Lett*., Vol. 2, No. 6, pp. 655–660, 2011.

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Ultrasonic Stir Welding Development for Ground-Based and In Situ Fabrication and Repair for In-Space Propulsion Systems/Commercial Space Sector

Project Manager(s)/Lead(s)

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Sponsoring Program(s)

Space Technology Mission Directorate
Center Innovation Fund, Tech Excellence Program,
Center Strategic Defense Steering Group

Project Description

The completed Center Innovation Fund (CIF) project used the upgraded Ultrasonic Stir Weld (USW) Prototype System (built in 2013/2014) to begin characterizing the weld process using 2219 aluminum (fig. 1). This work is being done in Bldg. 4755 at NASA Marshall Space Flight Center (MSFC). The capabilities of the USW system provides the means to precisely control and document individual welding parameters. The current upgraded system has the following capabilities: (1) Ability to 'pulse' ultrasonic (US) energy on and off and adjust parameters real-time (travel speed, spindle rpm, US amplitude, X and Z axis positions, and plunge and pin axis force; (2) Means to measure draw force; (3) Ability to record US power versus time; (4) Increasing stiffness of Z axis drive and reduce head deflection using laser technology; (5) Adding linear encoder to better control tool penetration setting; (6) Ultrasonic energy integrated into stir rod and containment plate; (7) Maximum 600 rpm; (8) Maximum Z force 15,000 lb; (9) Real-time data acquisition and logging capabilities at a minimum frequency of 10 Hz; and (10) Two separate transducer power supplies operating at 4.5 kW power.

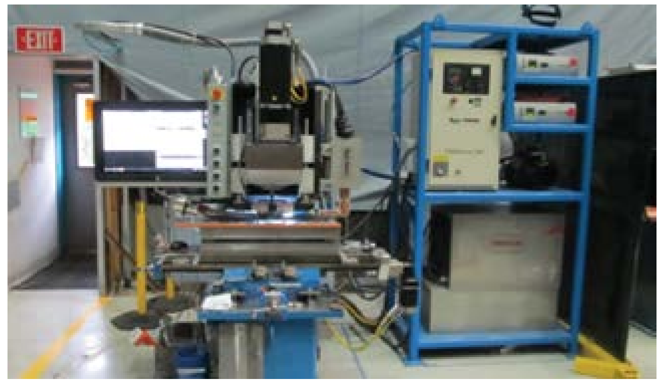

Figure 1: USW System at MSFC.

USW is NASA owned evidenced through the following U.S. Patents: No. 7,568,608, "Ultrasonic Stir Welding Process and Apparatus," No. 8,393,520, "Pulsed Ulltrasonic Stir Welding System," and No. 8,393,523, "Pulsed Ultrasonic Stir Welding Method."

Welding trials were conducted as part of the CIF project. Figure 2(a) shows the effect of US energy on plunge loads. Here, US energy was integrated into the stir rod (spindle) at amplitudes ranging from 60% to 90%. Data show 33% reduction in plunge force when the ultrasonic power was run at 90% amplitude. Figure 3(b) shows the effect of traverse force reduction when US amplitude begins at 90% during the first half of the weld and is reduced to zero during the second half of the weld.

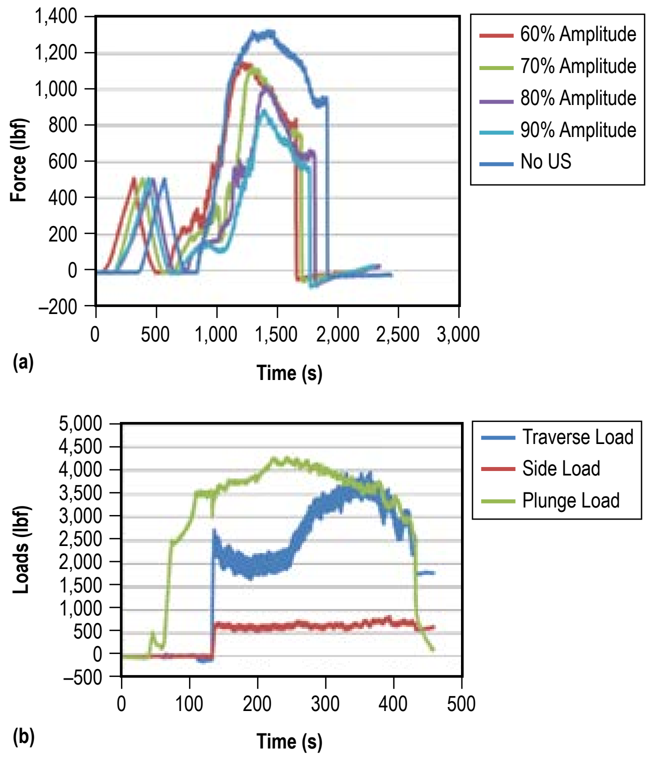

Figure 2: Data showing (a) reduced plunge forces and (b) decreased shear loads.

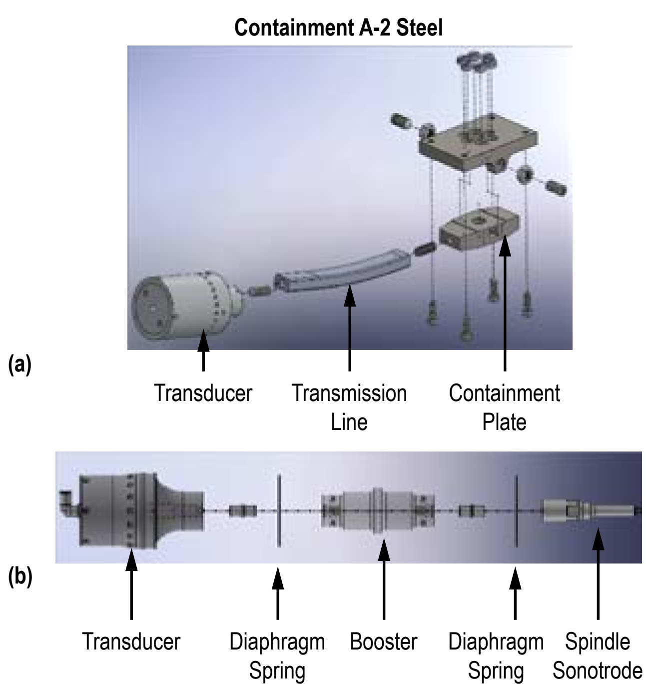

Figure 3: Ultrasonic assembly in (a) containment plate and (b) the spindle sonotrode.

Anticipated Benefits

The results of the proposed effort are intended to produce experimental data showing the effects and benefits of high power ultrasonics technology relative to NASA interests. These can include improvements in the morphology of the weld zone; reduced welding forces, thus permitting existing machines to make larger welds or existing welds to be made with smaller machines; and faster production speeds. Increased tool life, especially when welding heat-resistant alloys, will be demonstrated. In addition, it is expected to realize higher weld mechanical properties as compared to the traditional friction stir weld properties.

Potential Applications

All the expected benefits of ultrasonically assisted stir welding processes will have a profound impact on the NASA mission relative to ground-based and in situ welding and weld repair. Higher weld properties will provide greater margin of safety in as-welded weldments. Reduced forces will allow integration with inexpensive off-the-shelf robots allowing precision welds on both ground and in situ. Recognizing the safety of the in situ operator is paramount; ultrasonically assisted stir welding processes are solid state, meaning, there is no melting of weld material. There are no high energy beams or weld spatter that are found in the electron beam weld process.

Notable Accomplishments

USW process characterization has commenced. In addition to the data presented in this paper, additional welding trials are being conducted using 2219 aluminum. The aluminum is being used first as it is one of the most used alloys in solid state weld development and is well within the welding engineering knowledge base.

References

Procurement Specification No. 42004736672: "Upgrades to the Ultrasonic Stir Welding (USW) Prototype System Performance Work Statement PR 42004736672."

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Lightweight Damage Tolerant, High-Temperature Radiators for Nuclear Power and Propulsion

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Sponsoring Program(s)

Space Technology Mission Directorate
Center Innovation Fund

Project Description

NASA is increasingly emphasizing exploration to bodies beyond near-Earth orbit. New propulsion systems and new spacecraft are being built for these missions. As the target bodies get further out from Earth, high energy density systems, e.g., nuclear fusion, for propulsion and power will be advantageous. The mass and size of these systems, including supporting systems such as the heat exchange system, including thermal radiators, will need to be as small as possible. Conventional heat exchange systems are a significant portion of the total thermal management mass and size.

Nuclear electric propulsion (NEP) is a promising option for high-speed, in-space travel due to the high energy density of nuclear fission power sources and efficient electric thrusters. Heat from the reactor is converted to power for use in propulsion or for system power. The heat not used in the power conversion is then radiated to space as shown in figure 1.

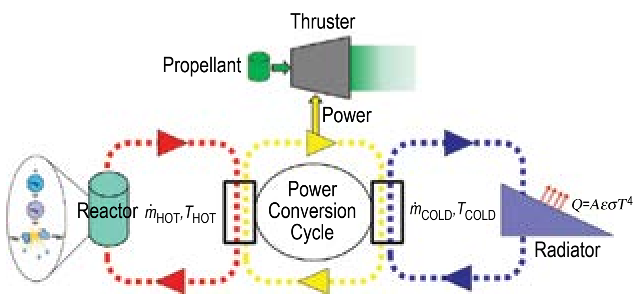

Figure 1: NEP system.

Advanced power conversion technologies will require high operating temperatures and would benefit from lightweight radiator materials. Radiator performance dictates power output for nuclear electric propulsion systems. Pitch-based carbon fiber materials have the potential to offer significant improvements in operating temperature, thermal conductivity, and mass. These properties combine to allow significant decreases in the total mass of the radiators and significant increases in the operating temperature of the fins.

A Center-funded project at NASA Marshall Space Flight Center has shown that high thermal conductivity, woven carbon fiber fins with no matrix material, can be used to dissipate waste heat from NEP systems and because of high specific power (kW/kg), will require less mass and possibly less total area than standard metal and composite radiator fins for radiating the same amount of heat.

This project uses an innovative approach to reduce the mass and size required for the thermal radiators to the point that in-space NEP and power is enabled. High thermal conductivity carbon fibers are lightweight, damage tolerant, and can be heated to high temperature.

Areal densities in the NASA set target range of 2 to 4 kg/m^2 (for enabling NEP) are achieved and with specific powers (kW/kg) a factor of about 7 greater than conventional metal fins and about 1.5 greater than carbon composite fins. Figure 2 shows one fin under test. All tests were done under vacuum conditions.

Anticipated Benefits

Woven bare carbon fibers used as the radiating surface or fin is an innovative approach. Using the bare carbon fiber with no, or little, matrix material avoids the additional mass of the matrix material and a reduced thermal conductivity also associated with the matrix material.

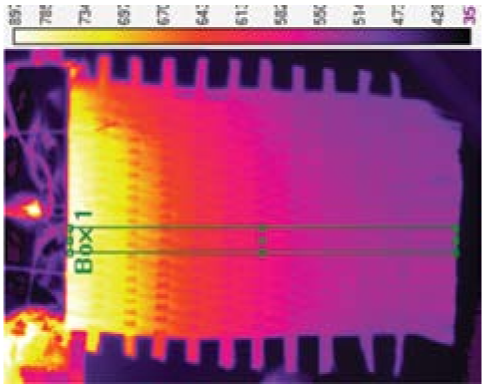

Figure 2: Woven bare carbon fibers under test in vacuum chamber.

Potential Applications

Woven bare carbon fins are applicable to all future missions using nuclear electric power and propulsion and to some solar system planetary surface missions for which solar power is not a viable option.

Notable Accomplishments

The following accomplishments were achieved: (1) Weaving the high thermal conductivity carbon fibers into a mat. This was done, apparently for the first time with K13D2U, by Textile Engineering and Manufacturing, a commercial company. The fact that fins using the K13D2U can be woven commercially means the fins can be mass produced; and (2) Attaching the fins to a heat pipe. Figure 3 shows the cross section of an experimental sample attachment using TiCuSil, a commercially available active braze material.

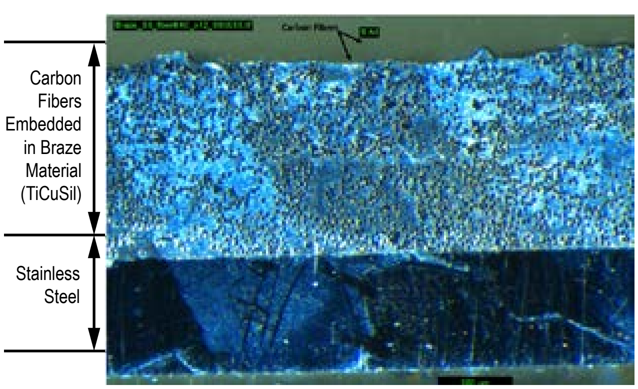

Figure 3: Cross section of braze sample processed in the vacuum isothermal oven.

Publications/Presentations

SanSoucie, M.P.; Rogers, J.R.; Craven, P.D.; and Hyers, R.W.: "Experimental Studies of Carbon Nanotube Materials for Space Radiators," Poster Presentation, National Space & Missile Materials Symposium (NSMMS), Tampa, FL, June 25–28, 2012.

Hyers, R.W.; Tomboulian, B.N.; Craven, P.D.; and Rogers, J.R.: "Lightweight, High-Temperature Radiator for Space Propulsion," 19th Advanced Space Propulsion Workshop, Huntsville, AL, November 27–29, 2012.

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Solid State Ultracapacitor

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Sponsoring Program(s)

Space Technology Mission Directorate
Center Innovation Fund, SLS Advanced Development,
Oak Ridge National Laboratory

Project Description

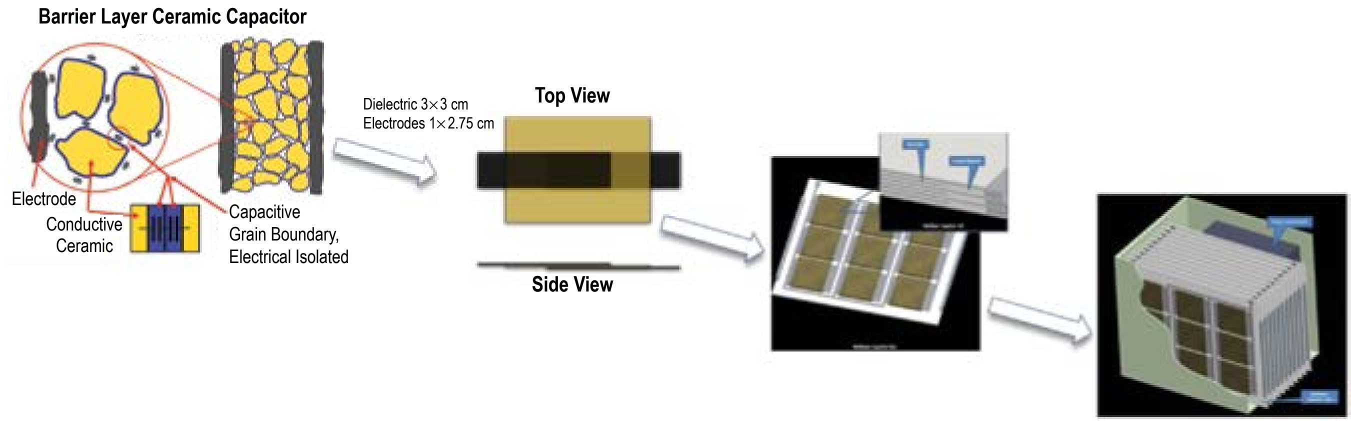
NASA analyzes, tests, packages, and fabricates electrical, electronic, and electromechanical (EEE) parts used in space vehicles. One area that NASA wishes to advance is energy storage and delivery. Currently, space vehicles use rechargeable batteries that utilize silver zinc or lithium ion electrochemical processes. These current state-of-the-art rechargeable batteries cannot be rapidly charged, contain harmful chemicals, and suffer from early wear-out mechanisms. A solid state ultracapacitor is an EEE part that offers significant advantages over current electrochemical and electrolytic devices.

The objective of this research is to develop an internal barrier layer ultracapacitor (IBLC) using novel dielectric materials as a battery replacement with a focus on these advantages: longer life, lower mass-to-weight ratio, rapid charging, on-demand pulse power, improved on-pad standby time without maintenance, and environmental friendliness.

The approach is unique in two areas. A deposition technique is used that has been shown to produce a more uniformly coated nanoparticle than sol-gel, which has resulted in colossal permittivities. These particles are then distributed in an ink formulation developed at NASA Marshall Space Flight Center (MSFC) and deposited utilizing a 3D aerosol jet technique. This additive manufacturing technique controls layer thickness, resulting in extremely large capacitance and energy density.

First ultracapacitor single cell built at MSFC (electrodes are dark blue and active material is pale blue). This device weighs <10 gm but has an equal capacitance and voltage of a bank of capacitors weighing over 490 gm.

Ultracapacitor single cells printed using 3D aerosol jet printing—the first board printed using multiple single cells to test scalability.



The ultimate goal of this project is to advance the state of the art from a concept of nanoparticles and nanoparticle manipulation to a single cell to a board with multiple cells to a module with multiple boards. This research project is currently building multiple cells on a board to test scalabilty.

Current state-of-art energy densities of various energy storage solutions compared to the MSFC developed solution.

Device	Energy Density (J/cc)
Aerospace Battery (Li-ion/28 V)	172 (calculated from spec)
Aerospace Range Safety Battery (Ag Zn/28 V)	57 (calculated from spec)
Commercial Electrolytic Ultracap (59 V)	15 (provided by manufacturer)
ES43 HESSCap Module/Multilayer Device	200 (calculated from model)
ES43 Single Layer/Single Cell Device (50 V)	1 (measured)

Anticipated Benefits

Once scalability has been achieved, energy densities of tens of J/cc are predicted in a small robust package. This will pave the way for smaller and more robust power sources in CubeSats and nanosats. Additionally, the large breakdown voltages and fast discharge rates that have been demonstrated will greatly benefit applications that require pulse power such as electric propulsion systems. If sufficient energy density is achieved in the final module, it could replace lithium ion batteries with a more reliable, longer lasting, and safer alternative.

Potential Applications

The Propulsion Research Center at MSFC is already considering this technology for their electric propulsion systems in order to replace wet tantalum capacitors. The CubeSat community is also looking at this technology to provide emergency supplemental power as primary power systems drain below required operating levels.

Notable Accomplishments

Ultracapacitors with energy densities exceeding 1 J/cc have been produced. Devices have shown charging times in milliseconds, breakdown voltages as high as 900 V in a 30 micron layer, and demonstrated ability to activate light-emitting diodes. This work has resulted in the submission of three patent applications and discovery of two spinoff technologies. The spinoffs include creation of a low-temperature conductor ink that was not commercially available and the construction of an ultrasensitive ceramic humidity sensor element that is only 30 microns thick.

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Spherically Actuated Motor

Project Manager(s)/Lead(s)

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Sponsoring Program(s)

Space Technology Mission Directorate
Center Innovation Fund

Project Description

A three degree of freedom (DOF) spherical actuator is proposed that will replace functions requiring three single DOF actuators in robotic manipulators providing space and weight savings while reducing the overall failure rate.

Exploration satellites, Space Station payload manipulators, and rovers requiring pan, tilt, and rotate movements need an actuator for each function. Not only does each actuator introduce additional failure modes and require bulky mechanical gimbals, each contains many moving parts, decreasing mean time to failure. A conventional robotic manipulator is shown in figure 1. Spherical motors perform all three actuation functions, i.e., three DOF, with only one moving part. Given a standard three actuator system whose actuators have a given failure rate compared to a spherical motor with an equal failure rate, the three actuator system is three times as likely to fail over the latter. The Jet Propulsion Laboratory reliability studies of NASA robotic spacecraft have shown that mechanical hardware/mechanism failures are more frequent and more likely to significantly affect mission success than are electronic failures. Unfortunately, previously designed spherical motors have been unable to provide the performance needed by space missions. This inadequacy is also why they are unavailable commercially. An improved patentable spherically actuated motor (SAM) is proposed to provide the performance and versatility required by NASA missions.

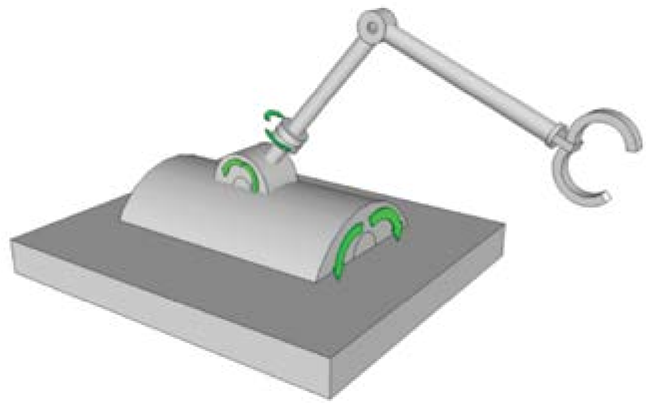

Figure 1: Conventional robotic manipulator.

Anticipated Benefits

Using SAM instead of conventional actuators in robotic manipulators would have the following benefits: Reduced failure rates and maintenance costs, longer service life, lower mass, and reduced volume.

Potential Applications

The proposed spherical motor has properties making it useful for a rolling/walking rover. In normal mode (fig. 2), the rover would turn its wheels to accomplish exploration missions as always. If difficult terrain or sandy soil is encountered and wheels rendered useless, the walking property of SAM (fig. 3) can be used to traverse the area. This innovation will add new versatility to NASA robotic missions.

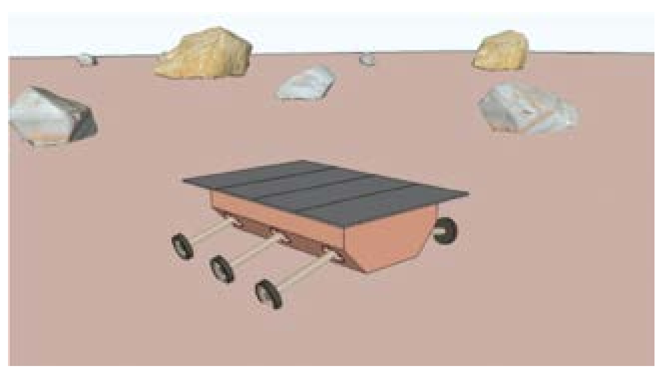

Figure 2: Exploration rover in normal mode.

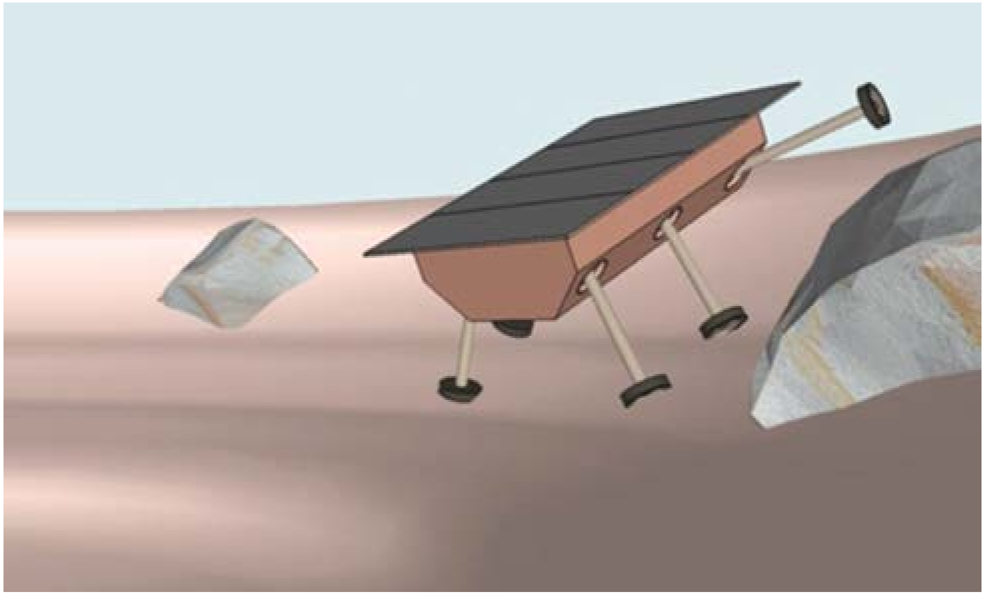

Figure 3: Exploration rover in walking mode.

There are many other uses in spaceflight. Spherical motors can be the basis for robotic manipulators in landers and sample return missions. Satellites and probes could use them to point instruments or high gain antennas. The International Space Station could use it in robotic manipulator arms to move payloads, make repairs, or even to point sensors or cameras in payload experiments. Having only one moving part gives the spherical motor an extended service life, making it ideal for long-duration missions. Since the cost for space access is measured by the pound, weight savings offered by this design over traditional multi-actuator design merit significant project savings.

In the commercial sector, applications in human prosthetics and exoskeletal suits could give wounded soldiers, the elderly, and the disabled new mobility, enhancing their quality of life.

Factory assembly line robots could also benefit from the use of simpler robotic actuators, thus lowering production costs.

Notable Accomplishments

The 3D model of SAM has been completed and printed. One prototype SAM has been built, validating the proposed unique manufacturing technique.

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Targeted Structural Optimization With Additive Manufacturing of Metals

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Sponsoring Program(s)

Space Technology Mission Directorate
Center Innovation Fund

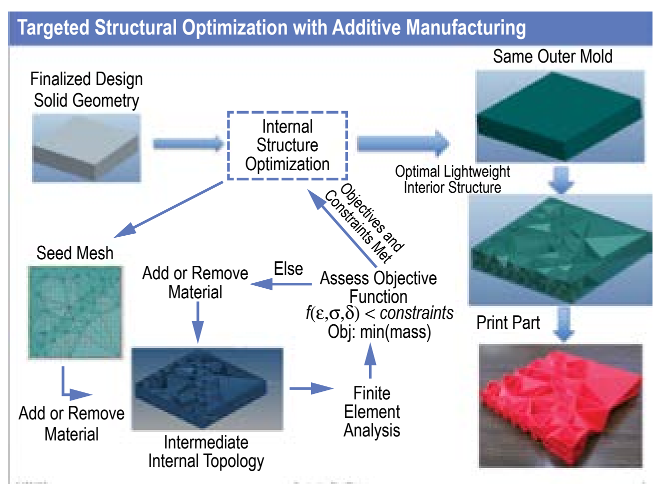
Project Description

The recent advances in additive manufacturing (AM) of metals have now improved the state-of-the-art such that traditionally nonproducible parts can be readily produced in a cost-effective way. Because of these advances in manufacturing technology, structural optimization techniques are well positioned to supplement and advance this new technology. The goal of this project is to develop a structural design, analysis, and optimization framework combined with AM to significantly lightweight the interior of metallic structures while maintaining the selected structural properties of the original solid. This is a new state-of-the-art capability to significantly reduce mass, while maintaining the structural integrity of the original design, something that can only be done with AM.

In addition, this framework will couple the design, analysis, and fabrication process, meaning that what has been designed directly represents the produced part, thus closing the loop on the design cycle and removing human iteration between design and fabrication. This fundamental concept has applications from lightweighting launch vehicle components to in situ resource fabrication.

This design automation and optimization framework is akin to a field of research known as topology optimization combined with a variation of shape optimization. Topology optimization is often used to minimize the mass required by a part while maintaining the overall stiffness required for the structure by removing unloaded material. This area has seen a plethora of attention in the literature and academia and has been implemented in many commercial applications in the general sense. The research activity proposed here effectively combines topology with AM, resulting in minimal mass hardware, and furthers this area by using adaptive mesh refinement with shape optimization, which is a relatively new area of research.

The process is simple in thought; typically structural analysis utilizes the finite element method. This process discretizes continuum structures into discrete solid elements to perform an analysis that will determine the overall strength of the structure. The core of the idea is this. What if, using these solid elements, the solid fill could be removed, but the defining faces of that solid remain as shells? The part will now be lighter, with a similar overall strength and stiffness. This is essentially the core concept behind grid-stiffened structures; this time the outer profile remains intact to maintain form, fit, and function. In traditional manufacturing, this concept is impossible to implement without joining panels, adding complexity and cost, but AM can easily achieve this.



Automation and optimization framework.

The process begins with a part that has already been designed to meet form, fit, and function and is considered to be mature in the design cycle, meaning all applicable requirements (loads, environments, etc.)

have been estimated. The first step in the optimization is to produce a 3D finite element model using tetrahedral elements and run an analysis to determine where material is not being fully utilized. From there, the optimization will begin removing material by converting tetrahedral elements to 2D shell elements with a minimal thickness, thus hollowing the element and removing inefficiently utilized mass. The newly formed shell model is then rerun in the analysis and assessed and ranked based upon an objective function. This loop is repeated until convergence is met. A 3D computer-aided design model of the optimized internal topology is then generated automatically. The outer mold and new internal topology are passed to the AM process to be produced. This concept stands on the shoulders of two well-grounded areas of research, structural optimization and stiffened structures. There is much literature and technical work to draw upon in these disciplines. The goal of this project is not to reinvent either concept, but to utilize all research available in these areas and fine-tune its application through a novel combination with AM.

Anticipated Benefits

Investment in this research will result in developing an enabling technology for AM. Breaking the boundaries here will position NASA Marshall Space Flight Center (MSFC) to continue being a leader in this community and make strides toward being able to produce flight parts or structures entirely by AM.

In addition to this, successful completion of the work outlined in the project will lead directly to follow-on work. Called out in this project is to specifically focus on structural strength aspects of this process, but once this concept is proven, extensions can be made to other areas such as thermal and dynamic design problems. Once this Center Innovation Fund is completed, more attention can be given to structural strength considerations and what problems remained to be solved to make this process acceptable for the production of flight hardware.

Potential Applications

This project will develop a supporting technology that will aid in the structural design process. By extension, the results have a broad scope of application that aligns with many Center strategic priorities. Several key areas of high impact have been identified. Lightweighting metallic structures on International Space Station (ISS) payloads can dramatically reduce up-mass and therefore decrease costs of payloads being delivered to the ISS and allow cargo vehicles to carry more: (1) Advanced manufacturing within in situ fabrication repair —This process would help on-orbit manufacturing by reducing the amount of material needed to build a component and therefore help to limit the amount of raw material needed; (2) Rapid, innovative affordable manufacturing of propulsion components—AM has already been used successfully in a hot-fire of a rocket engine at MSFC. Increasing capabilities of AM would be beneficial to this effort; (3) Affordable and innovative technologies for sample return—A key aspect to sample return is maximizing structural efficiency so as to minimize the amount of propellant needed to be carried on the mission. This technology will support that goal; and (4) Small Spacecraft Enabling Technologies—The ability to both lightweight spacecraft as well as tailor structural properties could be highly useful in the design of spacecraft. Ultimately, this sort of technology could be used to produce small spacecraft chassis entirely by AM.

Notable Accomplishments

The framework for the optimization process was laid out. Several algorithms were developed that allowed creation of a design space that would be suitable for use with a genetic algorithm. The optimization routine is being tuned for the specific problem and manufacturing constraints are in the process of being incorporated into the optimization routine.

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Flexible Electrostatic Technologies for Capture and Handling, Phase 1

Project Manager(s)/Lead(s)

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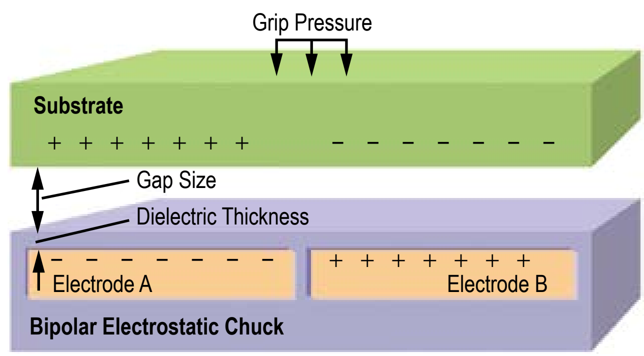
Sponsoring Program(s)

Space Technology Mission Directorate
Center Innovation Fund

Project Description

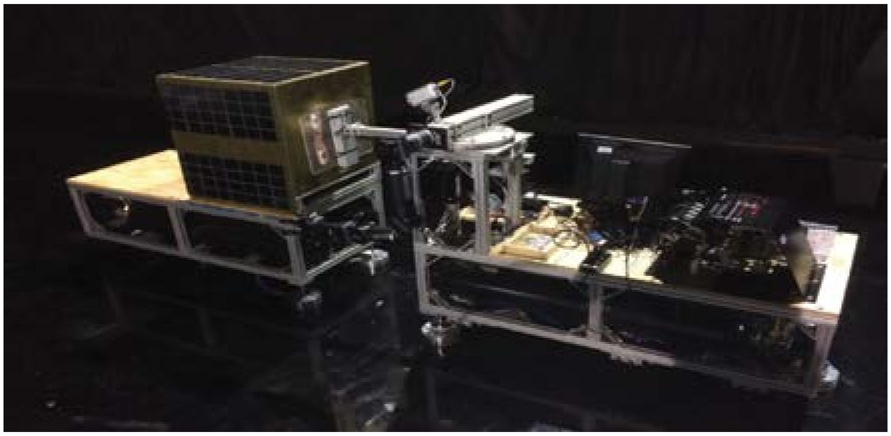
Fundamental to many of NASA's in-space transportation missions is the capture and handling of various objects and vehicles in various orbits for servicing, debris disposal, sample retrieval, and assembly without the benefit of sufficient grapple fixtures and docking ports. To perform similar material handling tasks on Earth, pincher grippers, suction grippers, or magnetic chucks are used, but are unable to reliably grip aluminum and composite spacecraft, insulation, radiators, solar arrays, or extra-terrestrial objects in the vacuum of outer space without dedicated handles in the right places.

The electronic Flexible Electrostatic Technologies for space Capture and Handling (FETCH) will enable reliable and compliant gripping (soft dock) of practically any object in various orbits or surfaces without dedicated mechanical features, very low impact capture, and built-in proximity sensing without any conventional actuators. Originally developed to handle semiconductor and glass wafers during vacuum chamber processing without contamination, the normal rigid wafer handling chucks are replaced with thin metal foil segments laminated in flexible insulation driven by commercial off-the-shelf solid state, high-voltage power supplies. Preliminary testing in NASA Marshall Space Flight Center's (MSFC's) Flat Floor Robotics Lab demonstrated compliant alignment and gripping with a full-sized, 150-lb microsat mockup and translation before a clean release with a flip of a switch. The flexible electrostatic gripper pads can be adapted to various space applications with different sizes, shapes, and foil electrode layouts even with openings through the gripper pads for addition of guidance sensors or injection of permanent adhesives. With gripping forces estimated between 0.5 and 2.5 lb/in^2 or 70–300 lb/ft^2 of surface contact, the FETCH can turn on and off rapidly and repeatedly to enable sample handling, soft docking, in-space assembly, precision relocation, and surface translation for accurate anchoring.



Electrostatic grip illustration.

Actual electrostatic gripper (unmounted).



FASTSAT mockup capture and handling from air-bearing mini space tug simulator.

CIF

Anticipated Benefits

The need to capture, handle, and assemble very large objects and modules is a key technology gap that will enable or prevent MSFC and this Agency to piece together the giant ships that will be used to sail beyond Earth orbit and the Moon. The ability to reach out and grip and handle objects enabled the evolution of primates to travel across the oceans and now across space to other worlds and any technology that will enable us to grip and handle with greater capability in various environments will enhance NASA's capability for space exploration. NASA has investigated the flexible electrostatic (ES) grippers for 2 years in MSFC's Flat Floor Robotics Lab with various development activities including purchase, testing, modification, and demonstration of the ES grippers with various spacecraft materials and configurations, with future ongoing testing.

Potential Applications

This new capability to sense proximity, flexibly align to, and attract and cleanly grip and capture\translate practically any object or shape in space without any predesigned physical features or added sensors or actuators will enable or enhance many of MSFC's strategic emphasis areas in space transportation and space systems: (1) Flexible ES grippers on booms will enable assembly of thermal shields, radiators, or arrays from modules to form the vehicle stacks for advanced in-space propulsion technology test-bed demonstrations and transportation missions (using Cryogenics, nuclear, sails, tethers, etc.) for beyond Earth orbit (BEO) exploration such as Mars missions; (2) Flex ES grippers on booms will enable commercial cargo vehicles to berth to the International Space Station (ISS) from a safe station-keeping distance with minimum crew support and without the ISS robot arm; (3) Flexible ES grippers will enable noncontaminating inspection robots to crawl outside and inside modules, engines, and the ISS using only power with no rails, handles, and without the fuel, complexity, and safety issues of free-flying robots to support advanced in-space propulsion test-beds and systems, innovative BEO exploration, habitation module outfitting, and low-cost ISS payloads; (4) An ES gripper-based rover can attach to and transverse any slope, any angle under low or no gravity in vacuum without anchors, crevasses, propulsion, or contamination and will enable 'gravity boots' for extravehicular activity walking cradles for exploration; and (5) Flexible ES grippers on booms can capture, de-spin, and handle sample canisters and space vehicles from a safe distance with minimal thruster use for sample return, satellite servicing, and debris relocation.

Notable Accomplishments

We have demonstrated that a flexible electrostatic or electroadhesion gripper that is all electric and can conform and capture various shapes, sizes, and materials without target preparation generates pull-in force across the gap to grip and self-align (similar to magnetics), and releases cleanly without active motors in space. The following video is a demonstration of a thruster propelled approach to a full-scale, fast, affordable science and technology satellite (FASTSAT) mockup on air-bearings (~150 lb) and the electrostatic gripper activating, gripping, and moving the mockup through the gripper with the mini space tug simulator's thrusters: <https://www.youtube.com/watch?v=Zm-naczMdhU>.

Direct Drive Solar-Powered Arcjet Thruster

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Sponsoring Program(s)

Space Technology Mission Directorate
Center Innovation Fund

Project Description

Electric thrusters typically require a power processing unit (PPU) to convert the spacecraft-provided power to the voltage and current that a thruster needs for operation. NASA Marshall Space Flight Center has initiated fundamental studies on whether an arcjet thruster can be operated directly with the power produced by solar arrays without any additional conversion. Elimination of the PPU significantly reduces system-level complexity of the propulsion system, and lowers developmental cost and risk. The proposed work will aim to refine the proof-of-concept presently being assembled and begin to identify and address technical questions related to power conditioning and noise suppression in the system, and heating of the thruster in long-duration operation. The apparatus proposed for investigation has a target power level of 400 to 1,000 W. The proposed direct-drive arcjet is potentially a highly scalable concept, applicable to spacecraft with up to hundreds of kilowatts and beyond.

The design of the arcjet built for this effort was based on previous low power (1 kW class) arcjets.[1–3] It has a precision machined 99.95% pure tungsten anode that also serves as the nozzle with a 0.040-in- (1-mm-) diameter, 0.040-in-long constrictor region. An additional anode with a 0.020-in- (0.5-mm-) diameter, 0.020-in-long constrictor region was purchased, but has not yet been used. The cathode is a 0.125-in-diameter tungsten welding electrode doped with lanthum-oxygen; its tip was precision ground to a 308° angle and terminates in a blunt end. The two electrodes are separated by a boron-nitride insulator that also serves as the propellant manifold; it ends in six small holes which introduce the propellant gas in the diverging section of the nozzle, directly adjacent to the cathode. The electrodes and insulator are housed in a stainless-steel outer body, with a Macor insulator at the mid-plane to provide thermal isolation between the front and back halves of the device. The gas seals were made using Grafoil gaskets. Figure 1(a) shows the assembled thruster; figure 1(b) shows the thruster in the vacuum chamber with electrical and propellant connections.

(a)

(b)

Figure 1: Direct drive arcjet: (a) In the vacuum chamber and (b) in operation.

Anticipated Benefits

Direct drive of an electric propulsion system confers the advantage of reducing or eliminating the PPU that is typically needed to convert the spacecraft-provided power to the voltage and current needed for thruster operation. Since the PPU is typically the most expensive piece of an electric thruster system, from both a fabrication and qualification standpoint, its elimination offers the potential for major reductions in system cost and risk.

Potential Applications

Arcjets are widely used for station keeping of satellites and, in higher power incarnations, may be used for orbit raising. A direct-drive electric propulsion system would be comprised of a thruster that operates with the power supplied directly from the power source (typically solar arrays) with no further power conditioning needed between those two components. Arcjets are best suited for direct drive, as the voltage and current levels they require are close to the output levels of photovoltaic arrays. Demonstration of direct-drive operation would significantly reduce cost and lead time in the deployment of these systems.

Notable Accomplishments

Initial testing was conducted in a 3.5-ft-diameter vacuum chamber (see fig. 2); the ultimate pressure reached during quasi-steady operation of the thruster was about 330 millitorr. The thruster was powered with a high current, 15-kW power supply. The discharge was initiated with a high-voltage (~10 kV) spark initiator that was isolated from the supply by a stack of diodes. Initial testing indicated that an operating point exists within the I-V characteristics that is typical of solar arrays; for a flow rate of 20 mg/s (argon), the arc could be sustained at a voltage of about 20 V and a current of 25 A (500 W).

Figure 2: The direct drive arcjet in operation.

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Active Collision Avoidance for Planetary Landers

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Sponsoring Program(s)

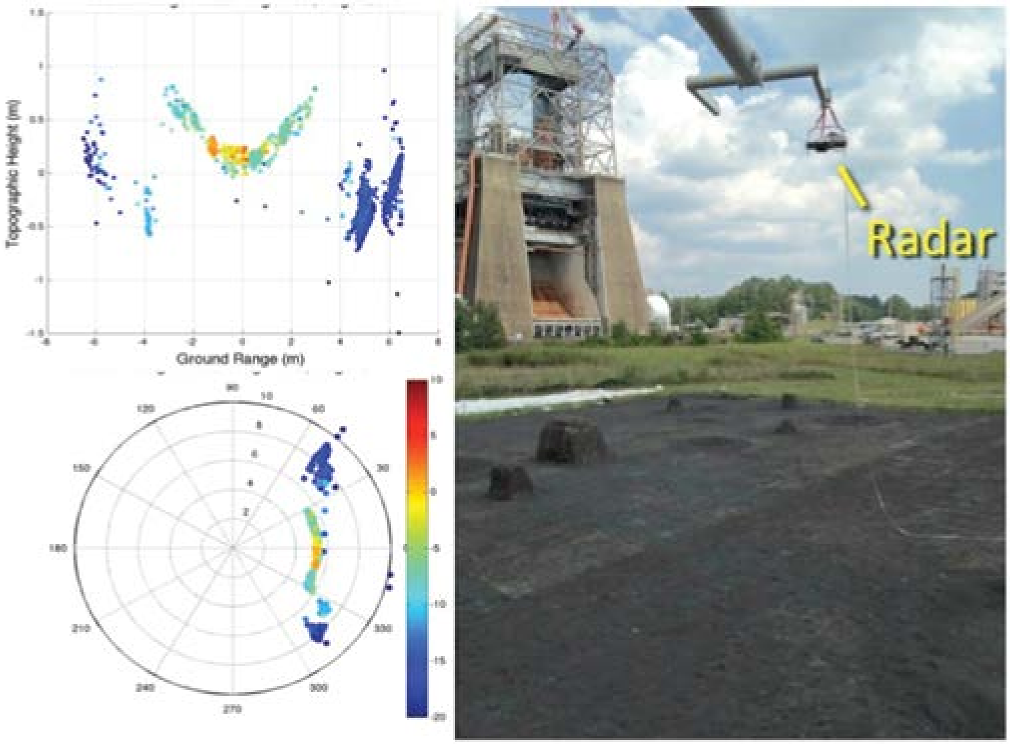
Space Technology Mission Directorate
Center Innovation Fund

Project Description

The use of automotive radar systems are being evaluated for collision avoidance in planetary landers. Our focus is to develop a low-cost, light-weight collision avoidance system that overcomes the drawbacks identified with optical-based systems. We also seek to complement the Autonomous Landing and Hazard Avoidance Technology system by providing mission planners an alternative system that can be used on low-cost, small robotic missions and in close approach. Our approach takes advantage of how electromagnetic radiation interacts with solids. As the wavelength increases, the sensitivity of the radiation to isolated solids of a specific particle size decreases. Thus, rocket exhaust-blown dust particles, which have major significance in visible wavelengths, have much less significance at radar wavelengths.

Dust being blown by a lander's rocket exhaust at the MSFC Lunar Terrain Testbed.

Summer intern Morgan Minton holding the interferometric radar mounted on an aluminum backplate.



Radar reflectivity and topographic height measured by the radar in the lunar terrain field. The radar unit is suspended from a boom.

Anticipated Benefits

The system under test, which is a commercially available unit used in automobiles for hazard detection, requires lower power and has smaller mass than alternative technologies being tested by NASA. It should also escape the limitations created by movement of the planetary regolith caused by the rocket exhaust of the approaching lander. It also takes advantage of the huge investments made in this technology by the automotive industry.

Potential Applications

Present-day robotic missions to other planets require superlative knowledge of the terrain in order to predetermine a landing spot that is relatively safe. Acceptable landing sites can be miles from the mission objective or mission objectives must be tailored to suit landing sites. Requiring precise, a priori knowledge of local terrain is often neither practical nor is it an efficient way of selecting landing sites for robotic missions. Future robotic exploration missions should be capable of autonomously identifying a safe landing target within a specified target area selected by mission requirements. Such autonomous landing systems must have three capabilities—'see' the surface, identify a suitable target, and land the vehicle. The interferometric radar technology being tested has the potential of providing the necessary information for autonomous lander control.

Notable Accomplishments

Preliminary tests of a commercial off-the-shelf automotive radar system were conducted. A low data acquisition system was developed for the radar based on a Raspberry Pi, and data processing and visualization software were developed. Preliminary tests with the radar were conducted at various locations including the NASA Marshall Space Flight Center lunar terrain field. Results from these tests show that radar can be used to generate topographic maps of surfaces such as the lunar terrain field. Further tests in FY 2015 with this system will be conducted to further characterize the radar and investigate the possibility of generating topographic maps in real time.

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A Magnetron Sputter Deposition System for the Development of X-ray Multilayer Optics

Project Manager(s)/Lead(s)

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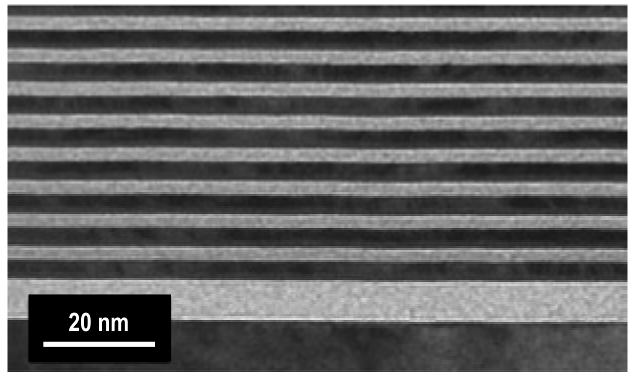
Sponsoring Program(s)

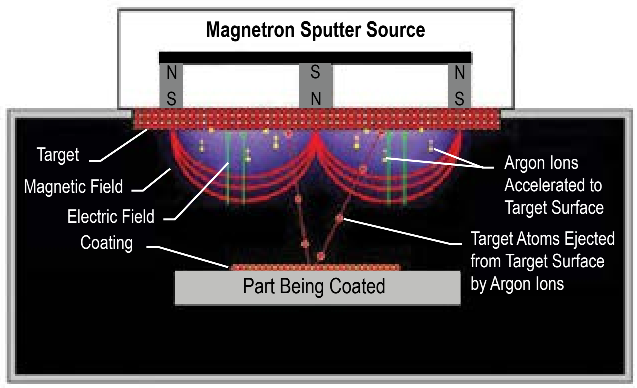
Space Technology Mission Directorate
Center Innovation Fund

Project Description

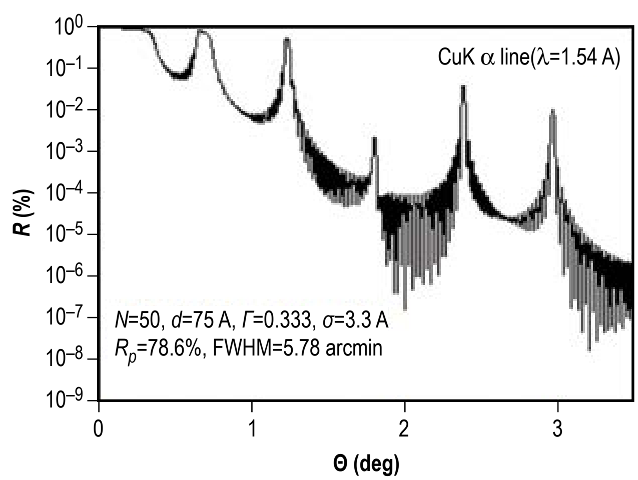
The project objective is to establish the capability to deposit multilayer structures for x-ray, neutron, and extreme ultraviolet (EUV) optic applications through the development of a magnetron sputtering deposition system. A specific goal of this endeavor is to combine multilayer deposition technology with the replication process in order to enhance NASA Marshall Space Flight Center's (MSFC's) position as a world leader in the design of innovative x-ray instrumentation through the development of full shell replicated multilayer optics. The development of multilayer structures are absolutely necessary in order to advance the field of x-ray astronomy by pushing the limit for observing the universe to ever-increasing photon energies (i.e., up to 200 keV or higher), well beyond Chandra's (~10 keV) and NuStar's (~75 keV) capability. The addition of multilayer technology would significantly enhance the x-ray optics capability at MSFC and allow NASA to maintain its world leadership position in the development, fabrication, and design of innovative x-ray instrumentation, which would be the first of its kind by combining multilayer technology with the mirror replication process. This marriage of these technologies would allow astronomers to see the universe in a new light by pushing to higher energies that are out of reach with today's instruments. To this aim, a magnetron vacuum sputter deposition system for the deposition of novel multilayer thin film x-ray optics is proposed. A significant secondary use of the vacuum deposition system includes the capability to fabricate multilayers for applications in the field of EUV optics for solar physics, neutron optics, and x-ray optics for a broad range of applications including medical imaging.



Transmission electron microscopy image of multilayer structure.



Schematic diagram of the magnetron sputtering process.



Calculated reflectivity from a periodic multilayer structure.

Anticipated Benefits

The ultimate goal is to provide the x-ray astrophysics community with improved instrumentation for the discovery of how the universe works from the very moment of its creation through the evolution of galaxies, stars, and planets, how it will continue to evolve, and what its ultimate fate may be.

This project is specifically related to the following technology theme: x-ray telescope systems and associated technologies.

The activity of this project also stimulates the neutron, EUV, and x-ray instrumentation development in other fields including medical imaging.

Notable Accomplishments

Funding cuts in the first year prohibited the completion of first year goals. However, a vacuum chamber was designed, procured, and received.

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Electronegative Gas Thruster

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Sponsoring Program(s)

Space Technology Mission Directorate
Center Innovation Fund

Project Description

The project is an international collaboration and academic partnership to mature an innovative electric propulsion thruster concept to Technology Research Level-3 (TRL-3) through direct thrust measurement. The project includes application assessment of the technology ranging from small spacecraft to high power. The Plasma propulsion with Electronegative GASES (PEGASES) basic proof of concept has been matured to TRL-2 by Ane Aanesland of Laboratoire de Physique des Plasma at Ecole Polytechnique. The concept has advantages through eliminating the neutralizer requirement and should yield longer life and lower cost over conventional gridded ion engines. The objective of this research is to validate the proof of concept through the first direct thrust measurements and mature the concept to TRL-3.

Traditional electric propulsion thrusters such as conventional gridded-ion thrusters (GITs) or Hall thrusters use a heavy gas that is ionized to produce a heavy positive ion. For a typical GIT, a screen grid biased below the anode potential is used to align charged particles, leaving the thruster in order to maximize thrust and limit the erosion of the downstream, negatively biased acceleration grid. A plasma sheath forms between the two grids extracting positive ions from the plasma and accelerates them to generate thrust. Electrons are collected by an anode in the discharge region and expelled at the thruster exit through a neutralizer cathode to maintain quasineutrality of the far-field plume. This thruster is unique through the use of an electronegative gas combined with a magnetic filter. The electronegative thruster then uses a temporally varying approach for ion extraction where a single grid assembly used an alternating voltage bias that changed from positive to negative over the course of a periodic waveform (e.g., sinusoidal, square, etc.) allowing for an alternating acceleration of positively and negatively charged species. The thruster concept and magnetic filter model are illustrated in figures 1 and 2, respectively.

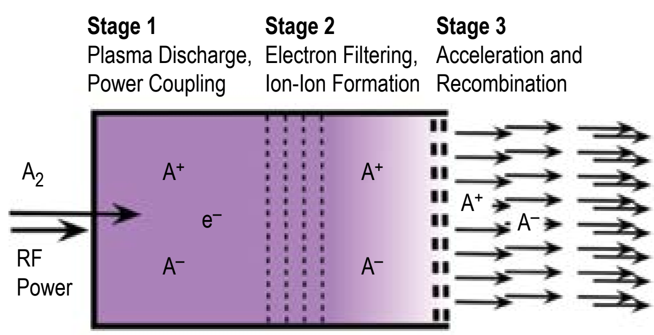

Figure 1: Concept of the electronegative gas thruster.[1]

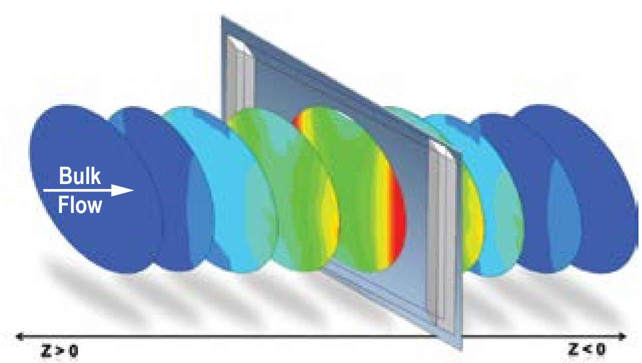

Figure 2: Modeling of the magnetic filter.

The project included system optimization studies, FLUENT simulators of the gas flow, magnetic field optimization, gas distributer optimization, thermal modeling for grids, two iterations of the thruster design, integrated power electronics, performance of preliminary testing, and presenting progress at a technical conference. The thruster alone demonstrated very simple ignition and operation relative to conventional gridded ion thrusters. No thruster (cathode) conditioning was required. Testing conditions included flow rates between 2 and 20 sccm on argon, SF6, and xenon, radio

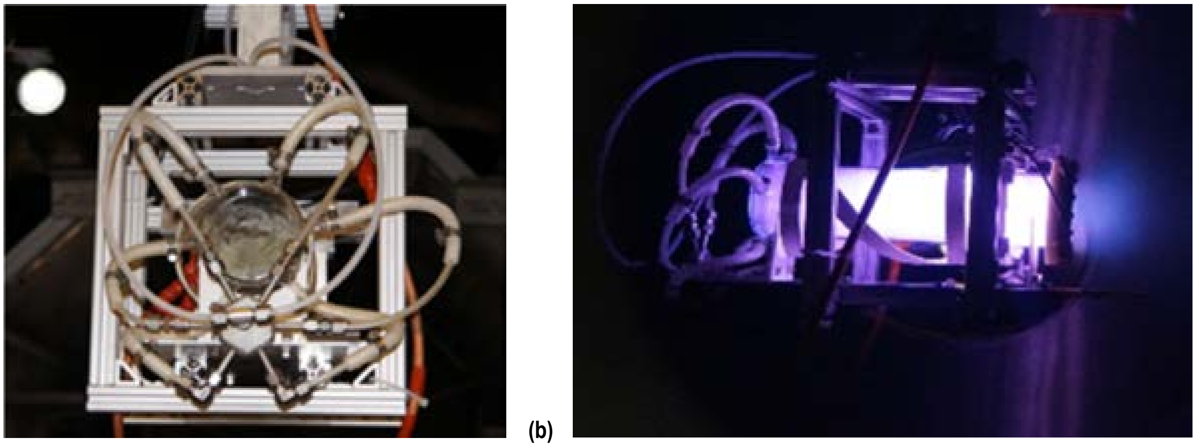

Figure 3: Electronegative thruster on the MSFC thrust stand: (a) Configuration and (b) operation.

frequency (RF) power levels from 100 to 600 W, and RF frequencies of 13.56 MHz and 4 MHz for two different antenna configurations.

Anticipated Benefits

While electric propulsion may be the only viable method for very high ΔV capability for small spacecraft, electric propulsion thrusters are often cost prohibitive. Though the electronegative thruster is not expected to achieve performance of conventional gridded ion and Hall thrusters, the thruster represents a potential for a lower cost electric propulsion thruster. A conventional gridded ion engine requires a main propellant flow, an ionization cathode, and a neutralizer cathode while the electronegative thruster only requires one. The elimination of the cathode reduces propellant cost by reducing propellant purity concerns and simplifies propellant loading and handling and reduces system conditioning requirements. The increased recombination speed of the plasma should reduce spacecraft plume interactions, and charge exchange erosion is reduced, increasing grid life.

Potential Applications

The applications pursued included low-cost electric propulsion missions. However, the performance estimates are significantly lower than state-of-the-art thrusters and the complexity of the thruster places additional burden on the power processing unit. Even with the concepts thruster advantages, the low performance combined with the additional power system complexity is likely to limit infusion opportunities. The thruster can serve as a test-bed for future plasma physics studies. The thruster may have increased mission potential through an advantage of a xenon/iodine propellant combination.

Notable Accomplishments

This project produced two new technology reports that could result in patents.

References

1. Aanesland, A.; et al.: "Directions for the Future: Successive Acceleration of Positive and Negative Ions Applied to Space Propulsion," Laboratoire de Physique Des Plasmas, CNRS Ecole Polytechnique, France, doi: 10.5170ICERN-2013-007.575, 2014.

2. Schloeder, N.R.; Lie, T.M.; Walker, M.L.; et al.: "Design and Preliminary Testing of Electronegative Ion Thruster," AIAA No. 2014-3425, 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, July 28–30, 2014.

Green Application for Space Power

Project Manager(s)/Lead(s)

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Sponsoring Program(s)

Space Technology Mission Directorate
Center Innovation Fund
Space Launch System Advanced Development

Project Description

Most space vehicle auxiliary power units (APUs) use hydrazine propellant for generating power. Hydrazine is a toxic, hazardous fuel that requires special safety equipment and processes for handling and loading. In recent years, there has been development of two green propellants (less toxic) that could enable their use in APUs. The Swedish government, in concert with the Swedish Space Corporation, has developed a propellant based on ammonium dinitramide (LMP-103S) that was flown on the Prisma spacecraft in 2010. The United States Air Force (USAF) has been developing a propellant based on hydroxylammonium nitrate (AF-M315E) that is scheduled to fly on the Green Propellant Infusion Mission in the spring of 2016 to demonstrate apogee and reaction control thrusters. However, no one else in the Agency is currently pursuing use of green propellants for application to the APUs. Per the TA-01 Launch Propulsion Roadmap, the Space Technology Mission Directorate had identified the need to have a green propellant APU by 2015. This is our motivation for continuing activities.

The plan proposed by NASA Marshall Space Flight Center (MSFC) is to utilize existing F-16 and Space Shuttle hardware to provide a low-cost demonstration testbed for green propellant APUs. During preparation for the TDM12 solicitation, MSFC was able to acquire a solid rocket booster gas generator and an orbiter APU residing at White Sands Test Facility that were no longer needed by the Space Launch System (SLS). Since these test assets are limited in number, a Department of Defense equivalent asset was identified. The F-16 fighter jet uses H-70 propellant (30% diluted hydrazine) for providing the plane emergency power if the pilot loses engine power. Since there have been over 4,400 F-16 planes built, there are a number of these planes that have been retired and await destruction at the Davis Monthan Air Force Base in Tucson, AZ.

The feasibility testing funded by MSFC investment was to utilize a modified version of the USAF's green propellant to decompose with the F-16 gas generator, a main component within the emergency power unit (EPU) assembly. MSFC worked closely with engineers/chemists at the Air Force Research Laboratory (AFRL), adding water content to the AF-M315E to lower anticipated combustion temperatures. AFRL mixed the propellant, performed catalyst heating tests, and provided 5 gallons of propellant to MSFC for test operations. MSFC disassembled the EPU and configured the test setup shown in figure 1. A series of 64 pulse operations were performed over the course of 2 days.

Anticipated Benefits

Demonstration of green propellant with an alternative catalyst material could lead to cost savings across the F-16 fleet and SLS booster nozzle gimballing. This testing could further be extended to testing the other green monopropellant that has matured: LMP-103S. Both leading green propellants offer not only increase performance characteristics compared to hydrazine (density and impulse) but also are less hazardous. Safety testing reveals that SCAPE (self-contained atmospheric protective ensemble) suits are not required for transport, loading, and handling of the propellant, which would lower operations costs and allow for serial operations to occur for aircraft and spacecraft preparation.

Potential Applications

Besides the F-16 EPU and the SLS booster APU, the U-2 spy plane also uses a form of hydrazine for engine restart at altitude. Given further interest, there may be the opportunity to investigate that platform as well.

Figure 1: F-16 gas generator installed at MSFC Component Development Area Test Cell.

Notable Accomplishments

MSFC recently completed feasibility testing of an F-16 EPU gas generator using a variant of the AF-M315E (higher water content). MSFC demonstrated that the gas generator can develop 300 psi of pressure. What is unique about this accomplishment is that the propellant mixture was reactive with the hydrazine catalyst material (Shell 405). With additional testing, there could be a significant cost savings and safety improvement if the F-16 System Program Office decides to implement this propellant across the vast fleet of F-16 users. Likewise, SLS may consider transitioning from hydrazine-powered APUs to a green propellant alternative.

References

MSFC 2014 Center Innovation Fund Final Report, Green Application for Space Power, J. Robinson.

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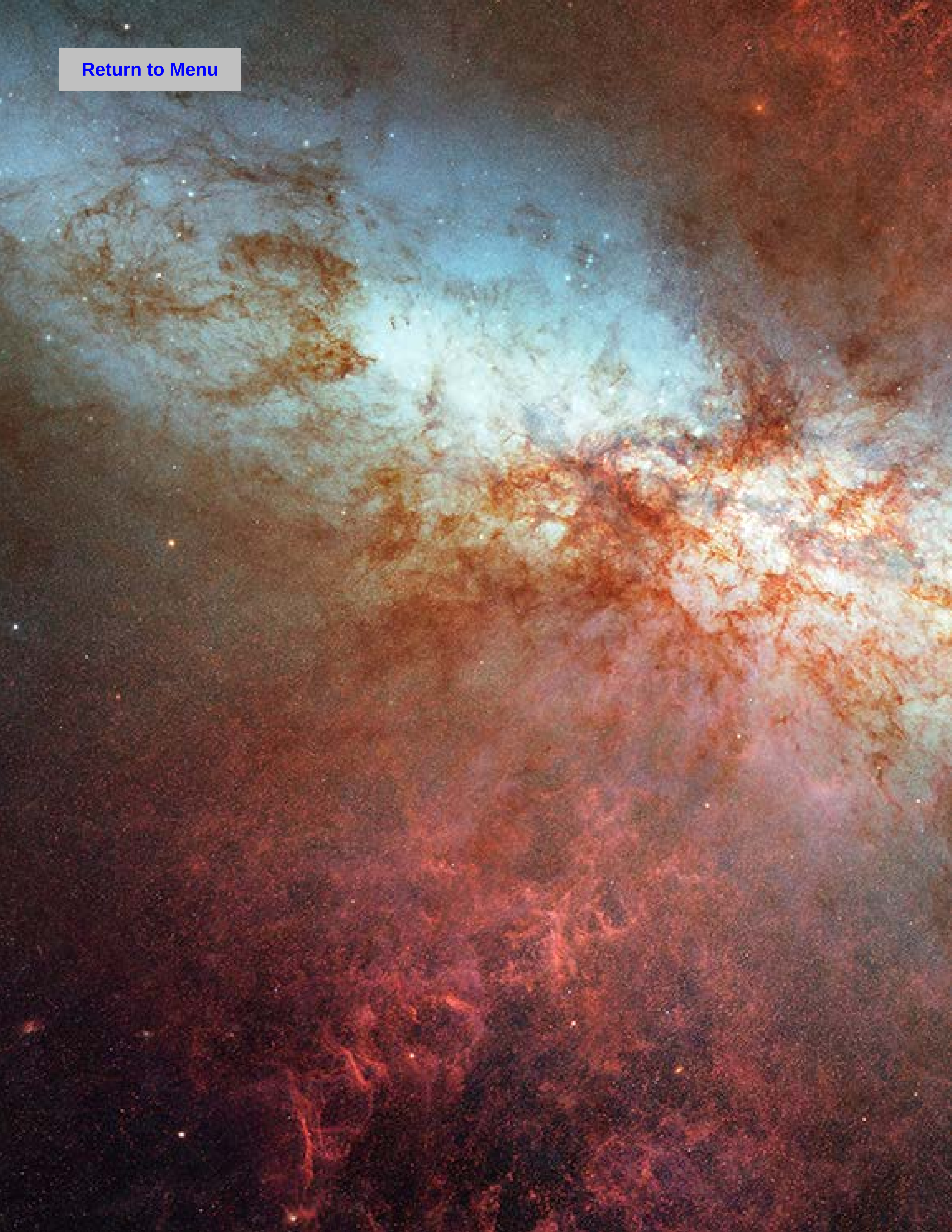

Marshall Space Flight Center (MSFC)/
Center Management and Operations (CMO)

Technology Investment Program (TIP)

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Low-Energy Microfocus X-Ray Source for Enhanced Testing Capability in the Stray Light Facility

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Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Technology Investment Program

Project Description

Research toward high-resolution, soft x-ray optics (mirrors and gratings) necessary for the next generation large x-ray observatories requires x-ray testing using a low-energy x-ray source with fine angular size (<1 arcsecond). To accommodate this somewhat demanding requirement, NASA Marshall Space Flight Center (MSFC) has procured a custom, windowless low-energy microfocus (~0.1 mm spot) x-ray source from TruFocus Corporation that mates directly to the Stray Light Facility (SLF) (fig. 1).

MSFC X-ray Astronomy team members are internationally recognized for their expertise in the development, fabrication, and testing of grazing-incidence optics for x-ray telescopes. One of the key MSFC facilities for testing novel x-ray instrumentation is the SLF. This facility is an ~100-m-long beam line equipped with multiple x-ray sources and detectors. This new source adds to the already robust compliment of instrumentation, allowing MSFC to support additional internal and community x-ray testing needs.

This new windowless (low-energy) source has an aluminum target and adjustable focal spot size of 100 to 150 µm and can operate from zero to 10 V and zero to 2 mA.[1] Figure 2 is an image taken of the front of the control panel, with primary features labeled.

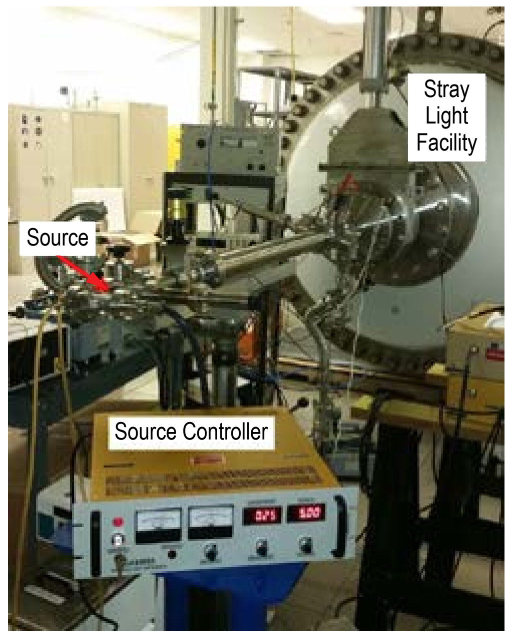

Figure 1: TruFocus x-ray source attached to MSFC's Stray Light Facility.

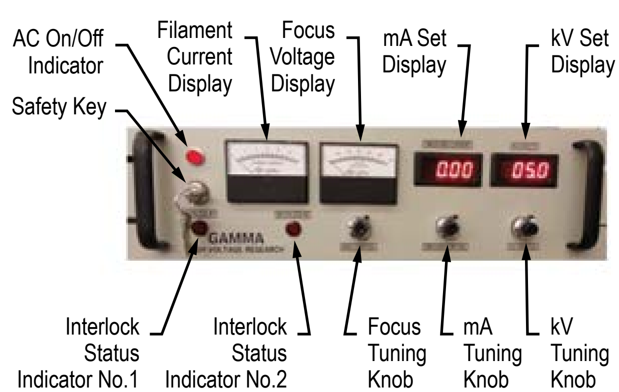

Figure 2: Image of the front of the source controller/power supply.

Anticipated Benefits

MSFC is currently involved in several internal and external projects related to the testing of high-resolution x-ray optics and gratings. Meeting science requirements and extending these and new collaborations to subsequent technology development proposals hinges significantly upon MSFC's capabilities in performing existing x-ray testing needs.

Potential Applications

Enhancing MSFC's capability to test state-of-the-art, high-resolution x-ray optics and gratings allows MSFC to maintain its status as a world-class facility for such work. Applications include testing from internal and external NASA sources.

Notable Accomplishments

This source has been tested at MSFC with a stable response over the course of several days. Further testing is planned.

References

1. TruFocus User Guide, "Low Energy X-ray Sub-System: (Source) TFS-10-2-AL-Sub, (Power Supply) PS-10-2-G.

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Charge Analyzer Responsive Local Oscillations

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Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Technology Investment Program

Project Description

The first transatlantic radio transmission, demonstrated by Marconi in December of 1901, revealed the essential role of the ionosphere for radio communications. This ionized layer of the upper atmosphere controls the amount of radio power transmitted through, reflected off of, and absorbed by the atmospheric medium. Low-frequency radio signals can propagate long distances around the globe via repeated reflections off of the ionosphere and the Earth's surface. Higher frequency radio signals can punch through the ionosphere to be received at orbiting satellites. However, any turbulence in the ionosphere can distort these signals, compromising the performance or even availability of space-based communication and navigations systems.

The physics associated with this distortion effect is analogous to the situation when underwater images are distorted by convecting air bubbles. In fact, these ionospheric features are often called 'plasma bubbles' since they exhibit some of the similar behavior as underwater air bubbles. These events, instigated by solar and geomagnetic storms, can cause communication and navigation outages that last for hours. To help understand and predict these outages, a world-wide community of space scientists and technologists are devoted to researching this topic. One aspect of this research is to develop instruments capable of measuring the ionospheric plasma bubbles.

Figure 1 shows a photo of the Charge Analyzer Responsive to Local Oscillations (CARLO), a new instrument under development at NASA Marshall Space Flight Center (MSFC). It is a frequency-domain ion spectrum analyzer designed to measure the distributions of ionospheric turbulence from 1 Hz to 10 kHz (i.e., spatial scales from a few kilometers down to a few centimeters). This frequency range is important since it focuses on turbulence scales that affect VHF/UHF satellite communications, GPS systems, and over-the-horizon radar systems. CARLO is based on the flight-proven Plasma Local Anomalous Noise Environment (PLANE) instrument, previously flown on a U.S. Air Force low-Earth orbiting satellite, which successfully measured ion turbulence in five frequency decades from 0.1 Hz to 10 kHz (fig 2).

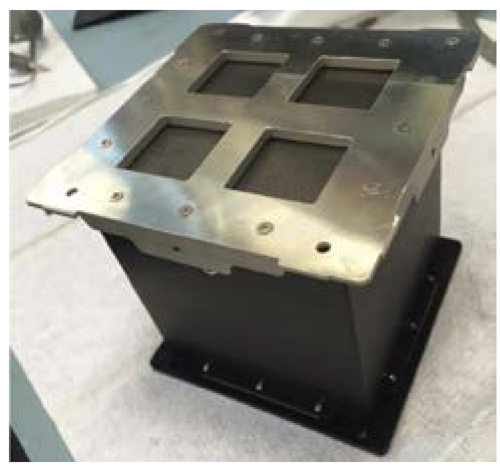

Figure 1: CARLO engineering unit.

Anticipated Benefits

CARLO was designed to foster the plug-n-play development approach for rapid/modular spacecraft development. An overview of the CARLO assembly appears in figure 3. CARLO's new features include an additional capability to measure turbulence in temperature, an increase in frequency resolution to 20 passbands, its own microprocessor for onboard spectral analysis, and standard mechanical, electrical, and telemetry interfaces to the CubeSat platform.

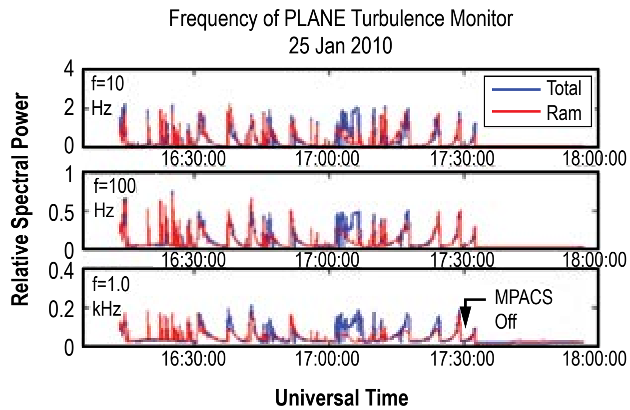

Figure 2: Data from CARLO's predecessor. Ionospheric density fluctuations in three bands were observed during operation of an onboard pulsed plasma thruster.

Potential Applications

With its modular design, CARLO can be operated as a conventional retarding potential analyzer, an ion drift meter, or a planar Langmuir probe. For terrestrial missions, appropriate platforms include sounding rocket, International Space Station external, CubeSats, suborbital reusable launch vehicle external flight, and other spacecraft that sample the Earth's ionosphere from 50 km through 1,000 km in altitude.

Notable Accomplishments

In 2014, the CARLO sensor heads passed their functional testing when exposed to a wide range of ion densities and drift energies in two separate MSFC plasma chambers. Since the CARLO instrument was selected by the InterAmerican University (IAU) in Puerto Rico as the primary science payload for the IAU's 3U CubeSat, it is anticipated this mission will serve as the heritage flight for this instrument. The IAU CubeSat is being developed for a low-Earth orbit mission, which will allow the CARLO to be used (with other data and models) to investigate ionospheric-magnetospheric coupling mechanisms.

References

Habash Krause, L.; Enloe, C.L.; and McHarg, M.G.: "In situ measurements of ionospheric plasma turbulence over five frequency decades: Heritage flight of the Plasma Local Anomalous Noise Experiment (PLANE)," *Adv. Space Res*., Vol. 52, No. 11, pp. 2006–2014, 1 December 2013.

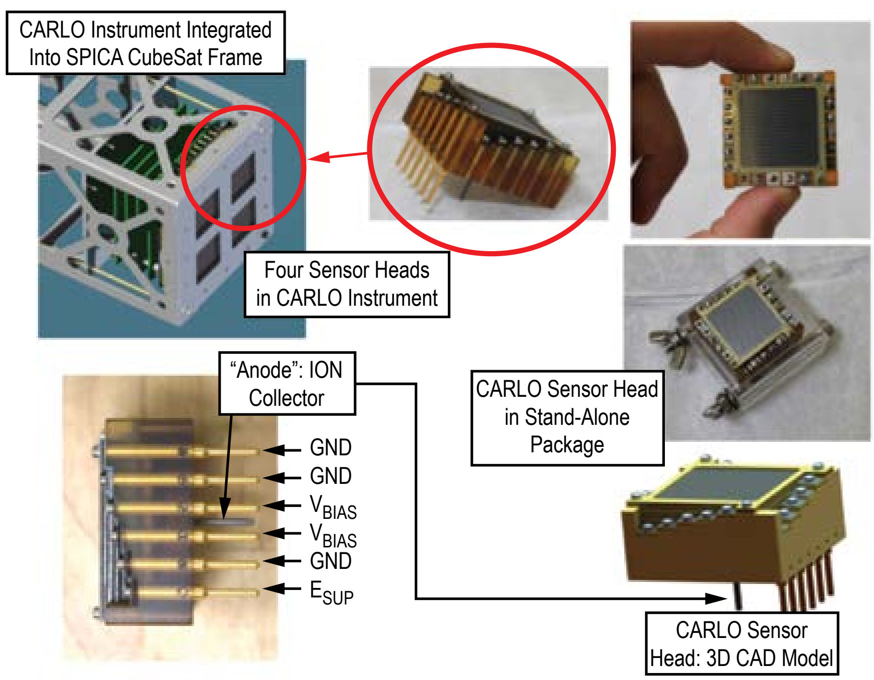

Figure 3: Overview of CARLO sensor heads assembled into the CARLO instrument, which is then integrated into the SPICA CubeSat. The CARLO takes up <1U of CubeSat volume.

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High Thermal Conductivity NARloy-Z-Diamond Composite Liner for Advanced Rocket Engines

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Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Technology Investment Program

Project Description

NARloy-Z (Cu-3Ag-0.5Zr) alloy is state-of-the-art combustion chamber liner material used in liquid propulsion engines such as the RS-68 and RS-25. The performance of future liquid propulsion systems can be improved significantly by increasing the heat transfer through the combustion chamber liner. Prior work[1] done at NASA Marshall Space Flight Center (MSFC) has shown that the thermal conductivity of NARloy-Z alloy can be improved significantly by embedding high thermal conductivity diamond particles in the alloy matrix to form NARloy-Z-diamond composite (fig. 1). NARloy-Z-diamond composite containing 40vol% diamond showed 69% higher thermal conductivity than NARloy-Z. It is 24% lighter than NARloy-Z and hence the density normalized thermal conductivity is 120% better. These attributes will improve the performance and life of the advanced rocket engines significantly.

The research work consists of (a) developing design properties (thermal and mechanical) of NARloy-Z-D composite, (b) fabrication of net shape subscale combustion chamber liner, and (c) hot-fire testing of the liner to test performance. Initially, NARloy-Z-D composite slabs were made using the Field Assisted Sintering Technology (FAST) (fig. 2) for the purpose of determining design properties. In the next step, a cylindrical shape was fabricated to demonstrate feasibility (fig. 3). The liner consists of six cylinders which are sintered separately and then stacked and diffusion bonded to make the liner (fig. 4). The liner will be heat treated, finish-machined, and assembled into a combustion chamber and hot-fire tested in the MSFC test facility (TF 115) to determine performance (fig. 5).

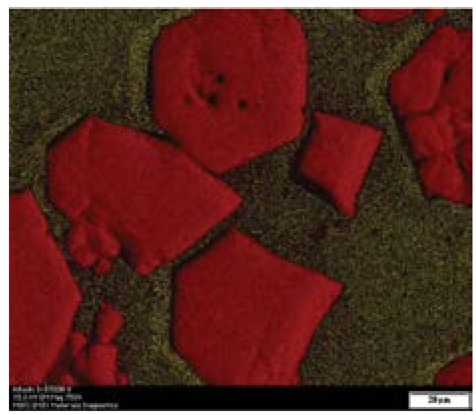

Figure 1: NARloy-Z-diamond composite microstructure (diamond particles shown in red).

Figure 2: Sintering at high temperature using FAST at Applied Research Laboratory, Pennsylvania State University.

Figure 3: NARloy-Z-40vol% diamond composite cylinder fabricated by FAST.

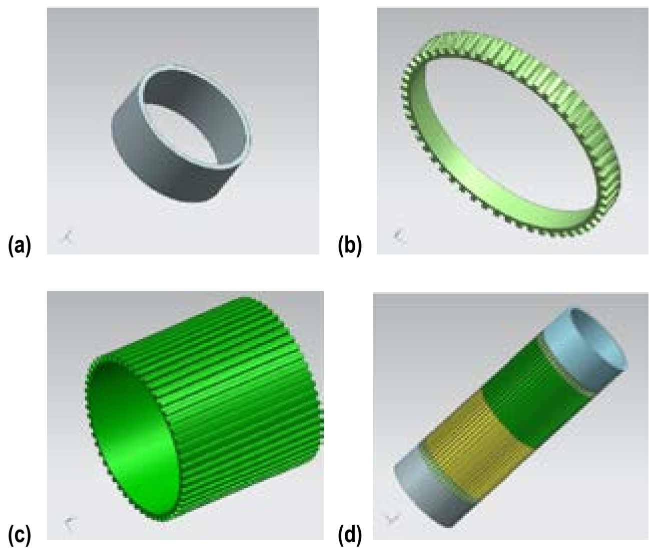

Figure 4: Combustion chamber liner components (schematic): (a) Outer cylinders, (b) inner cylinders, and (c) middle cylinders. Six cylinders will be fabricated, stacked, and diffusion bonded to make the liner (d).

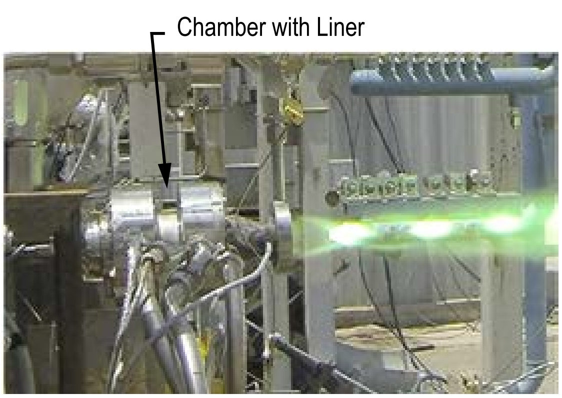

Figure 5: Hot-fire testing in TF 115.

Anticipated Benefits

This project will demonstrate the capability to make our future propulsion systems lighter and higher performing using a higher thermal conductivity material for the combustion chamber liner. Turbo pump power is expected to increase up to 2×. Increased heat transfer will directly result in increased thrust. There is potential for an increase in specific impulse for regeneratively cooled rocket engines such as the RL-10/NGE, RL-25E/F, and J-2X. Significant weight savings are possible due to the use of lightweight and higher thermal conductivity material. System-level trades need to be conducted to determine the overall weight savings, but as one example, it may be possible to maintain the current performance and reduce the engine mass.

Potential Applications

This project addresses an important material technology area that has high payoff in terms of affordability and performance of rocket propulsion systems. It will advance the Technology Readiness Level (TRL) from current TRL-3 to TRL-5, at which point it will be ready for implementation in an engine program such as RL-10/NGE, RL-25E/F, and/or J-2X. Furthermore, the high thermal conductivity NARloy-Z-diamond composite material developed in this program will have many applications in the industry, e.g., thermal management for computer hardware (heat sinks), heat exchangers, etc.

Notable Accomplishments

NARloy-Z-40vol%diamond cylinders have been successfully sintered using the FAST process (fig. 3). Diffusion bonding tests have been successful and showed acceptable bond strength.

References

1. Bhat, B.N.; et al.: “Copper-Multiwall Carbon Nanotubes and Copper-Diamond Composites for Advanced Rocket Engines,” 60th JANNAF Joint Subcommittee Meeting, Colorado Springs, CO, April 28–May 3, 2013.

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Portable Virtual Training Units

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Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Technology Investment Program

Project Description

The Mission Operations Lab initiated a project to design, develop, deliver, test, and validate a unique training system for astronaut and ground support personnel. In an effort to keep training costs low, virtual training units (VTUs) have been designed based on images of actual hardware and manipulated by a touch screen style interface for ground support personnel training. This project helped modernized the training system and materials by integrating them with mobile devices for training when operators or crew are unavailable to physically train in the facility. This project also tested the concept of a handheld remote device to control integrated trainers using International Space Station (ISS) training simulators as a platform. The portable VTU can interface with the full-sized VTU, allowing a trainer co-located with a trainee to remotely manipulate a VTU and evaluate a trainee's response. This project helped determine if it is useful, cost effective, and beneficial for the instructor to have a portable handheld device to control the behavior of the models during training. This project has advanced NASA Marshall Space Flight Center's (MSFC's) VTU capabilities with modern and relevant technology to support space flight training needs of today and tomorrow.

Figure 1: VTU in Lab training complex.

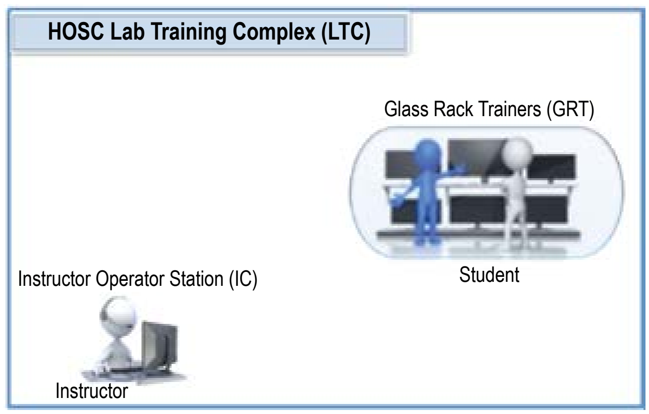

Figure 2: VTU configuration in Huntsville's Operations Support Center (HOSC).

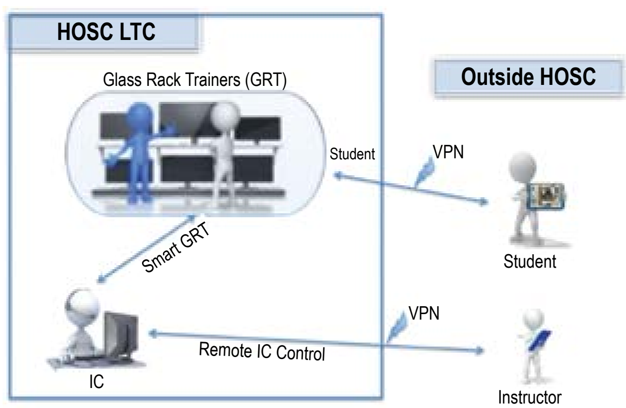

Figure 3: Portable virtual training unit configuration.

Anticipated Benefits

By strengthening MSFC's virtual training capability, this project will enhance payload operations training processes and lay the groundwork for making MSFC's portable VTU capabilities accessible from virtually anywhere and anytime. VTUs for a variety of mobile and desktop platforms will bring training capabilities not only to the payload flight controllers at MSFC, but to flight crew, payload developers, and any other human habitat element design and support personnel.

The United States' fiscal situation will constrain NASA and other government agency budgets for the indefinite future. In order to fulfill the Agency's goals, we will have to leverage off current technology and skills while doing it more affordably. A 21st century Space Agency will need to employ the latest technology and create a platform that allows that technology to evolve. The portable VTU is a highly expandable and reconfigurable system. The expansion of capabilities of the portable VTUs is almost limitless. As the phases are developed, they strengthen MSFC's near- and long-term capabilities for flight controller and crew training.

Potential Applications

The Mission Operations Laboratory is working to incorporate the portable VTU into flight controller training by enabling ground controllers to use this portable technology to more efficiently train by having 'desktop' access to training systems. Mission Operations is pursuing using this training concept for deep space exploration habitation missions. This technology has large potential for Department of Defense (DoD) Air Force applications.

This MSFC effort is in large about ensuring that NASA fully leverages a technology with the potential to transform its mission operations, enhance safety, and promote mission success. In some areas of the technology, NASA is at the leading edge and has captured the interest of other agencies and departments. These vetted technologies, at any point in the phased development, can be marketed to other agencies, DoD, commercial partners, etc. to leverage VTU technology for identified opportunities.

Notable Accomplishments

The portable VTU project has demonstrated the feasibility and usefulness of a standalone VTU on a mobile device and built the infrastructure to access the integrated Lab Training Complex (LTC) simulations from mobile devices. The security and networking for remote access to the LTC that was put in place under the FY 2014 Technology Investment Program makes it possible to bring high-fidelity, scenario-based training to the student—effectively creating a 'portable' LTC.

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Radio Frequency Identification for Space Habitat Inventory and Stowage Allocation Management

Project Manager(s)/Lead(s)

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Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Technology Investment Program

Project Description

To date, the most extensive space-based inventory management operation has been the International Space Station (ISS). Approximately 20,000 items are tracked with the Inventory Management System (IMS) software application that requires both flight and ground crews to update the database daily. This audit process is manually intensive and laborious, requiring the crew to open cargo transfer bags (CTBs), then Ziplock bags therein, to retrieve individual items. This inventory process contributes greatly to the time allocated for general crew tasks.

Radio frequency identification (RFID) technology is currently certified for the ISS in the form of next generation barcode handheld readers and specific RFID tags. Although the next generation handheld reader results in significant savings in crew time, it falls far short of a fully automated inventory management and tracking system that would save crew time.

This project integrated NASA's in-house RFID innovations as well as those spawned from other agencies, commercial, and academic communities to automate payload stowage and logistics. RFID tags are revolutionizing processes across commercial and government sectors because the tags can be scanned without having a direct line of sight with the label, unlike barcode tags. RFID tags placed on consumables can assist with autonomously updating inventory which reduces the amount of man hours spent conducting audits. For example, the on-orbit handheld reader is not able to discern which CTBs contain a specific tagged item unless the CTB is placed in an isolated (tag-free) environment on the ISS. Contents in CTBs buried two or three deep are likely to be missed unless CTBs are manually pulled and individually scanned.

Conversely, a CTB equipped with an RFID tag can be scanned in about 10 s, reporting all of the internal contents without opening the bag. In addition, many other contents kept within conductive containers that normally reflect the RFID signal (such as International Subrack Interface Standards (ISIS) drawers on Expedite the Processing of Experiments to Space Station racks, freezers, and middeck lockers) will not be detected by the handheld readers. So even though the mobile handheld reader is a very useful RFID tool for space-based habitat environments, it is only one of several RFID subsystems that will be required to assure high inventory accuracy and to altogether remove the crew from audits and from the task of searching for missing items. Location tracking algorithms and software from previous NASA-funded studies were utilized. All of the RFID readers are based on the EPCglobal class 1, generation 2 protocol, which is currently the standard targeted by the ISS international partners. It is estimated that crew time savings may be in the ballpark of 2 hr/day at an ISS rate of $2 million/hr. Time is an expensive commodity and similar concepts can be put in place for future operations.

Anticipated Benefits

NASA Marshall Space Flight Center's (MSFC's) Engineering Directorate will identify RFID tags and a handheld reader for scanning crew provisions, and is supporting the concept of operations for international partners to use RFID for crew provisions. The Human Research Program has modified an RFID reader to outfit one of their pantries for use on the ISS. This same technology with a few enhancements can also benefit the broader payloads community. The Payload Operations Integration Center's Laboratory Training Complex will serve as a test bed for the RFID concepts and can afford future testing and human factors usability analysis opportunities for payload developers that may desire to use RFID tags for their payload needs.

This effort is, in large, about ensuring that NASA fully leverages the technology with the potential to transform its mission operations, enhance safety, and promote mission success. The ultimate outcome is to provide recommendations for producing an integrated RFID system that minimizes crew involvement in inventory management and localization of equipment and consumables for future missions that involve space habitation.

Potential Applications

The objectives target advancement of the technology readiness level for integrated RFID-based automated inventory management, both for flight and ground applications. Other candidate RFID technologies expected to be required in an integrated and automated RFID environment include RFID-enabled enclosures, smart shelves, and portal/zone readers. These technologies have all been demonstrated in laboratory environments at the component level and at a subsystem level with simple RFID applications. Utilizing these core technologies and modifying them for Advanced Exploration Systems payloads specific use will help reduce the real-time errors that occur as a result of improper location callout for equipment/items. Longer term projects that can potentially evolve from this development are RFID soft stowage racks and preprogramed hovering readers.

Notable Accomplishments

The following goals were accomplished: (a) Integrated core RFID technologies at the component level and a subsystem level to demonstrate a modified application for spaceflight use (fig. 1); (b) demonstrated an RFID system that optimally automates processes associated with habitation (recycling, reusability, inventory management, localization, and science sample tracking); and (c) demonstrated RFID middleware and network technologies for payloads stowage allocation.

The objectives of a follow-on project target the integration of these technologies into ISS facilities and building an internal Wi-Fi RFID-enabled CTB that not only reports its internal contents but can be located via triangulation through Wi-Fi access points. Another objective of the follow-on project will result in a significant time savings for the Microgravity Science Glovebox project by automating the inventory audit process for their three ISIS drawers on orbit and allow them to locate their own CTBs via Wi-Fi enabled tags. By strengthening MSFC's inventory tracking and asset management capability, this technology can be used to make living and working in space easier for future long-range missions where autonomous crew operations will be necessary.

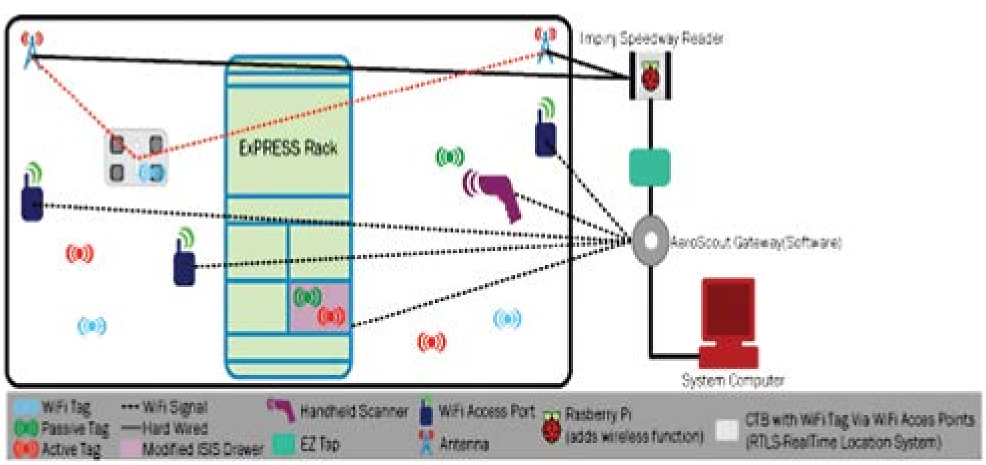

Figure 1: Integrated core technologies.

TIP

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Formation Flying for Satellites and Unmanned Aerial Vehicles

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Sponsoring Program(s)

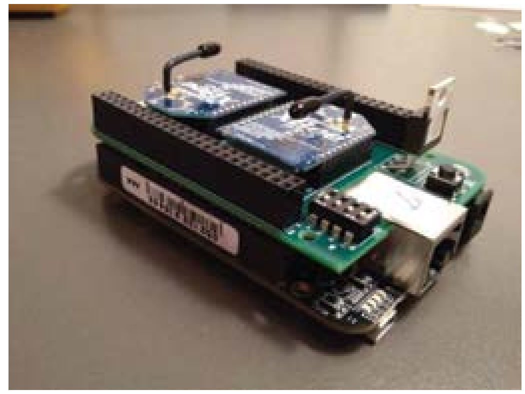
Marshall Space Flight Center/Center Management and Operations
Technology Investment Program

Project Description

The shrinking size of satellites and unmanned aerial vehicles (UAVs) is enabling lower cost missions. As sensors and electronics continue to downsize, the next step is multiple vehicles providing different perspectives or variations for more precise measurements. While flying a single satellite or UAV autonomously is a challenge, flying multiple vehicles in a precise formation is even more challenging.

The goal of this project is to develop a scalable mesh network between vehicles (satellites or UAVs) to share real-time position data and maintain formations autonomously. Newly available low-cost, commercial off-the-shelf credit card size computers will be used as the basis for this network. Mesh networking techniques will be used to provide redundant links and a flexible network. The Small Projects Rapid Integration and Test Environment Lab will be used to simulate formation flying of satellites. UAVs built by the Aero-M team will be used to demonstrate the formation flying in the West Test Area.

The ability to test in flight on NASA-owned UAVs allows this technology to achieve a high Technology Readiness Level (TRL) (TRL-4 for satellites and TRL-7 for UAVs). The low cost of small UAVs and the availability of a large test range (West Test Area) dramatically reduces the expense of testing. The end goal is for this technology to be ready to use on any multiple satellite or UAV mission.



Formation node.

Eight nodes.

Quadcopter UAV.

Quadcopter UAVs in formation.

Anticipated Benefits

Demonstrating the concept on small, inexpensive UAVs provides a unique testing platform and way to raise the TRL level before taking on a multiple satellite mission. In addition, the same technology can be directly applied to UAVs in the rapidly expanding small UAV market. In 2015, the Federal Aviation Administration will start allowing commercial UAVs in U.S. airspace. The formation flying system cannot only be directly applied to a multiple vehicle formation, but also as a method of avoiding collisions between all small UAVs in the area. Being at the forefront of formation flying for satellites and UAVs not only allows leveraging across platforms, but keeps NASA Marshall Space Flight Center at the forefront of autonomous flight control in unmanned systems.

Potential Applications

There are many applications for satellites in a cluster formation that provide benefits over a single larger platform. The Space Launch System/Interim Cryogenic Propulsion System will be deploying CubeSats in deep space on the Exploration Mission-1 that could use this technology. A follow-on mission to the Edison Demonstration of Smallsat Networks CubeSat mission could utilize this technology to enhance the intervehicle communication and provide a more robust network topology.

Notable Accomplishments

The code that was developed for the formation nodes controls the mesh network and enables formation maneuvers made available to U.S. citizens through the NASA Software Catalog.

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Programmable Ultra-Lightweight System Adaptable Radio Satellite Base Station

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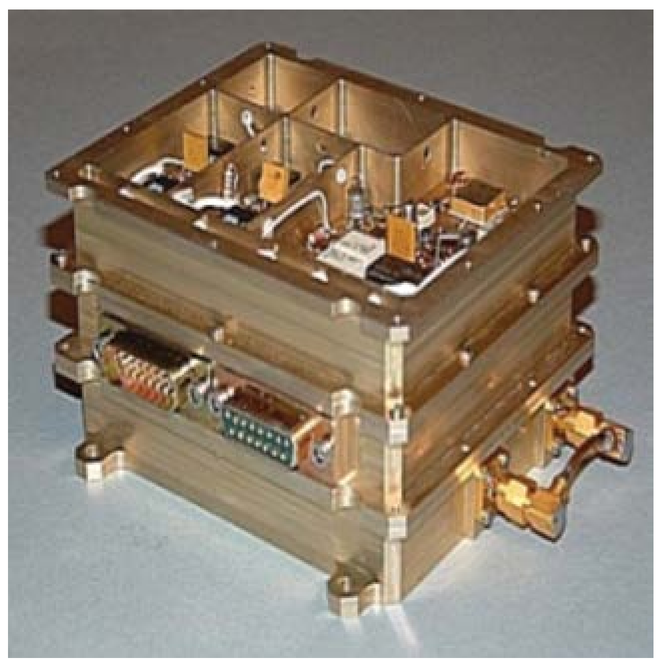
Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Technology Investment Program

Project Description

With the explosion of the CubeSat, small sat, and nano-sat markets, the need for a robust, highly capable, yet affordable satellite base station, capable of telemetry capture and relay, is significant. The Programmable Ultra-Lightweight System Adaptable Radio (PULSAR) is NASA Marshall Space Flight Center's (MSFC's) software defined digital radio, developed with previous Technology Investment Programs and Technology Transfer Office resources. The current PULSAR will have achieved a Technology Readiness Level-6 by the end of FY 2014. The extensibility of the PULSAR will allow it to be adapted to perform the tasks of a mobile base station capable of commanding, receiving, and processing satellite, rover, or planetary probe data streams with an appropriate antenna.

Ground station antennas.



Pulsar stack.

Anticipated Benefits

MSFC does not have a tracking antenna and relies on the Near Earth Network (NEN) to implement its data processing requirements of payload operations for the International Space Station. A deployable asset, such as GATR Technologies' portable antennas, provides an avenue for the MSFC Engineering Directorate personnel to engage directly with the tracking, commanding, and processing of satellite systems and data. This provides an avenue to gain hands-on experience with rapid deployment and operation) of base station assets.

Potential Applications

With a coming explosion of small sats and nanosats, the current NENs will become overworked quickly trying to accommodate all of these satellites and their data/commanding requirements. By having an affordable, mobile ground station, many of these satellites could talk directly to the organizations that launched them.

A mobile base station will augment the few ground station resources available east of the Mississippi, strategically positioning MSFC with a competitive advantage to secure future competed work in the areas of Office of Chief Technology exploration programs such as the HOPE, LCAS, EV-I, TMD-12, as well as FASTSat-HSV01 follow-on small sats and CubeSats. This will provide the ability to accommodate small, short-term missions.

Notable Accomplishments

Individual components are arriving at MSFC for test and integration.

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Laser Imaging Detection and Ranging Performance in a High-Fidelity Lunar Terrain Field

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Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Technology Investment Program

Project Description

The prime objective of this project is to evaluate Laser Imaging Detection and Ranging (LIDAR) systems and compare their performance for hazard avoidance when tested at the NASA Marshall Space Flight Center's (MSFC's) lunar high-fidelity terrain field (see fig. 1). Hazard avoidance is the ability to avoid boulders, holes, or slopes that would jeopardize a safe landing and the deployment of scientific payloads. This capability is critical for any sample return mission intending to land in challenging terrain. Since challenging terrain is frequently where the most scientifically attractive targets are, hazard avoidance will be among the highest priorities for future robotic exploration missions. The maturation of hazard avoidance sensing addressed in this project directly supports the MSFC Tier I priority of sample return.

Possible sources for the LIDAR sensor itself are Ibeo LIDAR contributed by Auburn University, commercial Faro LIDAR, commercial Leica LIDAR, and LIDAR sensor packages and software contributed by Astrobotic and Moon Express. We will evaluate how well these sensors are able to identify hazards and produce 3D maps. Strengths and weaknesses of each system will be documented and compared.

Figure 1: MSFC's lunar high-fidelity terrain field.

Anticipated Benefits

Some of the anticipated benefits include supporting the MSFC Tier I priority of sample returns, connecting with commercial providers of space landers and rovers, providing a platform technology for spacecraft landing and rover navigation testing at MSFC, bring in FTEs to the Center, and add value competencies to the Center through hands-on experience with the LIDAR hardware.

Potential Applications

Hazard avoidance technology using LIDAR by this project is important to sample return and other autonomous space landing missions because, without it, landing sites have to be relatively free of hazards. As with all previous unmanned missions, a landing site can be selected in a broad flat area. High-value scientific targets, however, are often in areas with hazards. These 'challenging' landing sites include landing near an outcrop or in a crater. In a Monte Carlo analysis for a lunar landing, the probability of a safe landing without hazard avoidance is 23% and 99% with a LIDAR-based hazard avoidance system.

Notable Accomplishments

The project team has successfully completed four LIDAR tests at the MSFC high-fidelity lunar terrain field with Ibeo, Faro, and Leica LIDAR. The first test used four balloons to lift the LIDAR package above the terrain field (see fig. 2). The package included an Ibeo LIDAR, Advantech processor, lithium battery, and GPS/INS system. Four balloons provided about 60 lb of lift force to the LIDAR package. Four internal LIDAR mirrors were pointing downward to scan the terrain field while the package was ascended to about 150 feet and descended to the ground. The second test transferred the LIDAR package to a pipe that mounted to the fork of a bucket truck. By moving the arm up and down and by adding a weight to the side of the package, the LIDAR was pointed to the ground with various scan angles. The third test was jointly conducted with a Faro contractor to obtain a truth model of the terrain field (see fig. 3) and the fourth test used a Leica LIDAR to map a truth model of the field.

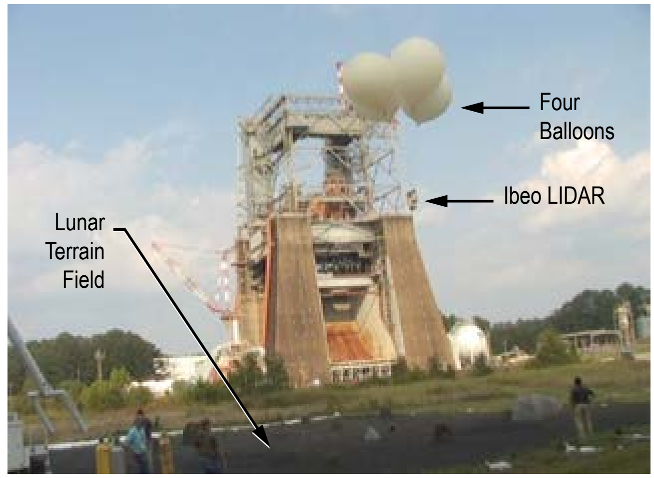

Figure 2: Ibeo LIDAR balloon test.

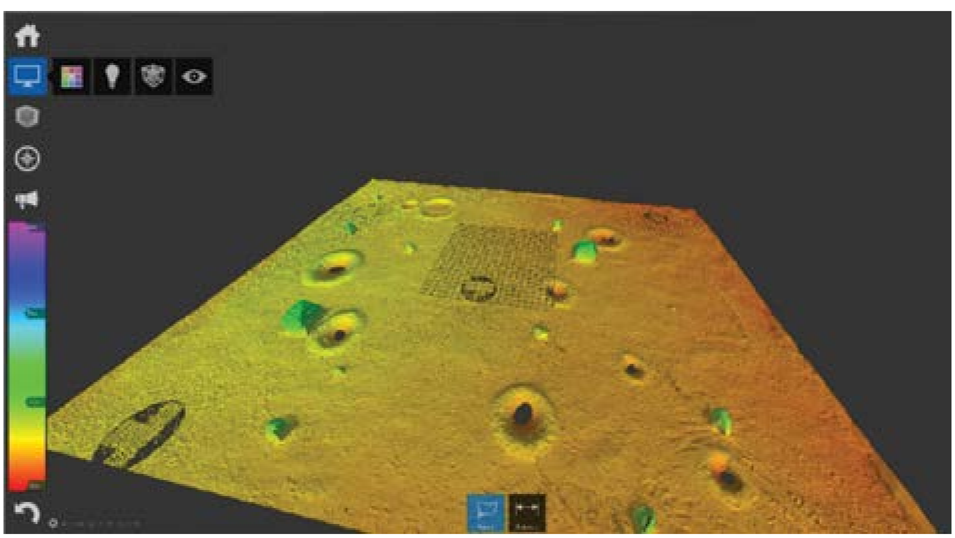

Figure 3: Faro LIDAR mapping.

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Marshall Space Flight Center (MSFC)/ Center Management and Operations (CMO)

Center Strategic Development Steering Group (CSDSG)

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Grazing Incidence Optics Technology

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Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Center Strategic Development Steering Group—Internal Technology Development Funds

Project Description

This project is to demonstrate the capability to directly fabricate lightweight, high-resolution, grazing-incidence x-ray optics using a commercially available robotic polishing machine.

Typical x-ray optics production at NASA Marshall Space Flight Center (MSFC) uses a replication process in which metal mirrors are electroformed on to figured and polished mandrels from which they are later removed. The attraction of this process is that multiple copies can be made from a single master. The drawback is that the replication process limits the angular resolution that can be attained.

By directly fabricating each shell, errors inherent in the replication process are removed. The principal challenge now becomes how to support the mirror shell during all aspects of fabrication, including the necessary metrology to converge on the required mirror performance specifications.

This program makes use of a Zeeko seven-axis computer-controlled polishing machine (see fig. 1) and supporting fabrication, metrology, and test equipment at MSFC. The overall development plan calls for proof-of-concept demonstration with relatively thick mirror shells (5–6 mm, fig. 2) which are straightforward to support and then a transition to much thinner shells (2–3 mm), which are an order of magnitude thinner than those used for Chandra. Both glass and metal substrates are being investigated.

Currently, a thick glass shell is being figured. This has enabled experience to be gained with programming and operating the polishing machine without worrying about shell distortions or breakage. It has also allowed time for more complex support mechanisms for figuring/polishing and metrology to be designed for the more challenging thinner shells. These are now in fabrication.

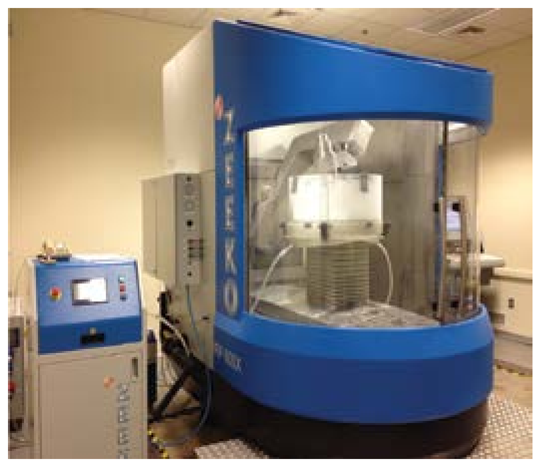

Figure 1: Zeeko polishing machine.

Figure 2: Thick glass shell on coordinate measuring machine.

Anticipated Benefits

Direct fabrication of individual full-shell optics, as was done with the Chandra program, can lead to the highest quality mirrors, far superior to those fabricated via replication processes of polished and figured masters or mandrels. Full-shell optics are inherently stable, due to their closed form and, particularly if they contain both ‘parabolic’ and ‘hyperbolic’ portions of the traditional Wolter-1 x-ray optics prescription, are easier to mount and align compared to other segmented optic approaches. These factors also lead to superior angular resolution for the final mirror assemblies.

The use of modern, automated polishing machines also helps reduce the overall cost of mirror fabrication. In addition, the use of commercially available machines potentially allows for easy transition to industry for future large-scale programs.

Potential Applications

A wide range of applications exist for lightweight, high-resolution x-ray optics. These range from small explorer class missions up to probe or even facility class observatories. Of particular interest at this time is the use of wide field x-ray optics for use in a survey-type astronomical instrument. By figuring special optical prescriptions, the resulting telescope can be made to have a flat angular resolution response over a relatively wide field. This makes possible a very efficient x-ray instrument for all sky surveys. Such surveys are routinely carried out at other wavelengths, but have not been done in x-rays since the early 1990’s. A wide field survey instrument could be realized on a probe class or even possibly a mid-size explorer class mission.

Notable Accomplishments

Custom fixturing has been designed and is under fabrication to provide the necessary level of support for all thin-shell fabrication steps including metrology (fig. 3). Further, special polishing tools have been developed to minimize the introduction of spurious ripple in the mirror figure that could degrade imaging performance. Software has been developed to stitch together metrology data and provide a direct input to the Zeeko polishing machine (fig. 4). In addition, machine control software has been written to adapt the Zeeko machine from normal incidence operation to grazing incidence optics fabrication.

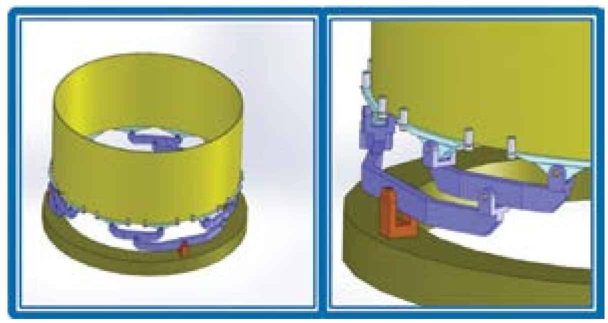

Figure 3: Metrology support stand for thin shell.

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CSDSG

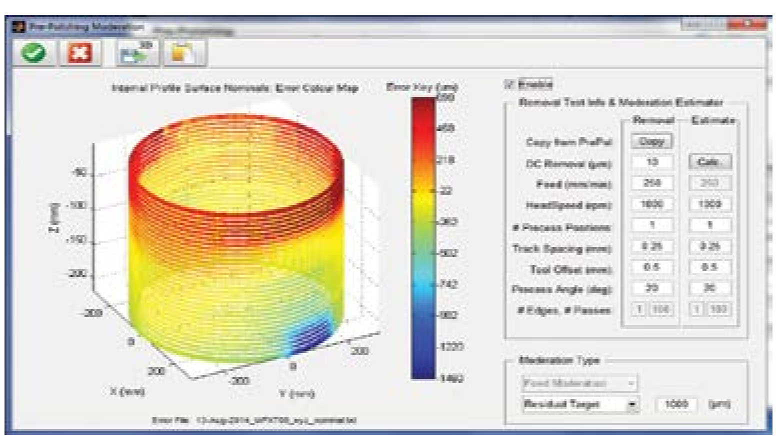

Figure 4: Metrology of test optic, stitched to provide full inside-shell coverage.

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Peregrine Sustainer Motor Development

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Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Center Strategic Development Steering Group

Project Description

The Peregrine sounding rocket is an in-house NASA design that provides ~15% better performance than the motor it replaces. The design utilizes common materials and well-characterized architecture to reduce flight issues encountered with the current motors. It engages NASA design, analysts, test engineers and technicians, ballisticians, and systems engineers. The in-house work and collaboration within the government provides flexibility to efficiently accommodate design and program changes as the design matures and enhances the ability to meet schedule milestones. It provides a valuable tool to compare industry costs, develop contracts, and it develops foundational knowledge for the next generation of NASA engineers.

Motor cases ready for processing.

Exit cone.

Anticipated Benefits

This project creates a NASA-owned design to facilitate easier design evolution in the future as well as provides a hands-on learning experience to hone NASA's internal propulsion expertise. It also establishes multiple vendors to mitigate supply risk and helps foster a competitive market.

Potential Applications

After demonstration tests, the sustainer motor will be available to support many sounding rocket missions including near-Earth flights for Earth-bound science projects.

Motor loaded into test stand.

Notable Accomplishments

The team is implementing the development phase of the project, which includes three flight tests. The static test of the motor is scheduled for January 2015 at NASA Marshall Space Flight Center's East Test Facility. The domestic manufacturers have been identified for development and production phases. During development, additional ways were found to reduce the costs of motor production, making it a competitive cost and performance choice over its replacement.

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Iodine Satellite

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Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Center Strategic Development Steering Group

Project Description

This project is a collaborative effort to mature an iodine propulsion system while reducing risk and increasing fidelity of a technology demonstration mission concept.[1] The FY 2014 tasks include investments leveraged throughout NASA, from multiple mission directorates, as a partnership with NASA Glenn Research Center (GRC), a NASA Marshall Space Flight Center (MSFC) Technology Investment Project, and an Air Force partnership.

Propulsion technology is often a critical enabling technology for space missions. NASA is investing in technologies to enable high value missions with very small and low-cost spacecraft, even CubeSats. However, these small spacecraft currently lack any appreciable propulsion capability. CubeSats are typically deployed and drift without any ability to transfer to higher value orbits, perform orbit maintenance, or deorbit. However, the iodine Hall system can allow the spacecraft to transfer into a higher value science orbit. The iodine satellite (iSAT) will be able to achieve a ΔV of >500 m/s with <1 kg of solid iodine propellant, which can be stored in an unpressurized benign state prior to launch.

The iSAT propulsion system consists of the 200 W Hall thruster, solid iodine propellant tank, a power processing unit, and the necessary valves and tubing to route the iodine vapor. The propulsion system is led by GRC, with critical hardware provided by the Busek Co.

The propellant tank begins with solid iodine unpressurized on the ground and in-flight before operations, which is then heated via tank heaters to a temperature at which solid iodine sublimates to iodine vapor. The vapor is then routed through tubing and custom valves to control mass flow to the thruster and cathode assembly.[2] The thruster then ionizes the vapor and accelerates it via magnetic and electrostatic fields, resulting in thrust with a specific impulse >1,300 s.

The iSAT spacecraft, illustrated in figure 1, is currently a 12U CubeSat. The spacecraft chassis will be constructed from aluminum with a finish to prevent iodine-driven corrosion. The iSAT spacecraft includes full three-axis control using wheels, magnetic torque rods, inertial management unit, and a suite of sensors and optics. The spacecraft will leverage heat generated by spacecraft components and radiators for a passive thermal control system.

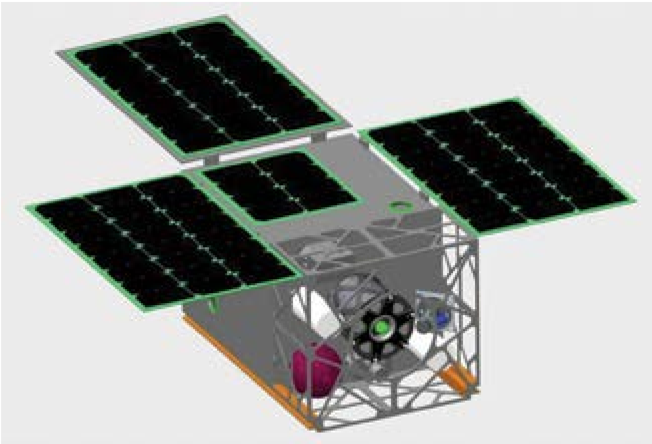

Figure 1: Preliminary FY 2014 12U concept design.

Anticipated Benefits

The benefits of the iodine Hall technology and iSAT demonstration include enabling significant small spacecraft maneuverability with a propulsion system viable with secondary payload launch opportunities.[3] Most of the technology benefits are derived from the unpressurized storage, low pressure operation, and high density. The storage and operating pressures allow for additive manufacturing of the propellant tank and shapes to maximum volume. Also, the iodine density components with the Hall thrusters results in more than an order of

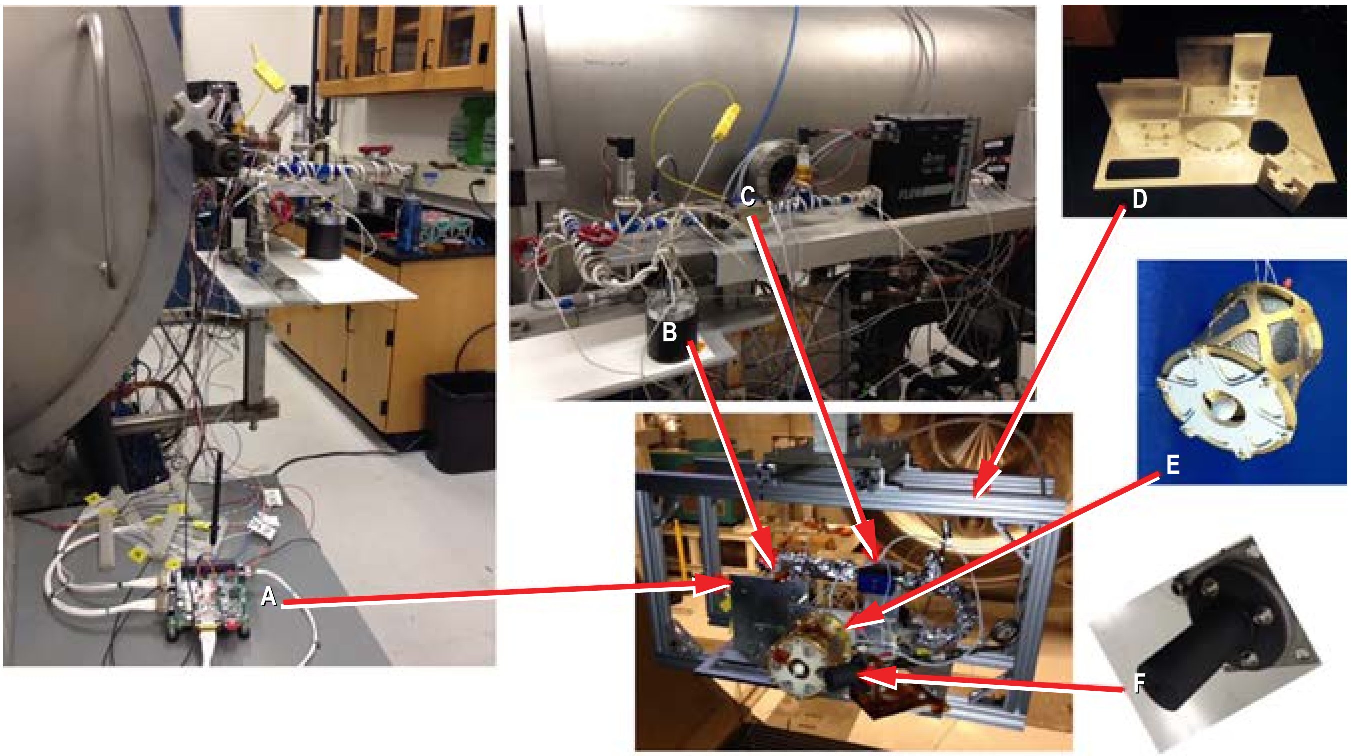

Figure 2: Custom control electronics (A), propellant reservoir (B), VACCO iodine valve (C), integrated test plate (D), Busek BHT-200-I thrusters (E), and Colorado State University electride cathode (F) on the MSFC pendulum thrust stand B4205 R101.

magnitude improvement in ΔV per unit volume of small sat state of the art.

Potential Applications

The primary applications are geocentric maneuverability and interplanetary transit for small spacecraft. The technology enables cost-effective geocentric constellation deployment, orbit maintenance, and deorbit. The technology can also enable EELV Secondary Payload Adapter class small sats to depart from geosynchronous transfer orbit and go to the Moon, asteroids, Mars, and Venus, saving potentially upwards of $100M in launch costs to interplanetary destinations. Higher power systems can also be used for orbit transfer vehicles and eventually have potential for human exploration activities with ground test and propellant packaging advantages.

Notable Accomplishments

This project was approved under the Small Spacecraft Technology Program for a technology demonstration mission in early FY 2017.

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2. Dankanich, J.W.; Szabo, J.; Pote, B.; et al.: "Mission and System Advantages of Iodine Hall Thrusters," 50th Joint Propulsion Conference, Cleveland, OH, July 28–30, 2014.

3. Polzin, K.A.; and Peeples, S.: "Iodine Hall Thruster Propellant Feed System for a CubeSat," 50th Joint Propulsion Conference, Cleveland, OH, July 28–30, 2014.

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NanoLaunch

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Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Center Strategic Development Steering Group, Technology Investment Program, Center Investment Fund, Technology Excellence

Project Description

NASA's NanoLaunch effort will provide the framework to mature both Earth-to-orbit and on-orbit propulsion and avionics technologies while also providing affordable, dedicated access to low-Earth orbit for CubeSat-class payloads. The project will also serve as an early career personnel training opportunity with mentors to gain hands-on project experience.

NanoLaunch is a three-phase, high-risk research and technology development project that will focus on developing the insertion stages needed to place a nano-class payload (1–10 kg) in orbit. In addition, the project will design and build the test vehicles and avionics for the test flights. Phase 1 (FY 2013) developed and static fire tested an 8-lb motor as proof of concept of a fully printed solid rocket insertion stage. Additionally, avionics using an android cell phone and reaction control system (RCS) using a paintball canister was developed and tested on Phase 1 test vehicles (fig. 1). These vehicles are reusable, 4- and 6-in-diameter hobby rocket kits with commercial-off-the-shelf 'K,' 'M,' or 'O' booster motors and serves as hands-on training in rocket assembly and integration for the team (fig. 2). Phase 2 (FY 2014/2015) focuses on the development of a full-scale insertion stage avionics, RCS, separation system, and assembly and integration of a two-stage, 9-in-diameter, reusable test vehicle. Phase 3 will utilize the phase 2 vehicle as the upper stage on top of a heritage sounding rocket configuration that provides a testbed for suborbital and orbital capability for this class of payloads.

Figure 1: Local test flight of the Avionics and RCS on the NL1D ('Wildman' amateur hobby rocket kit w/M3400 motor).

Figure 2: Hands-on training building rockets.

The current phase 2 vehicle, NL2A, is scheduled for its first flight in the spring of 2015. The NL2A is a two-stage, 9-in-diameter, carbon fiber airframe vehicle measuring 17.5 ft in length powered by an O-8000 booster motor. The 9M upper stage motor is an integrally overwrapped phenolic tube and nozzle with printed forward dome attached to a loaded propellant cartridge (fig. 3).

Figure 3: Insertion stage motor, 9M.

The NL2A will demonstrate the manufacturing techniques of the 9M upper stage motor, provide a flight test opportunity for multiple nanolaunch-class vehicle avionics, and exercise the NanoLaunch team's ability to design, build, integrate, and fly a launch vehicle. The NL2A is co-manifested with payloads from NASA Ames Research Center (ARC), NASA Kennedy Space Center (KSC), and ATK. The NL2A project is providing test flight opportunities to ARC's Advanced Vehicle Avionics (AVA), KSC's Rocket University avionics package, and ATK's wireless sensors. NL2A is also utilizing the S-Band transmitter module of NASA Marshall Space Flight Center's (MSFC's) programmable ultra-lightweight system adaptable radio.

Anticipated Benefits

Anticipated benefits include flight opportunities for high-payoff technologies, orbital access for CubeSat-class payloads, and training for the next generation of rocket engineers, project managers, and chief engineers.

Potential Applications

The qualification, by flying on NanoLaunch, of these technologies and approaches will raise the competitive bar and increase the available alternatives enabling launch service providers to create and maintain an affordable launch service without having to take on the full development cost and risk. Within this paradigm, a new stage can be tested in flight within the scope and budget of a phase 2 Small Business Innovation Research (SBIR). Aggressive technology maturation raises the competitive bar, benefiting multiple programs like Airborne Launch Assist Space Access, NASA Launch Enabling eXploration and Technology, Defense Advanced Research Projects Agency, Operationally Responsive Space, and others. It also strengthens inter-Center cooperative competition, increases academic outreach, and improved SBIR/Small Business Technology Transfer focus.

Notable Accomplishments

This activity is providing hands-on training while at the same time placing MSFC in a lead role in the development of a robust NanoLaunch development system.

The NanoLaunch project successfully laid a path forward to enable the design, development, and testing of low-cost solutions to components and systems needed to reduce the cost of the NanoLaunch vehicle, including the capability of low-cost avionics components and an Android cell phone to track and telemeter data from the rocket, and the capability of a low-cost plastic 3D printed igniter assembly that utilizes a commercially available hobby rocket igniter motor.

An RCS was developed and tested, utilizing a commercially available paintball canister.

Additive manufacturing techniques needed specifically to build a flight weight insertion stage motor was developed.

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Low Noise Camera for Suborbital Science Applications

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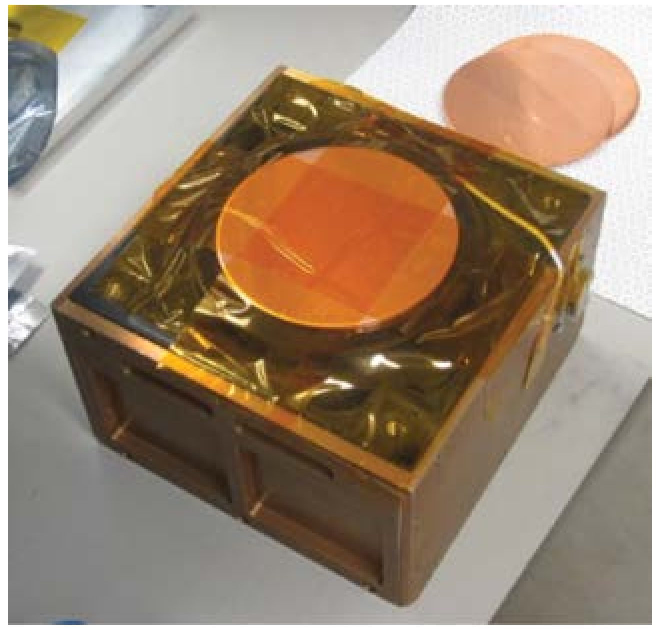
Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Center Strategic Development Steering Group, Center Investment Fund

Project Description

Low-cost, commercial-off-the-shelf- (COTS-) based science cameras are intended for lab use only and are not suitable for flight deployment as they are difficult to ruggedize and repackage into instruments. Also, COTS implementation may not be suitable since mission science objectives are tied to specific measurement requirements, and often require performance beyond that required by the commercial market. Custom camera development for each application is cost prohibitive for the International Space Station (ISS) or midrange science payloads due to nonrecurring expenses (~$2,000 K) for ground-up camera electronics design. While each new science mission has a different suite of requirements for camera performance (detector noise, speed of image acquisition, charge-coupled device (CCD) size, operation temperature, packaging, etc.), the analog-to-digital conversion, power supply, and communications can be standardized to accommodate many different applications. The low noise camera for suborbital applications is a rugged standard camera platform that can accommodate a range of detector types and science requirements for use in inexpensive to mid range payloads supporting Earth science, solar physics, robotic vision, or astronomy experiments. Cameras developed on this platform have demonstrated the performance found in custom flight cameras at a price per camera more than an order of magnitude lower.



Low noise camera for the CLASP mission.

Comparison of observed noise performance with cameras at comparable price (COTS-based) and performance (custom flight) points.

Camera	Observed Noise Performance
COTS-Based	60–100 e-
Custom Flight	10 e-
Low Noise Camera	7 e-

Anticipated Benefits

The demonstrated performance advantage of the low noise camera over COTS solutions will enable researchers to develop higher performance experiments at a cost compatible with low-cost flight opportunities. The relatively low cost associated with the performance of these cameras enables a greater proportion of project funds to be invested in other components or subsystems to enhance science objectives or reduce overall mission risk.

Potential Applications

The Extreme Ultraviolet (EUV) Snapshot Imaging Spectrograph (ESIS) is a next-generation imaging spectrograph being developed by Montana State University to investigate reconnection in explosive events, and transport of mass and energy through the transition region of the Sun's atmosphere. The instrument consists of a pseudo-Gregorian design telescope with light projected by concave diffraction gratings to four of the NASA Marshall Space Flight Center- (MSFC-) developed low noise cameras. The ESIS experiment is scheduled to be flown from White Sands Missile Range in the summer of 2017.

The Marshall Grazing Incidence X-ray Spectrograph (MaGIXS) is a stigmatic grazing-incidence spectrograph experiment designed to observe spatially resolved soft x-ray spectra of the solar corona for the first time. The instrument consists of a Wolter type-1 sector telescope and a slit spectrograph. A single MSFC-developed low noise camera will be used to capture the spectral image. This camera will also be used to provide solar images in a reflight of the successful 2012 High Resolution Coronal Imager (Hi-C) sounding rocket mission. The main objective of the Hi-C investigation is to determine the geometric configuration and topology of the structures making up the inner corona. The secondary objective is to examine the dynamics of those structures within the constraints of the 300-s observing time available from a sounding rocket. Use of this lower noise camera will significantly enhance the image quality and effective resolution from this instrument.

Notable Accomplishments

The version of this camera using an e2v CCD57 detector is currently integrated into the Chromospheric Lyman-Alpha SpectroPolarimeter (CLASP) instrument, scheduled for launch in the summer of 2015. Modifications to the standard platform to accommodate the CCD230 detector for the ESIS, MaGIXS, and Hi-C reflight missions are nearing completion.

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Dual-Use Technology Cooperative Agreement Notice (CAN)

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Improving Interlaminar Shear Strength

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Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Dual-Use Technology Cooperative Agreement Notice

Project Description

To achieve NASA's mission of space exploration, innovative manufacturing processes are being applied to the fabrication of complex propulsion elements.[1] Use of fiber-reinforced, polymeric composite tanks are known to reduce weight while increasing performance of propulsion vehicles. Maximizing the performance of these materials is needed to reduce the hardware weight to result in increased performance in support of NASA's missions. NASA has partnered with the Mississippi State University (MSU) to utilize a unique scalable approach of locally improving the critical properties needed for composite structures. MSU is responsible for the primary development of the concept with material and engineering support provided by NASA.

Figure 1: 18-ft- (5.5-m-) diameter, all composite tank at MSFC.

The all-composite tank shown in figure 1 is fabricated using a prepreg system of IM7 carbon fiber/CYCOM 5320-1 epoxy resin. This is a resin system developed for out-of-autoclave applications. This new technology is needed to support the fabrication of large, all composite structures and is currently being evaluated on a joint project with Boeing for the Space Launch System (SLS) program. In initial efforts to form an all-composite pressure vessel using this prepreg system, a 60% decrease in properties was observed in scarf joint regions. Inspection of these areas identified interlaminar failure in the adjacent laminated structure as the main failure mechanism. This project seeks to improve the interlaminar shear strength (ILSS) within the prepreg layup by locally modifying the interply region shown in figure 2.[2]

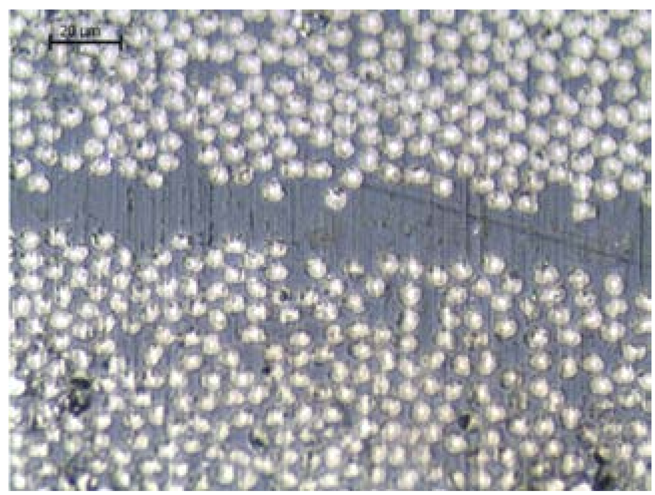

Figure 2: Resin-rich area between plies.

Anticipated Benefits

The prepreg system uses a continuous carbon fiber to realize the overall global strength of the part. This approach can also be applied locally by use of reinforcing additives, such as carbon nanotubes (CNTs) within the epoxy resin. In studies on neat resins using various

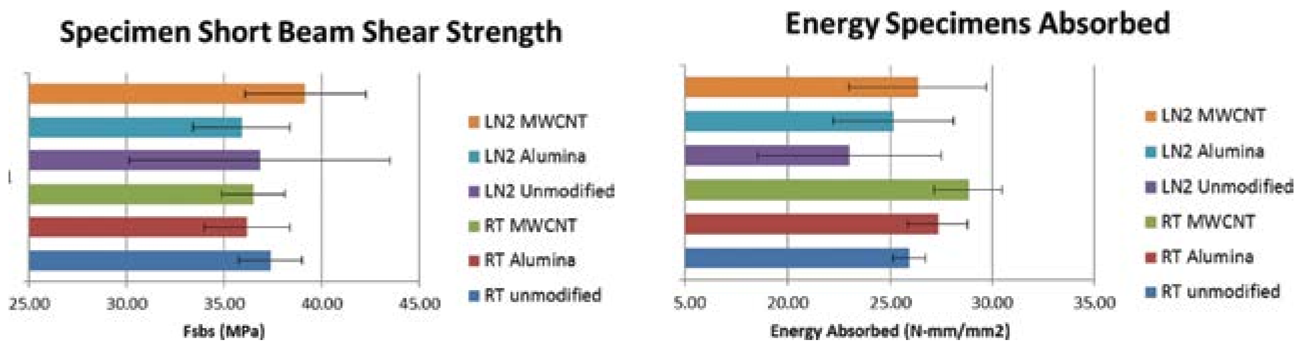

Figure 3: Improved shear strength and energy absorbed has been demonstrated using a local modification of nanoparticles.

additives, an increase has been shown both in strength and toughness.[3] As ILSS is reported to be matrix driven, methods to improve the strength and toughness of the resin are of interest. However, these types of modifications cannot be applied to an existing prepreg system without extensive development costs.

MSU is exploring methods to embed reinforcing nanoparticles in the resin between plies to strengthen and toughen the matrix. Although preliminary research has shown this to show promise in improving shear strength as shown in figure 3, the studies are continuing to optimize both the selection of the dispersant as well as the additives. Once identified and proven, this concept can be readily implemented into current fabrication schemes.

Potential Applications

Methodology being developed in this project can immediately benefit current production of an out-of-autoclave fuel tank for the SLS program as well as have commercial interests in transportation usage of alternative cryogenic fuels.

Use of CNTs as piezoelectric sensors is also being pursued on other studies at NASA.[4] Proving that CNTs are effective in locally modifying joint properties may be possible to provide local monitoring for structural health.

Notable Accomplishments

Use of three-point bend tests on coupon specimens indicated that both the shear strength and energy absorption can be improved at both room and cryogenic temperature.

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Printing Outside the Box: Additive Manufacturing Processes for Fabrication of Large Aerospace Structures

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Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Dual-Use Technology Cooperative Agreement Notice

Project Description

To achieve NASA's mission of space exploration, innovative manufacturing processes are being applied to the fabrication of propulsion elements. Liquid rocket engines (LREs) are comprised of a thrust chamber and nozzle extension as illustrated in figure 1 for the J2X upper stage engine. Development of the J2X engine, designed for the Ares I launch vehicle, is currently being incorporated on the Space Launch System. A nozzle extension is attached to the combustion chamber to obtain the expansion ratio needed to increase specific impulse. If the nozzle extension could be printed as one piece using free-form additive manufacturing (AM) processes, rather than the current method of forming welded parts, a considerable time savings could be realized. Not only would this provide a more homogenous microstructure than a welded structure, but could also greatly shorten the overall fabrication time.

The main objective of this study is to fabricate test specimens using a pulsed arc source and solid wire as shown in figure 2. The mechanical properties of these specimens will be compared with those fabricated using the powder bed, selective laser melting technology at NASA Marshall Space Flight Center. As printed components become larger, maintaining a constant temperature during the build process becomes critical. This predictive capability will require modeling of the moving heat source as illustrated in figure 3. Predictive understanding of the heat profile will allow a constant temperature to be maintained as a function of height from substrate while printing complex shapes. In addition, to avoid slumping, this will also allow better control of the microstructural development and hence the properties. Figure 4 shows a preliminary comparison of the mechanical properties obtained.

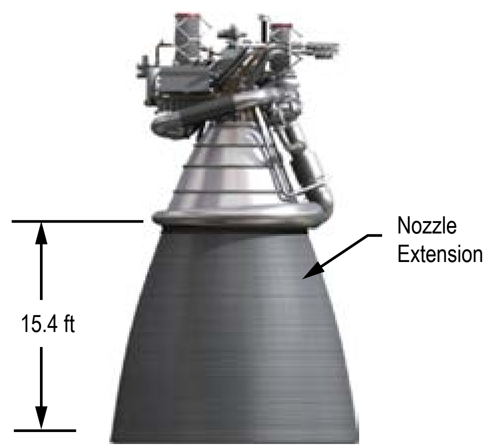

Figure 1: Nozzle extension for the J2X LRE.

Figure 2: Preliminary build of Inconel 718 for mechanical property testing.

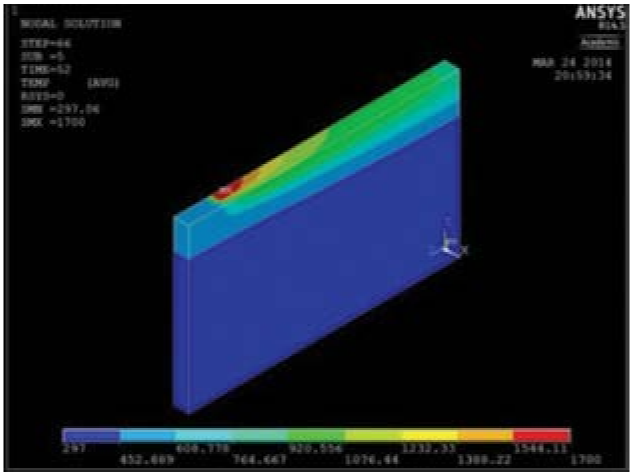

Figure 3: ANSYS transient heat analysis for specimen shown in figure 2 (temperature = °C).

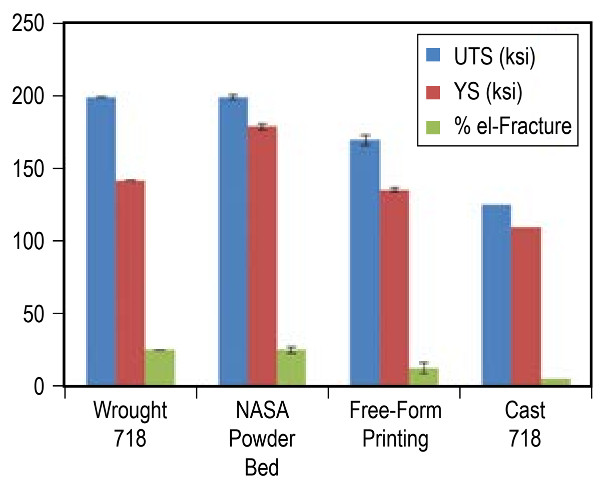

Figure 4: Comparison of properties obtained using powder bed process versus the free-form printing.

Anticipated Benefits

As the technology developed under this proposed effort is of interest to NASA as well as industrial partners, it is anticipated that teaming agreements could be made between manufacturers of robotic equipment for spin-off technologies. Validated thermal modeling of the build process conducted under this proposed effort will be made available to NASA. It is anticipated that this thermal model will be modular in design and can be readily implemented into the robotic controls.

Key to developing spin-off technology will be establishing the property-microstructure relationships for the pulsed arc source to advance its usage. While the margin of safety for components and systems may vary depending on requirements for cyclic life and impact resistance, a constant requirement among different applications is a basic knowledge of the constituent material capabilities as influenced by the manufacturing process. Without this, no designer can arrive at a safe, robust, and reliable design. It is expected that the enhanced control capability and predictive features of this proposed effort will enable a better selection of process parameters.

Potential Applications

Potential NASA applications for the free-form AM technologies developed under this effort include large structures such as solid and liquid rocket motor casings, liquid rocket nozzle extensions, and liquid rocket combustion chambers in addition to other demanding applications for complex designs and their repair.

Notable Accomplishments

The preliminary properties shown in figure 4 are comparable with the referenced standards.[1] Variation in properties may result from a slight difference in the NASA heat treatment that used a (°F solutionizing temperature versus that of the 1750 °F[2] for the powder bed specimens.[2]

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CAN

Interplanetary Radiation and Fault Tolerant Mini-Star Tracker System

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Sponsoring Program(s)

Marshall Space Flight Center/Center Management and Operations
Dual-Use Technology Cooperative Agreement Notice, Center Strategic Development Steering Group

Project Description

The Charles Stark Draper Laboratory, Inc. is partnering with the NASA Marshall Space Flight Center (MSFC) Engineering Directorate's Avionics Design Division and Flight Mechanics & Analysis Division to develop and test a prototype small, low-weight, low-power, radiation-hardened, fault-tolerant mini-star tracker (fig. 1). The project is expected to enable Draper Laboratory and its small business partner, L-1 Standards and Technologies, Inc., to develop a new guidance, navigation, and control sensor product for the growing small sat technology market. The project also addresses MSFC's need for sophisticated small sat technologies to support a variety of science missions in Earth orbit and beyond. The prototype star tracker will be tested on the night sky on MSFC's Automated Lunar and Meteor Observatory (ALAMO) telescope.

The specific goal of the project is to address the need for a compact, low size, weight, and power, yet radiation hardened and fault tolerant star tracker system that can be used as a stand-alone attitude determination system or incorporated into a complete attitude determination and control system for emerging interplanetary and operational CubeSat and small sat missions.

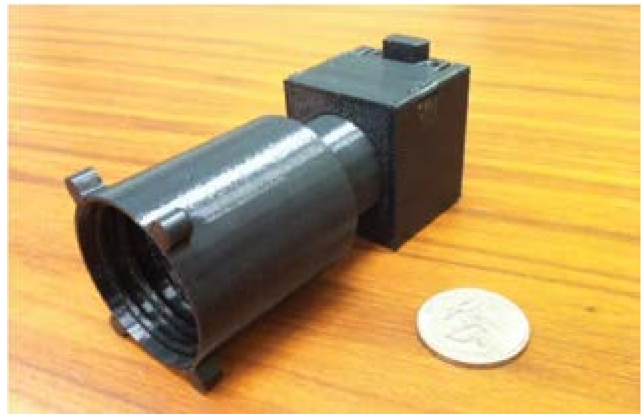

Figure 1: Model of mini-star tracker.

Anticipated Benefits

This star tracker will provide an affordable option for precision attitude determination (~10 arcseconds) and navigation on small spacecraft. Its small volume will fit into microsatellites and CubeSats. Its radiation tolerance will enable long-duration small sat missions in low-Earth orbit and beyond.

Potential Applications

This star tracker could support constellations of Earth-observing, precision nadir pointing spacecraft with mission durations >1 year. It will be well suited to polar orbits where radiation doses are higher. The star tracker will be valuable for future interplanetary CubeSat missions requiring fine pointing for science observations, communication, and navigation state updates.

Notable Accomplishments

The project kickoff was completed in August 2014 and performance requirements have been defined. Prototype design is underway including electronics, optics, and software. A bracket has been designed and fabricated for mounting the prototype on the ALAMO telescope (fig. 2).

Figure 2: Star tracker mount on ALAMO telescope.

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REPORT DOCUMENTATION PAGE

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14. ABSTRACT

Many of NASA's missions would not be possible if it were not for the investments made in research advancements and technology development efforts. The technologies developed at Marshall Space Flight Center contribute to NASA's strategic array of missions through technology development and accomplishments. The scientists, researchers, and technologists of Marshall Space Flight Center who are working these enabling technology efforts are facilitating NASA's ability to fulfill the ambitious goals of innovation, exploration, and discovery.

15. SUBJECT TERMS

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