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Marshall Space Flight Center

2023 Research & Technology Report

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Research and Technology Report 2023

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FOREWORD

Fiscal Year 2023 (FY23) has been stellar for NASA and the Marshall Space Flight Center. FY23 began with a key milestone for the nation's space program. The work our center contributed to the successful launch, flight, and splashdown of Artemis I is worth celebrating. The data from Artemis I, coupled with continued innovation and development, will power future Artemis missions. Alongside the launch, the center made incredible progress in core areas critical to our Moon to Mars mission objectives and future space exploration.

In FY23, Marshall continued to make significant contributions to Cryogenic Fluid Management (CFM). The center oversees a portfolio of CFM technology development and demonstration projects led by our workforce, other NASA centers, and industry partners. Our contribution to additive manufacturing was also significant. The Reactive Additive Manufacturing for Fourth Industrial Revolution (RAMFIRE) project focuses on advancing lightweight, additively manufactured aluminum rocket nozzles, which have the capability to send more cargo to deep space destinations. The Additive Manufacturing Enabled Biofilm Prevention (AMEBoP) project leverages additive manufacturing to fortify Environmental Control and Life Support Systems (ECLSS) manifolds and other vulnerable components against biofilm growth, enabling longer-term human missions beyond Low-Earth Orbit. Innovative advancements on extraterrestrial printing of sodium-ion batteries may enable longer stays on the lunar surface while contributing to the establishment of a sustainable lunar presence.

Marshall has a long history of excellence in propulsion research, and our work on solar sail technologies is providing a new capability for long-duration deep space science and observation missions. The agency's space nuclear propulsion project, led by Marshall, is essential to ensure crewed missions to Mars become a reality. Marshall is assisting with the Mars Sample Return (MSR) program, a truly extraordinary mission to bring the first samples of Mars materials to Earth. Marshall is developing the Mars Ascent Vehicle (MAV), which will launch the samples from the surface of Mars to Martian orbit. In FY23, the center matured development on an advanced Supersonic Split Line Nozzle, a component of the MAV solid rocket motors. This nozzle will enable MAV to meet the mission's stringent mass and environmental requirements.

I am incredibly proud of the Marshall Space Flight Center workforce progress made in FY23. Our achievements demonstrate the expertise, imagination, and innovation needed to return to the Moon and explore Mars and beyond.

Joseph Pelfrey

Acting Center Director
NASA Marshall Space Flight Center

INTRODUCTION

For me, 2023 was a reminder of the just how important first principles are to even the most advanced technologies and innovations. The basics of thermal design and control have had significant impact for NASA MSFC's research and technology portfolio, as a leader in thermal systems for extreme environments. The James Webb Space Telescope (JWST) reporting an incredible discovery in June with the observation of the first light that suffused the early Universe and the discovery of ancient galaxies. This is providing remarkable insights into the evolution of the universe and role of early stars in shaping our cosmic history. This discovery was made possible through the mastery of thermal design. The JWST mirrors from MSFC included technology development for the characterization of the mirror base materials such that they could be fabricated at ambient conditions and then would only come into focus at its ~50k (-220oC) operating temperature.

The MSFC impact from the mastery of thermal design continued with multiple projects and infusion opportunities. NASA MSFC demonstrated actively cooled long duration operation of the Rotating Detonation Rocket Engine (RDRE) with complex thermal control approaches, enabled by Advanced Manufacturing and novel cooling approaches first demonstrated through a Center Innovation Fund (CIF) investment. The RDRE was then awarded an active Early Career Initiative (ECI) project to build on that success and enable key missions with a step function in improved rocket engine performance. An earlier ECI for the Lunar Thermal Regulation for Mission Sustainability (TheRMiS) partnered through a Small Business and Innovative Research (SBIR) investments for a novel Variable Conductance Heat Pipe (VCHP) manifested for the December 2023 launch of a Lunar lander on the path to surviving the Lunar night. Whether it's for our flagship great observatories or from concept to flight in 3-years on a commercial Lunar lander, the MSFC RandT investments continue to yield dividends. I am once again proud to share our annual portfolio and highlight the accomplishments of my team.

John W. Dankanich

Center Chief Technologist
NASA Marshall Space Flight Center

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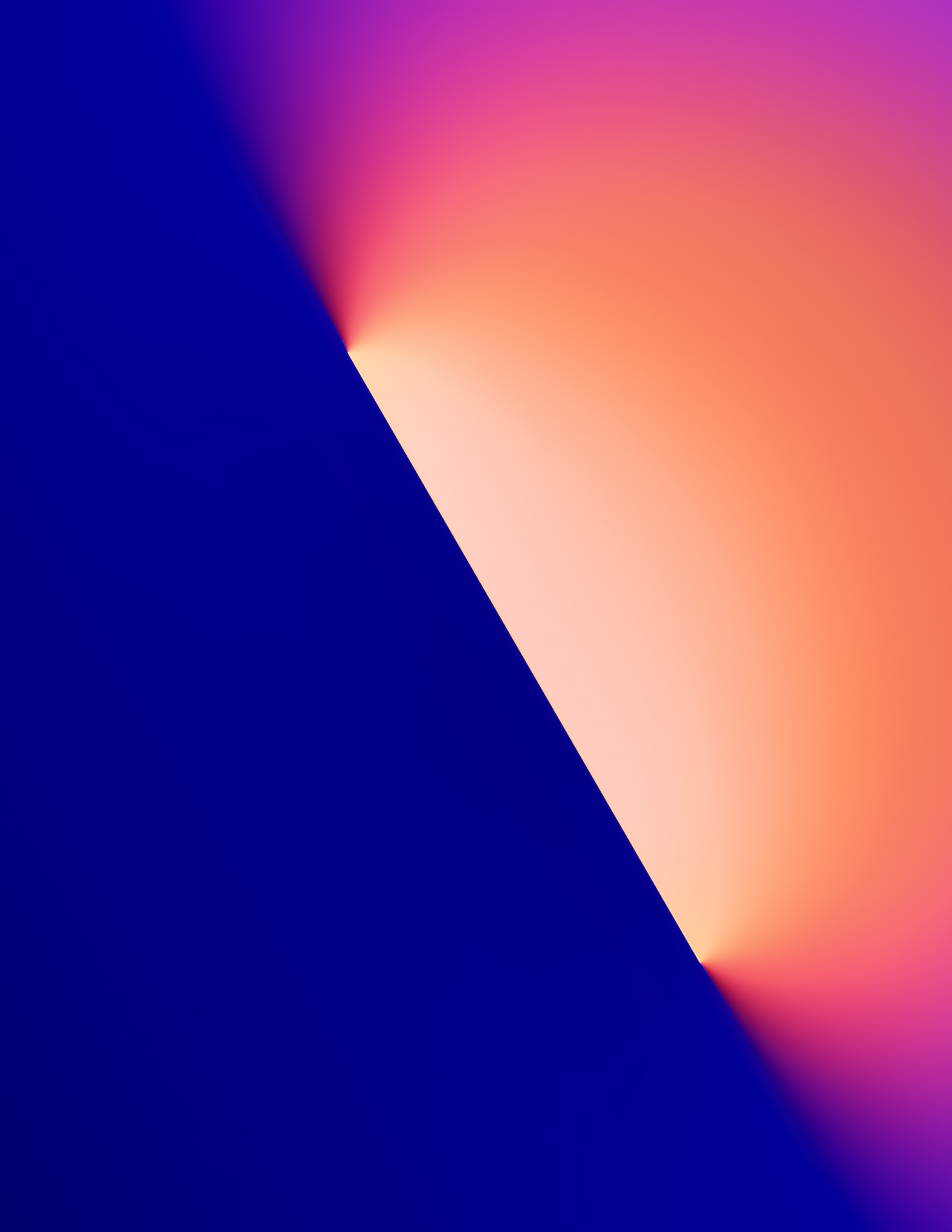


TECHNOLOGY AREA 01

PROPULSION SYSTEMS

Mars Ascent Vehicle (MAV) Supersonic Split Line (SSSL) Nozzle

PROJECT OBJECTIVE: To demonstrate the use of the Mars Ascent Propulsion System (MAPS) Supersonic Split Line (SSSL) nozzle during the first stage flight of the Mars Ascent Vehicle (MAV).

PROJECT GOAL/DESCRIPTION

The MAV, as part of the integrated Mars Sample Return (MSR) mission, must survive extreme martian environments including hardware temperatures down to –40 °C and near-vacuum pressure. The MAV must also be mass efficient, as it is a payload within the Mars Sample Retrieval Lander before it is utilized as a launch vehicle to carry the martian soil samples into orbit around Mars to deliver them to the European Space Agency's Earth Return Orbiter.

The MAPS Supersonic Split Line (SSSL) nozzle design is necessary to meet these demanding requirements for the propulsion system. The purpose of this project is to advance the Technology Readiness Level (TRL) of the SSSL. The SSSL nozzle is the portion of the Solid Rocket Motor 1 (SRM1) nozzle assembly mechanism that the Thrust Vector Control system interfaces with and gimbals to guide the direction of the MAV first stage launch off the surface of Mars. The requirements for the SRM1 nozzle, which include extreme cold capability and mass efficiency, are driving the necessity to mature this state-of-the art nozzle technology.

FIGURE 1. Artist concept of the MAV in powered flight off the surface of Mars.

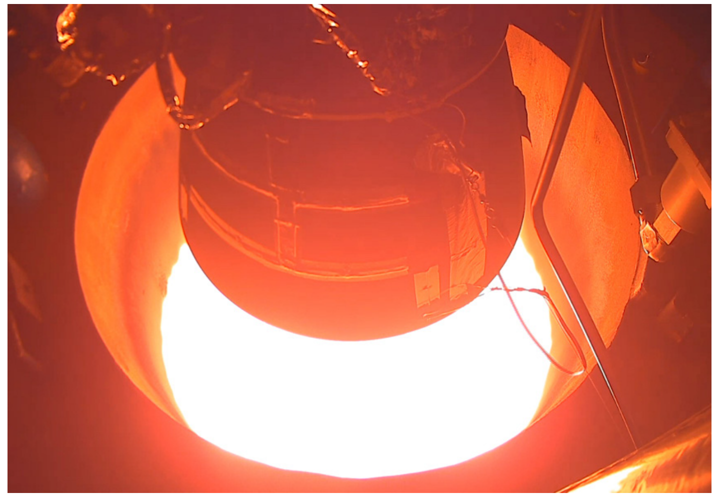


FIGURE 2. The MAPS SRM1 DM-1 static fire.

APPROACH/INNOVATION

The SSSL nozzle technology has been used in previous applications, but not with the environments anticipated as part of the MAV mission. The technology maturation readiness goal to move from TRL 5 to TRL 6 was predominately accomplished as part of a test series. The two primary test activities that occurred to justify the maturation of SSSL from TRL 5 to TRL 6 were the Nozzle Bench Test (NBT)-1 and Development Motor (DM)-1 static fire. These two tests put the SSSL nozzle through relevant static, thermal, pressure, and motor operation environments.

The SSSL nozzle architecture imparts less normal force on the bearing and seals, reducing friction, which reduces actuator structural mass and battery power draw. Additionally, the geometry of a SSSL type trapped ball leads to less exhaust particles penetrating the split line which mitigates a risk of operation with a cold initial nozzle temperature. The next steps for the SSSL will include design maturation, NBT-2 static and dynamic loads testing, and the DM-2 and DM-3 static tests.

RESULTS/ACCOMPLISHMENTS

The entire motor assembly was thermally conditioned for static testing in the Air Force Research Laboratory (AFRL) altitude test facility. The DM-1 static test was successfully fired on April 7, 2023. The SSSL successfully vectored thrust for the full duration motor burn.

Detailed assessment of the post-test hardware condition determined that the SSSL technology is mature for the required MAV environments. The AFRL test facility utilized three load cells to measure thrust data that describes how the SSSL performed very close to nominal pre-test predictions. Based on the successful results obtained in the NBT-1 and DM-1 tests, the technology has been properly matured to TRL 6.

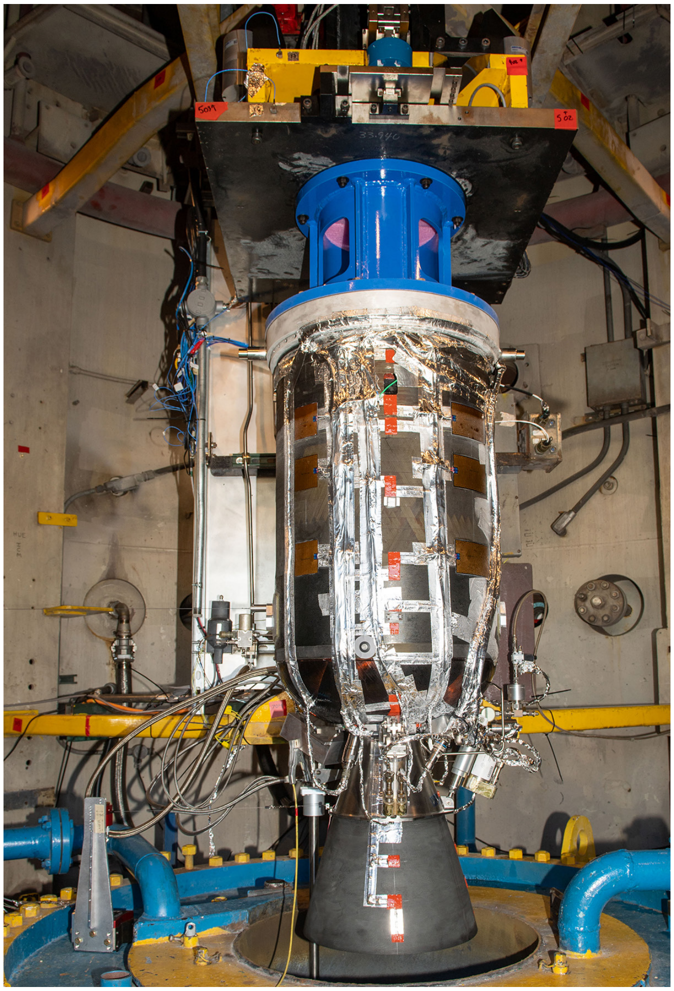


FIGURE 3. The MAPS SRM1 DM-1 shown within the AFRL altitude chamber following the static hot-fire test.

PARTNERSHIPS

The SSSL is designed, developed, tested and provided by Northrop Grumman in Elkton, MD as part of the SRM1 final assembly being delivered to the government under the MAPS contract. Northrop Grumman is an industry leader in solid rocket motor technology. The MAPS contract will provide development motor tests, qualification motor tests, and one flight motor delivery for the SRM1 and SRM2. The Mars Ascent Vehicle is a crucial mission partner for the NASA Jet Propulsion Laboratory-managed MSR mission that will return martian soil samples to Earth for scientific evaluation.

SUMMARY

The MSR mission is a critical step toward the scientific evaluation of whether ancient life existed on the planet Mars. The MAV plays a critical role in returning those martian soil samples to Earth as part of this mission. The MAV propulsion system development has now been demonstrated to be at the appropriate technology maturation level to progress toward the final vehicle design. The outcome of the testing activities with relevant martian environments for the NBT-1 and DM-1 static hot-fire test on the MAPS SRM1 SSSL have matured this technology to TRL 6.

Principal Investigator(s): Ben Davis
Partners: Northrop Grumman Corp.; NASA Jet Propulsion Laboratory
Funding Organization(s): Science Mission Directorate
For more information:
https://youtu.be/rb2CLp2HIkc?si=_RTRTsPKt_9Y2dnT

Electromagnetic Solar Sail Coupling (ESSC)

PROJECT OBJECTIVE: To enable higher performing solar sails through the development of novel electromagnet coupling technologies.

PROJECT GOAL/DESCRIPTION

One of the most efficient ways of exploring deep space is through the deployment of solar sails. A solar sail consists of a spacecraft bus (where all the electronics and other systems are located) that deploys a large sail. The Sun's light and solar wind pushes against the sail, allowing it to "sail" much like a sailboat uses the wind to sail the ocean. For a solar sail to steer, one of the most effective methods is to move the spacecraft off the sail's center, changing the center of mass (CM). Any shift in the spacecraft's CM relative to the center of pressure caused by the Sun causes a change in the angle of thrust on a sail, allowing it to steer much like a sailboat.

Currently, this is achieved using large mechanical systems to move the spacecraft along the sail's booms. This limits the sail's pointing and steering ability, requires complex and risky deployment of mechanical systems, and requires heavy mass for the mechanical systems. Here, we developed an electromagnetically coupled system that allows the spacecraft to move in relation to the sail by adjusting the attractive or repulsive force on permanent magnets attached along the booms. The advantages of this approach are that magnetic coupling is simple, frictionless, an order of magnitude more mass efficient than all other mechanical alternatives, and allows six degrees of freedom control of the spacecraft bus for pointing and steering.

Electromagnetic coupling also allows the solar sail to rotate independently of the bus, permitting for the construction of larger, rotating solar sails that may support much higher mass and/or, enable more complex spacecraft capable of executing science missions to more distant and/or more difficult targets. The objective of this project is to advance

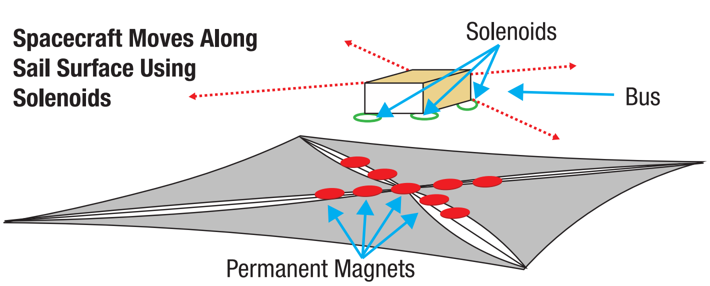


FIGURE 1. Conceptual overview of electromagnetically coupled solar sail.

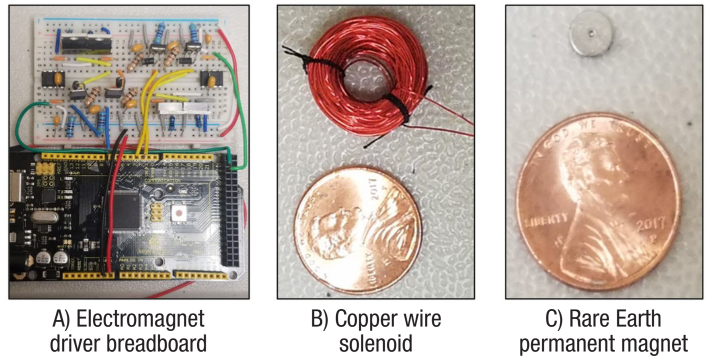


FIGURE 2. Prototype hardware.

this novel tethering technology from Technology Readiness Level (TRL) 3 to TRL to 4 through the construction and testing of a mock sail and Bluetooth-controlled spacecraft.

APPROACH/INNOVATION

EElectromagnetic coupling has never been developed or used for solar sail control before. It is a completely novel means of sail craft attitude control and steering. This revolutionary technological advancement has many promises and applicable to all types of solar sails, both current and future sailing concepts.

In addition to the novel technology concept of using electromagnets and permanent magnets to wirelessly tether solar sails, the team employed several innovative ideas: extensive use of commercial-off-the-shelf (COTS) components, e.g. Raspberry Pi devices, cameras, bench power supply, water bath and air hockey table, etc. The extensive use of COTS components allowed for the development of a rapid, low budget prototype. Through the development of video signal processing algorithms, tracking and control algorithms were developed based on the detection of April tags (similar to a QR code) on the satellite bus.

RESULTS/ACCOMPLISHMENTS

Project milestones include the development of prototype plans, procurement of several pieces of COTS hardware, satellite bus tracking algorithms through the development of video tracking algorithms, development of algorithms to control the spacecraft bus's location, construction of the prototype apparatus, construction of the stepper motor and electromagnet drivers, and many more. The team was able

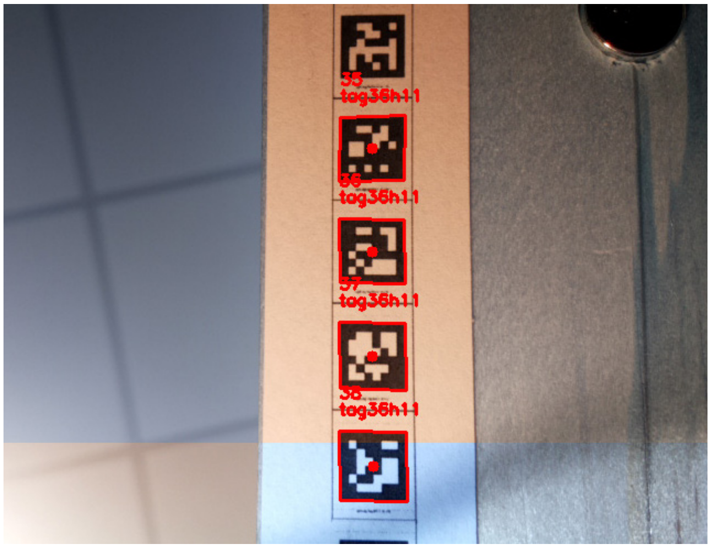
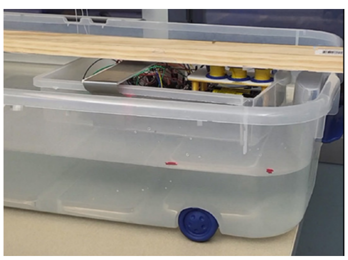
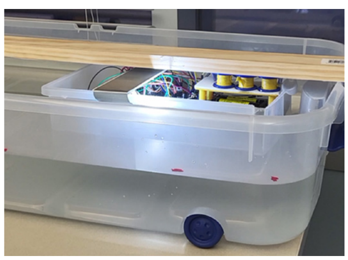


FIGURE 3. Video signal processing of April tags for tracking.

to successfully demonstrate the project's major test objectives by moving the prototype bus 3 cm in left/right and up/down directions as well as sideways in a water bath. Water bath steering trails were fully autonomous and ran for more than 2 minutes. All electronics were powered by inexpensive, rechargeable 18650 lithium-ion batteries.

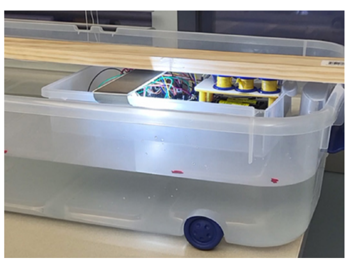


A) Beginning of steering test (+0 sec)



B) Light denotes control algorithm is taking a picture (+21 sec)

C) Prototype being steered to the left and sideways (+24 sec)



D) Prototype being steered more to the left and sideways (+29 sec)

FIGURE 4. Prototype spacecraft bus being actively steered with electromagnets and tracked in a water bath.

SUMMARY

Ultimately, this effort continues to leverage NASA's rich legacy in pushing the state-of-the-art of advanced exploration technologies. Specifically, this project seeks to develop the necessary technologies to enable us to explore the solar system through the deployment of higher performing solar sails, collecting new data and knowledge for the benefit of all humankind. This novel technology can allow greater steering of solar sails, which enables the ability to have more complex trajectories. Greater steering control can allow the exploration of dwarf bodies, near-Earth asteroids, and other bodies of interest within the solar system that are very difficult to get to. This novel technology weighs a lot less than conventional state of the practice of using mechanical tethering, which can drastically reduce travel times from over a decade to a handful of years. Lastly, this technology can also enable rotating solar sails (i.e., a solar sail that rotates for deployment and stability), which allows for larger solar sails. Larger solar sails, in turn, allow for lower mission durations and much greater science payload sizes to explore the secrets of our solar system more quickly and with higher quality.

Principal Investigator(s): Manuel J. Diaz
Funding Organization(s): Center Innovation Fund
NTR/Patent Number: NTR 1628170647

Optimized and Repeatable Components in Additive Manufacturing (ORCA)

PROJECT OBJECTIVE: The Optimized and Repeatable Components in Additive Manufacturing (ORCA) project builds upon the successful evolution of additive manufacturing (AM) core technology under the Low Cost Upper Stage-Class Propulsion (LCUSP) and Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) projects for liquid rocket components and provides high payoff optimized performance technologies and enabling materials in AM for combustion chambers, injectors, nozzles, and turbomachinery. ORCA is enabling new opportunities within AM and postprocessing to further optimize performance of these components.

PROJECT GOAL/DESCRIPTION

The ORCA project is advancing several aspects of AM focused on enabling materials and critical processing steps. The project focus has three stages: (1) develop alloys enabled by AM that deliver high performance in extreme temperatures and high-pressure, oxygen-rich environments; (2) advance development of postprocessing surface enhancements and polishing techniques for small- and large-scale propulsion components; and (3) mature process modeling to enable the AM of large-scale, long-duration component builds that are repeatable with limited build failures.

APPROACH/INNOVATION

The ORCA project is focusing on advancing several AM processing and postprocessing techniques to enable optimization of the entire AM process supply chain. ORCA is also focusing on advancing postprocessing surface enhancement and polishing techniques for various AMed alloys. Surface texture is typically higher for AM processing and often requires postprocessing to balance friction factors and pressure drop for internal and external features, fatigue life, and balance with heat transfer aspects and component aesthetics. ORCA is evaluating these surface enhancements on various alloys using the laser powder bed fusion (L-PBF) and laser powder directed energy deposition (LP-DED) processes to establish mechanical properties, flow performance, and component performance in relevant environments.

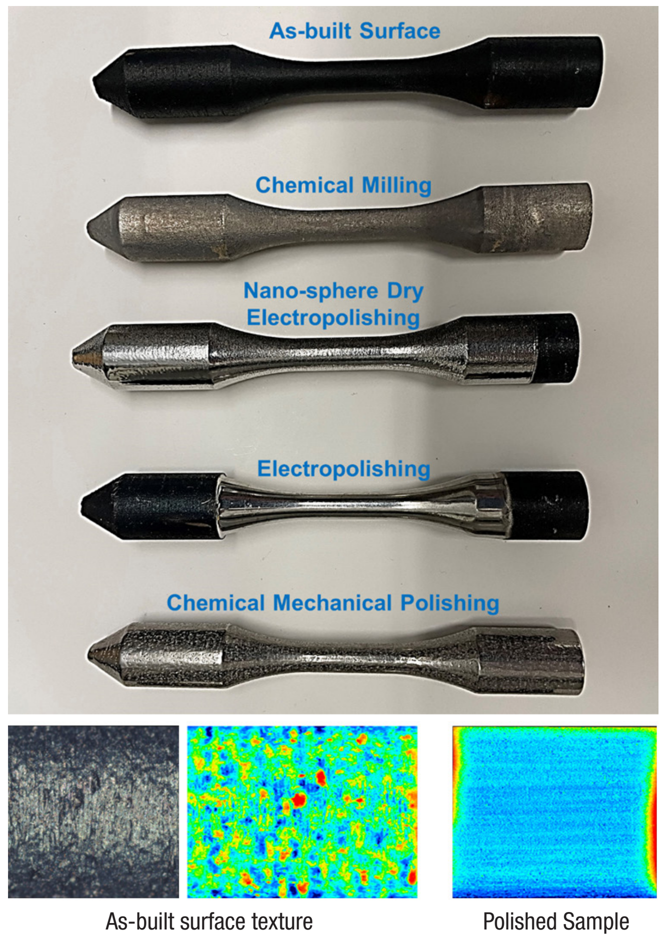


FIGURE 1. Various surface enhancement (polishing) processes.

As rocket engines are being pushed to higher pressures and more extreme environments, new alloys are required to meet these challenging requirements. Oxygen compatibility is also required of these alloys for staged-combustion propulsion systems. ORCA is using integrated computational materials engineering (ICME) to develop new alloys for these environments, enabled by AM. These alloys will be advanced using various AM processes, complete characterization and mechanical testing, and component demonstrations and testing.

FIGURE 2. Hot-fire Test of GRX-810 alloy.

RESULTS/ACCOMPLISHMENTS

The ORCA project leveraged technological improvements from previous projects (such as RAMPT) to advance NASA's capabilities in AM of space propulsion components. ORCA led the effort to build and test injectors and nozzles made from a novel alloy named GRX-810, developed by NASA Glenn Research Center. To further mature the GRX-810 alloy, a liquid oxygen/methane (LOX/CH4) injector and nozzle were designed, 3D printed using L-PBF, and hot-fire tested at the NASA Marshall Space Flight Center Test Stand 115. The LOX/CH4 test series was completed July 19th. The nozzle achieved 90 starts and 2,309 seconds of accumulated time. The injector was tested for a total of 2,228 seconds and 84 cycles. Notably, the injector appears to provide a ~5× improvement in life (erosion) compared to currently used superalloys, such as nickel (Ni) alloys INCONEL® 625 and INCONEL 718.

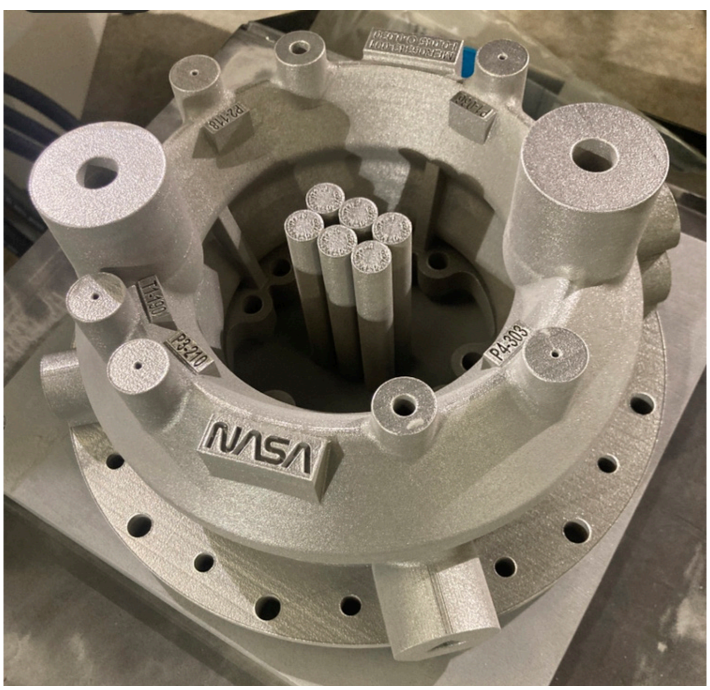


FIGURE 3. GRX-810 Injector.

In collaboration with NASA White Sands Test Facility, the project completed flammability testing on several AM alloys, providing crucial data to aid engineers in selection of materials for oxygen-rich environments. This data provided a baseline for new alloy design using ICME with oxygen resistance as a primary requirement under extreme temperatures.

PARTNERSHIPS

Another critical aspect of maturing AM is a complete characterization of the various alloys, heat treatment optimization, and mechanical and thermophysical testing. The ORCA project partnered with Auburn University to test and characterize material properties for over 50 AM alloys, further expanding our nation's technical capabilities and knowledge in this area. This data will be made available at the conclusion of the ORCA project.

SUMMARY

The ORCA project will address several fundamental technical challenges required for full infusion of AM for current and future missions. This maturation of AM will support the Space Technology Mission Directorate Strategic Framework in all thrust areas of Go, Live, and Explore, and will benefit NASA's science and exploration missions.

Principal Investigator(s): Paul Gradl
Partners: Auburn University
Funding Organization(s): Game Changing Development

Reactive Additive Manufacturing for the Fourth Industrial Revolution (RAMFIRE) Announcement of Collaborative Opportunity (ACO) with Elementum 3D

PROJECT OBJECTIVE: Advance large-scale directed energy deposition (DED) of high-strength aluminum alloys through process development, characterization, and testing and make a supply chain available for use by the broader aerospace, automotive, and other industries.

PROJECT GOAL/DESCRIPTION

Through this project, NASA sought to help further increase performance and reduce cost by advancing novel additive manufacturing (AM) of aluminum materials through partnerships with commercial AM service vendors and commercial space partners for large-scale complex rocket components and launch vehicle structures.

Under the Announcement of Collaborative Opportunity (ACO), NASA partnered with Elementum 3D and leveraged patented Reactive Additive Manufacturing (RAM) technology to develop a family of printable high-strength aluminum feedstocks, originally used for laser powder bed fusion (L-PBF) AM. These feedstocks have strengths equaling or exceeding comparable high-strength wrought aluminum alloys while also being weldable and printable, unlike the wrought alloys. This project evolved these aluminum alloys to large-scale DED process, providing significant new design opportunities for engines, launch vehicles, and habitats.

APPROACH/INNOVATION

The project significantly advanced this alloy and processing through feedstock specification and validation, process development and validation, microstructural and mechanical property characterization, hot-fire testing of a small regeneratively cooled nozzle (Fig. 1), and printing of large-scale components.

RESULTS/ACCOMPLISHMENTS

Elementum 3D developed the novel aluminum alloy Al6061-RAM2 material by using their patented RAM technology. Al6061-RAM2 is a high-strength feedstock that was specifically designed for weldability and printability while still maintaining, or exceeding, the strength properties of high-strength wrought aluminum alloys. NASA Marshall Space Flight Center completed design, analysis, and manufacturing of an integral channel liquid engine rocket nozzle. Testing was conducted with a lander-class 7,000 lbf thrust engine using liquid oxygen (LOX)/liquid hydrogen (LH_2) and LOX/liquid methane (LCH_4). During the hot-fire test series (see Fig. 2), the novel laser powder directed energy deposition (LP-DED) hardware accumulated 9 starts and 303 seconds of duration using LOX/LH_2 propellants and 13 starts and 276 seconds of duration using LOX/LCH_4. The Al6061-RAM2 nozzles performed exceptionally well, considering the novelty of the alloy and the lack of historical information on aluminum alloys being used in high heat flux environments.

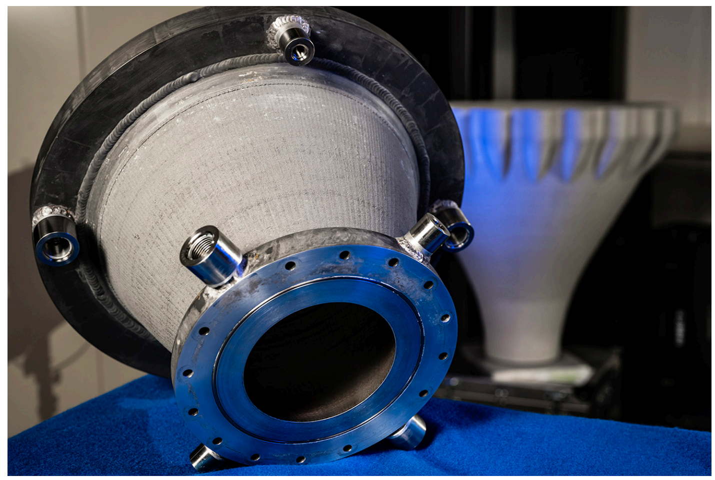


FIGURE 1. Al6061-RAM2 Nozzle.

PARTNERSHIPS

Elementum 3D played a key role in the project, including: developing and providing feedstock with proper particle size and validation for DED process, supporting process development, providing requirements for RAM alloy

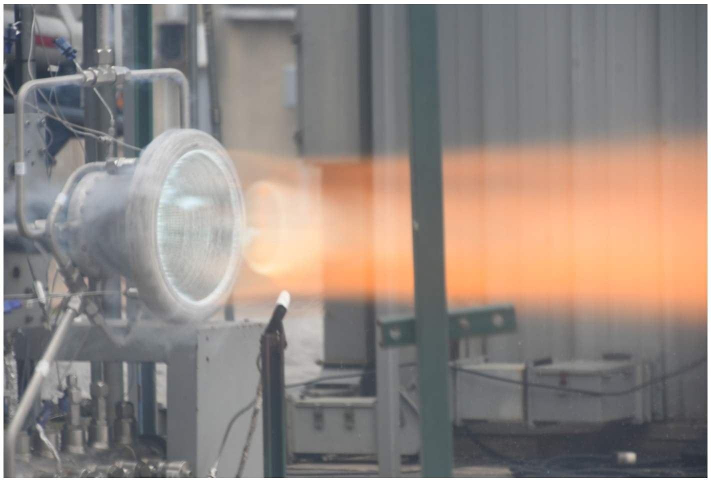


FIGURE 2. Hot-fire Test of Al6061-RAM2 Nozzle.

and helping to determine process adjustments, analyzing microstructures and validating mechanical properties in accordance with ASTM standards, and completing metallography and characterization of RAM alloys during process development.

Additional support came from RPM Innovations for the LP-DED process development and printing of the nozzles. Auburn University completed characterization of the LP-DED Al6061-RAM2 alloy, including a powder recycling study.

SUMMARY

The RAMFIRE program was the product of an ACO with Elementum 3D, NASA, and RPM Innovations. The goal of the project was for NASA and the industry partners to advance the LP-DED AM of Al6061-RAM2 by establishing print parameters, characterizing the material, and hot-fire testing two LP-DED nozzles with complex internal cooling channels. The development of the Al6061-RAM2 material and these nozzles successfully advanced high-performance, lightweight materials and their ability to be used in large-scale parts. The data and materials results are available for industry use and infusion.

Principal Investigator(s): Paul Gradl; Ben Williams; Tessa Fedotowsky
Project Manager: John Fikes
Partners: Elementum 3D; RPM Innovations; Auburn University
Funding Organization(s): Game Changing Development

Rapid Analysis and Manufacturing Propulsion Technology (RAMPT)

PROJECT OBJECTIVE: Reducing design and production schedules while allowing for reduced part count, increased reliability, and significant mass reduction; creating a healthy American supply chain for large-scale, regeneratively-cooled liquid rocket engines.

PROJECT GOAL/DESCRIPTION

The RAMPT project has advanced large-scale, regeneratively cooled liquid rocket engine technology by utilizing multimetallic freeform additive manufacturing (AM), composite overwrap techniques, and advanced AM analysis capabilities. RAMPT reduced the design, analysis, fabrication, and assembly lead times, while also reducing parts and weight and increasing reliability. RAMPT engaged the manufacturing community and facilitated infusion of technology into the commercial industry through public-private partnerships to create a healthy American supply chain.

FIGURE 1. Thrust chamber assemblies at various sizes: 2k-lbf, 7k-lbf and 40k-lbf.

APPROACH/INNOVATION

RAMPT has advanced the following technical areas: (1) laser powder directed energy deposition (LP-DED) to fabricate an integrated regeneratively-cooled channel wall nozzle; (2) composite overwrap techniques to reduce mass and provide structural integrity; (3) bimetallic and multimetallic AM deposition to optimize material performance; (4) modeling and simulations for large-scale deposition to obtain property predictions and to develop “smart” toolpaths; and (5) integrated regeneratively cooled combustion chamber and nozzle design tool to reduce design cycles.

RESULTS/ACCOMPLISHMENTS

NASA’s RAMPT project has designed and manufactured a series of AMed coupled combustion chambers and nozzles to advance new AM processes and materials with the goal of reducing cost and schedule for engine manufacturing (Fig. 1). These designs incorporated bimetallic AM and carbon-fiber composite overwrap to reduce overall thrust chamber assembly (TCA) mass. Early designs targeted a 2,000 lbf thrust TCA with coupled and decoupled testing. Successful testing progressed to 7,000 lbf thrust TCAs, followed by manufacturing and test planning for 35,000 lbf thrust TCAs. The baseline engine design for all thrust classes included a laser powder bed fusion (L-PBF) copper alloy GRCop-42 combustion chamber liner with a composite overwrap structural jacket and a LP-DED integral channel wall nozzle deposited directly onto the chamber. The LP-DED nozzles focused on development of a new hydrogen-resistant alloy, NASA HR-1.

Each thrust class TCA included a coupled and decoupled design. The decoupled TCAs utilized a standard bolted flange interface between the combustion chamber and the nozzle. The coupled TCAs fabricated the combustion chamber and nozzle as a single component by using freeform integrated DED to build the nozzle directly onto the aft end of the combustion chamber. This axial interface required a bimetallic joint where the GRCop-42 chamber transitions to a copper-nickel or INCONEL® material followed by the NASA HR-1 nozzle. Material characterization, bimetallic interfaces, and expanded manufacturing capabilities were necessary to bring these TCAs to complete hot-fire testing at NASA Marshall Space Flight Center (MSFC) Test Stand (TS) 115 and TS116.

In August and September 2023, testing was completed at MSFC TS116 on three 40,000 lbf thrust TCA configurations (see Figs. 2 and 3).

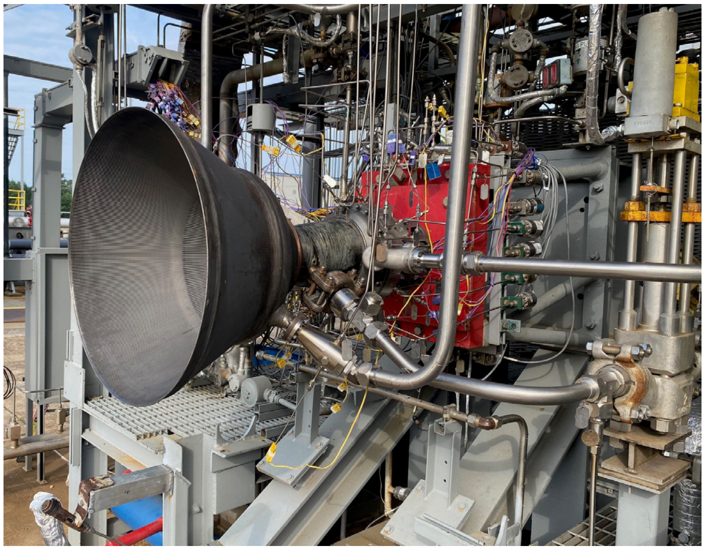


FIGURE 2. 40k-lbf thrust chamber assembly with composite overwrap installed in the test stand.

FIGURE 3. Hot-fire test of 40k-lbf thrust chamber assembly with composite overwrap (Sept. 2023).

- TCA#1 with a metal jacket main combustion chamber (MCC) and NASA HR-1 DED nozzle
  – was successfully tested for a total of 190 seconds mainstage duration with 4 starts at a maximum chamber pressure of 1,527 psia
- TCA#2 with a composite overwrap structural jacket on MCC
  – was successfully tested for a total of 70 seconds mainstage duration with 3 starts at a maximum chamber pressure of 1,485 psia
- TCA#3 is the coupled unit that demonstrated all our new technologies being developed under RAMPT: NASA HR-1 DED nozzle, composite overwrap jacket, and bimetallic joints with continuous coolant channels from chamber to nozzle
  – Final testing on the coupled unit with liquid oxygen/liquid hydrogen reached 1,250 psia, mixture ratio of 5.2 and duration of 54.5 seconds

In addition to component development, RAMPT has enabled the industrial supply chain through public-private partnerships and development of several RAMPT technologies at commercial space companies. NASA has continually publicized data and test results for industry use. Under the RAMPT project, an extensive textbook was published titled *Metal Additive Manufacturing for Propulsion Applications* (P. Gradl, O. Mireles, C. Protz, C. Garcia, 2022, AIAA) to provide lessons learned throughout the entire AM process.

PARTNERSHIPS

NASA has engaged Auburn University under contract to develop and operate the RAMPT public-private partnership with over 13 specialty manufacturing vendors to enable a long-term supply chain available to the government and the commercial rocket industry. This allows for cost sharing from industry and rapid infusion of processes throughout the supply chain.

SUMMARY

The RAMPT project met all major objectives including advancing the GRCop-42 alloy through flight, development of the directed energy deposition process for large scale integral channel-wall nozzles, composite overwrap of combustion chambers for mass savings and also AM modeling and simulations to reduce build failures. RAMPT completed various manufacturing demonstrations of large-scale liquid rocket engine components and successful hot-fire testing up to the 35,000 lbf thrust level with coupled hardware. The RAMPT team has partnered with entities throughout the United States, including other government agencies, private industry, and academia to share costs and leverage industry expertise.

A closeout report is planned for October 2023.

Principal Investigator(s): Paul Gradl
Project Manager: John Fikes
Partners: Auburn University
Funding Organization(s): Game Changing Development
For more information:
https://www.nasa.gov/directorates/spacetech/game_changing_development/projects/RAMPT
Patent Number: US 11,333,105 B1

Hot-Fire Testing of Additively Manufactured Injector Elements for Rockets

PROJECT OBJECTIVE: A collaborative effort between Auburn University and NASA Marshall Space Flight Center (MSFC) is underway to hot-fire test additively manufactured (AM) injector element schemes for injector optimization toward higher engine C*.

PROJECT GOAL/DESCRIPTION

Well atomized and mixed propellants yield high overall combustion efficiency in all types of combustion devices, particularly liquid rocket engines (LREs) and rotating detonation rocket engines (RDREs). Additively manufactured (AM) injector elements need to be characterized for performance parameters before they can be used in full scale engines. The goal of this effort is to enhance MSFC's propulsion systems and test AM capability limits. Hot-fire testing of novel AM injector elements allows for measurement of combustion performance parameters necessary for subscale hardware development. Auburn University Combustion Physics Lab (AUCPL) has conducted single-element cold flow and hot-fire testing of individual select AM injector elements. It is therefore the current research goal of AUCPL to scale up hot-fire testing of subscale RDREs over a broad range of operating conditions with our high-pressure gaseous oxygen (GOX)/methane (CH_4) combustion facility and to analyze injector combustion efficiency and face ablation. These measurements will be paired with past work investigating the cold flow performance of the same injector elements using stereophotographic imaging to determine cold flow atomization and mixing capabilities (Fig. 1).

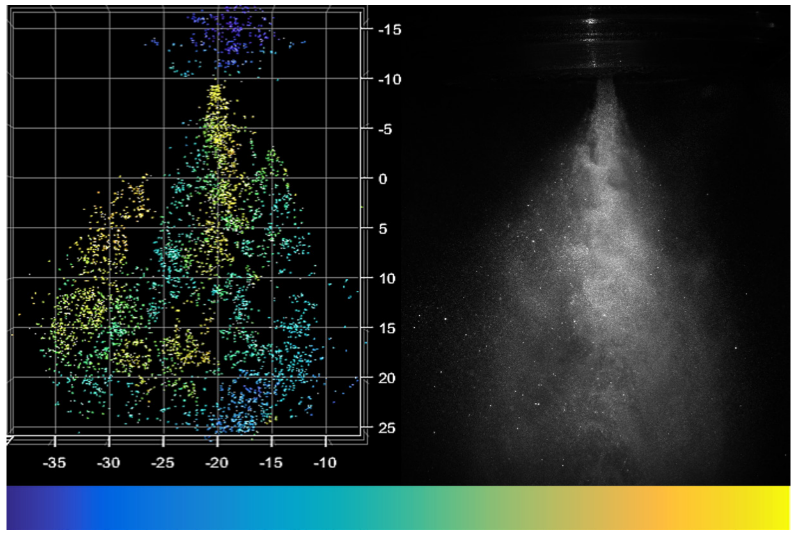


FIGURE 1. Side-by-side of stereophotographic generated 3D point cloud with parula color scheme and instantaneous image of injector spray. Point color represents depth, with blue closest to camera pair and yellow furthest. Maximum depth limited to injector centerline.

APPROACH/INNOVATION

Facility development was threefold under this project. Cold flow system test capabilities were extended to allow for 3D instantaneous visualization of test articles in preparation for hot firing. These images allow for assessment of local propellant distribution, an essential diagnostic for short combustion chamber length engines like RDREs where there is limited residence time for mixing to occur in the combustion chamber. A GOX/CH_4 low flow system was developed for the hot-fire testing AM injector element schemes for injector optimization. This allows for comparisons in hot-fire performance with cold flow metrics found using stereophotogrammetry. This facility was designed to act as a small-scale test bed for single injector element hot-fire testing, complimenting the preexisting large-scale flow facility. These capabilities enable the development and testing of subscale RDREs at AUCPL.

A single element pentad fuel injector has been designed and AM out of copper alloy GRCop–42. This injector was designed to be able to switch between gaseous methane (GCH_4)-centered and GOX-centered configurations, as well as tolerate GCH_4 and liquid oxygen low flow rates. This injector has been hot-fire tested multiple times using the low flow GOX/CH_4 system, igniting reliably under a sweep of mixture ratios from 2.0 to 4.1. This single injector element serves as a hot-fire system capability demonstration (Fig. 2).

RESULTS/ACCOMPLISHMENTS

A stereo photogrammetry system coupled with a dual-pulse neodymium-doped yttrium aluminum garnet laser (New Wave Solo III, 50 mJ/pulse) with a 20 ns pulse duration has been chosen for 3D visualization of cold flow for char-

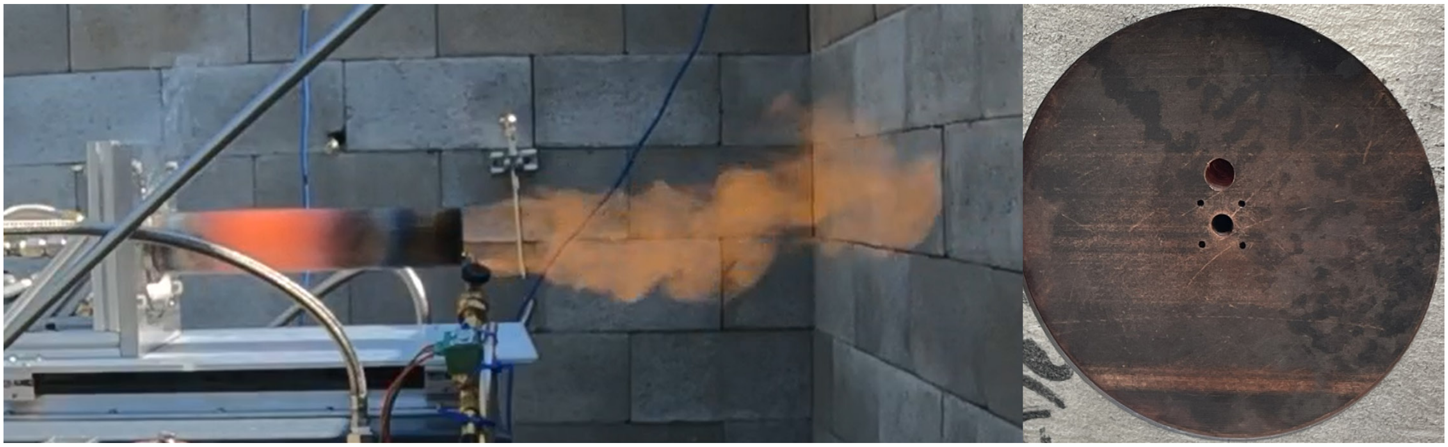


FIGURE 2. Hot-fire experiments of AM pentad single element injector using low flow gaseous oxygen and methane system.

acterizing test articles. Pulsed illumination at this speed eliminates the blur effect due to rapidly moving droplets. The data obtained from the AM pentad injector has been conducted, producing a 3D point cloud of the spray. The cold flow experiments compliment active hot-fire experiments using the low flow system developed under this work (see Fig. 1).

The AM injector shown was designed as a preliminary test article in preparation for subscale RDRE testing. As a part of this work, a 6-in-long water jacket outer body is in development to allow for visual diagnostics of the detonation wave progress while overcooling the outer body. This water jacket allows for 7 gal/min of water at pressures up to 120 psig, which is sufficient cooling for individual injector elements or the outer body of a subscale RDRE. The proposed subscale RDRE will serve as the workhorse for future hot-fire research.

PARTNERSHIPS

Auburn University is the primary collaborator for the work outlined in this report. The spray facility, hot-fire facility, and diagnostic equipment is setup at the AUCPL on Auburn's campus. Dr. David Scarborough, an associate professor, and Ari Goldman, Alabama Space Grant Fellow graduate researcher, are the primary collaborators at Auburn University. They have significantly advanced the progress of this work for NASA and will continue this collaborative effort in Fall 2023.

SUMMARY

This effort is an important step in developing high-performance propellant injectors for LREs and RDREs and in developing a diagnostic tool for understanding how the 3D structures of injector sprays influence combustion performance. This capability will substantially benefit NASA MSFC by providing a resource for future performance enhancement designs of AM liquid rocket injectors. This effort also works to enhance NASA MSFC's test capacity with buildup toward a subscale RDRE test facility. Next steps will continue along the following three paths: (1) The diagnostic tools developed from cold flow testing of ultra-high-performance injectors will be applied to subscale RDREs; (2) continued hot-fire testing of individual injector elements; (3) the development of a subscale RDRE test facility to allow NASA a fast-prototyping platform.

Principal Investigator(s): Dr. David Scarborough, Auburn University; Thomas Teasley
Partners: Auburn University
Funding Organization(s): Cooperative Agreement Notice

Development of High-Efficiency Rotating Detonation Rocket Engines

PROJECT OBJECTIVE: Demonstrate the closing of remaining critical technology gaps for RDREs that are preventing industry from utilizing this novel propulsion system.

PROJECT GOAL/DESCRIPTION

The goal of this project is to develop a promising high-efficiency propulsion system that enables a sustainable long term human presence on the Moon and Mars. It is critical that a high-efficiency propulsion system is developed to meet NASA requirements for a sustainable and cost-effective space flight economy. The continuously rotating detonation rocket engine (RDRE) has been demonstrated by NASA in 2022 to be a feasible advanced propulsion concept for Mars propulsion architectures. In addition, the RDRE has the potential to close the payload gap needed to reach Mars. As such, this Early Career Initiative (ECI) project aims to close the remaining technology development gaps preventing the RDRE from moving toward a flight configuration. An image of NASA's 10,000 lbf RDRE tested in Summer 2023 is shown in Fig. 1.

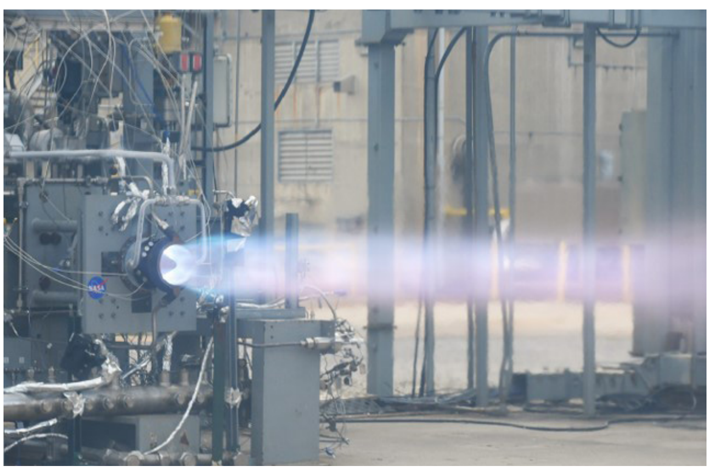


FIGURE 1. NASA 10,000 lbf regenerative RDRE.

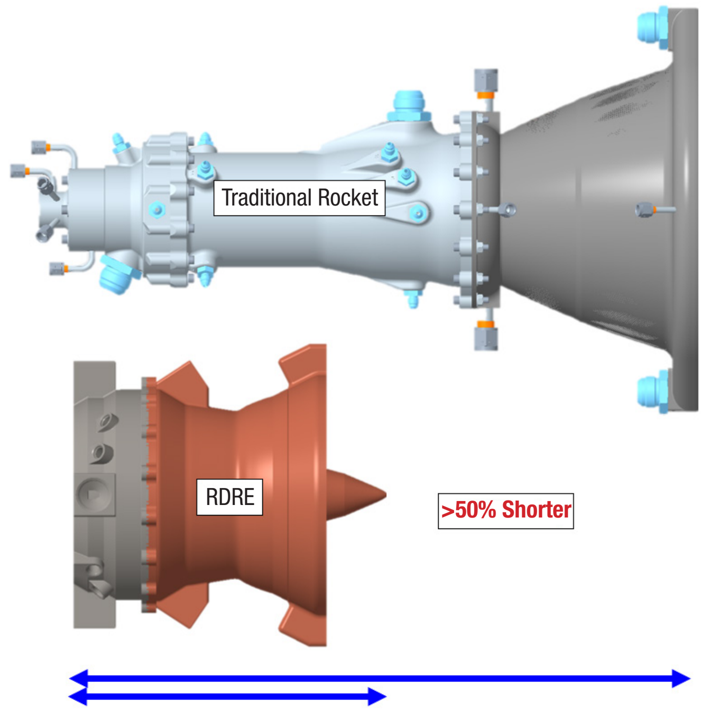


FIGURE 2. Relative length comparison between NASA lander RDRE and traditional liquid rocket.

APPROACH/INNOVATION

One major benefit of RDRE technology for NASA and the national aerospace community includes a compact annular design that reduces the overall engine length by greater than 50% (see Fig. 2). This alone reduces vehicle mass and increases the possibilities for vehicle design and integration. In addition, the cost and time required for fabrication are radically reduced. The chamber volume for an RDRE is very low, at approximately 20% to even 10% that of a traditional liquid rocket. Typically, this means that efficiency would suffer, but this is not the case for detonation cycle engines. Combustion efficiency (C*) is near 100% even at throttled conditions.

The work being conducted under this ECI represents a major step forward for the technology domestically. Core to this advancement is integration of additive manufacturing (AM), which is widely considered the future of rocket hardware production. AM considerably reduces hardware development lead times on the order of 2–10× and reducing costs often by greater than 50%. While AM proof of concept has been demonstrated to be successfully integrated with RDREs under previous NASA work, it is still a linchpin for the technology. Experimental data from this previous work was used to optimally design chamber coolant channels, injector orifices, and nozzle coolant channels to demonstrate experimentally that the remaining Key Performance Parameters can be closed.

This effort has demonstrated NASA's first use of a dual-regenerative liquid methane (LCH_4)/liquid oxygen (LOX) RDRE and represents a major milestone for the technology. Over the course of about 2.5 weeks of hot-fire testing, the hardware accumulated ~14 starts and over 680 seconds of mainstage duration. This test time also included a single run of over 250 seconds, which sets the world record for longest continuous hot-fire of an RDRE. It also proves that the technology can survive for a true mission burn duration.

RESULTS/ACCOMPLISHMENTS

To date, this work has successfully demonstrated multiple hot-fire test scales of hardware with different and similar propellants. Purdue University has fired a 4-in RDRE using rocket propellant (RP)/gaseous oxygen (GOX) showing successful wave operation even under pre-burned conditions. The University of Alabama at Huntsville test fired a subscale 3-in RDRE using gaseous methane (GCH_4)/GOX and saw high pressure wave modes. This combustor also had an extended outer shroud nozzle to obtain wall static pressure. These data will inform the design of the ECI year two full scale RDRE nozzle. Finally, a 2-in subscale RDRE was developed and fired at NASA Marshall Space Flight Center (MSFC) Test Stand 115 using GCH_4/GOX propellant. This RDRE was water cooled with integrated coolant channels and an optional water-jacketed quartz outer body. This allowed for researchers to view the detonation event inside of the chamber. Most test cases showed detonation wave activity and yielded heat load data at different conditions and hot wall configurations. In all cases, combustion efficiency was found to be extremely high, given the total length of these combustors. This means that NASA can now utilize the RDRE for reduced length applications.
In addition, each of these combustion chamber designs allow for NASA to assess scalability of the new propulsion system for different applications including lander, upper stage, hypersonics, and even launch vehicle main propulsion.

NASA's full scale 10,000 lbf RDRE was developed in a single year and fired September 2023 at MSFC Test Stand 115. Several critical lessons learned will be implemented during Summer 2024 testing for iteration on design and demonstration of greater performances compared to the current state of the art.

PARTNERSHIPS

The primary partner on this effort was Venus Aerospace, who coordinated hardware development and postprocessing in addition to the design of a primary injection system concept. The Air Force Research Laboratory and NASA Glenn Research Center contributed to the design and testing of the technology as well.

SUMMARY

NASA has successfully tested multiple thrust classes of rotating detonation rocket engines and met several major technology goals. First, completion of combustion was found to be equivalent to state-of-the-art (SOA) liquid rockets, but at one quarter of the total length. Nozzle attachment of supersonic flow was found to be viable for high expansion ratio designs greater than the SOA. Long duration firings of a traditional lander mission profile were found to be possible given cooling requirements of the combustor using only propellants as coolant.

Principal Investigator(s): Thomas Teasley
Partners: Venus Aerospace
Funding Organization(s): Early Career Initiative

Composite Conductor Power Tether Cable

PROJECT OBJECTIVE: **Project is to develop a compact, high-strength power and data cable to tether small space tugs, electrostatic sails, and deployed surface systems by using composite conductor as the outer shield and mechanical load path with seven times the tensile strength as stainless steel and insulated center conductors.**

PROJECT GOAL/DESCRIPTION

The goal of this project is the development of lightweight, high-strength flexible power tethers that can be used between two or more space vehicles to support "*GO*" and for power transfer from surface power generation landers to habitats, 3D construction printers, or resource processors to support "*LIVE*". Two such technology gaps have been identified by the Space Technology Mission Directorate (STMD): Propulsion Gap STMD-Prop-022 or S5-G1 for "Unique Platforms: Sails and Tethers" and Power Gap STMD-Power-002 for ">300V Power Transmission Cabling" supporting Game Changing Development Tethered Power Systems. With the availability of high-strength lightweight power tethers, more tether length can be stored on a given reel and used to: (1) enable tethered space tugs to inspect, to perform automated rendezvous and capture/docking using a host vehicle's power, and to safely start removing orbital debris; (2) use electric CubeSat space tugs to deploy and maintain the formation of electrostatic sail (E-Sail) tethers; and (3) transfer the power from centralized lunar power sources to the planned stationary and mobile users.

NASA Marshall Space Flight Center (MSFC) has expertise in composite material and fabrication technology, and strong technical background with tether satellite systems, Small Expendable Deployer System (SEDS) 1 and 2, and Propulsive SEDS (ProSEDS). The existing expertise and research of flown tethers and new E-Sail tethers and other composite structures provides a technical basis for a transition from metal conductor cables reinforced with composite fibers to a radically new tether structure and configuration with a strong flexible outer sheath of flexible conductive composite fibers. This shift to conductive composite cables will provide both tether tensile strength and an electromagnetic interference shield with insulated center conductor(s) (perhaps made from conductive composite) that can operate as a lunar surface power tether and support E-Sails and retrieval of space tugs and cargo.

APPROACH/INNOVATION

As a Technology Readiness Level (TRL) 1 technology in process of development, we will research and develop the following areas:

- Technical requirements for the three planned applications
- Manufacturers' products and fabrication capabilities
- Splicing and connection capabilities and problems
- Critical key performance parameters based on planned use (leakage/loss into regolith)
- Applicable electrical standards and hardware

RESULTS/ACCOMPLISHMENTS

During our research and development, we made some exciting discoveries and found new products:

- The project team found that sheathing provider Glenair can custom manufacture Amberstrand sheathed cables with single- and multiconductor cores with space-rated materials up to 3000–4000 m with their existing fabrication capabilities, alleviating the need for MSFC to fabricate test samples or need splicing for many applications.
- The project team purchased 95 ft of Glenair's new composite tether cable and will perform mechanical and electrical characteristics testing, and incorporate the tether into a flat floor tether space tug simulator for retrievals.
- The project team found Single Pair Ethernet and Power over Data Lines standards, and found that semiconductor manufacturing company Analog Devices carries commercial-off-the-shelf (COTS) breadboards with power coupling provisions for 50 V DC @ 1.7 A while supporting 10 MB Single Pair Ethernet with HD cameras and commanding up to 1.7 Km. These specifications exceed both of our short-term Key Performance Indices for power transfer and data rate (New technology for Automotive, Aviation, Industrial Facility Monitoring).

- The project team plans to assemble a COTS Power and Data Testbed to test the new composite tether cable and to start mechanical termination development and tether reeling tests to raise the concept from TRL 1 to TRL 3–4.

SUMMARY

The original Center Innovation Fund proposal for Composite Conductor Power (and Data) Tether Cable planned to buy composite conductor sheathing and assemble a cable in-house, but found out that Glenair, sheathing provider, also builds custom space-grade shielded cable for what we need. Glenair has created a product drawing/specification for the Power/Data tether cable and are manufacturing a test length for MSFC. We have also purchased single line Ethernet chipset development boards and testbed set from Analog Devices that supports the new standards for Power over Data Lines and Single Pair Ethernet, including commands to a remote device and an internet protocol HD video camera. We will be integrating these with the new tether cable to demonstrate a tethered retrieval vehicle simulator on the Flat Floor Robotics Lab.

The team has determined that we can build a tethered articulated retrieval tug for flight experiments with COTS space hardware with these currently existing technologies:

- Composite power/data tether cables (3000–4000m)
- Thruster gimbals (supplier: Tethers Unlimited, Inc.)
- Electric high specific impulse thrusters
- Space-rated Arduino processors
- Space-qualified electropermanent magnetic gripper \ “MAGTAG” (Supplier: Altius-Space)

Principal Investigator(s): Thomas C. Bryan
Funding Organization(s): Center Innovation Fund

Development and Qualification of Solenoid Valves for ASCENT Propulsion Systems

PROJECT OBJECTIVE: **Demonstrate the closing of remaining critical technology gaps for RDREs that are preventing industry from utilizing this novel propulsion system.**

PROJECT GOAL/DESCRIPTION

The project goal is to build on the results of the NASA Lunar Flashlight (LF) Program to develop and qualify a thruster valve for larger class CubeSat systems. Specifically, the collaborative effort completes flight-qualification of a 5-newton solenoid valve that could be incorporated into a satellite propulsion system by Flight Works, Inc. The low toxicity ("green") ASCENT propellant developed by the Air Force Research Lab and demonstrated as part of the NASA Green Propellant Infusion Mission in 2019 offers increased performance over traditional storable propellants while drastically reducing operational costs and constraints of space missions thanks to its low toxicity.

APPROACH/INNOVATION

NASA and Flight Works share the desire to develop small propulsion systems and associated miniature components that can operate with ASCENT propellant. Previously they partnered on the development of components for the LF Mission. Flight Works developed and spaceflight-qualified the ASCENT pump used in that mission's propulsion system, while NASA developed the other components including the thruster valves, isolation valve, and service valves. This effort was aimed at building on the successful LF thruster valve qualification campaign and qualifying a 5 N thruster valve that Flight Works could incorporate into a flight propulsion system. The new valve is a larger version of the 0.1 N thruster valve qualified by NASA for LF propulsion system and of the similarly designed isolation valve used for that system which has been used as thruster valve in a 4-8U system. The goal was to qualify the 5 N design for use as thruster valves for Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA)-class systems that utilize ASCENT propellant.

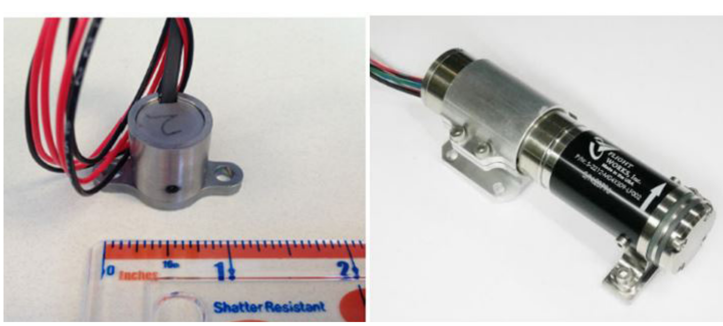


FIGURE 1. 0.1 N Thruster Valve and Miniature Pump Qualified for the LF Mission.

The goal was to manufacture a short production run of units, 11 units in total, of which one would be utilized for the qualification test program. That program would be conducted by Flight Works and consist of a series of tests including random vibration, thermal, duty cycle, life cycle and burst testing, typical for qualification of this type of component. A second qualification unit would be sent to NASA Marshall Space Flight Center (MSFC) for ASCENT propellant exposure testing. The remaining flight worthy units would be sent to MSFC for use on a future program.

RESULTS/ACCOMPLISHMENTS

MSFC and Flight Works teamed to generate interface and performance requirements for the 5 N design. MSFC then completed the detailed design process of the valve using the LF Propulsion module mission as a reference for environments and duty cycle. The design process was completed with a Critical Design Review and then drawings and part models were turned over to Flight Works for manufacturing. They developed the manufacturing, assembly, integration, and test plans based on their internally certified and proven procedures. Assembly was completed and initial units were manufactured. There were delays associated with the manufacture of the initial units due to a national shortage of specific magnetic materials; however, Flight Works persevered and has completed manufacture of the initial production run of units. Testing is underway and should be completed early in 2024.

PARTNERSHIPS

Flight Works was founded in 2002 to meet a growing demand for miniature fuel pumps for the nascent microturbine market. They are a manufacturer of high-tech, miniature pump and other fluidic components for aerospace, medical, chemical, energy and other industries. They have previously teamed with NASA on the LF

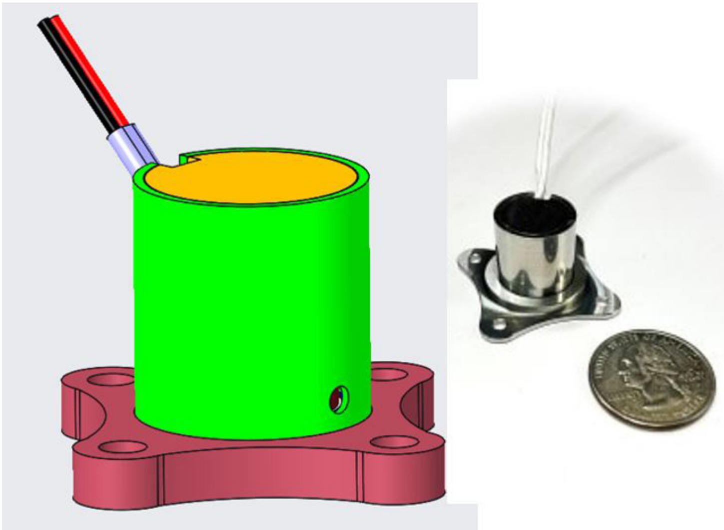


FIGURE 2. 5 N Thruster Valve Model and Finished Product.

Program and a Small Business Innovation Research project, and currently have a Research License Agreement with NASA to transition the miniature green propellant valve technologies in order to provide a commercial supply of these small valves for ASCENT propulsion systems.

SUMMARY

NASA and Flight Works share the desire to develop components for the ASCENT propellant and demonstrate a "green" alternative to conventional chemical propulsion systems for future spacecraft. This task was another step toward increasing the size of spacecraft that are commercially available with this new and novel propellant. NASA MSFC and Flight Works teamed to generate performance requirements, complete a detailed design, manufacturing plan, and qualification test campaign of a 5N thruster valve for ASCENT thrusters. Much of this work was based on the LF Program on which both had collaborated previously. An initial set of thruster valves have been fabricated and qualification testing at Flight Works facilities has begun. Once complete, ASCENT propellant exposure testing will take place at MSFC.

Principal Investigator(s): Christopher Bostwick, Flight Works, Inc.; Brad Addona
Partners: Flight Works, Inc.
Funding Organization(s): Cooperative Agreement Notice

Space Nuclear Propulsion

PROJECT OBJECTIVE: Partner with the Defense Advanced Research Projects Agency (DARPA) to fly a nuclear thermal propulsion (NTP) demonstration engine by 2027 while simultaneously developing technologies needed for operational Space Nuclear Propulsion (SNP) systems and supporting university research related to very high performance SNP systems.

PROJECT GOAL/DESCRIPTION

The SNP project is addressing the need of NASA and partner agencies for high performance in-space propulsion systems. The primary focus of the SNP project is partnering with DARPA to fly a demonstration NTP engine by 2027. The DARPA/NASA/industry team will design, develop, fabricate, launch, and operate an NTP system. The launch will represent the first US launch of a space fission system since 1965, and the first time any country has launched an NTP system. The demonstration flight Demonstration Rocket for Agile Cislunar Operations (DRACO) will also allow the new US space nuclear launch approval process (NSPM-20) to be fully exercised. Technologies needed for an operational SNP system are being developed in parallel with the flight, and university research is being performed to help enable very high performance SNP systems that take advantage of the full potential of fission technology.

FIGURE 1. Artist concept of NASA/DARPA NTP Demonstration Engine.

APPROACH/INNOVATION

The partnership between NASA and DARPA will allow the strengths of both agencies to be combined to field the first US space fission system since 1965 and to field the first NTP system in history (Fig. 1). The integrated SNP project approach will also help ensure that operational SNP systems can become available soon after the DRACO flight, and that university research helps enable very high performance SNP systems in the future.

Extensive innovation is required to ensure success. First, the SNP systems under consideration use high assay low enriched uranium, eliminating many of the security and proliferation concerns associated with using highly enriched uranium and facilitating safe, rapid, and affordable development and utilization. Second, when available established technologies are being used. Technologies requiring development are evaluated based on several factors, including Advancement Degree of Difficulty (AD^2). A low AD^2 implies that the new technology can be developed quickly and affordably. NASA is working closely with the Department of Energy (DOE) and industry to develop those technologies. Technologies related to neutron moderation, thermal insulation, structures, instrumentation and control, and other key areas are being advanced. Third, when possible existing facilities are used to conduct non-nuclear and nuclear testing. These facilities include the Compact Fuel Element Environmental Tester (CFEET) and Nuclear Thermal Rocket Element Environmental Simulator (NTREES) facilities at NASA Marshall Space Flight Center (MSFC) (Figs. 2 and 3), Idaho National Laboratory's "TREAT" reactor, and the MIT Nuclear Reactor Laboratory. All four facilities have been used to complete NTP fuel testing and other testing required by the SNP program. In addition, the Hot Hydrogen Environmental Atmospheric Test facility will be online at MSFC in early 2024, providing additional capability for realistic non-nuclear testing of SNP fuels and materials.

RESULTS/ACCOMPLISHMENTS

Rapid progress is being made toward the demonstration of an NTP engine in 2027. The NASA/DARPA partnership has been finalized, and contractors selected. Engine design is progressing rapidly, and initial fuel segments have been designed, fabricated, and tested (Fig. 4). Long lead components and materials are being procured.

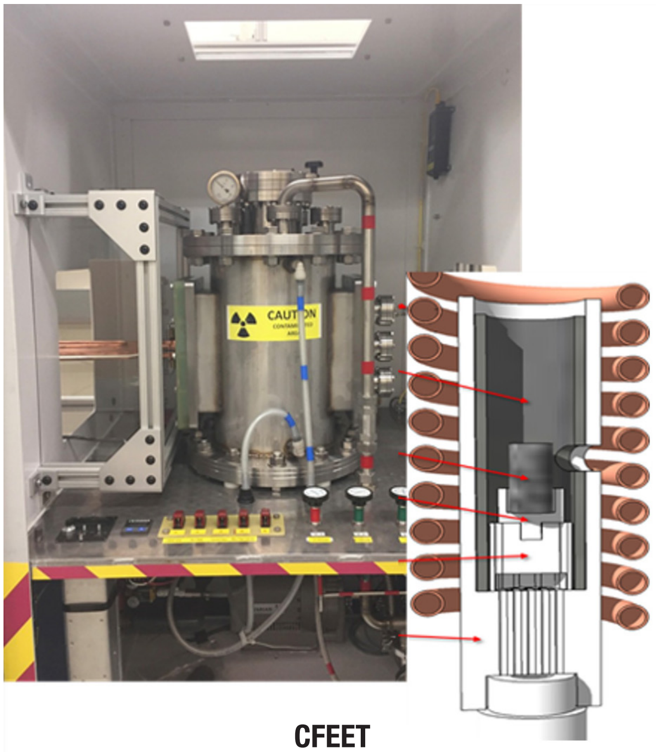


FIGURE 2. Compact Fuel Element Environmental Tester.

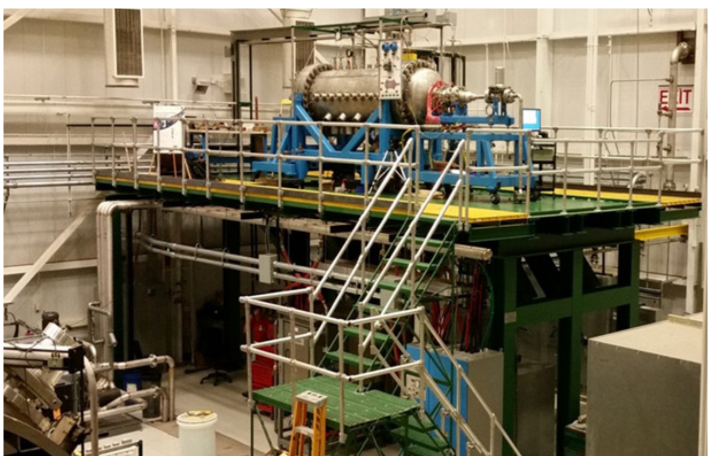


FIGURE 3. Nuclear Thermal Rocket Element Environmental Simulator.

Additionally, work within DOE and industry continues on technologies required for operational SNP systems, and multiple universities are continuing to perform both experimental and computational research related to very high performance SNP systems capable of enabling advanced missions in cislunar space and beyond.

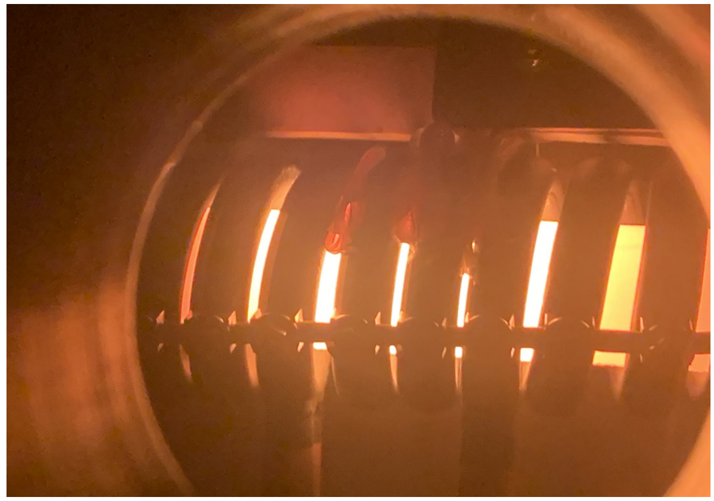


FIGURE 4. NTREES fuel element developmental test.

PARTNERSHIPS

NASA is partnering with DARPA to fly a demonstration NTP engine by 2027. The United States Space Force is also assisting with the DRACO launch and launch-related activities.

SUMMARY

The SNP project is addressing the need of NASA and partner agencies for high performance in-space propulsion systems. The primary focus of the SNP project is partnering with DARPA to fly a demonstration NTP engine by 2027. The SNP project is also working with industry and the DOE to develop technologies needed for operational SNP systems, and supporting both computational and experimental research at universities to help enable very high performance SNP systems capable of enabling advanced missions and architectures.

Principal Investigator(s): Jason Turpin; Rebekah Whitten; Kurt Polzin; Michael Houts; Harold Gerrish; Tom Godfroy; Doug Burns, Idaho National Laboratory
Partners: Defense Advanced Research Projects Agency
Funding Organization(s): Space Technology Mission Directorate

Solar Cruiser

PROJECT OBJECTIVE: **Solar Cruiser continues to mature solar sail propulsion technology that will enable near-term, compelling space missions for Heliophysics, NASA, and the nation.**

PROJECT GOAL/DESCRIPTION

Solar Cruiser is designed to fly a small spacecraft (~100 kg) with a large (>1,600 m^2) solar sail, attaining a characteristic acceleration of >0.12 mm/s^2. The mission concept includes successful deployment of the solar sail (Fig. 1), validation of all sail subsystems, controlled stationkeeping inside of the Sun-Earth L1 point (Fig. 2), demonstration of pointing performance for science imaging, and finally an increase in heliocentric inclination (out of the ecliptic plane).

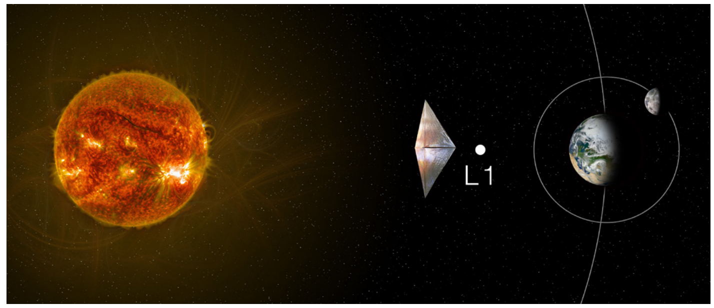


FIGURE 2. Solar Cruiser in sub-L1 orbit on the Sun-Earth line.

APPROACH/INNOVATION

Solar Cruiser is a technology development project funded in 2022, 2023 and 2024 to continue the development on key solar sail technology systems through testing and analysis. The focus technologies are the active mass translator (AMT), reaction control devices (RCDs), and Solar Sail System (which includes the sail deployment mechanism, four 100-ft booms, the solar sail membrane, and the launch restraint mechanism). An Agency-approved Technology Maturation Plan outlines the tasks needed to raise the Technology Readiness Level (TRL) of these systems.

Testing large deployable structures (100-ft booms) with a 4,300-ft^2 sail the thickness of a human hair in 1g is challenging. Techniques used to load test lengthy booms, manufacture massive membranes, or deploy large solar sail systems are applicable to the Solar Cruiser design, as well as future sailing missions.

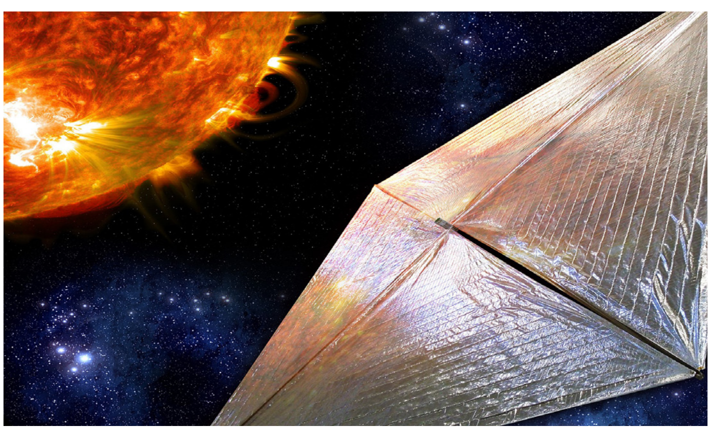


FIGURE 1. Artist concept of the solar sail propelled Solar Cruiser conducting Heliophysics science.

Solar Cruiser technology enables missions across a broader NASA, National Oceanic and Atmospheric Administration, and US Department of Defense (DOD) user community providing space weather science and prediction, high delta-V small spacecraft for Heliophysics, Earth, and Planetary Science, and DOD Space Situational Awareness applications. The Solar Cruiser design is inherently scalable to significantly larger sails and tailorable to meet specific mission needs.

Solar Cruiser will continue TRL development based on a detailed Technology Maturation Plan for the technology systems, achieving TRL6 for the entire Solar Sail System and TRL5 for the RCDs by early 2024.

RESULTS/ACCOMPLISHMENTS

The Solar Cruiser team officially completed all objectives related to the full-scale sail quadrant deployment test, including: (1) full deployment of sail deployment mechanism's (SDM) 100-ft booms and (2) full deployment using an integrated full-scale quadrant prototype (Fig. 3). At full deployment, the sail quadrant measures approximately 400 m^2 (4,300 $ft.^2$), representing the largest sail quadrant ever deployed (i.e., ¼ of the Solar Cruiser's full sail).

Design life verification testing was successfully completed on the AMT. This test was conducted first in an ambient environment then in a thermal vacuum chamber, for a total of 1,450 testing cycles.

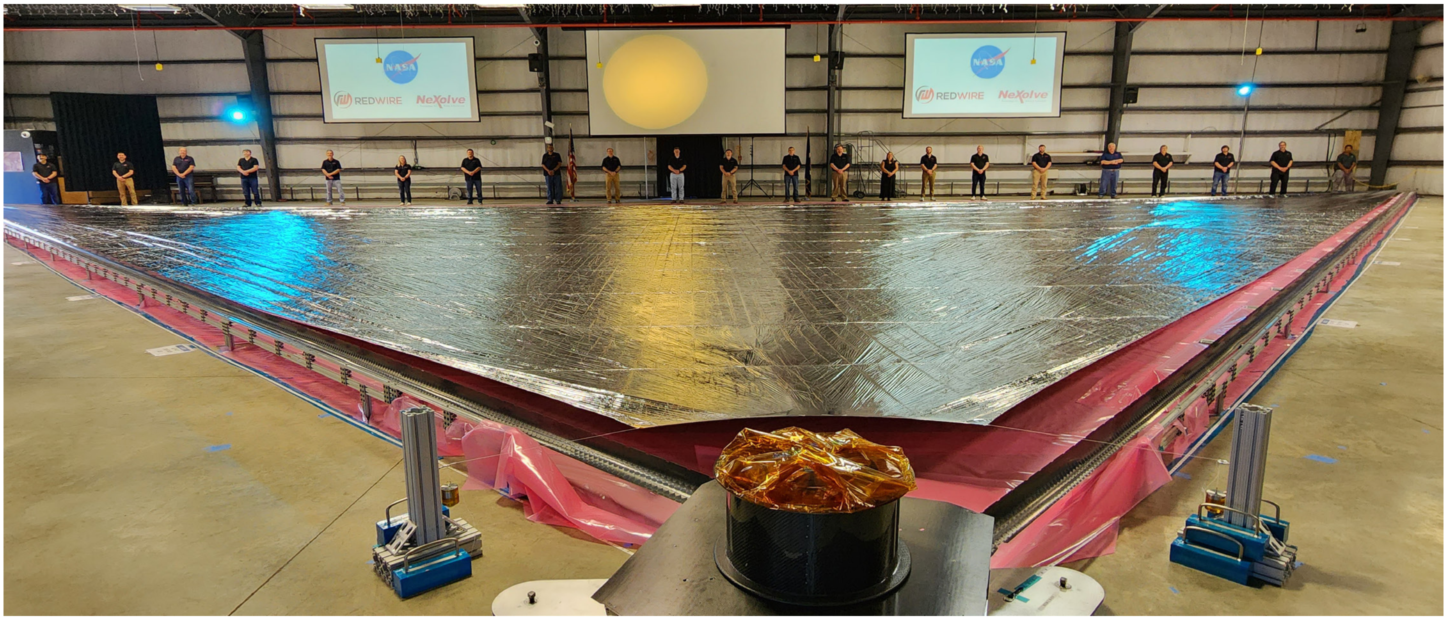


FIGURE 3. Solar Sail Deployment.

PARTNERSHIPS

The project has been a collaborative effort between NASA Marshall Space Flight Center, Ball Aerospace, Redwire Space and NeXolve. Ball Aerospace is responsible for bus systems engineering including mission-specific modifications; procuring the sailcraft bus from Blue Canyon Technologies LLC; integrating the bus, SSPE and launch separation system; and testing and shipping the integrated space vehicle. Redwire is responsible for the Solar Sail System, including the SDM, booms, and AMT, and subcontracts with NeXolve to develop, build, and integrate the sail membrane.

SUMMARY

Solar Cruiser continues to mature solar sail propulsion technology by advancing the TRL of the systems to TRL 6 by 2024. These technologies enable NASA to make plans for near-term missions and is a pathfinder for many potential missions using sail technology in the future.

Principal Investigator(s): Les Johnson
Partners: NASA Langley Research Center; Ball Aerospace; NeXolve; Redwire Space
Funding Organization(s): Science Mission Directorate

Green Propulsion Dual Mode (GPDM) Technology Demonstration Mission

PROJECT OBJECTIVE: The Green Propulsion Dual Mode (GPDM) project seeks to demonstrate the feasibility of dual-mode (chemical and electrospray) propulsion using a low-toxicity or “green” propellant using the same propellant, tank, and feed system on a 6U sized CubeSat.

PROJECT GOAL/DESCRIPTION

Rocket propulsion is the primary means of translation in the space environment. The performance of a rocket engine depends on how efficiently it converts energy via reaction (e.g., chemical combustion or ionization) into propulsion. Chemical rocket engines can produce high thrust translations but are not as efficient as electric thrusters in terms of specific impulse (Isp), only producing hundreds rather than thousands of seconds of Isp. Electrospray thrusters can produce much higher seconds of Isp than chemical thrusters, but are orders of magnitude lower in terms of thrust. The GPDM project will use an ionic liquid rocket propellant known as Advanced Spacecraft Energetic Non-Toxic (ASCENT) to produce both modes of propulsion (i.e., higher thrust via a chemical thruster and higher Isp via four electrospray thrusters) using the same tank and feed system. The small spacecraft 6U form factor (1U is 10 × 10 × 10 cm) is sufficient to demonstrate dual-mode propulsion with a green propellant on a mission to a to-be-determined low-Earth orbit altitude. The GPDM mission objectives includes demonstrating both modes of propulsion and subsequently performing orbital maneuvers where each mode is most effective and efficient.

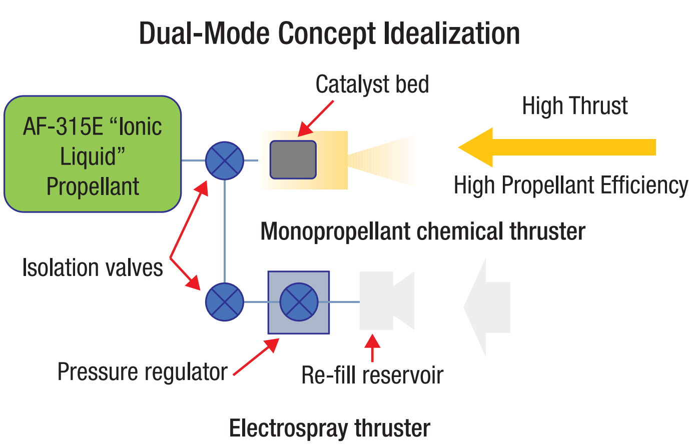


FIGURE 1. GPDM system concept sketch. AF-315E is the Air Force Research Lab designation for ASCENT propellant.

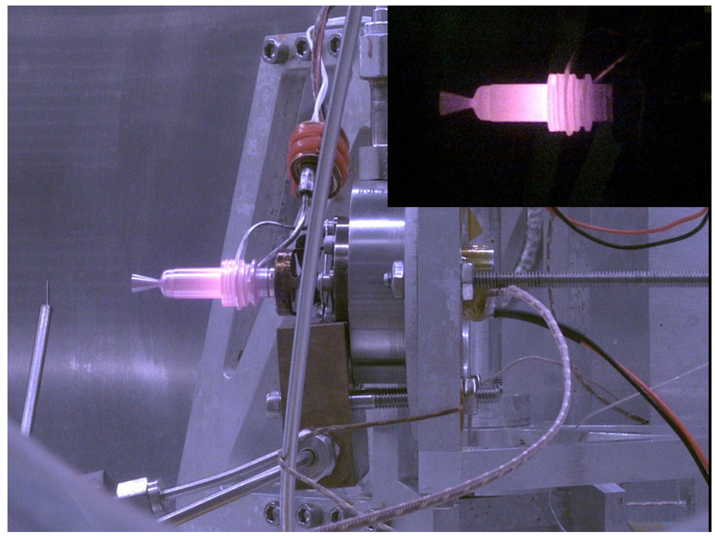


FIGURE 2. GPDM ASCENT chemical thruster during a Flat Sat ground test performed at MSFC in the Green Propulsion Lab.

APPROACH/INNOVATION

The GPDM project is funded by the Small Spacecraft Technology Program within the Science and Technology Mission Directorate (STMD) and managed by the Science and Technology Office at NASA Marshall Space Flight Center (MSFC). GPDM will comprise of a dual-mode propulsion system which will serve both as the propulsion and the payload of the CubeSat. From a technology development standpoint, the dual-mode concept is currently being demonstrated via a laboratory scale ground test unit, known as the Flat Sat unit. MSFC is conducting a series of ground test of the GPDM chemical and electrospray thrusters, computer flight controllers, power boards and other propulsion system hardware components.

The Flat Sat ground test system is being used to validate the dual-mode concept as the team works toward developing a flight unit which is planned for completion in 2024. The GPDM spacecraft will include a chemical propulsion subsystem module, electrospray thrusters, pressure reduction system, isolation valves, and structural housing

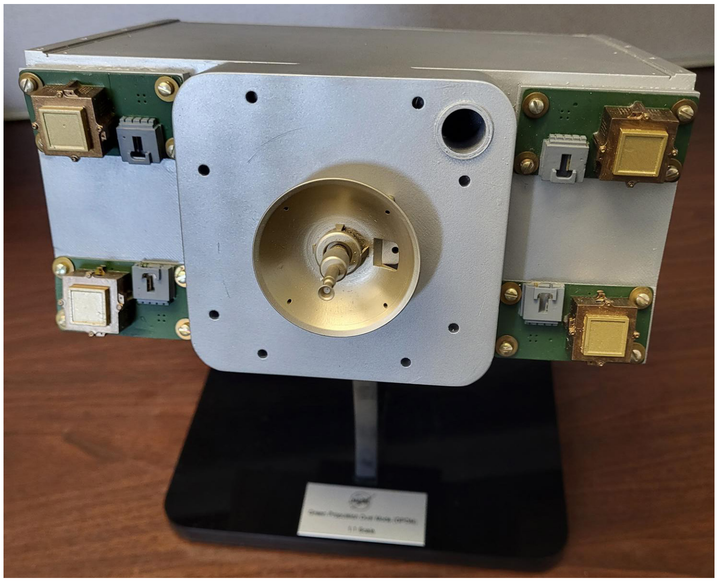


FIGURE 3. GPDM Flat Sat ground testing is being performed at MSFC in the Green Propulsion Lab.

components. The GPDM project is also working with the CubeSat Launch Initiative (CSLI) Program for a payload assignment targeting 2025.

RESULTS/ACCOMPLISHMENTS

The GPDM project has made substantial progress in calendar year 2023. Thus far, the project successfully demonstrated hot-fire demonstrations of the chemical propulsion portion of the Flat Sat dual-mode system as well as hydrostatic proof testing of the GPDM chemical propulsion module, known as 'Sprite'. The flight controller for the GPDM spacecraft has also been integrated into the Flat Sat ground test facility and plans exist to conduct integrated testing at the start of the last quarter in 2023. GPDM project team members were represented at the Small Satellite Conference in Logan, UT in August 2023 where they shared an initial 3D printed model replica of the GPDM propulsion bus at the MSFC booth.

PARTNERSHIPS

While some of the effort to develop GPDM is done in-house at MSFC within several engineering organizations, partnerships with university and industry comprise of much of the hardware for the GPDM propulsion bus. In particular, the chemical propulsion subsystem includes a 3D printed, self-contained propulsion unit which is developed by the Rubicon Space Systems division of Plasma Processes, Inc., while the power and propulsion units are developed by E-Space, Inc.

A university partnership with Massachusetts Instituteof Technology (MIT) is being leveraged to develop the electrospray thrusters while Georgia Tech is working the spacecraft integration, various structural component developments funded by a university grant.

The GPDM project is subsequently planning to partner with Georgia Tech to operate the GPDM spacecraft during the full duration of the mission. Key milestones for this project include ground testing of the dual-mode concept (done at MSFC), development of the chemical propulsion unit at Rubicon, long-life electrospray testing at MIT and spacecraft structural component development at Georgia Tech.

SUMMARY

The GPDM Technology Demonstration mission will be the first of its kind in that it will demonstrate chemical and electrospray propulsion using a common propellant (the ionic green liquid propellant known as ASCENT) using a common propellant tank and feed system. While 2023 saw significant laboratory scale milestone accomplishments, GPDM is looking to develop a full flight unit in 2024 (targeting a 2025 launch), leveraging university and industry partnerships the development and integration of specific spacecraft hardware components.

Principal Investigator(s): Nehemiah Joel Williams, Ph.D.
Partners: Georgia Institute of Technology; Massachusetts Institute of Technology; E-Space, Inc.; Plasma Processes, Inc.
Funding Organization(s): Space Technology Mission Directorate

Cryogenic Coupler

PROJECT OBJECTIVE: To advance cryogenic fluid coupling technology through industry collaboration, testing within additional fluid environments and ensuring efficient liquid hydrogen transfer with minimal leakage for future space missions.

PROJECT GOAL/DESCRIPTION

The purpose of this project was to advance cryogenic fluid coupling, or “cryocoupler,” technology through technology risk assessment, design, and prototype testing, with SpaceX and NASA Marshall Spaceflight Center (MSFC) working in collaboration (Fig. 1). A secondary purpose was to leverage the knowledge gained from the design and prototype testing to assist in the development of a guidelines document for cryogenic fluid couplers.

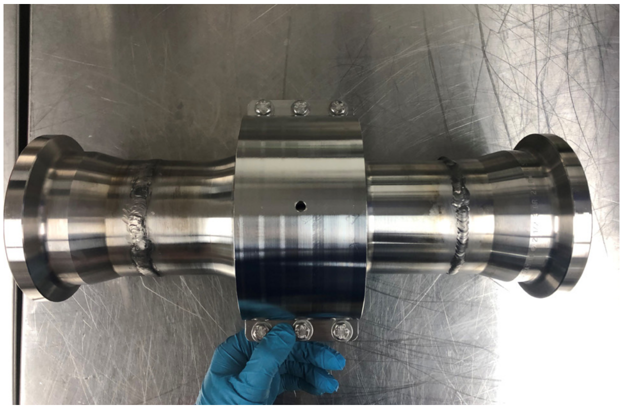


FIGURE 1. Cryocoupler Inlet and Outlet.

Such guidelines will aid in helping programs and suppliers to understand what NASA expects regarding certification of vehicles for in-space fluid transfer. These guidelines will aid in the design of in-space fluid couplers and mating systems, as well as enable mating, de-mating, and propellant transfer between NASA and commercial partner vehicles. Advancement of fluid coupler technology will enable any future missions that require orbital propellant depots or that require on-orbit refueling.

APPROACH/INNOVATION

Large-scale, cryogenic couplers for in-space fluid transfer are a new technology. Ground based hardware exists and was the starting point for designs. However, actuating the coupler using ground support equipment versus actuating a coupler system in microgravity is a much more complex problem. Performance requirements for these couplers are challenging. This task with SpaceX was the first step in standardizing mating/de-mating of vehicles for cryogenic fluid transfer.

RESULTS/ACCOMPLISHMENTS

SpaceX developed prototype couplers and successfully tested them using liquid nitrogen (LN_2). SpaceX then submitted coupler drawings to MSFC. MSFC subsequently fabricated additional couplers and tested them using liquid hydrogen (LH_2). Testing with LH_2 proved to be just as successful as with LN_2 and resulted in very low leakage rates. The prototype hardware is at Technology Readiness Level (TRL) 4.

The information gleaned from the design and test activities will aid in the further development of a guidelines document (currently in draft form), pending further study. When complete, the guidelines document will address all aspects of cryocoupler design and performance, as well as overall NASA expectations for certification of the propellant transfer process for any NASA mission.

PARTNERSHIPS

This effort was in partnership with MSFC and the SpaceX Corporation using a Tipping Point Contract over the span of two years. While it was envisioned that coupler fabrication would be performed by SpaceX and testing would be provided by MSFC, in fact coupler fabrication and testing was performed at both SpaceX and MSFC facilities.

SUMMARY

This task was a first step in developing and standardizing the mating and de-mating of space vehicles for the purpose of cryogenic fluid transfer, and it is fundamental to the continued manned exploration of the Moon and the development of cislunar operations. Beyond the fueling and refueling of spacecraft, it is anticipated the technology will be used by future propulsion systems, such as nuclear-thermal propulsion and nuclear-electric propulsion. In-space propellant depots would be another application.

Principal Investigator(s): David Eddleman
Partners: SpaceX
Funding Organization(s): 2019 Tipping Point

TECHNOLOGY AREA 03

AEROSPACE POWER AND ENERGY STORAGE

SIBatt-3D: In-Space/on-Surface 3D Printing of Sodium-Ion Batteries Using In-Situ Materials

PROJECT OBJECTIVE: To 3D print shape-conformable sodium-ion batteries through vat photopolymerization (VPP) or material extrusion processes using materials found in lunar and/or martian regolith as feedstocks.

PROJECT GOAL/DESCRIPTION

Right now, rechargeable batteries are being used in many space applications from exploration robots to crew health monitors, and currently all batteries must be brought from earth though a lengthy and expensive process. The SIBatt-3D project is focused on in-space manufacturing of shape-conformable batteries using in-situ resources from lunar and martian regolith. 3D-printed batteries allow for complex electrode geometries that lead to improved performance and are shape conformable, so they can be co-designed with a system to minimize the dead-volume and mass. Sodium-ion batteries are of interest due to their improved safety and the relative abundance of materials that can be used as printing feedstocks found on the Moon and Mars. These novel geometries have the potential to improve performance and rival traditionally manufactured batteries despite the usual losses associated with additive manufacturing and 3D printing. This project paves the way toward in-space/on-surface development of freeform energy storage devices that will fill unique volumes and save dead space for applications like small spacecraft, portable power devices, robots, and lunar/martian habitats.

APPROACH/INNOVATION

Our team is pursuing two printing methods, material extrusion and VPP, to develop the most efficient and reliable method for in-space and on-surface shape-conformable sodium-ion battery printing. The electroactive materials were selected based on the availability on the Moon and Mars. Tailored ionic liquid extraction processes to obtain sodium-ion battery materials and precursors from regolith are being developed in tandem with the printing methods. For both printing types, adequate printable materials (loaded inks/slurries and ultraviolet (UV)-curable resins) corresponding to each battery component were developed, printed, post-processed, and characterized separately and tested in half-cell configurations. The best performing electrodes are then tested in full cells with our printed gel polymer electrolyte. This effort is one of the earliest among 3D printing of sodium-ion batteries and contributes greatly to the state of the art required for next-generation batteries development. Moving forward the project focus is shape conformability and solid polymer electrolytes.

RESULTS/ACCOMPLISHMENTS

Fiscal year 2023 was the second year of SIBatt-3D Early Career Initiative (ECI) project. While the first year focused mainly on material selection and feedstock formulation, year two focused on material extraction techniques, print optimization, electrolyte formulation, and battery testing and characterization. Originally the project looked at using ilmenite, an abundant material on the lunar surface, as feedstock since iron and titanium can be separated easily using ionic liquids. However, as battery testing began it was discovered that iron-based materials had problems with oxidation during 3D printing. We then shifted to material extraction through vacuum pyrolysis and thin film distillation using the Marangoni effect to extract materials such as manganese, which have shown more promising results.

For the direct ink write route, the hard carbon (anode) and $Na_{0.44}MnO_2$ (cathode) electrode inks formulated during year one were further optimized to improve printability and adhesion while maintaining a high percentage of active material. Using direct ink write 3D printing and our optimized inks, functional electrodes were produced and tested in half-cell configurations. For the VPP method, the hard carbon (anode) resin from year one was optimized, and a new $NaV_2(PO_4)_3$ (cathode) resin was developed to counter act the oxidation issues with the previous material. The resins were printed using VPP to produce electrodes with a variety of geometries for testing. The printed parts then underwent sintering and de-binding to remove as much of the polymer as possible and maximize the amount of active material. Half-cell batteries using these electrodes as

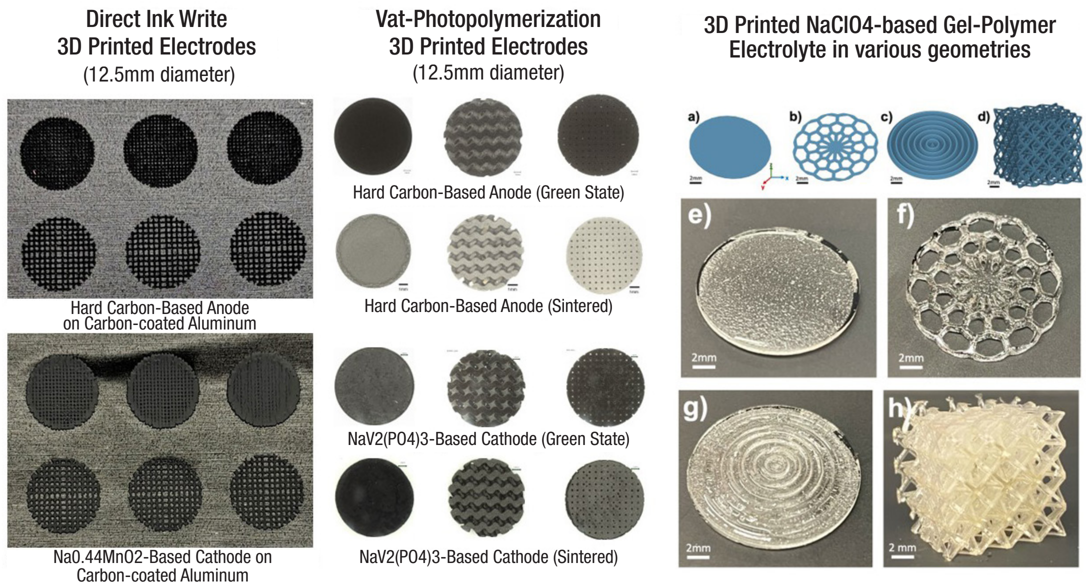


FIGURE 1. 3D Printed Electrodes and Electrolytes.

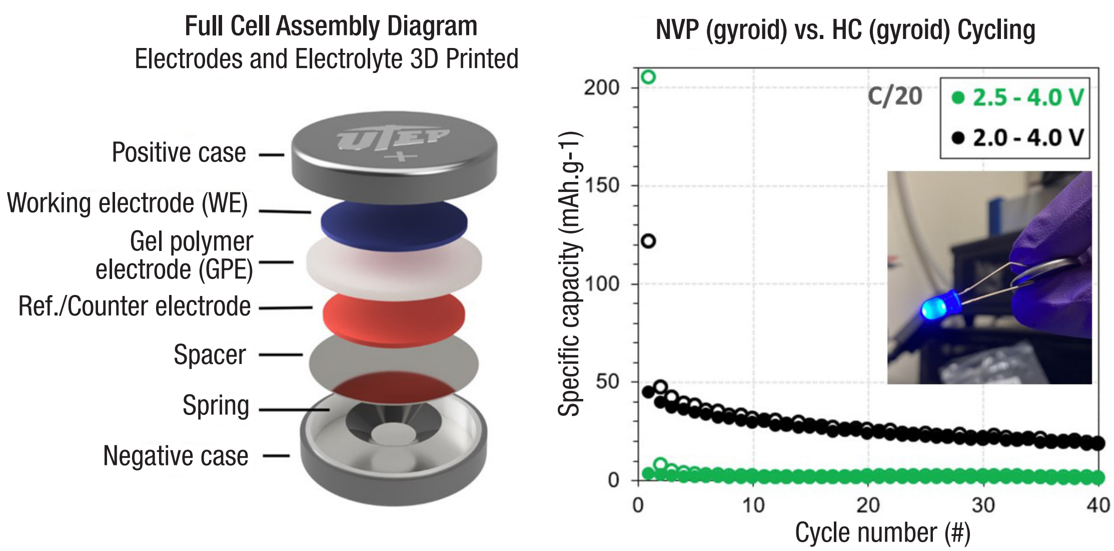


FIGURE 2. Cell Assembly Diagram, VPP-printed battery cycling results, LED powered by printed battery.

working electrodes were assembled and galvanostatically tested. The two best performing designs are disks with a gyroid infill and a larger grid infill, due to their inherent surface macro- and microporosity that allowed liquid electrolyte impregnation. Printable $NaClO_4$-based gel polymer electrolytes were developed by combining the electrolyte material with a UV-curable polymer resin. Various ratios of resin to electrolyte were tested for printability and performance before a ratio of 1:4 resin to electrolyte was selected as optimal. The material can be printed through both VPP and direct ink writing with UV postprocessing.

Our most exciting accomplishment this year was the demonstration of fully printed battery cells using both methods of 3D printing. The battery cells produced are rechargeable and have successfully powered an LED repeatedly after charging. So far, VPP has shown more promise over direct ink writing, likely due to the higher levels of active material in the final electrodes. We are continuing to optimize our materials and assemblies to improve battery capacity.

PARTNERSHIPS

The University of Texas at El Paso (UTEP) is known for its leadership in the advanced manufacturing field. UTEP's role during year two was to develop printable gel polymer electrolytes and performing electrochemical testing and evaluation of the printed parts. Youngstown State University (YSU) provided invaluable expertise in printing ceramics and other custom materials. YSU's role in year two was to develop and optimize the materials, printing, and postprocessing methods for the VPP-printed electrodes.

SUMMARY

The SIBatt-3D ECI project's goal is to develop methods to 3D print sodium-ion batteries in-space/on-surface from in-situ materials. SIBatt-3D has identified potential electroactive materials for each battery component based on the in-situ availability and extractability of materials on the Moon and Mars along with their theoretical performance. The identified battery materials have been printed through two different methods: VPP, using loaded resins; and direct ink writing, using custom inks, to determine the preferred method for future manufacturing efforts. The printed battery components have been evaluated individually through cycling in the half-cell configuration. The best performing electrodes from each method have been combined into full cells giving the project our very first fully function 3D printed batteries. The project has just completed year two and is moving forward with a 6-month no cost extension focusing on shape-conformable batteries and 3D-printable solid polymer electrolytes.

Principal Investigator(s): Cameroun Sherrard
Partners: University of Texas at El Paso; Youngstown State University; Formlabs; ICON
Funding Organization(s): Early Career Initiative
NTR/Patent Numbers: 1694456656, 1694649179, 1694651002, 1694652143, 1694653469, 1694653916, 1694654293, 1694654717, and 1694655401

TECHNOLOGY AREA 04

ROBOTIC SYSTEMS

Development of a High-Fidelity Robotic System Digital Twin for In-Space Welding

PROJECT OBJECTIVE: To create digital and hardware twins to conceive, design, and develop robotic systems to support in-space welding activities.

PROJECT GOAL/DESCRIPTION

In-Space Servicing, Assembly, and Manufacturing (ISAM) can dramatically expand space-based capability by extending the lifespan of existing satellites and decoupling spacecraft design from launch constraints. Fully realizing this potential requires that ISAM be performed by an individual or a team of inexpensive robotic agents that exploit the microgravity environment to enable large work volumes and precise control. The work explored in this joint project between The University of Texas at El Paso (UTEP) Aerospace Center and NASA Marshall Space Flight Center (MSFC) EM32 Metal Processes and Manufacturing Branch has the overarching goal of expanding the possibilities of space manufacturing by developing digital and hardware models of robotic systems to perform a butt weld joint fit-up.

APPROACH/INNOVATION

This project uses digital engineering tools to expedite and continuously monitor the design, manufacturing, and test of a robotic system for butt weld joint fit-up. This approach allows the transition from a document-based design process to a model-based design process. Therefore the continuous monitoring of requirements, expectations, and performance criteria is possible directly on the files and systems. By doing this, all stakeholders have the ability to know the status of the project based on the design and manufacturing tasks in real time and can remotely manipulate the files and systems to perform various test scenarios in both the hardware and the digital twin. Once the digital twin achieves the required level of fidelity, one can use it to perform different analyses without relying entirely in the hardware system to support decision-making.

Besides, this solution creates a digital thread to enable communication and traceability to guide the stakeholders during the project life cycle and beyond. The use of the digital twin also provided the ability to obtain the value of variables that are difficult or cannot be measured directly, such as force and deformations.

RESULTS/ACCOMPLISHMENTS

Through this project, we have been able to develop the following:

- A digital thread that includes hardware, Internet of Things (IoT), and cloud services and computing, digital models, and processes.

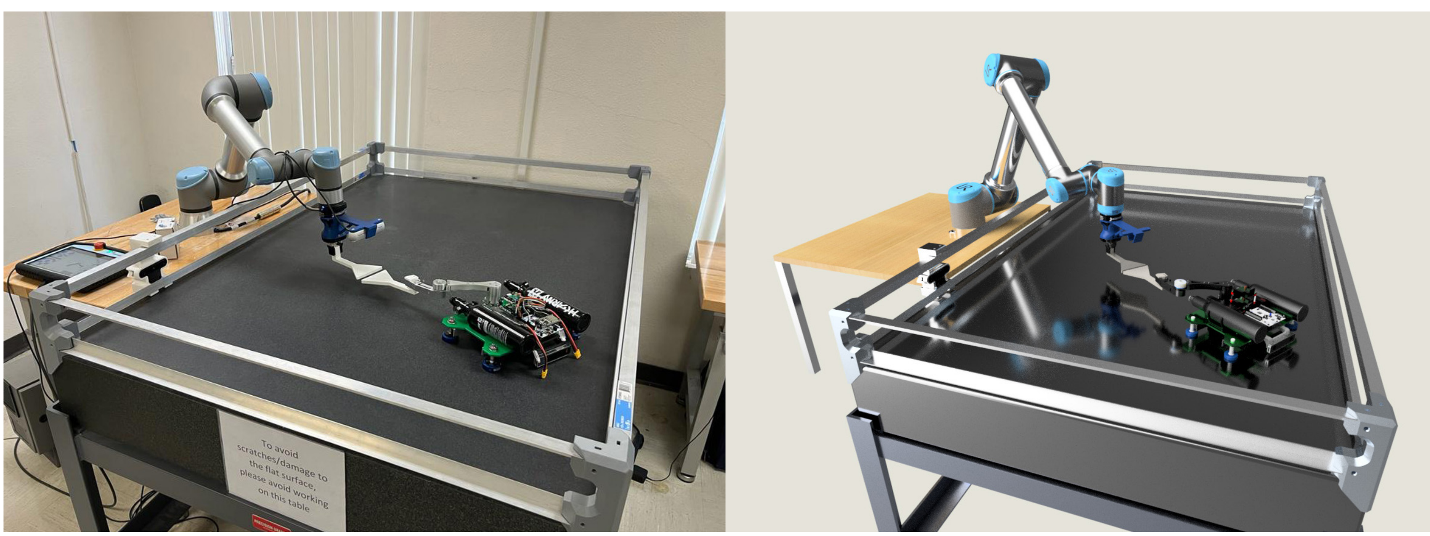


FIGURE 1. The experimental platform to perform the joint fit-up of two parts on an airbearing table to mimic a reduced-gravity environment. Left: the hardware system. Right: a digitalized model.

- Digital and hardware models of digital and hardware twins of a robotic system to support in-space welding.
  The Avionics and Information Processing system to communicate all the digital and hardware components.
- A computer vision system to monitor the joint fit-up robotic process and provide feedback to the robot control system.

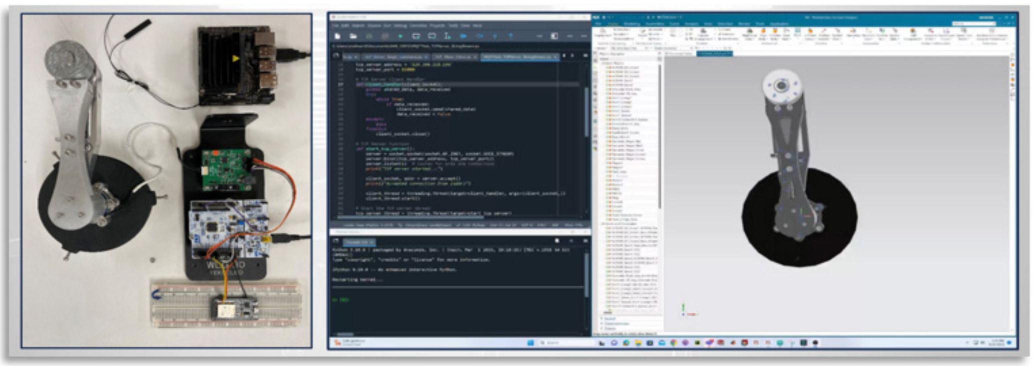


FIGURE 2. The hardware and digital twins of a two-Degrees-of-Freedom (2DOF) robotic arm. They both communicate in a bidirectional fashion through IoT and cloud services.

By implementing the project, we have educated and trained students in the understanding and use of the Digital Engineering (DE) paradigm and tools to prepare them to design, operate, and maintain the new DE-based systems.

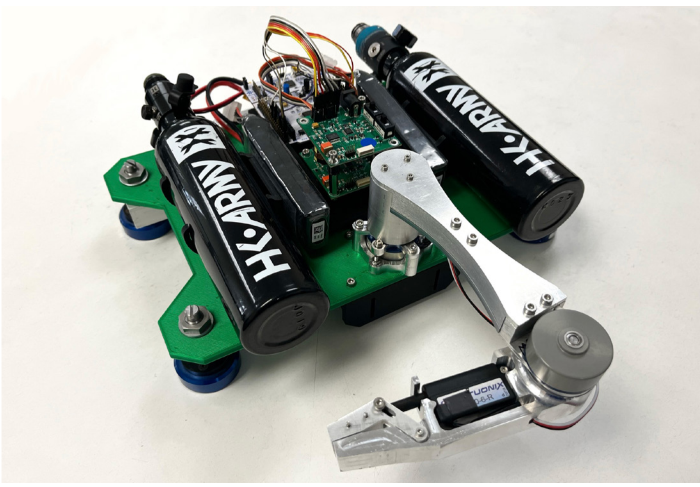


FIGURE 3. 2DOF robotic arm in its free-floating sled.

PARTNERSHIPS

UTEP's Dr. Angel Flores-Abad and his team are leading the robotic in-space manufacturing advancement research. MSFC and UTEP are exploring follow-on projects to take the technology toward future low-gravity mission payloads.

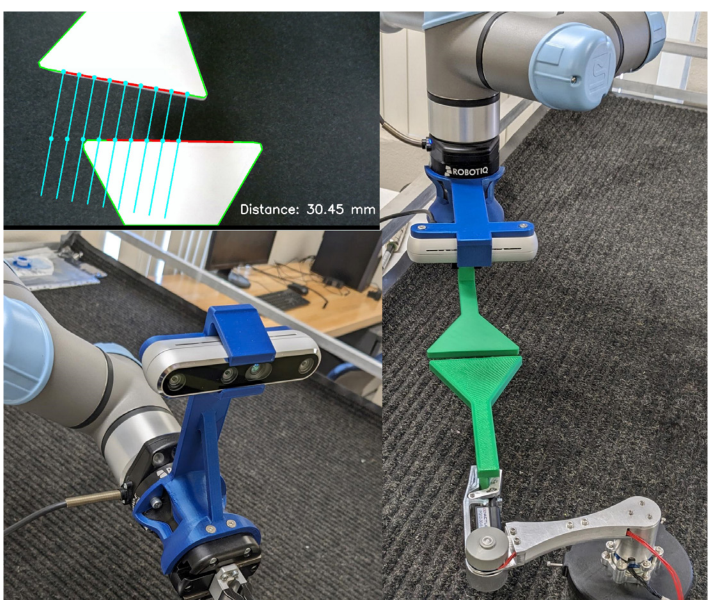


FIGURE 4. Computer vision system to determine the separation distances and mismatch to correctly perform the joint fit-up process.

SUMMARY

ISAM efforts have been conducted at NASA with the vision of supporting future commercial operations to extend the lifespan of satellites by repairing, refueling, or upgrading them; removing space debris; and creating space assets in orbit. This effort advances current ISAM methods by creating digital and hardware twins of an exemplary robotic system to perform space welding. The project also develops the digital threat to connect all the physical and digital entities in a digital engineering framework. The need to expand the ISAM-literate workforce has also been addressed in the project by inspiring, educating, and training the next generation of engineers that will design and operate the future space systems using digital engineering methods and tools.

Principal Investigator(s): Dr. Angel Flores-Abad, The University of Texas at El Paso; Dr. Fredrick Michael, MSFC EM32
Partners: The University of Texas at El Paso (UTEP)
Funding Organization(s): Cooperative Agreement Notice

TECHNOLOGY AREA 06

HUMAN HEALTH, LIFE SUPPORT, AND HABITATION SYSTEMS

Instantaneous Clarity of Ambient Environment Capability (ICAN-C)

PROJECT OBJECTIVE: Instantaneous Clarity of Ambient eNvironment Capability (ICAN-C) will increase visibility in scenarios of obscured and hazy vision, leveraging Structural Design and Analysis Division's (EV30's) optical technology and Artificial Intelligence/ Machine Learning (AI/ML) to improve any low visibility scenario, such as lunar dust obscuring astronauts' vision in landing or In-Situ Resource Utilization (ISRU).

PROJECT GOAL/DESCRIPTION

As NASA prepares to return humans to the Moon, the need for near-instant image and video denoising will become vitally important to decision making. One of the use cases for video denoising will be for landing leg attenuation on the Human Landing System during lunar descent. ICAN-C uses Marshall Space Flight Center's (MSFC's) optical technology and AI/ML to improve scenarios of obscured or hazy vision.

APPROACH/INNOVATION

ICAN-C leverages a 'find and replace' approach to video denoising. This fiscal year (FY), the team has successfully created a video processing technique for locating the areas of vision obscuring dust and lofted lunar regolith.

A key challenge to utilizing AI in spaceflight is the verification and validation of the method. The team tackled this requirement by producing a custom training dataset utilizing MSFC's Lunar Regolith Terrain to simulate blowing regolith with actual lunar images from Lunar Reconnaissance Orbiter (LRO) as a backdrop. This allowed for numerical validation of the generative AI. Next steps will be to run the network on the entire 160,920 video clip dataset.

RESULTS/ACCOMPLISHMENTS

A major component of ICAN-C is the ability to detect and identify the boundaries of obscured regions in incoming video. Earlier this year the team designed and tested software to accomplish this task.

This development led to a spinoff technology for tracking fireball growth.

Additionally, the team built and trained a preliminary neural network for generating lunar images based on LRO and Clementine images.

The preliminary neural network was foundational to building the context-informed network. The context-informed network considers the clear, unobscured sections of the frame to generate the relevant image for the obscured portions.

ICAN-C has the endorsement of the Dust Mitigation Stakeholders Forum and has matured from Technology Readiness Level (TRL) 1 to TRL 5 in one year.

FIGURE 1. Apollo 16 Extravehicular Activity (EVA) footage original (left), and dust detected (right, in white).

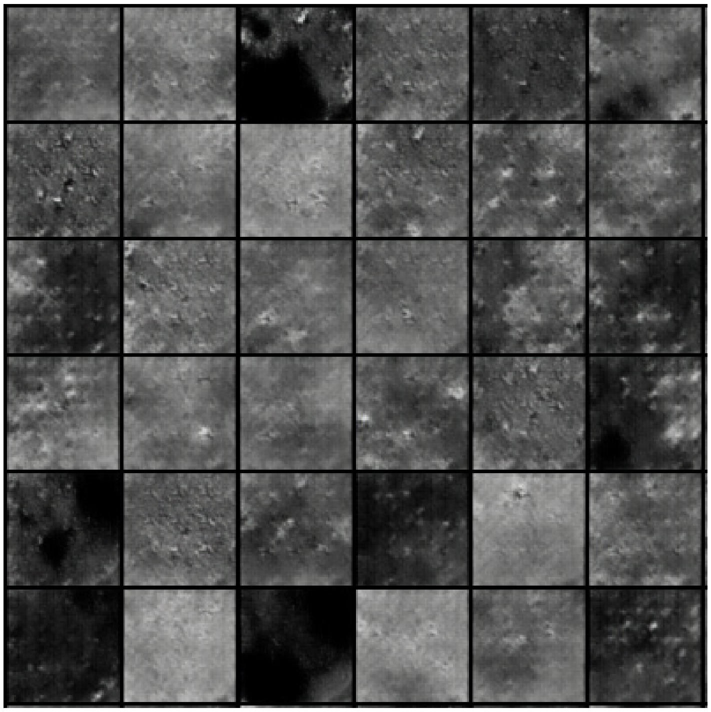


FIGURE 2. AI Generated lunar terrain after 368 iterations, trained on Clementine Spacecraft images.

PARTNERSHIPS

Agreements are in place with other center departments (Human Exploration Development and Operations Office, Science and Technology Office, Aerosciences Branch, and Structural Dynamics and Integration Branch) to continue providing support to ICAN-C. Plans are in place to deploy the bundled software and cameras into a light-weight package onto a drone in the Lunar Regolith Terrain to demonstrate the instantaneous capability of ICAN-C by the end of FY24.

SUMMARY

ICAN-C answers the need for onboard video denoising for use in Moon to Mars missions. The ability to use ICAN-C on any video means it is flexible enough to use on Forward-Looking Infrared, Short-Wave Infrared/Long-Wave Infrared, high-speed, or ordinary video in any environment. Near real-time capability allows the user to make instantaneous decisions by reducing the visual obstruction of nearby terrain.

The short-term motivation is to improve the visual clarity of lunar terrain based on Human Landing System (HLS) needs. There is no other similar technology on the market today. Using a custom training dataset for our AI/ML models, this system is best suited for lunar and Martian operations; however, the neural network can be retrained to be useful on any soil or weather conditions (i.e., blowing southeastern U.S. clay vs. Saharan dust vs. snow). In this FY, the ICAN-C team successfully produced software to identify vision obscuring sections of video and replace the section with a relevant lunar environment.

After this year the team will continue to fine tune the models and add an additional network for minimally obscured video. Later next year the team will bundle the software and cameras into a light-weight package. Plans are in place to deploy it on a drone in the Lunar Regolith Terrain to demonstrate the instantaneous capability of ICAN-C by the end of FY 2024.

Principal Investigator(s): Kelsey Buckles
Funding Organization(s): Center Innovation Fund

Use of Cold Plasma as a Novel Cleaning Technique for Planetary Protection

PROJECT OBJECTIVE: Develop a quantitative approach to measure microbiological burden reduction on solid surfaces treated with cold plasma that can be easily applied to an array of diverse materials.

PROJECT GOAL/DESCRIPTION

Mitigation of microbial growth and contamination is an important objective in many areas of space exploration, both crewed and robotic. Planetary protection of other solar system bodies means reducing, and where possible eliminating, Earth microorganisms from hardware prior to launch. At the same time, biofilm reduction and pathogen control in habitats are essential for safety and sustainability of long-term crewed missions. While several approved sterilization protocols exist, most of them either rely on interventions that are not suitable for certain materials and/or geometries or rely on a consumable supply of chemical sterilant, which is undesirable for long-term missions. This project explores the feasibility of using cold plasma for sterilization of spaceflight-relevant materials. We aim to analyze cold plasma bactericidal action on bacteria and spores contaminating materials relevant to space hardware and crewed missions. The knowledge gained from this research will provide a potential new technology for reduction of microbial burden on space hardware for the purpose of planetary protection.

APPROACH/INNOVATION

This project will provide the first quantitative comparison of plasma treatment sterilization on two representative materials under normal gravity conditions. Our team is uniquely qualified to perform cold plasma sterilization and optimization for dried microbes on relevant spacecraft materials. Previous research in this field, both by our lab and others, have focused on actively growing species of human pathogens. While cold plasma use for bioburden reduction has been proposed or attempted for other NASA microbial mitigation projects (e.g., plasma waste remediation, water treatment, and air revitalization at NASA Kennedy Space Center), to our knowledge, this work is the first of its kind to apply cold plasma sterilization as a planetary protection cleaning method. Next steps upon completion of this work will be to study impacts of optimized cold plasma sterilization technology on material surface and bulk properties. To support these efforts, the team will seek funding through competitive solicitations from the Department of Defense (DoD), Department of Energy (DOE), and NASA.

RESULTS/ACCOMPLISHMENTS

Initial work included the adaptation of cold plasma sterilization to solid surfaces using ultraviolet radiation as a control. An argon (Ar) plasma jet was used to treat the planetary protection-relevant organisms *Deinococcus radiodurans* ATCC BAA-816 and *Bacillus atrophaeus* ATCC

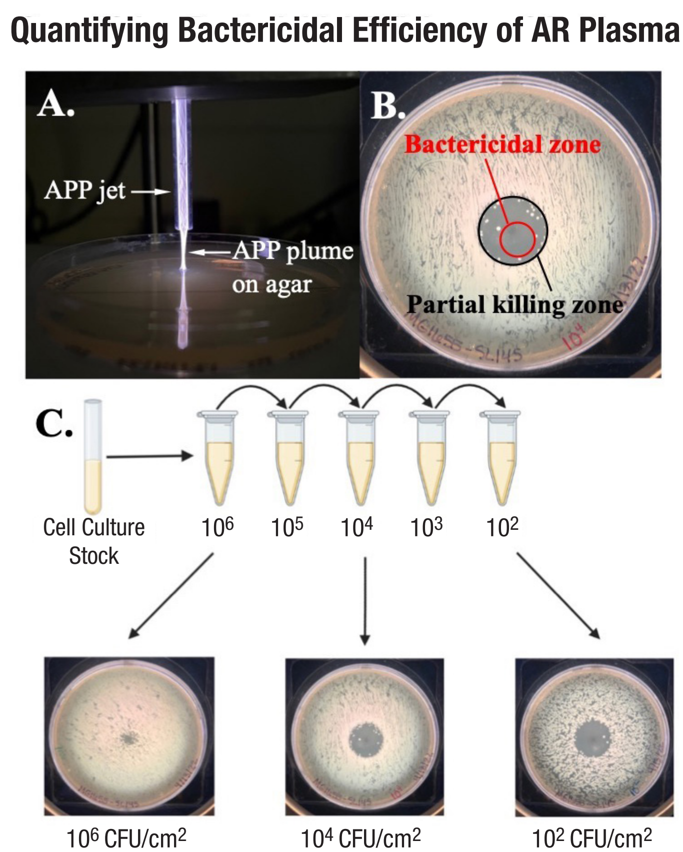


FIGURE 1. Measuring bactericidal effects of cold Ar plasma with plasma jet setup.

A. Sterilization by cold Ar plasma plume located at 6 mm above the agar surface loaded with cells at fixed surface density.

B. Bactericidal zone post-exposure and incubation overnight to allow growth of surviving bacterial cells. Cleared bactericidal zones are measured to quantify bactericidal efficiency.

C. Surface cell density is controlled by the serial dilution of cell culture and result in reducing bactericidal efficiency for higher cell densities.

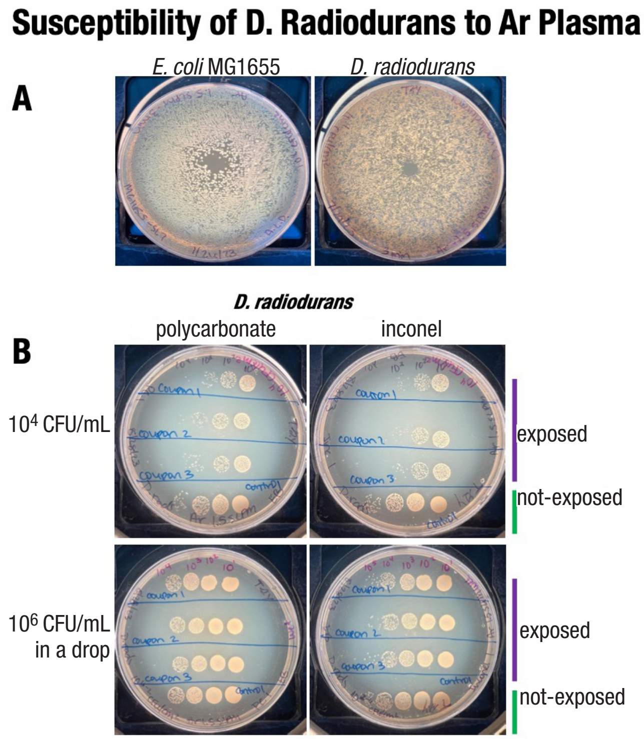


FIGURE 2. Measuring susceptibility of bioindicator—vegetative *Deinococcus radiodurans* cell to cold Ar plasma.

A. Exposure of agar-supported cells of *Escherichia coli* MG1655 and *D. radiodurans* to Ar plasma (6 kV, 1.5 SLPM, 3 min exposure) at 10^4 CFU/cm^2 density. This comparison illustrates that *D. radiodurans* is susceptible to plasma but to lesser than *E. coli* extend.

B. Exposure of dry and suspended in a drop *D. radiodurans* cells at ~10^4–10^6 CFU/cm^2 densities (Ar plasma 6 kV, 1.5 SLPM, 3-min exposure). These examples highlight that higher densities and presence of liquid reduce susceptibility of *D. radiodurans* to plasma exposure.

9372 growing on nutrient agar. For both, the team observed Zones Of Inhibition (ZOI) in the middle of the plates. In both cases, the strains appeared to be more resistant to the detrimental effects of cold plasma when compared with previously tested strains. Next, as the intent of this work is to study the efficacy of cold plasma sterilization on dry microbial samples, the team exposed both microbes at various stages of drying on aluminum coupons. Initial results show drastically reduced bactericidal activity on solid surfaces for high cell densities.

The team is currently continuing these efforts by developing protocols to sterilize spacecraft-relevant materials like polycarbonate and INCONEL® in an attempt to develop a robust method of loading cells to the surface of coupons. Furthermore, they will develop various loading methods and densities to quantify the reduced plasma killing activity in wet and dry approaches on solid surfaces and compare killing efficacy on both materials. These studies will be compared with various methods commonly employed by NASA planetary protection for microbial reduction.

PARTNERSHIPS

This is an effort led by The University of Alabama in Huntsville (UAH) Department of Biological Sciences. Support also comes from the Plasma and Electrodynamics Laboratory within the Department of Mechanical and Aerospace Engineering at UAH. Partnerships within NASA include planetary protection within the Space Environmental Effects Team in EM41 and the Human Landing System (HLS) Mission Capability and Risk Reduction Team in LP40.

SUMMARY

Microorganisms can have significant impacts on various aspects of NASA missions, including compromising the integrity of scientific investigations, threatening crew health, and damaging materials. Specific to this proposal is the discipline of planetary protection which aims to reduce and, where possible, eliminate microbes from robotic spacecraft venturing to sensitive bodies within the solar system. Currently, NASA has only a couple approved techniques for reducing contaminating microbes from spacecraft materials. In an effort to expand those techniques, this project is investigating the use of cold plasma as a cleaning method relevant to planetary protection.

In the months since this award began, the team has studied the susceptibility of two planetary protection-relevant microbes known as *Deinococcus radiodurans* and *Bacillus atrophaeus*. While demonstrating increased resistance to cold plasma when compared with previously studied organisms, the team has seen indication that cold plasma may be a reasonable approach for cleaning microbes from certain surfaces. To continue these efforts, the team is examining the potential of cold plasma to clean a small subset of spacecraft-relevant materials. Ultimately, these efforts could help expand the repertoire of planetary protection cleaning approaches and may also be relevant to other fields where microbial control is critical.

Principal Investigator(s): Tatyana A. Sysoeva, The University of Alabama in Huntsville
Partners: The University of Alabama in Huntsville
Funding Organization(s): Cooperative Agreement Notice

Additive Manufacturing Enabled Biofilm Prevention (AMEBoP)

PROJECT OBJECTIVE: Additive Manufacturing Enabled Biofilm Prevention (AMEBoP) is exploring how additive manufacturing can enhance life support systems subjected to extended periods of dormancy, like those required for Lunar Gateway, lunar surface habitats, and other lunar and martian exploration systems.

PROJECT GOAL/DESCRIPTION

Dormancy, or a period of disuse, can allow microbes to grow on wetted surfaces within Environmental Control and Life Support Systems (ECLSS). These microbial colonies form biofilms that reduce performance and cause malfunctions. ECLSS designers at NASA Marshall Space Flight Center (MSFC) have already shown that additive manufacturing can reduce the mass of manifolds and similar components by up to 40%. We hope to extend this work and show how additive manufacturing can also be used to reduce biofouling. By leveraging the complex geometries enabled by additive manufacturing, dead legs can be eliminated and the stagnant volume of components can be reduced. This means less nutrients for microbes to grow. Components can also be printed from inherently biocidal or antimicrobial materials, like certain metals and impregnated polymers, that can help control growth as well.

APPROACH/INNOVATION

To assess the potential of this approach, four different variations of a representative manifold will be subjected to periods of dormancy and their performance compared. All manifolds are designed to have the same interfaces and be functionally identical, but vary in their manufacturing technique, their geometry, and their material. We will be using a traditionally manufactured manifold machined from stainless steel to establish a baseline for a typical ECLSS manifold's tolerance to dormancy. We will then compare that manifold's performance to a similar manifold machined from copper, as well as to manifolds with optimized geometries printed from stainless steel and from a copper alloy. Each of these manifold types will be subjected to dormancy periods of two, four, and six months.

To characterize the performance of these test articles, three metrics will be used: differential pressure, microbial analysis, and destructive analysis. Changes in flow characteristics will be captured by pushing fluid through each manifold and measuring the differential pressure across the manifold before and after dormancy. We will also take samples from the flow path of each manifold after dormancy. These samples will be plated and the number of colony forming units that grow, and their species, will be recorded. Manifolds will also be cut apart and the flow path will be inspected for biofilm formation.

RESULTS/ACCOMPLISHMENTS

Test articles are currently being manufactured and the test setup is being assembled. Testing is anticipated to begin in Fall 2023. The described testing will establish an initial baseline for the dormancy tolerance of a typical ECLSS manifold. This type of component level testing has not been done previously and will answer an important knowledge gap. It can then be established if the manifolds printed with optimized geometries or from biocidal materials show any significant improvement over this baseline. This will determine if the approach should be explored further and lay the groundwork for additional testing to pinpoint what geometries and materials offer the most benefit to ECLSS operating beyond low-Earth orbit.

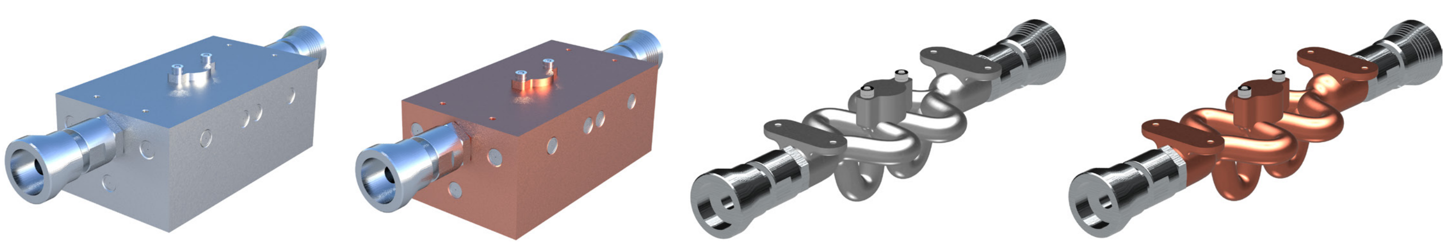


FIGURE 1. Test Articles.

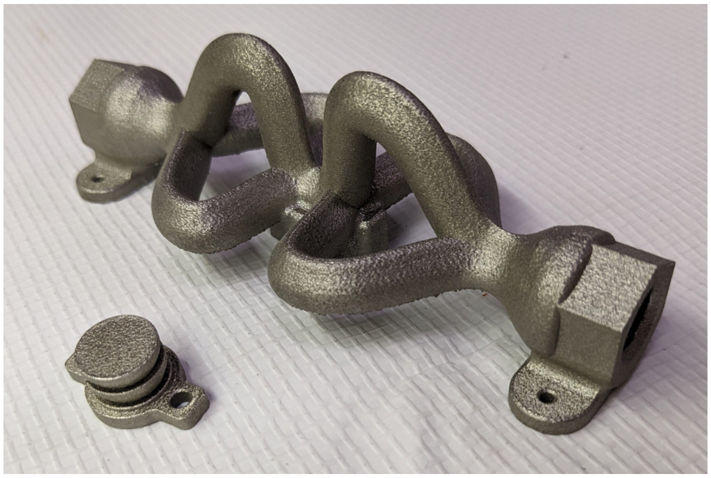


FIGURE 2. Test Article Additively Manufactured from Stainless Steel.

PARTNERSHIPS

Undergraduate students from the University of Texas System, Lone Star College System, and William Rainey Harper College have participated with literature searches and preliminary design efforts through the NASA Proposal Writing and Evaluation Experience Academy.

SUMMARY

The AMEBoP project is exploring how additive manufacturing can be used to reduce biofouling in ECLSS that will be crucial to Lunar Gateway, lunar surface habitats, and other lunar and martian exploration systems.

During dormancy, or a period of disuse, microbes can grow on wetted surfaces within ECLSS. These microbial colonies form biofilms that reduce performance and can cause malfunctions. The AMEBoP project will test four different variations of a representative manifold to assess the potential of additive manufacturing to prevent biofilm growth. The manifolds will vary in their manufacturing technique, geometry, and material. The manifolds will be subjected to dormancy periods of two, four, and six months and their performance will be characterized using three metrics: differential pressure, microbial analysis, and destructive analysis. This testing will establish an initial baseline for the dormancy tolerance of a typical ECLSS manifold. It will also determine if manifolds printed with optimized geometries or from biocidal materials show significant improvements.

This work aligns with MSFC's pursuit of ECLSS and habitation systems for the Moon and Mars as well as taxonomy areas TX06.1.2 Water Recovery and Management, TX06.1.3 Waste Management, TX06.6.6 Maintainability and Supportability, and TX12.1.7 Special Materials. It also complements other efforts at the center that are conducting coupon testing and dormancy testing at the system level. Biofilm mitigation is a multifaceted problem, and it requires a multifaceted solution. The AMEBoP team hopes that additive manufacturing can be used in conjunction with other mitigation techniques to offer additional protection to vulnerable components or to fortify components that cannot be protected in other ways.

Principal Investigator(s): Walter King; Anna Shipman
Funding Organization(s): Center Innovation Fund
For more information: https://ntrs.nasa.gov/citations/20230009131

A Promising Adsorbent for Removal of Dimethyl Sulfone in Wastewater on the International Space Station

PROJECT OBJECTIVE: Evaluate a deep eutectic solvent coated adsorbent for removal of dimethyl sulfone in wastewater on the International Space Station under simulated actual conditions.

PROJECT GOAL/DESCRIPTION

Dimethyl sulfone ($DMSO_2$) is a problematic and challenging compound in the Water Process Assembly (WPA) on the International Space Station (ISS). Because of its inert nature and low affinity for many adsorbents, including those employed in the WPA, $DMSO_2$ cannot be efficiently removed by any of the present treatment methods in the WPA, including adsorption, ion exchange, and catalytic oxidation. Our previous research in collaboration with the Environmental Control and Life Support System office at NASA Marshall Space Flight Center (MSFC) resulted in a promising modified adsorbent called deep eutectic solvents (DES) coated biochar (Fig. 1) delivering >99% removal efficiencies of $DMSO_2$ in spiked deionized water. In that research, the adsorbent was not subjected to challenging conditions, including the presence of specific co-contaminants and background constituents in actual wastewater on the ISS. The main goal of the proposed project is to demonstrate that our previously developed adsorbent is capable of removing $DMSO_2$ under simulated challenging conditions on the ISS.

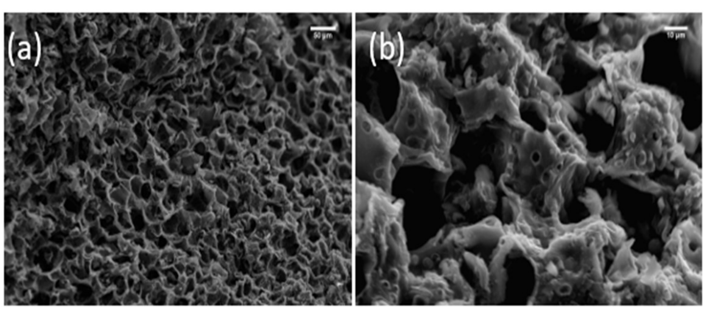


FIGURE 1. Electron microscopy images of walnut biochar: (a) surface and (b) micropores.

APPROACH/INNOVATION

The main research approach is to coat DES, a green and sustainable solvent, on an emerging adsorbent, biochar, and apply it for removing $DMSO_2$ in simulated wastewater of the ISS. Granular activated carbon (GAC), a widely used commercial adsorbent for contaminant removal from water and wastewater, was also tested for comparison along with uncoated biochar. Our results so far show that the commercial GAC and uncoated biochar provide low $DMSO_2$ removal efficiency (Fig. 2). Our next step is to determine the $DMSO_2$ removal performance of the DES-coated biochar in batch and continuous column settings and to conduct a scale-up study, including cost estimation and potential environmental and physical footprints of the technology (Fig. 3).

RESULTS/ACCOMPLISHMENTS

The removal efficiencies of $DMSO_2$ in simulated wastewater using GAC and uncoated biochar were evaluated at various initial $DMSO_2$ concentrations (50, 100, and 250 μg/L). At all three initial $DMSO_2$ concentrations tested, GAC performed better than uncoated walnut biochar. The highest $DMSO_2$ removal performance by GAC was 36% at 50 μg/L of $DMSO_2$. The $DMSO_2$ removal efficiency dropped for both the GAC and uncoated walnut biochar with increasing initial $DMSO_2$ concentration. These results demonstrate the challenge in the removal of $DMSO_2$ in water and wastewater by a widely used commercial technology (GAC) and an unmodified/virgin adsorbent (walnut biochar). The $DMSO_2$ removal by DES-coated biochar is currently being investigated and preliminary results show equal or better performance compared to GAC.

PARTNERSHIPS

NASA MSFC is working in collaboration with The University of Nevada, Las Vegas and Enova Water.

SUMMARY

$DMSO_2$ is a persistent contaminant in the water cycle of the ISS. The current water and wastewater treatment technologies are not capable of degrading and removing $DMSO_2$. This project is built on a previous Cooperative Agreement Notice project that demonstrated DES-coat-

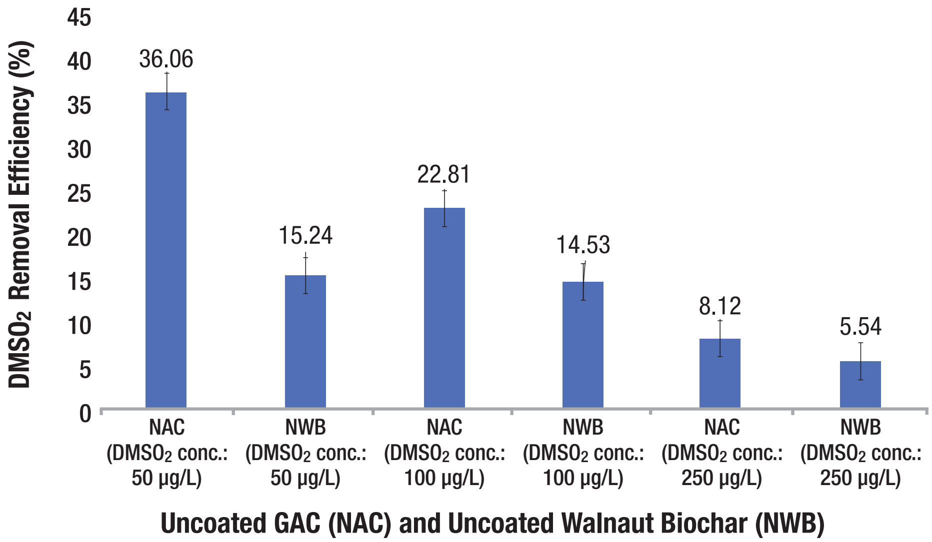


FIGURE 2. Removal efficiencies of $DMSO_2$ by GAC and uncoated biochar in batch experiments at various initial concentrations of $DMSO_2$ (50, 100, and 250 µg/L).

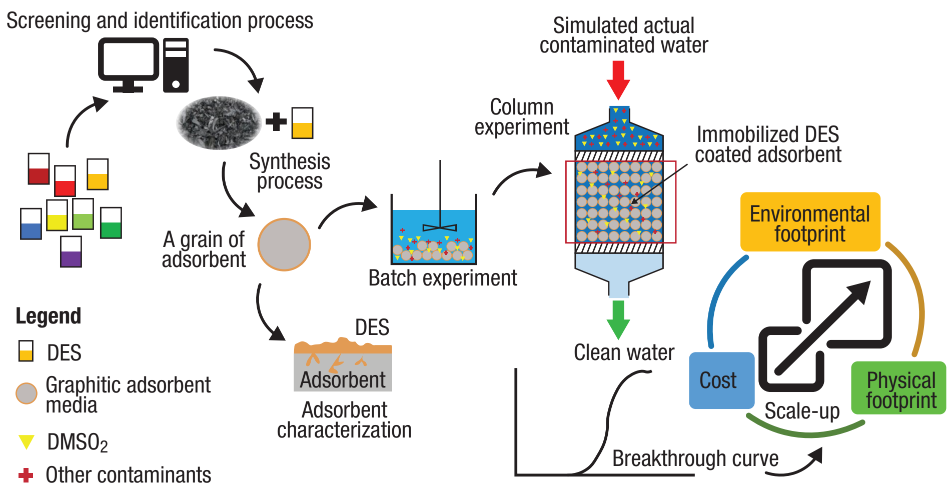


FIGURE 3. Project overview and workflow with a scale-up study being the last step.

ed walnut biochar as a promising adsorbent for $DMSO_2$ removal through preliminary experiments under ideal conditions with deionized water as a background matrix. This project tests the performance of DES-coated walnut biochar in comparison with those of GAC and uncoated biochar under simulated challenging conditions, especially with wastewater synthesized to be similar to actual wastewater on the ISS as a background matrix. Results revealed the inability of existing and traditional adsorption technologies, GAC and uncoated biochar, to effectively remove $DMSO_2$. The DES-coated biochar is currently being tested for $DMSO_2$ removal and its performance seems to be equal or better than the two existing technologies, pending further verification.

Principal Investigator(s): Eakalak Khan, University of Nevada, Las Vegas
Partners: University of Nevada, Las Vegas; Enova Water
Funding Organization(s): Cooperative Agreement Notice
NTR/Patent Number: NTR ID 1650343932

Bioremediation of Microgravity Biofilms and Water Processor Health

PROJECT OBJECTIVE: To deliver a natural solution to deter biofilm formation in water systems.

PROJECT GOAL/DESCRIPTION

The Water Processor Assembly in the International Space Station (ISS) is an intricate part of the urine-to-water conversion process. However, it has faced issues with biofilm formation. As such, multiple technologies have been in development to tackle this issue. Aside from applications in space, biofilms are a threat to public health and such biofilm formations often colonize biomedical equipment and wounds. Due to payload restrictions with future Mars missions, natural treatments that can be produced in situ may be preferred to harsh chemicals. The project aims to inhibit biofilm formation with the use of conjugative plasmids and conjugation methods to propagate genomic changes that disrupt phenotypical characteristics involved in the production of thick biofilms. Plasmid treatments have been previously explored, but insertions/deletions have not been tested for treatment of wastewater biofilms. Our project goals are to provide optimal constructs for an optimal treatment: (1) insertion of antibiofilm proteins; and (2) CRISPR deletion of genetic regions that promote biofilm using conjugation assays at benchtop testing, further testing under microgravity conditions, and subsequent delivery assays.

APPROACH/INNOVATION

This project aims to implement natural means to promote genetic mutations unfavorable for biofilm proliferation. Robust life support systems are sought for continued human space exploration; one of the main issues is the risk of biofouling and clogging. Multiple technologies have been sought, but this proposed solution pursues a new gene knock-out method for bacterial genomics. This innovative approach utilizes conjugative plasmids and allows for conjugative methods to propagate genomic changes that prevent phenotypical characteristics that support thick biofilms and antimicrobial resistance. CRISPR gene editing currently dominates the market for genetic engineering and requires a live vector for delivery. Plasmids, however, are known to survive in wastewater streams without the need of an infectious vector. The development of knock-out plasmids could advance both the fields of environmental engineering and genetic engineering in several aspects. They would use guide RNAs and Cas complexes like CRISPR and would allow promotion of plasmid to daughter cells similar to the antibiotic resistance trait, expanding on the knowledge of wastewater plasmid collections and the usage of environmental genomes. Additionally, knowledge would be gained in understanding the role of horizontal gene transfer in relation to biofilm formation compared to CRISPR.

The technical approach involves the use of hybrid Illumina-MinION sequencing techniques to understand our ground plasmidome of biofilm and antibiotic related genomes. Plasmid constructs are developed in a cloud-based informatics platform and used to perform conjugation experiments. Efficiencies of conjugation and gene knock-outs are tested with antimicrobial plating and mRNA analysis. Ground testing consists of plasmidome research and gene and organism down-selection from genetic data. This will be followed by conjugation experiments and validation of a gene drive model tool.

FIGURE 1. As part of a flight project analysis, biofilm re-capturing hardware from the wastewater stream is being studied.

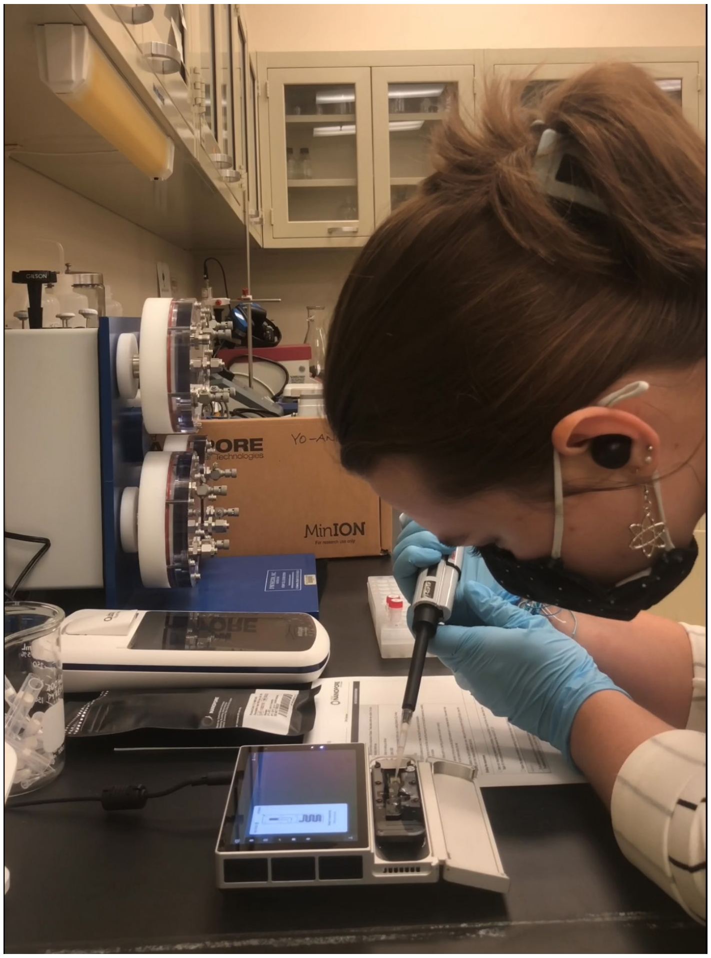


FIGURE 2. Sequencing capabilities were established to support plasmid engineering verifications. Molecular biologist intern inserts samples into sequencing apparatus to investigate use in this format.

RESULTS/ACCOMPLISHMENTS

- Relevant strains were gathered and short- and long-read sequencing was performed on the genome samples. The whole genomes were obtained via hybrid assembly by using the Unicycler pipeline.
- Pangenome analysis was performed using existing pangenome analysis tools like OrthoMCL and Anvi'o utilizing all hybrid assemblies in order to have all potential shared genes aligned.
- The pangenome analysis provides data for in-silico analysis of function overlaps at DNA level.
- Once overlapping DNA was determined, it was used as a target sequence. If not found, a mixture of targeted plasmids was suggested to account for a mixture of targets.
- Plasmids were developed to contain target regions and parts necessary for insertion/deletion.
- Flight Experiment Verification Test is planned to understand the fundamental science of conjugation, and the project has been placed in an integrated payload list.
- The project was assigned a payload integration manager and a research portfolio manager.

PARTNERSHIPS

The partners for this project are NASA Johnson Space Center, NASA Ames Research Center, Texas State University, The University of Alabama in Huntsville, and BioServe.

SUMMARY

Robust life support systems are sought for continued human space exploration and one of the main issues facing them is the risk of biofouling and clogging. This proposed solution has developed methods for conjugation that cause the cleaving of some essential genes for biofilm formation using horizontal gene transfer and a new gene knock-out method. Additionally, new genome sequencing and analysis processes for large-scale target selection and deletion were developed consisting of primary, secondary, and tertiary analysis that are scalable and can serve as a basis for future work. The project additionally aligns with NASA Marshall Space Flight Center's ongoing work in developing robust water recycling systems for human exploration and Advanced Exploration Systems capability gaps related to ID 06-104 Water Recovery Mitigation for Dormant Periods.

Principal Investigator(s): Jonathan P. Wilson; Yo-Ann Velez Justiniano
Partners: NASA Johnson Space Center; NASA Ames Research Center; Texas State University; The University of Alabama in Huntsville; BioServe
Funding Organization(s): Center Innovation Fund
NTR/Patent Number: NTR ID 1663686131

Comparing the Performance Characteristics of Auxetic Foams in Neuropathy Treatment Applications

PROJECT OBJECTIVE: To investigate and compare the performance characteristics and efficacy of auxetic foams as a neuropathy aid and fortification methodology in spatial structures, in order to highlight and address postural and balance deficiencies in neuropathic victims (e.g., returning astronauts) due to adverse space conditions.

PROJECT GOAL/DESCRIPTION

Technologies geared toward the health, muscular longevity, and Earth applications of returning astronauts are important but currently are scarce at NASA. Astronauts in space are exposed to 10 times more radiation than being on Earth and are much more susceptible to degenerating muscular and nerve diseases and conditions, such as neuropathy and limited mobility. In fact, Scott Kelley, a former astronaut during NASA's Shuttle Discovery mission, suffered from posture and balance deficiencies upon his return to Earth. Technologies in the sustainment of health of returning astronauts and impacting society with such technologies are underdeveloped and are a necessity. Moreover, 20 million people suffer from limited mobility and neuropathy, and this market is inclusive of returning astronauts.

Auxetic foams are foams with negative Poisson's ratios. They expand when stretched and shrink when compressed. This is contrary to almost all naturally occurring or synthetic materials, whose Poisson's ratios are positive. Auxetic foams exhibit many desired properties (e.g., significantly improved cushioning and pressure relief, superior shape conformity, optimal dynamics, enhanced toughness, shear resistance, bending stiffness, improved impact and indentation resistance, etc). Auxetic foams are multicomponent and multiphase cellular materials from the reactive foaming and phase separation of urethane, alcohol and water as the main reactants. The foams consist of both hard phase (domain), which provides strength, and soft domain, which provides elasticity and ductility. Additional rigid filler particles can be incorporated to further increase the strength and stiffness of the foams. By varying the amount of the filler particles, auxetic foams with different mechanical characteristics (e.g., strength, modulus, durability, and dynamic responses) can be further tuned. This research supports the investigation and comparison of the performance characteristics of auxetic foams, and the evaluation of its efficacy as a neuropathy aid. Additionally, this research supports the investigation of the material characteristics of the auxetic foam for potential applications in astronaut's suits and structures for deep space exploration systems.

APPROACH/INNOVATION

A sample of six neuropathic subjects, who attribute their neuropathy to personal injury, cancer, diabetes, or other diseases, were solicited. Subjects were instructed to walk across a force plate with and without the auxetic foam material, in which ground reaction forces (GRFs) and gait patterns of neuropathic victims were collected. A 3 by 5 (insole x neuropathy) repeated analysis of variance experiment on the impacts of neuropathic conditions (due to the aforementioned causes) and the impact of the auxetic foam material on the vertical, media lateral, and anterior-posterior GRFs, was conducted.

Additionally, the auxetic foam material was also investigated, in which dynamic mechanical analysis testing was performed utilizing a TA Instruments Dynamic Mechanical Analyzer (DMA) 2980 compression clamp with 15-mm-diameter platens, as well as a Q800 DMA-RH accessory clamp for humidity testing. Strain sweeps and humidity versus temperature testing were conducted. Furthermore, the foam was tested via acoustic and vibration analyses.

Innovative aspects of this project include the neuropathic prototype that was developed sufficient for optimal circulation and the management of neuropathic symptoms, and the spatial structures that will be fortified as a result of incorporation of the auxetic material. Neuropathy is a symptom to many underlining causes and diseases, and is not partial to age, race, or position. Therefore, returning astronauts, U.S soldiers, athletes, diabetics, cancer victims, victims of car accidents, victims of stroke, etc. will benefit from the technology. Follow-on activities are anticipated in order to engage in comparative analysis of a variety of materials, engage industry, and optimize the developed neuropathic aid.

FIGURE 1. Examples of the auxetic foam in action, showing the expansion of the foam in transverse direction after being stretched.

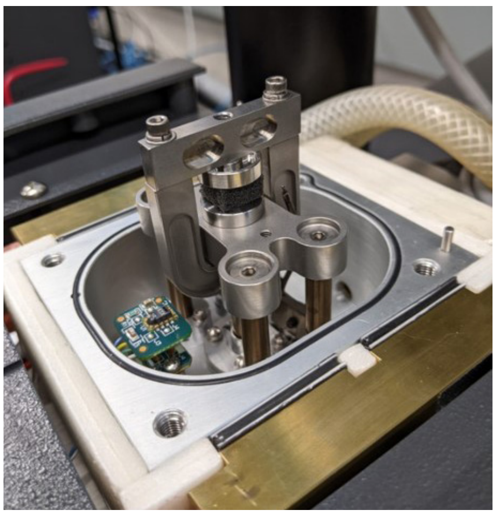


FIGURE 2. DMA cylinder pump used to perform DMA testing of auxetic foam material.

RESULTS/ACCOMPLISHMENTS

The auxetic foam proved to be more comfortable in comparison to other materials, and the subjects' walking and coordination improved by 100%. Material testing data results revealed that the auxetic foam material is able to sustain the use for several hours with sweat and humidity.

This follow-on project has successfully completed its second phase of testing, providing insight into the impact of the different attributes of neuropathy, and the characteristics and mechanics needed for a sufficient neuropathic aid. Additionally, this project has successfully evaluated and analyzed the auxetic material for incorporation and fortification of spatial structures. Furthermore, this project has initiated the careers and enhanced the educational careers of a plethora of interns, enabling them to pursue doctoral degrees and obtain fellowships. Lastly, this project has successfully partnered with academia, opening up avenues for collaboration opportunities across the NASA agency.

PARTNERSHIPS

This research and project partners with Florida A&M University-Florida State University (FAMU-FSU) College of Industrial and Manufacturing Engineering. FAMU-FSU provided the auxetic foam material and contributed auxetic material insights, providing recommendations for study design and data collection methodologies. Follow-on activities with FAMU-FSU are anticipated in order to compare other material, and to assess the depth of areas of optimization and incorporation into spatial structures.

SUMMARY

This project will not only help alleviate pain experienced by returning astronauts and other neuropathic victims, but it will fortify spatial structures that will enable deep space exploration and longer missions. This project will improve the quality of life of more than 20 million individuals by minimizing the symptoms and pains associated with neuropathy conditions.

Principal Investigator(s): LaBreesha Batey; Dr. Enrique Jackson
Partners: Florida A&M University—Florida State University College of Industrial and Manufacturing Engineering
Funding Organization(s): Cooperative Agreement Notice
NTR/Patent Number: NTR MFS-34387-1

TECHNOLOGY AREA 08

SENSORS AND INSTRUMENTS

Vacuum Brazed Aluminum Mirror Feasibility Study

PROJECT OBJECTIVE: Evaluate cryogenic surface deformation of vacuum brazed aluminum panels for potential use as telescope mirror in space and high-altitude balloon applications.

PROJECT GOAL/DESCRIPTION

This study evaluates the cryogenic optical performance of vacuum brazed aluminum panels with the goal of making large cryogenic mirrors that operate in the far- to mid-infrared (IR) spectrum. NASA's Astrophysics Program Office has identified "Large Cryogenic Optics for the Mid-IR to Far-IR" as a Tier 1 technology gap with a need to increase stiffness and overall size while decreasing mass density and cost. Missions currently in work that have an aluminum primary mirror range from 1 m aperture with a 3 µm diffraction limit (Atmospheric Remote-sensing Infrared Exoplanet Large-survey, or ARIEL) to 2.5 m aperture and 122 µm operating wavelength (Astrophysics Stratospheric Telescope for High Spectral Resolution Observations at Submillimeter-wavelengths, or ASTHROS). The 2020 Astrophysics Decadal recommend medium-scale "probe" class missions, which are capped at $1.5 billion and which include far-infrared (>10-µm) missions. Current proposals, such as the Probe Far-Infrared Mission for Astrophysics (PRIMA) and the Far-IR Spectroscopy Space Telescope (FIRSST), are proposing 2-m class telescopes with aluminum primary mirrors. As the operating wavelengths get shorter and apertures increase, new manufacturing technologies are needed to push development in the direction shown in Fig. 1.

APPROACH/INNOVATION

Vacuum brazing allows a panel to be made from metal alloys that are very similar with a geometry that maximizes bending stiffness. A panel is made up of a lightweight core structure having a honeycomb geometry with face sheets bonded to either side. Bonding the panel together occurs in a vacuum furnace where the bonding material is an alloy of the same metal as the core and face sheet, but with a slight-

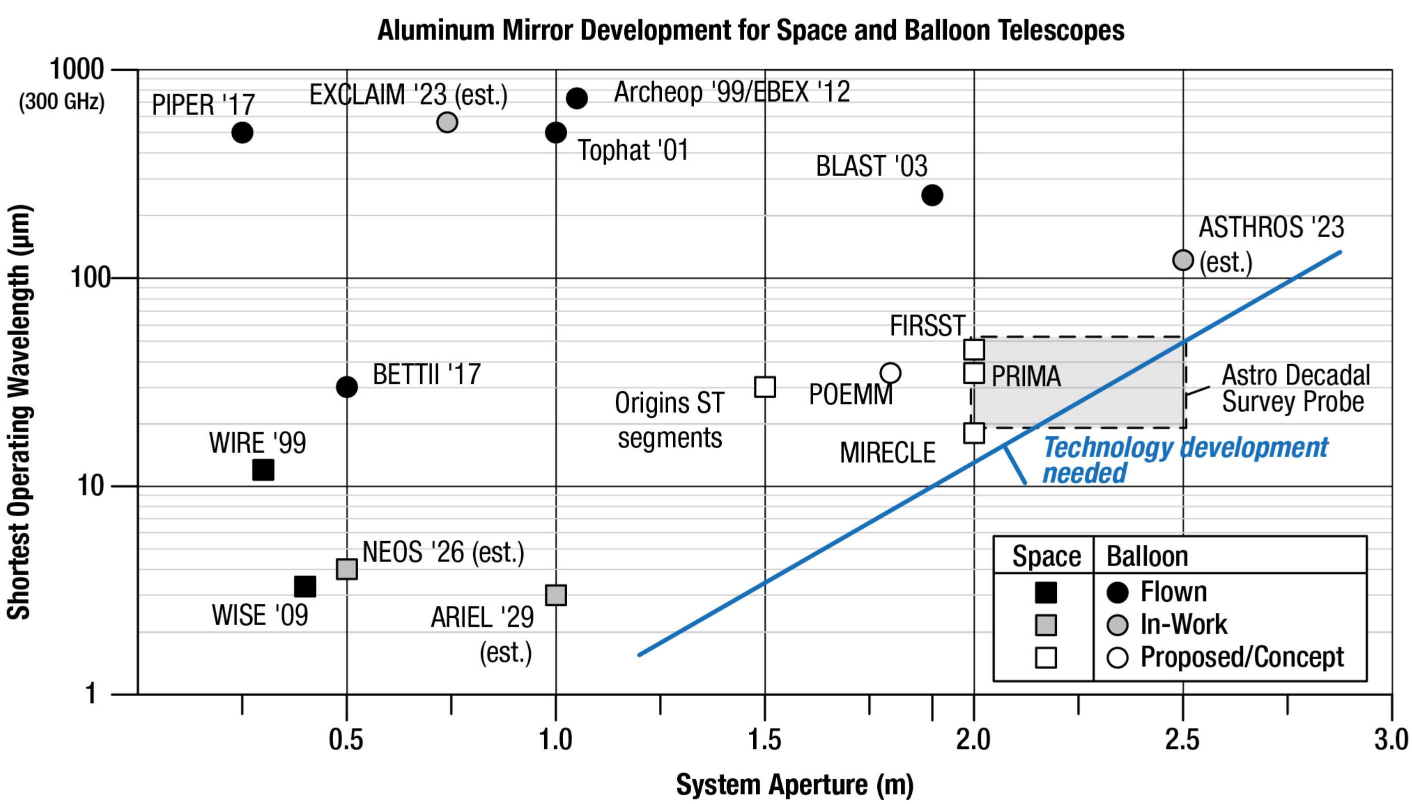


FIGURE 1. Comparison of operating wavelength versus system aperture for past and future IR missions that fly an aluminum primary mirror.

ly lower melting temperature. Vacuum brazing of aluminum is not new technology; the novel aspect is the application to cryogenic mirrors that are diffraction limited in the mid-IR spectrum. Because of the all-aluminum construction, the difference in the coefficient of thermal expansion (CTE) between the alloys is small and such a mirror should be as stable as a mirror made from billet aluminum. However, a vacuum brazed mirror has much less mass and is stiffer than a billet mirror of the same size.

This project seeks to verify the thermal stability of a vacuum brazed aluminum mirror. The steps taken involve finding vacuum brazing suppliers, design and fabrication of the test articles, and cryogenic optical metrology. The key challenge is a panel design that compatible with vacuum and is vented to ensure there is no enclosed volume. Testing is performed at room temperature and at 30 K on a flat, 5-in-diameter coupon that has been polished such that the surface can be measured on a 632.8 nm interferometer. The difference in surface measurements at the two temperatures is the error. If the thermal stability meets the requirements for mid-IR performance, the next steps would be to make a curved mirror and increase size.

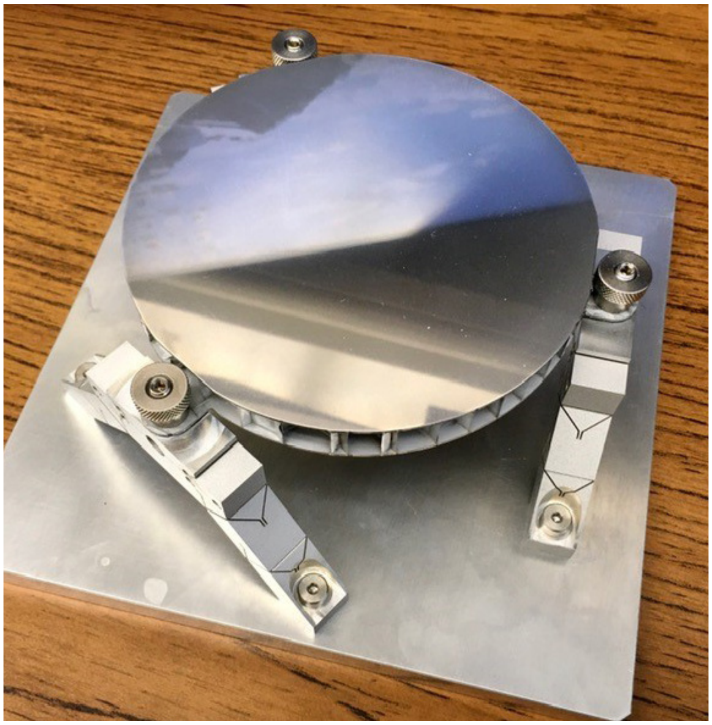


FIGURE 2. Hardware fabricated to date. Quasi-kinematic all-aluminum support and surrogate test coupon used to test fit and polishing process.

RESULTS/ACCOMPLISHMENTS

An ongoing effort is underway surveying the industry looking for aluminum vacuum brazing capabilities. This is a specialized niche within vacuum brazing, as it requires specialized knowledge and equipment. Fifteen companies have been contacted, with three able to vacuum braze aluminum. Procuring a sample panel is still in process.

The test setup has been designed and fabricated and is shown in Fig. 2. An epoxy bonded aluminum honeycomb panel served as a surrogate for fitment purposes (and is what's shown in the figure). The mirror support is quasi-kinematic and also made from aluminum with adjustment for tip and tilt. The surrogate was polished to verify a surface measurement was possible using a 632.8-nm interferometer.

Cryogenic testing is scheduled for the first quarter of 2024 at the NASA Marshall Space Flight Center X-Ray Cryogenic Facility.

SUMMARY

The program evaluates the feasibility of using vacuum brazed aluminum honeycomb panels for the construction large cryogenic mirrors that operate in the far- to mid-IR spectrum. As a first step (and the scope of this project), we look at quantifying the optical effect that differences in CTE have between the various aluminum alloys used in construction of the panel. Based on the outcome, a potential follow-on program would be to produce a sub-scale curved mirror. The project is a small investment in time and resources to quickly evaluate if vacuum brazed aluminum honeycomb panels merit additional research to address NASA's Tier 1 astrophysics technology gap.

Principal Investigator(s): Christopher Hopkins
Funding Organization(s): Center Innovation Fund

Advanced Microwave Precipitation Radiometer (AMPR)

PROJECT OBJECTIVE: To provide calibrated measurements of the Earth's atmospheric and surface characteristics from an airborne platform.

PROJECT GOAL/DESCRIPTION

The Advanced Microwave Precipitation Radiometer (AMPR) is an airborne, polarimetric, passive microwave radiometer producing brightness temperatures at 10.7, 19.35, 37.1, and 85.5 GHz. These frequencies are sensitive to the emission and scattering of precipitation-size ice, liquid water, and water vapor. AMPR is thus able to provide information on surface and atmospheric parameters, including precipitation over ocean and land surfaces, cloud liquid water and atmospheric water vapor over the ocean, sea surface temperature and near-surface wind speed, soil moisture, and sea ice. AMPR is a cross-track scanning radiometer, and its polarization basis varies as a function of scan angle. In order to retrieve geophysical information, the calibrated horizontally- and vertically-polarized microwave brightness temperature values need to be determined. This is accomplished by deconvolution of polarization-variable measurements from two orthogonal channels per frequency.

APPROACH/INNOVATION

During fiscal year (FY) 2023, the instrument was deployed for the third season of a NASA field campaign called Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS). The January/February 2023 deployment saw AMPR integrated on the NASA ER-2, which is a high-altitude aircraft that serves in a "satellite simulator" role for providing remote sensing observations of snowstorms. AMPR also flew on the ER-2 for a field campaign in July 2023 called ALOFT, which stands for Airborne Lightning Observatory for Fly's Eye Geostationary Lightning Mapper (GLM) Simulator (FEGS) and Terrestrial Gamma-ray Flashes (TGFs). In ALOFT, AMPR measured the structure of thunderstorms producing gamma-rays.

RESULTS/ACCOMPLISHMENTS

In Fig. 1, observations from AMPR and other instruments of a TGF-producing thunderstorm during ALOFT are

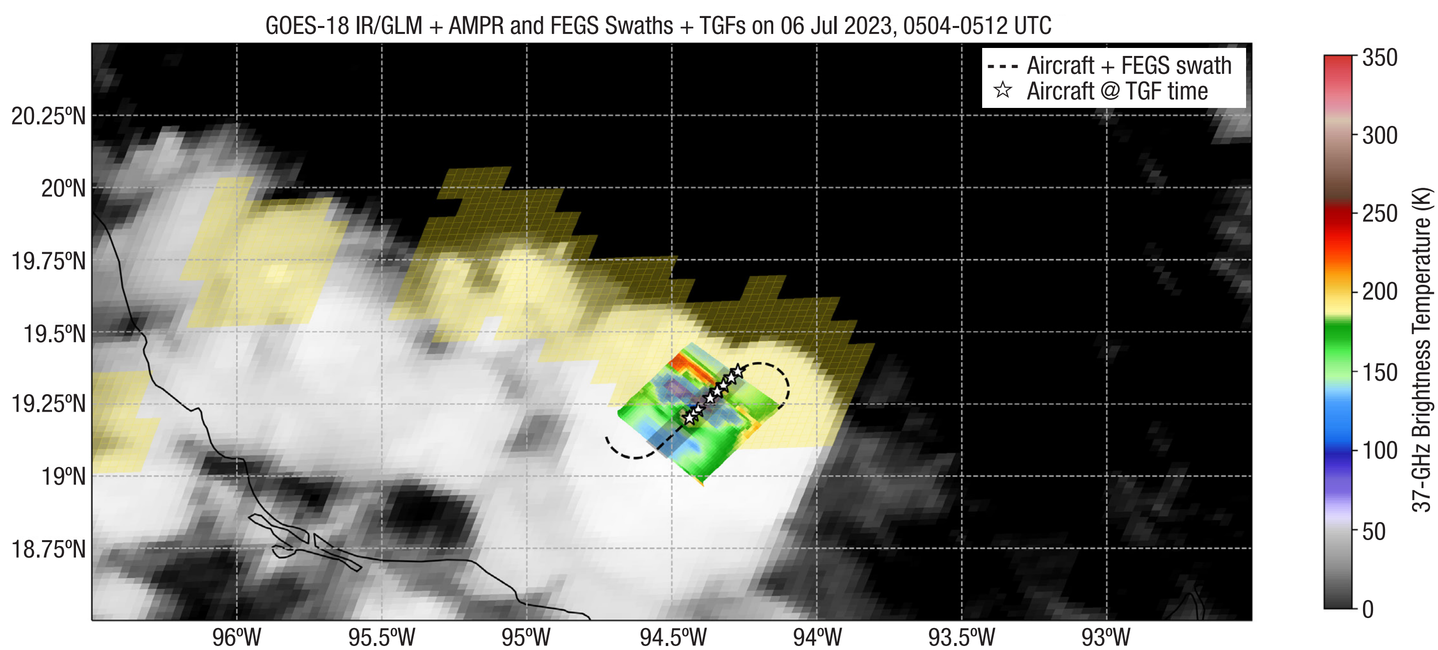


FIGURE 1. Geostationary Operational Environmental Satellite (GOES) 18 (West) observations of a storm off the coast of Mexico on 6 July 2023. Shown are the clean infrared (IR) channel, GLM flash extent density, and the AMPR 37 GHz (A) channel brightness temperatures during 0504–0512 UTC. Also indicated are the aircraft flightpath during this time, the swath of the FEGS instrument (shaded region around the dashed black curve), and the positions of the aircraft when TGFs were observed on this science leg.

shown. During this science leg, reduced brightness temperatures were observed on the 37 GHz (A) channel, which indicates the presence of precipitation-sized ice like graupel and small hail. This thunderstorm also produced as many as 8 TGFs during this single science leg, something that was not previously known to be possible. ALOFT made unprecedentedly detailed measurements of TGFs and the thunderstorms that produce them, and AMPR played a significant role in characterizing the structure and evolution of TGF-producing thunderstorms during the campaign. Overall, in FY 2023 AMPR gathered dozens of hours of data on thunderstorms, snowstorms, and other notable features during ALOFT and IMPACTS 2023.

PARTNERSHIPS

AMPR partners include The University of Alabama in Huntsville, which performs significant maintenance, upgrades, and operation of the instrument, as well as The Aerospace Corporation, which advises the AMPR team on data calibration and analysis.

SUMMARY

AMPR provided useful scientific data on snowstorms and thunderstorms during a field campaign in FY 2023. These data are being analyzed now while instrument development continues in order to maintain operational readiness.

Principal Investigator(s): Timothy Lang
Partners: The University of Alabama in Huntsville; The Aerospace Corporation
Funding Organization(s): Science Mission Directorate
For more information: https://weather.msfc.nasa.gov/ampr

International Space Station Lightning Imaging Sensor (ISS LIS)

PROJECT OBJECTIVE: To measure the global distribution of lightning from space.

PROJECT GOAL/DESCRIPTION

NASA Marshall Space Flight Center has long been a world leader in the detection of lightning from space. This leadership culminated with the launch of the International Space Station Lightning Imaging Sensor (ISS LIS) in 2017. ISS LIS has now operated for more than 6.5 years on orbit, and continues to extend the multidecade global climatology of lightning not only in time but also to higher latitudes (55° vs. 38°) than the previous LIS instrument on the Tropical Rainfall Measuring Mission (TRMM; 1997–2015).

APPROACH/INNOVATION

During fiscal year (FY) 2023, ISS LIS continued to operate nominally on orbit. This stability has been accomplished mainly through the use of an automated Timeliner script, which enables rapid recovery from single event upsets that often occur when the ISS is over high latitudes or passing through the South Atlantic Anomaly. ISS LIS is scheduled for decommissioning, likely in November 2023 after SpaceX-29 launches with another instrument that requires the LIS location on the ISS.

RESULTS/ACCOMPLISHMENTS

Since early 2022, two microwave radiometers have operated on the ISS. These radiometers, called Compact Ocean Wind Vector Radiometer (COWVR) and Temporal Experiment for Storms and Tropical Systems (TEMPEST), cover frequencies ranging from 18 to 182 GHz. This combination of passive microwave radiometry with ISS LIS lightning measurements (Fig. 1) recreates much of the original thunderstorm-observing capabilities of the TRMM mission, but with additional high frequency channels and coverage of the midlatitudes. In May 2023, a ground-based NASA Lightning Mapping Array was deployed to South Korea in order to support validation of ISS LIS. Additional

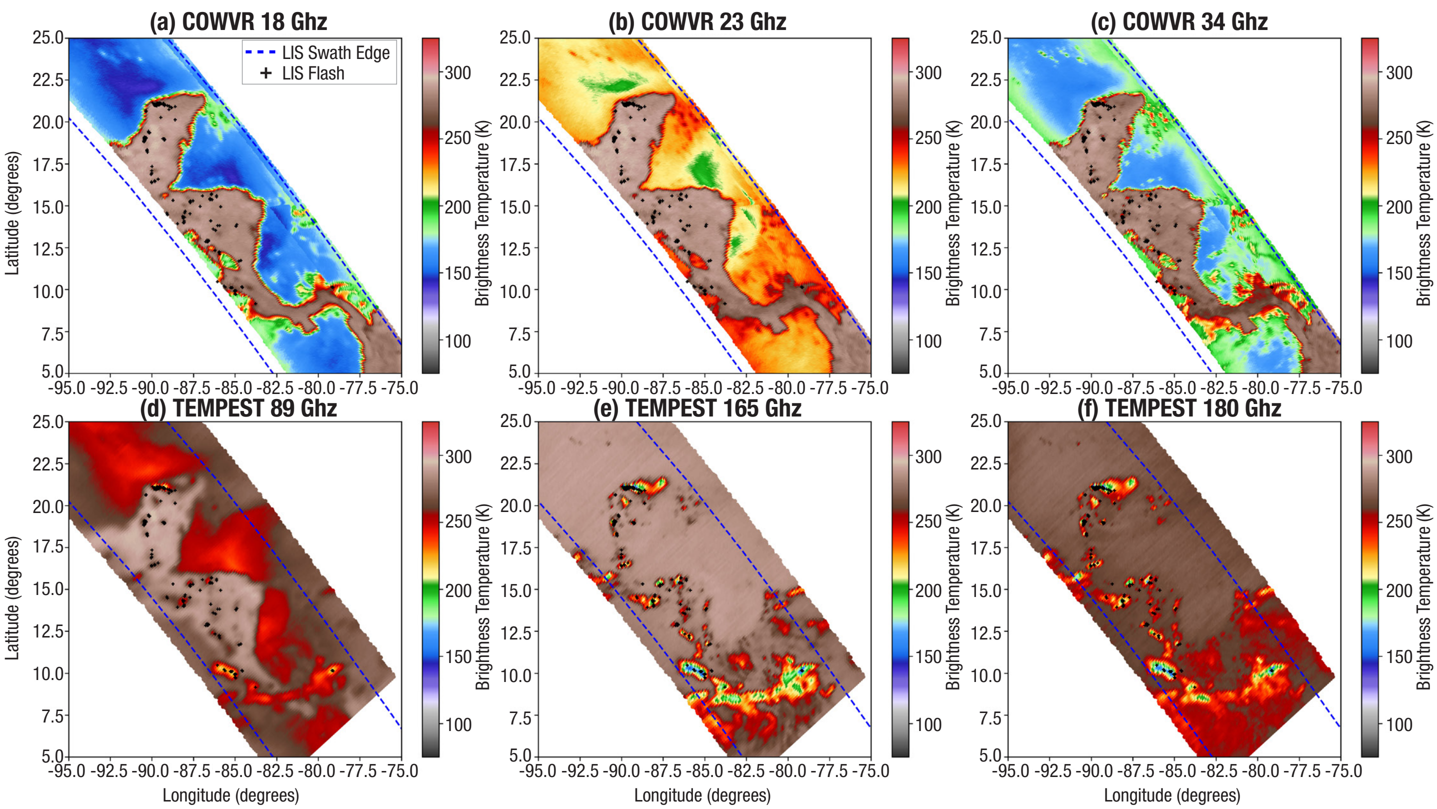


FIGURE 1. ISS LIS flashes during an overpass of Central America in 2022, combined with brightness temperatures from microwave radiometers on the ISS. (a) COWVR 18 GHz; (b) COWVR 23 GHz; (c) COWVR 34 GHz; (d) TEMPEST 89 GHz; (e) TEMPEST 165 GHz; (f) TEMPEST 180 GHz.

validation was done using suborbital underflights of ISS LIS with the NASA ER-2 during a field campaign in July 2023 called ALOFT, which stands for Airborne Lightning Observatory for Fly's Eye Geostationary Lightning Mapper Simulator and Terrestrial Gamma-ray Flashes.

PARTNERSHIPS

Space Test Program provides the host payload for ISS LIS and is a key partner in ISS LIS operations. The University of Alabama in Huntsville also is an important partner that processes ISS LIS data and assists with instrument operations. Universities Space Research Association maintains and improves ISS LIS data processing algorithms.

SUMMARY

In FY 2023 ISS LIS continued to operate nominally, with planned decommissioning after SpaceX-29 launches, which is currently scheduled for November 2023. Additional suborbital validation was done using the NASA ER-2 aircraft and a ground-based LMA. ISS LIS combined with the COWVR and TEMPEST microwave radiometers recreates much of the thunderstorm-observing capabilities of the original TRMM mission.

Principal Investigator(s): Timothy Lang
Partners: Space Test Program; The University of Alabama in Huntsville; Universities Space Research Association
Funding Organization(s): Science Mission Directorate
For more information: https://ghrc.nsstc.nasa.gov/lightning/data/data_lis_iss.html

Marshall Space Flight Center (MSFC) Advanced X-ray Optics: Formulation to Flight

PROJECT OBJECTIVE: Develop the next generation of sub-arcsecond, full-shell replicated x-ray mirrors and mirror assemblies; continue to supply low-cost, moderate-resolution flight mirrors and assemblies; enhance the performance of full-shell and segmented optics through low-stress coatings.

PROJECT GOAL/DESCRIPTION

This year (2023) marks the 30th anniversary of full-shell replicated x-ray mirror development at NASA Marshall Space Flight Center (MSFC). We have supplied the scientific community with x-ray mirrors for astronomical missions (e.g., High Energy Replicated Optics—HERO, Imaging X-ray Polarimetry Explorer—IXPE, Spectrum-Roentgen-Gamma Astronomical Roentgen Telescope-X-ray Concentrator—SRG ART-XC), heliophysics missions (e.g., Focusing Optics X-ray Solar Imager—FOXSI, Marshall Grazing Incidence X-ray Spectrometer—MaGIXS), and for use in multiple ground-based applications from neutron imaging to small-animal functional imaging. MSFC researchers are continuing to work toward the development of a large-area, high-angular resolution (<0.5 arcsecond) mirror modules for use on a future Great Observatory x-ray mission that will ultimately succeed the Chandra X-ray Observatory. The current state of the art for a MSFC-developed x-ray mirror module for spaceflight is 5–7 arcseconds. Current research focuses on improving tall-pole technical challenges primarily related to distortions due to plating and separation stresses. The near-term goals are to fabricate, coat, assemble, and test a two-shell module using full-shell optics that achieves <2 arcseconds half power diameter (HPD) and to establish an error budget to achieve <1 arcsecond HPD mirror-module performance.

APPROACH/INNOVATION

Electroformed replicated technology provides the ability to produce full-shell, lightweight, high-resolution optics, making this an attractive choice for developing astronomical x-ray telescopes. In this approach, an aluminum mandrel is plated with electroless nickel, which is then diamond turned, lap polished, and deterministically polished using a Computer Numerical Control (CNC) polishing machine to match the desired optics prescription and the required surface roughness. The mandrel is then placed in an electroforming tank, where a mirror shell of the desired thickness is electroplated onto the mandrel surface. Following electroforming, the mandrel/shell unit is placed into a bath of cold water to allow for the coefficient of thermal expansion (CTE) mismatch between the two to enable separation. We currently use a nickel-cobalt (NiCo) alloy for electroforming due to its high-tensile strength. The inner surface of the replicated NiCo shell is a replica of the polished mandrel, including the surface profile and roughness features. A single mandrel can be reused to replicate multiple shells without significantly degrading the surface quality, making it a cost-effective technique for producing many mirror shells.

While replication produces mirrors about two orders of magnitude thinner than those used for the Chandra mirrors, they have yet to achieve sub-arcsecond angular resolution. Residual profile errors from mandrel polishing, electroforming stresses, shell separation stresses, and mounting errors contribute to performance degradation. We continue to investigate these processes at various stages of fabrication to improve mirror-shell and mirror-module performance. Recent work includes the use of azimuthally varying CNC polishing to improve mandrel figure, detailed mathematical modeling software (COMSOL) simulations to study and optimize the electric-field distribution present during mirror shell electroforming, and thermally compensated shell alignment during final module assembly.

RESULTS/ACCOMPLISHMENTS

Over this past year, MSFC has significantly improved its x-ray optics capabilities in mandrel preparation, replication, and assembly. In mandrel preparation, enhanced end-to-end polishing procedures have resulted in significantly improved mandrel performance, from 8–10 arcseconds to 1–2 arcseconds HPD. In replication, process simulation has improved our replication capability from 8–10 arcseconds to 4–6 arcseconds HPD. A mirror shell of this quality as it is being prepared for x-ray testing is shown in Fig. 1a. In

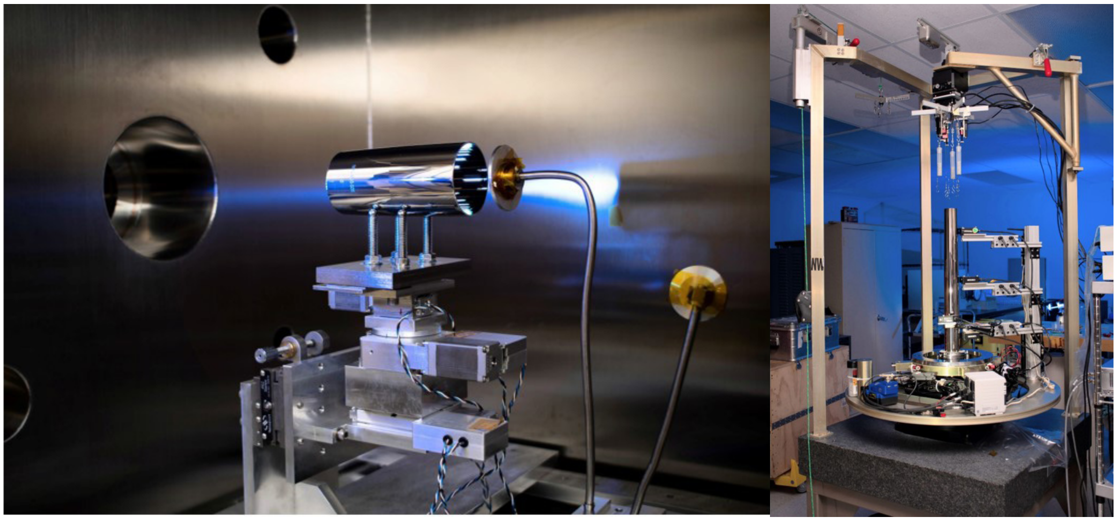


FIGURE 1. (a) Single replicated x-ray mirror shell being prepared for x-ray testing; **(b)** Custom in-house mirror alignment station.

assembly, improvements to an in-house designed alignment station, shown in Fig. 1b, reduced metrology artifacts from 45 arcseconds to 0.4 arcseconds and reduced bonding-induced distortion below 1 arcsecond HPD. The combined overall capabilities have improved the performance of our mirror modules from ~20–25 arcseconds to ~5–7 arcseconds (with contributions from gravity subtracted out), and we are working on demonstrating this for larger-diameter mirrors and modules.

PARTNERSHIPS

MSFC regularly partners with other NASA Centers, academia, and government entities to develop x-ray mirrors and mirror modules, improve processes, and/or perform x-ray testing and calibration. Some of our partners include the Smithsonian Astrophysical Observatory, The University of Minnesota, Boston University, Massachusetts Institute of Technology, NASA Jet Propulsion Laboratory/CalTech, European Space Agency, National Ignition Facility, National Institute of Standards and Technology, and Aerospace Corporation.

SUMMARY

MSFC has a long history developing and flying relatively low-cost, full-shell replicated optics.[1,2] While the current generation of medium-resolution x-ray mirrors is still in high demand, research and development toward achieving relatively low-cost, lightweight, higher-resolution (sub-arcsecond) full-shell mirrors is still needed. However, further progress is needed in several areas, with the primary focus areas related to replication and shell separation. We continue to view this technology as a healthy candidate for future large-scale astrophysics missions and are considering related manufacturing cost factors as we progress in our RandD efforts.

This technology addresses Tier 1 Technology Gap for high-resolution, lightweight x-ray optics (https://apd440.gsfc.nasa.gov/tech_gap_priorities.html) and is essential to realizing multiple future astrophysics missions.

References

1. 1. Ramsey, Brian D. et al., "First Images from HERO, a Hard X-Ray Focusing Telescope," The Astrophysical Journal, vol. 568 (March 20, 2002): 432-435. https://xanth.msfc.nasa.gov/xray/research/papers/apj568.432.pdf
2. 2. Engelhaupt, Darell E. et al., "The Fabrication of Replicated Optics for Hard X-Ray Astronomy," Paper presented at the OSA Optical Fabrication and Testing Meeting, Quebec, Ontario, Canada, June 18–22, 2000. https://ntrs.nasa.gov/citations/20000074479

Principal Investigator(s): Jessica Gaskin, On Behalf of the X-ray Optics Team (ST12, ES23)
Partners: Other NASA Centers, Other Government Agencies (OGAs), Academia
Funding Organization(s): Internal Scientist Funding Model Directed Work

CubeSat Lightning Imaging and Detection Experiment (CLIDE)

PROJECT OBJECTIVE: Design a multispectral, high-resolution lightning imaging system that can be used for small satellite missions.

PROJECT GOAL/DESCRIPTION

Observing global lightning activity is essential for understanding extreme weather and how it affects the environment, which is of utmost importance for mitigating impacts of climate change. Lightning flashes occurring around the globe are mapped from space using high-speed camera systems that acquire hundreds to thousands of images every second and detect transient pulses of light emanating from storm clouds. As simple as this sounds, it involves a large amount of image processing and designing a lightning mapper capable of detecting all the lightning flashes produced by various storm types occurring both day and night is by no means trivial. Current satellite-based lightning mappers detect only 50–70% of global lightning activity and can be less during very intense phases of a storm. Recent lightning observations from the International Space Station and from a recent NASA airborne field campaign suggest higher resolution sensors with spectrally diverse imaging capabilities are needed to obtain a more complete picture of lightning activity, especially in severe storms. The goal of this project is to design a new lightning mapping instrument with these capabilities that can be hosted on small satellite platforms—a direction both government and commercial Earth observing is rapidly moving.

APPROACH/INNOVATION

CubeSat Lightning Imaging and Detection Experiment (CLIDE) is a new bispectral lightning mapping instrument being developed at NASA Marshall Space Flight Center for future small satellite missions. Like existing lightning mappers, CLIDE will detect lightning both day and night by triggering off its thermal emission signature in the near-infrared (NIR) spectrum, albeit with higher resolution. It will also include a second channel in the ultraviolet (UV) spectrum that triggers off lightning's molecular emission signature. CLIDE's event detector will use a new high-speed complementary metal oxide semiconductor (CMOS) image sensor, making it an all-digital design that should significantly reduce the size, weight and power of the camera electronics used for lightning mapping. However, going to higher resolution and adding more spectral channels requires balancing instrument performance and size. Increasing the spatial resolution calls for a larger aperture and adding a second spectral channel requires another CMOS image sensor, as well as additional optical components that separate the light into different wavelengths and focus it onto the sensor.

This phase of the CLIDE research and development (R&D) is focused on addressing the packaging problem. A key objective is to identify an optical solution that allows CLIDE to fit on commonly used CubeSats while increasing aperture size. Designs using free-form mirrors were explored as part of an earlier RandD effort since they can be very compact, but that solution could not achieve a wide enough field of view given the size of the aperture needed for detecting fainter lightning pulses. To cover the wide field of view, multiple lens assemblies could be used, but that is not a viable option for popular CubeSat sizes. This year we evaluated refractive optics solutions for CLIDE. The next step will be to build a higher fidelity model of CLIDE that can be tested in Marshall's lightning instrument laboratory.

RESULTS/ACCOMPLISHMENTS

The two types of refractive optics considered in this study can be categorized as either a barrel type or folded layout type. A barrel type design consists of an independent lens stack for each spectral band (i.e., NIR and UV channels), which results in overlapping but slightly offset fields of view. Very wide apertures can be attained with a barrel lens, especially for the UV channel, but at the expense of lengthening the instrument. With a folded layout type, the overall volume can be reduced by using mirrors and/or prisms that fold the optical path, but it comes at the expense of aperture size. An advantage of folded optics is that it offers a collocated field of view, which reduces uncertainties in the bispectral detection algorithm.

We evaluated the aperture sizes that could be achieved using both folded layout and barrel type designs for several CubeSat payload volumes. Designs that deliver sufficient energy across the focal plane array to detect lightning include apertures of at least 6–9 mm (F/1.1 to F/1.6) for the NIR channel and 8–12.2 mm (F/0.8 to F/1.2) for the

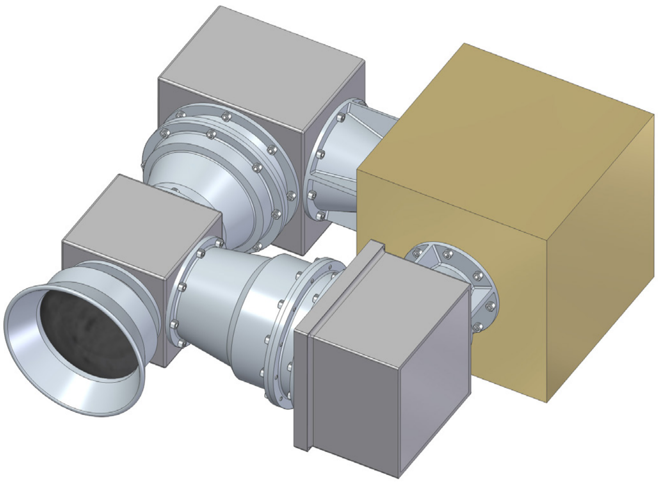


FIGURE 1. A folded optics design of CLIDE that occupies 4U of a CubeSat volume. The brown cube will hold the event detector electronics.

UV channel. These are considered very fast lens systems, and their ability to focus the light energy over such a short distance limits the minimum resolution. The diameter of the NIR channel aperture is two to three times as wide as the current Lightning Imaging Sensor (LIS) onboard the International Space Station (ISS). The optical assembly of ISS LIS, which consists of only a NIR channel, would occupy approximately 2U of payload volume on a CubeSat satellite. The optical assembly for CLIDE would occupy twice that volume but use a 2× larger aperture and include a second channel in the UV, which would ultimately enable detection of fainter lightning pulses and hence provide a more complete depiction of lightning activity, especially in severe storms.

SUMMARY

This R&D project designed an innovative optical system for a new lightning mapping instrument being developed for use on future small satellite missions to observe thunderstorms. The objective was to design a new optical system for the CLIDE instrument that seeks to detect smaller and fainter lightning than existing lightning mappers. This will be achieved with new CMOS image sensor technology to get higher-resolution mapping and by adding a UV channel needed to improve the amount of lightning discharges detected, especially in severe storms. The design challenge was packaging the optics into a small satellite form factor since the optical system requires a wide field of view (to observe large storm systems), collimated light (to maximize transmission of lighting signals through the interference filter), and a fast lens system (to collect more light for detecting fainter signals). During this project, a variety of new optical designs were produced that will facilitate trade-offs in detection capabilities and payload volume for future lightning mappers. A compact design consisting of a common entrance aperture for both spectral channels and folded optics to direct the light onto a common electronics package that would allow CLIDE to be hosted on a 6U CubeSat was selected to move forward into the next phase of development.

Principal Investigator(s): Patrick Gatlin; Mason Quick
Funding Organization(s): Technology Innovation Program
NTR/Patent Number: 1688570660

Moon Burst Energetics All-sky Monitor (MoonBEAM) Phase A Concept Study

PROJECT OBJECTIVE: Moon Burst Energetics All-sky Monitor (MoonBEAM) is a gamma-ray Small Satellite (SmallSat) mission concept in cislunar orbit to observe relativistic astrophysical explosions and address the key scientific priority of the Astro2020 Decadal Survey in Time-Domain Astrophysics.

PROJECT GOAL/DESCRIPTION

MoonBEAM is a Mission of Opportunity selected for Phase A concept study in the 2021 Astrophysics Explorers Program. The mission concept is led and managed by NASA Marshall Space Flight Center, with key roles in science, management, engineering, safety and mission assurance, instrumentation, and ground systems. MoonBEAM is a highly sensitive gamma-ray mission in a cislunar orbit to observe the entire sky instantaneously for relativistic astrophysical explosions. It is designed to observe and report in near real-time the first emission from relativistic transients, which are the most extreme phenomena in the known universe; they can be produced by mergers of compact objects, core collapse supernovae, or magnetar giant flares. These transients produce emissions across the entire electromagnetic spectrum and multi-messenger signals, encompassing photons, gravitational waves, neutrinos, and cosmic rays. MoonBEAM provides unprecedented wide-field, sensitive, and continuous gamma-ray observations to study astrophysical jet formation, structure, and evolution and to facilitate simultaneous broadband observation campaigns with prompt reporting of gamma-ray bursts.

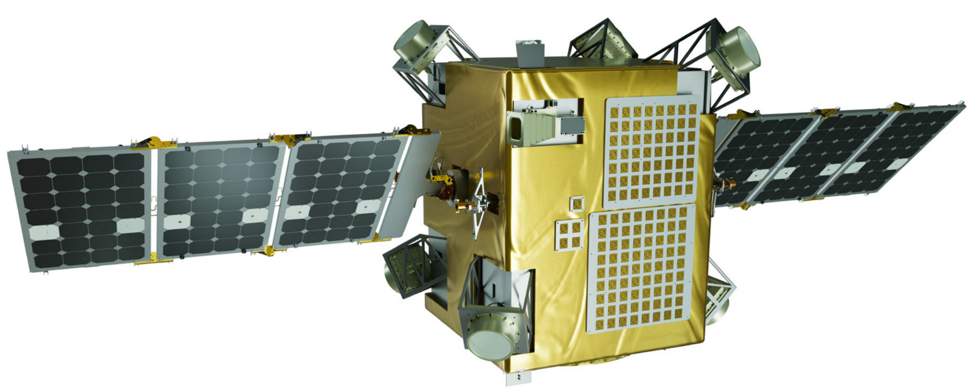


FIGURE 1. MoonBEAM gamma-ray mission concept.

APPROACH/INNOVATION

MoonBEAM achieves continuous all-sky observations based on its instrument design and its cislunar orbit. The instrument consists of six gamma-ray detectors sensitive to a broad energy range of 10–5,000 keV photons, positioned on corners of the spacecraft to achieve instantaneous coverage of the entire sky with no slewing requirement. The Earth-Moon Lagrange Point 3 orbit minimizes Earth occultation and variations in the background radiation environment, which are typical challenges that impact instrument sky coverage and duty cycle in Low Earth Orbit. MoonBEAM will reach the science orbit from an Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) Grande rideshare provided by NASA's Launch Services Program. The spacecraft is a Lockheed Martin SmallSat bus with a high-heritage, deep-space propulsion system. Rapid alerts of gamma-ray events will be downlinked and distributed with dedicated ground stations provided by the Near Space Network.

RESULTS/ACCOMPLISHMENTS

The MoonBEAM team submitted the Phase A concept study report on May 31, 2023 and completed the two-day, in-person site visit by the program evaluation panels in September 2023. The target date for continuation decision is the first quarter of calendar year 2024.

PARTNERSHIPS

MoonBEAM spacecraft bus partner is Lockheed Martin Space. The University of Alabama in Huntsville (UAH) is a co-developer of the gamma-ray detector and instrument software, and the student collaboration lead institution. Universities

Space Research Association (USRA) is co-developing the science operations and data analysis. The scientific collaboration includes UAH, USRA, Louisiana State University, Cornell University, NASA Goddard Space Flight Center, George Mason University, University of Western Australia, and Deutsches Elektronen-Synchrotron (DESY) Zeuthen.

SUMMARY

MoonBEAM will be the first gamma-ray burst mission beyond Low Earth Orbit with sensitive all-sky coverage for all gamma-ray transients, independent localization capability, and rapid communication. The MoonBEAM mission will address the Astro2020 Decadal priority in Time-Domain and Multi-Messenger Astrophysics and serve as a critical piece of astrophysics infrastructure by providing the essential continuous and instantaneous all-sky gamma-ray observation.

Principal Investigator(s): C. Michelle Hui
Partners: Lockheed Martin Space; The University of Alabama in Huntsville; Universities Space Research Association; Louisiana State University
Funding Organization(s): Bid and Proposal

Nondestructive Technology for Red Plague Corrosion Detection and Monitoring

PROJECT OBJECTIVE: To develop nondestructive technology for red plague corrosion detection and monitoring in silver-plated copper cables used in aerospace and energy applications.

PROJECT GOAL/DESCRIPTION

Silver-plated copper cables are widely utilized in various high-performance applications, such as aerospace avionics and energy systems, due to their optimal electrical and thermal characteristics. However, they are highly susceptible to a specific kind of corrosion called “red plague.” Red plague describes the red cuprous oxide (Cu_2O) and eventually black cupric oxide (CuO), troublesome corrosion byproducts observed in the silver-plated copper cables, which can indefinitely lead to loss of mechanical and electrical properties of cables and eventually cause catastrophic system failures in aerospace avionics and energy systems. In this project, a nondestructive method of detecting and monitoring red plague corrosion in silver-plated copper cables based on time-dependent s-parameters is being developed. This approach— integrating experimental study and nondestructive technology—will not only facilitate a substantial reduction in system failures and associated costs due to red plague corrosion, but will also establish a corrosion monitoring method acting as a predictive tool for timely interventions.

In this study, the DUT is the silver-plated copper cables and interference is expected to be generated in output s-parameter signals (S_{11}, S_{12}, S_{21}, S_{22}) due to interactions of the waves/signals with dirty connections and corroded spots on the cables across different frequency ranges. From previous studies, the magnitude of interference in the s-parameter signals is expected to be proportional to the amount, area, and depth of corrosion spots on the cables. This proportional relationship implies that higher levels of interference would indicate greater corrosion, and vice versa. By analyzing these signals, we can discern information about the extent of corrosion on the cables, providing a nondestructive method of representing corrosion status in the cables. However, the primary challenge lies in the complexity involved in extracting precise corrosion data from the s-parameter signals as it requires sophisticated data analysis and interpretation techniques to distill meaningful information about the corrosion.

APPROACH/INNOVATION

In order to develop a nondestructive technology for red plague corrosion monitoring, the time-dependent s-parameter results were obtained from the cables (from 9 kHz to 3 GHz frequency range) using the vector network analyzer at different corrosion time points. S-parameters describe how the cables modify a signal transmitted or reflected in a forward or reverse direction. Four s-parameter S_{ij} measurements - S_{11} (input impedance), S_{12} (output match/impedance), S_{21} (forward gain/loss), and S_{22} (reverse gain/loss) are obtained by passing electromagnetic signals through the device under test (DUT) as depicted in the schematic in Fig. 1.

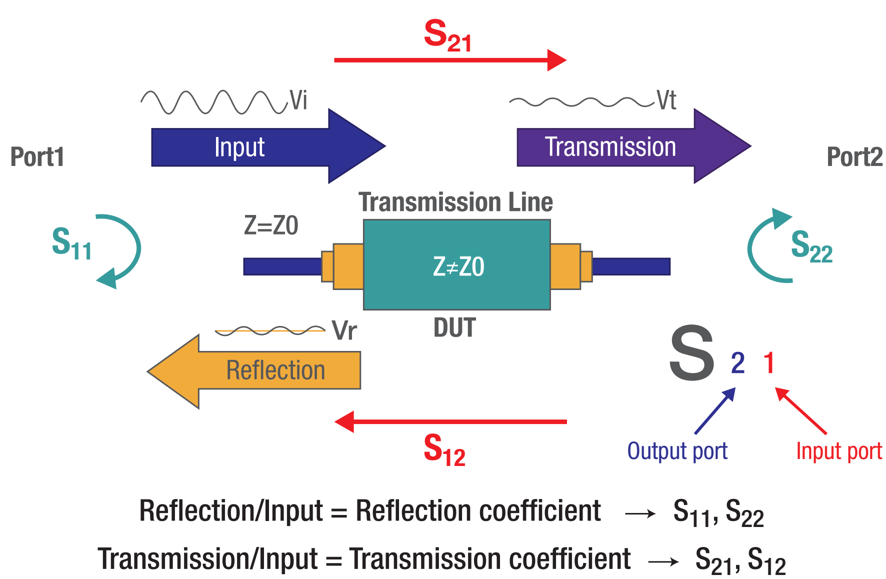


FIGURE 1. Time-dependent s-parameters. (Source: https://www.analogictips.com/what-are-the-functions-and-principles-of-s-parameters-part-1)

RESULTS/ACCOMPLISHMENTS

The s-parameter readings of silver-plated copper cables at room temperature and 90% relative humidity condition obtained at different corrosion time points were studied and analyzed to investigate the effect of corrosion. The variation/difference in the s-parameter readings of the cables placed in this condition and fresh cables (at the beginning of the experiment) in the frequency range of 10 MHz to 100 MHz was seen to increase as the corrosion time point increases. In order to validate this, the mean squared value of the difference between the s-parameter readings of the cables and that of a fresh cable was calculated up to the 18-month corrosion time points.

Fig. 2 shows the mean squared value of the difference between the s-parameter readings (S_{21} and S_{12}) of the cable in wet condition at several corrosion time points, and the fresh cable. The single number was seen to increase as the corrosion time point increased meaning this number can be used to indicate the difference in the corrosion status of cables. Overall, the trend shows an increase in variation of s-parameter readings as corrosion increases in the cable. However, there were some decreases in difference in some months which may be attributed to instrument/measurement error, or the current analytical method being used. Ultimately, this shows that the s-parameters readings in this frequency range (10 MHz–100 MHz) can be used to indicate the difference in the red plague corrosion status of silver-plated copper cables.

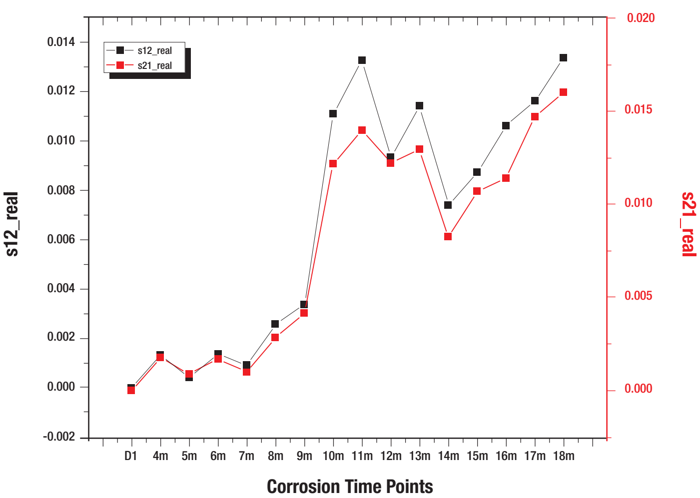


FIGURE 2. Numerical Difference between transmission parameters (S_{12}, S_{21}) of cables from 10 MHz–100 MHz.

PARTNERSHIPS

This technology development project is done in collaboration with the Materials Research and Education Center at Auburn University and Dr. Terry D. Rolin from NASA Marshall Space Flight Center.

SUMMARY

Silver-plated copper cables are highly susceptible to red plague corrosion which can indefinitely lead to loss of mechanical and electrical properties of cables and eventually causing catastrophic system failures in aerospace avionics and energy systems. This project aims develop nondestructive technology for red plague corrosion detection and monitoring based on s-parameters. Overall, the transmission parameter S_{12} and S_{21} in the frequency ranges (10 MHz–100 MHz and 100 MHz–1 GHz) can be used to monitor the corrosion. However, the primary challenge still lies in the complexity involved in extracting precise corrosion data from the s-parameter signals as it requires sophisticated data analysis and interpretation techniques to distill meaningful information about the corrosion. Other statistical methods are currently being explored.

Principal Investigator(s): Zhongyang Cheng, Auburn University; Terry Rolin
Partners: Auburn University
Funding Organization(s): Cooperative Agreement Notice
NTR/Patent Number: AU INV#2022-047

Upgrades to the Fly's Eye Geostationary Lightning Mapper [GLM] Simulator (FEGS)

PROJECT OBJECTIVE: Improved measurement of sub-millisecond multi-spectral lightning optical emission for the NASA Airborne Science Program.

PROJECT GOAL/DESCRIPTION

The Fly's Eye Geostationary Lightning Mapper [GLM] Simulator (FEGS) is an airborne multi-spectral radiometer array designed to measure the optical emission produced by lightning in thunderstorms. It is carried on the NASA ER-2 High Altitude aircraft to observe thunderstorms from a top-down perspective, mimicking the viewing geometry of satellite lightning detectors. Informed by measurements obtained in a previous flight campaign, several upgrades to the FEGS instrument were employed to improve its sensitivity, lightning detection performance, calibration accuracy, and science return.

FIGURE 1. The 2023 upgraded FEGS instrument looks downward through a 16-in-diameter viewport window mounted in the NASA ER-2 wing pod payload compartment.

APPROACH/INNOVATION

A targeted analysis of measurements previously recorded by FEGS was conducted to inform potential improvements in the capability of the instrument. It was determined that modifications to the front-end electronics would improve lightning detection during nighttime observations and devote more of the available dynamic range to transient lightning signatures. It was also determined feasible to add a broadband spectrometer to the multi-spectral radiometer assembly to collect additional spectral information contained in lightning emission signatures.

Following a thorough recalibration effort, it was determined that modifications to the optical design of the radiometers would simultaneously reduce stray light intrusion and improve out-of-band rejection. Analysis of the multispectral signal content indicated that a new selection of spectral bands would provide greater science return on future observation campaigns.

RESULTS/ACCOMPLISHMENTS

The FEGS radiometers were re-machined to enable inclusion of an additional out-of-band spectral rejection filter. Surface treatment applied to the aluminum radiometer housing was stripped and re-applied using an improved masked mix of chemical conversion and died anodic surface finish. Improvements and automation of the radiometer spectral response calibration set-up and procedure were accomplished to enable detailed testing of the radiometric performance. The modifications effectively mitigated out-of-band and stray light contamination, reducing undesired photo-current contributions by nearly 40%.

A new suite of spectral bands was selected including most notably a 340-nm channel and a 1.6-micron channel. These spectral bands enable discharge process discrimination and inform design of future space-based lightning imaging instruments. Modifications to the front-end amplifiers and gain selections improved nighttime lightning detection, background suppression, and devoted 2/3 of the FEGS dynamic range to transient lightning signatures, enabling detection of smaller and dimmer discharge phenomenon.

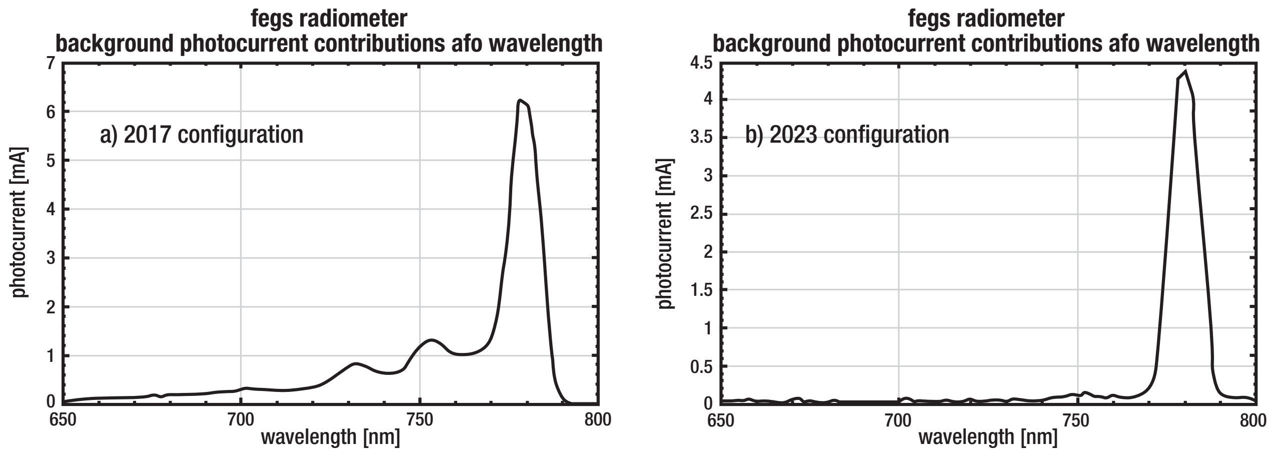


FIGURE 2. Calibration data following upgrades to the 780-nm spectral band radiometers showing significant reduction in out-of-band and stray light contamination from background cloud-top radiance.

A broadband spectrometer and associated data system was designed and installed into FEGS to offer more spectral information than is achievable with a multi-band system. Finally, to inform decision making during science flights, a low bandwidth real-time FEGS data product was implemented to be streamed through satellite downlink during aircraft flight.

These improvements were accomplished prior to the July 2023 ALOFT flight campaign and contributed to science returns from the highly successful mission. The ALOFT campaign observed thunderstorms in the American tropics including land and ocean storms near Florida, Mexico, and multiple central American countries. The primary science objective was to observe gamma-ray emission from storms in the region, a known hot bed for terrestrial gamma-ray flashes, and offered additional science opportunity to precipitation, convection, and lightning physics applications. FEGS observed more than 5,000 lightning flashes during the one-month campaign.

PARTNERSHIPS

The University of Alabama in Huntsville is a critical partner for engineering and calibration of FEGS and complimentary lightning instrumentation contributing to the NASA Airborne Science Program. Sandia National Laboratories was involved in developing the 1.6-micron spectral channel that was included in the 2023 FEGS flight configuration. The University in Bergen, Norway led the July 2023 ALOFT flight campaign in collaboration with NASA.

SUMMARY

An analysis of previously recorded measurements has informed modifications and upgrades to the FEGS instrument that have expanded its capability, improved its performance, and enhanced its science return. Improved calibration procedures have enabled verification of improved performance in the laboratory. These improvements were accomplished prior to a highly successful flight campaign in July of 2023 to observed thunderstorms in the American tropics and are already contributing to improved scientific understanding of lightning physics and advising design efforts toward future space-based lightning imagers.

Principal Investigator(s): Mason G. Quick
Partners: The University of Alabama at Huntsville; Sandia National Laboratories
Funding Organization(s): Science Mission Directorate–Earth Observing System Project
For more information: https://www.space.com/nasa-thunderstorms-gamma-rays-er-2-aircraft

Determining Flight Platform Needs for mm-wave Observations of the Sun

PROJECT OBJECTIVE: We worked to determine technologies and methodology necessary in order to use multiple space craft in order to perform aperture synthesis observations of the Sun in mm and sub-mm wavelengths.

PROJECT GOAL/DESCRIPTION

The solar chromosphere is one of the most important atmospheric layers of the Sun, and understanding the chromosphere is necessary to comprehend the bidirectional flow of energy from the photosphere to the corona. Millimeter and shorter (mm and sub-mm) wavelengths provide unique insight into these layers, as they directly measure the temperature in the chromosphere, and have the potential to measure the magnetic field in these regions. In order to obtain spatially resolved observations of the Sun in mm and sub-mm, large apertures are necessary. For example, at 100 GHz a 750 m aperture is required to obtain 1-in spatial resolution, and a 125 m aperture is required at 600 GHz. At these scales, a single mirror is unfeasible, and aperture synthesis is the most viable option. Additionally, these wavelengths are heavily impacted by the Earth's atmosphere, so one either needs to go to extremely high altitudes or to space. However, high altitudes, such as the site of the Atacama Large Millimeter Array, are still significantly impacted by weather, which greatly impairs their ability to observe regularly and with sufficiently large baselines necessary to obtain sufficient spatial resolution. Here we studied if a distributed system of orbiting spacecraft could be used to obtain mm and sub-mm observations of the Sun and have identified problems and potential solutions for these observations.

APPROACH/INNOVATION

Notable work is being done to make progress in obtaining mm and sub-mm observations of the Sun from the ground, though comparatively little effort has been focused on the space-based observations. We leverage the work of our ground-based colleagues in academia and industry to push for smaller instruments capable of space flight. We have been working to identify the challenges of translating these systems into spaceflight-capable instruments (such as the use of cryogenically cooled receivers) and have been working to alleviate the challenges.

Additionally, work is being done to implement space-based interferometric solar radio observations. These efforts are focused on longer wavelengths where the positional accuracy needed is significantly less, though these are still important steps to obtaining mm and sub-mm space-based interferometric observations. Our work identifies some possible techniques to achieve this necessary accuracy. The next steps are to refine these solutions and to develop some of the hardware to be used.

RESULTS/ACCOMPLISHMENTS

The project team has determined orbital system can work, using spacecraft positioning as a starting point for a calibration solution. The better the initial solution, a faster and better the final calibration solution can be obtained. This initial solution will be adjusted with calibration observations. These calibration observations are accomplished by observing and known astronomical source and adjusting the spacecraft locations until the observed signals are all in phase. We have determined four options for this.

The first is the traditional method used in ground-based observations: pausing observations of the source to observe the calibration source. This is likely the most inexpensive solution but causes gaps in the observations, which may impair the ability to perform time series analysis (Tarr et al., 2023).[1] The frequent motion of the spacecraft may also create jitter problems and extra wear and tear, limiting the lifetime of the instrument. The second option is to have a subset of antenna looking at a calibration source at any given time, with the others still on source. By rotating which antenna are calibrating, one can avoid the gaps in data, but the number of available baselines also decreases, and the ultraviolet coverage becomes time dependent, making data interpretation more difficult. A third option is to use antenna with a large field of view, so that a calibration source is (almost) always visible. This is simple, but will impact the scale sizes available, as the same amount of spatial resolution elements will need to cover a larger area and the impacts of vignetting will degrade interpretation. A fourth option is to equip each spacecraft with a second antenna angled at a calibration source in order to calibrate continuously. This is an expensive and untested method, but may provide the best characteristics for science return.

PARTNERSHIPS

While working on the project, an informal partnership has been developed with engeniusmicro to obtain and develop characteristics of possible receivers, with the potential future collaboration to develop and build the post-antenna receiver system for a future instrument. We are currently working to develop a technology plan and apply for future funding to build and design a suitable receiver system.

SUMMARY

We have worked to understand the possibilities for building and flying a space-based mm and sub-mm interferometer system for studying the solar chromosphere. As one of the first steps in this process, we worked to confirm whether the space craft positions could be known sufficiently well to successfully perform such observations. We identified four possible paths for this calibration and determined some of the benefits and limitations of each. We have also made progress in understanding the instrumentation needed and are working to develop solutions.

References

1. 1. Tarr, L. A., A. R. Kobelski, S. A. Jaeggli, M. Molnar, G. Cauzzi, and K. P. Reardon, "Spatio-temporal comparisons of the hydrogen-alpha line width and ALMA 3 mm brightness temperature in the weak solar network," *Frontiers in Astronomy and Space Sciences* vol. 9 (January 2023): 978405, https://doi.org/10.3389/fspas.2022.978405

Principal Investigator(s): Adam Kobelski
Funding Organization(s): Center Innovation Fund

Marshall Grazing Incidence X-ray Spectrometer (MaGIXS) Sounding Rocket Project

PROJECT OBJECTIVE: Marshall Grazing Incidence X-ray Spectrometer (MaGIXS) is an instrument developed to make solar observations on a NASA sounding rocket.

PROJECT GOAL/DESCRIPTION

For over four decades, x-ray, extreme ultraviolet (EUV), and UV spectral observations have been used to measure physical properties of the solar atmosphere. During this time, there has been substantial improvement in the spectral, spatial, and temporal resolution of the observations in the EUV and UV wavelength ranges. At wavelengths below 10 nm, however, observations of the solar corona with simultaneous spatial and spectral resolution are limited, and not since the late 1970s have spatially resolved solar x-ray spectra been measured. X-ray spectroscopy provides unique capabilities for answering fundamental questions in solar physics. Because the soft x-ray regime is dominated by emission lines formed at high temperatures, x-ray spectroscopic techniques yield insights to fundamental physical processes that are not accessible by any other means. The Marshall Grazing Incidence X-ray Spectrometer (MaGIXS) was designed, built, and launched to observe the active solar corona from the 0.6–2.4 nm wavelength range with high spatial resolution over a large field of view (see Fig. 1). During its design and build, multiple technologies were developed that made the MaGIXS instrument possible, including grating manufacturing, mirror fabrication techniques, x-ray calibration procedures, and development of inversion algorithms.

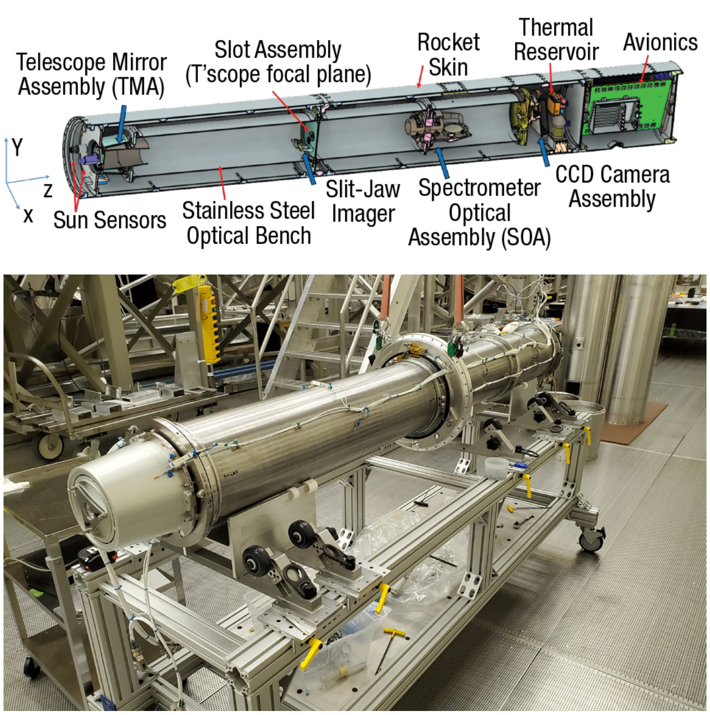


FIGURE 1. The MaGIXS optical design (top) and fabricated instrument (bottom).

APPROACH/INNOVATION

One of the most significant technological advancements required for MaGIXS was the production of nickel-replicated, high-resolution x-ray optics. The replicated optics fabricated at NASA Marshall Space Flight Center (MSFC) are electroformed around a mandrel. Previous optical modules had a spot size (half-power-diameter) of >20 arcsecs. The spatial resolution goal for MaGIXS was 6 arcsecs, implying a new method was needed. The MaGIXS mandrels served as a pathfinder for deterministic polishing specifically tailored to correct low-spatial frequency figure errors, leading to high-resolution grazing incidence mirror mandrels. The process utilizes a Zeeko Intelligent Robot Polisher (IRP) 600X computer numerical controlled (CNC) polishing machine and is deterministic due to its ability to provide precise control of polishing tools that are guided by a meteorological feedback cycle (Gubarev et al., 2016; Davis

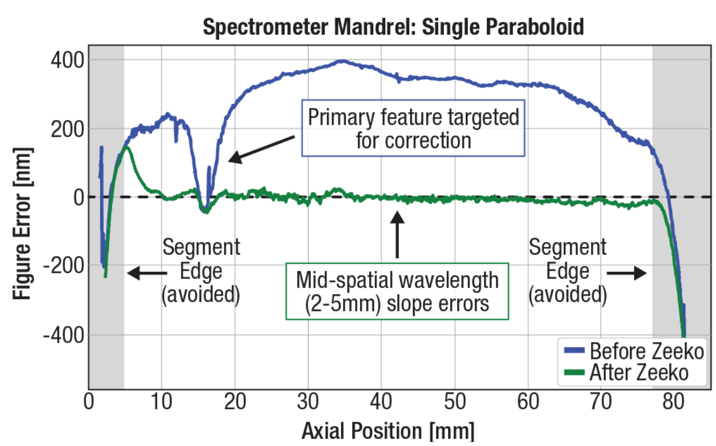


FIGURE 2. The figure error in a MaGIXS mandrel before (blue) and after (green) deterministic polishing.

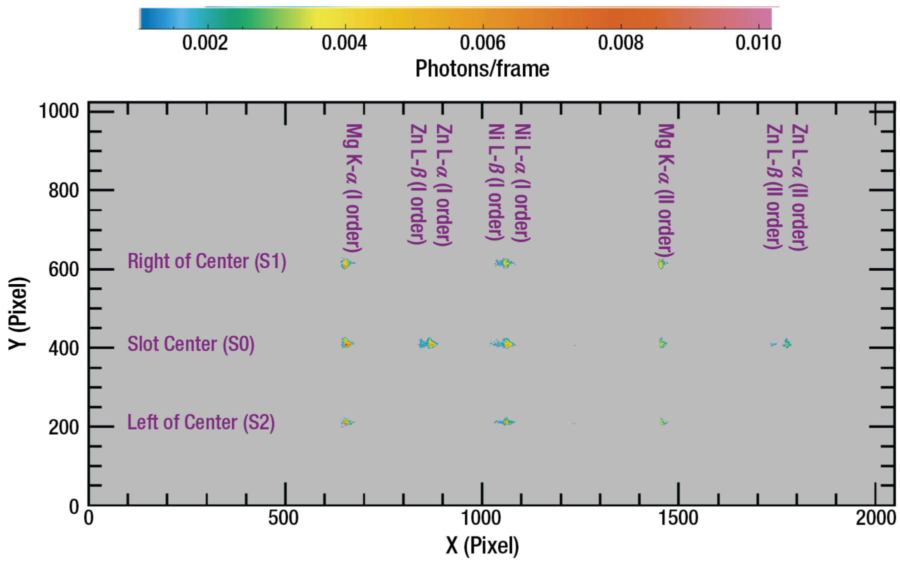


FIGURE 3. The MaGIXS calibration product (Athiray, et al., 2021, ApJ, 992, 65).

FIGURE 4. The MaGIXS launch team under the MaGIXS payload at White Sands Missile Range.

et al., 2019).[1,2] The process has demonstrated an ability to reduce low-frequency figure errors at spatial wavelengths >7 mm.

Fig. 2 shows the before and after residual figure error on a segment of one of the MaGIXS mandrels. The blue profile is the measurement taken before the deterministic polishing. The green profile is from a measurement taken after five polishing iterations with the Zeeko machine. Only the features between 10–115 mm in axial position were addressed. Axial slope errors (the sources of the larger spatial resolution) were reduced from >4 in to 0.72 in on this mandrel segment.

RESULTS/ACCOMPLISHMENTS

The MaGIXS mirrors were fabricated by MSFC and gratings were fabricated by the Smithsonian Center for Astrophysics (SAO). The mirrors and gratings were aligned at SAO. The two mirror modules were then aligned to each other at MSFC. An MSFC-built low-noise charge-coupled device camera was then installed. The MaGIXS instrument was calibrated, and its performance verified by testing in the MSFC X-Ray Cryogenic Facility. The calibration tests included measuring the emission lines from multiple targets. The calibration output (Fig. 3) demonstrated both the spot size and the dispersion of the instrument.

PARTNERSHIPS

The Smithsonian Astrophysics Observatory led the development and manufacture of the x-ray grating and the internal alignment of the optical system.

SUMMARY

MaGIXS was launched on July 30, 2021, at White Sands Missile Range (see Fig. 4). During the ~5 minutes of data, MaGIXS observed a partial active region and two x-ray bright points. The flight data have been used to validate the instrument response that was modeled and measured during on-ground calibration prior to flight. The technologies developed for MaGIXS are now being applied to a future satellite instrument.

References

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2. Gubarev, M. et al., "Development of a direct fabrication technique for full-shell x-ray optics," *Proc. SPIE* vol. 9905 (July 2016), https://doi.org/10.1117/12.2233666

Principal Investigator(s): Amy Winebarger; Ken Kobayashi
Partners: Smithsonian Astrophysics Observatory
Funding Organization(s): Bid and Proposal

Development of Complementary Metal-Oxide-Semiconductor (CMOS) Cameras for Sounding Rocket, CubeSat, and Satellite Missions

PROJECT OBJECTIVE: **NASA Marshall Space Flight Center (MSFC) is developing low-noise, rapid-cadence cameras for multiple instruments on various platforms.**

PROJECT GOAL/DESCRIPTION

Many spaceborne instruments operating across the visible, ultraviolet, and x-ray spectrum require low-noise, rapid-cadence cameras. Complementary metal-oxide-semiconductor (CMOS) chips can provide required data rates and noise characteristics and radiation hardened or radiation tolerant, science-grade detectors have recently become available from multiple manufacturers. New technologies were necessary to realize the high data rates from the camera.

APPROACH/INNOVATION

MSFC is developing a high cadence CMOS camera capable of acquiring data and completing onboard summing, data compression, and data storage. The high cadence and dynamic range requirements are met using the high frame rate CIS120 CMOS sensor from Teledyne e2v, which has an internal analog-to-digital converter and is capable of 20 frames per second readout speed at 12 bits/pixel resolution. Multiple buttable 4096 × 2048 versions of the CIS120 sensor can be included in each camera.

A proof-of-concept breadboard CMOS camera was developed at MSFC (Fig. 1). It consists of an off-the-shelf Xilinx Kintex field programmable gate array development board and a custom imaging board incorporates an engineering version of the CIS120 sensor, using parts with available radiation tolerant alternatives. Imaging at the required frame rate, on-camera summing, and data transfer have been demonstrated successfully. Science characterization of the sensor in a thermal chamber has also occurred; the measured gain and noise are similar to published results.

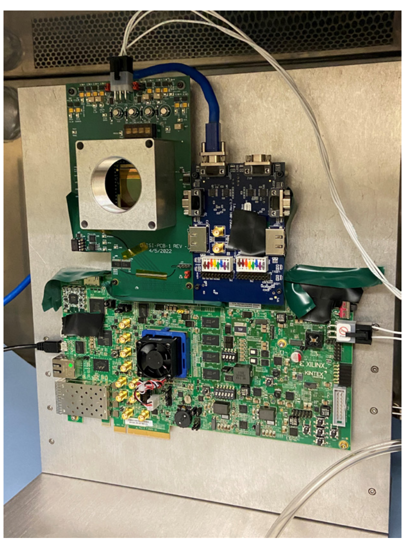


FIGURE 1. Proof-of-concept CMOS camera.

RESULTS/ACCOMPLISHMENTS

An Engineering Test Unit (ETU) is currently in development (Fig. 2), with expected Technology Readiness Level (TRL) 6 testing expected to occur in October 2024. The ETU will include the capabilities of onboard data compression and storage. The ETU will provide an ethernet connection to allow for data retrieval at a more moderate rate than images are acquired.

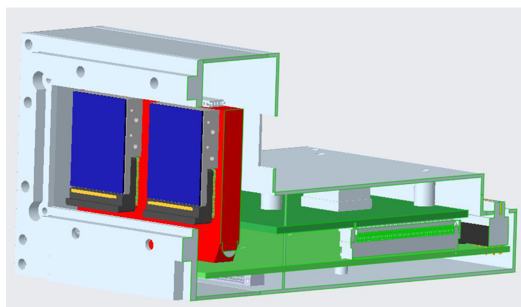


FIGURE 2. Computer aided design model of engineering test camera.

SUMMARY

MSFC has been developing charge-coupled device cameras for use on suborbital platforms for many years. We have recently started development of cameras around CMOS chips and have developed multiple new technologies to realize the large data volume that is associated with high cadence datasets. We expect this new camera to be TRL 6 by October 2024 and to be available for flight on multiple suborbital and orbital platforms.

Principal Investigator(s): Amy Winebarger
Funding Organization(s): Bid and Proposal

TECHNOLOGY AREA 10

AUTONOMOUS SYSTEMS

Advanced Internally Redundant Load Switching Power Distribution System

PROJECT OBJECTIVE: To develop an internally redundant power system prototype that has the capability to internally switch power channels to different loads of the similar type.

PROJECT GOAL/DESCRIPTION

The proposed prototype was intended to demonstrate a capability that could change the standard architecture for power systems in space applications. The prototype is designed to be capable of detecting power failures and automatically isolate various power faults. The prototype implements an internal load switching circuit that replaces the redundant power system architecture that is currently used. This system also has the potential to reduce power distribution system mass. NASA Marshall Space Flight Center key mission applications for this technology include Mars transportation vehicles, Mars surface bases, and outer planet science probes. These missions will require autonomous fault detection, diagnosis, and correction techniques.

APPROACH/INNOVATION

Current systems are designed with redundancy but little else to resolve faults. The Advanced Internally Redundant Load Switching Power Distribution System was designed from a fault management perspective that provides the flexibility to isolate and resolve the power system faults. The main capability of providing adaptable redundancy is scalable and can increase the power system's fault tolerance beyond one fault tolerance. This capability may also result in potential payload weight savings.

The system is also capable of source selection. Having source selection allows the system to select the power source for each load independently and balance the usage based on available supply. This could be used as a contingency in the event one of the sources is not able to supply nominal power. For example, if a solar panel is damaged in a way that reduces the overall panel output, the result may be the inability to keep the batteries at an acceptable state of charge. In that case, the load distribution can be distributed to offset the reduction in efficiency.

Future work includes continuing the prototype hardware and software integration, testing, and development. Currently, the software has only basic functionality and further iterations in testing and development are needed to bring the system to the fully planned capability. There are also plans to integrate more advanced hardware that was unable to be incorporated in fiscal year 2023 due to supply chain timeline issues.

RESULTS/ACCOMPLISHMENTS

During this effort, a Simulink model of the Advanced Internally Redundant Load Switching Power Distribution System was developed. The results of the system model were compared to the results of the concept hardware testing. This combination of Simulink model results along with the proof-of-concept hardware testing provided evidence to show that the circuit design functioned as expected and provided information was used to down select components for the prototype build. The prototype was designed, and parts procured for the build. Basic software was also developed for the hardware checkout and software/hardware integration testing.

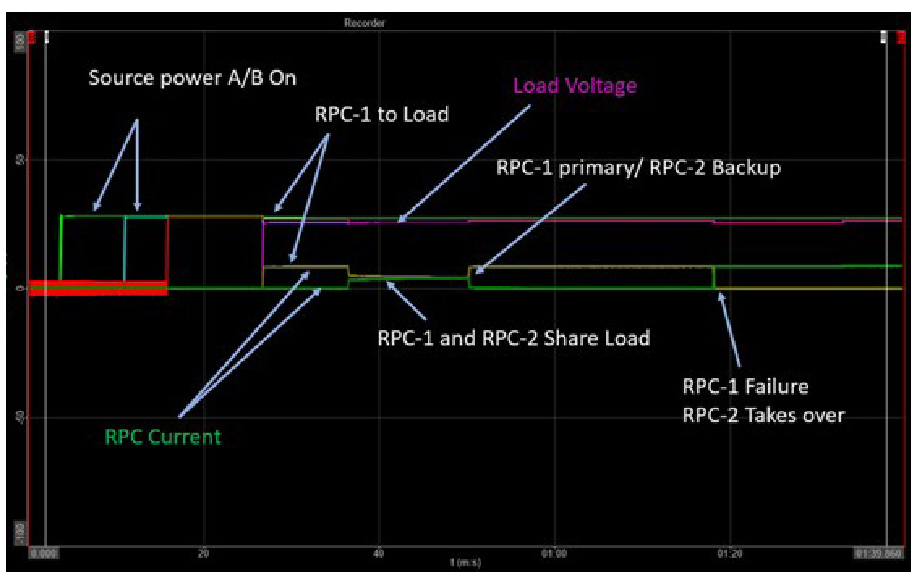


FIGURE 1. Proof-of-concept test results.

SUMMARY

During this effort we were able to demonstrate proof of concept supporting further development into a fully functional prototype. The prototype design was also completed and required parts ordered for the build. Basic software was also developed and ready to begin continuing development through integrated testing. The system shows promise in increased flexibility and adaptability in future designs. This activity has brought the Technology Readiness Level (TRL) for this system from a TRL 1 to a TRL 3. Further work completing the prototype and software integration will bring the system from a TRL 3 to a TRL 4.

Principal Investigator(s): Benjamin Stolz; Douglas Bearden; Peter Berg
Funding Organization(s): Center Innovation Fund
NTR/Patent Number: 1661455597

TECHNOLOGY AREA 11

SOFTWARE, MODELING, SIMULATION, AND INFORMATION PROCESSING

A New Agnostic Criterion for Solidification Cracking Indexing of Metallic Alloys

PROJECT OBJECTIVE: Develop an agnostic, robust, and easy to use solidification cracking index based only on chemical composition, offering a valuable tool for assessing solidification cracking susceptibility in a wide range of metallic alloys.

PROJECT GOAL/DESCRIPTION

Solidification cracking is a form of intergranular cracking, which involves liquid and which occurs within the mushy (partially solidified) zone. It plagues manufacturing processes that involve material melting and solidification, like casting, welding, and additive manufacturing (AM), seriously compromising performance and even hindering materials processing and service. Computational materials engineering and AM technologies are revolutionizing the way we conceive, develop, and deploy new alloys. Today the cycle for new materials development to deployment is accomplished in a fraction of the time and at significantly reduced costs compared to traditional trial-and-error methods. Central to this accelerated and much more efficient materials development cycle, the need to properly predict the impact of material chemistry on manufacturability and subsequently performance, such as susceptibility to solidification cracking has become a pressing necessity. Nevertheless, in the rapidly evolving field of alloy development, a need exists for a straightforward, swift, yet highly accurate method to predict solidification cracking susceptibility. Covered by a Cooperative Agreement Notice with The Ohio State University (OSU), NASA Marshall Space Flight Center (MSFC) and OSU have further improved and developed a fast acting and simple to use tool to evaluate solidification cracking susceptibility based on the flow resistance index (FRI) formerly proposed by OSU.[1]

APPROACH/INNOVATION

This work presents an innovative, easy to use graphical user interface (GUI) that implements the FRI calculation, which allows the user to predict metallic alloys solidification cracking susceptibility based only on the material chemical composition. This tool has enabled OSU and NASA teams to expedite and to lower risk in their efforts on new alloys development, and it will enable many other groups to take advantage of this innovation. The presented technique links computational thermodynamic and fluid dynamics concepts, based on the solid/liquid interface[2] and the interdendritic fluid pressure drop concept.[1] This combination yields a robust solidification cracking index solely based on chemical composition. Using CALPHAD-based software to calculate the a simplified representation of solidifying microstructure, approximated by temperature vs. the square root of the fraction of solid ($\sqrt{f_s}$). Subsequently, fluid dynamics is used to address the flow of the liquid alloy through the material solidification structure, which enables us to calculate the unique FRI index for the

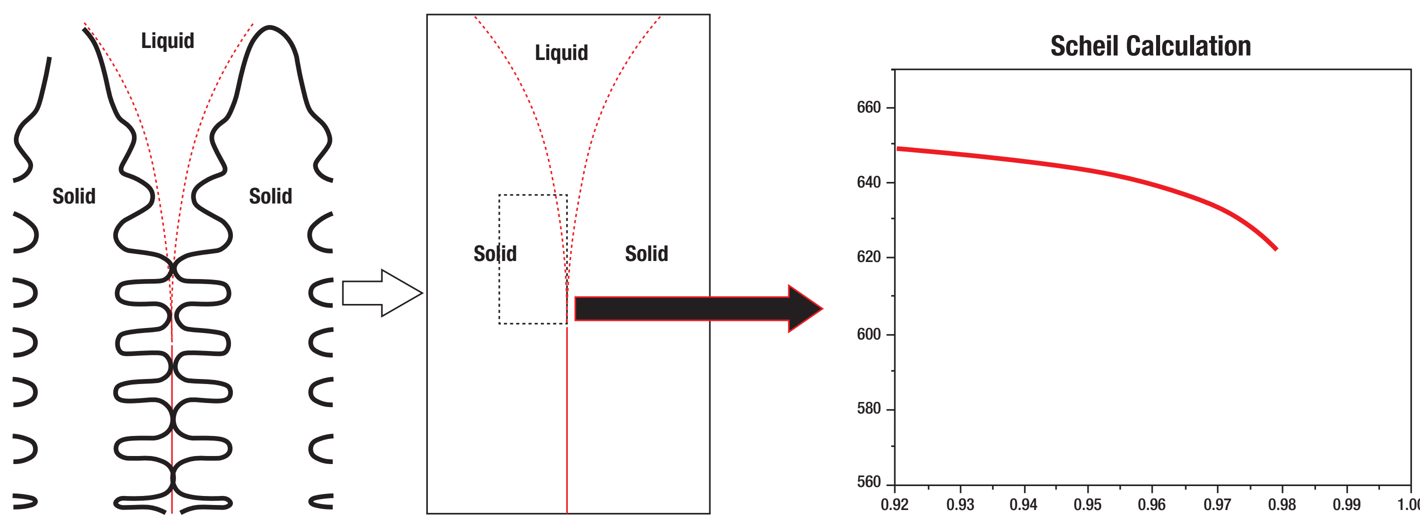


FIGURE 1. Scheil calculation, dendrite profile, and fluid dynamics concept.

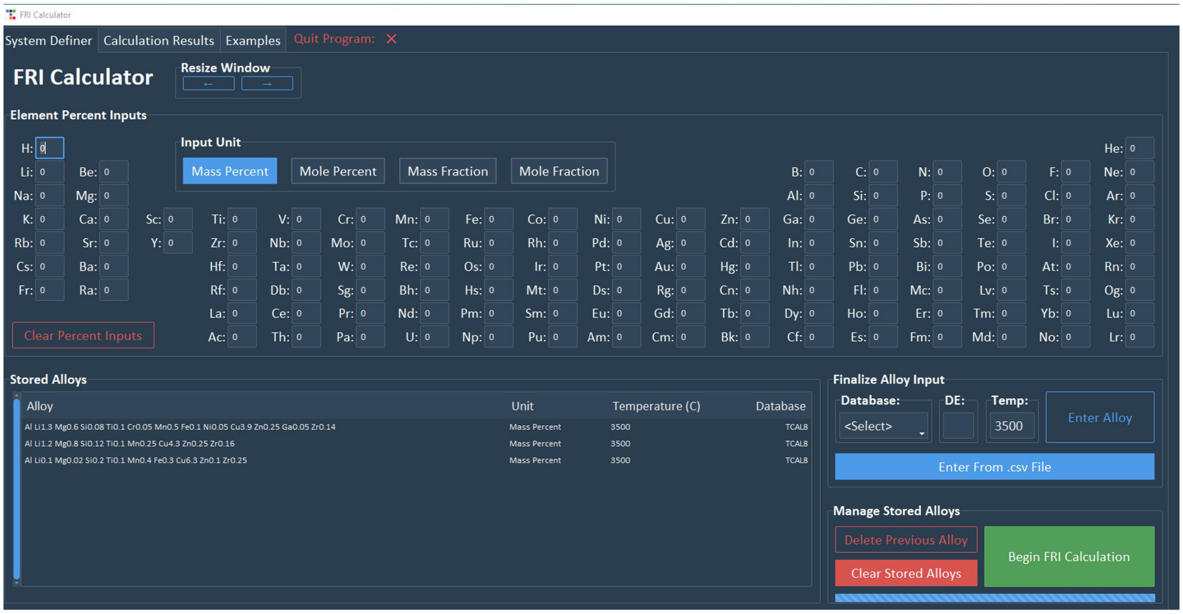


FIGURE 2. GUI for solidification cracking alloy indexing, developed using TC-Python.

material of interest.interference in the s-parameter signals is expected to be proportional to the amount, area, and depth of corrosion spots on the cables. This proportional relationship implies that higher levels of interference would indicate greater corrosion, and vice versa. By analyzing these signals, we can discern information about the extent of corrosion on the cables, providing a nondestructive method of representing corrosion status in the cables. However, the primary challenge lies in the complexity involved in extracting precise corrosion data from the s-parameter signals as it requires sophisticated data analysis and interpretation techniques to distill meaningful information about the corrosion.

This project unfolds in three primary stages: (1) Verification of the methodology performance based on available literature and NASA's solidification cracking data; (2) quantification of the FRI index prediction using experimental solidification cracking susceptibility testing (i.e., Transvarestraint testing); and (3) development of a user-friendly GUI using Python software.

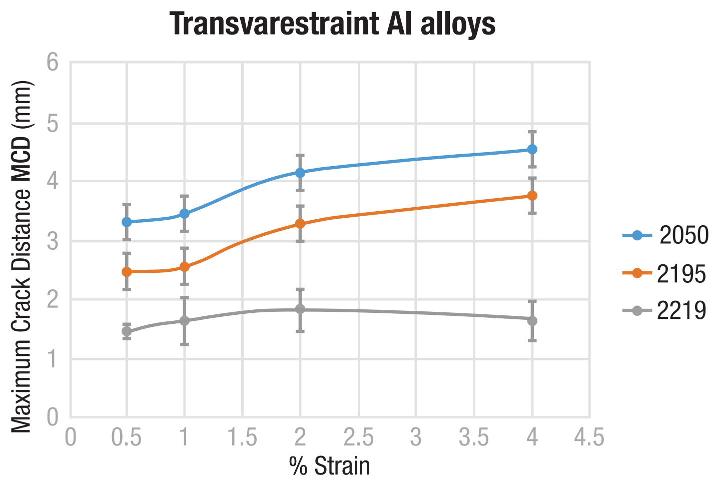
RESULTS/ACCOMPLISHMENTS

The outcome of this project is a user-friendly Python-based GUI which alloys the assessment of solidification cracking susceptibility of a metallic alloy. This tool has the potential to significantly impact and simplify the alloys design and development process. Utilizing ThermoCalc (TC)-Python, the calculation of FRI is automated; thus requiring less manual input and decreasing the likelihood of errors, ultimately saving time.

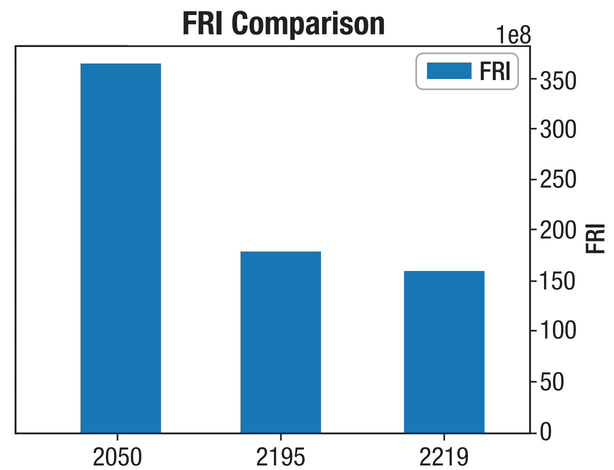
The NASA-OSU research team conducted a comprehensive FRI index verification, which included aluminum (Al) and nickel alloys, steels, and refractory alloys, using existing literature data. Experimental verification verification of the predicted FRI index was also carried out using Transvarestraint testing. Fig. 3A illustrates the relationship between maximum crack distance (MCD) and % of strain for Al alloys AA2050, AA2195, and AA2219. The calculated FRI index aligns vey well with the solidification cracking testing results, which is presented as the GUI calculation result (see Fig. 3B). Fig. 3C provides a top-view perspective of the used Transvarestraint test, where MCD is measured perpendicular to the solid-liquid interface. Fig. 3D shows a bent sample after Transvarestraint test.

PARTNERSHIPS

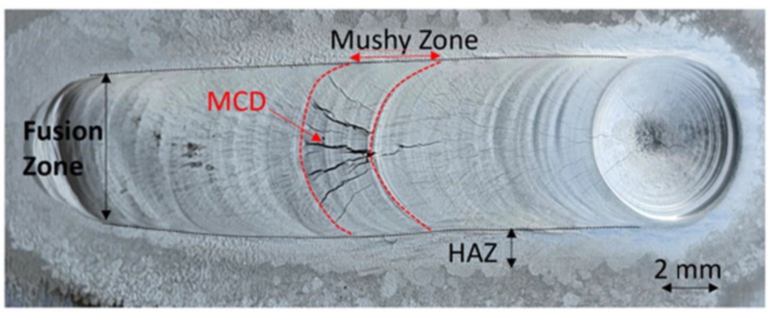
OSU is the primary collaborator for the work outlined in this report. Dr. Antonio J. Ramirez, Professor of Welding Engineering Program, and Henry Leon-Henao, Ph.D. student of Welding Engineering Program, are the primary collaborators at OSU.



A. Maximum Crack Distance (mm) results



B. Flow Resistance Index results



C. Top view of Transvarestraint sample

D. Bent sample

FIGURE 3. Transvarestraint testing for model verification using aluminum alloys.

SUMMARY

This GUI can be relevant to scientists, engineers, and technicians engaged in the development and deployment of current and new alloys for all industrial fields, including aerospace. The findings indicate that experimental solidification cracking test results are in excellent concordance with those of the FRI, highlighting their comparable performance in assessing solidification cracking susceptibility.

Principal Investigator(s): Antonio J. Ramirez
Partners: The Ohio State University
Funding Organization(s): Cooperative Agreement Notice

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Short-Term Prediction Research and Transition (SPoRT) Center

PROJECT OBJECTIVE: Transition unique NASA Earth Science satellite observations and research capabilities to improve short-term weather forecasting and societal applications.

PROJECT GOAL/DESCRIPTION

The Short-term Prediction Research and Transition (SPoRT) center at NASA Marshall Space Flight Center in Huntsville, AL is a NASA-funded activity with a vision of accelerating the translation of NASA science to applications by collaborating with researchers, innovators, and stakeholders. SPoRT was established in 2002 and is funded under the NASA Earth Science Division Research and Analysis Program's Weather and Atmospheric Dynamics Focus Area. Therefore, SPoRT's early focus was on transitioning NASA products to the operational weather community to improve short-term forecasting with end users within the National Oceanic and Atmospheric Administration's National Weather Service. Today, SPoRT focuses on applied research and applications in six focus areas that span weather, atmospheric, and land surface topics: Synoptic and Mesoscale Processes, Tropical Systems, Lightning and Convection, Land Surface Processes, Hydrology, and Air Quality. With partnerships across government, academia, and the private sector, SPoRT's "research-to-operations/operations-to-research" (R2O/O2R) paradigm has been the basis for transitioning over 40 satellite products to stakeholders over 20 years.

Over the past several years, SPoRT has been broadening its reach and has begun to apply its known R2O/O2R paradigm to partners that can benefit from the integration of unique NASA Earth Science satellite observations and research capabilities into their operations, applications, and decision making. For example, SPoRT has seen an expansion of data products that support new collaborating partners and stakeholders across additional federal and state government agencies, such as the US Forest Service, US Department of Agriculture, US Geological Survey, US Air Force, US Drought Monitor, National Ocean Service, US Environmental Protection Agency, CAL Fire, and the Alaska Interagency Coordination Center. SPoRT also partners with other NASA programs such as the NASA Disasters program, Applied Remote Sensing Training program, and SERVIR to further the use and benefit of NASA data for applications. Additionally, SPoRT engages with the community to foster relationships and innovation between science and applications of future missions and mission concepts. Therefore, SPoRT applies and utilizes its R2O/O2R paradigm to support the current suite of NASA Earth Science satellites, to lead new mission Applications Programs, and to inform future missions in formulation related to the Earth System Observatory.

APPROACH/INNOVATION

The SPoRT R2O/O2R paradigm (Fig. 1), with focused end user interaction, has been the basis for successfully translating NASA Earth Science to applications and transitioning over 40 satellite products to stakeholders over 20 years. SPoRT's approach involves collaborative interaction with end users and scientists to transition research data and capabilities to meet stakeholders' needs and to

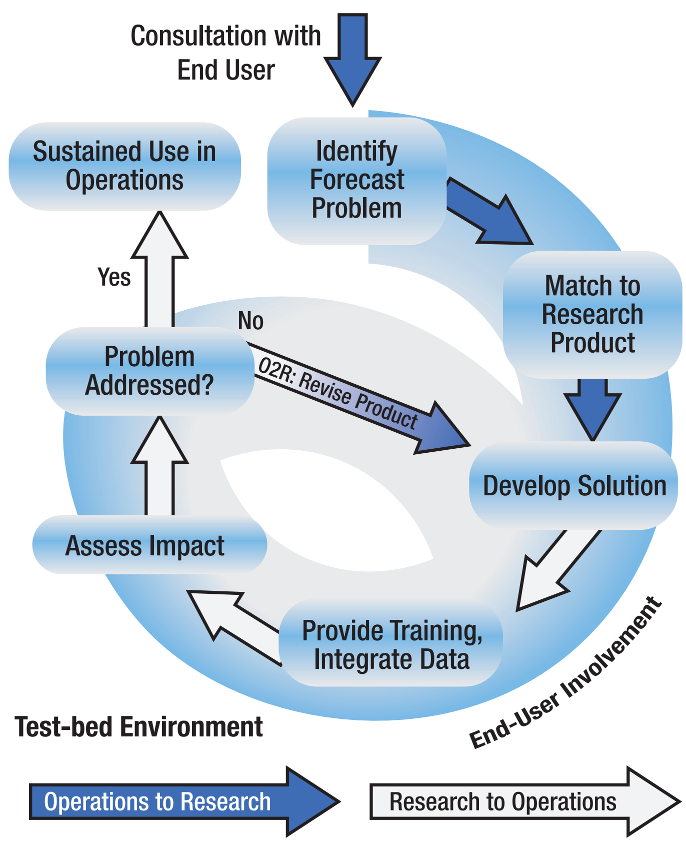


FIGURE 1. The SPoRT R2O/O2R paradigm.

promote sustained use of NASA data. The main goals of the SPoRT paradigm include: (1) early and intentional interaction with stakeholders; (2) identifying and/or developing user-driven science solutions from NASA observations and research capabilities; (3) timely delivery of data products for early stakeholder testing and feedback; (4) integration of data products and capabilities in user-friendly formats, visualizations, and display systems; (5) targeted applications-based training highlighting use cases, examples, product advantages and limitations; (6) stakeholder assessments and product testing; and (7) prioritizing stakeholder or O2R feedback to tailor capabilities to meet users' needs. The SPoRT paradigm enables intentional interaction between scientists and stakeholders throughout the entire R2O/O2R lifecycle to develop innovative solutions through an iterative process that meets stakeholder needs, are tailored for their application, and promotes sustained use of NASA observations and research capabilities. SPoRT values innovation, collaboration, and engagement to bridge the gap between science and applications and maximize the benefit of NASA Earth Science data for operations, applications, and decision making.

RESULTS/ACCOMPLISHMENTS

Building and maintaining interaction with stakeholders is fundamental to SPoRT's objective in transitioning research to stakeholders to support decision making. This year, SPoRT started a Stakeholder Summit and Seminar Series with the goal of engaging current stakeholders in the R2O/O2R process, accelerating the translation of science to applications, and recruiting new collaborative partners. The first SPoRT Stakeholder Summit highlighted an overview of SPoRT and updates from each thematic area, while subsequent Stakeholder Summits focused on one or two topics

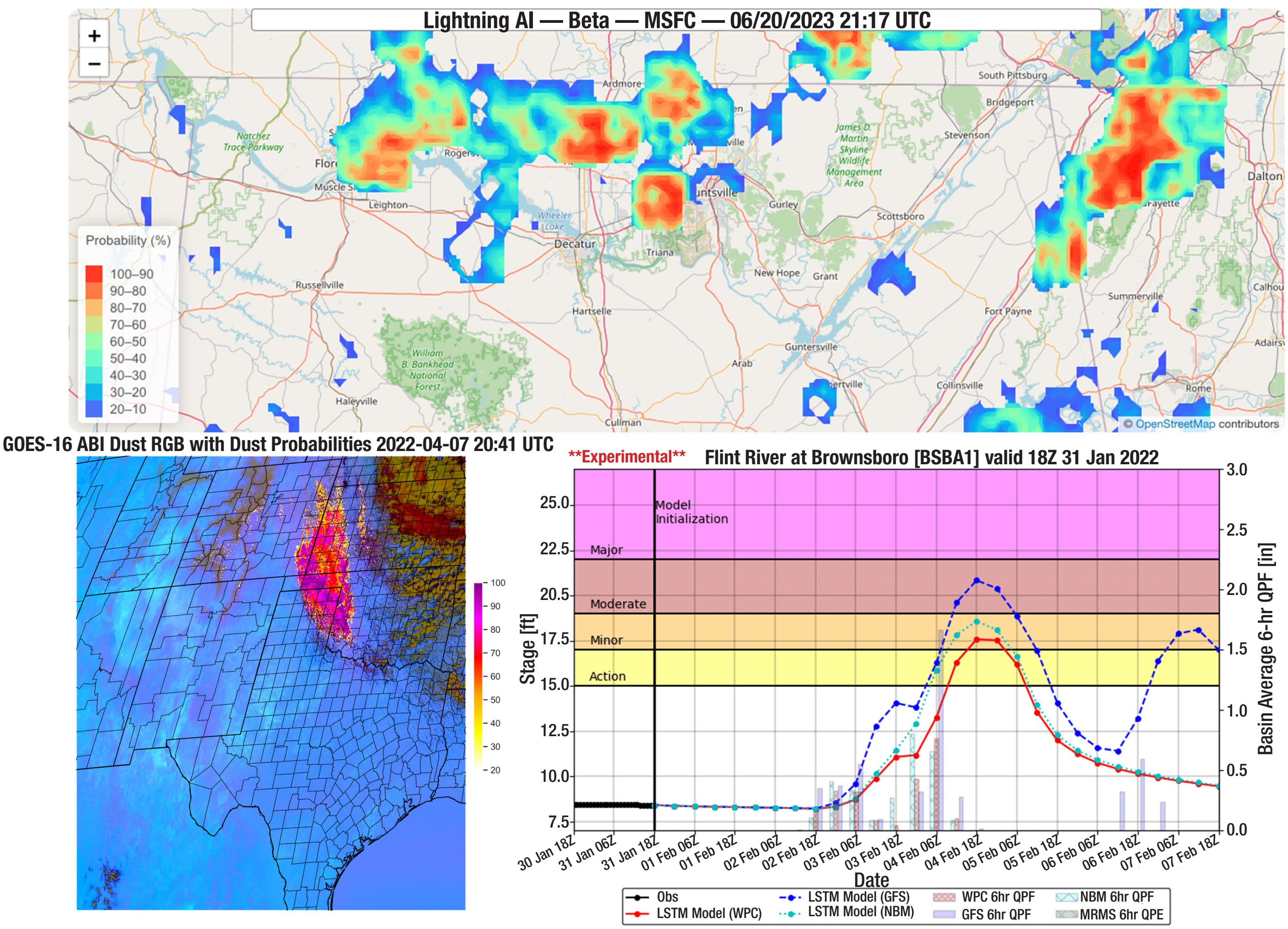


FIGURE 2. Machine learning/AI products developed by SPoRT: Lightning-AI (top), DustTracker-AI (bottom left), and Streamflow-AI (bottom right).

and smaller communities of end users to facilitate interaction and dialogue.

This year SPoRT continued to development on three artificial intelligence (AI) products, the DustTracker-AI, Lightning-AI, and Streamflow-AI. DustTracker-AI continues to be used by the operational weather community to monitor duststorms and issue public warnings. This year, Lightning-AI was officially deployed in real-time and has already been used by stakeholders and NASA field campaigns to make decisions to stop activities due to lightning threat. The Streamflow-AI adds value to river flooding decision support and continues to be expanded to cover additional areas of the United States and draw new stakeholders from operational weather and river forecasting centers.

PARTNERSHIPS

The SPoRT team consists of a diverse group of scientists from The University of Alabama in Huntsville Earth System Science Center, Jacobs Space Exploration Group, and ENSCO, Inc.

SUMMARY

SPoRT is an end-to-end program designed to accelerate the transition of NASA Earth Science research capabilities to applications through intentional interaction with stakeholders. While SPoRT was established in 2002 with a focus on transitioning NASA products and capabilities to the operational weather community, SPoRT has grown capabilities and partnerships that span government agencies, universities, and the private sector. With six thematic research areas, SPoRT develops and provides unique products to partners who need weather, air quality, and land surface information to make decisions that impact society. SPoRT pioneered a R2O/O2R paradigm that involves interaction with stakeholders throughout the R2O/O2R life cycle to develop products and capabilities that meet user needs and promote sustained use of NASA data for operations, applications, and decision making.

Principal Investigator(s): Emily Berndt
Partners: The University of Alabama in Huntsville Earth System Science Center; Jacobs Space Exploration Group; ENSCO, Inc.
Funding Organization(s): Science Mission Directorate–Earth Science Division Research and Analysis Program
For more information: https://weather.ndc.nasa.gov/sport/

Science Discovery Engine (SDE) to Enable Open Science

PROJECT OBJECTIVE: Provide a unified search and discovery capability for NASA's Science Mission Directorate (SMD) data and information.

PROJECT GOAL/DESCRIPTION

NASA's SMD is building an open-source science infrastructure to enable open, collaborative, and interdisciplinary science. One key component of the open-source science infrastructure is the Science Discovery Engine (SDE). The SDE project is building an integrated SMD search capability to enable discovery of open data and information across SMD's five divisions, including Astrophysics, Biological and Physical Sciences, Earth Science, Heliophysics, and Planetary Science. Currently, NASA's science data is dispersed across 50 domain-specific repositories or may be found on a number of mission-specific websites. An integrated search capability will reduce the time needed to discover SMD data and will accelerate the time to actionable science.

APPROACH/INNOVATION

The SDE is implemented in Sinequa, an intelligent search capability. The SDE team partnered with the NASA Enterprise Data Platform team and Sinequa engineers to create the initial implementation. Sinequa uses connectors to index content from multiple sources including both unstructured content (word processor files) and structured content (metadata). The ability to index both structured and unstructured content allows the SDE to meet the goal of enabling discovery of both data and contextual information such as software, code, tutorials, and documentation. The SDE team has built and deployed custom entity extraction methodologies in Sinequa to provide the semantic context needed for the five SMD divisions. The SDE team has also built a web application called the SDE Indexing Helper to simplify and optimize the data curation process.

RESULTS/ACCOMPLISHMENTS

Initial development of the SDE was completed in Sinequa in September 2022 and was unveiled to attendees at the American Geophysical Union (AGU) 2022 fall meeting in December 2022. The initial version of the SDE includes data and information from all five of the SMD divisions (Astrophysics, Biological and Physical Sciences, Earth Science, Heliophysics, and Planetary Science). Users can

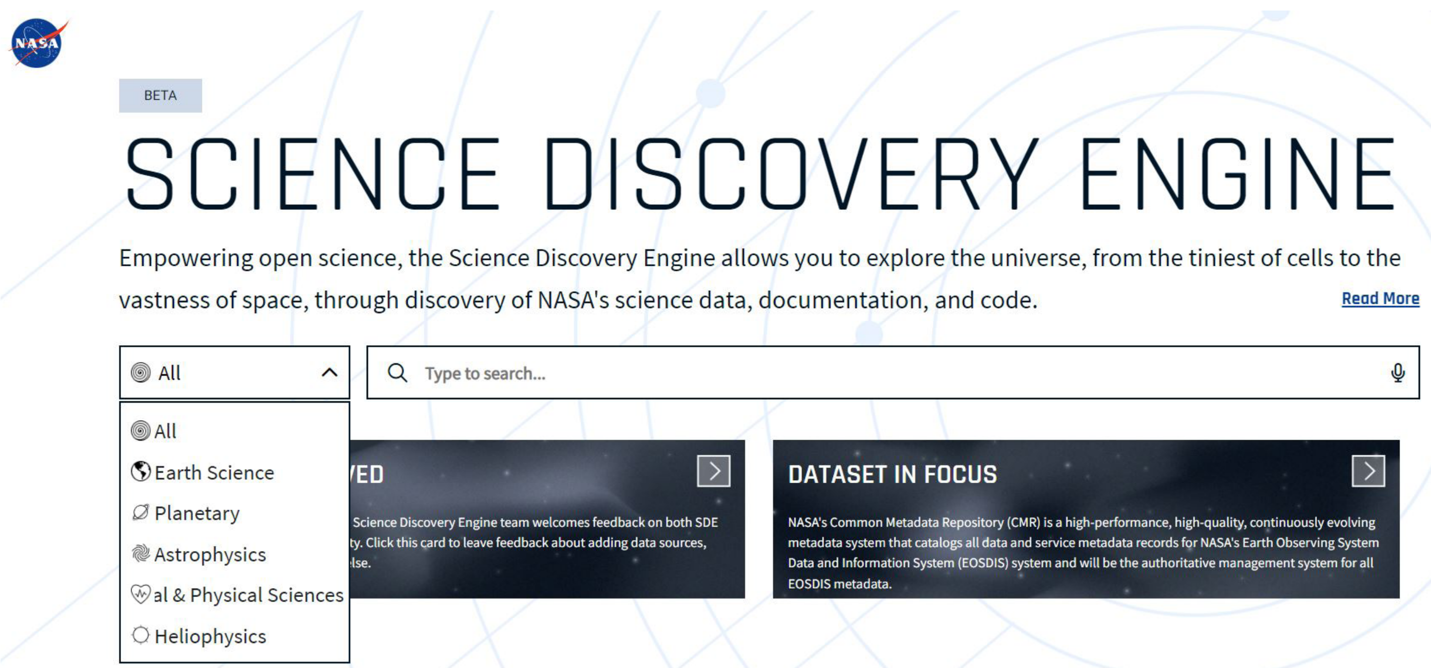


FIGURE 1. SDE Landing Page.

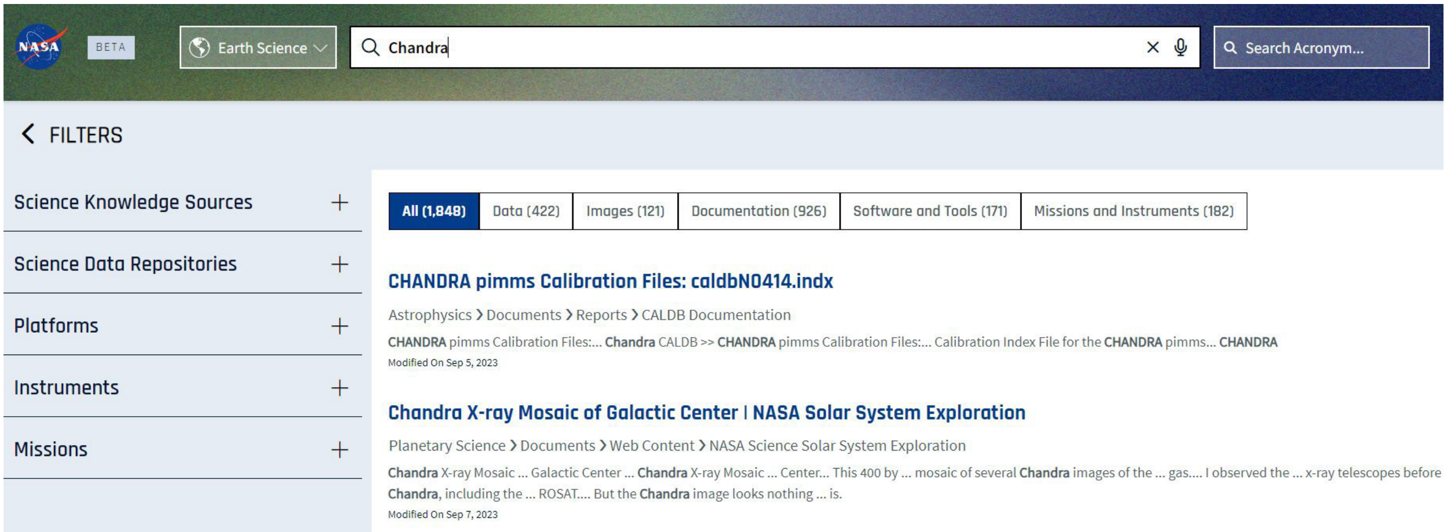


FIGURE 2. The SDE Search Interface.

perform free-text searches and apply text-based facets to refine results based on SMD topical area, data repository, source name, and document type. To support discovery within the SDE, an SMD vocabulary extraction workflow was developed. This workflow leveraged over 50 glossaries, thesauri, and keywords across the SMD to generate term lists such as platforms, instruments, and missions. The first iteration of the term lists has been integrated as facets into the SDE to enable guided discovery for users.

The SDE team has continued to work with Sinequa, an intelligent search platform developer, and Left Right Mind, a digital design consulting firm, to refine both the back- and front-end features of the SDE. In the future, the team aims to integrate additional natural language processing techniques to fine-tune the scope and specificity of user search results.

PARTNERSHIPS

SDE has partnerships with The University of Alabama in Huntsville, Development Seed, Left Right Mind, NASA's Information, Data, and Analytics Services (IDAS) team, and Sinequa.

SUMMARY

The SDE enables the seamless discovery of open data and information across NASA'S five SMD divisions by providing a consolidated search interface for scientists, decision-makers and the broader public.

Principal Investigator(s): Kaylin Bugbee
Partners: The University of Alabama in Huntsville; Development Seed; Left Right Mind; NASA's Information, Data, and Analytics Services (IDAS) team; Sinequa
Funding Organization(s): Science Mission Directorate
For more information: https://science.data.nasa.gov/science-discovery-engine/

Visualization, Exploration, and Data Analysis (VEDA)

PROJECT OBJECTIVE: Empowering scientific exploration and discovery with dynamic visualization, collaborative compute environment, and seamless data sharing using a redeploying software infrastructure.

PROJECT GOAL/DESCRIPTION

Visualization, Exploration, and Data Analysis (VEDA) is an open innovative platform empowering researchers to explore and analyze Earth science data in the cloud. By combining interactive storytelling with open science principles, VEDA enables researchers to engage new audiences and share their analysis results effectively. VEDA significantly reduces barriers to accessing Earth science data and computational resources needed for exploring and processing the petabyte-scale Earth data archives in the cloud. VEDA's achievement exemplifies the core principles of NASA's Open-Source Science Initiative, showcasing commitment to promoting transparent, accessible, and collaborative scientific research.

APPROACH/INNOVATION

VEDA is designed to be an open-source modular suite of data services supporting exploration and analysis of geospatial data in a lightweight visualization dashboard. The data services enable scientists and their teams to perform research with collaborative compute environments and interactively communicate the importance of their work in a way that is engaging and consumable by a general audience. Development of the data services aligns with community standards to facilitate interoperability with similar cloud-based platforms and NASA's Enterprise Geographic Information Systems. The modular design of the VEDA platform allows for the various components to be reused in part or in whole to serve additional geospatial applications. Adhering to standards and emphasizing reusability are fundamental principles of VEDA. Not only do they ensure reproducibility, but they also foster an open community around the VEDA, broadening the range of contributors to the platform's capabilities.

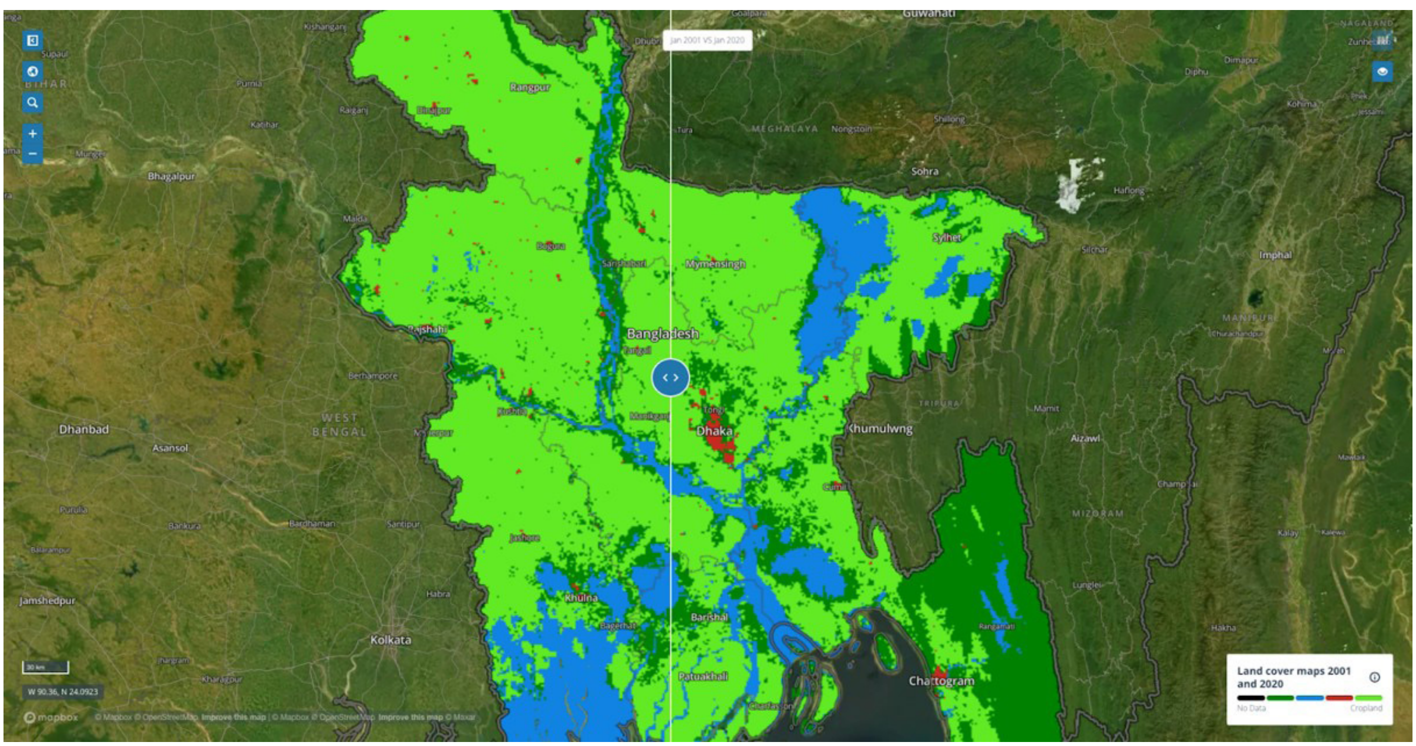


FIGURE 1. Comparison slider for land cover in Bangladesh visualized in the VEDA dashboard.

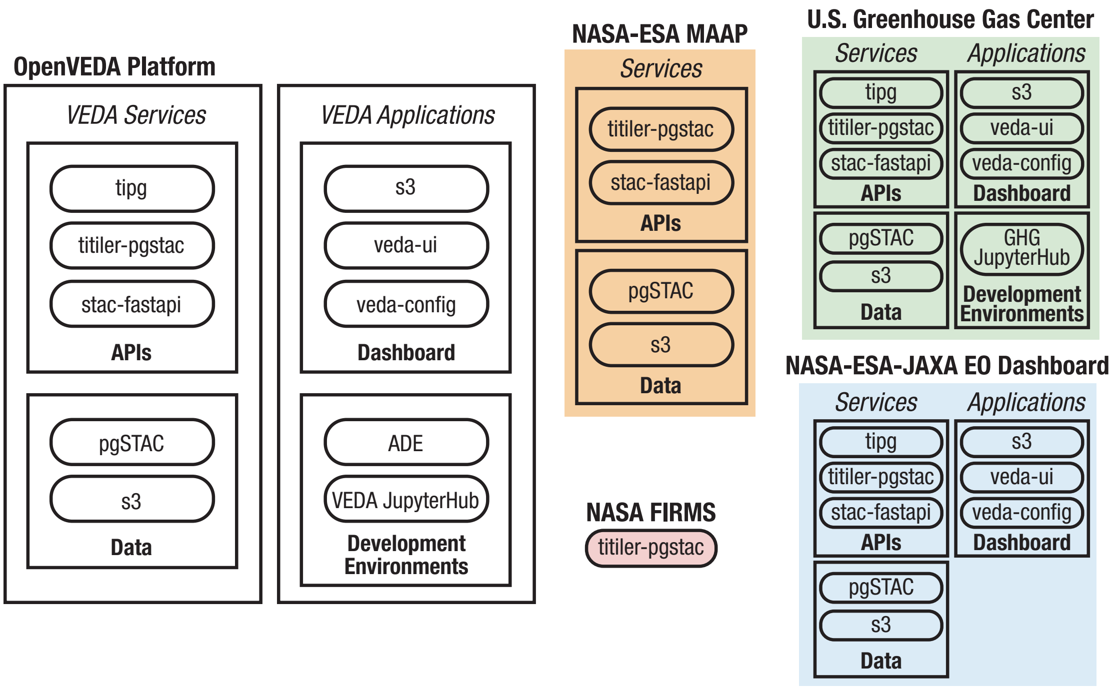


FIGURE 2. VEDA data services components.

RESULTS/ACCOMPLISHMENTS

Reusing the core components of VEDA, a prototype of the new U.S. Greenhouse Gas (GHG) Center data and information system was developed by IMPACT and released on October 2, 2023. The U.S. GHG Center is a collaborative initiative among multiple agencies to consolidate greenhouse gas information and data from observations and models into a single, open platform. This platform offers credible and quality-checked greenhouse gas emissions products for decision-making, aiming to speed up the delivery of reliable GHG information, which includes a curated set of GHG datasets, workflows, and visualizations. VEDA data services have been reused to support the joint NASA-European Space Agency multi-mission algorithm and analysis platform to more efficiently serve data to the biomass research community. The dynamic visualization service developed within VEDA has been reused tby the joint NASA-U.S. Forest Service Fire Information Resource Management System to visualize NASA's Harmonized Landsat Sentinel-2 (HLS) data in order to support wildfire response.

PARTNERSHIPS

The partners for VEDA are Development Seed, Element 84, The University of Alabama in Huntsville, Georgia Institute of Technology, International Interactive Computing Collaboration (2i2c), Earth Science Data and Information System (ESDIS) Project, NASA Science Managed Cloud Environment (SMCE), and NASA Mission Cloud Platform (MCP).

SUMMARY

VEDA is an open-source platform designed to facilitate exploration and analysis of geospatial data through interactive visualizations and data stories. The platform includes a collaborative compute environment collocated with NASA's Earth science data in the cloud to ease the transition for the science community to the commercial cloud. The modular design of the VEDA allows for reuse of the platform in part or in whole, which has been demonstrated in several NASA applications, including the U.S. GHG Center data and information system.

Principal Investigator(s): Dr. Manil Maskey
Partners: Development Seed; Element 84; The University of Alabama in Huntsville; Georgia Institute of Technology; International Interactive Computing Collaboration; Earth Science Data and Information System Project; NASA Science Managed Cloud Environment; and NASA Mission Cloud Platform
Funding Organization(s): Science Mission Directorate
For more information: https://www.earthdata.nasa.gov/dashboard/

Foundational Artificial Intelligence Geospatial Models

PROJECT OBJECTIVE: Exploring artificial intelligence (AI) technology, specifically Foundation Models (FMs), to extract insights and knowledge.

PROJECT GOAL/DESCRIPTION

Artificial intelligence FMs represent a significant shift in the AI paradigm. Contrary to conventional task-specific machine learning (ML) models that serve singular purposes, FMs are designed and built to span a myriad of downstream applications. These models harness the potential of self-supervised learning methodologies, enabling them to be structured atop diverse sequence data types. One of the inherent strengths of self-supervised learning is its ability to obviate the necessity for voluminous annotated datasets during the training phase. Implementing and operationalizing applications using FMs considerably reduces the time and resources that would otherwise be expended in creating models from the foundational level. This project is exploring the design, building, and evaluation of AI FMs for NASA science data to accelerate the development of downstream applications and to broaden its use.

APPROACH/INNOVATION

In January 2023, a formal partnership between NASA and IBM Research was established via a Space Act Agreement. In collaboration with Clark University's Center for Geospatial Analytics, the European Space Agency (ESA), United States Geological Survey (USGS), and Oak Ridge National Laboratory (ORNL), IBM and NASA Interagency Implementation and Advanced Concepts Team (IMPACT) developers constructed a cloud-based FM using IBM's watsonx FM stack and Cloud Vela supercomputer. To tailor the model for Earth observation analysis, NASA's Harmonized Landsat and Sentinel-2 (HLS) imagery was selected as the data to pretrain this FM. Several different domain-specific applications were identified and utilized for model validation.

RESULTS/ACCOMPLISHMENTS

In May 2023, NASA and IBM Research announced the successful production of the first geospatial FM specifically trained with NASA's Earth observation satellite imagery. The model was trained on NASA's Harmonized Landsat Sentinel-2 (HLS) dataset, which provides surface reflectance data from NASA, USGS and European Union satellites. This model, named the HLS Geospatial Foundation Model, empowers numerous potential Earth science research pursuits, such as monitoring floods caused by natural disasters and mapping burn scars from forest fires. The model was released to the public on August 3, 2023 via Hugging Face, a data science platform that enables machine learning developers to openly build, train, deploy, and share models. The HLS Geospatial FM pipelines are called Prithvi on Hugging Face and are based on a Masked Auto Encoder with a Vision Transformer backbone, which is adapted to satellite data by extending the spatial attention to capture the temporal dimension. The model was fine-tuned on labeled data for flood and burn scar mapping and demonstrated 15% improvement over the current state of the art using 50% lesser labeled data. The release marks a major achievement in applying state-of-the-art AI approaches to Earth science

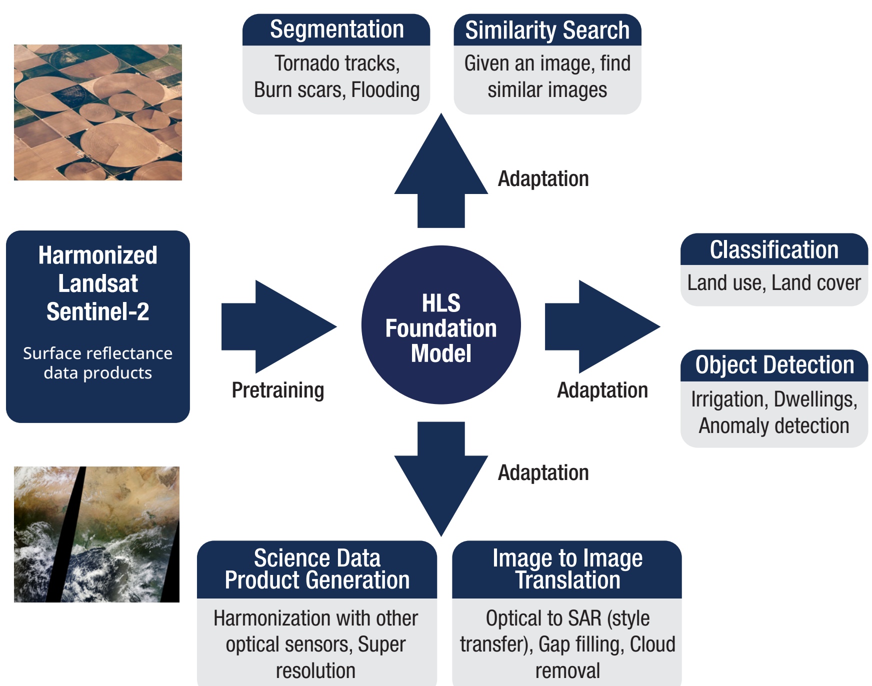


FIGURE 1. Representation of the HLS Geospatial FM's adaptability to multiple scientific use cases.

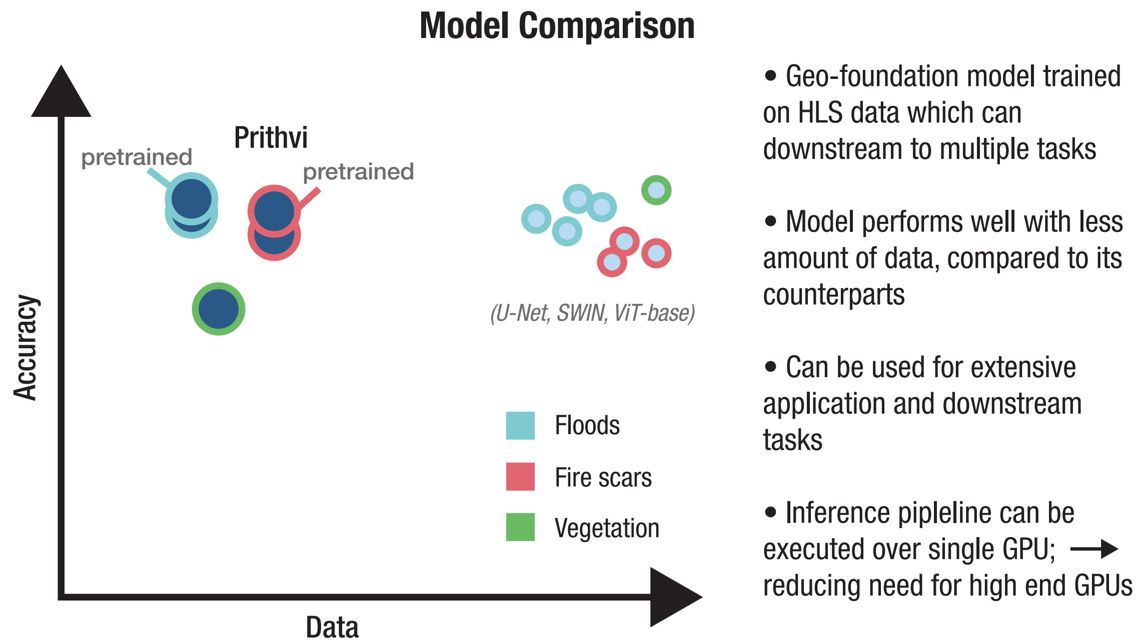


FIGURE 2. HLS Geospatial FM (Prithvi) comparison to other models trained on specific downstream tasks.

research and highlights IMPACT's role in fostering the development and adoption of these emerging technologies.

PARTNERSHIPS

A formal partnership between NASA and IBM Research was established via a Space Act Agreement. IMPACT and IBM developers also collaborated with Clark University's Center for Geospatial Analytics, the ESA, USGS, and ORNL. IMPACT is based out of The University of Alabama in Huntsville's Lab for Applied Science.

SUMMARY

Foundation models are AI models pretrained on comprehensive datasets using self supervised learning and can be used for many different downstream tasks. Along with the work accomplished on the HLS Geospatial FM, NASA and IBM are developing other applications to extract insights from Earth observations, including a large language model based scientific literature from each of the five NASA Science Mission Directorates.

Principal Investigator(s): Dr. Rahul Ramachandran
Partners: The University of Alabama in Huntsville; Clark University Center for Geospatial Analytics; the European Space Agency; United States Geological Survey; and Oak Ridge National Laboratory
Funding Organization(s): Science Mission Directorate
For more information: https://huggingface.co/ibm-nasa-geospatial

The Satellite Needs Working Group (SNWG): Assessment of SNWG Agency Needs

PROJECT OBJECTIVE: The Satellite Needs Working Group (SNWG) provides services that address Earth-observing needs of Federal agencies; the SNWG Management Office (MO) at NASA Marshall Space Flight Center (MSFC) manages all phases of the SNWG lifecycle including a tri-agency assessment of Federal agency satellite data needs.

PROJECT GOAL/DESCRIPTION

Every two years, the SNWG administers a survey to assess the Earth-observation measurement and data product needs of over 25 Federal civilian agencies. The survey responses are assessed by NASA, National Oceanic and Atmospheric Administration (NOAA), and U.S. Geological Survey (USGS) to identify agency needs, potential data gaps in the current NASA program of record, and relevant datasets. Through a careful review process, responses to these surveys become the inspiration for new NASA projects, instruments, and campaigns that provide novel Earth science data.

APPROACH/INNOVATION

At the conclusion of NASA's assessment of Federal agency satellite data needs, each agency that submitted a survey will receive an assessment report containing analysis of their satellite need and a list of resources that help meet the need—including current and upcoming satellite missions, specific data products, training resources, and newly proposed activities. To streamline the process of organizing the information gathered through these interviews, a team of researchers and developers from the Inter-agency Implementation and Advanced Concepts Team (IMPACT) and Development Seed created the Report Generation Tool (RGT).

RGT provides an interface for SNWG assessment teams to collaboratively curate standardized reports. RGT provides access to databases with pre-curated data about satellite missions, instruments, commercial data products, and SNWG solution activities that can be easily selected and populated into the reports. If this data needs to be updated, the RGT will automatically disseminate the updates across all SNWG existing reports, ensuring the report information is up-to-date and consistent. Finally, the reports are export-

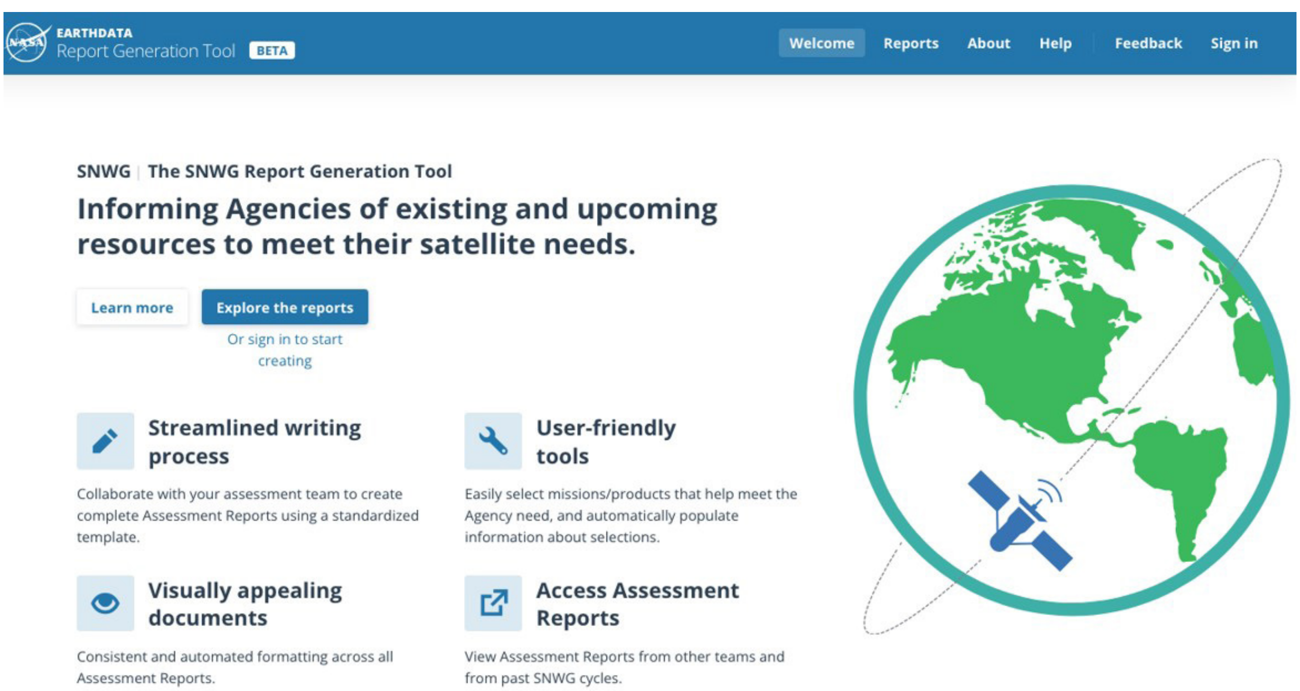


FIGURE 1. RGT Landing Page.

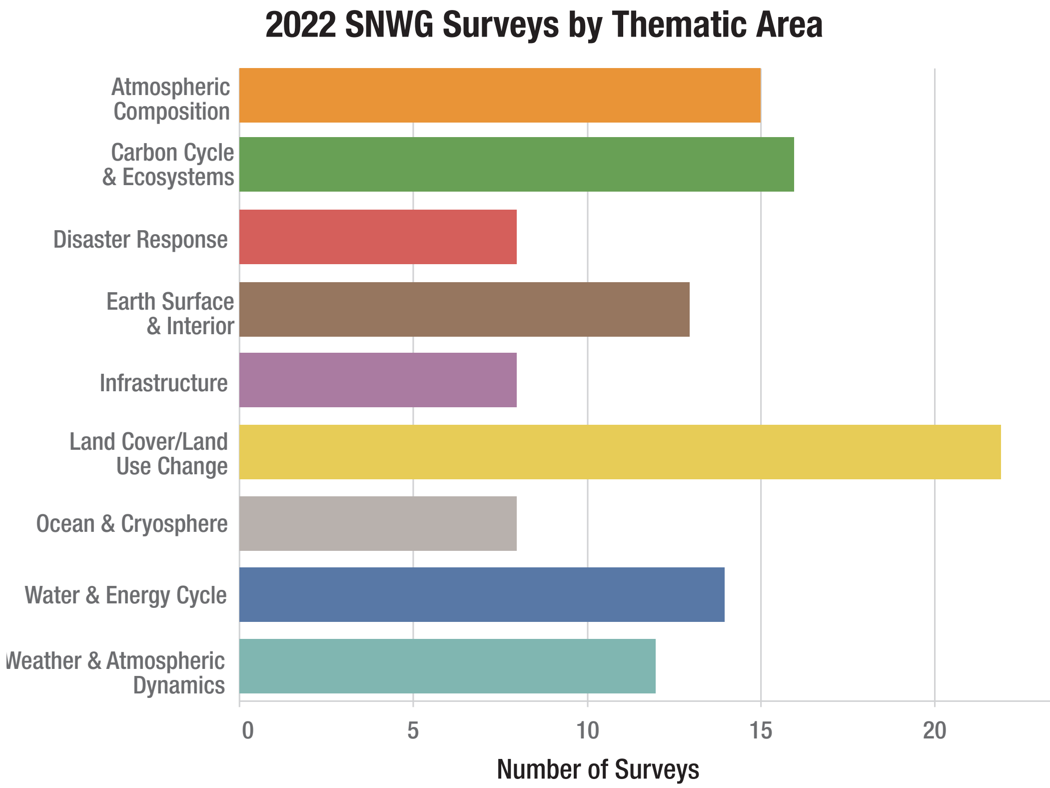


FIGURE 2. SNWG assessment surveys are categorized into nine Earth science themes.

ed in a polished and shareable format and are shared with the agencies who submitted surveys.

RESULTS/ACCOMPLISHMENTS

At the conclusion of the SNWG-2022 survey in September 2022, NASA received 116 completed surveys from more than 25 agencies. The SNWG MO managed the assessment process that involved reviewing and sorting all received surveys into nine Earth science thematic areas, conducting follow-up interviews with 99 respondents, and drafting thorough assessment reports. Federal agency responses to the SNWG survey have increased over the past several years with a 50% spike in submissions during the 2020 and 2022 cycles. Using RGT, the team was able to standardize the final reports, update information across multiple entries, saving countless hours of effort compared to managing the changes manually. New workflow management practices were also implemented during this cycle to enable assessment teams to collaborate more efficiently and to communicate better with agency representatives.

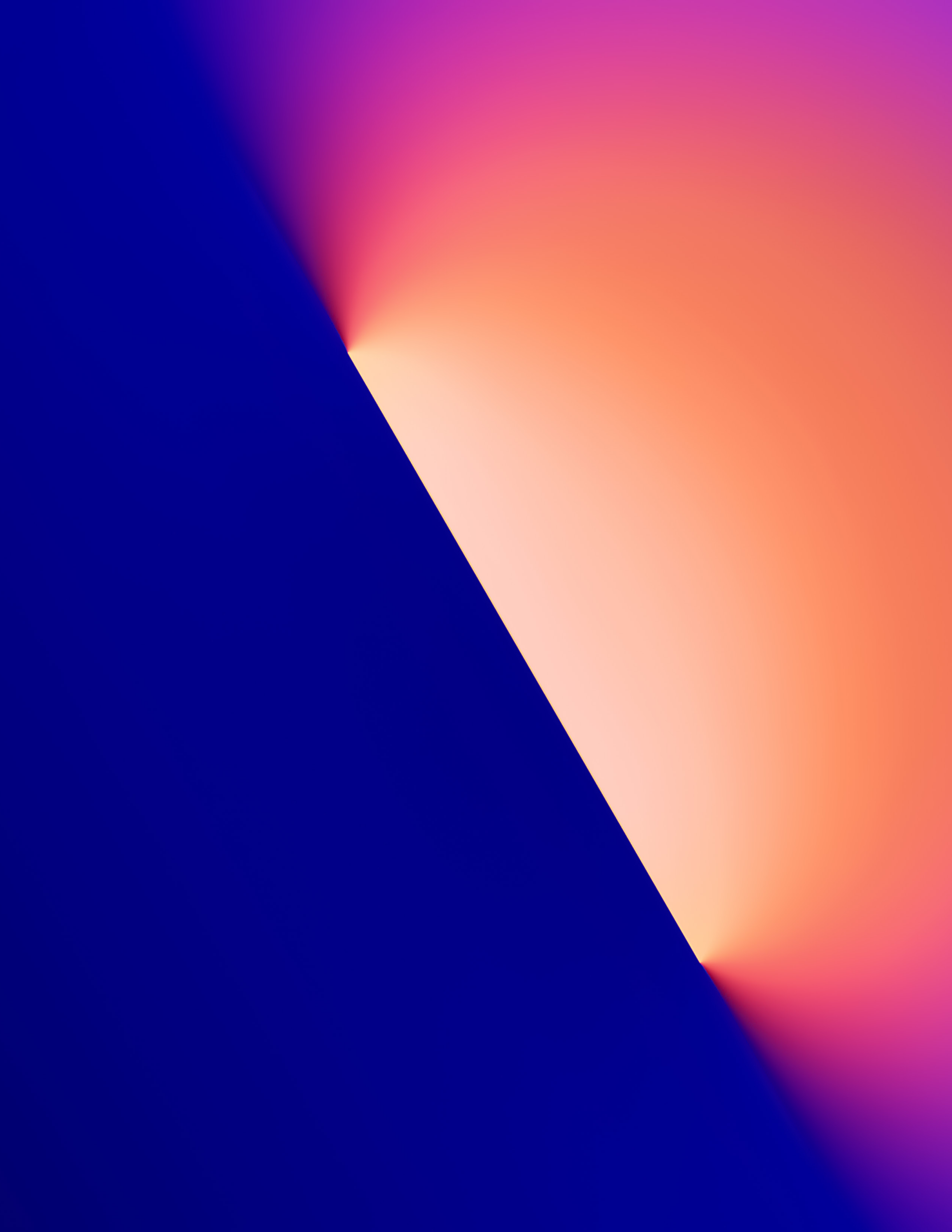
PARTNERSHIPS

SNWG has partnered with The University of Alabama in Huntsville and Development Seed.

SUMMARY

The SNWG addresses the Earth-observing needs of U.S. Federal agencies by levering existing and upcoming satellite assets. The SNWG MO at MSFC formulates the biennial surveys, assesses agencies' needs, and manages solution implementation and stakeholder engagement.

Principal Investigator(s): Dr. Rahul Ramachandran
Partners: The University of Alabama in Huntsville; Development Seed
Funding Organization(s): Science Mission Directorate
For more information: https://www.earthdata.nasa.gov/esds/impact/snwg



TECHNOLOGY AREA 12

MATERIALS, STRUCTURES, MECHANICAL SYSTEMS, AND MANUFACTURING

On-Demand Manufacturing of Multimaterials (ODMM)

PROJECT OBJECTIVE: **Development and demonstration of the feasibility of a low-gravity, on-demand manufacturing system for metal and polymer parts on the International Space Station (ISS).**

PROJECT GOAL/DESCRIPTION

The ON-Demand Manufacturing of Multimaterials (ODMM) project is a part of the In-Space Manufacturing (ISM) portfolio and developed hybrid additive manufacturing technologies for demonstration aboard the ISS. Systems demonstrated on the ISS could be infused into future missions beyond low-Earth orbit (LEO) to reduce logistics demands and enable a commercial manufacturing ecosystem in LEO. Currently, all tools, spares, and components necessary for use in space must be manufactured on the ground and launched. Additive manufacturing of payloads developed by the ODMM project would allow the crew to print components of either metal or plastic on demand at the location of use in microgravity. The ODMM project is closing at the end of fiscal year (FY) 2023 due to reductions in budget.

APPROACH/INNOVATION

The current ISS logistics model is heavily dependent upon Orbital Replacement Units (ORUs) for system-based repair and maintenance. Logistics support and habitat outfitting is a significant challenge for sustainable, extended human operations in space, especially for missions beyond LEO where timely resupply or abort in the event of emergency would not be possible. The ODMM project has partnered with Redwire Space Technologies, Inc. (formally known as Techshot, Inc.) to develop a system capable of demonstrating the manufacturing of metal, polymer, and electronic components aboard the ISS.

FIGURE 1. ISM project portfolio graphic.

The FabLab system consisted of three modules housed in a full EXpedite the PRocessing of Experiments to the Space Station (EXPRESS) rack. The Printer Module printed metal parts as a thick paste via Bound Metal Deposition (BMD). The Furnace Module and Process Gas Drawer allowed for the postprocessing of the printed parts by thermally removing solvent and binders to produce solid metal parts. The Printer Module also contained a toolhead for subtractive manufacturing and part finishing via a mill.

In 2023, the FabLab system completed a delta Preliminary Design Review (PDR) showing a feasible path to flight. In addition, the payload completed a Payload Safety Review Panel (PSRP) Phase I and all open hazards were closed by the review panel.

RESULTS/ACCOMPLISHMENTS

The ODMM project focused on the development of additively manufactured metal parts from titanium alloy Ti64. During project conception, solvent debinding was considered state of the art for the post processing of BMD produced parts. However, solvent debinding is not well suited for the space environment due to the need for liquid immersion baths and the generation of waste material. This project advanced the capability for thermal debinding BMD produced metal parts, which is now a more common approach. The project produced metal test specimens of Ti64 with near wrought properties.

This project developed a micro-furnace specifically designed for use on the ISS in an EXPRESS rack. This required a significant reduction in size so that the furnace would fit in the rack. The designed furnace contained a bigger hot zone and higher temperature capabilities than any current equipment on the ISS. In addition, the furnace power draw needed to be reduced from 5 kW in the prototype to 2 kW. Ultimately, the furnace still required 2.25 kW at the time of project cancellation, so it did not meet that goal. However, several mitigation actions were planned, including the development of a thermal model to inform locations of thermal leakage, changing the sintering profile to sinter at lower temperature, and the development of alternative alloy pastes that sinter at lower temperature.

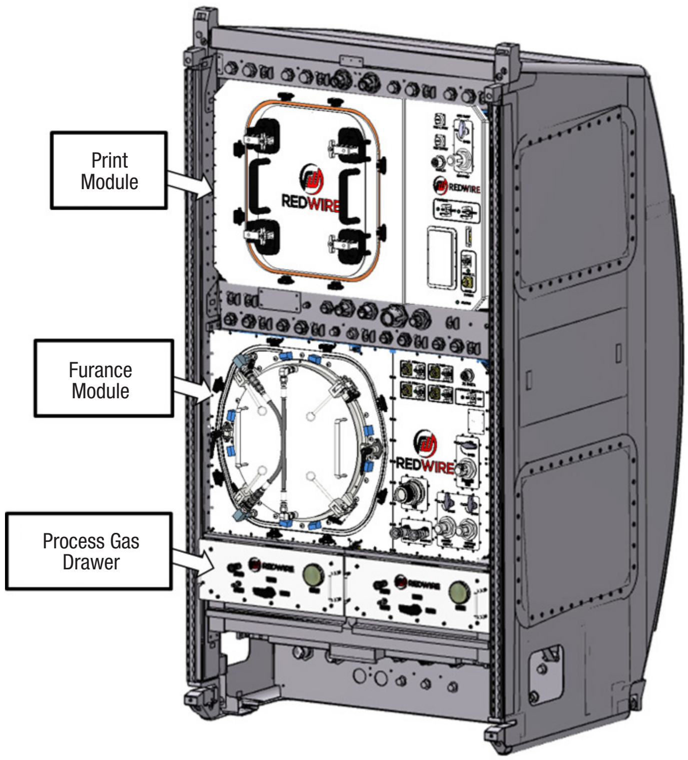


FIGURE 2. Diagram of Techshot FabLab system.

To achieve the necessary reduction in power draw for the micro-furnace, the Thermal and Mechanical Analysis group at NASA Marshall Space Flight Center developed a thermal model to identify areas of thermal leakage. The model also validated that there would not be a safety concern pertaining to the outer touch temperature of the furnace by determining the maximum temperature the exterior of the furnace could reach in the event of a power disruption and loss.

A Technology Maturation Plan (TMP) for the on-demand manufacturing of multimaterials in space was developed by the engineering project team. The purpose of the TMP was to document the major technical accomplishments necessary to develop manufacturing systems from the current phase through infusion into mission architecture for surface or transit applications and show the interactions between technology development efforts.

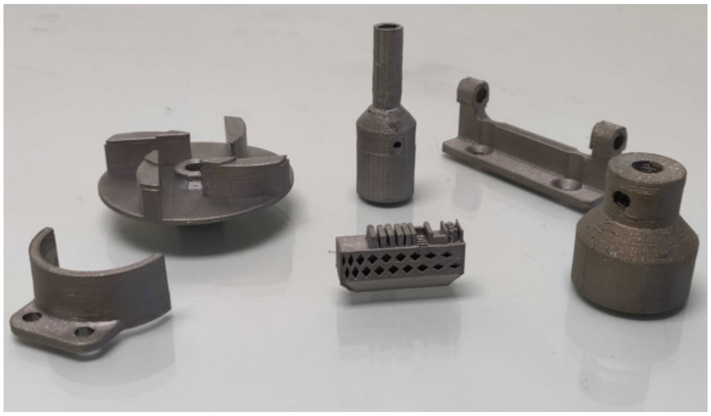


FIGURE 3. Images of BMD-produced Ti64 parts.

PARTNERSHIPS

Redwire Space Technologies, Inc. (formally known as Techshot, Inc.) was the prime contractor for the development the FabLab payload. The contractor provided a wealth of experience as a payload developer and is currently on contract for 2024 to continue to mature an On-Demand Manufacturing of Electronics (ODME) project version of the payload with the Printer Module only.

SUMMARY

The ODMM project aimed to development and demonstrate the feasibility of a low-gravity, on-demand manufacturing system for metal and polymer parts on the ISS. This was approached by maturing a BMD process with the FabLab system. At the time of project closure, FabLab had completed a delta PDR and PSRP Phase I. The furnace module power draw was still 0.25 kW over the allowed value, but there were several potential mitigations to pursue, and a complete thermal model of the furnace was produced. Although the ODMM project is closing at the end of FY 2023, it is anticipated that the technologies developed will be utilized on future endeavors.

Principal Investigator(s): Jennifer Jones; Alex Blanchard
Partners: Redwire Space Technologies, Inc. (f/k/a Techshot, Inc.)
Funding Organization(s): Game Changing Development

Software Platform for Printing Robust Alloy Parts

PROJECT OBJECTIVE: Develop and customize MatVerse, a data analytics platform, to predict additive manufacturing part performance utilizing in-situ datasets.

PROJECT GOAL/DESCRIPTION

Polaron Technologies is currently working on the development of MatVerse, a robust data analytics platform. This platform is designed to effectively identify anomalies within the additive manufacturing (AM) process by analyzing in-situ monitoring data collected from AM machines. A single AM part can generate extensive in-situ datasets. These datasets are often so large that manual human review becomes impractical and interpretation is difficult. Therefore, there is a clear need for an automated and efficient program to process these datasets and accurately pinpoint AM layers with a high likelihood of containing defects. AM anomalies include lack of fusion, keyholing, porosity, and short feed defects whose development can lead to a reduction in mechanical properties of the AM part, such as fatigue and fracture toughness. Polaron Technologies is actively developing machine learning models. These models are intended to process in-situ data, classify, and predict defects, and ultimately integrate these predictive capabilities into the MatVerse platform. This integration will enable quick and effective data analysis. By examining in-situ data and identifying anomalies along with their associated probabilities, this system can highlight the inherent flaws present in the final AM part. This knowledge is invaluable for AM part certification, especially for complex components that cannot be inspected through traditional nondestructive evaluation methods like computed tomography.

APPROACH/INNOVATION

In-situ data can take various forms, but in many systems, it involves capturing images of each layer as an AM part is being constructed on the build plate. However, the resulting datasets can become exceptionally large depending on the size of the part. Polaron Technologies has devised a solution that relies on three key machine learning tools: a convolutional autoencoder (CAE), a K-Means (KM) clustering algorithm, and a convolutional neural network (CNN).

Task 1 involves developing a CAE to preprocess the in-situ images before feeding them into their machine learning models. The CAE's role is to learn, distinguish, and identify noise from defects in these images. It accomplishes this by denoising the images, creating a cleaner and more accurate representation of the AM layer to be used in training the CNN. However, for effective CNN training, it's essential to have image datasets with labels corresponding to specific defect states. Manually labeling thousands of in-situ images is impractical. To streamline this process, Task 2 involves developing an unsupervised KM clustering algorithm capable of grouping images with similar defect signals. This algorithm identifies various types of flaws associated with these clusters and assigns appropriate labels. Through this approach, cluster characteristics can be labeled and linked to specific defect states, facilitating the development and training of the CNN.

Task 3 involves building an initial CNN model using the labeled datasets from Tasks 1 and 2. After training and testing, the fully integrated CNN will be capable of identifying anomalies in the layer-wise images and classifying a defect state based on the images' distinctive features. The development of the CNN will be an iterative process, refining hyperparameters to suit different datasets obtained through various sensor modalities, such as infrared (IR) thermography or optical tomography.

Task 4 will pull all the developed software together and integrated it into the MatVerse platform. This platform will be accessible to NASA personnel, enabling them to import AM in-situ datasets and receive information about potential anomalies in the AM part. Future objectives include assessing the defect state of AM parts and providing realtime predictions of their fatigue response.

RESULTS/ACCOMPLISHMENTS

To enable a CNN to effectively identify and categorize AM defects in in-situ images, it's crucial to have a substantial quantity of labeled datasets for model training. NASA Marshall Space Flight Center (MSFC) has an archive of historical in-situ data collected from past AM studies. These datasets encompass both naturally occurring and artificially induced defect states. Polaron received these datasets for preprocessing and for utilization in training and testing CNN models.

One of the defect states involved short feed anomalies, which result from inadequate or uneven powder distribution across the build plate. Over time, this leads to an excessively thick powder layer, resulting in inadequate bonding between layers. These in-situ images also contained inherent noise, including dead pixels caused by data acquisition issues. Polaron Technologies developed their CAE to denoise these in-situ datasets. The CAE effectively isolated the dead pixels and other noise, preparing the data for use with the CNN models. Since defects in an AM build occur infrequently, there naturally exist more pristine images than defective ones. To develop a robust CNN, it's essential to maintain an appropriate ratio of training images representing both pristine layers and defective ones. To generate more defective layers for CNN training, Polaron implemented various data augmentation techniques. These techniques involved actions like rotating, flipping, and applying threshold values to the original images to emphasize defect morphology, then generated new defect images through this augmentation process. With this updated dataset, Polaron successfully created new CNN models designed to identify and classify short feed defects within the AM in-situ data. By using this augmented dataset for training and testing, and after fine-tuning the models, the CNN achieved an accuracy rate of nearly 100% in detecting short feed defects in the in-situ images.

Fig. 1 displays the in-situ images before undergoing denoising by the CAE. Fig. 2 presents both the denoised image and a fidelity score, which indicates whether the CNN has accurately identified a defect image. Captions are included to specify the type of defect and the fidelity score, providing insight into whether the in-situ image contains a defect or not. Notably, Fig. 2 demonstrates an accuracy rate of 98%. Our ongoing efforts involve extending the same augmentation and training techniques to detect defects in images characterized by lack of fusion, keyholing, and skipped layer defects. Additionally, we are actively developing the KM algorithm to cluster labels for the various

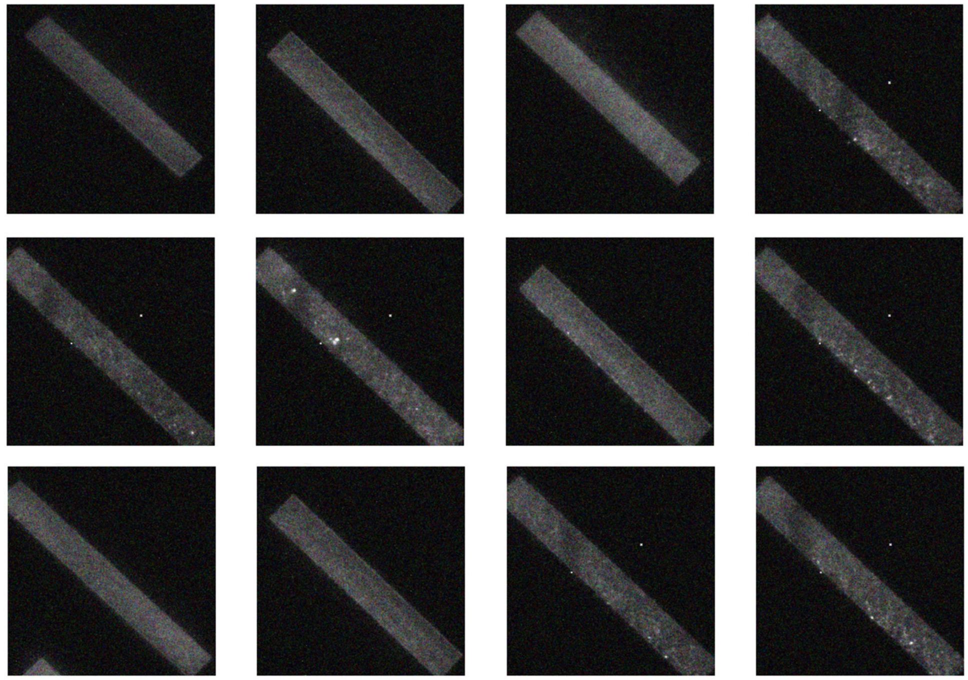


FIGURE 1. Impact of Noise in In-situ Data.

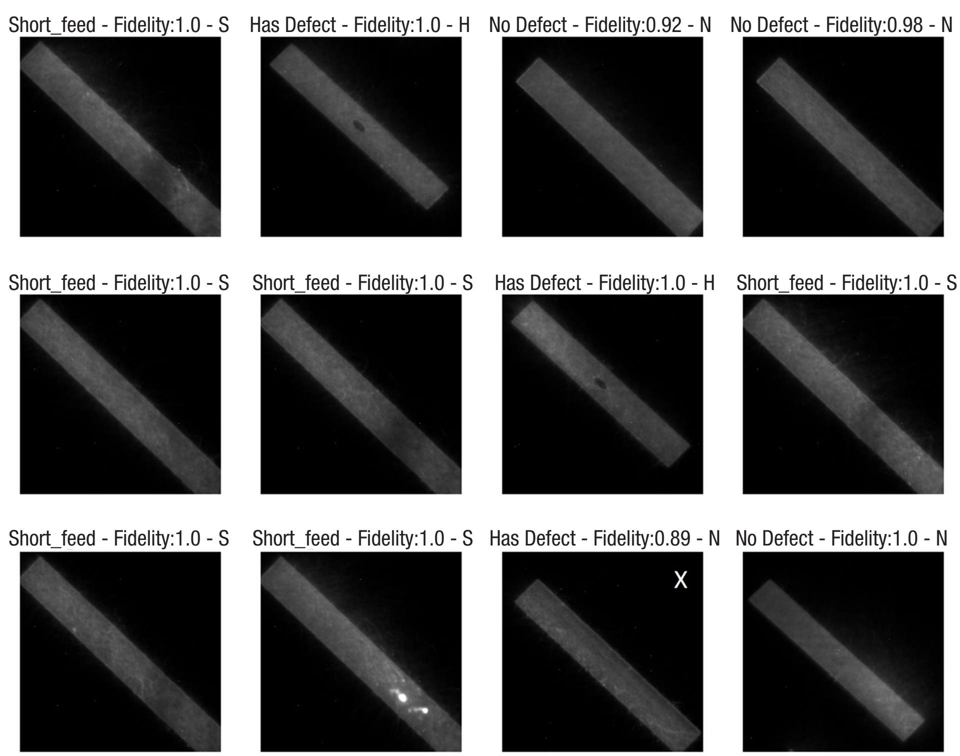


FIGURE 2. CNN Defect Detection and Classification in In-situ Images.

defect types. To develop more diverse datasets, MSFC and University of Dayton Research Institute (UDRI) have collaborated to manufacture coupons exposed to degraded airflow conditions. These airflow-induced defects will be captured by a range of in-situ sensors and used to further enhance the CNN's training data.

PARTNERSHIPS

Polaron Technologies was incorporated in September 2017 to serve government and private organizations in the data analytics and modeling and simulations areas. The company won three subcontracts from UES Inc. when the company provided services to Air Force Research Laboratory. The company received its first Small Business Innovation Research Phase I award from the Department of Energy in 2019 and recently won a Small Business Technology Transfer Phase I award from Space Force in collaboration with UDRI. This is the company's first collaborative partnership with NASA.

SUMMARY

Polaron Technologies, in partnership with UDRI and MSFC, is actively developing machine learning models aimed at efficiently analyzing extensive volumes of in-situ data. The primary objective is to identify and classify the defect state within AM parts. These models will undergo training using MSFC's existing in-situ data accumulated over several years, which encompasses a wide spectrum of anomaly types. In addition to leveraging historical data, UDRI and MSFC will creating additional training datasets by manufacturing coupons and deliberately introducing so-called "process escapes," such as insufficient gas flow, to naturally induce defects within the AM parts. This deliberate approach will generate fresh and viable in-situ data. As soon as a sufficient amount of data has been collected, the CNN models will undergo updates to accommodate newly discovered defect states. Ultimately, these models will be integrated into the MatVerse platform, ensuring accessibility for future NASA personnel. This platform will empower users to extract diagnostic information regarding their printed parts, enhancing the efficiency and accuracy of AM part assessment.

Principal Investigator(s): Dr. Rahul Bhowmik, Polaron Technologies, Inc.
Partners: CFD Research Corporation; Polaron Technologies, Inc.; University of Dayton Research Institute
Funding Organization(s): Cooperative Agreement Notice

Optimally Tailored Architected Materials for Lightweight and High-Strength Part Design and Manufacturing

PROJECT OBJECTIVE: The goal of the project is to develop novel computational approaches for the design and manufacture of ultralight, high-strength aerospace parts with mechanical metamaterials.

PROJECT GOAL/DESCRIPTION

The primary objective is mass mitigation in structural design of space flight hardware. This project aims to employ architected cellular materials for aerospace structural design. This will result in structural components effectively being internally sculpted to provide specified capabilities with required margin while minimizing mass. The inherent challenges will be addressed, such as computationally expensive simulations and complex geometries. The expected outcome of the project is an optimization framework for aerospace parts design and manufacturing with complex topologies, spatially graded properties, and hierarchical structures. The established framework will lead to an optimized layout of multiple microstructural materials within a target shape and additively manufactured continuously smooth graded interfaces.

APPROACH/INNOVATION

The research objective of this project is to develop an optimization framework for functional parts design and manufacturing with spatially varying, hierarchical structures. The established framework will lead to an optimized layout of multiple microstructural materials within a target shape and additively manufactured continuously smooth graded interfaces. Several real-world parts, such as the bracket and human bone implants, are optimally designed and additively manufactured. As illustrated in Fig. 1, we firstly construct a structure-property map for parameterized cellular materials to address the computational challenges of effective material properties calculation. In this map, the effective material property space (i.e., Young's modulus, Poisson's ratio, and thermal conductivity tensor) of cellular structures is constructed with computational

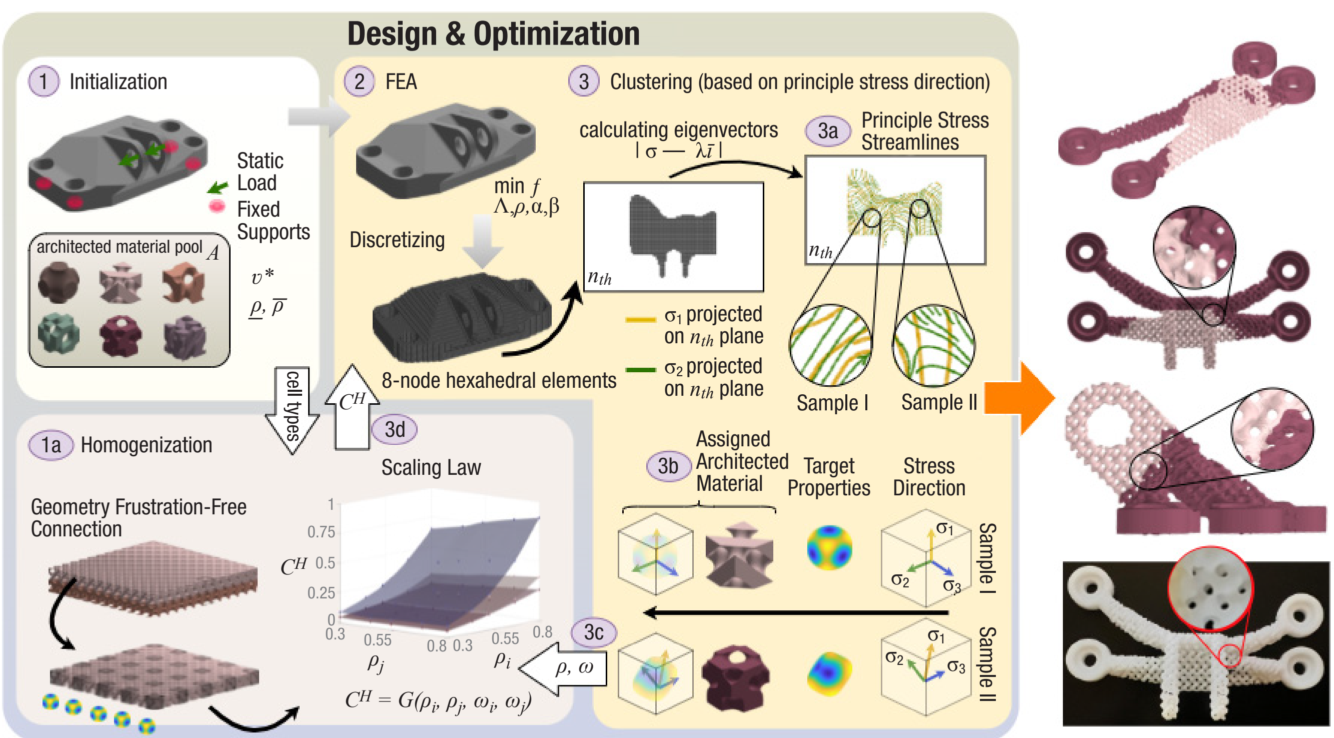


FIGURE 1. Proposed computational framework for lightweight functional part design with architected materials.

homogenization method. Such a property space provides basis for inverse property-structure mapping in the structure optimization process.

The next step is to design lightweight functional part with prescribed requirements (e.g., loading and boundary conditions, specified thermal conductivity, etc.). To design such functionality-driven parts, we will formulate an optimization problem. The objective function will be the desired functionality performance, such as minimizing structural compliance, maximum concentrated stress, or mean temperature within part. Based on the specified objective, a multiscale structure optimization problem will be formulated. Since the optimization process involves computationally expensive finite element simulation, we propose to employ Bayesian optimization to solve the problem. Lastly, considering the manufacturing conditions, the compatibility of adjacent microstructures will be investigated, and we aim to achieve a smooth and reinforced interface of infilling cellular structures that are amiable to additive manufacturing.

The anticipated next step will be to manufacture the designed parts with novel additive manufacturing process developed at the University of Illinois at Chicago (UIC). Specifically, a novel selective self-binding laser sintering and alternative hybrid manufacturing (self-assembly and coating) processes will be investigated to fabricate the designed hierarchical structures with various materials. Mechanical and other tests will be conducted on the printed parts to validate the performances that can adapted to a hypothetical extreme space environment.

RESULTS/ACCOMPLISHMENTS

During this partial first year of the Cooperative Agreement Notice project, UIC has made significant progress in the development of the proposed computational design framework. This project has resulted in two journal publications, three conference publications, and one more journal paper that is under preparation. The following tasks have been accomplished:

- An extensive function-based representation (FRep) microstructure database was established, and a resulting structure-property map was built, the mechanical properties of the microstructures include isotropic, orthotropic, and anisotropic material properties.
- A multiscale hierarchical design optimization framework that incorporates topology optimization, geometry frustration-free, and functional gradation was proposed. The design framework was successfully validated on an engine bracket and human bone implant design.
- A design for additive manufacturing scheme was developed to eliminate the requirement of high-memory Standard Tessellation Language files. A direct slicing algorithm for architected materials based on the analytical functions (FRep) was developed for multiscale structures with complex porous geometries.
- A preliminary fabrication experiment on additive manufacturability was studied: the impact of cross-sections on the energy absorption of architected materials in the established database was theoretically and experimentally investigated.

PARTNERSHIPS

The partner with NASA Marshall Space Flight Center for this project is UIC.

SUMMARY

A holistic design-through-printing framework with implicitly represented cellular materials for high-resolution structured materials design and manufacturing is developed. The presented design framework fully exploits the merit of implicitly represented architected materials and fulfills multifunctional structural design needs (e.g., thermal exchange, fluid flow, and energy absorption). Future directions of this work can be the programmability (e.g., reaction to external stimuli) of the unit cells of the multiscale design to transform the design and manufacturing of intelligent biomimetic materials and impact fields such as shape morphing and neuromorphic metamaterials. The developed multiscale structure optimization framework is a technology with many potential NASA and commercial applications in the coming years.

Principal Investigator(s): Dr. Jida Huang, University of Illinois at Chicago; Dr. Yayue Pan, University of Illinois at Chicago
Partners: University of Illinois at Chicago
Funding Organization(s): Cooperative Agreement Notice

Laser Additive Technique Tailored for Iridium Catalyst Engineering (LATTICE)

PROJECT OBJECTIVE: To advance platinum group metal (PGM)-based additive manufacturing (AM) Technology Readiness Level (TRL) by developing processes to create PGM AM-optimized isotropic catalysts for integration in refractory AM green propulsion chambers to test under prototypical operating environments.

PROJECT GOAL/DESCRIPTION

Reaction control systems are usually powered by monopropellants like hydrazine and/or Advanced Spacecraft Energetic Non-Toxic (ASCENT) green propellant and use ceramic/carbon-based iridium (Ir)-coated catalyst beds, given the high temperature requirements. Traditional manufacturing of these catalysts is time-consuming and expensive and, with only a few vendors, long lead times are the norm. Current ceramic/carbon-based Ir-coated catalyst beds exhibit anisotropic properties leading to low performance and inferior mechanical properties with limited reproducibility. Due to the low volume, high complexity, and high cost, AM can be leveraged to create PGM AM-optimized isotropic catalysts for integration in refractory AM green propulsion chambers and testing under prototype operating environments. The implementation of AM will reduce long lead times and enable fine tuning of catalyst design for specific needs.

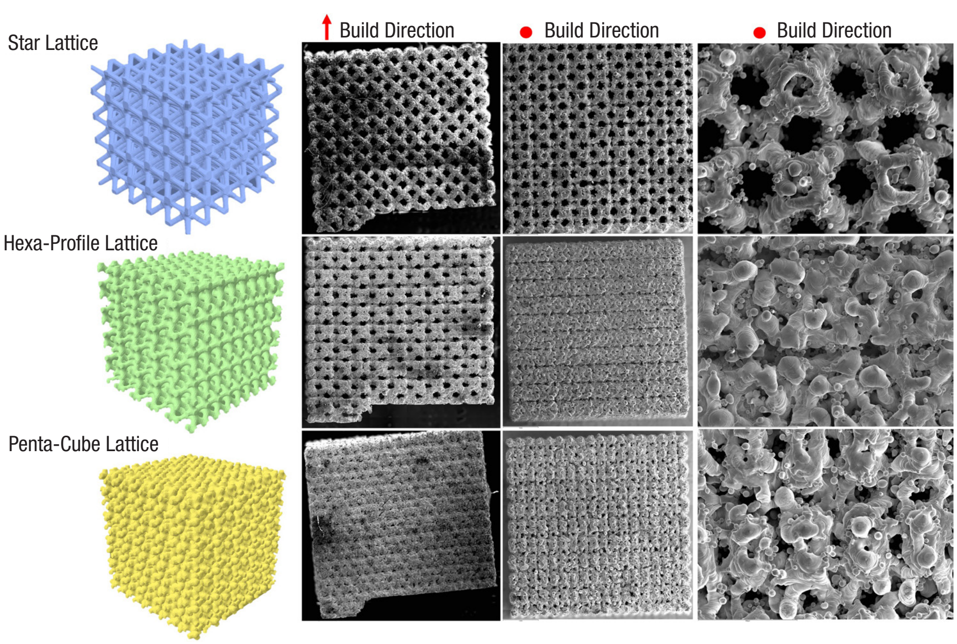


FIGURE 1. Molybdenum (Mo) AM microlattices using different lattice design geometries: star, hexa-profile and penta-cube.

APPROACH/INNOVATION

Additively manufactured Ir-based catalyst beds (i.e., ultra-fine lattices) will be integrated into AM-enabled refractory metal 1N thruster chambers and tested in prototype environments to be used in small satellites. For testing, molybdenum (Mo) and tungsten (W) have been identified as surrogate materials to minimize development costs. Initial lattice penetrability would need to be verified using surrogate materials. As there are currently no available AM feedstock materials for Ir, the feedstock will need to be processed in-house to create AM-optimized powders (i.e., spherical and fully dense). Additively manufactured Ir-based catalysts will be assessed for performance and considered for thrusters of up to 22 N. Most monopropellant propulsion systems (>90%) use Ir-based catalysts; therefore, industry adoption after technology demonstration is expected (like industry adoption of AM C103 and GR-CoPp alloys for rocket engines). If successful, NASA Marshall Space Flight Center (MSFC) will be able to create rapid, low-cost tailorable AM Ir/PGM ultra-fine lattices for propulsion catalysts with extensive market applicability. This effort complements green propulsion infusion and the application and development of AM-optimized materials by industry and academia to replace more complex and costly processes. The performance of printed lattices will be assessed and compared to traditionally made catalyst geometries.

Some key technical challenges to be addressed are feedstock production of PGM powders and printability/post-processing of Ir specimens. Future innovations that would support this work would be based on performance-driven development using

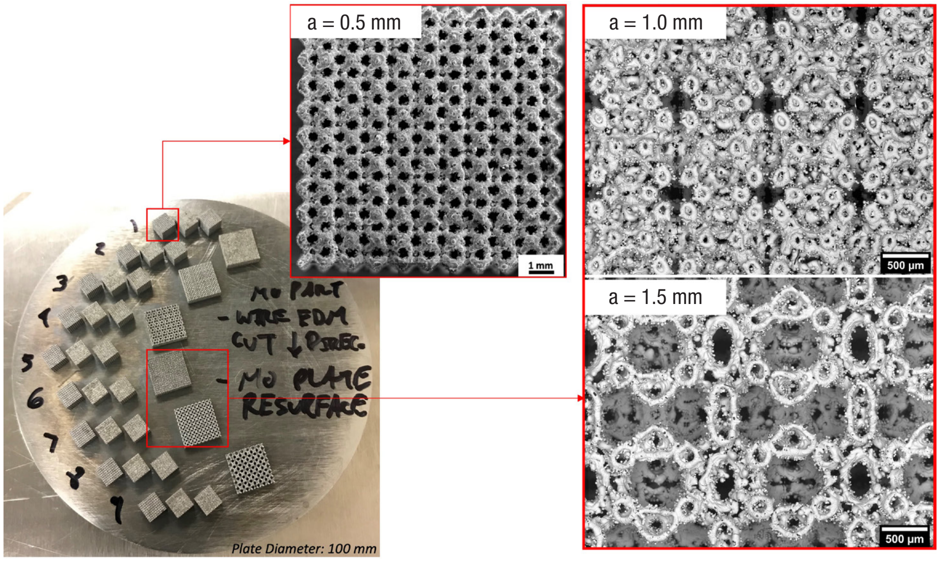


FIGURE 2. EOS M 100 AM build plate showing printed lattices on plate with different unit cell size and hollow microlattices.

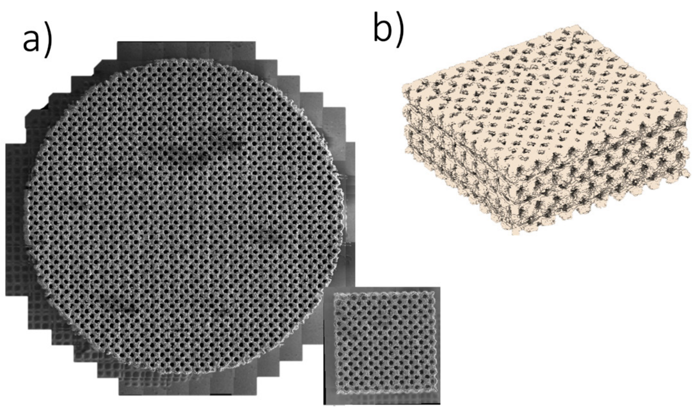


FIGURE 3. (a) Tungsten (W) microlattices at different sizes (20 mm diameter cylinder and 5 mm cube); (b) 3D reconstruction of lattice cube using robomet data.

Design for AM (DfAM) incorporating all thruster components to enable better combustion control, propellant savings, and scalability.

RESULTS/ACCOMPLISHMENTS

Following the approach highlighted in the previous section, we showed that Ir-surrogate material (i.e., W and Mo) lattices can be printed using laser powder bed fusion (L-PBF) using different geometries, including 1 N thruster geometries. The Mo lattices were printed in different geometries (i.e., star, hexa-profile, and penta-cube) to obtain the select the best lattice for testing (see Fig. 1). These lattices show porosities similar to those in traditionally made catalysts, but with higher strength. We found that we can also create hollow microlattices, which could also be beneficial for increasing the surface area of the material and improving the catalytic reactions that takes place in these thruster systems (see Fig. 2). As a risk mitigation strategy, a hybrid approach can be followed in which W lattices can be printed and then coated with Ir. Therefore, W lattices were printed (Fig. 3) to show printability of different geometries and to characterize the lattice morphology.

PARTNERSHIPS

The Refractory Alloy Additive Manufacture Build Optimization (RAAMBO) Project provided funding to purchase Ir powder and allowed use of refractory AM-dedicated L-PBF machine.

SUMMARY

Traditional manufacturing techniques of propulsion catalysts are time consuming and expensive. Catalysts are usually made of ceramic or carbon foams/lattices coated with PGM elements such as iridium. The result is an anisotropic pore distribution with non-uniform coating that leads to varied performance, reduced strength, and limited reproducibility. Additive manufacturing methods were used to design and manufacture catalysts like ultra-fine microlattices via L-PBF of refractory materials that are used as Ir surrogate materials. The resulting lattice structures were characterized to obtain morphology information. Results show that printed lattices have similar pore size and strut thickness as traditional catalysts, but they exhibit higher strength and are isotropic.

Principal Investigator(s): Fernando Reyes Tirado; Omar Mireles; Nicole Vaughn

Partners: Refractory Alloy Additive Manufacture Build Optimization (RAAMBO) Project
Funding Organization(s): Center Innovation Fund

Ultra-High-Temperature Testing of Refractory Alloys

PROJECT OBJECTIVE: To develop the methodology and instrumentation to perform unique mechanical testing of refractory alloys at temperatures up to ~3,000 °C under controlled atmosphere and apply such tests to additively manufactured tungsten (W)-, molybdenum (Mb)-, and niobium (Nb)-based alloys to support NASA endeavors for deep space exploration.

PROJECT GOAL/DESCRIPTION

New challenges are arising as NASA is developing technologies to 3D print complex and critical components made of refractory alloys for propulsion, power, and reentry applications. Refractory alloys were developed decades ago, long before printability was a factor in alloy design. With the increasing adoption of 3D printing, also called additive manufacturing (AM), the development of innovative alloys especially suited for AM processes is getting a lot of attention. NASA is developing formulations that are resistant to cracking during the printing process. There is limited elevated temperature mechanical performance data for AM refractory alloys, which is paramount for further alloy development. Elevated temperature testing of refractory alloys is further complicated by how readily they oxidize in trace oxygen environments, necessitating vacuum and/or an inert atmosphere environment. Therefore, the development of rapid and low-cost ultra-high-temperature testing methodologies for these alloys is critical for furthering and accelerating such alloys development. This development work is supported by computational modeling followed by lab-scale experimental demonstrations.

Covered by a Cooperative Agreement Notice (CAN) with NASA Marshall Space Flight Center (MSFC), The Ohio State University (OSU) in collaboration with NASA Glenn Research Renter (GRC) developed a testing methodology to perform high temperature mechanical testing of AM refractory alloys. Testing of W, Mo and Nb-based alloys was performed.

APPROACH/INNOVATION

This research utilized computer-aided design and finite element analysis software to design innovative samples and grips printed by NASA utilizing laser powder bed fusion. The samples were designed to be printed vertically with a tapered breakaway cone with no additional supports. Due to the cost and difficulty of machining refractory alloys, an alternative to standard tensile sample threads was developed.

The experimental set up was based on the use of an advanced thermomechanical testing system, where the samples to be tested are heated by passing an elevated electrical current through them, which avoid the challenges of heating elements capable of achieving ultra-high temperatures. This unique experimental setup was developed at the Welding Engineering Program at the Ohio State University. The used thermomechanical testing system can exert up to 10 tons of static force, heating samples at rates of up to 10,000 °C/s, while keeping the experimental chamber at a vacuum level of 10^{-5} Torr. To enable the required extreme target temperatures, the sample holding system design (Fig. 1) and its cooling were optimized. Additionally, needed extreme temperatures also exceed the capability of high temperature thermocouples, so a special two-color

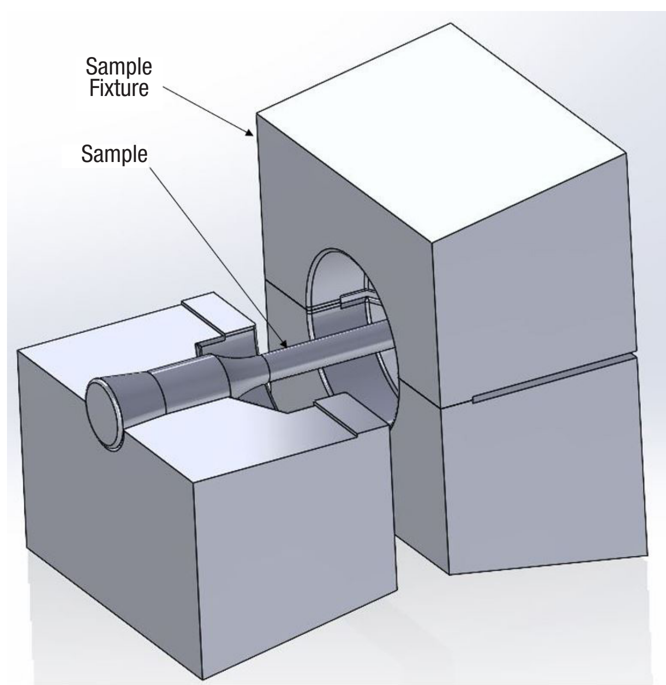


FIGURE 1. Sample holding system used for ultra-high-temperature testing.

pyrometer capable of measuring up to 3,500 °C was utilized to measure and control the sample temperature (Fig. 2). Both American Society for Testing and Materials (ASTM) E8—Standard Test Methods for Tension Testing of Metallic Materials and ASTM E21—Standard Test Methods for Elevated Temperature Tension Testing of Metallic Materials were used as a reference, but not rigorously followed due to the unprecedented and extreme conditions required for this testing.

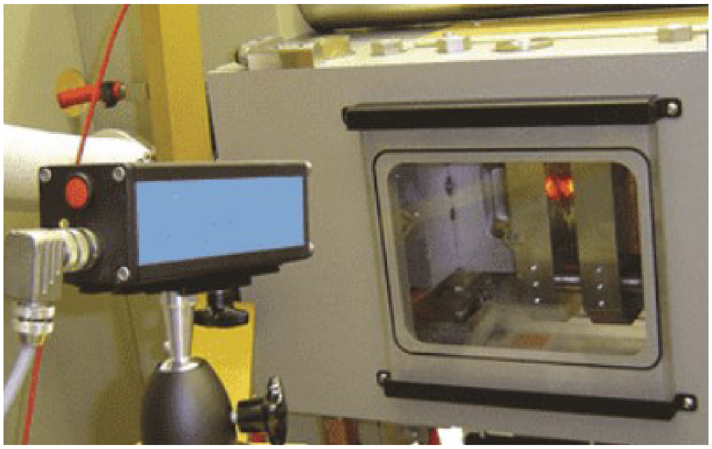


FIGURE 2. Pyrometer located outside the testing chamber used to measure and control temperature.

RESULTS/ACCOMPLISHMENTS

The outcome of this project is a rapid, low-cost testing methodology for ultra-high-temperature mechanical testing of metallic materials, which focused on AM refractory alloys. Special sample support devices were designed and manufactured using 3D printing. The thermomechanical testing system has been modified to withstand these extreme temperatures and to improve its vacuum system. Testing in vacuum minimizes oxygen levels within the chamber to limit alloy contamination, enabling reliable and reproducible testing.

PARTNERSHIPS

The Ohio State University is the primary collaborator for the work outlined in this report. Dr. Antonio J. Ramirez, Professor of Welding Engineering Program, and Kelly Orsborn, M.S. student of Welding Engineering Program, are the primary collaborators at OSU. GRC is also collaborating on the project.

SUMMARY

This rapid, low-cost testing methodology was successfully implemented using a commercial thermomechanical testing system to perform ultra-high-temperature mechanical testing of metallic materials, including 3D-printed refractory alloys. The data provided by this testing then be used to feed into modeling efforts, further refining them, and verifying the mechanical performance of the innovative alloys that NASA and other organizations are developing. This testing is ongoing and will be used to develop refractory alloys specifically for AM processes.

Principal Investigator(s): Antonio Ramirez, The Ohio State University; Eric Brizes, NASA Glenn Research Center; Fernando Reyes Tirado
Partners: The Ohio State University; NASA Glenn Research Center
Funding Organization(s): Cooperative Agreement Notice

Additive Manufacturing of Refractory Carbides for Nuclear Thermal Propulsion Fuel and In-Core Structural Applications

PROJECT OBJECTIVE: Investigate consolidation of high-density zirconium carbide (ZrC) by means of an additive manufacturing (AM) process.

PROJECT GOAL/DESCRIPTION

The current work intends to establish an attractive and cost-effective fabrication process for ceramic materials of interest for NASA's Nuclear Thermal Propulsion project. Rutgers University seeks to employ their state-of-the-art ceramic AM capabilities in order to develop printing parameters along with a consolidation approach to fabricate ceramic materials. This effort will focus on two goals to advance the printability of refractory carbide materials. The first goal is to show the feasibility to print porous ZrC by adapting a stereolithography (SLA) AM platform and parameterize the printing parameters for dark, high scattering materials. The second goal is to evaluate sintering additives and sintering parameters to densify ZrC to near-theoretical density by liquid phase sintering (LPS).

APPROACH/INNOVATION

The main challenges in fabricating carbide fuel are the consolidation and the postprocessing of near-net-shapes (i.e., complex geometries), where machining this robust material can be extensive and generally increases the manufacturing cost and leadtime. The proposed work intends to investigate the AM of ceramic material ZrC. This compound can be employed as a precursor material for the nuclear fuel uranium-zirconium carbide. Additionally, ZrC is in high demand for other propulsion applications where it can be incorporated as heat sink material due to its thermal properties.[1,2]

The sintering of ZrC by means of topological thermodynamic driving forces or associated thermally activated mass transport processes is very challenging. To overcome these difficulties, ZrC is sintered by electric field-assisted methods, such as spark plasma sintering, to obtain dense polycrystalline ceramics. However, complex-shaped and near-net-shaped ZrC ceramics need to be hot-consolidated by pressureless sintering methods. The current work employed an LPS approach[3] to reduce the sintering temperature in order to achieve sintered densities that are >95% at temperatures in the range of 1,900–2,200 °C, while preventing the oxidation of ZrC into zirconium dioxide.[4] The proposed process involves aluminum oxide (Al_2O_3)-yttrium (III) oxide (Y_2O_3) compositions (eutectic temperature is 1,811 °C)[5] as the LPS agent, which will also act as an oxygen-getter as both Al_2O_3 and Y_2O_3 are very stable oxide formers.

RESULTS/ACCOMPLISHMENTS

A low-oxygen-content and phase-pure ZrC powder was used in this study. LPS of ZrC using 8% by weight (21 mol% Y_2O_3 and 79 mol% Al_2O_3) sintering aid at 2,200 °C for time frames ranging from 5–20 min results in sintered densities of 97% theoretical density (TD) or more. Based on the results of this study, sintering times of 10 min or higher resulted in the highest sintered density. Fig. 1 displays the microstructure of a highly dense polycrystalline ZrC sample with well-formed grain boundaries. High densities were obtained as a result of the sintering aids used at 2,200 °C in 5 min or more, with densities reaching as high as 99% of the x-ray density. This work demonstrates that LPS is a viable methodology for consolidation of ZrC via an AM process.

PARTNERSHIPS

Rutgers University supported the ink formulation development along with the AM platform ADMATEC Admaflex130 to produce the high-density ZrC samples.

SUMMARY

ZrC is a hard refractory ceramic that has been used in many demanding applications due to its high thermal conductivity, positive irradiation results, and high temperature resistance. Though these properties are favorable, the post-processing and machining requirements to create complex parts from such hard ceramic materials can be costly and challenging. Additive manufacturing as a method of producing complex ceramic green body components poses a solution to the intensive post processing and material removal performed in ceramic machining. By using an ADMATEC stereolithography apparatus and photocurable

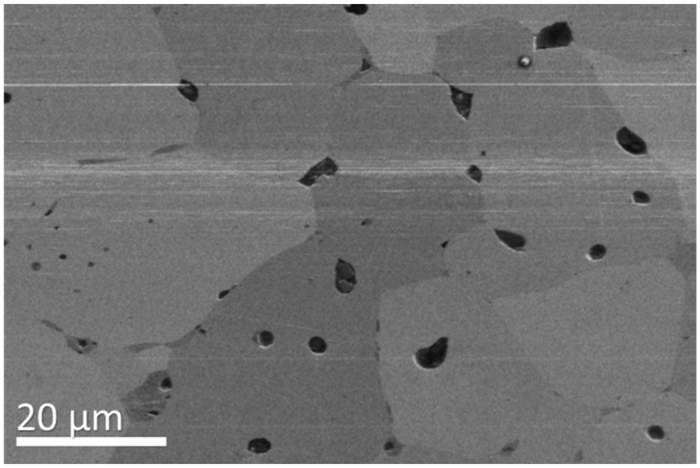


FIGURE 1. Microstructure of non-transient LPSed ZrC at 2,200 °C for 5 min.

ceramic resin, intricate and highly accurate ceramic parts can be fabricated layer by layer.

This work aims to study the development of ZrC suspensions for stereolithography printing and to address the challenges of the process while investigating the parameters that impact their dispersion and printability. Parameters including sample volume, dispersant type, and solids content and their effects on powder dispersion in the resin were studied. Once the suspensions were developed, the relationship between energy dose and cure depth was investigated. This relationship was then used to determine which parameters are important to consider when attempting to print multilayer green bodies out of ZrC. Such parameters include the material layer thickness and doctor blade thickness, as well as the minimum energy dose necessary to adhere material to the platform and to subsequent layers.

Upon achieving successful layer adhesion with as-is powders in suspension, we demonstrated the successful printing of a ZrC coupon. LPS of ZrC was attempted with Al_2O_3-Y_2O_3 sintering aid to explore the possibility of pressureless densification of a such a highly covalent ceramic. By using 8% by weight sintering aid of eutectic composition and a sintering temperature of 2,200 °C, we were able to achieve >97% densification in 5–20 min, providing proof that LPS is a viable approach to the pressureless sintering of ZrC.

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Principal Investigator(s): Jhonathan Rosales
Partners: Rutgers University
Funding Organization(s): Cooperative Agreement Notice

Laser Beam Welding in Space: Maturation and Model Validation with Flat Floor and Parabolic Flights

PROJECT OBJECTIVE: To demonstrate the first fiber laser weld of realistic joint on a three degrees-of-freedom flat floor and the first instrumented fiber laser weld on a parabolic flight to inform computational process models of in-space laser welding.

PROJECT GOAL/DESCRIPTION

It has been 50 years since NASA made a weld in space. Development and demonstration of welding processes are needed now to get ahead of assembly and manufacturing needs required for the booming in-space economy. Relevant physics have not been captured during laser beam welding (LBW) and processing including the primary in-space environmental effects of reduced gravity, reduced pressure, and extreme temperature. Also, the fit-up and autonomous robotic precision requirements are unknown to realize an in-space laser weld. This work leverages and combines in-house laser processing technology, integrated computational materials engineering (ICME) and digital twin modeling, and a three degrees-of-freedom space simulator to capture the above. Computational models of in-space welding are being developed by coupling the experimental approach with weld diagnostics and testing.

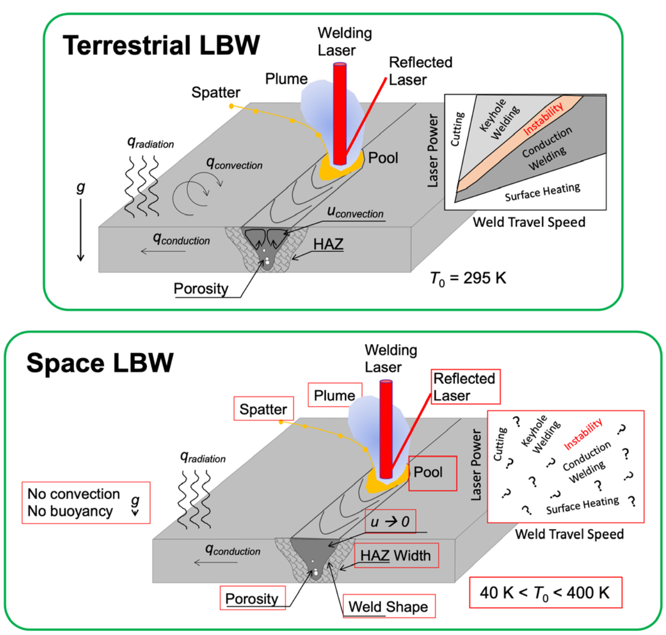


FIGURE 1. Key physical differences in terrestrial versus in-space LBW.

APPROACH/INNOVATION

This research utilizes a flat floor space simulator to replicate an in-space assembly process that uses laser welding. Two free-floating aluminum objects are docked, and a series of laser welds are placed on the docked components to realize a permanent metallurgical bond. This bond has a stronger and stiffer structure compared to other methods, such as fastening. A digital twin of the assembly is produced in parallel to the actual joint and provides a method for the analysis and determination of key differences between the intended design and the final assembly. Digital features are captured with 3D white light scanning and thermography during and after the welding process. Data are used to calibrate computational models of the welding processes and subsequent analysis will allow the optimization of the long-term health monitoring of a component assembled in space by tracking features such as geometry and weld distortion. Models already show profound differences between laser welding in a space environment and a weld made on Earth with the same weld process settings.

RESULTS/ACCOMPLISHMENTS

The project outcome will increase the Technology Readiness Level (TRL) of in-space LBW from TRL 3 to TRL 4 by maturing confidence in the process through understanding of its application and through identification of limiting factors in deployment in a space simulator. The project informs experimental design of future parabolic flights of laser welding and digital twin models that will determine fit-up/precision requirements for future in-space welding operations. Finally, the work is used to anchor computational models of in-space welding to experimental data that captures appropriate process physics of the space environment.

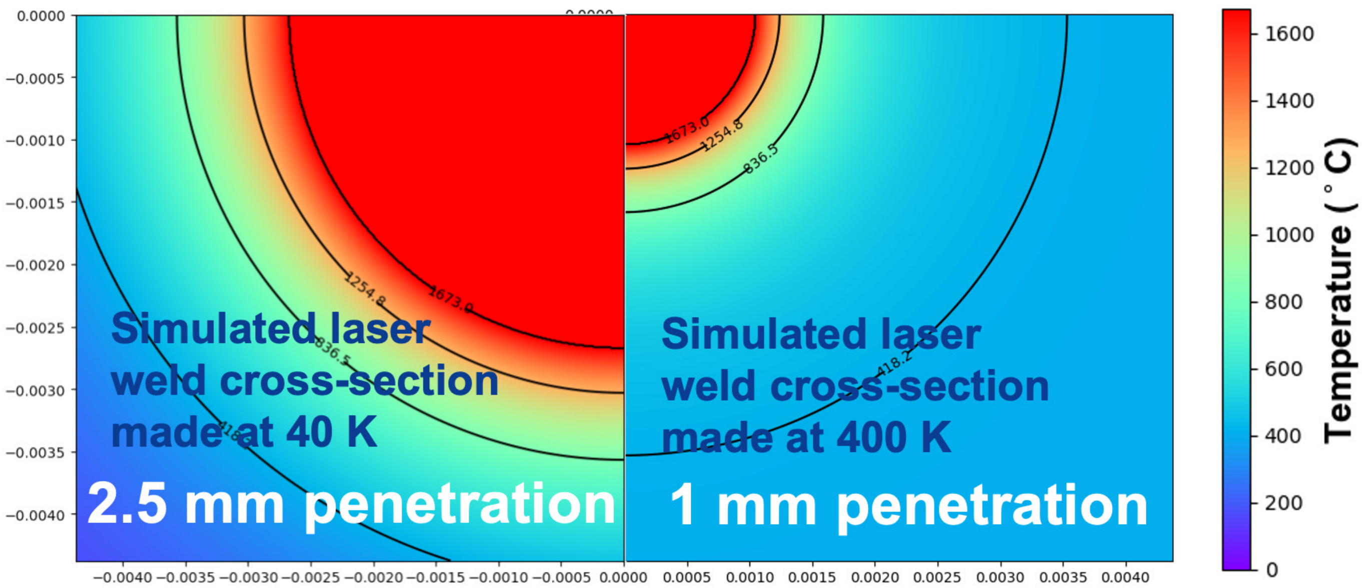


FIGURE 2. Simulated weld cross sections of a laser weld produced in space (left) and on Earth (right) using the same laser power settings.

PARTNERSHIPS

The project is led by a team at the NASA Marshall Space Flight Center. Collaborations with universities help inform experimental design of future parabolic flights of laser welding (with The Ohio State University) and digital twin models that determine fit-up/precision requirements (with The University of Texas at El Paso).

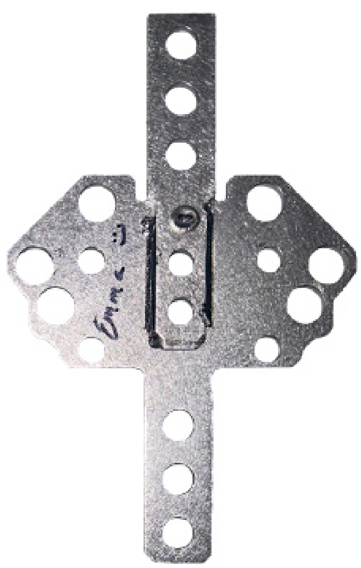


FIGURE 3. Laser beam welds made on aluminum alloy in-space assembly components.

SUMMARY

NASA is developing and deploying in-space laser beam welding experiments to enhance computational capabilities and to increase TRL for in-space manufacturing with relevance to the Agency's Moon to Mars objectives.

Principal Investigator(s): Zach Courtright; Thomas Bryan; Chris Protz; Jeff Sowards
Partners: The Ohio State University; The University of Texas at El Paso
Funding Organization(s): Technology Innovation Program

Additive Manufacturing Certification Capability Maturation

PROJECT OBJECTIVE: Develop expertise and conduct risk-mitigating projects supporting additive manufacturing (AM) material and part certification.

PROJECT GOAL/DESCRIPTION

Additive manufacturing technology is rapidly evolving, and NASA requires sufficient knowledge of AM materials, processes, and equipment to conduct necessary technical evaluations of AM hardware in support of flight-critical certification efforts. This project sought to develop expertise in AM materials and processes and conduct investigations to mitigate risks for the use of AM materials in critical applications. The project was divided into four sub-tasks:

1. Experience with multilaser laser powder-bed fusion platforms.
2. Training for AM certification.
3. Fracture Control framework for uninspectable AM components.
4. Qualification of in-situ monitoring technology for certification.

APPROACH/INNOVATION

Additive manufacturing is increasingly adopted for spaceflight applications, including applications where failure of a component can have catastrophic consequences. NASA needs to conduct technical evaluations of AM hardware in support of flight-critical certification efforts for projects such as Space Launch System, Human Landing System, and Commercial Crew Program. NASA has recently published standards for the use and control of AM materials, and experience must be gained in the applications of these requirements to flight programs. Additionally, AM components can have difficulty meeting other NASA requirements, such as those for non-destructive evaluation or fracture control.

Experience with newer metallic AM systems was developed through procuring material and test samples from several recently developed AM machines and by leasing a multilaser AM system for hands-on operation. AM certification trainings were prepared, building upon NASA Marshall Space Flight Center (MSFC) expertise in AM process qualification, and a pipeline of new AM certification subject matter experts (SMEs) was initiated at MSFC and across the Agency. Additionally, approaches were evaluated for assessing the risks of AM material flaws on fracture critical components. Finally, studies on the correlations between in-situ monitoring indications and physical material flaws were conducted to evaluate pathways to qualification of in-situ monitoring technologies.

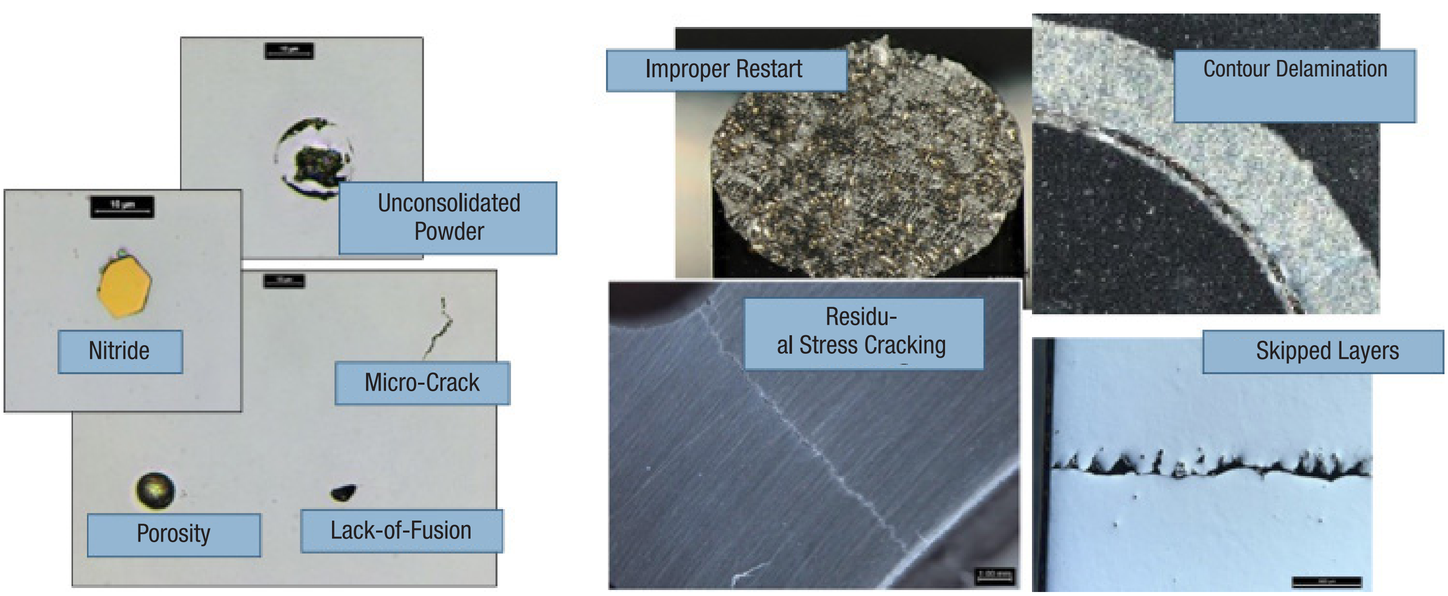


FIGURE 1. Examples of flaws that can occur in metallic AM processes.

RESULTS/ACCOMPLISHMENTS

Under this project, MSFC completed a lease agreement for a multilaser AM machine that has been installed, yielding valuable insight into newer multilaser AM systems. Additionally, material from other multilaser AM systems was procured and investigated, with insight gained on appropriate means for evaluating these systems and producing material for metallurgical and mechanical characterization. A training course on AM certification, based on the philosophy and requirements established in NASA-STD-6030, was prepared and provided to Materials and Processing engineers at MSFC and across the Agency. The training supported developing a pipeline of AM certification SMEs, who received the training and hands-on AM certification experience during this project.

Approaches for fracture control for AM components with uninspectable regions was investigated. These approaches are likely to be based on understanding the flaws that an AM process inherently produces and comparing those flaws to flaws that might be critical for the particular component. Probabilistic damage tolerance analysis tools were investigated as potential approaches for assessing risks associated with inherent AM flaws. Additionally, approaches for assessing risks due to AM process errors were investigated through the use of process failure modes analysis. Summaries of these efforts were presented at international conferences.

This project supported an industry workshop with the American Society for Testing and Materials (ASTM) International AM Center of Excellence on in-situ monitoring technology development, focusing on methodologies for in-situ monitoring qualification and the current state of readiness.

In addition to the workshop effort, experimental in-situ monitoring investigations focused on methodologies for generating realistic AM flaws for the purposes of developing a qualification approach for in-situ monitoring technologies. Builds were conducted with intentionally induced flaws and with build parameter variations, and the specimens were examined with in-situ monitoring, computed tomography (CT), and destructive metallurgical inspection. Results indicated that the in-situ technique was capable of detecting intentionally seeded flaws, but was not capable of reliably detecting more natural AM flaws. Approaches will need to be developed to link in-situ monitoring data with flaw formation in AM processes.

PARTNERSHIPS

Partners included Southwest Research Institute, who provided expertise in probabilistic damage tolerance; the ASTM International AM Center of Excellence, who supported AM process failure modes analysis; and Computational Fluid Dynamics Research Corporation, who helped to develop tools for visualization of in-situ, CT, and metallographic data for flaw detection.

SUMMARY

Additively manufactured components are rapidly being integrated into NASA flight programs and the ability for NASA to appropriately assess components produced with AM will improve the safety and reliability of those missions. Through this project, expertise was developed in new multilaser AM systems and training was prepared to develop SMEs in AM certification. Potential approaches for certification or risk assessment for critical AM components with uninspectable regions were investigated, focusing on AM process characterization, probabilistic damage tolerance, and process failure modes analysis. Finally, in-situ monitoring capabilities were assessed with the goal of developing approaches for qualification of in-situ technologies for AM certification.

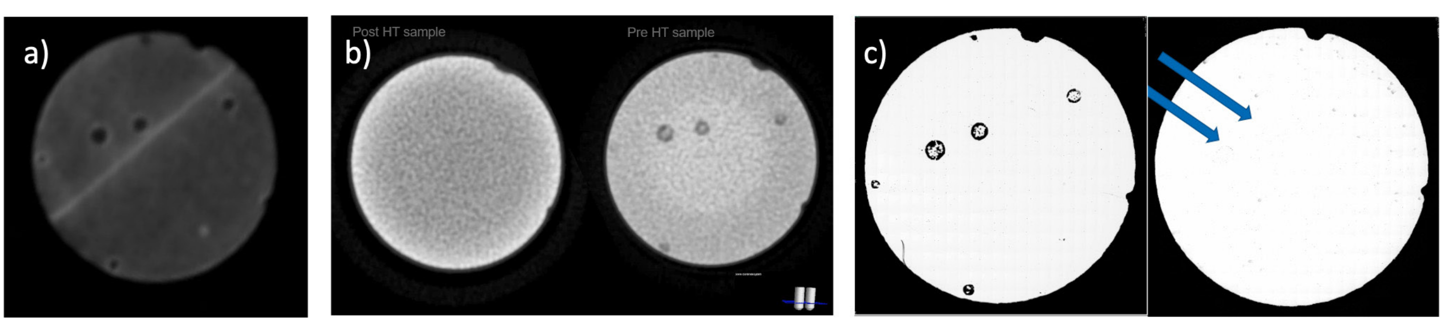


FIGURE 2. Comparison of seeded flaw indications in (a) in-situ monitoring; (b) CT; and (c) metallographic inspection.

Future efforts will include continuing development of expertise in newer and developing AM processes that will be used in spaceflight application and broadening the base of experts in AM certification. Additional work is needed to develop methodologies for AM inherent flaw state characterization and validating the use of probabilistic damage tolerance. Finally, future works will continue to investigate the links between physical AM flaws and in-situ monitoring data indications with the goal of developing approaches for qualification of in-situ monitoring for AM material process control or defect detection.

Principal Investigator(s): Will Tilson; Mallory James; Erin Lanigan; Brian West
Partners: ASTM International; Southwest Research Institute; Computational Fluid Dynamics Research Corporation
Funding Organization(s): Exploration Capabilities
For more information: https://amcoe.org/in-situtechnologyreadiness/; https://ntrs.nasa.gov/api/citations/20230003172/downloads/ESCCMET_Paper_23_Tilson_Wells.pdf

In-Space Manufacturing (ISM) Portfolio

PROJECT OBJECTIVE: The In-Space Manufacturing (ISM) portfolio of projects seeks to develop technologies for long-duration space missions. ISM can provide on-demand fabrication, repair, and recycling for critical systems, habitats, and mission logistics and maintenance. ISM is developing these capabilities by using new technologies and modifying them for use in the space environment.

PROJECT GOAL/DESCRIPTION

The current ISM portfolio includes two projects: On-Demand Manufacturing of Multimaterials (ODMM) and On-Demand Manufacturing of Electronics (ODME). Recycling/reuse, outfitting, and welding are additional areas of interest but are not currently funded outside of NASA Marshall Space Flight Center (MSFC) internal funds.

ODMM developed hybrid additive manufacturing technologies for demonstration aboard the International Space Station (ISS). Systems demonstrated on the ISS could be infused into future missions beyond low-Earth orbit (LEO) to reduce logistics demands and enable a commercial manufacturing ecosystem in LEO. Currently, all tools, spares, and components necessary for use in space must be manufactured on the ground and launched. Implementation of payloads developed by the ODMM project would allow the crew to print components of either metal or plastic on demand at the location of use in microgravity. The ODMM project is closing at the end of fiscal year (FY) 2023 due to reductions in budget.

ODME is critical for NASA's future in-space and planetary expeditions. Electronic devices such as sensors, communication electronics/infrastructure (e.g., cabling), printed energy storage devices, and power generation elements will all need to be manufactured on-demand in an orbital or extraterrestrial habitat environment in order to replace failed components or manufacture new systems on long-duration, earth-independent missions. The primary goal of ODME is to create a deposition system or manufacturing suite as a demo on ISS which is capable of manufacturing a set of selected electronic devices on demand in microgravity. This will require integration and miniaturization of several different materials deposition technologies, new processes and materials for multilayer circuit stacking, postprocessing technologies, and development of in-situ functional verification methods for manufactured devices.

FIGURE 1. ISM Patch.

APPROACH/INNOVATION

The current ISS logistics model is heavily dependent upon orbital replacement units for system-based repair and maintenance. Logistics support and habitat outfitting is a significant challenge for sustainable, extended human operations in space, especially for missions beyond LEO where timely resupply or abort in the event of emergency would not be possible. The ODMM and ODME projects have partnered with Redwire Space Technologies, Inc. (formerly known as Techshot, Inc.) to develop a system capable of demonstrating the manufacturing of metal, polymer, and electronic components aboard the ISS.

The Redwire-developed system consisted of three modules housed in a full EXpedite the PRocessing of Experiments to the Space Station (EXPRESS) rack. The Printer Module prints metal, polymer, and electronic parts. The Furnace Module and Process Gas Drawer allowed for the postprocessing of printed metals by thermally removing solvent and binders to produce solid metal parts. The Printer Module also contained a toolhead for subtractive manufacturing and part finishing via a mill.

The limitations of ISM of electronics include the lack of space for normal ground-based manufacturing systems, challenging extreme environments, lack of available power for thermal processing, and a need for manufacturing operations to run autonomously as much as possible. The ODME-advanced toolplate, part of the Redwire-developed system, has optimized deposition tools for printing a wide range of electronic and semiconductor materials in microgravity. These tools will also allow for very precise deposition of high-density circuitry down to less than 50 microns of feature size.

In addition, ODME is developing novel directed energy curing processes for the electronics inks and materials that will be printed. Directed energy postprocessing means very low power requirements, increased processing speed, and the elimination of bulky, heavy thermal ovens for postprocessing.

RESULTS/ACCOMPLISHMENTS

ODMM developed a micro-furnace specifically designed for use on the ISS in an EXPRESS rack. This required a significant reduction in size so that the furnace would fit in the rack. The designed furnace contained a bigger hot zone and higher temperature capabilities than any current equipment on the ISS. In addition, the furnace power draw needed to be reduced from 5 kW in the prototype to 2 kW. At the time of publication, the furnace power was approximately 2.25 kW. However, several mitigation actions were planned, including the development of a thermal model to inform locations of thermal leakage, changing the sintering profile to sinter at lower temperature, and the development of alternative alloy pastes that sinter at a lower temperature.

A Technology Maturation Plan (TMP) for the on-demand manufacturing of metal parts in space was developed by the engineering project team. The purpose of the TMP was to document the major technical accomplishments necessary to develop manufacturing systems from the current phase through infusion into mission architecture for surface or transit applications and show the interactions between technology development efforts.

ODME reports several accomplishments in 2023:

- Evaluation of Thin Film (<25 microns) Deposition systems for microgravity. Two different deposition systems were evaluated during the year, with a total of four (4) Parabolic Flight Campaigns utilized to evaluate these systems in zero gravity. One system was an Electrohydrodynamic Inkjet deposition system, which is being incorporated into our space manufacturing of semiconductor plans.
- ODME and Auburn University have collaborated to develop new materials and processes for multilayer fabrication of electronic circuits on flexible substrates. This research will enable the in-space fabrication of wearable, flexible wireless sensors for astronaut crew health monitoring.
- New on-demand printing technologies for power generation and energy storage devices to support ODME-fabricated devices. These technologies will eliminate the need for external power or batteries for printed sensor networks and wearable electronic devices. These technologies include printed thermoelectric devices, printed power generation antennas for harvesting power from Wi-Fi electromagnetic radiation, and supercapacitors for storing energy.
- A new flexible design of the Crew Health Wearable Sensor for cortisol (crew stress) monitoring was completed through prototype and pre-production manufacturing and testing.

PARTNERSHIPS

ISM, through its ODME and ODMM projects, maintains numerous partnerships. As of this writing, ISM is partnered with at least 20 academic institutions, nine NASA centers, and six aerospace research companies.

SUMMARY

The two ISM projects were quite successful in 2023. The ODMM project aimed to development and demonstrate the feasibility of a low-gravity, on-demand manufacturing system for metal and polymer parts on the ISS. Although the ODMM project is closing at the end of FY 2023, it is anticipated that the technologies developed will be utilized on future endeavors. The ODME project is developing leading-edge deposition and materials technologies for manufacturing on the ISS and other LEO microgravity applications, and these innovative technologies will be ported on future manufacturing systems for the lunar surface, Gateway, and extended missions to Mars and beyond. Already, one new project will be utilizing ODME deposition and materials technology for manufacturing solar cells on the lunar surface. In addition, internal MSFC funds are being leveraged to identify and perform low Technology Readiness Level development on technologies relevant to the ISM strategy, such as welding and cutting. Many additional infusion opportunities await, as ISM is enabling the future of long-term space missions and human sustainability in space.

Principal Investigator(s): Jennifer Jones; Curtis Hill; Zach Courtright
Funding Organization(s): Game Changing Development

Magnetic Field-Assisted Finishing of NASA HR-1 Internal Channels for Liquid Rocket Engine Components

PROJECT OBJECTIVE: Use oscillatory magnetic-field assisted finishing (MAF) to develop mechanical finishing technology for large-scale thrust chambers with multiple cooling channels manufactured using laser powder directed energy deposition (LP-DED).

PROJECT GOAL/DESCRIPTION

LP-DED shows potential for fabrication of large-scale thrust chambers, nozzles and heat exchangers with an array cooling channels. However, LP-DED has higher surface texture than traditional manufacturing techniques and development of an internal surface finishing process with limited material removal is attractive to optimize the design. The goal of this project is to use oscillatory MAF to develop mechanical finishing technology that enables fine control of both surface characteristics (e.g., roughness, waviness, and texture) and material removal. This process will be tested on internal channels of liquid rocket engine components made from iron (Fe)-nickel (Ni) alloy NASA HR-1 using LP-DED.

APPROACH/INNOVATION

The use of oscillatory MAF improves flow-channel performance by enabling the reduction of both roughness and waviness of internal channels while controlling the material removal. Oscillatory MAF utilizes a magnetic field to both exert finishing force and to control the finishing tool motion. In this process, permanent magnet finishing tools are inserted into a channel along with abrasive slurry. Magnets positioned outside of the channel called "driving magnets" attract the magnet finishing tools while pressing the abrasive slurry onto the inner surface of the channel. When the workpiece is oscillated, the magnet finishing tools with the abrasive slurry experience relative motion against the internal channel surface and finish the surface. Translating the driving magnets along the channel enables finishing of the entire channel surface. The innovation in this project is the use of magnetic field to manipulate finishing tools that allow access to difficult-to-polish areas (e.g., internal channels) and fine control of material removal from the desired locations. The finishing characteristics of the developed oscillatory MAF process and the performance of internal channels finished using the developed process are to be analyzed against the relevant specifications.

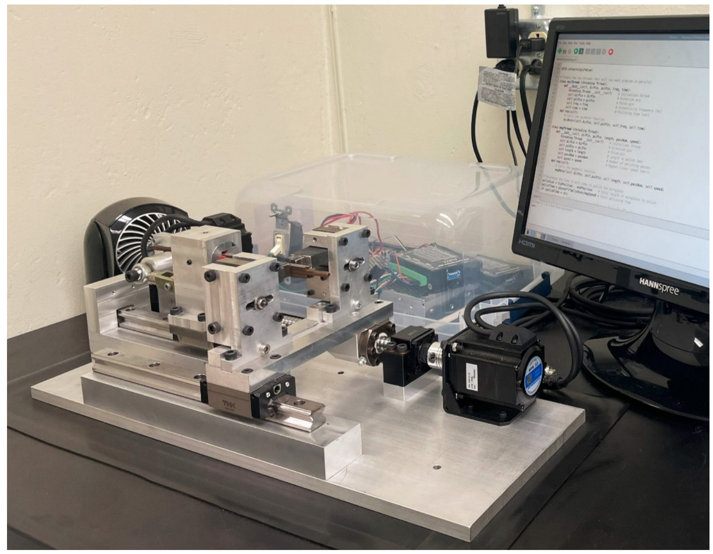


FIGURE 1. Oscillatory MAF machine.

RESULTS/ACCOMPLISHMENTS

The NASA HR-1 Fe-Ni alloy components with internal channel surfaces made using LP-DED consisted of high-frequency asperities (i.e., roughness) arising from loosely adhered particulates deposited on low-frequency undulations (i.e., waviness) from the deposited layers. The target is to remove both the high- and low-frequency surface irregularities with minimal material removal. During the fiscal year (FY) 2022 Cooperative Agreement Notice (CAN) project, a team effort between the University of Florida (UF) and NASA Marshall Space Flight Center (MSFC) made significant progress toward that target. First, a new processing principle using oscillatory MAF was developed for internal finishing of the NASA HR-1 channels manufactured provided by NASA. Second, finishing equipment to realize the principle was developed at UF (Fig. 1). To finish the internal channels, it is essential to generate relative motion between the finishing tool and the channel surface and to deliver abrasive for cutting the surface material. This study identified the dimensions and arrange-

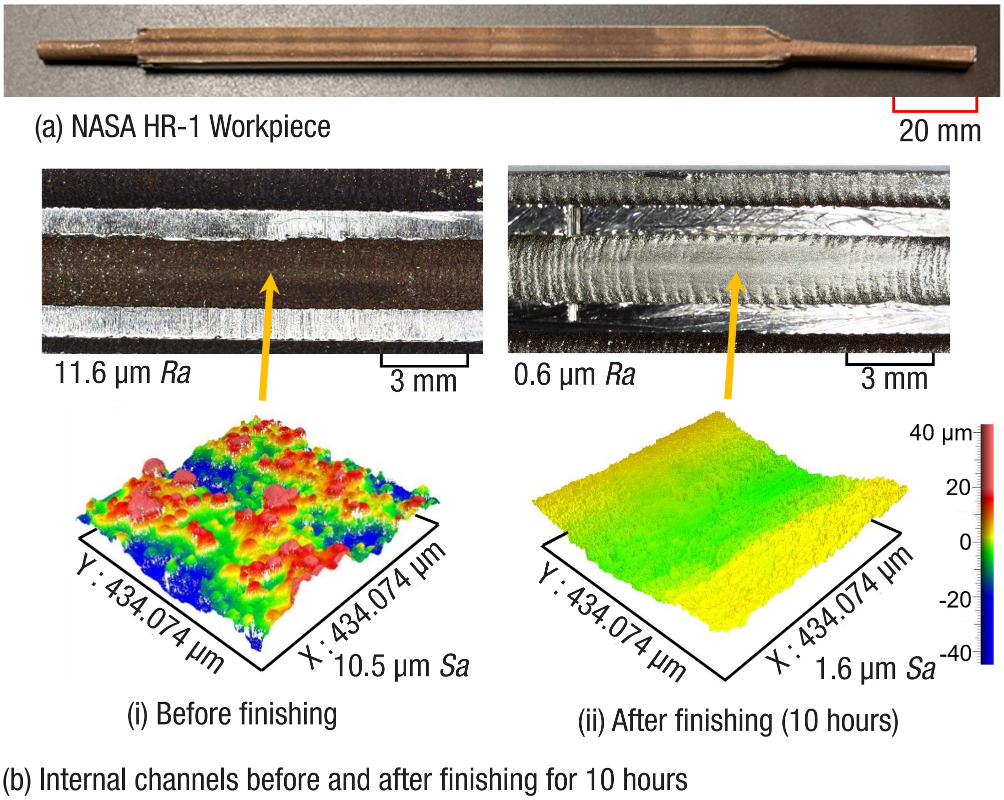


FIGURE 2. NASA HR-1 workpiece and internal channels before and after finishing.

ment of the driving magnets and magnet finishing tools for generating the tool motion needed for finishing. In addition, effects of the diamond abrasive and lubricant on the material removal from the channel surfaces were identified. Finishing experiments demonstrated the feasibility of the developed oscillatory MAF process to reduce the arithmetic average surface roughness (Ra) from 10.5 µm to 1.31 µm (Fig. 2). The average waviness (Wa) was reduced from 27.8 µm to 6.5 µm. The maximum change in the channel wall thickness was 70 µm (from 1.10 mm to 1.03 mm).

PARTNERSHIPS

A team effort between UF and MSFC reveals knowledge specific to the developed polishing tool, magnetic manipulation of the polishing tool, and material removal of LP-DED internal coolant channels.

SUMMARY

The FY 2022 CAN project supported the development of the oscillatory MAF process that has great potential for finishing internal channels in liquid-rocket-engine-nozzle components. The developed process was tested on straight NASA HR-1 channels manufactured using LP-DED (though the principal can also be applied to curved channels), and the process feasibility to smooth the channel surfaces was successfully demonstrated. Further development of this process will include internal finishing of entire channel surfaces including flow testing to determine the effect of surface roughness on flow performance.

Principal Investigator(s): Hitomi Greenslet, University of Florida; Paul Gradl
Partners: University of Florida
Funding Organization(s): Cooperative Agreement Notice

On Demand Manufacturing of Electronics in Space (ODME)

PROJECT OBJECTIVE: The goal of this project is to develop a manufacturing system capable of printing a range of electronic devices, sensors, and semiconductors in a microgravity environment.

PROJECT GOAL/DESCRIPTION

The availability of on-demand manufacturing of electronic devices is a critical element for NASA's future in-space and planetary expeditions. Electronic devices such as sensors, communication electronics/infrastructure (e.g., cabling), printed energy storage devices, and power generation elements will all need to be manufactured on-demand in an orbital or extraterrestrial habitat environment in order to replace failed components or manufacture new systems on long-duration, Earth-independent missions. Currently, many devices that fall into these categories have been demonstrated using ground-based processes both by NASA and by commercial partners, but the systems (e.g., printers) used to make these devices cannot be readily flown and the processes and materials have not been demonstrated in microgravity.

The primary goal of this project is to create a deposition system or manufacturing suite as a demo on the International Space Station (ISS) that is capable of manufacturing a set of selected electronic devices on demand in microgravity. This will require integration and miniaturization of several different materials deposition technologies, new processes and materials for multilayer circuit stacking, postprocessing technologies, and development of in-situ functional verification methods for manufactured devices. This work aligns directly with NASA's 2020 Technology Taxonomy for TX 12, "Materials, Structures, and Manufacturing."

Project Goals:

1. The primary goal of this project is to create a deposition system or manufacturing suite as a demo on ISS which can manufacture a set of selected electronic devices on demand in microgravity.
2. Development of integration and miniaturization of several different materials deposition technologies, new processes and materials for multilayer circuit stacking, and postprocessing technologies.
3. Development of new processes, materials, and semiconductor devices for commercial manufacturing in space for terrestrial markets. Stimulation of low-Earth orbit LEO economy for semiconductors.

APPROACH/INNOVATION

The limitations of in-space manufacturing of electronics include the lack of space for normal ground-based manufacturing systems, challenging extreme environments, lack of available power for thermal processing, and a need for manufacturing operations to run autonomously as much as possible.

The ODME project is developing a multimaterial 3D printer with optimized deposition tools for printing a wide range of electronic and semiconductor materials in microgravity. These tools will also allow for very precise deposition of high-density circuitry down to less than 50 microns of feature size.

In addition, ODME is developing novel directed energy curing processes for the electronics inks and materials that will be printed. Directed energy postprocessing means very low power requirements, increased processing speed, and the elimination of bulky, heavy thermal ovens for postprocessing.

ODME incorporates a great deal of collaborative research to accomplish the objectives of the project. During 2023, ODME collaborated with nine NASA Centers and 17 research universities.

RESULTS/ACCOMPLISHMENTS

During the second year of the ODME project, many accomplishments have been completed. The following accomplishments are highlighted:

1. Evaluation of Thin Film (<25 microns) Deposition systems for microgravity. Two different deposition systems were evaluated during the year, with a total of four parabolic flight campaigns utilized to evaluate these systems in zero gravity. This system was an electrohydrodynamic inkjet deposition system, which is being incorporated into our plans for in-space manufacturing of semiconductors.

2. ODME and Auburn University have collaborated to develop new materials and processes or multilayer fabrication of electronic circuits on flexible substrates. This research will enable the in-space fabrication of wearable, flexible wireless sensors for astronaut crew health monitoring.
3. New on-demand printing technologies have been developed for power generation and energy storage devices to support ODME fabricated devices. These technologies will eliminate the need for external power or batteries for printed sensor networks and wearable electronic devices. These technologies include printed thermoelectric devices, printed power generation antennas for harvesting power from wi-fi electromagnetic radiation, and supercapacitors for storing energy.
4. A new flexible design of the Crew Health Wearable sensor for cortisol (crew stress) monitoring was completed through prototype and pre-production manufacturing and testing (Figure 1).

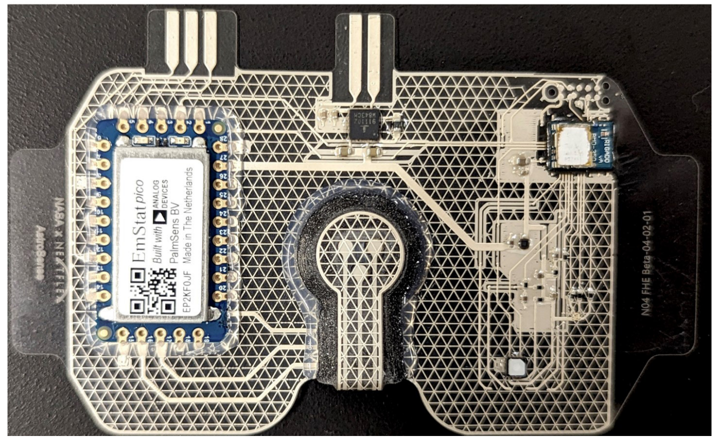
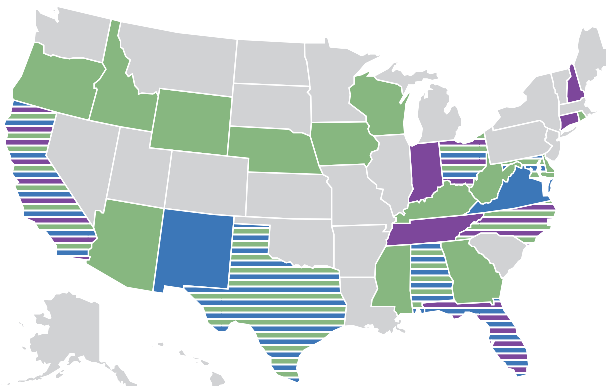


FIGURE 1. ODME-developed AstroSense Wireless Wearable Sensor for Astronaut Crew Heath Monitoring.

PARTNERSHIPS

The ODME team has worked with nine NASA Centers and with more than 35 external partners across academia, industry, and government. The full list of partners and a map showing the locations of partners is shown in Fig. 2.

ODME Partnerships — 2023



Exploration & Science

NASA Exploration and Support "In Space for Space" development

- ECLSS Sensors
- Wearable sensors
- Printed Power & Energy
- Logistics — spares and upgrades for missions

Commercialization

Support "In Space for Earth Applications" development

- Semiconductors

Academic

- University of Louisville
- University of Alabama, Huntsville
- Appalachian State
- Auburn University
- Boise State
- Georgia Tech
- Cal Tech
- Iowa State University
- Florida A&M University
- Oregon State University
- West Virginia University

NASA Centers

- Marshall Space Flight Center
- Ames Research Center
- Johnson Space Center
- Kennedy Space Center
- Goddard Space Flight Center
- Jet Propulsion Laboratory
- Glenn Research Center
- Langley Research Center
- Armstrong Flight Research Center

Industry/Government

- Techshot
- Redwire Space
- Cornerstone Research Group
- LambdaVision
- Faraday Incorporated
- Laboratory for Physical Sciences
- Intel
- Fujifilm
- Axiom Space
- ISS National Lab
- Goeppert
- NextFlex
- nScrypt
- Multi3D

FIGURE 2. ODME Partnerships from Academia, Government and Industry, and other NASA Centers in 2023.

SUMMARY

The ODME project is developing leading-edge deposition and materials technologies for manufacturing on the ISS and other low earth orbit microgravity applications, but these innovative technologies will be ported on future manufacturing systems for the lunar surface, Lunar Gateway, and extended missions to Mars and beyond.

Already, one new project will be utilizing ODME deposition and materials technology for manufacturing solar cells on the lunar surface.

ODME is leading NASA's development of technologies that are required to enable in-space manufacturing of semiconductors in LEO.

Principal Investigator(s): Curtis Hill
Funding Organization(s): Game Changing Development

The Keystone of Lunar Infrastructure: Wire-Arc Additive Manufacturing

PROJECT OBJECTIVE: To develop the cold metal transfer wire arc additive manufacturing process with aluminum alloys as a method for lunar infrastructure, outfitting, and manufacturing.

PROJECT GOAL/DESCRIPTION

The primary goal of this project was the development of stable and effective processes, complex geometry, and vacuum welding environment evaluation for novel cold metal transfer (CMT) wire arc additive manufacturing (WAAM) with aluminum alloys as a pivotal step in implementing it as a key manufacturing technology for lunar infrastructure. WAAM is a high value process for off-world advanced manufacturing for large-scale structures and applications as it does not require special containment to reduce explosion hazards such as powder-based additive manufacturing (AM) processes and feedstock. CMT welding as an AM process is still young, but as a reciprocating wire welding process, it may overcome challenges other fusion-based additive and welding processes may experience in alternate gravity and vacuum environments. This is due to the reduced heat input of CMT as compared to traditional fusion processes. This project addresses the use case of CMT-WAAM as an advanced manufacturing method through the printing of a “bracket” demonstrator with complex geometry (including overlaps, intersections, and tapers) from a solid model, and additionally investigating applicability to the intended service environment through experimental welding and AM in high vacuum.

APPROACH/INNOVATION

CMT-WAAM with aluminum alloy feedstock is relatively new, so this project firstly required considerable process development to determine parameters for stable AM building of these material families. Intended materials developed and tested included AA2319, AA5183, AA2050, and specialty B218 wire. Planned testing of the printed structures included, but was not limited to, uniaxial tensile testing, macrographs of the layered depositions to examine microstructure, and heat treatment development where applicable. The key parameters to determine success of the project include analysis of the deposited material compared to the intended geometry and efficiency of the process compared to state-of-the-art subtractive manufacturing. Future testing recommended for this material includes dynamic materials testing and characterization of the thermal gradients with respect to location in the AM component.

The CMT-WAAM process has been verified to operate well within a terrestrial environment with nominal gravity and shielding gas, but little is known about its capability within a vacuum environment and if a stable arc is achievable within this setting. This investigation into this unknown began by designing a new three-axis tabletop system with vacuum-rated stepper motors to achieve AM in the NASA Marshall Space Flight Center (MSFC) V20 vacuum chamber. Controls include a bespoke LabVIEW based motion system to program the AM walls. The tabletop AM system can be repurposed after this year’s project as an additional process development station—increasing capabilities at MSFC—and parabolic flight payload to test the AM process in alternate gravity environments.

RESULTS/ACCOMPLISHMENTS

The team achieved design, analysis, and fabrication of the tabletop printing system for use in vacuum, shown in Fig. 1. The LabVIEW controls system was completed and is operational with respect to motions of the three axes. Challenges from procurement and shipping delays resulted in the schedule of testing in the vacuum environment outside of the current fiscal year, but this is a planned activity for the MSFC ET20 Experimental Fluids and Environmental Test Branch and MSFC EM32 Metal Processes and Manufacturing Branch teams to perform in November 2023.

Process development for various AM feedstocks was performed and included aluminum alloys AA2319, AA5183, and AA2050. The AA5183 printed parts show promise to meet the desired cast material properties of wrought comparable alloy AA5083; however, samples of AA2319 were unable to be tested by the end of the fiscal year to determine their initial properties. An initial heat treatment of this material was developed by the MSFC EM31 Materials Science and Metallurgy Branch; however, it requires further iteration with the developed time frames to elucidate a further response from the material. This in currently in work and is

FIGURE 1. Assembled test fixture for printing in high vacuum.

estimated to be completed in December 2023. The AA2050 aluminum-lithium feedstock was friction-stir extruded from wrought billet, demonstrating potential for in-space reuse and recycling of debris and retired hardware. These walls will undergo nondestructive evaluation to characterize macro-level cracks, microcracking, and porosity content before being sent for subscale tensile testing, microhardness testing, and macrograph examination.

Freeform structures were printed with manual point-to-point methods, then as the integrated cell matured the team was able to print an arbitrary bracket geometry from a computer-aided design (CAD) solid model with AA2319 (Fig. 2). This was then scanned with structured light to capture a point cloud of the resulting structure, which was then compared back to the original intended model. Both underbuilding and overbuilding compared to the nominal geometry occurred in most areas of the build, in a range of –9.8% to 34%. The original target of 15% was not achieved uniformly, indicating further process development to refine the deposition should be performed in order to minimize costly postprocessing. Evaluation of the buy-to-fly (BTF) ratio and cost of the process compared to the state-of-the-art subtractive manufacturing of the bracket geometry shows a reduction in cost and BTF ratio from 8.7:1 to

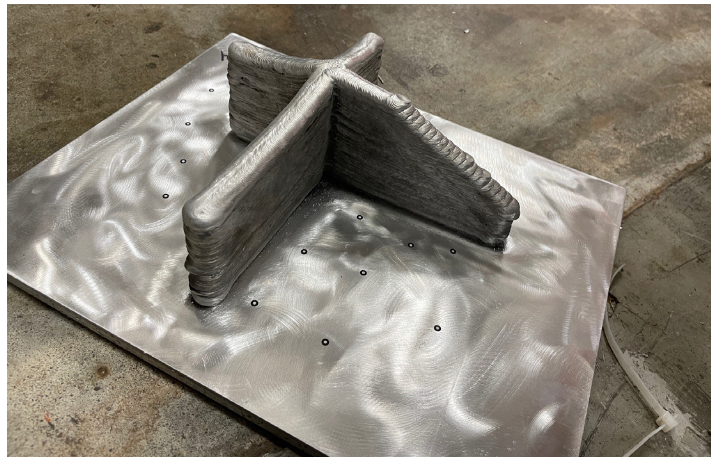


FIGURE 2. Bracket demonstrator printed with AA2319 from CAD model.

1.32:1. Further optimization of the material and process would further improve this business case.

PARTNERSHIPS

The project has been a great partnership with the team members from MSFC EM32, MSFC ET20 testing facility and personnel, and those from the MSFC ET50 Special Test Equipment Design Branch to design and analyze the 3-axis vacuum welding table structure. The University of South Carolina provided the AA2050 wire.

SUMMARY

Considerable effort into process development was accomplished for CMT-WAAM of aluminum feedstock alloys AA5183, AA2319, and AA2050. The proof of concept for aluminum CMT-WAAM is successful to demonstrate a decreased cost and BTF ratio compared to the state-of-the-art. Progress in the maturity of the cell at MSFC was able to achieve printing of geometry directly from a computer-designed model. This effort was also able to demonstrate a use case of reuse/recycling of aluminum structures for in-space manufacturing through acquiring friction-stir extruded feedstock from aluminum-lithium wrought alloy AA2050 and deposition of this with the CMT-WAAM process. Future development and optimization of this technology will continue and includes testing of the process in high vacuum, weld development for additional alloys, and large-scale demonstrators.

Principal Investigator(s): Ilana Lu
Partners: University of South Carolina
Funding Organization(s): Center Innovation Fund

Metallic Environmentally Resistant Coatings Rapid Innovation Initiative (MERCRII)

PROJECT OBJECTIVE: Development of coated conventionally and additively manufactured materials for tribological and radiation resistance improvement at lunar and martian surfaces.

PROJECT GOAL/DESCRIPTION

Lightweight alloys such as aluminum (Al) and titanium (Ti) are often specified for space systems to minimize mass. However, such alloys have poor tribological response (i.e., high friction and wear) especially in abrasive lunar and martian surface environments. To address this weakness, we propose to develop advanced wear- and radiation-resistant coatings for lightweight parts for use in lunar and martian architectures, and to design unique wear characterization techniques comparing different lunar simulants. The materials will include Al and Ti alloys as substrates and cold-sprayed and plasma-sprayed boron nitride (BN)-based and nickel-titanium (NiTi) metallic coatings.

APPROACH/INNOVATION

Two coatings will be developed for the ubiquitous core spacecraft materials Al and Ti: BN-based coatings and NiTi-based coatings. Both coatings exhibit high wear resistance, and the BN-based coatings are expected to provide additional radiation shielding improvement. BN-based nanomaterials are well known for their excellent mechanical and thermal properties, high impact resistance, low friction coefficient, chemical inertness, corrosion resistance, and good interfacial adhesion with Al and Ti metals.

It has been observed that coatings that perform best in sliding are not always the hardest, but rather those with a high hardness/elastic modulus ratio. NiTi-based materials offer a unique combination of high hardness, low modulus, and extensive elastic deformation range resulting in superior static indentation load capability. Based upon laboratory static load tests performed at NASA Glenn Research Center (GRC), bearings made with NiTi alloys provide up to ten times higher tolerance to denting damage compared to conventional steel bearings. This novel bearing material has the potential to be highly resistant to damage caused by lunar and martian dust.

The coatings will be applied through two process technologies: atmospheric plasma spray (APS) and vacuum plasma spray (VPS). The coatings will be exposed to thermal cycle and radiation environments and subjected to tribological tests in the presence of lunar dust after exposure, to guarantee the survival of the coatings to the extreme space environment. The coating technology will be demonstrated to enable the use of both conventionally manufactured (CM) as well as additively manufactured (AM) mechanisms. The coatings will be applied to three mechanisms of action: joint, torsional, and sliding, which will be fabricated from Al and Ti, both CM and AM. These mechanisms of action encompass commonly utilized mechanisms and will enable this technology development effort to create optimized advanced wear coating options that will protect an array of future mechanisms for the Moon, Mars, and beyond.

RESULTS/ACCOMPLISHMENTS

Hardness Comparison

Irradiated coatings show higher surface hardness than virgin coatings in the cross-section and across the layers. This is consistent with the literature that shows black dot defects, dislocation clusters and dislocation loops after irradiation, which increase surface hardness.[1]

Wear Rate

The wear rate for irradiated coatings show the same trend as that seen for virgin conditions, with Ti/2% hexagonal boron nitride (hBN) performing better than Ti/10% hBN coatings. Coatings exposed to combined radiation and thermal cycle exposures show less wear compared to coatings exposed to radiation only (brittle fracture by hardening) and coatings that see thermal cycles only (cyclic thermal stress).

Porosity increases for APS coatings (375% for radiation only and 515% for combined exposures) and for VPS coatings (58%) due to cracking and brittle fracture by radiation, and crack widening and propagation due to thermally induced stress from thermal exposure.

- Scanning electron microscopy results show microstructural cracking and delamination from radiation-induced brittle fracture.
- Thermal cycles induce cyclic thermal stresses, which opens cracks and accelerate crack propagation.
- Irradiated coatings show high surface hardness compared to virgin coatings in the cross-section and across the layers. Literature shows black dot defects, dislocation clusters, and dislocation loops after irradiation, which increase surface hardness.
- Wear rate shows the same trend as virgin conditions, with Ti/2% hBN performing better than Ti/10% hBN coatings.
- Coatings with combined exposures show improvement in wear compared to coatings exposed to radiation only (brittle fracture by hardening) and coatings that see thermal cycle exposure only (cyclic thermal stress).
- Neutron shielding tests indicate an 8% increase in linear and mass absorption coefficients for the coatings subjected to combined exposures.

PARTNERSHIPS

NASA Langley Research Center (LaRC): Dr. Park and Dr. Chu serve in this Early Career Initiative (ECI) project as the LaRC team leads to develop optimized BN-based metallic matrix composites and to study radiation effects both experimentally (neutron) and computationally (galactic cosmic ray and solar particle event). They provide mentorship to LaRC's early career employees and serve as technical mentors for the project.

NASA GRC: Dr. Howard, Dr. Jimenez, and Dr. Dellacorte provide technical mentorship and input for space mechanisms, serving as mentors for the development of new tribological materials and solutions for aerospace mechanisms (e.g., testing design, forensic engineering).

Florida International University (FIU): On the ECI, FIU is responsible for developing BN-based coatings using APS. The tasks include feeder stock powder preparation and optimization of spraying parameters for the spraying technique. FIU is also responsible for the high-pressure simulant erosion testing to investigate the effects of lunar/martian dust on the rover external surfaces. Dr. Agarwal and Dr. Zhang are leading the effort with Abhijith Kunneparambil as PhD student.

Plasma Processes, LLC: Plasma Processes provides NiTi intermetallic coatings and BN-based coatings on AM and CM aluminum and titanium alloy test panels as fabricated by NASA Marshall Space Flight Center. Coatings will be applied using existing cold spray and plasma spray equipment at Plasma Processes. Plasma Processes is in charge of providing a vacuum chamber for simulated space environment to test the mechanisms in the presence of lunar dust. Plasma Processes brings 27 years of aerospace coating production experience to the team. Additionally, Mr. Tim McKechnie and Mr. Michael Renfro are key technical personnel available to support this work. Upon technology maturation, Plasma Processes is interested in working to license the technology for commercial use.

SUMMARY

Economical and durable NiTi- and BN-based metallic coatings for prolonged use on the lunar and martian rovers are developed using VPS and APS techniques. Additionally, AM Al and Ti alloys have been tested. Wear tests include three-body abrasion and surface erosion (to simulate Mars storms). Test results also demonstrate differences in wear for vacuum tests compared to ambient tests and demonstrate the effects of particle radiation on material wear resistance. Finally the coatings will be demonstrated on simulated space environments applied to mechanisms relevant to the Human Landing System and in-space manufacturing.

References

1. Zhu, Yabin, Jianlong Chai, Zhiguang Wang, Tielong Shen, Lijuan Niu, Shufen Li, et al., "Microstructural damage evolution of (WTiVNbTa)C5 high-entropy carbide ceramics induced by self-ions irradiation," *Journal of the European Ceramic Society* vol. 42 (2022) 2567–2576

Principal Investigator(s): Sara Rengifo
Partners: Plasma Processes, LLC; Florida International University; NASA Langley Research Center; NASA Glenn Research Center
Funding Organization(s): Early Career Initiative
NTR/Patent Number: 1663169943
For more information: Development of Coated AM Materials for Tribological and Radiation Resistance Improvement at Lunar and Martian (sharepoint.com)

Optimized Isogrid Structures Using Hybrid Additive Manufacturing

PROJECT OBJECTIVE: To demonstrate fabrication of an isogrid structure using hybrid additive manufacturing (AM) and to test the subsequent structure against a conventionally machined structure.

PROJECT GOAL/DESCRIPTION

The goal of this project is to further develop generative engineering and large-scale AM for a more material-efficient, cost-effective and streamlined approach to manufacturing isogrid structures. Big Metal Additive (BMA) will produce multiple full-scale isogrid panel sections approximately 18 × 36 in using their metal AM process for test and evaluation at NASA Marshall Space Flight Center (MSFC). Specifically, mechanical testing will be performed to compare the following three designs: (1) isogrid machined from billet, (2) the same geometry produced using AM, and (3) an isogrid panel designed using topology optimization and produced using AM.

The goal of this project is to show the viability of AM to reduce material waste, product cost, and leadtime for relevant hardware geometries such as isogrid panels and domes while achieving comparable performance to legacy components.

Primary Objectives:

- Compare mechanical performance of AM aluminum alloy AA2319 isogrid panels with conventional machined AA2219 isogrid panels
- Design an efficient isogrid patten using topology optimization that takes advantage of the AM process capabilities
- Produce the topology optimized geometry, perform testing, and compare results to legacy isogrid pattern
- Analyze at a high level what impacts a scaled AM approach would have on future optimized load bearing structures for U.S. industry and MSFC.

APPROACH/INNOVATION

Manufacturing isogrid structures for space applications is an expensive process with long leadtimes and poor material yield. BMA is developing a generative engineering approach to large metal structures, combining topology optimization with the ability to create complex structural components for commercial and government applications. Large format metal hybrid AM and generative engineering are well positioned to provide significant, if not massive schedule, cost, and material savings for the Human Landing System, Habitats, and Common Berthing Mechanisms. These same cost and schedule advantages are applicable across many U.S. industry applications where large, long leadtime aluminum billets are reduced to low yield structural products while creating significant waste from traditional machining operations. The automotive industry, commercial space, and commercial aerospace are all eager to realize these advantages. BMA has current automotive, space, and aerospace customers that are pushing to adopt this approach in their products.

BMA will collaborate with MSFC experts through multiple stages of the project. The first stage of the project will determine the mechanical tests and heat treatment strategy. The BMA team will move into design and simulation of a MSFC test geometry to path plan and simulate the production of traditional test coupons, followed by production of these articles. The final stage of the project will use generative engineering to finalize the path planning and simulation of the optimized coupon geometry, followed by the optimized coupon design deliverable. The optimized coupons will be produced after the traditional coupon. All test articles will be thoroughly inspected prior to the postprocessing phase of heat treatment and final machining, prior to the final coupon deliverables. Test and analysis will occur at MSFC, and the project will conclude with a Final Report deliverable.

RESULTS/ACCOMPLISHMENTS

During the 2023 calendar year, BMA and MSFC have completed the following deliverables for this project:

- Design and simulation of all coupon hardware described in the approach above (Fig. 1)
- Design and demonstration of AA2319 heat treatment schedule

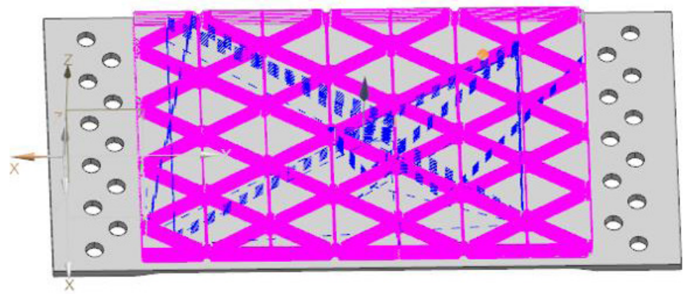


FIGURE 1. Simulation of the isogrid AM build path.

- Hybrid AM print of AA2319 coupons for heat treatment and mechanical property testing
- Hybrid AM fabrication of two pathfinder articles built with AA2319
- Hybrid AM fabrication of one legacy isogrid panel (18 × 36 in) produced using AA2319 wire (Fig. 2)

Key Lesson Learned: During examination of optimization of the isogrid geometry, it was determined that the legacy design was already optimized for structural/weight considerations and the best form of optimization is increasing producibility through the manufacturing methods.

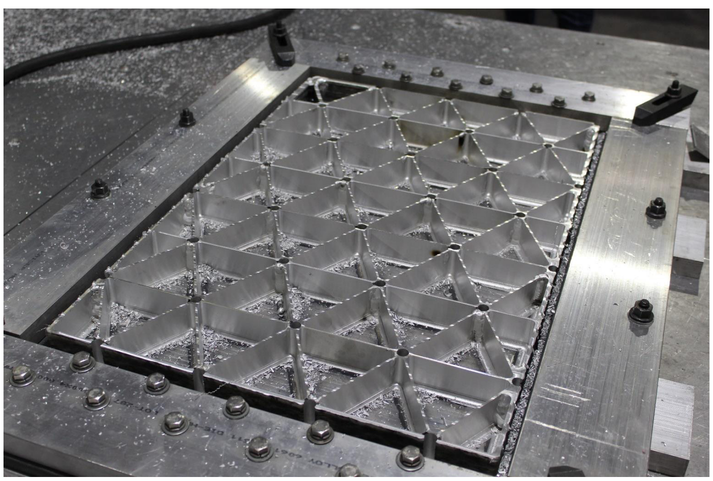


FIGURE 2. Final isogrid panel built with hybrid AM.

PARTNERSHIPS

BMA is a manufacturer of parts using hybrid AM process, which utilizes wire-arc directed energy deposition. BMA also specializes in manufacturing complex, optimized geometries. They have multiple government and commercial contracts to produce prototypes, first articles and production components. BMA is the primary producer of test hardware for this Cooperative Agreement Notice (CAN) project. There are several plans to continue collaborating with BMA, including continuation of this CAN project and a fiscal year 2024 Tipping Point award.

SUMMARY

BMA has demonstrated their hybrid AM process, for this application, through production of multiple coupons and pathfinder articles. Due to delays in schedule the testing arm of this project has not begun at MSFC. However, a no cost extension has been provided for this contract to continue work through January 2024. BMA plans to deliver the coupons for testing in October 2023. MSFC will be conducting heat treatment on the coupons delivered by BMA. Following heat treatment, MSFC will be conducting mechanical testing on said coupons.

Principal Investigator(s): William Evans; Chris Protz; Parker Shake
Partners: Big Metal Additive
Funding Organization(s): Cooperative Agreement Notice

Freeform Fabrication of Large Aluminum Structures using Large Scale Direct Metal Deposition (DMD) Additive Technique

PROJECT OBJECTIVE: To demonstrate large-scale additive manufacturing (AM) of aluminum alloys for spaceflight applications.

PROJECT GOAL/DESCRIPTION

The primary goal of this proposal is to demonstrate freeform fabrication of large aluminum structures for usage in space industry vehicles. This will be achieved by performing a trial of three select aluminum alloys, identifying the most suitable alloy, and finally building a large aluminum structure using a downselected alloy chosen from the initial three alloys investigated. The three alloys being tested in this program are alloy AA2219, alloy AA2050, and Scalmalloy. The freeform fabrication will be performed using DM3D Technologies's proprietary Direct Metal Deposition (DMD®) technology. The secondary goal of the proposal is to demonstrate that this technology is feasible for such thin-walled structures and to further realize significant cost savings and schedule improvements over traditional manufacturing techniques for large components such as propellant tanks. The main objectives of this program were as follows:

1. Evaluation and downselection of three different aluminum alloys for DMD printing of large structures
2. Process optimization and manufacture of test coupons for distortion and mechanical property evaluation
3. Performance of thermal, residual stress and distortion simulations for large structures
4. DMD printing of a large aluminum structure to demonstrate feasibility

APPROACH/INNOVATION

Large aluminum parts are widely used in space industry for launch systems, human lander systems, habitats, and satellites. These could be fuel tanks, ring forgings and other parts. Current manufacturing processes for aluminum dome structures involve forging, spin forming, and welding operations that are expensive and require long leadtime. Currently there is only one supplier in the United States that can spin form large structures. Developing an alternative manufacturing technique for such components will be of immense benefit to not only NASA, but the entire space industry in general. In addition, the US Department of Defense also has similar needs for large aluminum components and a successful development of laser-powder directed energy deposition technology will reduce cost and leadtime for these components. At the time of this project, aluminum alloys are not widely used by industry for large-scale AM techniques. Most applications utilize smaller format AM or have focused on aluminum alloys not readily utilized for space flight hardware.

RESULTS/ACCOMPLISHMENTS

During this project, three aluminum alloys were tested for their response to the large-scale AM process and to post-build heat treatment. Their mechanical properties were also determined via tensile testing. Of the three alloys, AA2219 exhibited the best response to the AM process with no significant defects observed post build and post heat treatment. Both AA2050 and Scalmalloy exhibited build defects at some point during the project. Alloy AA2050 exhibited solidification related cracking issues and Scalmalloy exhibited post-heat-treatment cracking.

Heat treatment was conducted on both AA2219 and Scalmalloy due to their favorable response to the initial build process. Alloy AA2219 was heat treated to a conventional T6 condition and Scalmalloy was heat treated to a condition published by the material's manufacturer. Following all AM-related processing, AA2219 and Scalmalloy were tensile tested using E8 round tensile bars. AA2219 met or exceeded properties of forged AA2219-T6 per the American Society for Metals (ASM) handbook values, while Scalmalloy demonstrated weaker properties than what was achieved using small-scale AM techniques (Fig. 1).

Due to the poor response to the AM process exhibited by AA2050, a secondary objective was initiated to find a method to relieve the solidification cracking issues. A process known as acoustic mixing was selected to coat a powdered form of AA2050 with inoculants. The acoustic mixing process was pioneered by NASA Glenn Research Center's materials team on alloy GRX-810, a nickel-co-

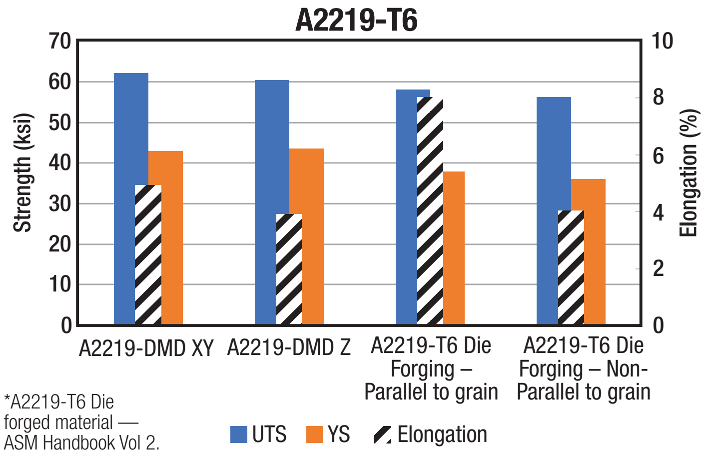


FIGURE 1. Plot of mechanical properties of AA2219 AMed on this project.

balt-chromium alloy that is revolutionizing the jet engine industry. The team selected alumina, yttria, and titanium diboride as inoculant materials, with the goal to reduce grain size and improve material properties. Titanium diboride exhibited the best result with a marked shrinkage in grain size.

Finally, AA2219 was selected to be used for the demonstration of the large-scale AM process on a pathfinder article. The build geometry selected for the pathfinder was chosen by the Space Launch System (SLS) Exploration Upper Stage project office, and a subscale liquid oxygen tank Y-ring was selected as the highest value component to demonstrate. Fig. 2 provides an example geometry of the pathfinder article and an in-process image of the pathfinder article being printed using the DMD freeform AM process.

PARTNERSHIPS

DM3D Technology was the primary partner on this Cooperative Agreement Notice (CAN) project, putting forward over 50% of the budget for the technology development. DM3D is a pioneer in large-scale AM and has been working in the AM field for over 15 years. They have partnered with NASA Marshall Space Flight Center (MSFC) on several AM-related technology development programs, including development and deposition of a full-scale RS-25 rocket engine nozzle. MSFC and DM3D are continuing to partner on AM process development and demonstration on space flight hardware. Currently DM3D has been awarded a Phase III Small Business Innovation Research grant to demonstrate the fabrication of a full-scale clevis tang ring for the SLS Booster element office. The work on this CAN is continuing with further deposition trials for AA2050 to start in Fall 2023.

SUMMARY

In summary, DM3D has demonstrated that aluminum alloys relevant to space flight hardware can be compatible with the large-scale freeform AM process. This demonstration opens the door for large-scale forging and casting replacement projects in the future, this will offer a large reduction in leadtimes for high value aluminum components for space flight hardware. This CAN effort is still ongoing, with an extension to continue work through January 2024 with the hope to further demonstrate printing with alloys AA2219 and AA2050. Both alloys are very relevant to SLS and the broader launch vehicle industry.

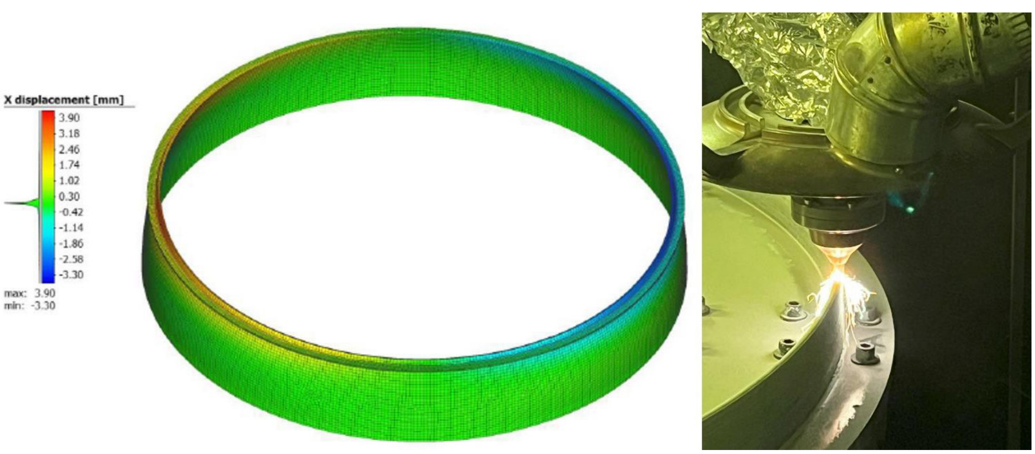


FIGURE 2. Distortion model of the pathfinder article used to demonstrate the large scale AM process and an image of the article during the AM process.

Principal Investigator(s): William Evans; Chris Protz; Parker Shake
Partners: DM3D Technologies
Funding Organization(s): Cooperative Agreement Notice

Wire-Arc Additive Manufacturing of Non-Gravity Aligned Aluminum Structures

PROJECT OBJECTIVE: To develop non-gravity aligned (NGA) bulk structures for aluminum alloy AA2319 additive manufacturing with the cold metal transfer welding process.

PROJECT GOAL/DESCRIPTION

There is considerable interest in fabricating large metal space structures using wire-arc additive manufacturing (WAAM) due to the cost and material benefits this process would provide for off-Earth environments that do not have access to terrestrial manufacturing processes. Existing WAAM equipment and processes are restricted to printing with welding torch orientations aligned parallel to the gravity vector. For large part geometries, such orientations restrict structure complexity and prohibit the fabrication of overhanging features in structures. The University of Tennessee, Knoxville (UTK) partnered with NASA Marshall Space Flight Center (MSFC) with this Cooperative Agreement Notice (CAN) to pursue robotically controlled WAAM for the fabrication of large space structures. Specifically, UTK was tasked to develop WAAM process technology necessary to fabricate bulk NGA features in aluminum alloy AA2319. The work builds upon prior UTK research to implement NGA for single-wall structures in low carbon steel.

APPROACH/INNOVATION

The approach is to first develop and provide the following: (1) process conditions for printing bulk NGA features in AA2319 feedstock using the short circuit gas metal arc welding process referred to as cold metal transfer (CMT); (2) path planning algorithms and code for printing bulk, multipass NGA features; and (3) in-situ melt pool monitoring capabilities aimed at future work to implement NGA process control. Each of these elements are foundational to realizing a manufacturing capability for the printing of large, complex space structures for NASA applications.

Steps within this plan include developing thin-wall gravity-aligned structures with AA2319 filler wire, then progressing to development of thick-wall structures. Stable parameters for this material must be developed as aluminum alloys for CMT-WAAM had not been attempted at the UTK cell before this work. A weave motion of the welding torch may be used to create thicker walls, or a multiple welding pass approach may be used. The development can then shift to the NGA alignment for both thin- and thick-wall builds. This would require additional parameter and toolpathing development for successful deposition of the overhangs and other NGA geometry.

Additionally, schedule transfer and variation of printed products generated by UTK and MSFC can be evaluated between one another, as they have similar foundational process principles but differ between the robotics and welding power supplies.

RESULTS/ACCOMPLISHMENTS

Thin-wall structure development for AA2319 feedstock was performed, and samples taken for primarily macro-evaluation and microhardness testing. Thick-wall development was also developed with this alloy with a triangular weave motion of the weld head. A wall sent to MSFC for uniaxial tensile testing is shown in Fig. 1. Samples are to be excised but may remain untested until the MSFC AA2319 heat treatment development is complete.

NGA printing development is currently in the process of evaluating thin-wall structures at a 90º angle from the gravity vector. An example of this development can be seen in Fig. 2. Challenges within this development include the potential for depositions to slump, fall, or create less than

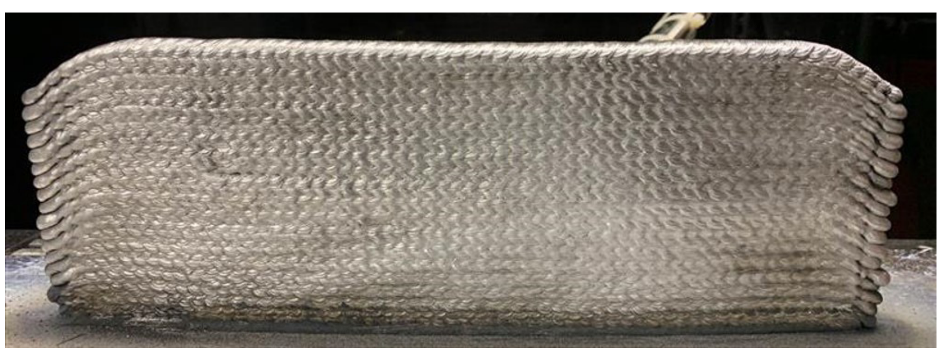


FIGURE 1. Wall from AA2319 feedstock printed for tensile properties testing.

FIGURE 2. Single-pass thin-walled NGA print development.

optimal contours of the stacking layers due to the pull of terrestrial gravity on the melt pool. In-situ process monitoring is also being evaluated for this exercise. Further development will continue for the remainder of period of performance to evaluate additional angles of the welding torch and workpiece or substrate orientations.

Interpass temperature of the material was maintained at 200 ºF for all structure prints based on prior work with other nonferrous alloys. Both UTK and the NASA teams converged independently on a method of performing first layers of the additive builds to use pulse metal inert gas welding to ensure sufficient heating of the build plate or substrate material rather than use a CMT waveform.

PARTNERSHIPS

This work was a partnership between doctoral graduate student Tiffany Quigley and Dr. Bradley Jared of UTK and the MSFC EM32 Metal Processes and Manufacturing Branch.

SUMMARY

Development of aluminum alloys and the CMT-WAAM process is making progress at the UTK cell in conjunction with the efforts at MSFC. Stable parameters and toolpathing for walls was well-characterized as the team transitions to the development of NGA efforts such as overhangs for this alloy. Work is still ongoing within the period of performance but estimates the final results to be achieved early in fiscal year 2024 and will contribute heavily to the Technology Readiness Level of WAAM for use in large-scale aluminum applications.

Principal Investigator(s): Tiffany Quigley, University of Tennessee, Knoxville
Partners: University of Tennessee, Knoxville
Funding Organization(s): Cooperative Agreement Notice

TECHNOLOGY AREA 13

GROUND, TEST, AND SURFACE SYSTEMS

Data Planning And Control (DPAC) Tool

PROJECT OBJECTIVE: **Automating spaceflight operations in a human spaceflight environment with a focus on the Data Management Coordinator (DMC) team at the International Space Station (ISS) Payload Operations Center.**

PROJECT GOAL/DESCRIPTION

As NASA missions and technologies evolve, ground operations will move away from 24/7 manual support. There is a need for autonomy within ground operations to support changing NASA operations requirements. The Data Planning And Control (DPAC) tool will automate the execution of planned activities by merging telemetry, flight control, and procedures into a seamless operational interface for the DMC team at NASA Marshall Space Flight Center (MSFC). DPAC will reduce workload, lower the risk for human errors, and provide modular interfaces for quick adaptation by other programs such as Gateway, Lunar Surface Ops, small science missions, and other NASA partnership missions. Long term, this tool offers the possibility to execute directly on a vehicle with onboard operators using its simplified scheduling capabilities to make changes without expert ground support involvement which becomes increasingly impractical for deep space missions. Our goal is to create a tool that can be used today on the ISS so that NASA is ready when we need the capability for future missions.

APPROACH/INNOVATION

Existing automated spaceflight operations systems typically require a strict schedule of activities. Each event is defined well in advance with known timing, command contents, and few, if any, variables. However, one of the key challenges in human spaceflight operations, particularly in a complex setting like the ISS, is working with a very dynamic timeline of activities. Crew members may be ahead or behind schedule, thus requiring real-time assessment on the timing, contents, and suitability of vehicle commands. Detailed planning models exist but rely on the operator to make all decisions related to execution. By integrating planning models, command procedures, commanding and telemetry systems, and a newly developed activity schedule/execution capability, the DPAC tool automates routine spaceflight operations with minimal operator oversight and risk. Ultimately, it provides the flexible yet automated approach to spaceflight operations that human spaceflight requires.

Once deployed, this tool will import planned activities, identify the necessary commands that need to be sent, queue the commands to either send automatically or send following operator review, send the command, and then verify the system in the expected state based on telemetry. DPAC also allows the operator to modify existing activities or even create new activities in response to unplanned requests. These capabilities have already been demonstrated in a non-interference flight following test. The DPAC tool completed its initial development and testing phase in 2023. Following final checkouts, flight qualification/certification, and training, the tool will be used in support of ISS Payload Operations at the Huntsville Operations Support Center (HOSC) starting in June 2024.

RESULTS/ACCOMPLISHMENTS

The DPAC task team began with an initial concept of what we hoped the tool would accomplish and a general approach to how the tool would function and interface with users and mission systems. The team then developed a robust concept of operations which was reviewed and approved by our user community. The team completed a prototype of the tool in May 2022, followed by three development cycles, each adding additional capabilities based on user feedback and testing. The DPAC team executed a robust flight following activity in the summer of 2023 to demonstrate the core tool capabilities in the flight environment, which verified and validated many of DPAC's systems and concepts. The team also received critical user feedback on secondary capabilities, which became the focus of the final phase of development in the fall of 2023.

The operations community at the HOSC is enthusiastic about this new tool and expects significant savings in training, operations staffing, reductions in error reporting, and other secondary benefits following deployment. As additional groups and programs beyond the ISS DMC team adapt the DPAC tool to their operations, the value of this tool will continue to become evident. A second ISS operations team is close behind the DMC team deployment and expects to be operational using this tool within a year, which is validation of the DPAC team's intentionality in

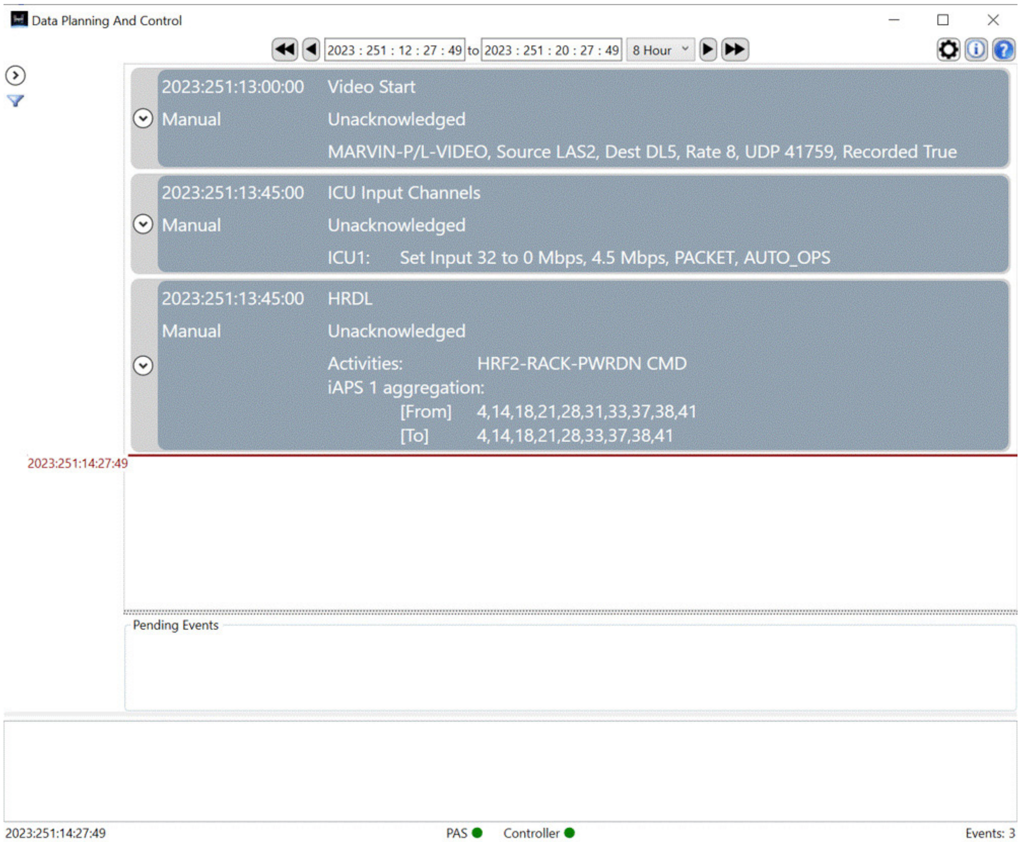


FIGURE 1. Main DPAC Operations User Interface.

designing a modular tool that can easily be adapted to any number of planning systems or operations concepts. The efficiencies gained through this tool will enable NASA to continue routine complex operations with minimal operator involvement. With enough time and experience with the tool, these efficiencies can be applied to future NASA missions where it becomes impractical to conduct ground operations due to long transmission times. When the need for such tools arrives, the DPAC tool will be thoroughly tried, tested, and ready for operations.

PARTNERSHIPS

This project was completed through contributions of civil servant and contractor team members at MSFC's Payload Mission Operations Division, with significant support from NASA Langley Research Center.

SUMMARY

The Data Planning And Control tool is an exciting advancement in spaceflight operations. The system seamlessly integrates previously independent systems which required a highly trained operator to manage. With this tool in place, operations personnel no longer have to manage minute-by-minute commanding tasks, but instead may focus on planning, coordination, and anomaly response. When combined with other tools that automate those aspects of operations, NASA's goal of true lights-out operations is achievable. DPAC is the first step along that path to mission success!

Principal Investigator(s): Mason Hall; Angie Haddock
Partners: NASA Langley Research Center
Funding Organization(s): Mars Campaign Office Polaris Project
NTR/Patent Number: e-NTR 1634138046

In-Situ Optical Measurements of Solid and Hybrid-Propellant Combustion Plumes

PROJECT OBJECTIVE: This project provides an inexpensive, minimally intrusive method that allows direct optical sensing of solid fuel and hybrid rocket systems combustion plume properties including flame temperature, radiant heat flux, and combustion species.

PROJECT GOAL/DESCRIPTION

The project focuses on technologies for sensing exhaust temperature and compositional characteristics of high-temperature/high-velocity jet engine and rocket exhaust plumes. High-temperature, high-velocity exhaust plumes present a uniquely challenging measurement environment. Wetted sensors, such as thermocouples and pressure transducers, degrade rapidly in these reactive, particle-laden, high-temperature, high-velocity plume flows, emphasizing a need for remote sensing approaches. This project has developed an alternative, minimally intrusive method for obtaining in-situ plume measurements.

APPROACH/INNOVATION

Presented research extends existing measurement technologies to operational systems, allows reduced configuration intrusiveness, increased sensor survivability, and analytical techniques for overcoming poor signal-to-noise ratio. In this approach, fiber optic cables are inserted into the solid fuel grain of a hybrid rocket motor and routed to look directly into the plume core flow (Fig. 1). The cables transmit optical signals from the internal flame zone to externally mounted spectrometers. Although the fiber optic cables inserted into the flow are consumed by the flame, the tips of the cables remain transparent and recede at the same rate as the regressing fuel surface, thereby providing data throughout the duration of operation. The sensed spectra are subsequently curve-fit to Planck's black body radiation law and flame temperatures are calculated from associated curve maxima (Wien's law) (Fig. 2). Spectral data have been collected from both small (1 N) and medium-scale (200 N) hybrid rocket systems.

Test results demonstrate that the selected sensing system fiber optics can survive temperatures greater than 3000 °C for durations of up to 25 seconds. The optical results for plume temperatures are shown to agree within a few degrees of the values predicted by equilibrium chemistry for both combustion (chamber) and nozzle temperatures. Nozzle data show clearly identifiable peaks for molecular nitrogen, atomic and molecular oxygen, and water vapor: all species known to exist in the exhaust plume. Work is in progress to improve system radiometric calibration—

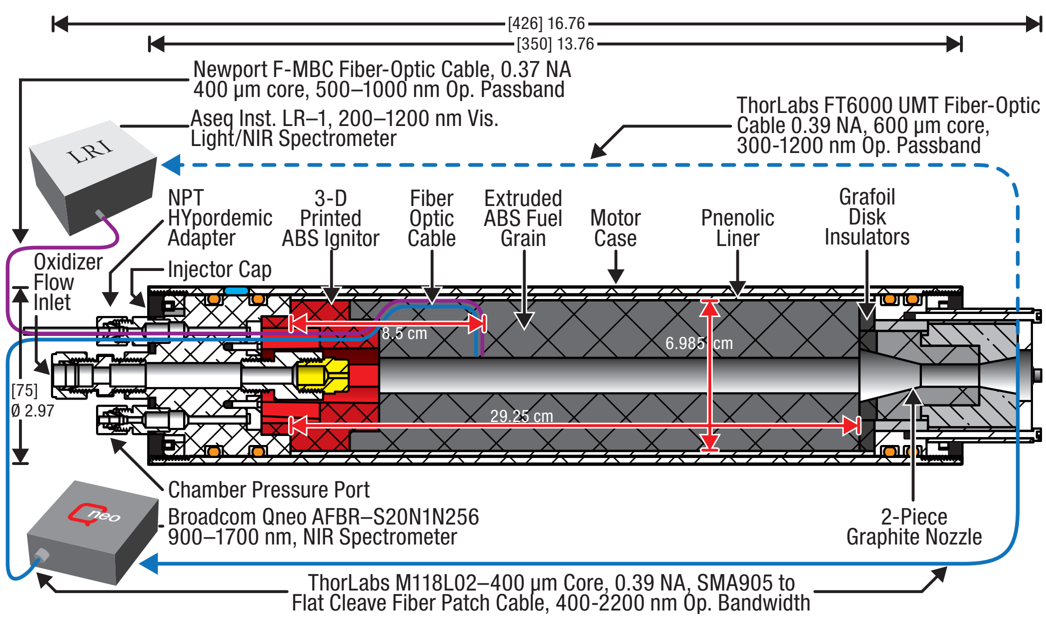


FIGURE 1. Layout of 75 mm Hybrid Motor with Dual-Band Fiber Optic Sensors.

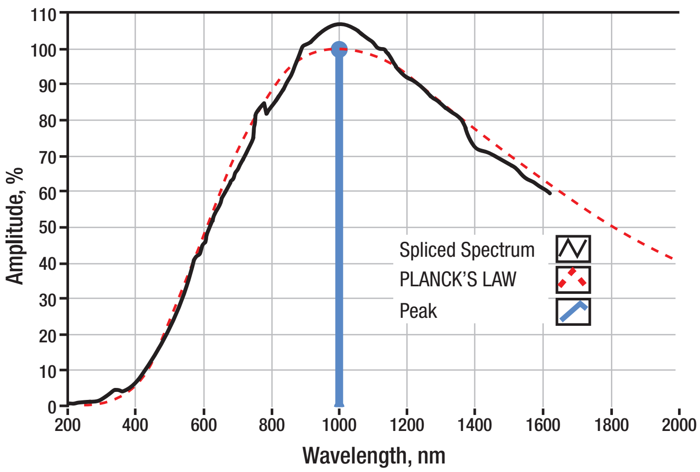


FIGURE 2. Normalized Dual-Band Spectrum, Curve-Fit to Planck's Law.

still learning "Best Practices." Better intensity (Y-axis) calibration may allow quantitative assessment of species mole-fractions using the Beer-Lambert law: a capability not possible with current state-of-the-art sensing technology.

RESULTS/ACCOMPLISHMENTS

- Dual-band fiber optic system with passband from 200–1600 nm developed, calibrated, and tested.
- Legacy hybrid rocket systems adapted for spectrometer hot-fire tests.
- 50 hot-fire tests successfully performed over a wide range of throttle settings and oxidizer-to-fuel ratios with integrated fiber optic system.
- Plume temperatures deduced in good agreement with theoretical values.
- Systems engineering completed, allowing adaptation of developed optical systems for testing at the NASA Marshall Space Flight Center (MSFC) Solid Fuel Torch facility.

PARTNERSHIPS

This project was a collaboration between Utah State University and MSFC ER43 Thermal Analysis Branch.

SUMMARY

The propulsion research lab at Utah State University has developed a minimally intrusive optical sensing system for high-temperature/high-velocity gas generator exhaust plumes, including rocket combustor chambers, high-enthalpy exhaust nozzles. and gas turbine engines. For this application, glass fiber optic cables, acting as radiation conduits, are inserted through the combustion chamber or nozzle wall and look directly into the flow core. The cables transmit data from the flame zone to externally mounted spectrometers. In order to quantitatively analyze the sensed spectra, narrow-band optical distortions must first be removed from the signal. This process involves radiometrically calibrating the end-to-end optical transfer function of the system components using a known wide band light source, and using optimal deconvolution (i.e., Wiener filter) to remove the associated optical data distortion. The processed spectra are subsequently curve-fit to Planck's black body radiation law and flame temperature is calculated from associated curve maxima (Wien's law). In this report, data collected from a lab-scale (200 N) hybrid rocket system are analyzed using the described method. Optically sensed flame temperatures are correlated to analytical predictions and shown to generally agree within a few degrees. Additionally, local maxima in the optical spectra are shown to correspond to emission frequencies of atomic and molecular oxygen, water vapor, and molecular nitrogen; all species known to exist in the hybrid combustion plume. Presented data demonstrate that the selected sensing system fiber optics can survive temperatures greater than 3000 °C for durations of up to 25 seconds.

Principal Investigator(s): Stephen A. Whitmore, Utah State University; Heath T. Martin
Partners: Utah State University
Funding Organization(s): Cooperative Agreement Notice

Microwave AeroGel Volatile Collector (MAGVC) AeroGel and Microwave Radiation Study

PROJECT OBJECTIVE: To develop and test a protype for the insulating chamber of the Microwave AeroGel Volatile Collector (MAGVC) system, including aerogel insulation testing and selection.

PROJECT GOAL/DESCRIPTION

In-situ Resource Utilization (ISRU) technology capable of extracting and repurposing extraterrestrial resources is vital to realizing NASA's Moon to Mars objectives of human establishment on the lunar surface. The MAGVC is a revolutionary volatile extraction system that uses microwave radiation to induce an outgassing effect in volatile-rich regolith. It is comprised of a magnetron, an aerogel-insulated chamber, a volatile storage system, and an autonomous operating system. The insulation of the chamber is key to the device's extraction efficiency and therefore its overall viability for infusion with future missions. This Center Innovation Fund (CIF) project focused on characterizing and downselecting aerogel variants for use in space environments, and then testing their efficiency for use in MAGVC. The expected outcome of the project is to have a small-scale proof of concept of the insulating chamber of the MAGVC system.

APPROACH/INNOVATION

The MAGVC system technology is revolutionary because the process of extracting volatiles using microwave radiation has been researched, but the deliverable of this project is to develop a prototype of the insulating chamber to contain the heat generated during this process and direct the volatiles into a collection system to increase the efficiency of the volatile extraction. Microwave radiation is very advantageous as an extraction mechanism because it can be tailored to specific regolith variants and mitigates risks associated with dust disturbance because it can extract volatiles without the need for excavation. Compared to other state-of-the-art (SOA) systems using pyrolysis, the MAGVC's design is simpler, more robust, and energy efficient. Additionally, the MAGVC is able to process large quantities of regolith without excavation and allowing it to have considerably lower mass than other SOA systems.

The key objectives of the project were to (1) downselect an aerogel insulator for increased efficiency of the volatile extraction process, and (2) test the efficiency of the developed insulating chamber design. These aerogels had not been characterized for space flight or microwave radiation environments, so this project needed to perform some basic exposures to down-select samples. Vacuum bakeout and vacuum microwave exposure chambers were built as major milestones and data from these exposures were used to achieve the first objective. Working with our partner at NASA Glenn Research Center (GRC) to cast the selected aerogel and with a vendor to machine the protype were the milestones used to achieve the second objective.

RESULTS/ACCOMPLISHMENTS

Aerogel infrared emissivity and microwave exposure mass loss was examined to compare the aerogels and to down-select for the chamber prototype. Infrared emissivity provides insight into the thermal performance of the aerogels and mass loss indicates the magnitude of contaminants outgassed from the aerogels when introduced to a vacuum environment and exposed to microwaves. Table 1 displays the top ten aerogels' infrared emissivity pre- and post-microwave exposure and mass loss from the microwave exposure. Overall, the infrared emissivity did not change greatly for the differing aerogel types, with the largest percent change being 0.90%, but they generally increased following the microwave exposure. For the microwave exposure mass loss, none of the top selected aerogel samples exceeded the benchmark 1% mass loss. The team could not obtain an accurate mass loss value for Sample 16 due to a handling issue prior to microwave exposure. Furthermore, some samples were seen to gain mass, most likely due to being within the measurement uncertainty of the mass balance.

The Rapid Microwave Exposure Chamber (R-MEC), shown in Fig. 1, was developed as a project milestone to conduct microwave radiation exposures on the aerogel

TABLE 1. IR Emittance and Mass Loss of Top 10 Aerogel Samples.

Sample	Pre-Microwave Infrared Emittance	Post-Microwave Infrared Emittance	Percent Change [%]	Microwave Exposure Mass Loss [%]
HG093103 (3)	0.93	0.92	0	0.01
HG112305 (6)	0.92	0.93	0.57	0.17
GR46.1 (9)	0.94	0.94	0.32	0.01
HG112304-5 (10)	0.93	0.93	0.54	0.00
HG08X102 (11)	0.93	0.94	0.78	0.23
HGCS 2022 (14)	0.93	0.93	0.86	0.04
HG110303 (15)	0.94	0.95	0.46	0.06
KC.01.9.2 (16)	0.94	0.94	0.57	NaN
HG092904-6 (17)	0.92	0.93	0.90	-0.08
SP-125 (24)	0.89	0.89	0.53	0.91

FIGURE 1. Image of Rapid Microwave Exposure Chamber.

variants supplied by GRC. It consists of a vacuum pump and tube, a residual gas analyzer (RGA), and a microwave radiation source. The system can pull vacuum down to 10^{-7} Torr and the radiation source produces microwaves at 2.45 GHz and 1.1 kW. The RGA provides gas analysis to understand the amount and type of volatile substance that is being released by the sample throughout the exposure. Understanding which samples withstand these environments, along with ease of handling, optical property changes, and density, allowed the team to downselect an aerogel for the prototype. This chamber was built for this project but remains as a capability for the MSFC EM41 Space Environmental Effects team.

In conjunction with aerogel microwave exposure and the downselect ion process, the aerogel-insulated chamber was designed, manufactured, and assembled. The prototype design is cylindrical with an inner and outer shell to sandwich an aerogel insulating layer. The top of the inner shell has a slot for a waveguide to be inserted for the microwave radiation to enter the chamber. The team brainstormed multiple design configurations, including a cone and a dome, but selected a simple cylindrical design to simplify manufacturing and to reduce cost and lead time. Surrounding the inner wall of the chamber is the 0.25-in-thick downselected aerogel insulation encapsulated by the outer shell. The aerogel insulation was cast and produced by GRC, while MNT Machine Inc. produced the prototype.

PARTNERSHIPS

The research team partnered with the Aerospace Polymeric Materials Lab and Inorganic Aerogels Group at GRC to provide aerogels for the insulation chamber prototype and microwave exposures. The optical property and microwave exposure data collected during the project was provided to GRC, filling a knowledge gap of the behavior of their aerogels in this specific environment.

SUMMARY

The MAGVC is a volatile extraction system that uses microwave radiation to outgas the volatiles contained within lunar regolith. The goal of this project was to design, build, and test a prototype for the aerogel-insulated chamber, including testing and downselecting aerogel candidate materials. The team downselected the aerogels by conducting vacuum bakeout and vacuum microwave exposures, gathering outgassing and optical property data. The team also completed the design and manufacturing of the insulation chamber. Some lessons learned include developing lab capabilities and working with a radiation safety officer and a laser safety officer to ensure safe operations. Another lesson the team learned was determining the considerations when navigating conflicting timelines and objectives with other programs to share capabilities. The final major lesson learned was the importance of spending funding in a timely manner and keeping in close contact with the team's resource analyst. The next step for this technology includes conducting system validation tests with MSFC EM41 and incorporating gas and water capturing capabilities with a funded fiscal year 2024 CIF grant.

Principal Investigator(s): Annette Gray; Meghan Carrico
Partners: NASA Glenn Research Center
Funding Organization(s): Center Innovation Fund
NTR/Patent Number: 1661461309
For more information: Microwave AeroGel Volatile Collector (MAGVC) Aerogel and Microwave Radiation Study (sharepoint.com)

TECHNOLOGY AREA 14

THERMAL MANAGEMENT SYSTEMS

Cryocooler Technology Development

PROJECT OBJECTIVE: The Cryofluid Management Portfolio Project (CFMPP) objective is to mature the Technology Readiness Levels (TRL) of high-efficiency, high-capacity cryocoolers to TRL 6.

PROJECT GOAL/DESCRIPTION

The CFMPP is developing two types of cryocoolers: a 20 Kelvin (K), 20 watt (W) cryocooler and a 90 K, 150 W cryocooler that operates on a Reverse Turbo Brayton (RTB) refrigeration cycle. These temperatures are important in long-term storage of liquid hydrogen, liquid oxygen, and liquid methane. Mars in-space vehicle missions will require high-efficiency, high-capacity, flight-weight cryocoolers that will operate for long periods of time to ensure propellant does not boil off during the mission. The goal of the project is to mature both technologies to TRL 6 per NASA Procedural Requirements (NPR) 7123.

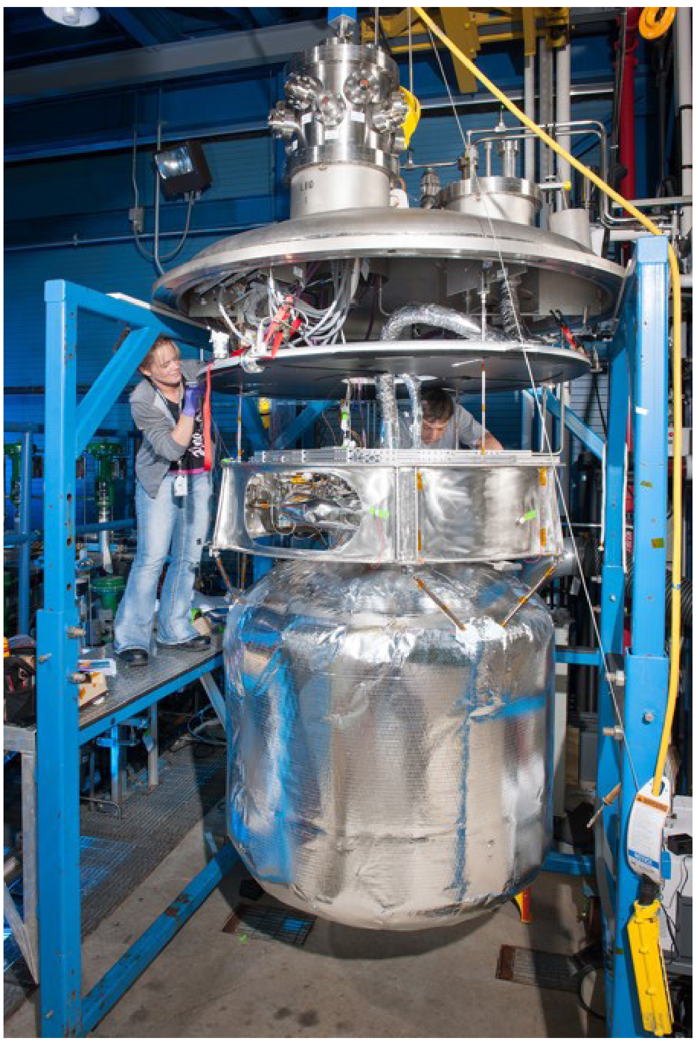


FIGURE 1. Cryocooler.

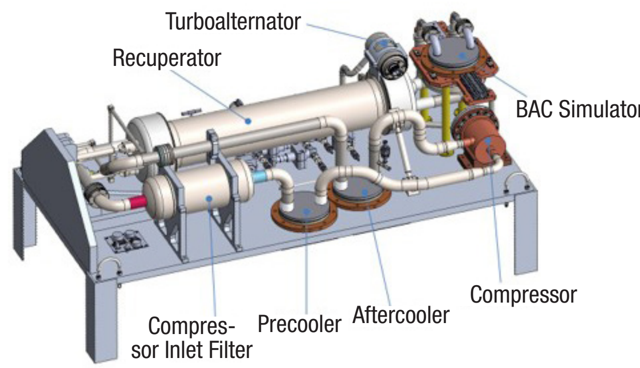


FIGURE 2. Diagram of 90 K, 150 W Cryocooler.

APPROACH/INNOVATION

The combination of integrated system technology, which includes miniature high-speed turbomachinery and heat exchangers as well as Reverse-Brayton cycles, enable these cryocoolers to operate to temperatures down to 20 K and 90 K and have cooling capacities from 20 W to 150 W, respectively. These unique innovations enable system operations to meet these low temperatures and system demands.

RESULTS/ACCOMPLISHMENTS

The Creare and NASA team successfully completed acceptance testing in May 2022 for the 20 K, 20 W cryocooler. This initially would have brought the 20 K, 20 W cryocooler to a TRL 5, but due to a restart issue after the testing, the team took a closer look at the design. Several improvements on reviewing data and instrumentation were implemented and no issues with the design were found to be the root cause. The team then put a plan together to achieve a TRL 5 after reassembling the cryocooler in the test chamber and repeating acceptance testing. A TRL 6 will be achieved after vibration testing and post-vibe and checkout testing. The 20 K cryocooler reached its Key Performance Milestones of 20 K and 20 W.

The Creare and NASA team successfully completed the recuperator and turboalternator brassboard testing for the 90 K, 150 W cryocooler. The data met test objectives.

FIGURE 3. 20 K, 20 W Cryocooler.

There are also plans in place to mature the 90 K, 150 W cryocooler to TRL 5 and TRL 6 after vibration testing and a functional verification test series. It will then be integrated into a system to perform liquefaction testing at NASA Glenn Research Center.

PARTNERSHIPS

Creare is the leading developer of the cryocooler technologies for the CFMPP. This work is being done through NASA Small Business Innovation Research contracts and being managed by CFMPP.

SUMMARY

The 20 K, 20 W and the 90 K, 150 W cryocoolers have gone through acceptance testing and brassboard testing respectively with successful results. More work needs to be done for both cryocoolers to mature their developments to TRL 5 and TRL 6, and the CFMPP has a plan in place to do that within the next two years. The 20 K cryocooler reached its Key Performance Milestones of 20 K and 20 W. The 90 K, 150 W cryocooler reached its functional testing results successfully.

Principal Investigator(s): Ben Nugent, NASA Glenn Research Center (20 K); Jonathan Stephens (90 K)
Partners: Creare; NASA Glenn Research Center
Funding Organization(s): Small Business Innovation Research
For more information: https://www.creare.com/

Low Leakage Cryogenic Valves

PROJECT OBJECTIVE: Development of low-leakage cryogenic valves for future long-duration missions.

PROJECT GOAL/DESCRIPTION

This project aims to develop and assess cryogenic valve technology designed to mitigate internal leakage challenges inherent to the utilization of cryogenic propellants during extended-duration space missions. Cryogenic propellants such as liquid hydrogen (LH_2) present challenges due to small molecular size, making them susceptible to permeation through materials. While current valve technology serves well for short missions, longer missions such as interplanetary endeavors will require a more robust solution. NASA Marshall Space Flight Center (MSFC) is developing low-leakage cryogenic valves for application within such missions. These valves incorporate a novel self-aligning poppet and seat design. This design utilizes a metallic poppet head with five degrees of freedom, allowing the poppet to self-align with a polymer seat and reducing the need for tight tolerances. The goal of this project is to develop large cryogenic valve technology capable of reducing internal leakage rates below a Key Performance Parameter (KPP) Goal Value of 1.0 standard cubic inches per minute (SCIM) (with a KPP Threshold Value of 5.0 SCIM) with LH2.

APPROACH/INNOVATION

A spherical poppet with conical seat is a relatively conventional design for poppet valves, but a key innovation of this project is to use a flexible coupling with load application below the seat contact point. This design reduces the potential for non-uniform seat stress associated with misalignment and allows the valve to mitigate the effects of imperfect contacts and misalignments between sealing surfaces. This design was assessed by evaluating its performance within a variety of environments and applications. Initial development efforts included a small-scale (1-in) seal test rig, a large-scale (3-in) seal test rig, and a large-scale life cycle test rig.

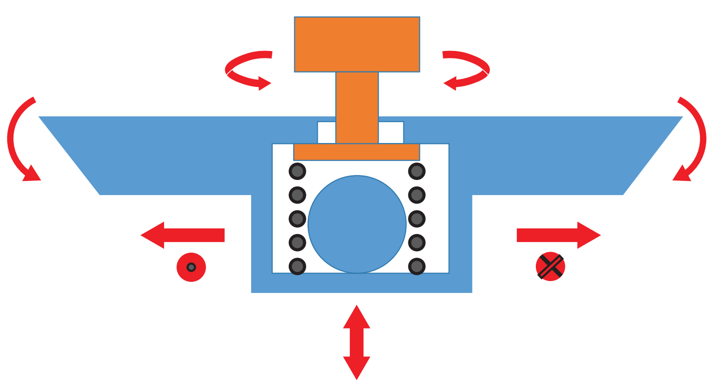


FIGURE 1. Self-Aligning Poppet and Seat Design.

The current generation of test articles were selected to demonstrate the application of this technology to various configurations, sizes, and environments that are often found in or around main propulsion systems. Each of these test valves underwent an initial test campaign, conducted either with liquid nitrogen (LN_2) or LN_2-chilled gaseous helium (depending on application). This LN_2 testing was conducted at the Component Development Area (CDA), located at MSFC Building 4656. Upon the completion of LN_2 testing, the test articles were moved to Test Stand 300 (in the East Test Area) to undergo LH_2 testing.

RESULTS/ACCOMPLISHMENTS

The self-aligning poppet and seat design demonstrated internal leakage rates that met or exceeded the activity KPPs in all LN_2 test measurements, and in 14 out of 15 LH_2 measurements. Upon review of the test data, it was determined that the single instance that exceeded the KPP Threshold Value was likely due to a procedural error. Additional areas for potential refinement include the improvement of measurement techniques to better assess fluid temperature and phase within the test article, and strategies to mitigate the impact of special test equipment on recorded measurements.

Anticipated next steps involve refining the valve design based on test results and establishing potential industry partnerships for commercial production.

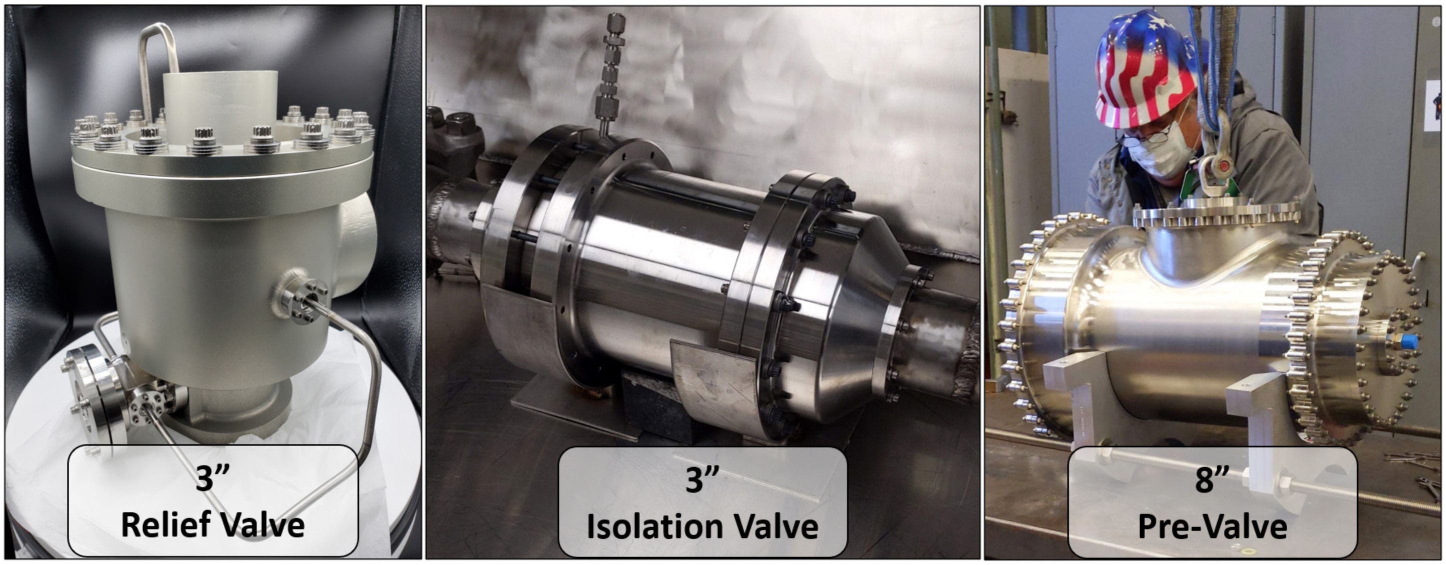


FIGURE 2. Low-Leakage Cryogenic Valves.

SUMMARY

Challenges continue to exist for future long-duration missions that seek to utilize cryogenic propellants. Although currently available valve technology could allow for an unacceptable amount of propellant loss, this self-aligning seat and poppet design may help mitigate the risk of propellant loss due to internal leakage. The test valves utilizing this technology have shown promising results in both LN_2 and LH_2 testing, and the design information is anticipated to be made available to potential industry partners in early fiscal year 2024.

Principal Investigator(s): Robert Walker; David Eddleman
Funding Organization(s): Space Technology Mission Directorate–Cryogenic Fluid Management Project

Thermodynamic Vent System Injector (TVSI)

PROJECT OBJECTIVE: To design, build, and test a novel spray injector augmented with a Thermodynamic Vent System (TVS) to demonstrate a simplified method of performing a tank-to-tank transfer of cryogenic propellant.

PROJECT GOAL/DESCRIPTION

NASA is focusing on the use of reusable cryogenic systems to enable future long duration missions. For a system to be considered reusable, it must be capable of being refueled on-orbit and/or on the lunar or martian surfaces. Propellant sources might include propellant tankers or depots, or in-situ resource utilization (ISRU) propellant liquefaction and storage facilities. The Human Landing System (HLS) Architecture includes the use of reusable cryogenic systems that will require refueling on-orbit, and eventually on the Lunar Surface.

Transferring cryogenic propellants from tank-to-tank is a complex procedure, as it involves the chill down of transfer hardware and the receiver tank, valve cycling, and the venting of boil-off gases. To simplify transfer operations and minimize propellant losses, this effort introduces a new transfer methodology using a novel spray injector, known as a TVS-augmented injector (TVSI), inside of the receiver tank. The overall goal is to simplify the transfer process and potentially reduce the amount of propellant required to chill the hardware in preparation for the transfer.

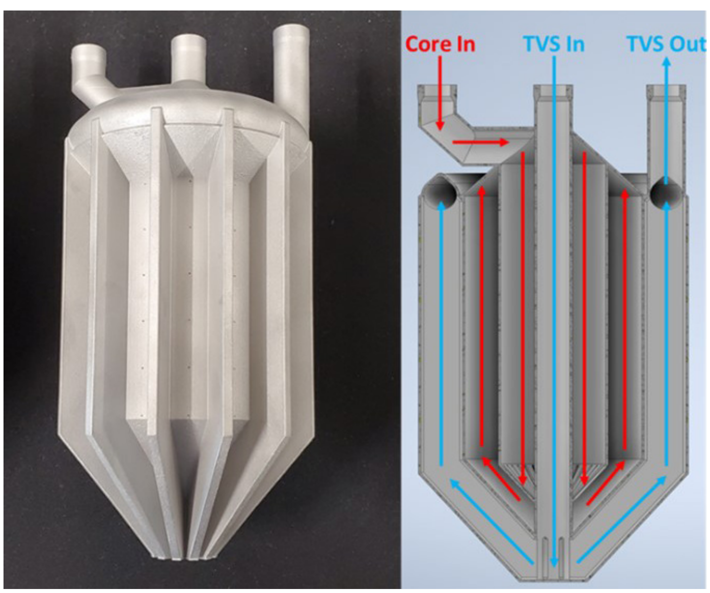


FIGURE 1. TVSI TVS injector.

APPROACH/INNOVATION

To simplify the operations associated with propellant transfer and explore potential mass savings, NASA has been experimenting with the Vented Chill/No-Vent Fill (VC/NVF) approach while enhancing the process using an additively manufactured TVSI.

The operations associated with the VC/NVF approach are straightforward. With an empty receiving tank at ambient temperature and vented to the atmosphere, the process is started by flowing the cryogenic liquid through a transfer line into the receiving tank using a spray injector. During this initial phase, the liquid absorbs heat from the transfer hardware, receiving tank walls, and the ullage, and begins to boil. The boil-off gas is vented from the receiving tank to avoid excessive pressure. This VC process continues until the tank temperature decreases to a predetermined "trigger point" value and the tank vent valve is closed. If sufficient heat is removed from the receiving tank during the VC process, then the spray pattern of the injector cools the ullage and tank walls, resulting in ullage collapse. This collapse decreases the pressure in the receiving tank without venting, and the liquid transfer can begin, filling the receiving tank to nearly 100% liquid level. If insufficient heat is removed from the receiving tank because of setting the "trigger point" temperature too high, then the fluid transfer will stop—called a stall. In the event of a stall, the TVS on the spray injector can be activated to provide additional cooling to condense the ullage in the propellant tank. The stalled flow can recover and allow the transfer to continue successfully.

RESULTS/ACCOMPLISHMENTS

Four TVSI prototypes were designed, built, and demonstrated in a medium-scale, American Society of Mechanical Engineers (ASME)-rated propellant tank. The activity successfully conducted multiple propellent transfers using the VC/NVF methodology and demonstrated TVS operation to assist the transfer. Numerous lessons learned associated with the additive manufacturing, propellant conditions,

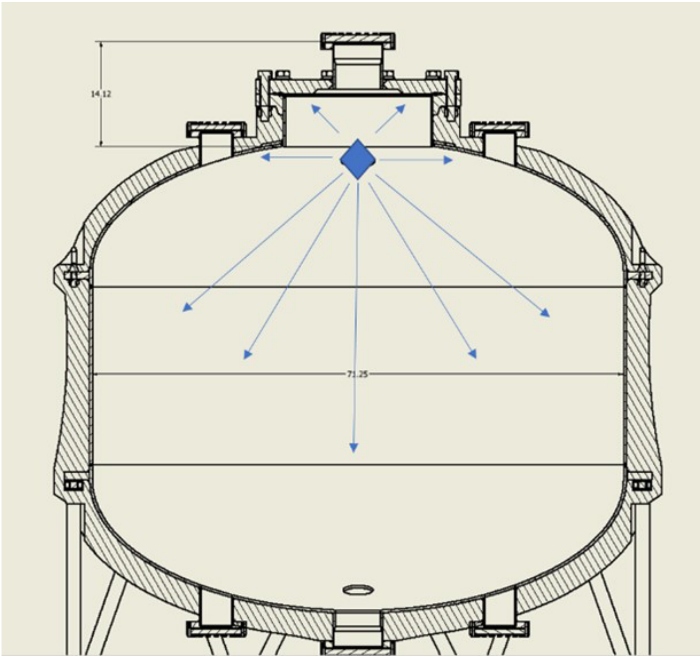


FIGURE 2. TVSI Vented Chill/No-Vent Fill (VC/NVF) receiver tank.

spray patterns, and TVS operations were documented. Data gathered from the transfer experiments is being used to develop models for cryogenic transfer.

A formal Technology Readiness Level (TRL) assessment is planned for October 2023. A TRL 3 or TRL 4 is anticipated. A patent on the TVSI technology is pending.

SUMMARY

Various injector design iterations provided insight into more effective design and operational choices, culminating in one final injector designed as part of the Enhanced Cryogenic Transfer Project. This injector was different from earlier designs in that it was designed to focus on condensing the tank ullage for pressure reduction rather than heat removal. This final design was proven successful in multiple demonstrations where the receiver tank was filled to 95% liquid level using the VC/NVF methodology.

Principal Investigator(s): Jonathan Stephens
Funding Organization(s): Space Technology Mission Directorate–Cryogenic Fluid Management Project

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Marshall Space Flight Center

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