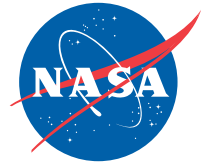


National Aeronautics and  
Space Administration



NASA/TM—2020—220471

Marshall Space Flight Center

# RESEARCH & TECHNOLOGY REPORT

# 2019

NASA/TM—2020—220471

Marshall Space Flight Center

RESEARCH AND TECHNOLOGY REPORT

2019



Marshall Space Flight Center  
**Research and Technology Report 2019**

*J.W. Dankanich and H.C. Morris, Compilers  
Marshall Space Flight Center, Huntsville, Alabama*

## ACKNOWLEDGMENTS

The points of contact and coordinator at Marshall Space Flight Center (MSFC) for this Technical Memorandum (TM) are John W. Dankanich (256-544-3441) and Heather Morris. The MSFC Office of Center Chief Technologist recognizes Janice Robinson, NiCarla Friend, and Kathy Jobczynski of the MSFC Scientific and Technical Information Group for assisting in the development of this report. The Center Chief Technologist, John Dankanich, and Technologist Heather Morris provided the support, insights, and decisions required for the compilation of this TM.

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## FOREWORD



Today, our calling to explore is greater than ever before, and here at Marshall Space Flight Center — we make human deep space exploration possible. A key goal for Artemis is demonstrating and perfecting capabilities on the Moon for technologies needed for humans to get to Mars.

This year's report features 10 of the Agency's 16 Technology Areas, and I am proud of Marshall's role in creating solutions for so many of these daunting technical challenges. Many of these projects will lead to sustainable in-space architecture for human space exploration that will allow us to travel to the Moon, on to Mars, and beyond. Others are developing new scientific instruments capable of providing an unprecedented glimpse into our universe.

NASA has led the charge in space exploration for more than six decades, and through the Artemis program we will help build on our work in low-Earth orbit and pave the way to the Moon and Mars. At Marshall, we leverage the skills and interest of the international community to conduct scientific research, develop and demonstrate technology, and train international crews to operate further from Earth for longer periods of time than ever before—first at the lunar surface, then on to our next giant leap, human exploration of Mars.

While each project in this report seeks to advance new technology and challenge conventions, it is important to recognize the diversity of activities and people supporting our mission. This report not only showcases the Center's capabilities and our partnerships, it also highlights the progress our people have achieved in the past year. These scientists, researchers and innovators are why Marshall and NASA will continue to be a leader in innovation, exploration, and discovery for years to come.

I hope you enjoy reviewing this year's report. We have made incredible progress, and I know we will see even more advancements in 2020.

A handwritten signature in black ink that reads "Jody Singer". The signature is fluid and cursive.

Jody Singer

Director  
Marshall Space Flight Center

## INTRODUCTION



It is always a humbling privilege to provide a summary of the Marshall Space Flight Center innovative technology investments. This 2019 report is not only a compilation of technology investments and activities, it is the visible tip of the iceberg representing the vast depth and breadth of the MSFC work force. MSFC is remembered as the Human Space Flight Center that successfully provided the transportation of mankind to the moon, the advanced manufacturing center that constructed the Hubble Space Telescope, the center that engineered the Space Shuttle and its role in the International Space Station. Some people refer to those accomplishments of the past as the glory days. With all that was accomplished, it is easy to appreciate that perspective.

As the Chief Technologist, I have a much different vantage point. NASA expertise is enabling a growing and successful cis-lunar commercial economy. In-space transportation advancements will deliver greater payloads, with increased precision, to destinations previously unattainable. We await the launch of the James Webb Space Telescope optics that passed through these gates, and are fabricating the Imaging X-ray Polarimetry Explorer optics today. Life support solutions are underway to extend human presence beyond Low Earth Orbit. We are learning not simply to return samples from the moon, but to use the lunar resources for sustainable exploration. Recent advanced manufacturing developments include reducing both fabrication durations and costs by an order of magnitude, and MSFC is leading the way for extreme environment applications of these technologies. We must always remember that investments made in research and technology plant the seeds of future success for the MSFC, NASA and the nation. These pages represent the sprouts of the glory days ahead.

A handwritten signature in black ink that reads "John W. Dankanich". The signature is fluid and cursive, with the first letters of the first and last names being capitalized and prominent.

John W. Dankanich  
Center Chief Technologist  
Marshall Space Flight Center

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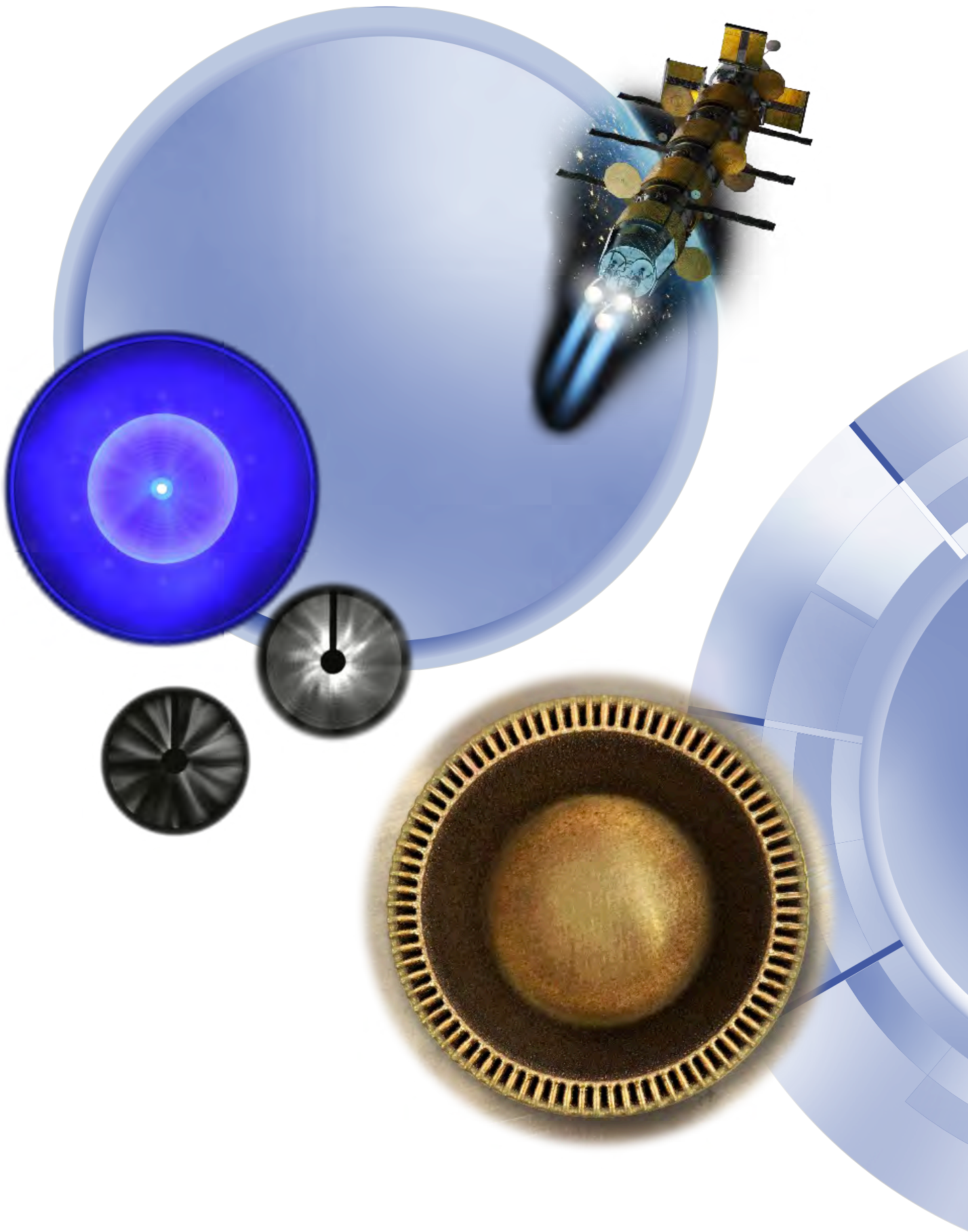
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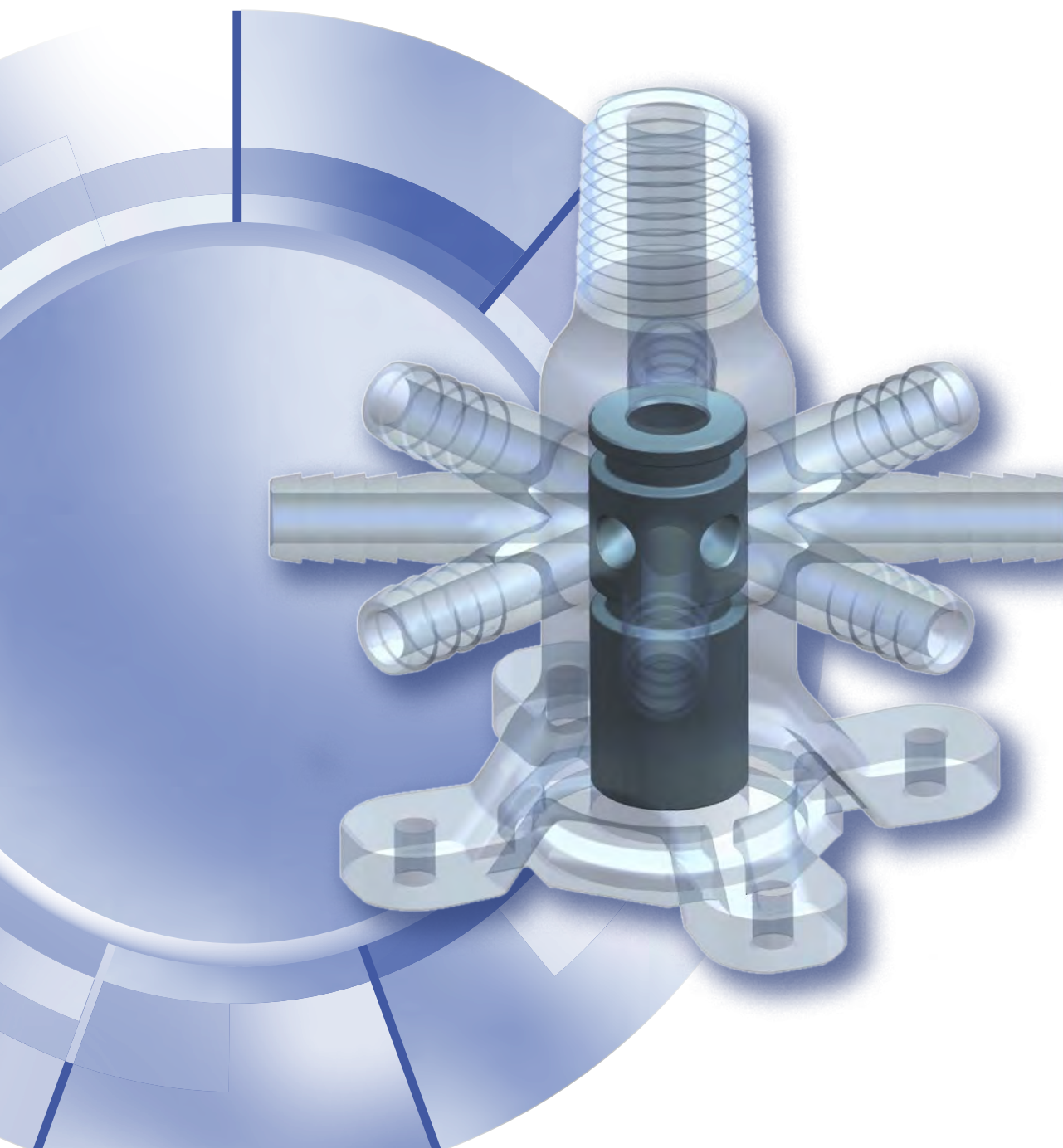
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# IN-SPACE PROPULSION SYSTEMS





# Additive Manufacture of Refractory Alloy C103 for Propulsion Applications

**OBJECTIVE:** *To investigate the feasibility to additively manufacture C103, optimize laser powder bed fusion (L-PBF) process parameters, establish design criteria, investigate post-process heat treatments, and determine material properties to enable the C103 for propulsion applications.*

## PROJECT DESCRIPTION

C103 is niobium alloy used in sustained high-temperature operating environments. Traditional manufacture methods suffer from feedstock constraints, difficulty in machining, high buy-to-fly ratios, and high costs resulting in a limited number of suppliers. Additive manufacture (AM) offers advantages in production of complex parts, improved properties, and reproducibility, with significant material cost and schedule savings. The objectives of this project were to investigate the feasibility to AM C103, develop powder feedstock, optimize laser powder bed fusion (L-PBF) process parameters, establish design criteria, investigate post-process heat treatments, and determine material properties.

## ACCOMPLISHMENTS

ATI developed gas-atomized L-PBF-grade C103 powder. Lab scale quantities of C103 powder were produced and underwent characterization to determine particle size distribution (PSD), morphology, density, and chemistry. Castheon conducted parameter development on a GE Concept Laser M2, while NASA Marshall Space Flight Center (MSFC) used an EOS M100. Vacuum stress relief (SR) and hot isostatic press (HIP) schedules were identified and applied at MSFC to specimens. Specimens underwent evaluation optical microscopy, scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) at MSFC, with electron backscatter diffraction (EBSD) and transmission electron microscopy (TEM) completed at The University of Alabama. Mechanical properties were determined as a function of material condition. Room temperature tensile tests were completed at MSFC, while tensile tests at 1093 °C



**FIGURE 1.** C103 AM on the Castheon GE Concept Laser M2.

were conducted by Westmoreland Mechanical Testing and Research, Inc. Compression tests at temperatures up to 1,700 °C were conducted by Portland State University (PSU).

Powder had spherical morphology, density > 99.9 % tapped density (TD), particle size distribution (PSD) D90 of 49.1 μm, and chemistry conformal to ASTM B625 with an oxygen except of 600 ppm for passivation to allow for safe handling. An optimized L-PBF parameters set was developed with sufficiently volumetric energy density and low residual stress induced geometric distortion. The as-built density was determined to be 99.986 %TD with SR+HIP at 99.993 %TD. Microstructure exhibits a refined grain size distribution that does not grow substantially from the as-built to heat treated conditions. Room temperature yield



strength (YS) and ultimate tensile strength (UTS) of L-PBF in all three conditions exceed wrought, with a slightly lower elongation. UTS at 1,093 °C of L-PBF in all three conditions is higher than wrought. The high strength is likely attributed to the small grain size. Micro-indentation shows some loss of hardness between the as-built and heat-treated conditions.

Traditional C103 manufacture has been expensive due to the cost of the feedstock and machining cost. Propulsion component shapes can result in 20:1 to 50:1 buy-to-fly ratios at high feedstock cost. C103 is difficult to machine with a limited number of machine shops able meet specifications.



**FIGURE 2.** NASA MSFC AM C103 Green Propulsion Thruster and standoff.

L-PBF AM allows for near net shapes to be produced and limit machining to interfaces with surface finish requirements. AM buy-to-fly ratio is approximately 1.1:1, and although L-PBF powder cost is slightly higher than wrought, the difference in production costs result in an order-of-magnitude cost reduction for an equivalent part. AM C103 cost savings, reproducibility, schedule control, and properties have significant industry implications for implementation.

## **SUMMARY**

AM C103 has been proven feasible and greatly increases design flexibility. The fast solidification rate from L-PBF process prevents microsegregation, meaning even large components will be compliant with ASTM B655, and the resulting small grain size distribution improves UTS and YS when compared to wrought and wire-fed AM properties. A series of successful hot fire tests of AM C103 thrusters were conducted to verify operational performance. AM C103 TRL increased from 3 to 5 and has enabled components to be produced at an order of magnitude cost reduction when compared to traditional manufacture processes. AM C103 is now readily available to be utilized into high temperature service applications such as RCS thrusters, Green Propulsion chambers, lander main propulsion systems, hypersonic vehicle surfaces, etc.

**PRINCIPAL INVESTIGATOR:** Omar Mireles

**PARTNERS:** Castheon Inc. and ATI Specialty Alloys

**FUNDING ORGANIZATION:** Cooperative Agreement Notice



# A High Repetition Rate, Scalable PPU for Pulsed Electric Propulsion Applications

**OBJECTIVE:** *To develop a power processing unit for pulsed electric thrusters that supports operation at pulse rates of 1 kHz or greater.*

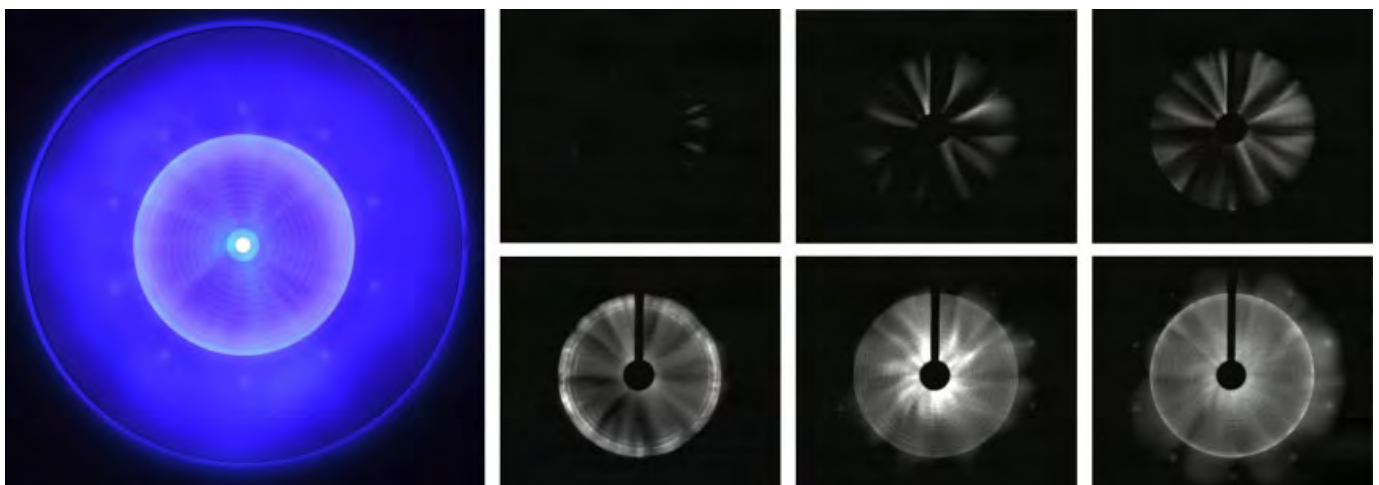
## PROJECT DESCRIPTION

The University of Washington (UW) and NASA Marshall Space Flight Center (MSFC) are partnering to develop a scalable power processing unit (PPU) for pulsed, high-power, in-space solar and nuclear electric propulsion systems operating at high repetition rates. High pulse rates enable pulsed electric thrusters to operate using a steady flow of propellant, thus, eliminating the need for failure-prone high-speed pulse valves known to limit thruster lifetime, reduce reliability, and significantly decrease propellant mass utilization and thrust efficiency. A reliable, long-life, high-efficiency pulsed thruster could reduce orbit raising times for communications satellites, provide orbit transfers for the Lunar Gateway, and enable new deep space science missions. At present, however, PPUs capable of supporting high pulse rate thruster operation are critically underdeveloped. Under this program, the UW Space Propulsion & Advanced Concepts Engineering (SPACE) Lab is designing and constructing a PPU for pulsed electric propulsion systems which demonstrates scalable, high power (1–10 kW, with scaling to  $\geq 100$  kW) operation at high pulse rates (1–10 kHz) while simultaneously

achieving high electrical efficiency ( $\geq 80\%$ ), low specific mass ( $\leq 3$  kg/kW), and compatibility with a standard large spacecraft bus ( $\leq 200$  V). Following successful benchtop PPU development at the UW SPACE Lab, the completed PPU prototype will be used to power the High Pulse Rate planar Pulsed Inductive Thruster (HiPeR-PIT) (Fig. 1) during first-of-its-kind performance testing of this device in the MSFC Propulsion Research and Development Lab's (PRDL) large vacuum facility.

## ACCOMPLISHMENTS

High pulse rate operation presents a unique challenge from a circuitry standpoint. The primary function of the PPU is to process power from the spacecraft to fully recharge the main capacitor banks of the thruster discharge circuit in the short time between pulses. In addition, the PPU must convert the spacecraft bus voltage ( $\approx 100$  V) to the level required for efficient inductive acceleration ( $> 1$  kV). For a 1 kHz pulse rate, near-optimal efficiency for specific impulses from 3,000 s to 5,000 s corresponds to an average power between 10–15 kW. Such power levels require the PPU to supply high voltages and large peak currents, while



**FIGURE 1.** Large current pulses are used to form and accelerate plasma in the High-Pulse-Rate Planar Pulsed Inductive Thruster experiment (left). High-speed images show the propellant breakdown and current sheet formation processes (right).



Converter	# Parallel	$V_{mb}/V_{DC}$	$f_{sw}$ [kHz]	$f_{rep}$ [kHz]	$\eta$ [%]
Parallel Boost	4	15	10	10	85
	8	15	10	10	89
Cascade Boost	4 (1st), 2 (2nd)	15	10	10	89
Series Resonant		15	50	5	67
Parallel Resonant		15	100	4	69
LLC		15	100	5	71
LCC		15	50	4	73

**TABLE 1.** Summary of SPICE modeling results shows the improved performance of boost-type circuits compared to other architectures.

operating at fast switching speeds to fully recharge the main capacitor bank in the short time between pulses (<1 ms at 1 kHz repetition rate). This project will analyze sophisticated PPU circuit architectures for their ability to meet the requirements of high repetition rate pulsed electric propulsion systems. A brassboard prototype of the most promising PPU design will be constructed and tested. Following benchtop validation at the UW SPACE Lab, the PPU will be integrated with the HiPeR-PIT thruster and its performance demonstrated at NASA MSFC facilities.

The role of the PPU in an inductive pulsed plasma thruster (IPPT) is to charge the energy storage capacitors to the nominal operating voltage of the thruster. As such, the PPU functions, in essence, as a spacecraft bus compatible capacitor charging power supply (CCPS). As a first step towards designing a new of PPU for enabling high pulse rate IPPT operation, a literature survey of CCPS designs used in terrestrial applications was completed. The results of this survey were then used to select promising CCPS designs for further evaluation using Simulation Program with Integrated Circuit Emphasis (SPICE)-based circuit simulation tools. Finally, the results of this modeling effort were used to select a CCPS topology for development into a physical prototype.

Accurate modeling of each of the components was critical to obtaining realistic results from the overall circuit models. For the present study, particular attention was given to modeling the switches, transformer, diodes, and inductors due to their central role in the operation of the various CCPS topologies investigated. To this end, SPICE models provided by the manufacturer of specific components were used whenever available. The performance of the selected CCPS designs based on the results of the SPICE simulations is summarized in Table 1. From these results, it is concluded that

the three boost-converter-derived topologies simulated, i.e., the 4x and 8x paralleled and cascaded with paralleled first and second stages, are the best designs for the new HiPeR-PIT PPU. Initial prototypes of these designs will be developed, and their performance compared against the predictions of the SPICE models.

## SUMMARY

The pulsed nature of PITs presents a number of challenges. In particular, pulsed gas valves do not presently exist that can survive operation over typical electric propulsion lifetimes. Furthermore, pulsed gas injection often results in propellant near the leading and trailing edges of the pulse escaping the thruster without being ionized or accelerated. These losses make high propellant utilization efficiencies difficult to achieve and lower the overall thrust efficiency. To understand and overcome propellant utilization losses, the UW SPACE Lab is presently developing the HiPeR-PIT. The HiPeR-PIT discharge circuit uses recent advances in IGBT switching technology to achieve a high pulse rate (>1 kHz), enabling propellant to be injected in a continuous or quasi-steady manner. In addition to high repetition rate operation, the use of antiparallel freewheeling body diodes allows for zero-current switching (ZCS) during IGBT turnoff, significantly reducing turnoff switching losses. Moreover, these diodes enable inductive energy recapture, allowing energy not imparted to the plasma to be returned to the main capacitor banks rather than being lost to ohmic heating of the thruster circuit. The anticipated consequence of these two innovations is a significant increase in both propellant utilization and electrical efficiencies.

**PRINCIPAL INVESTIGATOR:** Justin Little, University of Washington

**PARTNERS:** NASA MSFC (Adam Martin, Kurt Polzin)

**FUNDING ORGANIZATION:** Cooperative Agreement Notice

**FOR MORE INFORMATION:** [spacelab.uw.edu](http://spacelab.uw.edu)

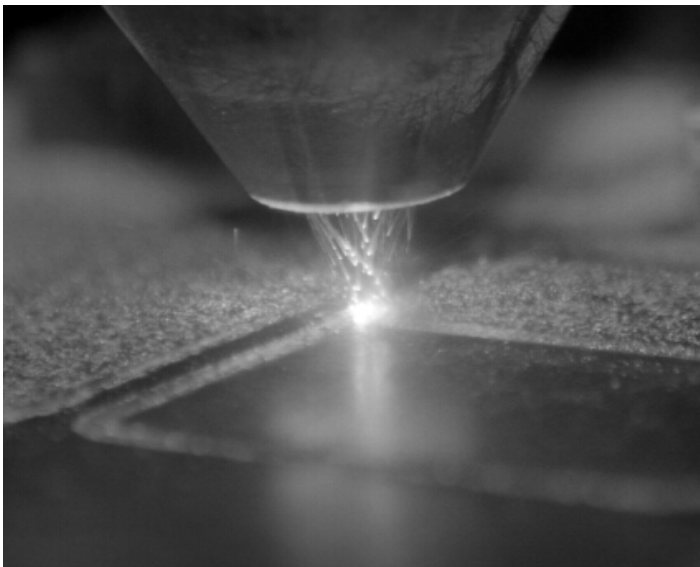


# Laser Metal Deposition of Copper-Alloys for Commercial Space Heat Exchanger Applications

**OBJECTIVE:** *To study the use of Infrared (IR) laser metal deposition (or directed energy deposition (DED)) for fabrication of highly reflective copper-alloy heat exchanger components.*

## PROJECT DESCRIPTION

Copper alloys are of great interest to the commercial space sector for use as combustion chambers, nozzles and heat exchangers for boost and upper-stage engines and nuclear thermal propulsion systems. High-conductivity copper-alloys are necessary within these applications to efficiently cool the walls of the combustor



**FIGURE 1.** IR Laser Directed Energy Deposition (DED) of GRCop-42.

without structural failure. However, it is this same thermophysical property, along with high reflectivity, that causes significant challenges in additive manufacturing of this material. Copper alloys have been successfully built using selective laser melting (SLM) powder-bed systems, but those systems are very limited in scale and do not address the larger-scale needs of commercial space combustion chamber and heat exchanger applications. By completing development of parameters for copper-alloy GRCop-42 (Cu-Cr-Nb)

and providing tensile samples and sample geometry components, the use of directed energy deposition (also known as laser metal deposition) for large-scale components can be studied for feasibility.

## ACCOMPLISHMENTS

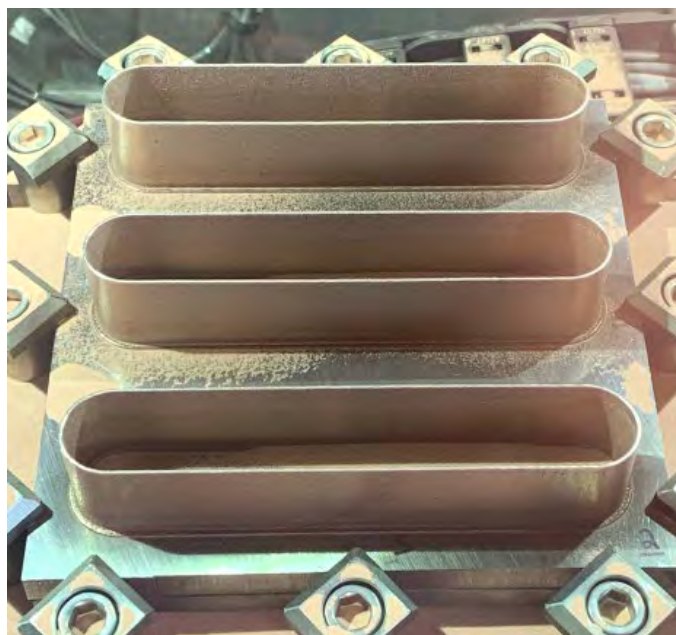
This project investigated the feasibility of processing GRCop-42 using a near-infrared (IR) laser as part of the directed energy deposition (DED) process for complex channel geometry. Initial development was explored using a DED system with a build volume of 200 mm<sup>3</sup>. The system demonstrated capability to process with copper alloys and refined the process parameters for a spot size near 1 mm made from GRCop42 and provided test and metallurgical samples to NASA Marshall Space Flight Center (MSFC). This material is of particular interest for large-scale combustion chambers and heat exchangers due to its high conductivity and high strength capabilities at extended duration elevated temperatures. The DED system used for the project is scalable to a large-format system with a build volume of 1 m<sup>3</sup> or greater, which can be used for potential future projects for full-scale parts.

The major tasks completed included the following:

- Developed process parameters for a 1mm spot size for GRCop-42 (Cu-Cr-Nb).
- Test and documented process parameters for GR-Cop-42 (Cu-Cr-Nb) builds to include laserpower, spot size, build speed, and powder flow.
- Built and provided to NASA-MSFC small race-tracks for mechanical testing.
- Demonstrated feasibility of the process for increased scale copper-alloy components with complex coolant channel geometry.
- Provided final report detailing the process parameters and results of the project.



**FIGURE 2.** GRCop-42 channel geometry built with FormAlloy X-Series.



**FIGURE 3.** GRCop-42 Racetracks for mechanical testing built with FormAlloy X-Series.

The DED system's deposition speed, in-process monitoring, and the unique capabilities for copper-alloy processing and gradient materials enabled the fabrication of GRCop-42 (Cu-Cr-Nb) tensile and channel simulated geometry samples. Process parameters were successfully developed with a 1.1-mm spot size, resulting in a wall thickness of approximately 1.6 mm. 'Racetracks' were built for metallurgical and mechanical testing, as well as a sample component with internal cooling channels to demonstrate feasibility.

**PRINCIPAL INVESTIGATORS:** Melanie Lang, FormAlloy and Paul Gradl, NASA

**PARTNERS:** FormAlloy, South Dakota State, South Dakota Experimental Program to Stimulate Competitive Research (EPSCoR)

**FUNDING ORGANIZATION:** Cooperative Agreement Notice

## **SUMMARY**

This project confirmed initial feasibility for a scalable, high quality metal additive manufacturing process capable of processing large-scale copper-alloy components for the aerospace industry. Specifically, initial studies have shown that DED is a viable technology for producing full-scale components from copper alloys such as GRCop-42 (Cu-Cr-Nb). Next steps include completion of a large format system that will enable adoption for full-size production applications.



# Nuclear Thermal Propulsion (NTP)

**OBJECTIVE:** To develop a low enriched uranium (LEU) NTP system which enables faster trip times, safeguards astronaut health, and provides abort scenarios not available from other propulsion architectures.

## PROJECT DESCRIPTION

NASA’s history with nuclear thermal propulsion (NTP) technology began in the earliest days of the Agency in 1958. An NTP system offers significant advantages over other propulsion architectures for human Mars missions and in cislunar space. NTP could also enable highly advanced science and exploration missions, and power systems derived from NTP could enable a power-rich environment anywhere in the solar system (or beyond).

The current NTP Project objective is to determine low enriched uranium (LEU) NTP feasibility and affordability with good cost and schedule confidence. The use of LEU offers potential advantages for a nuclear propulsion program that may include less burdensome security regulations, similar to those for a university research reactor. This opens the development effort to partnerships with industry and academia. The project is focused on the establishment of a conceptual design for an

LEU NTP engine in the thrust range of interest for a human Mars mission; the development of technologies that enable the robust production of LEU fuel elements and reactor core; and

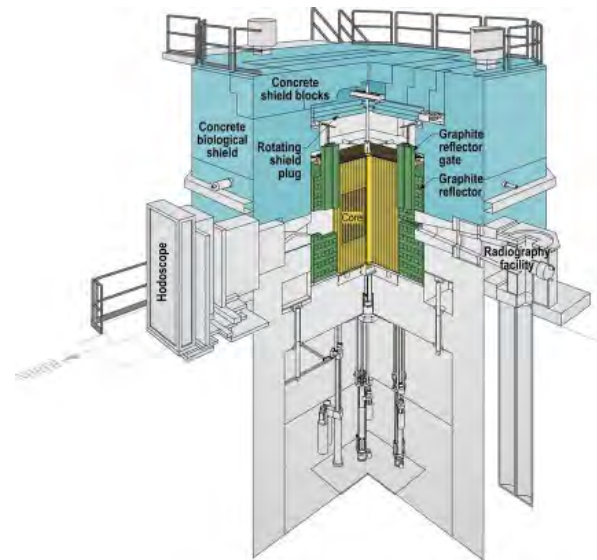


**FIGURE 1.** Model of possible future spacecraft powered by nuclear thermal propulsion.

demonstrating the feasibility of exhaust capture methods that can be used to test operations of a subscale nuclear rocket engine.

## ACCOMPLISHMENTS

One of the challenges to NTP development is maturing the technologies for fuel production



**FIGURE 2.** TREAT test facility.

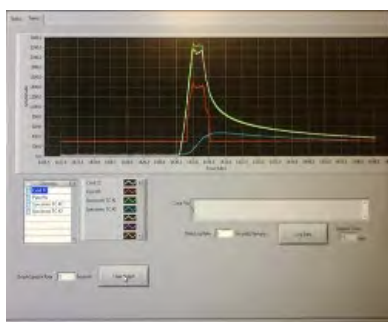
and fuel element manufacturing. The extreme temperature requirements for an NTP engine are not required by commercial power reactors.

The project is pursuing a multifaceted approach investigating both an LEU fuel system with a refractory metal-based fuel element and an LEU fuel system that builds on US experience and capability related to tristructural isotropic (TRISO) fuel particles. TRISO fuel compacts have been used extensively in terrestrial reactors and are of interest to multiple government agencies. The strategy also includes methods for incorporating the LEU fuel system into an engine in a way that provides multiple stage-level NTP benefits, including a high-efficiency orbital maneuvering system in addition



to the high efficiency NTP main propulsion. Tests of small fuel segments have been performed in both the MSFC Compact Fuel Element Tester (CFEET) and at the Idaho National Laboratory Transient Reactor Test (TREAT) Facility. Initial TREAT testing of a refractory-metal-based fuel element will be followed by test of a “Versatile TRISO” configuration focused on NTP applications.

The project successfully performed a transient nuclear power test of a hexagonal, 19-hole, tungsten-rhenium/UN cermet fuel sample, using 21% enriched uranium at the Idaho National Laboratory Transient Reactor Test (TREAT) Facility, and will conduct further testing at this facility. This was the first nuclear test of the project. Two spark plasma sintered (SPS) hexagonal molybdenum/tungsten/dUN fuel wafers were fabricated using a novel manufacturing process developed at MSFC, and were tested in the MSFC Compact Fuel Element Tester (CFEET) system. The project’s system feasibility assessment, completed in August, details the feasibility and affordability of a LEU engine, reactor, fuel and engine ground testing system with solid cost and schedule confidence.



**FIGURE 3.** Graphic of successful test.

## **SUMMARY**

NTP is directly relevant to the Agency’s vision, mission, and long-term goal of expanding human presence into the solar system and the surface of Mars. As missions aim for targets farther out into the solar system, nuclear propulsion may offer the only viable technological option for extending the reach of exploration, where solar panels can no longer provide sufficient energy, and chemical propulsion would require a prohibitively high mass of propellant and/or prohibitively long trip times. NTP provides the fastest trip time of all currently obtainable advanced propulsion systems. Fast trip times will safeguard astronaut health by reducing exposure to zero gravity and cosmic radiation. Reduced travel time also reduces risks associated with reliability uncertainties inherent in complex systems, as well as those associated with life-limited, mission critical systems. NTP also enables mission abort options not available from other propulsion architectures for human Mars missions.

**PROJECT MANAGER:** Sonny Mitchell

**PRINCIPAL INVESTIGATOR:** Michael Houts

**FUNDING ORGANIZATION:** Game Changing Development Program

**FOR MORE INFORMATION:** <http://gameon.nasa.gov/>



# Solar Cruiser

**OBJECTIVE:** *To mature solar sail propulsion and solar spectropolarimeter technologies to enable near-term, high-priority breakthrough science missions as defined in the NASA Solar and Space Physics Decadal Survey.*

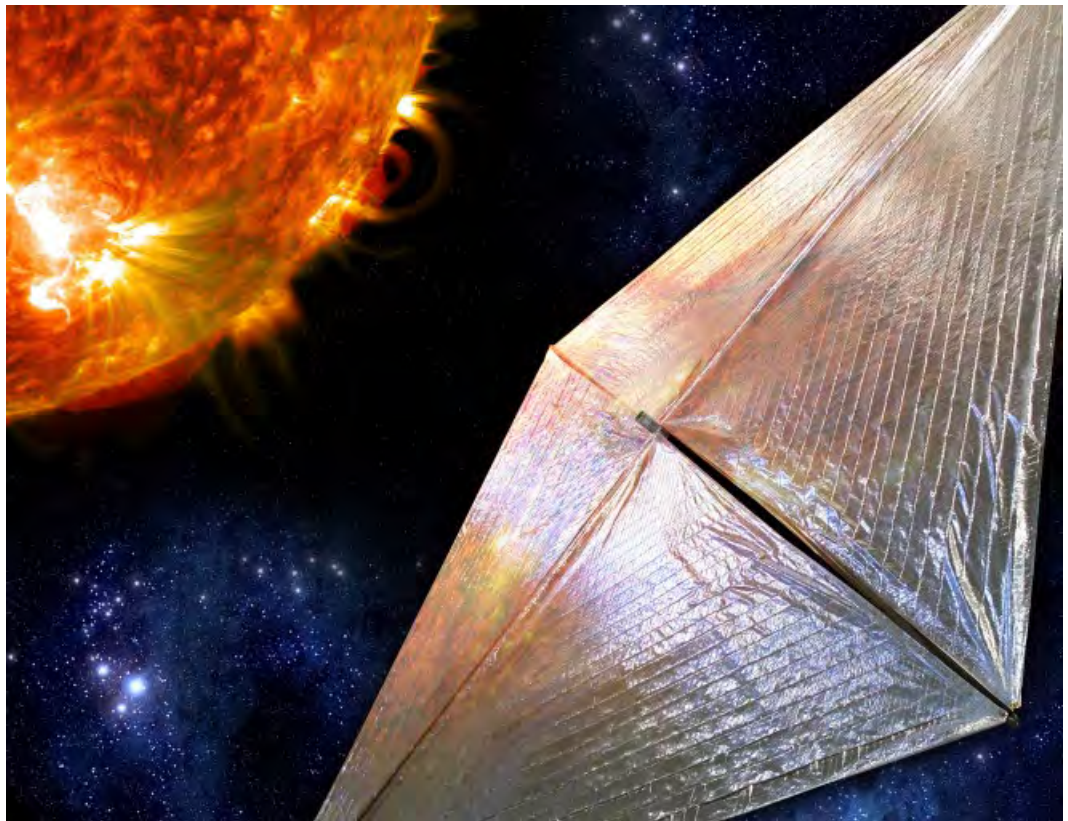
## PROJECT DESCRIPTION

The Solar Cruiser mission will mature solar sail technology for use in future Heliophysics missions as well as missions of interest across a broad user community (e.g., space weather and Earth polar observatories).

The onboard spectropolarimeter will observe the solar corona and coronal mass ejections (CMEs), allowing remote measurement of Berzelium, the out-of-ecliptic component of magnetic field as viewed from Earth and the most important parameter for assessing the geoeffectiveness of an event. In the current space weather paradigm, the magnitude and sign of Berzelium are generally not measurable more than roughly 1 hour before a CME

reaches Earth, due to the unavailability of remote-sensing measurements of the coronal magnetic field. Solar Cruiser will also serve as a pathfinder for missions to observe the solar environment from unique vantage points such as the Solar Polar Imager (SPI), opening a fundamentally new range of observational capabilities for the Heliophysics Program and for space weather monitoring. Observations away from the Sun-Earth line (SEL) present unique opportunities for answering the

outstanding science questions of Heliophysics, for improving space-weather monitoring and prediction, and for revealing new discoveries about our Sun and solar system. High solar inclinations are particularly compelling for enabling high-



**FIGURE 1.** Artist concept of the Solar Cruiser's solar sail and spacecraft during solar observations.

priority investigations of solar irradiance variations, the solar magnetic dynamo, and predictions of future solar activity cycles.

## ACCOMPLISHMENTS

Solar Cruiser will mature and demonstrate two technologies: a large solar sail, scalable in size to the needs of future science missions, and an imaging spectropolarimeter that will enable space-



based measurements of the sun's coronal magnetic topology and evolution for the first time.

Solar Cruiser will develop a solar sail with a characteristic acceleration ( $A_c$ ) of  $>0.13 \text{ mm/sec}^2$ , requiring a sail area of between  $>1250 \text{ m}^2$ . ( $A_c$  is defined as the normalized acceleration of a sailcraft at a distance of 1 AU from the Sun.)

The solar sail architecture uses a quadrant sail design with four composite booms that are deployed from a central rotating deployment mechanism and sail hub. The sail membrane is the space- and sail-proven aluminized CP1 polyimide substrate successfully flown on NanoSail-D2 and to be flown on NEA Scout. To further advance the solar sail architecture, Solar Cruiser also demonstrates polyimide embedded photovoltaics (PE-PV) to generate power and attitude control using reflectivity control devices (RCDs) on the sail surface.

Solar Cruiser was selected for Phase A funding by SMD in August 2019.

## **SUMMARY**

The Solar Cruiser mission was competitively selected by the NASA SMD Heliophysics Division as a potential Technology Demonstration Mission. Assuming a successful completion of Phase A and subsequent funding by SMD, Solar Cruiser will fly as a secondary payload with the Interstellar Mapping and Acceleration Probe (IMAP) mission in 2024. The Solar Cruiser's two primary technologies, the solar sail and the spectropolarimeter will enable wholly new science missions and observational capabilities to NASA.

**PRINCIPAL INVESTIGATOR:** Les Johnson

**PARTNERS:** Ball Aerospace, NeXolve, Rocco, High Altitude Observatory, University of California at Davis, NASA Goddard Space Flight Center

**FUNDING ORGANIZATION:** Science Mission Directorate



# High Power Heat Exchangers

**OBJECTIVE:** *To evaluate if metal foams, additively manufactured lattices, and topology optimized generated geometries can significantly increase the rate of heat transfer.*

## PROJECT DESCRIPTION

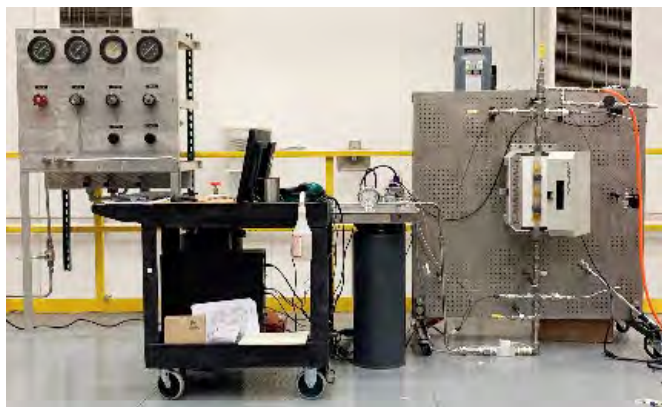
In nuclear thermal propulsion (NTP), there is an abundant amount of energy available, but it is limited by its ability to transfer it into the propellant. This power limitation drives system performance. Lattice generation and topology optimization algorithms can now be utilized in creating high surface area geometries that offer potential to increase the heat transfer power. However, these shapes tend to be complex and thereby infeasible to manufacture by traditional methods. With additive manufacturing (AM), such shapes can now be fabricated. The goal of this work is to identify a configuration that enhances heat transfer and see if such a configuration would significantly improve the current limitations.

## ACCOMPLISHMENTS

Past research at NASA Marshall Space Flight Center (MSFC) for enhancing performance for NTP systems has predominately focused on developing materials with high melting points in order to enhance heat transfer by maximizing the temperature difference between the heat source and the propellant. Past NTP reactor concepts have proposed fuel forms that enhance heat transfer via surface area and flow modification (i.e., particle beds and twisted ribbons). Use of metal foams as heat exchangers is starting to increase but has only rudimentarily been considered for NTP applications. Use of orderly lattice arrays is now beginning to be considered for general heat exchanger applications with the onset of lattice generation tools for additive manufacturing (AM). In utilizing foams, there appears to be a coupled tradeoff between enhancing surface area at the cost of more pressure drop. It remains to be seen if the regularity of the ordered meshes will provide equal or better heat transfer enhancement (HTE) for a lesser cost of pressure drop. Since inception of the original proposal, other HTEs for increasing power have been identified; therefore, the project scope has expanded beyond simply evaluating surface area enhancements. Thermal-hydraulic testing will be utilized to explore HTE features. Test articles will be AM and integrated

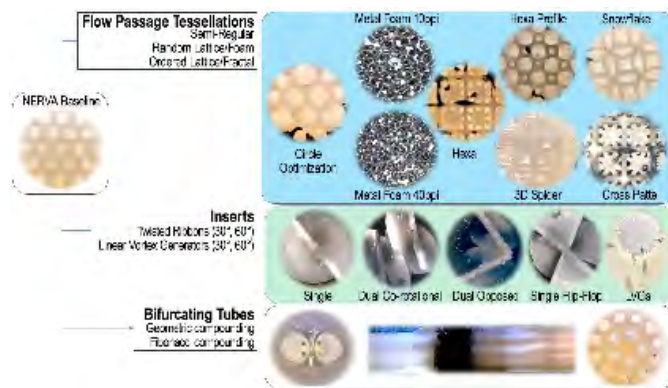
into a heated section of a ‘gas blower’ testbed. Temperature and pressure measurements will be used to infer dimensionless performance metrics, and comparisons will be made relative to a baseline (classical NTP fuel element). In addition, flow visualization techniques are being explored for testing of flow based HTEs. In parallel, porous media and multiphysics nonisothermal turbulent flow simulations, as well as topology optimization simulations will be utilized to help inform design decisions for the test articles.

The testbed has been designed, developed, and is now operational for testing. Based upon preliminary tests, a few required modifications and upgrades have been identified and are underway. Upcoming test results are expected to provide a better understanding of various design features and parameters to help identify key HTE features of interest, after which, additional hybrid test articles consisting of a combination of features is expected. Based upon those results, an optimal design is expected, and plans are to AM it from a high-temperature metal so that it can be tested for an NTP application. Currently, over 15 test articles consisting of HTEs of mesh lattices, various twisted ribbon, and linear vortex generator inserts as well as flow passage bifurcations have been AM for initial testing. One challenge in the utilization of AM parts is due to the restricted sizes that can be produced which thereby required joining of multiple segments. A segmented design that can be assembled has been completed and validated resulting in a generic design in which HTEs can be inserted into. Since the cost of AM metal test articles makes printing a large number of designs cost prohibitive, a strategy of utilizing low-cost, high-temperature poly resin for obtaining preliminary results to identifying key features has been adopted. However, a challenging aspect discovered in utilizing this material in the testbed is that even though it has a high temperature rating, it continues to cure from heating during testing, which reduces its capability to handle the loads from flow testing. In addition, if the thermal diffusivity of this material is so low that it chokes the heat transfer rate through the enhancement feature, it may mask any measureable HTE effect from manifesting in the gas



**FIGURE 1.** Thermal hydraulic test bed setup for characterizing performance of heat exchanger test articles.

outlet temperature. A potential solution to both these challenges has been identified and is being worked because being able to utilize this material is key for affordability and rapid turnaround—both of which are critical for a comprehensive evaluation. However, in conjunction, multiphysics modeling of various design features is being done to also help inform the design and down selection process. A nonisothermal turbulent flow model for the baseline design has been developed and benchmarked. Currently, models for other HTEs are being developed. Modeling of porous flow domains has been attempted in COMSOL, but current capabilities are not well suited for turbulent flow through a porous medium. As such, various lattice designs from a library of options were assessed based upon specific area and porosity which are thought to be the driving performance factors. Four candidate configurations and a lattice cell size were selected based upon this analysis and their evaluation will rely on testing. In the area of topology optimization, much experience has been gained in its utilization and implementation in the COMSOL multiphysics platform. Topology optimization models were attempted to find optimized designs for nonisothermal turbulent flows, but their use in this application has proved challenging due to the use of wall functions to model turbulence. This is because the wall distance initialization step is not part of the optimization process and as such is not recomputed when the wall locations are changed during optimization. Furthermore, an additional potential problem is that certain geometries could cause the flow to become highly nonlinear, which would result in not all combinations considered obtaining simulation convergence. As such, modeling laminar flow and thermal conductance approximations are planned. In the future, custom modifications to the topology



**FIGURE 2.** Heat Exchanger test article variations to be evaluated.

optimization could be considered so that the wall function approximations are included in the algorithm.

## SUMMARY

Being able to increase heat transfer power can improve any system in which the energy source is abundant, but it must be effectively transferred via heat. With manufacturing advances, novel, high-surface area foams and lattice array meshes are now feasible tools for designers. With advances in topology optimization, computer aided designs of custom lattices that enable a balanced optimization of heat transfer and flow restriction may soon be realizable. Furthermore, while maximization of surface area and operational temperatures are viable enhancements for heat transfer, there exist additional strategies involving fluid flow engineering. Identifying a comprehensive HTE strategy and utilizing the new capabilities of additive manufacturing may identify some novel heat exchanger designs that are capable of transferring a large amount of heat in a small distance because of their power capabilities. A thermal hydraulic testbed has been developed for rapidly testing design permutations which are also being virtually tested through multiphysics simulations when possible. A method of building test articles from AM parts has been identified, and methods for utilizing low cost materials are being explored in order to permit a comprehensive test and evaluation of many design permutations. To date, several initial test articles have been printed and cold flow tested, and many useful lessons have been identified as resolutions to the challenges are being worked.

**PRINCIPAL INVESTIGATOR:** Michael Schoenfeld

**FUNDING ORGANIZATION:** Technology Investment Program



# Lower Cost and Complexity of In-Space Propulsion

**OBJECTIVE:** To test the theory of replacing the multiple on/off valves of typical spacecraft reaction control systems (RCS) with the combination of one on/off valve and one rotary selector valve to route propellant.

## PROJECT DESCRIPTION

Lower cost and less complex solutions are constantly being sought in the growing small spacecraft industry. The rotary selector valve system (RSVS) addresses those goals by reducing components and leak paths. Monopropellant spacecraft currently have an on/off valve for each thruster. The RSVS eliminates all RCS on/off valves except for one. It then adds a stepper motor that turns a drum inside a manifold. When a maneuver is required, the motor rotates the two-port drum inside an eight-port manifold (for a typical monopropellant RCS) to the proper position for that maneuver. Once in position, the on/off valve is cycled as needed to initiate the maneuver. When the on/off valve is off, the stepper motor can move the drum to the next required position and the on/off valve is cycled again. The drum does not move while the propellant is flowing.

The goal of this CIF project was to design and test an 8-thruster prototype of the RSVS on Marshall Space Flight Center's (MSFC's) flat floor. This initial stage of development sought to prove that a test platform's movement could be controlled with the RSVS.

## ACCOMPLISHMENTS

To test the theory of the RSVS, a unique test platform was designed and 3D printed using Fused Deposition Method (FDM). The platform was placed directly onto an air bearing, which floats on air thereby removing ground friction. The 3D printed design, along with the reduction in valve components, reduced weight from the normal aluminum-plate test structures. The RSVS

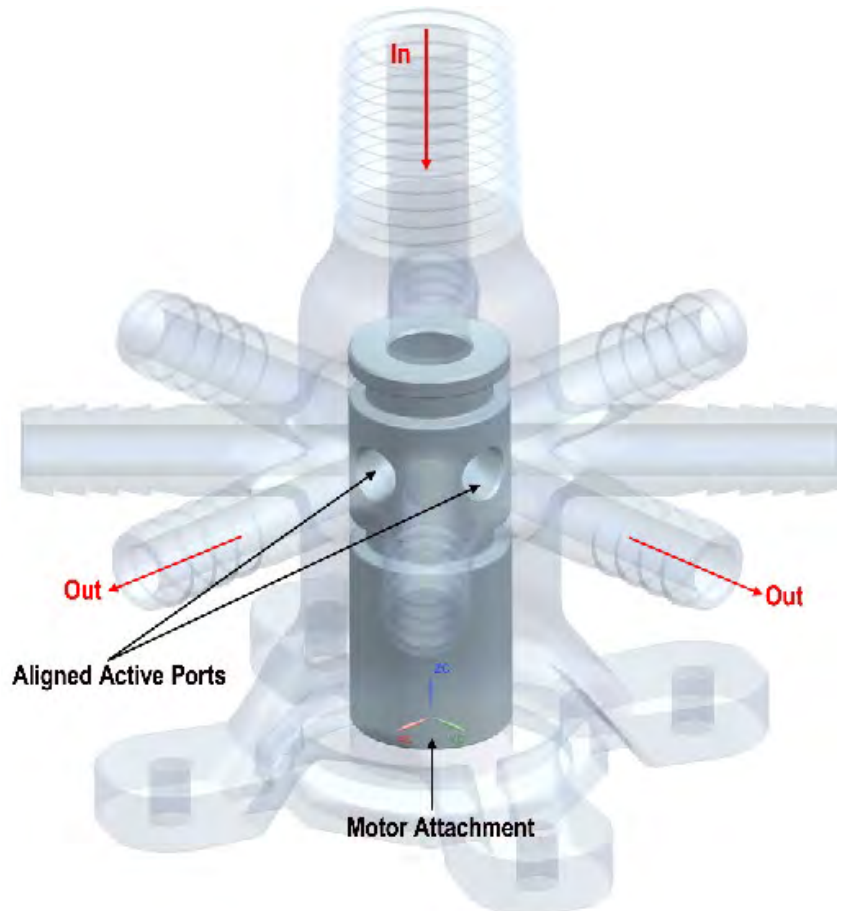


FIGURE 1. Rotary Valve.

platform was over 25% lighter than the current flat floor test platforms while containing almost three times the propellant volume and two and a half times the battery capacity. The center of gravity was also greatly lowered to prevent tipping. Due to surface finish and tolerance requirements, the RSVS and nozzles were printed with resin-based Stereolithography (SLA) using Formlabs Tough resin with a tested burst pressure of 1,600 psi. The RSVS was placed in the center of the printed platform with rubber hoses connecting the manifold to the nozzles. Four composite tanks fed compressed air at 300 psi to the single on/off valve, which fed straight into the RSVS inlet. An NVidia® Jetson Nano™, programmed in Python, controlled the electrical subsystems. The Jetson received commands via Wi-Fi from a laptop, and a wireless



PlayStation® 2 controller to control the position of the RSVS drum and on/off valve.

The greatest technical challenge of the RSVS is sealing the rotating drum. Although this type of valve seal is not new, the desire for a low minimum impulse bit (in this case, 1 valve cycle and worst-case 180° stepper repositioning) requires a drum that is easy to turn. Stepper motors have a torque curve that quickly falls as speed increases; therefore, a low friction seal was desired. Different seal designs were considered, but to reduce friction, it was decided to use just two o-rings. The two o-rings were placed on the rotating drum, one above and one below the two ports. The gap between the drum and manifold was .001 in (0.254 mm).

Use of the flat floor test platform showed that the theory of using a single on/off valve in conjunction with a single rotary valve works for dynamic control of a vehicle. The test platform responded as expected and was easily controllable with the wireless PlayStation 2 controller. Due to the use of a standard industrial stepper motor for the drum in the rotary valve and the on/off valve, the minimum impulse bit was about 100 ms. An on/off valve and rotary drum motor designed specifically for this purpose could greatly reduce that time. Autonomous programming for testbed control was not yet completed at time of testing.

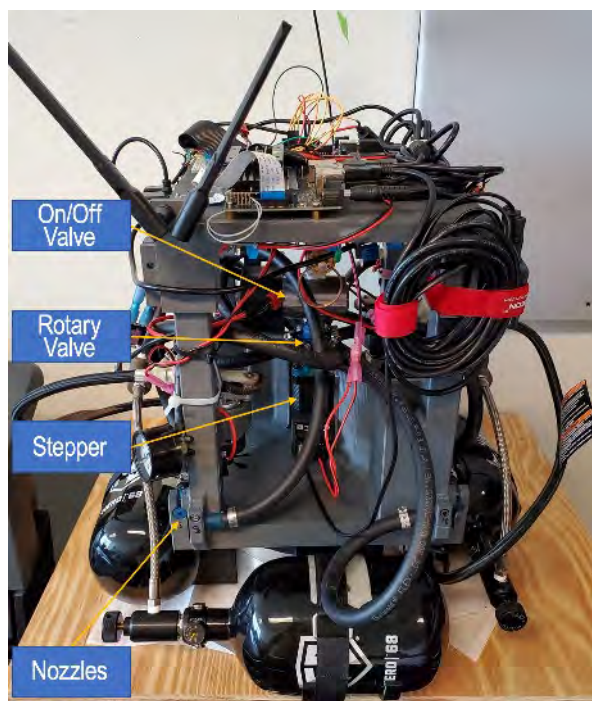


FIGURE 2. Air-Bearing Test Platform.

Testing also showed that a more robust drum seal is needed. Due to the backpressure generated by the nozzles, the drum leaked enough to require sealing four of the eight ports of the manifold. This removed lateral control, allowing the vehicle only forward/backward-translation and left/right-rotation. The leakage was augmented by misalignment of the manifold ports and drum. It was discovered that the stepper motor had an incremental, rather than absolute, encoder. Each time the machine was powered off and on, the drum position was lost; however, this is easily fixed by changing the encoder. Perfect seals would still require proper alignment of the ports. The next iteration of development will focus on the drum valve seal. Low friction materials and different designs are being looked at which would fully enclose each port on the rotor or manifold.

To compare the RSVS to current technology, a 3D-printable (Titanium 6Al-4V) RSVS module was designed with the same volume and interface as the VACCO Near Earth Asteroid Scout (NEAScout) RCS/propulsion module. This design had a second on/off valve for the non-RCS, translational thruster ports. Using industrial valves and stepper motor, the RSVS version of the propulsion module is 0.27 kg (10.6%) lighter and has 175 ml (17.5%) additional propellant volume. Further development would seek lighter aerospace grade valves and a custom 4-position stepper motor. An 8-position, 8-thruster version with the same size RSVS can also be designed which would eliminate the 45° efficiency loss of the current VACCO thruster design.

## SUMMARY

Success in controlling the test platform shows promise in the control of spacecraft—especially for small craft where reduction in mass, volume, and cost—is essential. Next steps involve refining the drum seal and reducing the minimum impulse bit. Future efforts would seek an SBIR to develop an optimized on/off valve and stepper motor with eight steps (rather than the current 20,000 steps) to speed valve response.

**PRINCIPAL INVESTIGATOR:** David Dominguez

**FUNDING ORGANIZATION:** Center Innovation Fund



# Near Earth Asteroid Scout

**OBJECTIVE:** *To use a solar sail to propel a small spacecraft on a 2-year mission to explore an asteroid using a solar sail.*

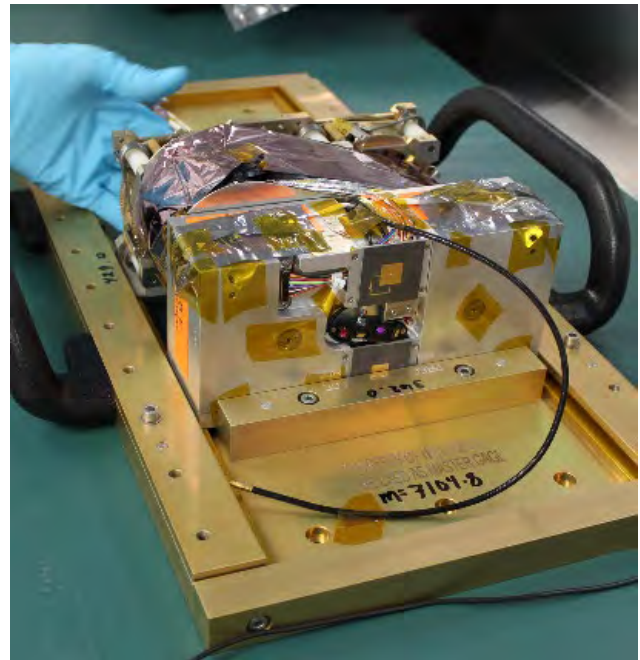
## PROJECT DESCRIPTION

Near-Earth asteroids (NEAs) are of interest not only for Human exploration, but also for science, in-situ resource utilization, and planetary defense. The NEA Scout, scheduled to launch in 2020, will use its solar sail propulsion system to send a small spacecraft to flyby asteroid 2013 WA44, providing important images and scientific measurements. Solar sails ‘sail’ by reflecting sunlight from a large, lightweight reflective material that resembles the sails of 17th and 18th century ships and modern sailing ships. Similar to how a ship uses the wind to sail, the solar sail derives thrust by reflecting solar photons. While the force exerted by sunlight is extremely small, it is relatively constant, resulting in a slow—but—constant acceleration that pushes the sail, (and the spacecraft attached to it,) to higher and higher speeds with minimal use of fuel for reaction control. Elements of NEA Scout were developed at Marshall Space Flight Center, Jet Propulsion Laboratory and Langley Research Center. MSFC manages the mission and developed the 86 m<sup>2</sup> solar sail propulsion system onsite.

## ACCOMPLISHMENTS

The NEA Scout spacecraft is housed in a ‘6U’ CubeSat form factor. A CubeSat is a very small spacecraft built on a modular design architecture of 10 cm<sup>3</sup> cubes. Each cube is called a ‘U’ and is typically allocated about two pounds of total mass. A spacecraft can then be built by combining these cubes together.

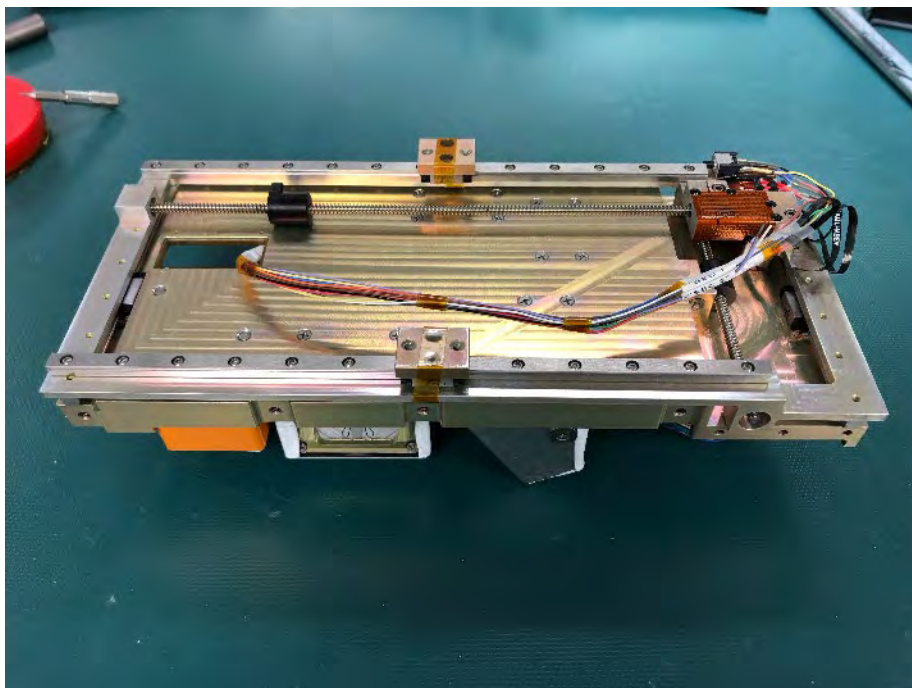
The innovations are the design, development, testing of a solar sail system that fits within such a small volume and that is capable of providing the propulsion required for the mission and the flight control system that will manage the sail’s continuous low thrust throughout the flight. The solar sail is a single sheet deployed on four booms from the center 2U of the 6U spacecraft. The solar sail subsystem consists of a single 86 m<sup>2</sup> colorless



**FIGURE 1.** NEA Scout solar sail and boom deployer assembled with other subsystems in the spacecraft integration fixture.

polymer (CPI), 2.5 μ thick aluminized sail that will sit on top of and be deployed by four Elgiloy (a stainless steel alloy) booms integrated with an Active Mass Translation (AMT) device to support attitude control of the spacecraft. Key objectives for the year included testing the AMT subsystem in the thermal vacuum chamber and beginning spacecraft integration. The spacecraft is planned to be delivered to the launch site next year.

The 86 m<sup>2</sup> flight solar sail and 6.8 m Elgiloy TRAC booms were integrated into the deployer and completed a successful full deployment and thermal vacuum tests in mid-2018. The AMT, developed to correct for the offset in the center of mass (CM) and center of pressure (CP) in the solar sail flight system, resides near the geometric center of NEA Scout and adjusts the CM by moving one portion of the flight system relative to the other. The flight AMT has been attached to the avionics box mid-plate and is being assembled into the rest of the spacecraft.



**FIGURE 2.** The NEA Scout active mass translator (AMT) shown assembled to the avionics box mid-plate assembly.

## **SUMMARY**

The NEA Scout will demonstrate the feasibility of using a low-cost, solar sail propelled CubeSat on an asteroid reconnaissance mission. If successful, it will be the USA's first interplanetary mission propelled by a solar sail and a pathfinder for many potential missions using sail technology in the future.

### **PROJECT MANAGER(S) AND/OR PRINCIPAL**

**INVESTIGATORS:** Joe Matus, PM, PI; Les Johnson, Solar Sail PI; and Julie Castillo-Rogez, Science PI

**PARTNERS:** NASA Jet Propulsion Laboratory and Langley Research Center

**FUNDING ORGANIZATION:** Advanced Exploration Systems

**FOR MORE INFORMATION:** <https://www.nasa.gov/content/nea-scout>



# Development of High Fidelity Solar Sail Dynamics Model

**OBJECTIVE:** To further advance the simulation, modelling, and orbital estimation capabilities of advanced solar sail missions.

## PROJECT DESCRIPTION

Over the last few years of solar sail research and development, it had become clear that NASA Marshall Space Flight Center (MSFC) was lacking the necessary high-fidelity tools required for solar sail dynamics modelling in a 6-Degree of Fidelity (DOF) environment. The current 6-DOF and other dynamics simulations that were being employed were not standardized, and any changes to the simulations themselves were convoluted and difficult to implement. Along with this, MSFC did not have the necessary orbit determination (OD) capabilities for solar sail missions. Orbit

## ACCOMPLISHMENTS

An important technical challenge that needed to be addressed quickly was the lack of standardization of inputs/outputs for solar sail simulations, both in the branch and throughout MSFC. To overcome this roadblock, a modular 6-DOF simulation suite was developed through this effort, and this tool is now named SkyCaptain. This solar sail simulation testbed has the capability to model several solar sail models in a ‘plug-and-play’ fashion, making comparisons of different force/torque models easy for comparison. As proving ground for the capability of this new 6-DOF solar sail modelling

suite, a new solar sail force/torque model was generated, which is referred to as the flexible reflective membrane (FRM) solar sail model. FRM is centered on a mesh-based force/torque model, with the capability to be flexible in shape as a function of a user desired input (such as sun incidence angle).

Along with the 6-DOF simulation suite, a baseline OD capability tool was developed using NASA Jet Propulsion Laboratory’s industry-leading OD Python library, called Monte. This OD suite works in tandem with SkyCaptain, as it has the capability to take input from

the 6-DOF simulation and simulate Deep Space Network (DSN) measurements in the same fashion that would be seen during flight. These simulated measurements can then be fed into an estimation filter, which attempts to characterize the forced experienced on the spacecraft due strictly to solar sail dynamics.

As work continues on this effort, SkyCaptain will continue to become more modular and standardized to meet the needs of upcoming simulation efforts. There are also discussions underway about

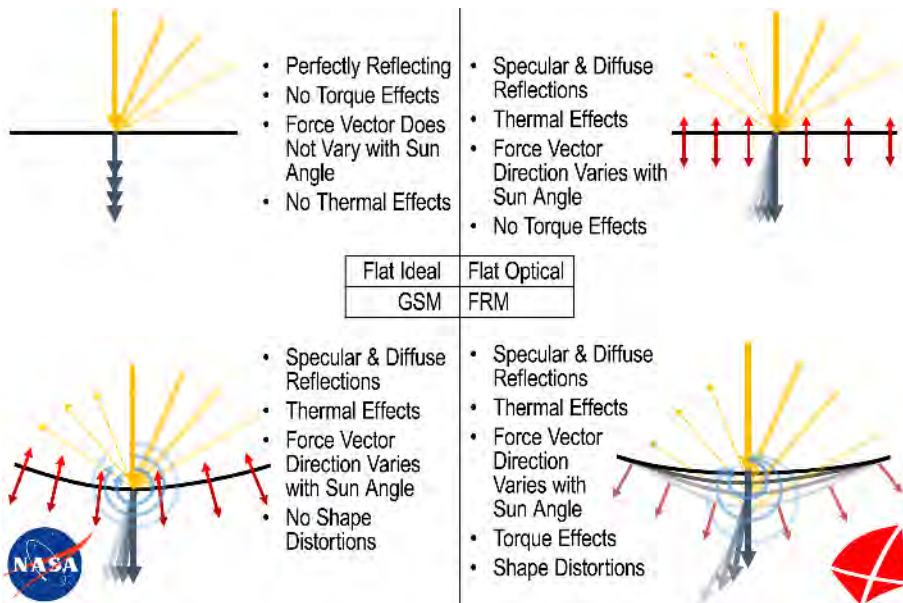
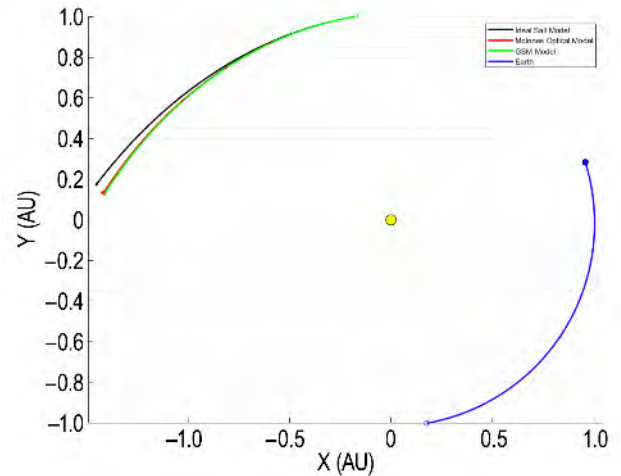
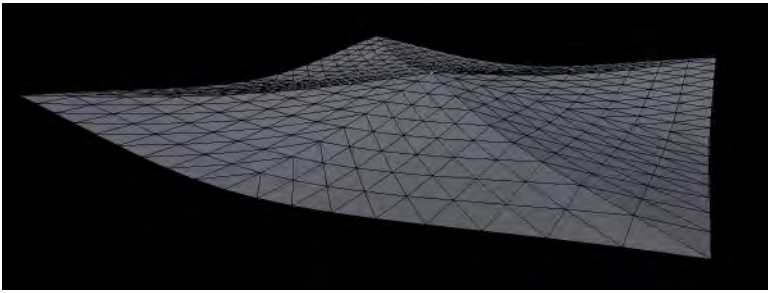


FIGURE 1. Solar sail force/torque model differences.

determination capabilities would be essential for long-term interplanetary solar sail missions to filter flight data to arrive at more realistically representative solar sail models (which would then be used to make our simulations more accurate). Solar sail technology is quickly advancing, and the goal of this effort was to develop a set of simulation and navigation tools to meet the demand for new proposals and for higher accuracy simulations of solar sail missions.



**FIGURE 2.** Left: Example of advanced solar sail mesh created for SkyCaptain simulation. Right: Differences in trajectory propagation due to different force models.

making the OD filter more robust to different sail configurations and to attempt to backtrack characteristics of the solar sail based on the OD filter solution over the course of certain trajectories.

SkyCaptain has now matured to a point where it has the capability to test a wide range of solar sail scenarios—from modeling an entire solar sail mission trajectory based on pointing input from other 3-DOF optimization tools, to testing the controllability of a specific solar sail shape at different distances from the sun while undergoing certain spacecraft control constraints. The high-fidelity FRM model has been implemented into SkyCaptain, alongside several other industry standard tools. These industry leading solar sail force/torque models have been tested and compared side-by-side to the new FRM force/torque model generated for this effort. From these studies, it is apparent that solar sail shape deformation plays a significant role in long-term solar sail trajectories.

Baseline GNC algorithms have been implemented into SkyCaptain and tested with all solar sail force/torque models. In order to test the controllability of advanced solar sail shapes, several 6-DOF configurations were tested in SkyCaptain that commanded varying spacecraft attitudes. When more advanced solar sail shapes were tested (upwards of 1,000 m<sup>2</sup>), the need for smarter and more properly tuned controllers as a function of sail shape became apparent very quickly. The difference in overall controllability of solar sails from different force/torque models spoke to the need to test several different dynamics models to ensure robustness of GNC algorithms over a wide range of sail configurations.

SkyCaptain, as well as the OD suite that was developed for this effort, have both been distributed

to others working on solar sail mission analysis and are being version controlled to handle future development. The OD suite allows for data from SkyCaptain to be fed directly into the DSN measurement data tool, and a basic filter was then developed to filter this simulated data. The entire workflow, from simulation configuration for sail filter development, has been documented for other potential users of the simulation.

## SUMMARY

Quickly advancing solar sail technology and hardware, and the proposals that come with, need a strong 6-DOF simulation suite to match, which is what this effort brings to MSFC. A simulation testbed has been developed that is modular, easy to be built upon, and customizable. This simulation has been made available to others at MSFC on solar sails for initial testing on several solar sail missions. The near-term objective is for these tools to be verified using flight data from previous and upcoming solar sail missions (i.e., Nano Sail D2, Light Sail 2, NEA Scout), while also being used for feasibility studies on much more advanced solar sail configurations such as Kon-Tiki/. An OD suite leveraging JPL's Monte toolkit has also been configured which will provide MSFC the capability to process in-flight data and compare it to the models currently available in simulation, in order to help create new, smarter force/torque models for solar sail mission analysis.

**PRINCIPAL INVESTIGATORS:** Naeem Ahmad and Jason Everett

**FUNDING ORGANIZATION:** Technology Investment Program



# Europa Lander Irradiation of Propellant at MSFC

**OBJECTIVE:** *To provide preliminary characterization on the effects of radiation on solid rocket motor materials and components.*

## PROJECT DESCRIPTION

The Europa Lander will utilize a solid rocket motor (SRM) to provide the braking function of the de-orbit stage (DOS) of the mission. Because the Jovian environment maintains a strong electromagnetic field, radiation was identified as a priority risk to the development of the DOS SRM. The DOS will be exposed to radiation for approximately 2.5 hours prior to ignition, which may result in estimated exposure dose of 1.5 Mrads in the propellant-liner-insulation (PLI) bond-line. Estimated radiation levels were provided by NASA Jet Propulsion Lab (JPL). An evaluation of the effects of radiation on propellant samples was performed to reduce the risk of failure for the program.

An initial pathfinder testing activity was performed using spare SRM materials provided by NASA Marshall Space Flight Center's (MSFC's) solid rocket propulsion department. The materials consisted of o-rings, insulations, liner, and inert propellant. The purpose of this test was to develop a set of lessons learned could aid in the testing of live propellant.

The main course of testing irradiated various live propellant types and PLI layups. Samples were provided by two SRM vendors, irradiated at MSFC's Combined Environment Effects Facility (CEEF) using the same methodology as the initial testing, and then samples were returned to the vendors for mechanical and ballistics property testing. The propellant types were designated as A, B, and C. Propellant A and B were similar heritage formulations for direct comparison. Propellant C was a formulation specifically designed for deep space purposes.

Propellant A was provided in various sample configurations: JANNAF dog bone, PLI matrix (PLIM), strand, TC-1, and G-block samples. Tests performed included tensile, bond-line strength,

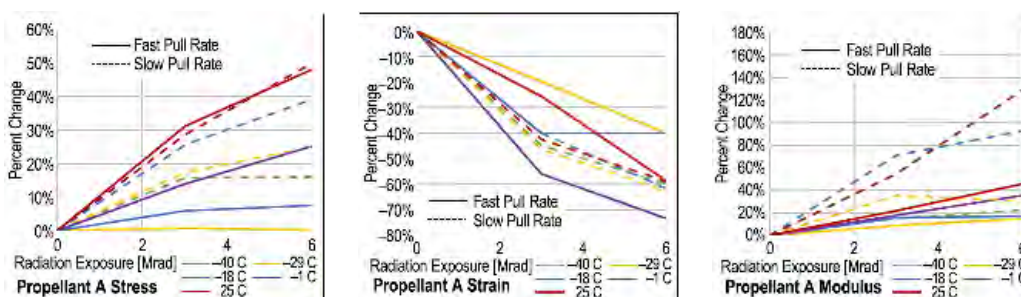
ballistics, hazards, differential thermal analysis, and scanning electron microscope (SEM) imaging. Propellants B and C were provided in slabs of varying thickness and in conical-bond-in-tension samples. Slabs were cut into post-test sample configurations.

This testing would mark the first time live propellant would be irradiated at MSFC. Before irradiation of live propellant was conducted, risk concerning internal electrostatic discharge (iESD) was investigated. Because the radiation source is high energy electrons, it is possible that charge could build up unevenly in the PLI materials, increasing charge potential until an arc releases it, potentially igniting the propellant. A step process was performed, in which an inert sample was radiated using an electron beam, then a 1 in<sup>2</sup> PLIM sample with live propellant, and finally full size live propellant bond-line samples.

## ACCOMPLISHMENTS

Initial analysis of the iESD analysis determined that PLI materials, charged with a 1.8 MeV electron beam at a 0.35 nA/cm<sup>2</sup> current density, remained below the dielectric strength of the material. Further testing of inert and live samples of PLI matrices concluded without visible arcing or incident.

Upon visual examination of the specimens, no discolorations, deformations, nor surface voids were observed. Measured weight loss displayed consistent, small weight loss for both tensile and motor grain samples. However, these were deemed insignificant and possibly the result of moisture loss. The scanning electron microscope (SEM) imaging presented no significant differences in any of the propellant types. Additional cracks were observed in the ammonium perchlorate (AP) of propellant B; however, the limited observations and weak evidence does not support a cause-effect relationship with radiation. The propellants maintained established thresholds in the hazard



**FIGURE 1.** Graphs showing the change in stress, strain, and modulus capabilities of Propellant A at different temperatures and exposure to varying levels of radiation.

testing, which will assist the radiation facility performing the sub- and full-scale motors for development and qualification testing. The mechanical testing results indicated no adverse effect in strength threshold or failure modes to the bond-lines. Burn rate results were deemed inconclusive, as strand sample tests are not very reliable. Tensile testing showed that strain significantly had degraded. These results were consistent across different temperatures and strain rates conditions.

## SUMMARY

Radiation exposure increases modulus and stress of propellant, while elongation decreases. Bond-line tensile and shear strengths resulted in no significant changes and no change in desired failure modes. Based on prior internal and external experience, all changes that resulted from high temperature aging or radiation exposure were expected. None of these changes preclude the successful use of a SRM for the application of the expected environments, provided selection of appropriate storage and

ignition temperatures base data supported by motor grain stress analysis and knockdown factors. Future tests will include subscale motor fire, simultaneous radiation and temperature testing of bond-line samples, and irradiated inert propellant loading.

**PRINCIPAL INVESTIGATOR:** Joshua Moore

**PARTNER:** JPL

**FUNDING ORGANIZATION:** Science Mission Directorate





# **ROBOTICS AND AUTONOMOUS SYSTEMS**

**AND**

# **HUMAN HEALTH, LIFE SUPPORT AND HABITATION**



# Cognitive Work Analysis of Manual Intervention in Highly-Automated Systems

**OBJECTIVE:** To improve human-automation coordination in highly automated systems using manual command of the Space Launch System (SLS) as a test case.

## PROJECT DESCRIPTION

Our goal is to develop crew information requirements to support manual command of the Space Launch System (SLS). Manual command is a proposed implementation of manual steering in which the crew prescribes a desired vehicle state, such as a desired attitude, and the ascent Flight Control System acts to reduce the error between the commanded state and the vehicle's current state. We use Cognitive Work Analysis, a human factors methodology, to analyze the transitions between automated flight and manually commanded flight of SLS and determine what information the crew needs in each flight mode. This project contributes to NASA's objectives regarding human-computer interface technologies for flight and ground systems. Furthermore, the work is benefitting Tennessee State University by expanding its capacity to compete for funding opportunities from NASA and other federal agencies related to human-technology interaction. Funds from the project are being used to support two undergraduate researchers.

## ACCOMPLISHMENTS

This project uses Cognitive Work Analysis to develop information requirements for SLS displays. This method, which involves five phases, analyzes a system by identifying constraints on operator behavior. Each phase examines various constraints on work and offers tools for analyzing workers' behavior in the system. For example, control task analysis (CTA)—the phase we have just completed—examines the information processing activities required for proper system operation during different modes of system operation. The results of each phase of the analysis feed into the next phase.

This work complements other work in industry and academia that has used the Cognitive Work

Analysis framework to analyze crew and operator information requirements in systems that operate at different levels of automation. After completing the Cognitive Work Analysis, we will conduct an Information Availability Analysis of the SLS crew displays. This portion of the proposed activities will examine the current SLS crew displays to determine whether their current design supports the range of tasks that will be required for manual command of SLS. We will use the results of the Cognitive Work Analysis as the basis for this analysis.

In September 2019, we completed a CTA of SLS manual command. CTA is the second phase of a Cognitive Work Analysis, and it describes the input/output transformations between information provided to a system's operators and the actions that the system operators take on the basis of this information. This work was performed using the results from the first phase of Cognitive Work Analysis, a Work Domain Analysis of SLS Core Stage flight during nominal conditions and manual command conditions, which had been completed previously.

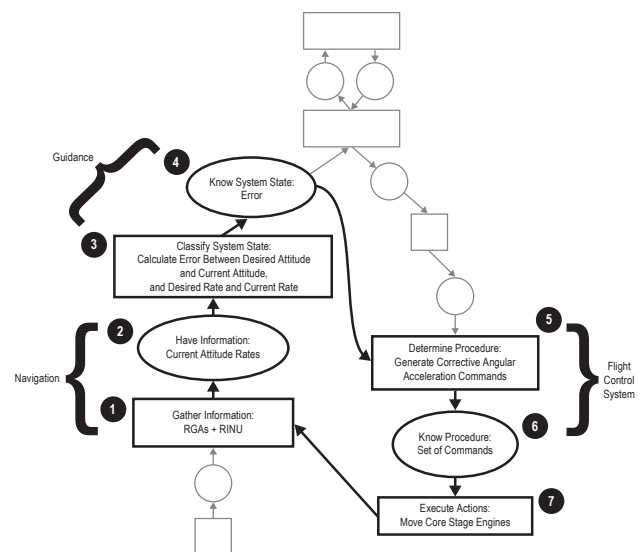


FIGURE 1. Decision ladder for nominal core stage flight.



# Bosch for Terrestrial Applications

**OBJECTIVE:** *To identify terrestrial applications for exploration life support space technology.*

## PROJECT DESCRIPTION

While NASA seeks to develop technologies that will enable long-duration manned missions beyond low Earth orbit, oftentimes these technologies result in corresponding benefits on Earth. One example of this is in the area of life support. Life support technology aims to provide those critical functions of maintaining breathable air, providing potable water, managing human wastes, and ensuring a habitable environment for humans in space. Oxygen recovery is a key area of development in life support for long-duration manned missions in which oxygen, exhaled by the crew as carbon dioxide, can be recovered using physical/chemical systems. The Bosch process is a chemical process in which carbon dioxide ( $\text{CO}_2$ ) is broken down, and when combined with water electrolysis, results in the production of oxygen ( $\text{O}_2$ ) and solid carbon ( $\text{C}_s$ ). The Bosch for Terrestrial Applications project seeks to identify Earth applications for Bosch technology, to evaluate the technical feasibility of using Bosch for a given application, and to determine the logistical and economic feasibility of Bosch technology in a commercial industry.

## ACCOMPLISHMENTS

In 2017, NASA patented an approach to use the Bosch process, originally developed for space, for the benefit of the cement industry. Introduction of this process into the production of cement results in two benefits. First, the Bosch process provides a method to reduce the considerable  $\text{CO}_2$  emissions from cement production by converting the exhaust to water and solid carbon. Second, the process uses the cement as a catalyst for the Bosch process, thereby capturing the solid carbon in the cement product. When the Bosch cement is then used to



**FIGURE 1.** Industrial rotary kiln ( $\approx 30$  ft diameter) in an operational cement plant.

produce concrete, the result is a material that resists the transport of harmful ions through concrete. By blocking these ions, the steel rebar providing support to concrete structures is protected from corrosion which may result in significantly longer life. Prior to 2018, economic and logistical feasibility of the approach had been reviewed and deemed sufficiently reasonable for continued evaluation. Technical feasibility, however, was limited to benchtop scale demonstration in a packed bed reactor. While the packed bed reactor provided data to prove the chemistry necessary to use the Bosch process with cement, it was not able to prove that the effect would be similarly achievable in an industry-scale process. Further, the packed bed reactor was significantly limited in the overall achievable processing rate due to high pressure drop across the reactor. In an effort to support adaptation of the Bosch process into industry and to increase the total processing rate, a more realistic proof of concept is necessary. To this end, a rotary kiln reactor, similar to those used in the production of cement (see Fig. 1) but at a laboratory scale, was purchased in FY 2018. Three milestones were

identified for FY 2019. The first was to complete the design of a test stand to support operation of the rotary kiln reactor. The second was to procure the necessary components and assemble the test stand. The final milestone was to begin experimentation of the Bosch process for cement in the rotary kiln reactor.

With support from multiple college interns from the University Student Research Association, all three targeted milestones for the project were achieved in FY 2019. An initial design for the test stand was prepared by engineers in the Environmental Control and Life Support Systems (ECLSS) Development Branch at MSFC. From there, an intern provided the day-to-day manpower to lead assembly of the Rotary Kiln test stand (see Fig. 2). The test stand provides the capability to test under targeted Bosch pressures and temperatures as well as developmental kiln parameters including 0–15° tilt and variable rotator speeds. Finally, initial testing was conducted using cement with the goal of demonstrating carbon formation from the Bosch process on the cement as well as increased reaction rates as compared to the packed bed reactor studies. These initial studies showed that the Bosch process was forming carbon on the cement in the rotary kiln reactor (see Fig. 3). Data reduction is ongoing to determine comparable carbon formation rates.



**FIGURE 2.** Laboratory rotary kiln reactor in rotary furnace. A custom quartz tube is used as the reactor in the furnace.

Future work will involve continued testing aimed at optimization of the rotary kiln for a demonstration of the Bosch process in the cement industry.

## SUMMARY

The Bosch for Terrestrial Applications project seeks to identify Earth applications for Life Support Bosch technology. The cement industry has been identified as an industry that could benefit from Bosch technology through both reduction in CO<sub>2</sub> emissions and an improvement in the durability of its resulting concrete product. In FY 2019, the project successfully designed and assembled a rotary kiln reactor in an effort to prove feasibility of the approach in a directly applicable reactor system.



**FIGURE 3.** Close up of the 2 in reactor tube containing Bosch cement. In this test, carbon formation was observed to form at the location nearest the gas inlet. This indicates unbalanced flow with respect to the aspect ratio of the reactor.

Data reduction continues to determine if initial testing showed higher reaction rates with a rotary reactor over a packed bed reactor. Future work will seek to optimize operation of the rotary kiln and to generate the necessary data to increase the overall scale of the Bosch process for implementation in the cement industry.

**PRINCIPAL INVESTIGATOR:** Morgan Abney

**PARTNERS:** Iowa State University, Concrete Preservation Institute, Lehigh Cement Company

**FUNDING ORGANIZATION:** Technology Transfer

# Plasma Pyrolysis Methane Post-Processor

**OBJECTIVE:** To recover and recycle hydrogen from Sabatier-produced methane to increase oxygen recovery from metabolic carbon dioxide.

## PROJECT DESCRIPTION

Life support is a critical function of any manned space vehicle or habitat. The Atmosphere Revitalization (AR) subsystem within the Life Support System (LSS) aboard International Space Station (ISS) provides a breathable atmosphere and comfortable living environment for the crew.



FIGURE 1.  $H_2/CH_4$  PPA Plasma.

For long-duration crewed missions, maximizing oxygen recovery is required to reduce resupply mass. The current AR subsystem employs a Sabatier reactor that recovers approximately 50% of the oxygen ( $O_2$ ) from carbon dioxide ( $CO_2$ ). In the Sabatier process, methane ( $CH_4$ ) is produced

as a byproduct and vented overboard. Because the system requires hydrogen ( $H_2$ ) as a reactant for  $CO_2$  reduction, the loss of methane (and corresponding hydrogen bound therein) results in a system that supplies only a portion of the required crew oxygen. One approach to achieve additional oxygen recovery is to recycle hydrogen by adding a methane post-processor to the Sabatier-based AR architecture. MSFC has been exploring the Plasma Pyrolysis Assembly (PPA) for this purpose.

The PPA technology, developed by Umpqua Research Company via Small Business Innovative Research (SBIR) projects uses a magnetron to generate a  $H_2/CH_4$  plasma (shown in Fig. 1) targeting Sabatier methane conversion to hydrogen and acetylene ( $C_2H_2$ ). Secondary reactions with methane and reactions with residual water vapor also occur in the PPA reactor resulting in an effluent mixture containing  $H_2$ , unreacted  $CH_4$ , product  $C_2H_2$ , and trace quantities of water, carbon monoxide (CO), ethylene ( $C_2H_4$ ), ethane ( $C_2H_6$ ), and solid carbon. In order to recycle the recovered hydrogen from the PPA product back to

the Sabatier, the hydrocarbon byproducts must be removed to prevent fouling of the Sabatier catalyst.

## ACCOMPLISHMENTS

A key aspect of this technology approach is the need to purify the hydrogen from the PPA product stream. In order to achieve this, NASA has been investigating an electrochemical hydrogen separator, developed by Skyre, Inc. (formerly known as Sustainable Innovations, LLC), to separate and purify the hydrogen from the product stream. An electrochemical hydrogen separator provides a means of selectively isolating hydrogen from a mixture of gases. In electrochemical separation, hydrogen is electro-oxidized to protons and electrons, and the resulting protons are electro-reduced in another chamber, combining them with the electrons, thus producing purified hydrogen.

The basic technology is well developed, but prior to 2014, was not directly applicable to the PPA product stream due to the relatively significant concentration of carbon monoxide in the product stream. At typical operating temperatures, the carbon monoxide would preferentially adsorb on the catalytic electrodes in the cell, and interfere with their ability to oxidize hydrogen. The carbon monoxide would desorb from the electrodes at temperatures above  $150\text{ }^\circ\text{C}$ , but the acidic polymer that it typically uses as the electrolyte is not serviceable at this temperature.

Through a Phase II SBIR contract, Skyre fabricated and delivered a full scale, 4-CM (crew member) electrochemical hydrogen separation cell stack in (FY) 2018. Significant issues were encountered during cell stack build up, such as acetylene hydrogenation, low pumping performance, and sealing issues including cross-cell and overboard leakage.

In FY 2019, Skyre worked to advance the development of the electrochemical hydrogen

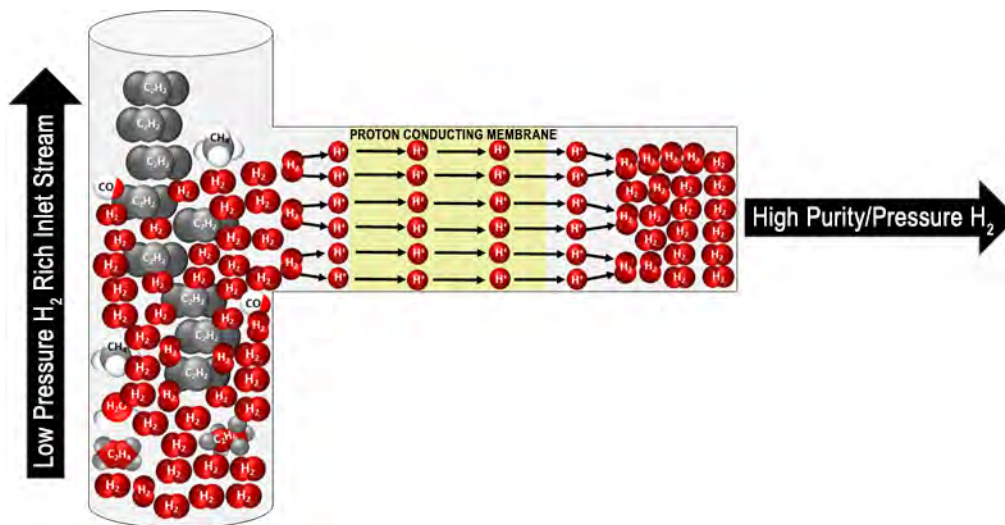


FIGURE 2. Schematic of electrochemical hydrogen separation process.

separator membrane technology such that integrated operation of the cell stack results in at least 85% hydrogen recovery from a nominal PPA effluent stream at a processing rate of four crew members. Another goal of the project was to improve the sealing technology and techniques of the stack in an effort to minimize all undesirable leak paths and total pressure drop across the cell stack. Skyre delivered two three-cell stack hydrogen separators to MSFC. Characterization and optimization testing of each cell stack will be completed in FY 2020.

## SUMMARY

This project, if successful, will increase oxygen recovery by recovering and recycling hydrogen from Sabatier-produced methane. The PPA converts methane to mainly hydrogen and acetylene. This product stream requires the hydrogen to be separated and purified from the mixed effluent. In FY 2019, efforts focused on the fabrication of two three-cell hydrogen separator units. Testing of the hydrogen separators will be completed at MSFC in FY 2020.

**PRINCIPAL INVESTIGATOR:** Cara Black

**FUNDING ORGANIZATION:** Advanced Exploration Systems

# Electrolytic Oxygen Recovery for ECLSS

**OBJECTIVE:** *To further develop a microfluidic electrochemical reactor to achieve an oxygen recovery efficiency of the process to greater than 50% and to scale up the system hardware to achieve a one crew member carbon dioxide conversion rate.*

## PROJECT DESCRIPTION

The current State of Art (SOA) Environmental Control and Life Support System (ECLSS) oxygen recovery technology is complex, heavy, and power consuming system that recovers approximately 50% of the oxygen from metabolic carbon dioxide ( $\text{CO}_2$ ). Lower mass and power consumption, less complexity, and higher oxygen recovery rates are all characteristics of an electrolytic oxygen recovery system, making it a desirable technology to be explored for future long duration missions. This project is a collaborative effort with the University of Texas Arlington that is focused on developing a microfluidic electrochemical reactor (MFECR). The MFECR converts  $\text{CO}_2$  and water into  $\text{CO}_2$  and ethylene ( $\text{C}_2\text{H}_4$ ) with a theoretical oxygen recovery rate of 73%. The MFECR operates at standard conditions, giving it an advantage over other technologies being investigated for future long duration missions which require high temperatures resulting in higher mass reactors and higher power consumption. The MFECR would replace three pieces of hardware for future ECLSS architectures: the current Carbon Dioxide Reduction Assembly (Sabatier reactor), the Plasma Pyrolysis Assembly (PPA), and the Oxygen Generation Assembly (OGA). It is designed to interface directly with the Carbon Dioxide Removal Assembly (CDRA) and Water Processing Assembly (WPA). This allows for a less complex system and higher reliability than the current SOA as well as reduced power, weight and water consumption of ECLS systems. Initial development efforts of the MFECR Engineering Development Unit (EDU) only achieved a single loop  $\text{CO}_2$  conversion of 37%. Current efforts to redesign the EDU to achieve a higher metabolic  $\text{CO}_2$  recovery rate of greater than 50% and scaling up the system hardware to achieve a one crew member conversion rate are underway.

## ACCOMPLISHMENTS

In the MFECR design, shown in Figure 1, a Gas Diffusion Layer (GDL) separates the gas channels and the electrolyte channel. The electrolyte used is a potassium hydroxide (KOH) and water ( $\text{H}_2\text{O}$ ) mixture.  $\text{O}_2$  is produced when the  $\text{H}_2\text{O}$  in the electrolyte is consumed at the anode, and the protons that are produced react with  $\text{CO}_2$  on the cathode. To maintain  $\text{H}_2\text{O}$  volume,  $\text{H}_2\text{O}$  may be occasionally added from the WPA. KOH is not consumed through the process; therefore, it does not have to be replaced. The GDL surfaces have an electrodeposited layer of nanocomposite particles that act as electrocatalysts for the reaction on the anode and cathode. To complete the reactions, an electrical potential is applied across the electrodes, and  $\text{O}_2$  and  $\text{C}_2\text{H}_4$  are produced on opposite sides of the cell, which allows for a gas separation process to be eliminated.

To achieve higher metabolic  $\text{CO}_2$  conversion rate, current efforts are focused on the following areas:

- (1) The production of hydrogen ( $\text{H}_2$ ) from competing reactions: Due to the competing  $\text{H}_2\text{O}$  splitting reaction, excess  $\text{O}_2$  and higher  $\text{H}_2\text{O}$  consumption occurs ultimately lowering the metabolic  $\text{CO}_2$  conversion. To help mitigate this issue, a fuel cell stack will be selected that will convert excess  $\text{H}_2$  and  $\text{O}_2$  to  $\text{H}_2\text{O}$  and also providing electrical power during the process.
- (2) Anode degradation: During initial testing, the anode showed rapid degradation with time resulting in loss of mechanical strength and conductivity which led to leaking of electrolyte into the  $\text{O}_2$ -side gas channel and loss of current density. The development of anode material will be completed and is essential for the success of an electrochemical reactor.
- (3) Loss of catalyst selectivity and activity of the cathode: The development of an advanced cathode catalyst will be completed because of observance of a shift in selectivity towards

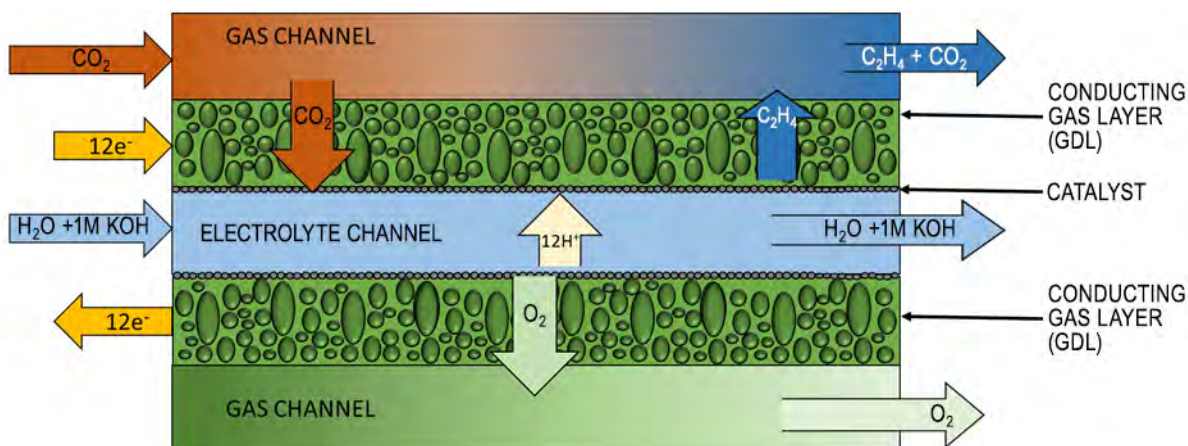


FIGURE 1. Cross section of a single cell MFEER.

hydrocarbons due to the compositional changes in the cathode electrocatalyst with time.

- (4) Selection of alternative electrolyte solution: Alternate electrolyte solutions will be investigated due to KOH corrosive properties.
- (5) Selection of a gas separator: In order to increase the metabolic  $\text{CO}_2$  conversion rate to as close to 73% as possible, a gas separator will be selected to separate  $\text{CO}_2$ ,  $\text{C}_2\text{H}_4$ , and  $\text{H}_2$  and recycle them back through the process.

Although the original EDU only achieved a single-loop  $\text{CO}_2$  conversion of 37%, small-scale testing of the original EDU design showed promising results with a 54% metabolic  $\text{CO}_2$  conversion. When the EDU was scaled, there were issues with fabrication of the EDU's small channel walls, which led to a redesign. In FY 2019, an alternative fabrication technique was used in order to successfully fabricate the original EDU's small channel design. Other modifications were also made to optimize the unit, such as alternative materials for the cell's electrical current distributor and electrolyte walls. For the electrical current distributor, nickel and cobalt-infiltrated graphite was selected, instead of pure graphite, to avoid degradation due to oxidation. Nonconductive pressing plates and alkaline-tolerant materials were chosen for electrolyte walls. Alternative anode materials (nickel foam, nickel wire mesh, and Platinum Titanium mesh) were investigated. Based on the results, nickel foam was selected as the best anode candidate. Alternative electrolyte solutions, such as sodium bicarbonate and ionic liquids, were explored. To date, no

alternative electrolyte to KOH has been chosen due to low performance. Additional efforts were made to develop a rigorous multi-physic 3D model on  $\text{CO}_2$  conversion to  $\text{O}_2$  and  $\text{C}_2\text{H}_2$  at standard conditions. The model includes all of the physics involved in the process such as electrochemical physics, microfluid flow, mass and heat transfer, generation, and conduction of DC electrical current. The model will provide the capability to optimize the cell design and operation of the MFEER.

## SUMMARY

The development of the MFEER is a highly attractive technology for future long-duration manned missions. This technology would have lower mass and power consumption, less complexity, and higher oxygen recovery rates than the current SOA  $\text{O}_2$  recovery system. Efforts have been made to continue the development of this technology by addressing the key issues identified in the initial development effort. Alternative fabrication techniques were explored to successfully fabricate complex EDU components, alternative anode materials; and electrolyte solutions were investigated, and a multi-physic 3D model was developed in order to optimize cell design and operation of the MFEER.

**PRINCIPAL INVESTIGATOR:** Brittany Brown

**PARTNER:** University of Texas Arlington

**FUNDING ORGANIZATION:** Advanced Explorations Systems

# Four-Bed Carbon Dioxide Scrubber

**OBJECTIVE:** To rapidly design and build a full-scale cabin air purification assembly for demonstration aboard the International Space Station (ISS) to prove the efficacy and dependability of physical adsorption-based carbon dioxide (CO<sub>2</sub>) removal processes for long-duration crewed exploration mission applications.

## PROJECT DESCRIPTION

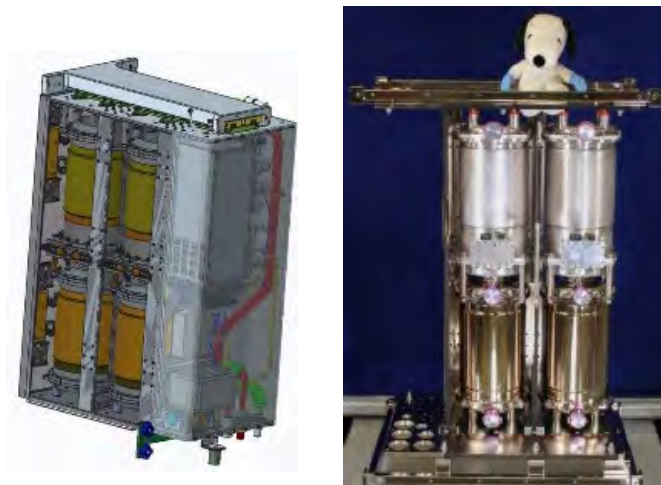
The four-bed carbon dioxide scrubber (4BCO<sub>2</sub>) flight demonstration aims to operate the next generation of four-bed molecular sieve technology and prove it as a reliable, semi-autonomous subsystem of the life support systems that can guarantee crewed deep space exploration mission success. The technology is derived from the ISS Carbon Dioxide Removal Assembly (CDRA), a primary carbon dioxide (CO<sub>2</sub>) removal system onboard the International Space Station. The ISS CDRA has a 20-year operational history from which valuable lessons have been learned that can

expected to remove more than 4 crew-equivalents of metabolic CO<sub>2</sub> at an inlet CO<sub>2</sub> concentration of 2 torr with minimal air and no water losses overboard. The product stream from this technology is high-purity, dry CO<sub>2</sub> that may be used for oxygen recovery within a closed-loop life support system architecture.

## ACCOMPLISHMENTS

The project is accelerating schedule by utilizing numerous outside material and manufacturing technologies. On-demand manufacturing from Xometry was utilized to machine one-piece sorbent beds as opposed to three-piece manufacturing and welding processes at NASA Marshall Space Flight Center (MSFC). Additive manufacturing (AM) from Carpenter Additive was used to produce air ducts which minimize pressure drop and provide attachment points throughout the system. A dust-tolerant magnetic bearing blower and controller from Calnetix is nearing delivery and will be part of an on-orbit upgrade. Commercially available components have been procured at as many points as possible.

In addition to material innovations, project leadership directed a co-located and conversational approach to development. This approach continues to enable early identification of design conflicts and promote innovative resolutions. To further



**FIGURE 1.** Recent 3D graphic (left) of the 4BCO<sub>2</sub> mechanical design and photo of Desiccant-Adsorbent Beds (right) in place during test fitting in the primary structure.

yield an improved design for use aboard exploration mission crewed vehicles and habitats. While various improvements to the ISS CDRA have increased its maintenance-free reliability to over 4 years, obsolescence requires a new equipment design; thus, the impetus for the 4BCO<sub>2</sub> project which will include applying the lessons learned from ISS CDRA flight operations to the contemporary design. The 4BCO<sub>2</sub> flight demonstration unit is



**FIGURE 2.** Manufacturing progress (left) and rendering (right) of Marshall dust-tolerant air selector valve.



**FIGURE 3.** Partially finished AM air ducts with bosses and attachment tabs.

accelerate schedule and ensure dust mitigation designs are precisely implemented, the sorbent beds were designed, built, packed with sorbent, and delivered as a product from the Environmental Control and Life Support Systems Development Branch to the ISS Program.

Work continued in 2019 that built upon the research and development work that led to material selection and initial design decisions in 2018. Computer simulation work resulted in ideal system sizing and extensive prototype and testbed work continues to be used to measure the performance envelope. Also, inspection of the testbed provides high confidence that the design changes successfully eliminated sorbent dusting as a system failure mechanism. The testbed performance envelope includes and exceeds four crew-equivalent removal rate at 2 torr partial pressure.

The 4BCO<sub>2</sub> project is receiving design and manufacturing support from multiple branches and Centers. Collaboration with NASA Johnson Space Center (JSC) is yielding both commercially available and modified commercially available components for integration. JSC has built a custom motor controller and designed tight thermal management to balance acoustic and LTL cooling requirements for the COTS vacuum pump. Flight sensors, as well as engineering development units have been fully qualified and delivered.

Sensor engineering development units are being integrated into the testbed at MSFC. MSFC has completed development of dust-tolerant valves with contributions from the Valves, Actuators, and Ducts Design and Development Branch in the Propulsion Systems Department and the Electronic Design Branch in the Space Systems Department.

## **SUMMARY**

The 4BCO<sub>2</sub> project was commissioned to demonstrate full-scale, robust operation of physical adsorption-based CO<sub>2</sub> removal technology suitable for future exploration missions aboard the ISS. The prototype testbed has experimentally proven successful solutions to the project goals. Innovative project acceleration methods are being utilized to rapidly deliver the flight demonstration hardware. The flight demonstration unit is being assembled with ground testing planned to begin in spring 2020.

**PRINCIPAL INVESTIGATOR:** Greg Cmarik

**PARTNER:** JSC

**FUNDING ORGANIZATION:** ISS Program and Projects Office

# In-Space Manufacturing of Crew Clothing

**OBJECTIVE:** *To explore the possibility of manufacturing and recycling crew clothing in space.*

## PROJECT DESCRIPTION

On the International Space Station (ISS), clothing is treated as a consumable. Once sufficiently worn by the crew, it is discarded and replaced. For missions beyond low Earth orbit, this approach will prove infeasible due to high logistic and resupply costs. Laundry facilities have been considered and developed to mid-technology readiness levels. However, these facilities invariably require considerable water, add complexity to the Environmental Control and Life Support (ECLS) Water Recovery system (due to the presence and challenge of handling surfactants), and require considerable design complexity for microgravity operation.



Textiles for clothing have historically been produced from natural sources that result in different textures, thicknesses, and thermal properties (e.g., silk versus cotton versus wool). For clothing, these properties allow for application-specific materials.



In the last century, synthetic textiles — such as polyester — have been developed and demonstrated incredibly versatile properties. For example, polyethylene terephthalate (PET) is used to produce satins, jerseys, flannels, and fleece. The added benefit of PET is that it is a thermoplastic and is 100% recyclable at moderate temperatures. In fact, PET is commonly recycled in industry to produce these various fabrics. This process may be miniaturized and adapted to space flight where complete recycling of materials is necessary to limit resupply and launch mass. The goal of this project was to explore an entirely new approach to providing what the astronauts wear. Rather than cleaning or replacing the clothing, this project explored an in-space manufacturing approach to produce and recycle crew clothes.

## ACCOMPLISHMENTS

This project explored two approaches to using PET as a recyclable material for crew clothing. A key concern with PET is its flammability.

Historically, NASA has avoided PET due to concerns with flame retardants damaging the life support systems. For this reason, the first approach involved exploring the production of PET yarns via a miniature extrusion system and identifying flame retardants compatible with existing ECLS systems. In this effort, the goal was to design and build a miniaturized PET extrusion system capable



of producing multifilament yarns. Simultaneously, the team leveraged the considerable experience of NASA's trace contaminate and control subject matter expert to help identify a compatible flame retardant. The second approach involved producing PET blends containing the inherently flame-



retardant polyimide 84 (P84). In this effort, the goal was to card and spin together various ratios of P84 and PET to produce a flame-retardant yarn that could be recycled using the traditional PET extrusion method.

This innovation, when successful, would eliminate the need for clothing resupply as well as the need for laundry facilities, dramatically reducing the complexity of the missions along with the ECLS systems dedicated to water recycling.

FY 2018 saw the procurement of the miniature PET extrusion system. The configuration of the extruder was in a horizontal position. Single-strand yarn was produced but lacked uniformity in strand thickness and strength. In FY 2019, the miniature PET extrusion system was modified into a vertical position which resembles industrial PET extrusions processes. The vertical positioning of the extruder allows for more consistent strand thickness. The miniature PET extrusion system is designed to accept PET pellets of a specific particle size and uniformity for consistent melting. To replicate this uniformity, commercially available PET fabric purchased at a local fabric store was melted down, cooled, and pulverized. Success was demonstrated by the production of a single strand of yarn. Various engineering controls will be employed in FY 2020 to improve the consistency and uniformity of PET strands.

To evaluate the second approach, yarns containing 100% PET, 90% PET/10% P84 and 80% PET/20% P84 were carded and spun. These yarns are due to be tested for flammability at NASA Johnson Space Center (JSC) in FY 2020.

## **SUMMARY**

This project sought to explore the possibility of manufacturing and recycling crew clothing in space. This effort resulted in the design and fabrication of a miniature PET yarn production stand and demonstrated the production of single-strand yarn recycled from PET fabric. Blended yarns containing both PER and P84 were also produced in an effort to address flammability concerns. Materials produced from this effort will be tested at JSC in FY 2020.

**PRINCIPAL INVESTIGATOR:** Gena Dalton

**FUNDING ORGANIZATION:** Center Innovation Fund



# Trace Contaminant Control Integrated Test

**OBJECTIVE:** To functionally demonstrate coupled trace contaminant control (TCC) and carbon dioxide (CO<sub>2</sub>) removal systems.

## PROJECT DESCRIPTION

The evolutionary development of the Trace Contaminant Control (TCC) system from the current International Space Station (ISS) architecture towards an exploration-ready process design aims to address adsorption and catalytic media obsolescence, mitigate component fouling, improve in-flight maintainability, and capture opportunities for mass and power reduction.

## ACCOMPLISHMENTS

One approach to reduce TCC subsystem mass penalties and power consumables is to investigate the coupling of exploration TCC and carbon dioxide (CO<sub>2</sub>) removal processes in order to utilize a shared process blower; this approach holds precedent within heritage vehicle cabin ventilation and life support system architectures such as Skylab, Shuttle, and Spacelab. A functional demonstration of a full-scale integrated process architecture is required to characterize the feasibility, flow anomalies, and interactions between the newly coupled processes.

The integrated test layout, shown in Figure 1, centered on the MSFC Environmental Test Chamber heating, ventilation, and air conditioning (HVAC) duct. The exploration CO<sub>2</sub> removal subsystem was represented by the Carbon Dioxide Removal Assembly Dash 4 Engineering Unit (CDRA-4EU). The TCC process leg (Fig.1, green) housed the adsorption guard bed packed with activated charcoal, typically serving to protect a downstream catalytic oxidizer. Due to anticipated process flow interruptions, no oxidizer was installed during this test phase. Instead, two large loops of tubing were used to simulate a representative pressure drop.

Flow was provided through the TCC process leg by the combination of upstream positive pressure

provided by the HVAC ventilation fan and downstream pull from the CDRA-4EU blower. A 25.4-mm-diameter orifice was installed into the existing CDRA-4EU process inlet line to encourage air draw through the TCC leg by backpressure balancing the tee junction. Flow through the TCC leg was further regulated by manual adjustment of a fine control hand valve as measured by a digital mass flowmeter.

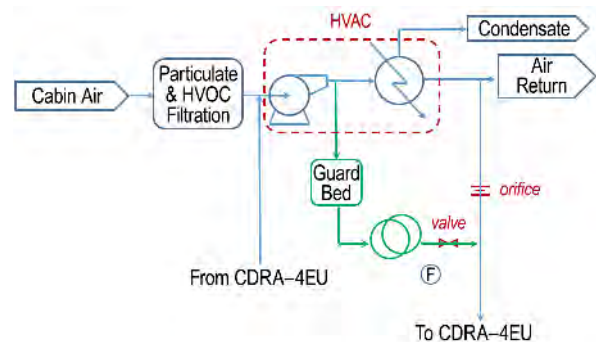
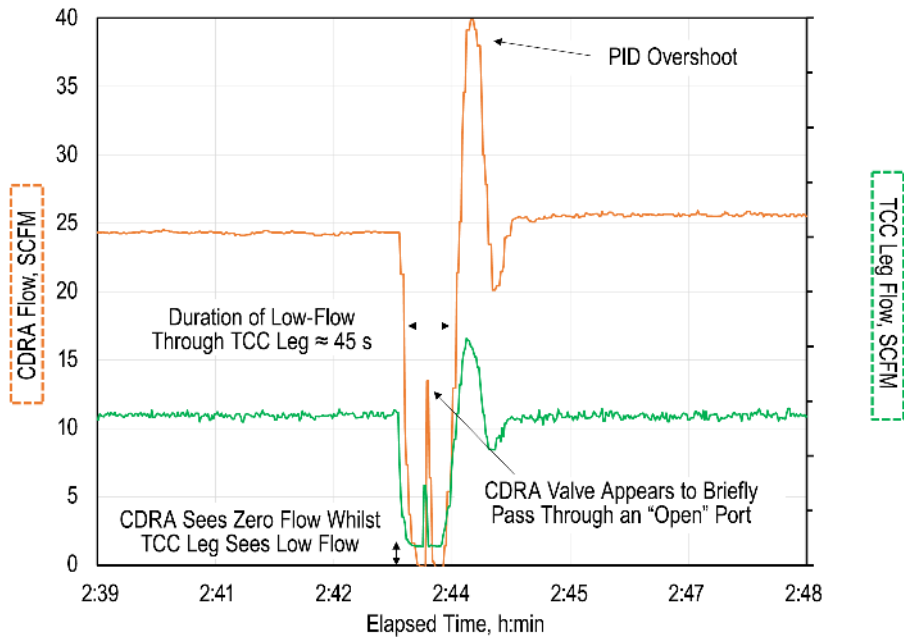


FIGURE 1. TCC integrated test process layout.

A functional demonstration of a candidate exploration integrated TCC process layout was successfully performed. Process flowrates were demonstrated ranging from 9.4–13.7 L/s for the CO<sub>2</sub> removal process and 0.66–1.04 L/s through the TCC process, without utilizing a dedicated TCC blower. An air flow interruption through the CO<sub>2</sub> removal process was observed, resulting in a TCC flow anomaly from subsystem integration. The behavior and duration of the CDRA-4EU no-flow condition during mode change is shown by Figure 2. A simultaneous low-flow condition through the TCC process was also discovered and its origin explained by flow reversal through the CO<sub>2</sub> removal inlet tee (i.e. flow back through the orifice-containing leg shown in Fig. 1 and returning to the cabin). The presence of the TCC low-flow condition serves to protect the catalytic oxidizer from overheating, benefiting this new arrangement.

A strategy to mitigate the introduction of a process overshoot artifact by modification of flow controller



**FIGURE 2.** The behavior and duration of the CDRA-4EU no-flow condition during mode change.

logic was proposed. Finally, required modifications to catalytic oxidizer process safety interlocks were characterized so as to not inadvertently damage the oxidizer. Based on the demonstrated flow balancing herein, it is recommended to proceed with computer-aided simulation and differential mass balance analysis of the process performance against a representative contaminant load, anchored against chamber testing. A CO<sub>2</sub> product quality characterization test phase should also be conducted.

Due to the proposed arrangement of TCC components and successful intercomponent flow balancing, it is possible to realize mass and power savings by eliminating the ISS Blower Assembly and ISS Sorbent Bed Assembly from the Exploration TCC system.

## SUMMARY

A candidate exploration TCC process layout was evaluated. In this arrangement, potential reductions in mass, power, and volume were demonstrated by flow balancing the TCC process against the CO<sub>2</sub> removal process, enabling the elimination of an existing process blower. Balanced process flows were successfully demonstrated over a range of test conditions. Unique process interactions resulting from the intimate coupling of the two subsystems were characterized and recommendations were made to modify system process control algorithms going forward. Future recommended process analyses and testing were identified.

**PRINCIPAL INVESTIGATOR:** Matthew Kayatin

**FUNDING ORGANIZATION:** Advanced Exploration Systems

# Series Bosch Carbon Formation Reactor Down-Select

**OBJECTIVE:** To complete a trade study based on earlier evaluations of a number of catalytic carbon formation reactors to further boost the maturity of a Series Bosch system for recovering and recycling up to 100% of the oxygen from the carbon dioxide exhaled by astronauts living in space.

## PROJECT DESCRIPTION

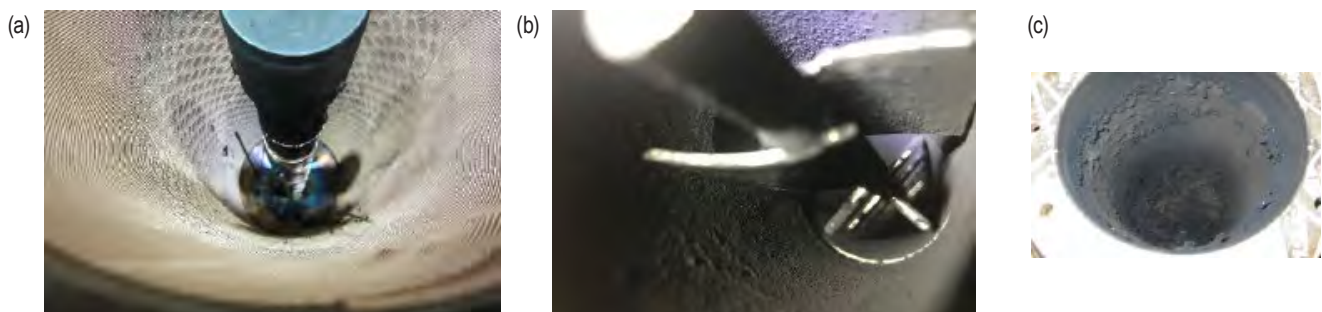
Human exploration missions to Mars and other destinations beyond low Earth orbit require highly robust, reliable, and maintainable life support systems that maximize the recovery of oxygen ( $O_2$ ). One process in development and under consideration is the Series-Bosch System (S-Bosch). This system is a two-stage reactor process that reduces carbon dioxide ( $CO_2$ ) with hydrogen ( $H_2$ ) to produce water and solid carbon. Theoretically, the Bosch process can recover 100% of the  $O_2$  from  $CO_2$  in the form of water, making it an attractive option for long duration missions. The S-Bosch system includes a reverse water gas shift (RWGS) reactor, a carbon formation reactor (CFR), a  $H_2$  extraction membrane, and a  $CO_2$  extraction membrane. To further the development of oxygen recovery systems, NASA awarded Phase I contracts to several entities under the Game Changing Development Program addressing Spacecraft Oxygen Recovery (SCOR). Two of the hardware deliverables were integrated into the Carbon Dioxide Reduction Test Stand (CORTS) at MSFC as carbon formation reactors and performance evaluations were executed at NASA Marshall Space Flight Center (MSFC). A trade study was performed between these two reactors and a reactor design developed by MSFC. Each reactor has a unique design, but all perform the same function, producing solid carbon. The data

provided in the trade study are key to selecting a CFR to advance the S-Bosch to a TRL 5.

## ACCOMPLISHMENTS

The three reactors included in the trade study are designed to perform the same function but are unique in comparison to one another. The differences include catalyst types, flow regimes, reactor internals, etc. All three reactors were integrated and evaluated separately in the CORTS. The reactors are at a TRL 3 and have much room for improvement resulting in a slightly different approach than a typical trade study. Generally, criteria such as power consumption, system mass and volume, efficiency, and consumable mass are quantified. In this case, power consumption was not known, only the reactor mass and volume were known, efficiency was based on performance data for  $CO_2$  flows equivalent for a 0.5 crew member, and consumable mass was estimated. Other criteria considered in this study were scalability and complexity of moving parts, carbon handling, ease of optimization, and catalyst regeneration/loading. Most of these later criteria were qualitative in nature.

The approach was to produce a report to be used for down-selection gate review. During the gate review the focus will be on discussion and ranking



**FIGURE 1.** Internal views of the reactors. (a) The MSFC developed reactor, (b) the pH Matter reactor, and (c) the Umpqua reactor.



in real time of each criterion. The down-selection gate review is scheduled for October 2019. In CY 2020, the CO<sub>2</sub> reduction brassboard test rig will be built and tested and the selected reactor will undergo further development and standalone testing before being integrated into the CO<sub>2</sub> reduction brassboard test rig.

During 2019, a design for the CO<sub>2</sub> reduction brassboard test rig model and drawings were produced. Approximately 95% of the system and subsystem components were procured. Additional integrated testing of one of the reactors was completed, and the trade study report was produced.

## **SUMMARY**

Future long-duration missions require systems that are closed-loop to eliminate the need to resupply water and oxygen. The S-Bosch system has the potential to meet this requirement by recovering up to 100% of the oxygen from expired CO<sub>2</sub>. The development of the CO<sub>2</sub> Reduction Brassboard takes us a step closer to meeting the challenge.

**PRINCIPAL INVESTIGATOR:** Christine Stanley

**PARTNERS:** pH Matter, LLC, and UMPQUA Research Company

**FUNDING ORGANIZATION:** Advanced Exploration Systems

# Advanced Oxygen Generation Assembly

**OBJECTIVE:** *To design an advanced oxygen generation assembly (OGA) for exploration missions*

## PROJECT DESCRIPTION

Future Exploration missions will require an advanced oxygen generation assembly (OGA) to electrolyze water to supply oxygen for crew metabolic consumption. The system design will be based on the International Space Station (ISS) OGA, shown in the lower right location in the Oxygen Generation Subsystem (OGS) rack (Fig. 1) but with added improvements based on lessons learned during ISS operations and technological advances since the original OGA was designed and built. These improvements will reduce system weight, crew maintenance time and spares mass while increasing reliability.

## ACCOMPLISHMENTS

Currently, the design team is investigating the feasibility of the upgrades by performing ground tests and analyses. Upgrades being considered include the following: redesigning the electrolysis cell stack, the cell stack Power Supply Module (PSM), the recirculation loop deionizing bed, and the process controller; deleting the hydrogen dome, the nitrogen purge equipment, and the wastewater interface; and replacing the hydrogen sensors. The upgrades will be first demonstrated on the ISS OGA.

In 2019, several advanced OGA studies were performed. Studies to define the advanced OGA cell stack configuration and nitrogen purge configuration were completed. Changes to the cell stack internal configuration are required to address obsolete membrane materials and to provide a longer operational life, based on lessons learned during ISS operations. Nitrogen purging will provide optimal conditions during shutdown and startup. Studies to enable the deletion of the hydrogen dome are continuing in 2019. These studies include a rack computational fluid dynamics (CFD) analysis and maximum design pressure (MDP) analysis. Analysis and testing of the ISS



OGA PSM design was started in 2019 to determine if it can be used for advanced OGA. Redesign of the recirculation loop deionizing bed started in 2019, which will allow a longer operational life and a lower delta pressure (dP).

## SUMMARY

Analysis and testing are currently ongoing to inform the advanced OGA design. Detailed advanced OGA design and hardware manufacturing will occur over the next two years. The ISS OGA will be upgraded to an advanced OGA configuration in the 2023 timeframe. Safe and reliable advanced OGA operations will be demonstrated on ISS for several years prior to being deployed on an Exploration mission.

**PRINCIPAL INVESTIGATOR:** Kevin C. Takada

**PARTNER:** UTC Collins Aerospace

**FUNDING ORGANIZATION:** International Space Station Program

# Hydrogen Sensor Technology Demonstration

**OBJECTIVE:** *To demonstrate commercial-off-the-shelf hydrogen sensor technology on the International Space Station Oxygen Generation Assembly.*

## PROJECT DESCRIPTION

The purpose of this project is to demonstrate commercial-off-the-shelf (COTS) hydrogen sensors in the International Space Station (ISS) Oxygen Generation Assembly (OGA) to determine the suitability for Exploration use. The ISS OGA requires hydrogen sensors as a hazard control to monitor for the presence of hydrogen in the product oxygen in the event of a cell stack failure. Currently, custom built hydrogen sensors are used, which have certain operational limitations.

## ACCOMPLISHMENTS

Four COTS hydrogen sensors will be installed onto the ISS OGA's oxygen outlet line. The technology demonstration hardware will include a manifold, flow meter, heaters, data acquisition, and power supply electronics as shown conceptually by Figure 1. The COTS sensors will be installed for a minimum of 3 years, and their performance will be continuously monitored by ground controllers. The crew will perform a sensor drift check periodically using calibration gas containing precise nonflammable mixtures of hydrogen in air. After on-orbit operations are complete, the sensors will be returned to the ground for further evaluation of sensor drift over time.

During 2017–2019, seven different COTS hydrogen sensor technologies were bench tested and endurance tested using the ground OGA Testbed. At the completion of testing a single sensor technology was selected for the flight technology demonstration. This sensor technology showed acceptable performance at the

flow rates and dew points of the OGA. In 2019, the mechanical, electrical and software design of the flight technology demonstration was started. A preliminary design review (PDR) was successfully completed in September 2019. The flight unit will be delivered in 2020 for launch and installation on the ISS OGA rack face.

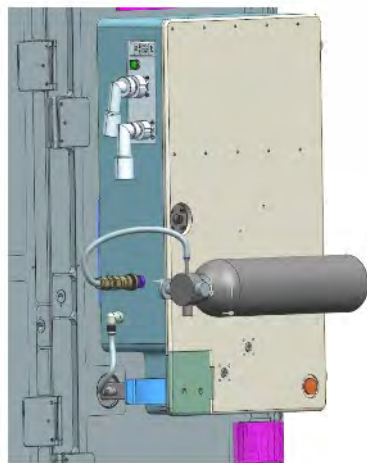
## SUMMARY

The hydrogen sensor flight technology demonstration design is currently underway. Delivery of the flight hardware will occur in 2020. The COTS sensor technology will be tested on ISS for a minimum of 3 years to demonstrate their suitability for use in an Exploration OGA.

**PRINCIPAL INVESTIGATOR:** Kevin C. Takada

**PARTNER:** UTC Collins Aerospace

**FUNDING ORGANIZATION:** International Space Station Program



# Urine Processor Assembly Upgrades

**OBJECTIVE:** *To provide improvements in the International Space Station Urine Processor Assembly (UPA) for reliability and maintainability in the Distillation Assembly and technology demonstration of a new scroll pump and separator assembly design, combining traditional liquid-gas separations functions and new purge pump technologies into one unit.*

## PROJECT DESCRIPTION

NASA Marshall Space Flight Center (MSFC) completed an extensive evaluation of the International Space Station (ISS) Urine Processor Assembly (UPA) hardware to identify all areas in which improved reliability would better position UPA as a viable technology for use by future crewed exploration missions. The UPA on the ISS is used to recover water from the urine produced by the crew. The UPA accomplishes this task by evaporating (distilling) water from urine in a microgravity-compatible Distillation Assembly (DA). The identified DA upgrades include modifications of the drive belt system, motor mount material, and the addition of a dynamic seal should address unwelcomed condensation issues, known to impact DA performance and reliability. Further redesign of existing technology in a liquid level sensor and demister seal material change should also improve component reliability. These upgrades will be incorporated into the ISS UPA to collect extended performance demonstration in an operational flight environment. Successful demonstrations will provide tangible life cycle cost benefits to the ISS over its remaining operational life and increase confidence that the UPA design can meet demanding exploration mission needs.

MSFC is also pursuing smaller, more efficient vacuum pump utilizing scroll pump technologies to replace the peristaltic pump used in the Pressure Control and Pump Assembly (PCPA). The scroll pump technology being pursued is roughly 25% the size of the heritage peristaltic pump which allows for the combination of two UPA sub-assemblies within a single sub-assembly. This will allow the purge pump and the separator plumbing assembly (SPA) to be replaced at the component level, rather than at the full assembly level leading to more

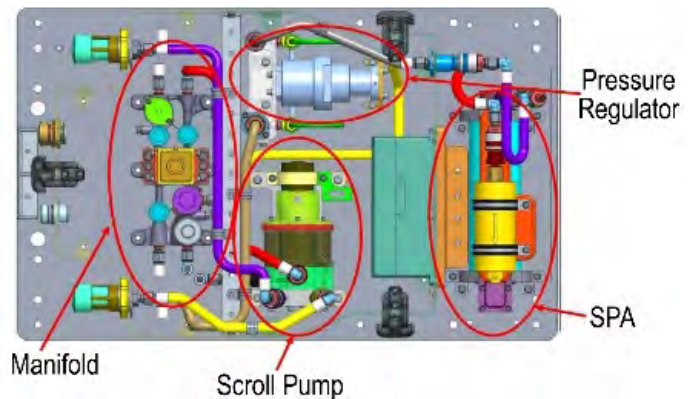


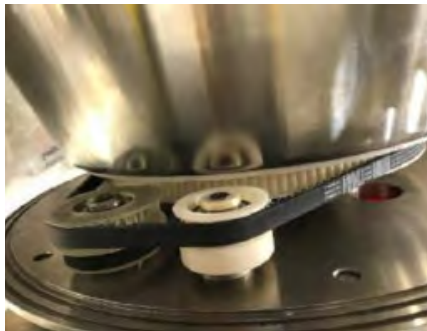
FIGURE 1. Model of Purge Pump and Separator Assembly.

efficient logistics support for the UPA. The new Purge Pump and Separator Assembly (PPSA), shown in Figure 1, is in development with the goal of demonstrating it aboard the ISS within the ISS UPA. A secondary goal of the PPSA's scroll pump is to reduce the mass and volume of UPA components for Exploration missions.

## ACCOMPLISHMENTS

The existing DA uses an o-ring drive belt system for rotation of the centrifuge. This o-ring is susceptible to stretching and has tendency to slip, particularly if condensation accumulates on the belt. Condensation outside of the evaporator has caused several other issues over the life of the UPA. Addressing this condensation concern will be achieved in several complementary ways. A combination of thermal isolation of the motor to minimize condensation of water vapor inside the stationary bowl and incorporating a synchronous (toothed belt) drive belt system to prevent slippage of the belt and avoid relaxation/stretching of the belt. Integrating this toothed belt into the design required a redesign of the compound pulley and an added tensioner within a tighter tolerance environment. Utilization of 3D printed pulleys and

tensioner for fit and function tests was pursued to minimize costly flight hardware manufacturing while also confirming viability of the designs. Figure 2 shows the installation of the 3D printed components for testing.



**FIGURE 2.** Test fit and functional testing using 3D printed components.

The existing PCPA uses peristaltic pump technology, which uses a rolling head to move the gas/ fluid mixture through plastic tubing. The first component to fail in this

type of pump is typically the tubing due to the constant compression and release of the Tygon® material. The PPSA addresses this failure mode by employing a scroll pump. The scroll pump based on commercial technology from Scroll Labs, Inc. provides the critical capability of pumping two-phase flow but eliminates the peristaltic tubing, thereby increasing the life of the pump. Due to the decreased size of the scroll pump, the SPA can now be repackaged into the same sub-assembly as the pump. This eliminates an entire sub-assembly from the UPA rack. Finally, introduction of the new pump provides an opportunity to decrease the overall mass of the manifold for the pump. The PCPA manifold was traditionally machined out of a block of solid titanium. New advanced manufacturing techniques now enable additive manufacturing of the manifold, resulting in a 40% decrease in overall mass, as seen in Figure 3.



**FIGURE 3.** PPSA manifold traditionally manufactured (left) and additively manufactured (right), resulting in ~40% mass savings.

All of the DA upgraded component designs and PPSA prototype scroll pump designs have been successfully integrated into the UPA ground-based development testbed at MSFC and testing results indicate performance is meeting expectations. The first phase scroll pump prototype from Scroll Labs, Inc., is currently in functional testing. This first prototype incorporates identified updates to make the off-the-shelf unit more flight like and compatible within the UPA. Compared to PCPA, this prototype scroll pump doubles the pump efficiencies within the DA. The scroll pump is able to draw the DA from ambient to operating vacuum in 45 min, versus over 1.5 hours necessary from the PCPA. As functional testing continues, another prototype phase may be requested.

The PPSA design phase is nearly 100% complete. The additive manufactured manifold has been delivered from the vendor and is currently being inspected for quality. As part of the final delivery of this technology development, an astronaut training unit has been in development. This training unit will allow future crewmembers to practice the component-level replacements within the PPSA. This training unit is using 3D printed components outfitted with a flight-like connector. This provides spatial likeness to the flight unit for crew to practice component level maintenance while saving costs in actual flight materials and manufacturing time.

## SUMMARY

The UPA provides the critical function of recovering water from crew urine. Key aspects of the UPA have been identified for improvement based on lessons learned from ISS. The PPSA serves to reduce the number of UPA sub-assemblies while enabling maintenance in preparation for Exploration-class missions. Testing and evaluation of the DA upgraded designs and PPSA prototype show technology viability for future flight demonstrations. Both the upgraded DA unit and PPSA flight demonstration are due to be delivered in March 2020 and September 2020, respectively.

**PRINCIPAL INVESTIGATOR:** Jill Williamson

**FUNDING ORGANIZATION:** International Space Station Program



# Extending MAG4 Code to New Operational Users



**OBJECTIVE:** *To add new research results into the NASA Marshall Space Flight Center (MSFC)/University of Alabama in Huntsville (UAH)-developed Magnetic Forecast (MAG4) solar event forecast model; advance the data download management and the graphical output of MAG4 towards a more flexible, robust, and maintainable pseudo-operational system in the open source Python scripting language; and transition the code to the Space Radiation Analysis Group (SRAG) at NASA Johnson Space Center (JSC) and the Community Coordinated Modeling Center (CCMC) at NASA Goddard Space Flight Center (GSFC).*

## PROJECT DESCRIPTION

Space weather—including large flares and coronal mass ejections that accelerate energetic particles from the Sun and drive geomagnetic storms—have potentially wide-ranging impacts on society and its infrastructure. NASA operates satellites measuring solar output; however, successfully bridging the gap between derived products from these missions and operational forecasters has proven challenging.

In our FY 2018 NASA Marshall Space Flight Center (MSFC)-funded effort, we demonstrated that the unique research-to-operations/operations-to-research (R2O/O2R) paradigm developed for terrestrial weather applications by the Short-term Prediction Research and Transition (SPoRT) Center can be used to transition experimental space weather products to operational users. The goals of this current project are to extend MSFC partnerships and prestige in the Space Weather enterprise by leveraging the MSFC/University of Alabama in Huntsville (UAH)-developed Magnetic Forecast (MAG4) model and the SPoRT paradigm to improve operational users' capability to forecast hazardous solar events and space radiation, and posture MSFC to play a greater role in implementing the 2019 National Space Weather Strategy and Action Plan.

## ACCOMPLISHMENTS

MAG4 is a space weather forecasting tool that provides probabilities that solar active regions will produce harmful space weather. MAG4 can run in near real-time, but the past generation of the product has been subject to periodic, lengthy downtime that

has limited its utility as an operational forecasting tool. To make the product more suitable for operations, MAG4 has been integrated into the robust operational data processing stream at SPoRT and is now disseminated via a dynamic website developed in conjunction with the forecasters.

This effort complements work by other space weather applications groups, including the Community Coordinated Modeling Center (CCMC) at NASA Goddard Space Flight Center (GSFC), who perform model validation and engage with the space weather community to expose them to new tools available for transition. The work performed here demonstrates an approach to take products identified as mature and value-added and accelerate them into operations through integration into decision support tools, development of training, and assessment to improve experimental products. We made a concerted effort to engage and collaborate with the Space Radiation Analysis Group (SRAG) at NASA Johnson Space Center (JSC), who makes decisions regarding space radiation hazards for astronauts. This partnership allowed both groups to achieve additional goals beyond what was originally planned. Another innovation was to engage in an Agency-level initiative called the Space Weather Science Applications Project (SWxSA), which is pulling together all of NASA's space weather groups to develop a national strategy for responding to challenges with space weather R2O/O2R. Lessons learned have informed the SWxSA strategy.

In this year's effort, improved MAG4 code was successfully integrated into the SPoRT operational data processing stream through the development



# Water Extraction Pump (WExPump)

**OBJECTIVE:** *To design an integrated system that performs the function of compressor, condenser, and separator in a single unit and results in a nominal gas stream water vapor concentration <0.1%.*

## PROJECT DESCRIPTION

For long-duration manned missions, life support systems are needed that will invariably include oxygen recovery technology to recycle oxygen from the carbon dioxide (CO<sub>2</sub>) exhaled by the crew. Each of the currently proposed oxygen (O<sub>2</sub>) recovery technologies involves gas compression, water condensation, and water separation steps. Traditionally, each of these functions are performed by distinct pieces of hardware. In addition to the hardware mass and volume requirements, both compressors and separators require motors, motor controllers, and logic to maintain optimum performance. Finally, current water separators result in gas streams containing ≈5% water vapor. Optimal operation of downstream system requires <0.05% water vapor. The goal of this project is to design an integrated Water Extraction Pump (WExPump) system that performs the function of compressor, condenser, and separator in a single unit and results in a nominal gas stream water vapor concentration <0.1%. A successful design combines the distinct operations into an integrated system that is expected to result in a mass and volume savings for oxygen recovery hardware. This is accomplished by eliminating the bulk of three systems and eliminating all but one motor and motor controller. Additionally, a single unit can reduce overall system complexity by eliminating interfaces and reducing the quantity of required logic. A staged approach to the system functions can also produce a system capable of achieving the targeted <0.1% water vapor content.

## ACCOMPLISHMENTS

### DESIGN APPROACH

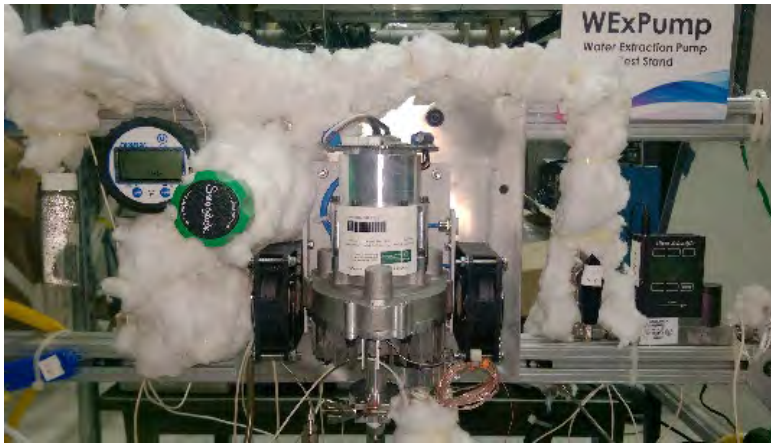
This effort seeks to develop a single-stage WExPump prototype based on a proprietary floating scroll system technology developed by Scroll Laboratories, Inc. The floating scroll system

consists of a scroll pair with a fully compliant mechanism that minimizes frictional wear while maintaining complete sealing contacts between scrolls. This technology allows the orbiting scroll to operate in near complete dynamic balance of force whereby the orbiting scroll ‘floats’ during operation and maintains a very light contact against the fixed scroll. This mechanism assures high volumetric efficiency of scrolls, and as the result, floating scroll pumps are more efficient and quieter. The characteristics of the Scroll Laboratories, Inc.’s technology that are beneficial to this effort include:

- No tip seal or PTFE debris
- No contamination of the media due to oil-free operation
- High performance
- Long product life
- Very quiet and low vibration
- High level of gas tightness
- Operates in any installed position
- Startup against pressure or vacuum
- Handles moisture or liquid

This effort also includes collaboration with United Technologies Collins Aerospace relative to research they have conducted on the International Space Station’s carbon dioxide reduction assembly rotary separator and leverages NASA MSFC’s knowledge of oxygen recovery technology architectures and test facilities such as the Carbon Dioxide Reduction Test Stand (CORTS).

During this effort, two full iterations of the compression portion of a single-stage WExPump is being designed, fabricated and tested to support integrated testing of the prototype with condensation and separation prototypes. The specifications or requirements of the compressor will be determined along with NASA and UTAS when the project starts.



**FIGURE 1.** Humified gas supply.

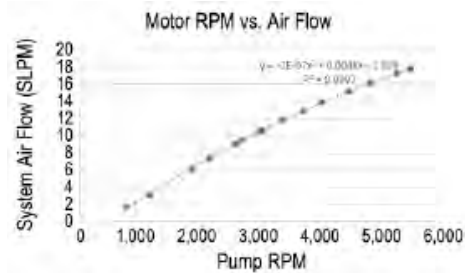
A test stand has been constructed to measure scroll pumps performance and water ingestion capabilities using a humidified gas supply (Fig. 1). The test stand consists of facilities supplied nitrogen, a mass flow controller, a humidifier, dewpoint sensors, pressure sensors, and a temperature-controlled water bath.

The scroll pump tested was able to ingest humidified nitrogen and H<sub>2</sub>O without any adverse effects. Due to some issues with the first iteration of humidifier chosen and line condensation accumulation the pump did ingest H<sub>2</sub>O and continued pumping without stalling or shutting down.

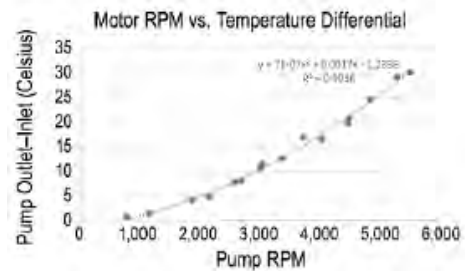
The scroll pump's flow rate, motor speed, inlet pressure, outlet pressure, inlet temperature, outlet temperature and scroll fin temperature have been measured to aid in the water separator design. Results are presented by the Figures 2–4.

**LESSONS LEARNED:**

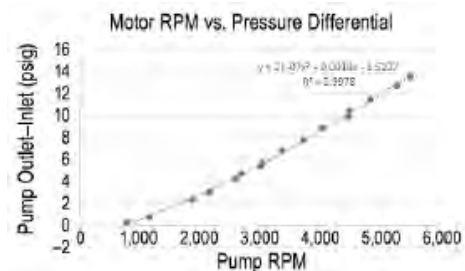
- (1) The pump supplied by Scroll Laboratories, Inc., is rated at 20 L/min while the test stand was initially set up for a scaled down version of the pump aiming at 3 to 5 L/min. The test stand had to be modified for the increased flow.
- (2) The initial membrane humidifier used allowed H<sub>2</sub>O to pass through to the pump inlet if the nitrogen flow to motor speed ratio was too low and allowed nitrogen to flow to the hot water bath by passing the humidifier and pump if the nitrogen to motor speed ratio was set to high. This issue has been addressed by changing the membrane style humidifier to a bubbler style humidifier.



**FIGURE 2.** Comparison of the scroll pump air flow rate versus the pump's rotations per minute.



**FIGURE 3.** Comparison of the pump's rotations per minute and the temperature differential between the inlet and outlet.



**FIGURE 4.** Comparison of the pump's rotations per minute and the pressure differential at the pump's inlet and outlet.

**SUMMARY**

The WEX Pump project continues to make steady progress toward its technical goal. The scroll pump tested shows potential for use in the WEX Pump assembly due to its ability to tolerate H<sub>2</sub>O in the supply line.

**PRINCIPAL INVESTIGATORS:** Morgan Abney, Jeffrey Mehan

**PARTNERS:** Scroll Laboratories, Inc.; United Technologies Collins Aerospace

**FUNDING ORGANIZATION:** Advanced Exploration Systems

# Biofilm Growth Inhibitor Test

**OBJECTIVE:** To determine and employ a method of biofilm growth inhibition for manned life support wastewater systems.

## PROJECT DESCRIPTION

The aim of the Aequor Biofilm Inhibitor Test is to determine then test a low concentration of biologically derived inhibitory chemicals to prevent biofilm growth in a wastewater holding tank analogous to the holding tank of the Water Processor Assembly (WPA) on the International Space Station. The data from this test are used to determine whether the specific inhibitor and concentration could be employed on board the International Space Station (ISS) and future manned-mission water processing systems.

## ACCOMPLISHMENTS

The approach taken involved testing a series of inhibitory chemical formulations provided by Aequor, Inc., as potential solutions for the ISS WPA biofilm growth issue. Minimum inhibitory concentration (MIC) tests were conducted with each chemical at a variety of concentrations with ersatz wastewater and an inoculation of a microbial cocktail provided by Boeing of three isolated species characteristic of the ISS WPA biofilm growth. From these tests, we narrowed down our choices to the inhibitor with the lowest concentration effective at preventing biofilm growth as measured by turbidity comparison. Such tests are common within microbiological research but not in the context of space life support wastewater systems.

The A1026 formulation was determined to have the lowest MIC at 0.06% concentration by mass, and so was selected as the test inhibitor for the next phase of the investigation. In this phase, five tanks were filled with 55 L of wastewater ersatz and a corresponding microbial cocktail concentration of  $1 \times 10^5$  CFU/mL. Two were control tanks, three contained 0.05% and 0.06% concentration of formulation A1026. Samples were sent to Aequor and EMSL Analytical, Inc., for plate

count comparison data and DNA analysis, to be compared against control samples over time.

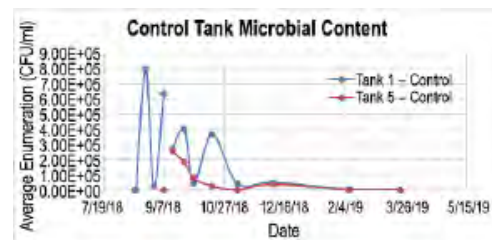
The antibiofilm inhibitor, A1026 at 0.06% (Tank 2 and Tank 3) and 0.05% (Tank 4) inhibited the growth of the mixed species biofilm forming bacteria (*B. cepacia*, *R. pickettii*, and silver-resistant *C. metallidurans*) with a 5-log (99.999%), 5-log (99.999%), and 4-log (99.99%), reduction respectively. The inhibition occurred rapidly, within the first day. The activity was sustained with a single treatment for over 8 months (Table 1).

**TABLE 1.** Antibacterial activity of A1026 in Tank 2 (0.06% v/v), Tank 3 (0.06% v/v) and Tank 4 (0.05% v/v).

A1026 Concentration	Average Enumeration (CFU/ml)	Log Reduction	Percent Reduction (%)
Tank 2 (0.06%)	<1E+01*	5	99.999
Tank 3 (0.06%)	<1E+01*	5	99.999
Tank 4 (0.05%)	<1E+01*	4.4	99.99

\*Detection limit is  $1E+02$  CFU/ml

Microbial counts in the two control tanks oscillated between high and low concentrations, due to settling of the bacteria during stagnant periods, while overall decreasing over time (Fig. 1). One possible explanation for the overall decrease in the control tanks is that microbial growth expands in



**FIGURE 1.** Graph of concentration of microbial content in control tanks presented as CFU/ml versus time. Data are the averages of two determinations performed in duplicate.

the presence of nutrients from the wastewater ersatz to a critical point where the population is too high for the amount of nutrition available. The result is a dying off until the population restores to a point



of nutrient surplus, at which point growth begins again. As of March 21, 2019, the concentration had consistently been greatly decreased from the first month of study, but further testing is needed to determine whether this is an inflection point to an upcoming microbial concentration increase or if this is the final steady state trend for this configuration. Future experiments may require a test redesign to ensure constantly high microbial content.

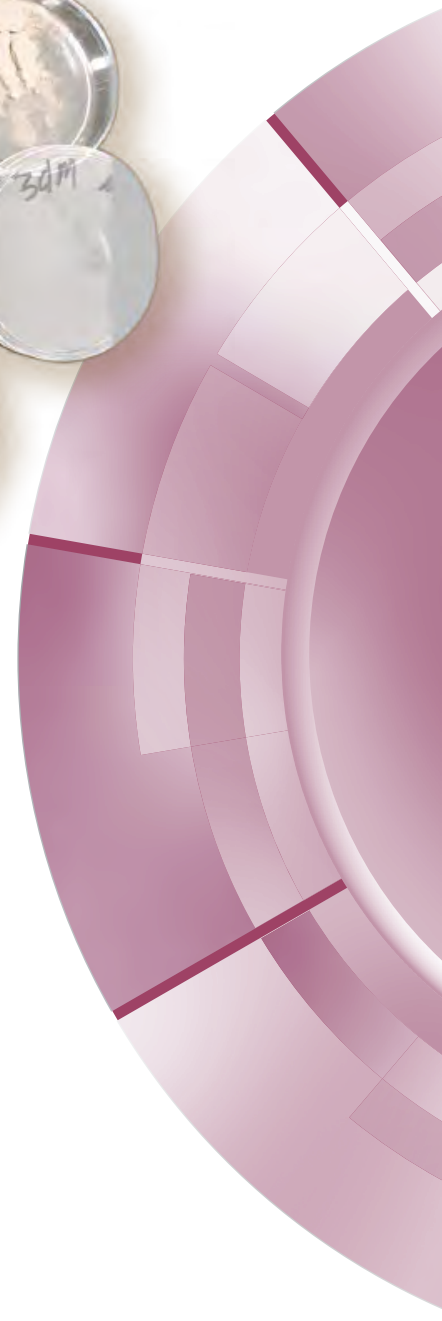
## **SUMMARY**

An antibacterial treatment for the ISS water system is critical, and to be successful, the antibacterial treatment also need to target bacterial biofilm. Aequor's A1026 antibacterial and antibiofilm inhibitor entirely eliminated microbial growth at the lowest concentration testing within the first day of large-scale experimentation and the initial treatment lasted 8 months. The results of this experiment will be used when comparing Aequor's A1026 chemical formulation against the efficacy of other potential biofilm growth inhibitors.

**PRINCIPAL INVESTIGATORS:** Mononita Nur, Layne Carter

**PARTNER:** Aequor, Inc.

**FUNDING ORGANIZATION:** Advanced Exploration Systems



# HUMAN EXPLORATION DESTINATION SYSTEMS

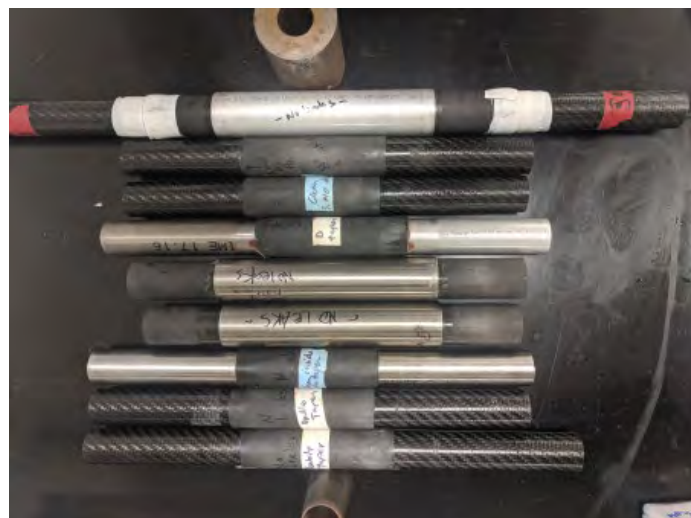


# Paramagnetic Ionic Liquids for Enhanced Gas Absorption

**OBJECTIVE:** *To demonstrate the spatial control of paramagnetic ionic liquid aerosols using applied magnetic fields.*

## PROJECT DESCRIPTION

Being able to easily separate two phase flow into liquid and vapor streams is a critically important part of many technologies relevant to NASA's long-term, deep-space exploration goals. Examples include advanced life support technologies such as the removal of carbon dioxide (CO<sub>2</sub>) from cabin air and in-situ resource utilization such as the purification of lunar cold volatiles. Separating two-phase flow is trivial under normal gravity on Earth, but becomes significantly more difficult in microgravity without gravity driven buoyancy. One potential solution to this problem is the use of paramagnetic ionic liquids (PILs). When placed in a magnetic field, a paramagnetic material is attracted to the magnet, providing a motive force for the separation of the two phases; thus, the goal of this project is to develop hardware capable of producing a PIL aerosol and demonstrating the control of the aerosol using applied magnetic fields.



## ACCOMPLISHMENTS

The key innovation in this work is the use of PILs, which are a relatively new development in the field of ionic liquids (ILs). Paramagnetic materials are materials that have unpaired electrons that align their spin in response when a magnetic field is applied. Under the influence of such a field, these materials are attracted to the magnetic field. Paramagnetism can be induced in an IL through the addition of functional groups containing transition metal cores that are surrounded by a shell that shields the unpaired electrons from others. It is important to note that inducing paramagnetism only requires the modification of one of the IL's ions. This will allow for the other ion in the pair to be freely selected. In this manner, the IL's properties can be tailored to meet the requirements of a specific application. It should, therefore, be possible to design a system that produces a PIL aerosol which responds to an applied magnetic field acting as a proxy for gravity. In fact, the motion of the IL mist can be directed by the magnetic field so as to produce complex motion not normally associated with a gravity driven process. This enhancement in the dynamics of the mist does not detract from the IL's ability to selectively absorb target gasses.

The work required to accomplish this can be divided into three objectives—(1) fabricating a spraying system suitable for use with IL, (2) demonstrating control of droplet distribution with static magnetic fields, and (3) demonstrating the use of time-variant magnetic fields to promote complex fluid flow and mixing.

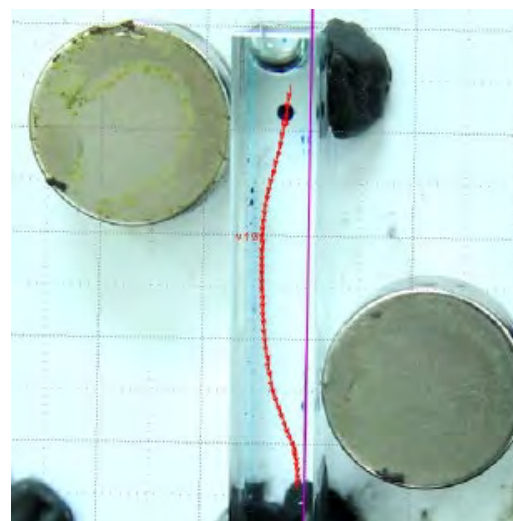
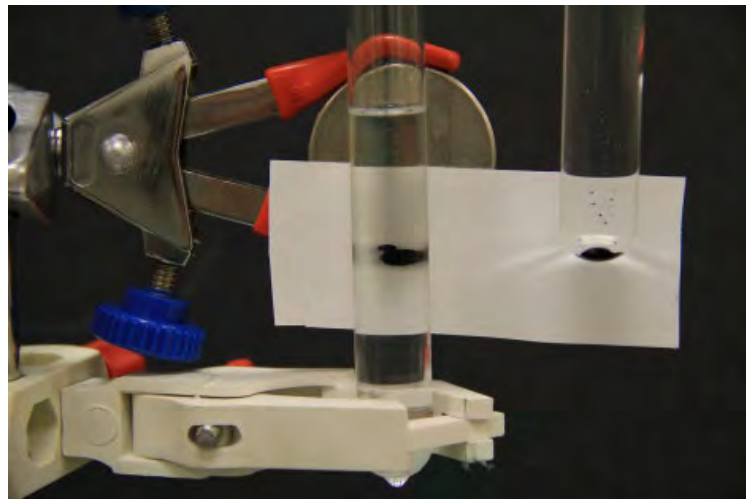
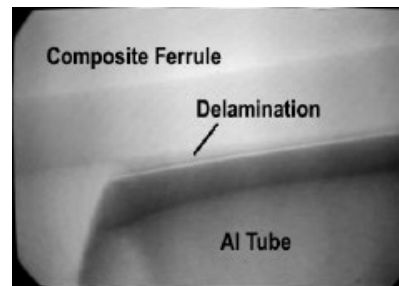
All three objectives were successfully met. A pneumatic spraying system, capable of reliably producing an aerosol of droplets less than 50 μm from two different PILs was fabricated, along with the required hardware necessary to contain the droplets, while still allowing for visual and laser

analysis of the suspension. Additionally, the sample chamber was designed to include capture plates for the gravimetric and energy Dispersive X-Ray Spectroscopy (EDS) scanning electron microscopy (SEM) analysis of drop settling distributions. When placed in an electromagnet, this hardware showed that the application of a magnetic field rapidly depletes the area around the magnet of the aerosol droplets. Additional testing showed that the use of time and position variant magnetic fields could result in different drop settling traces. Finally, the force applied to the PIL droplets was measured and shown to scale linearly with the magnetic susceptibility of the PIL. Together, these results show that it is possible to use magnetic fields as a substitute for gravity to collection PIL aerosols.

The next steps for developing this technology consist of two parts. The first is the design and synthesis of a PIL that is also functionalized to chemisorb carbon dioxide. An aerosol of this PIL would likely be a very effective means of removing carbon dioxide from cabin air while also offering a facile means of separating the PIL sorbent from the air stream being returned to the cabin. The second part is the development of the hardware necessary for a demonstration of this technology under microgravity conditions on a parabolic flight.

## SUMMARY

The use of paramagnetic materials and magnets is an intriguing route to overcome the lack of gravity driven separation of multiphase flow in microgravity. This study demonstrated that the application of relatively modest strength magnetic fields to paramagnetic ionic liquid aerosols will induce significant motion in the droplets and can deplete the local environment around the magnet of aerosol in relatively short order. This ability to create and collect such aerosols has many potential applications in microgravity, such as cabin air revitalization and in situ resource extraction. Future work will investigate tailoring paramagnetic ionic liquids to be used in such cases.



**PRINCIPAL INVESTIGATOR:** Eric Fox

**PARTNERS:** Matthew Marone, Mercer University (co-PI)

**FUNDING ORGANIZATION:** Center Innovation Fund

# Developing a Novel Method to Bond Planetary Regolith to Form Rigid Structures for Space Based Habitats

**OBJECTIVE:** *To develop a process for forming structural Martian regolith-bricks, suitable for autonomous construction technologies, which will be utilized to build the necessary infrastructure for deep space extended exploration missions.*

## PROJECT DESCRIPTION

Establishing permanent human presences on the Moon or Mars will require the construction of large structures including habitats, berms, and landing pads. The mass of building material to produce these structures is much too large to be economically feasible to supply construction efforts from the Earth. Numerous studies have examined developing concrete formulation using regolith as an aggregate. While many of these formulations offer the mechanical properties needed to build structures, they all require the use of large fractions of binder materials, which will either need to be supplied from Earth or fabricated in situ. This project seeks to develop a new method of creating building materials from regolith using materials known as ionic liquids (ILs).

## ACCOMPLISHMENTS

The proposed IL technology concept will evaluate a variety of acidic ILs to chemically convert the surface (to a depth on the order of 10  $\mu$ ) of particles of silica/alumina-bearing rocks and minerals into silicic acid (hydrated silica), which consists of reactive Si-OH groups. This treatment is to permit bonding of the particles to one another after the treated particles are pressed together and the excess ionic liquid (containing solubilized metal salts) is washed away. After removal of the IL, the Si-OH groups of silicic acid react with each other under mild heat and compression to form Si-O-Si linkages and thereby harden the material between the particles of rock and rigidize the structure. The recovered IL is recycled to treat more regolith. The treated regolith powder can be shaped or formed into useful geometries such as tiles or bricks prior



to the hardening treatment. A form of chemical sintering is thus produced, and—if desired—the treatments can be extended to large structures if the IL recovery and hardening can be carried out in a timely manner despite the scale-up. At the end of the process, the IL can be recovered and recycled to processes additional regolith. As such, the process is a closed loop regarding everything except for power and regolith.

Over the last year, 11 different ILs were evaluated for their ability to convert the surface of regolith to silica. Several analytical methods, including x-ray fluorescence and inductively coupled plasma spectroscopy were used to quantify the efficacy of each IL at removing metals from the regolith surface. Four of the ILs, including one commercially available, were found to readily process the regolith, producing particles with robust and uniform coatings of silica, with particles containing significant fraction of iron being the easiest to process. Early efforts produced silica coatings with depth ranging from 30 to 50  $\mu$ , which was found to be thicker than needed. As such, lower processing times and/or lower processing temperatures can be used to achieve a sufficient degree of processing.

In conjunction with the experimental work, molecular dynamics modeling was used to investigate the interaction of the ILs with regolith and each IL's ability to digest the metals present in the regolith. This effort produced Henry's law

constants for each IL-metal pair, which can be used to predict the processing time required to achieve a specific silica coating on regolith as a function of the regolith composition. Additionally, this modeling was also used to investigate the chemical and mechanical stability of binder materials when exposed to cosmic ray radiation.

## **SUMMARY**

The production of building materials from regolith is one of the most promising ways to reduce the cost of establishing permanent human settlements on the Moon or Mars. The project successfully demonstrated a new method of fabricating regolith bricks that can be used for construction. Additionally, the process is closed loop with respect to chemical reagents, allowing for the preparation of large quantities of building feedstock without expensive resupply from Earth.

**PRINCIPAL INVESTIGATORS:** Eric Fox, NASA Marshall Space Flight Center; William Kaukler, University of Alabama Huntsville; and Hunain Alkhateb, University of Mississippi

**PARTNER:** University of Mississippi

**FUNDING ORGANIZATION:** Cooperative Agreement Notice



# In-Space Manufacturing (ISM)

**OBJECTIVE:** *To develop and enable the technologies, materials, and processes required to provide affordable, sustainable on-demand manufacturing, recycling, and repair during Exploration Missions.*

## PROJECT DESCRIPTION

Long-duration Exploration Missions require a paradigm shift in the design and manufacturing of space architectures. The ability to perform In-Space Manufacturing (ISM) provides a solution towards sustainable, flexible missions (both in-transit and on-surface) through on-demand fabrication, repair, and recycling capabilities for critical systems, habitats, mission logistics, and maintenance. These capabilities provide tangible cost savings due to reducing launch mass as well as significant risk reduction due to decreasing dependence on spares and/or over-designing systems for reliability. ISM is developing these capabilities by leveraging the highly disruptive technologies being developed terrestrially and adapting them for operations in the space environment.

## ACCOMPLISHMENTS

ISM consists of an integrated task portfolio that culminates in the development of manufacturing and recycling systems and processes that will enable on-demand production of a wide array of parts and components. The ISM motto is “Make It, Don’t Take It!” The project is funded by both the Space Technology Mission Directorate (STMD) Game Changing Development (GCD) Office, and the Human Exploration and Operations Mission Directorate (HEOMD) Advanced Exploration Systems (AES) Division, with NASA Marshall Space Flight Center (MSFC) acting as the lead Center. ISM Partner Centers include Ames Research Center and Goddard Space Flight Center. The ISM project utilizes a streamlined management approach with moderate risk tolerance in order to obtain technical implementation within aggressive schedule and budget baselines. The current ISM portfolio consists of the following elements: the Multi-Material Fabrication Laboratory (Fab-Lab), the Refabricator, in-house work, the Additive Manufacturing Facility (AMF) and 3D Printing In

Zero-G (3D Print) plastic printers, and many Small Business Innovation Research (SBIR) awards for technology development.



### MULTI-MATERIAL FABRICATION LABORATORY (FABLAB)

The FabLab project builds on the previous success with 3D printing of plastics on the International Space Station (ISS) in 2014 as well as commercial development of several additive manufacturing technologies. This project seeks to expand the Station’s on-demand fabrication capability by

increasing the number of printable materials (feedstock) available while improving overall manufacturing efficiency. The FabLab payload goal is to demonstrate an end-to-end manufacturing process using multiple materials including metals. The FabLab is currently in Phase A development with three commercial companies under Broad Area Announcement agreements. Techshot completed a preliminary design review and delivered material specimens for testing. Interlog completed all required phase A activities and submitted a closeout report. Tethers Unlimited, Inc., (TUI) is in the process of completing their preliminary design review; no material specimens were required under contract for delivery.

### REFABRICATOR

Reuse of materials is a key aspect of ISM, as it helps to provide a sustainable capability. The Refabricator is an integrated 3D printer and recycler intended to demonstrate the repeatable, closed-loop process of recycling waste plastic and previously 3D printed parts into high-quality 3D printer filament to create new tools and parts. TUI designed the payload via multiple SBIR awards (Phases I, II, II-Extended, and III), to use Ultem® plastic recycled seven times to create parts that will be tested for quality on Earth. The Refabricator was launched to the ISS in November 2018. In January 2019, the payload was installed, and operations started in February 2019. An anomaly in the recycling system ceased operations; once the payload is returned in 2020, a determination of the origin of the anomaly will be made. A print cartridge with material recycled on Earth is now in the Refabricator's print system. Printing started, but TUI ceased printing when a power glitch occurred. Printing will be initiated again after power issues are resolved and bandwidth is available; operations are expected through 2019.

### IN-HOUSE DEVELOPMENT

The development of a design database is just a portion of the multiple efforts at MSFC that contribute to ISM's mission. The design database will be a collection of drawings, images, and machine fabrication parameters for spare parts, tools, electronics, sensors, or any other required equipment that can be manufactured in-situ during Exploration Missions. This database will interface with humans and the manufacturing

systems available on Exploration Missions. Over 500 parts are populated in the current version of the Design Database. Additionally, the company Geocent, that developed SPIDER (Space and Naval Warfare Systems Command/Program Executive Office (SPAWAR) Integrated Data Environment and Repository) database for the Department of Defense, will be working on the structure for ISM's Design Database.

A portion of the ISM team at MSFC is dedicated to developing materials and manufacturing processes to support the ISM Exploration Mission capability. This includes the invention and testing of new inks for printable electronics, sensors that interact with current radio frequency-enabled Identification (RFID) systems on the ISS, energy harvesting devices and batteries, and the development of wearable substrates and sensor arrays to monitor crew health currently called AstroSense. Crew health sensor development is in partnership with NASA Ames Research Center, NASA Johnson Space Center, universities through the Cooperative Agreement Notice mechanism, and NextFlex, one of the institutes under the Manufacturing, USA umbrella. The team was awarded four patents in 2019.

### ADDITIONAL ELEMENTS

The AMF produced acrylonitrile butadiene styrene tensile specimens that have been independently tested; a report will be submitted in early 2020. The 3D Print payload will be returning to Earth for modifications and reflow for another technology demonstration. All SBIR companies continue to help develop the capabilities needed for ISM and NASA for Exploration Missions.

**PROJECT MANAGER:** Phil Hall

**FUNDING ORGANIZATIONS:** Game Changing Development


**FOR MORE INFORMATION:** <https://www.nasa.gov/oem>



# An In-Situ Binder for Additive Construction on the Moon

**OBJECTIVE:** *To complete an assessment of the compatibility of ionic liquids-facilitated magnesium oxysulfate concrete with 3D printing technology.*

## PROJECT DESCRIPTION



Ionic liquids (ILs) are organic salts that are liquid at or near room temperature. ILs are highly tunable, allowing their physical properties (e.g. density, viscosity, conductivity, solvency) to be adjusted to meet task-specific requirements. Additionally, ILs generally have high thermal stability and low volatility, making them particularly suited for use in space environments. NASA has investigated the use of ILs for environmental control and life support, in situ resource utilization, electric and chemical propulsion, and structural materials.

To minimize launching construction materials from Earth and make deep-space missions more cost-efficient and sustainable, it is important to utilize the materials available on planetary surfaces. ILs provide a method to extract and refine needed resources from the regolith and atmosphere in situ. As part of a NASA Marshall Space Flight Center (MSFC) Center Innovation Fund (CIF) project, the work involves fabrication of a binder material from available planetary resources that, when combined with regolith in an aqueous solution of acidic ionic liquid, will provide a construction material that is compatible with additive construction, or 3D printing, technologies.

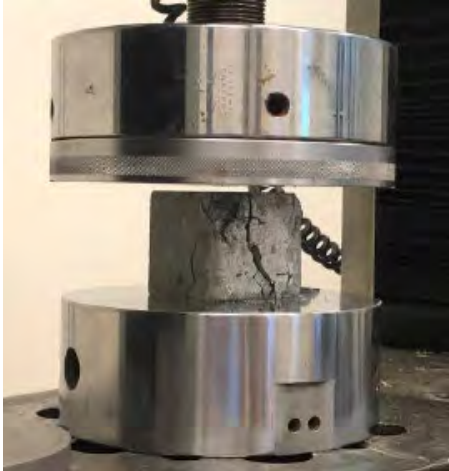
## ACCOMPLISHMENTS

An acidic IL (1-ethyl-3-methylimidazolium hydrogensulfate or EMI HSO<sub>4</sub>) is used to dissolve the regolith. Through several processes and steps, the IL is electrochemically regenerated and magnesium oxysulfate (3MgO + MgSO<sub>4</sub> + H<sub>2</sub>O) concrete is created. The magnesium oxysulfate is then used as a concrete binder with lunar regolith acting as the aggregate. No IL is consumed in the process, so the

initial volume of IL could be used to process an unlimited amount of regolith into magnesium oxysulfate concrete.

Different mixes of magnesium oxysulfate concrete with JSC-1A, lunar regolith simulant, were tested in order to study the compatibility of the concrete with 3D printing applications. Printing properties such as pumpability, buildability, and printability, as well as other properties such as porosity and compressive strength were observed. Pumpability can be described as the ease at which the concrete extrudes from a printing device. This property was made quantifiable by measuring the pressure required to initiate concrete extrusion from a makeshift 3D printer. The buildability, or workability, of the concrete was defined as the tendency of the concrete to hold its shape after extrusion. Buildability also relates to how well the concrete supports its own self weight and the weight of successive stacked layers. Buildability was quantified as the distance that an extruded concrete sample slumps over a period of 60 s. Printability was a nonquantifiable value that was defined as the tendency of an extruded sample to resist cracking and other deformations. Porosity is a measurement of the volume of air voids within a concrete sample. Porosity measurements helped to identify causes of certain behaviors of the material, as well as giving insight to other properties of the concrete. The last property that was measured was compressive strength. This is a standard strength test for concrete samples.

Through a few variations in mixing procedures, it seemed that the simplest way to mix the ingredients was to combine all of the dry ingredients together before adding the water to the mixture to begin the reaction. This was the procedure that was used throughout experimentation.



**FIGURE 1.** A sample after compressive failure test still in the machine.

The liquid nature of the reaction became an apparent issue with mixes of higher binder ratios (more magnesium oxysulfate vs simulant). Higher binder ratio mixes took longer to “harden,” which was a term used to represent the curing process from initial mixing until the mix was suitable for simulated printing. The age of the concrete also effectively changed the properties of the concrete for mixes of the same binder ratio. The middle binder ratios, 0.8 and 0.9, have the most promise for successful printing. This observation was based on the data collected during experimentation. When looking at the printing properties of the concrete, 0.8 and 0.9 binder ratios exhibit average pumpability with a fair amount of controllable slump. These samples also had the highest printability out of all of the binder ratio mixes. These binder ratios tended to have a lower hardening time while being able to extrude smoothly and without cracking. Almost all 0.8 and 0.9 binder ratio mixes had a compressive strength over 2,000 psi. Both mixes had an average porosity above 20%, which was a large number of air voids within the concrete. Future work could include scaling-up the process and testing samples created in a simulated lunar environment.

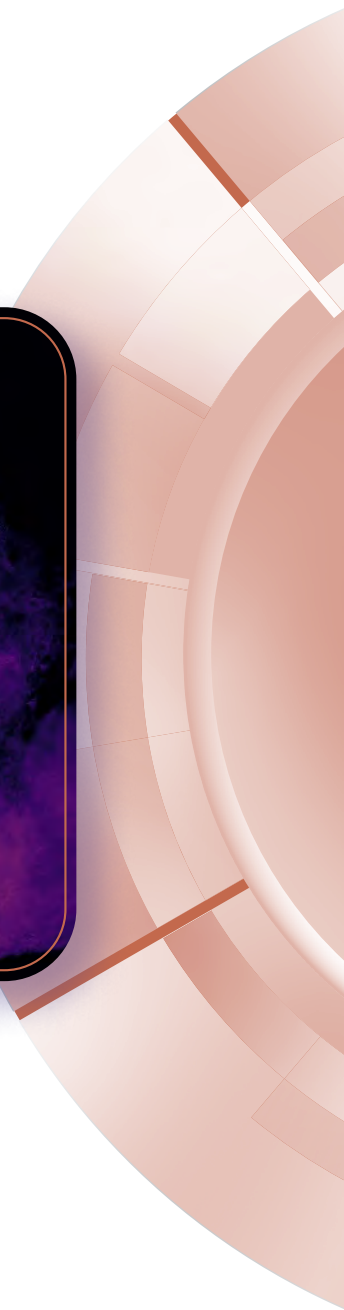
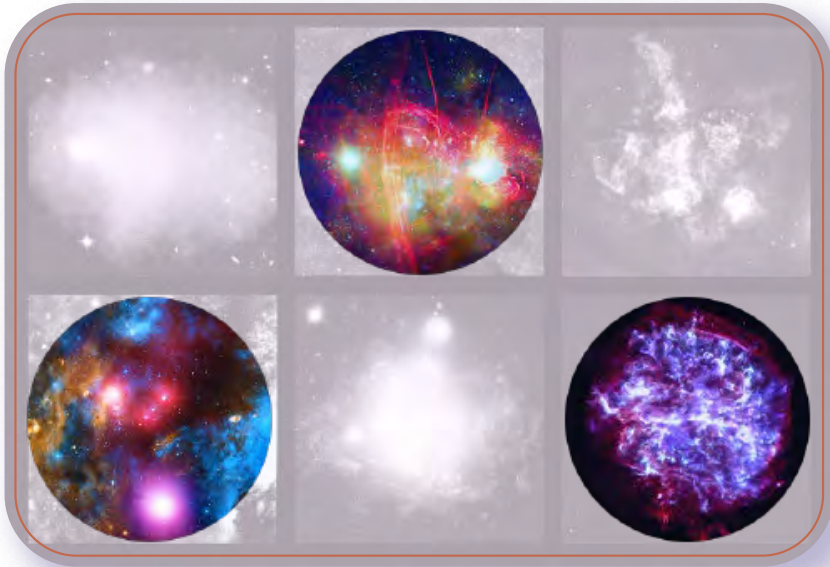
## SUMMARY

ILs-facilitated magnesium oxysulfate concrete shows promise for future lunar construction applications. Future work would include scaling up the process to create magnesium oxysulfate concrete from ionic liquids, automating the printing process, and optimizing the concrete mixture.

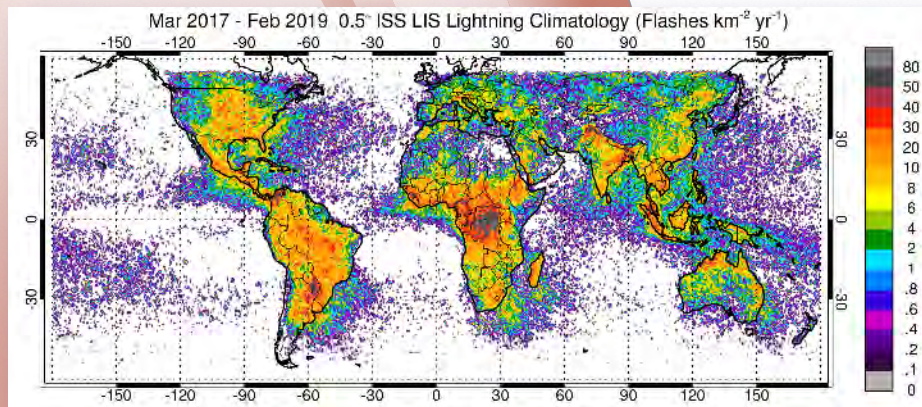
Magnesium oxysulfate concrete could be produced on both the Moon and Mars, reducing launches from Earth to supply building materials, as well as providing an on-demand method of producing construction materials. It expands the utilization of space by enabling manufacturing and resource utilization. This material enables a new mission architecture.

**PRINCIPAL INVESTIGATOR:** Mallory Johnston

**FUNDING ORGANIZATION:** Center Innovation Fund



# SCIENCE INSTRUMENTS, OBSERVATORIES, AND SENSOR SYSTEMS



# Lynx X-ray Observatory Concept Study

**OBJECTIVE:** *To conduct a concept study for consideration as NASA's next flagship astrophysics mission following JWST and WFIRST.*

## PROJECT DESCRIPTION

The Lynx X-ray Observatory is a large mission concept under study to aid the 2020 Astrophysics Decadal Survey Committee in formulating their recommendations for future NASA strategic astrophysics missions (for launch in the 2030s). The study goal was to deliver to the Decadal Survey Committee a mission concept that is scientifically compelling and feasible with respect to technical, cost, and risk factors. The study details the science objectives, the mission and observatory performance requirements needed to realize these objectives, a design reference mission, an assessment of the current technology and a roadmap for technology maturation (and the resources needed), a cost assessment, major-risk mitigation plans, and a top-level schedule for major development phases.

A final report has been submitted to the Decadal Committee.

## ACCOMPLISHMENTS

The Lynx X-ray Observatory is more than a concept. Spacecraft systems are currently available nearly off-the-shelf, and key technologies necessary to realize the mirror assembly and the science instruments are being developed at NASA Centers (including Marshall Space Flight Center (MSFC) and Goddard Space Flight Center (GSFC)), universities, and industry. Technology maturation plans were developed for these technologies and were submitted with the Lynx final report. A lifecycle schedule and project cost estimate were generated. The approach was to identify a feasible design for a flagship mission while maximizing the science value.

The Lynx study was performed under the leadership of a Science and Technology Definition Team (STDT) selected by NASA from the astrophysics community. A joint MSFC-Smithsonian Astrophysical Observatory (SAO) Study Office provided the Science and Technology Definition



**FIGURE 1.** Lynx final concept study report is available for download on the Lynx website: <https://www.wastro.msfc.nasa.gov/lynx/>

Team (STDT) with resources and support. The MSFC Advanced Concepts Office led the mission design and collaborated with the GSFC Instrument Design Lab and Mission Design Lab to produce in-depth studies of the science instruments and mission formulation and implementation. The Lynx Study Office established multiple partnerships with industry via Cooperative Agreement Notice contracts to perform assessments and provide inputs in areas of technology maturation, design, analysis and manufacturing. The Study Office also partnered with the University of Alabama Huntsville's School of Industrial and Systems Engineering to assist with Systems Modeling of the Lynx observatory focused on development of Concept of Operations (ConOps)-type content and identify cost, schedule, and requirements drivers.

The Lynx team has worked to build an exciting science case worthy of a flagship mission. This science case, which includes observing the very

first supermassive blackholes, identifying the drivers of galaxy formation and evolution, and expanding our view of stars and planets is enabled by an advanced assembly of lightweight X-ray optics coupled to a highly capable suite of science instruments. The science instruments include a low-noise megapixel imaging array called the High-Definition X-Ray Imager (HDXI), a large-format, high-spectral-resolution, small-pixel array also known as the Lynx X-ray Microcalorimeter (LXM), and a high-efficiency, high-spectral-resolution, dispersive spectrometer dubbed the X-ray Grating Spectrometer (XGS). Extensive trade studies and technology assessments on the payload and spacecraft were carried out by the Lynx team to define the Design Reference Mission elements and to assess the feasibility of additional developing technologies.

## SUMMARY

Only a unique X-ray observatory such as Lynx will give us the capacity to answer fundamental questions regarding the first black holes, galaxy formation and evolution and a range of high-energy processes needed to understand stellar life and death, star-planet interactions, origin of elements, energy feedback from star formation on a range of spatial scales, and protoplanetary disk formation. With its high angular resolution, large effective area and spectroscopic capability, Lynx will be uniquely positioned to provide synergistic observations with both ground-based and space-based observatories, including gravitational wave detectors, through the 2030s and beyond.



**PRINCIPAL INVESTIGATOR:** Lynx Science and Technology Definition Team and MSFC Study Office. Authors: Jessica A. Gaskin, Karen E. Gelmis, Douglas A. Swartz

**PARTNER:** Smithsonian Astrophysical Observatory (SAO)

**FUNDING ORGANIZATION:** Science Mission Directorate

**FOR MORE INFORMATION:** <https://wwwastro.msfc.nasa.gov/lynx/> and <https://www.lynxobservatory.com/>

**FIGURE 2.** Lynx has a 10-m focal length and consists of a high-resolution, 3-m diameter, large area x-ray mirror assembly with pre- and post-collimators surrounded by the spacecraft bus and complemented by an instrument suite that includes a low-noise megapixel imaging array (HDXI); a large-format, high-spectral-resolution, small-pixel array (LXM), and high-efficiency, high-spectral-resolution, dispersive spectrometer (XGS). Detectors for all three instruments are mounted onto the ISIM.

# Disaster Monitoring and Support

**OBJECTIVE:** *To apply Earth remote sensing and modeling capabilities to support disaster risk reduction, response, recovery, and resilience for meteorological hazards.*

## PROJECT DESCRIPTION

Hazards from severe weather include damaging thunderstorm winds, large hail, tornadoes, frequent lightning, heavy rains, storm surge from tropical cyclones, and their various combinations. Annually, hazardous and severe weather contributes to millions of dollars in insured losses, fatalities, damage to infrastructure, economic loss and long-term recovery. Earth remote sensing and complimentary modeling capabilities provide numerous opportunities to provide decision-support information to end users engaged in all facets of disaster management, including risk reduction, response, recovery, and building resilience. At NASA Marshall Space Flight Center (MSFC), our Earth Science Disasters Team focuses on collaborative development of tools to support disaster monitoring, mapping, and recovery efforts across a range of observables from space, including damage to structures and vegetation, changes in nighttime lights as a proxy for electrical power, mapping the evolution of floods, and working collaboratively across NASA to maximize the societal benefit of basic and applied research activities.



Space and Major Disasters and the USGS Hazards Data Distribution System.

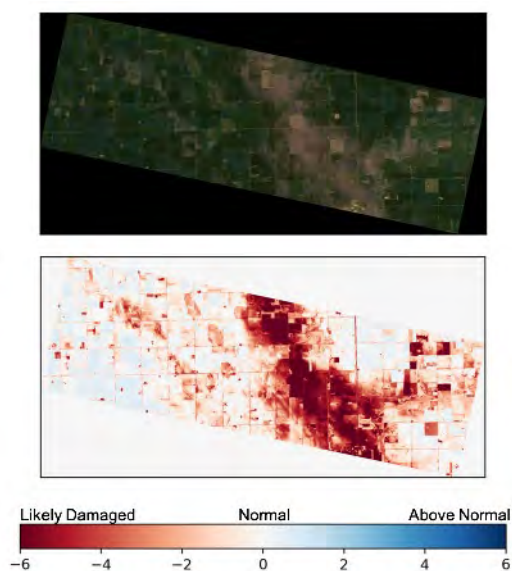
In collaboration with the IMPACT team at MSFC, we are further exploring big data and machine learning approaches to best utilize the growing volume of Earth remote sensing made available by NASA, U.S. Federal, international, and commercial partners.

Our MSFC Earth Science Disasters Team partners with other NASA Centers, academia, and industry to support response efforts for major meteorological disaster events. We routinely support federal partners such as FEMA and the U.S. National Guard, NOAA's National Weather Service and have opportunities to further collaborate with regional state emergency managers. Our efforts to map the extent of severe Midwestern U.S. flooding in March

## ACCOMPLISHMENTS

Our approaches explore the full range of satellite remote sensing capabilities with a focus on mapping disaster impacts, evolution, and recovery. We routinely use high spatial resolution commercial imaging from optical to near-infrared and thermal remote sensing to map severe weather damage resulting from tornadoes (in support of NOAA's National Weather Service), damage to agriculture, and the visible extent of floods from major weather events. We increasingly utilize multitemporal and multifrequency synthetic aperture radar (SAR) imaging from international, aerial, and commercial companies to complement these analyses, often in collaboration with the International Charter on

2019 provided extensive imaging used in situational awareness and response products by these partners, and collaborations were further advanced through participation in nationwide exercises helping partners to further develop their capacity for using Earth remote sensing in their decision-making process. As partners in NASA's Agency-wide Earth Science Disasters Team, MSFC team personnel regularly serve as coordination leads for regional and international events, ensuring benefits from



**FIGURE 1.** Landsat 8 true color image (top) depicting hail damage to agriculture (brown shades) and preliminary algorithm development for helping identify and extract those damage areas (bottom) based upon their proximity to known hail fall and severity of change in greenness.

NASA's basic and applied research are supporting disaster recovery efforts for a broad range of hazards and communities. Most recently, the team has served in lead roles for supporting response to major hurricanes such as Dorian's impact to the Caribbean (2019), similar to support for major U.S. hurricanes in 2017 (Harvey, Irma, Maria) and 2018 (Florence, Michael).

## SUMMARY

The MSFC Earth Science Disasters Team focuses on basic and applied research to develop decision-support analysis and tools from NASA, other federal, international, and commercial satellite platforms, emphasizing the mapping of damage from meteorological hazards such as severe weather and tropical cyclones. Their expertise further serves NASA's Agency-wide efforts to bring NASA Centers together in collaboration around disaster risk reduction, response, recovery, and resilience topics, helping to ensure that science and technology developments are applicable to the disaster response community.

**PRINCIPAL INVESTIGATOR:** Andrew Molthan

**PARTNERS:** FEMA, USGS, National Guard, NOAA/National Weather Service

**FUNDING ORGANIZATION:** Science Mission Directorate

# Advanced Microwave Precipitation Radiometer (AMPR)

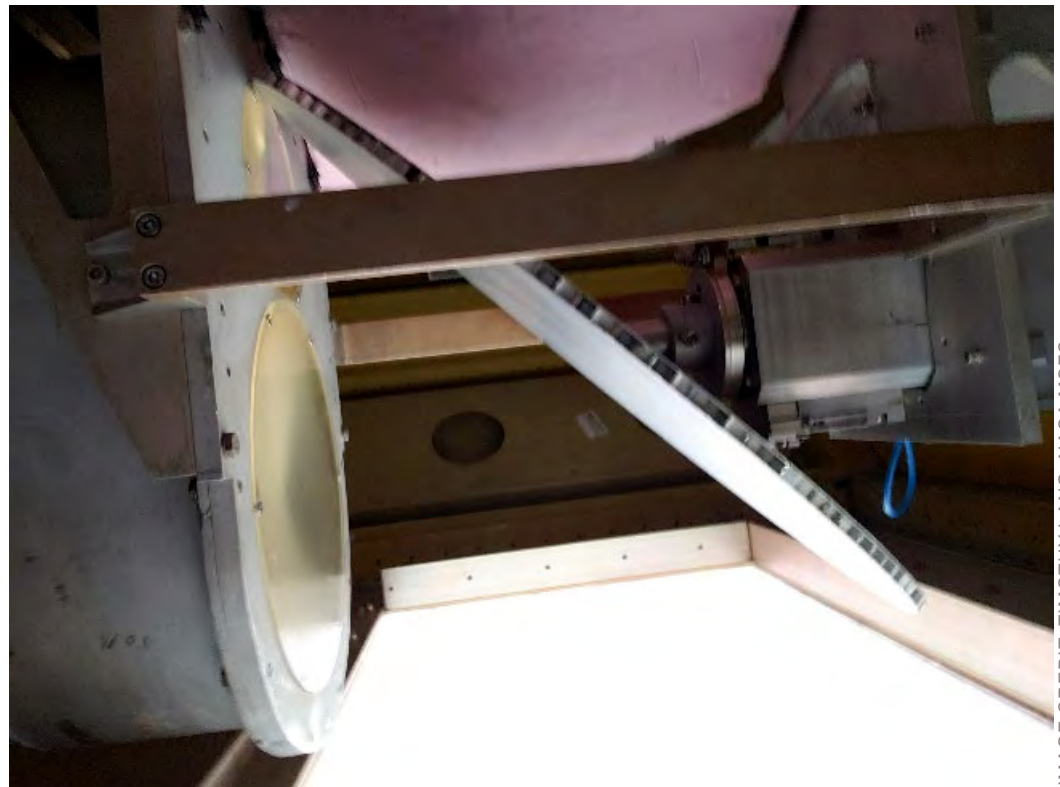
**OBJECTIVE:** *To provide calibrated measurements of the Earth's atmospheric and surface characteristics from an airborne platform.*

## PROJECT DESCRIPTION

The Advanced Microwave Precipitation Radiometer (AMPR) is an airborne, polarimetric, passive microwave radiometer producing brightness temperatures ( $T_b$ ) 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 (H) and vertically (V) polarized microwave  $T_b$  values need to be determined. This is accomplished by deconvolution of polarization-variable measurements from two orthogonal channels per frequency.

modifications to AMPR, laboratory, and rooftop testing of the instrument, then shipping and integration onto the NASA P-3B Orion aircraft, which was deployed to the Philippines to sample tropical maritime clouds in both polluted and clean environments.

During a previous field campaign on the P-3B in 2016, significant radio-frequency interference (RFI) occurred on AMPR's 37.1-GHz channels, caused by co-located operation of a Ka-band cloud and precipitation radar. In collaboration with the



**FIGURE 1.** AMPR instrument installed in the bomb bay of the NASA P-3B. The mirror is angled downward, pointing through AMPR's new multi-frequency radome, in a nadir-pointing sampling mode that was frequently used during CAMP2Ex.

## ACCOMPLISHMENTS

During FY 2019, the instrument was prepped for and participated in a field campaign called Cloud, Aerosol and Monsoon Processes Philippines Experiment (CAMP2Ex). This work involved

radar's home institution, Jet Propulsion Laboratory (JPL), during FY 2019 narrow passband filters were installed in AMPR's RF section, which extensive laboratory testing indicated would successfully filter most if not all of the RFI from the radar.

Integration on the P-3B required installation of one of AMPR's new multifrequency radomes. During FY 2019, both new radomes, procured in FY 2018, were successfully approved for flight by P-3B aircraft management. Based on rooftop sky testing prior to integration, it was determined that the flat radome provided slightly better transmissivity than the tapered radome, so it was installed as the primary radome with the tapered radome held in reserve as a potential spare (Fig. 1).

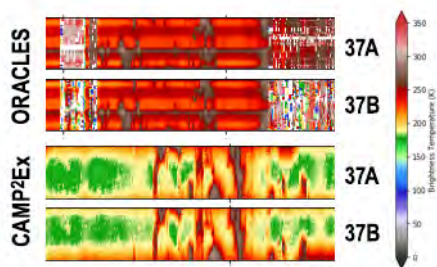
The 37.1-GHz filters and the new radome led to major improvements in data quality during CAMP2Ex (Fig. 2), which occurred from late August through early October 2019 in the Philippines. Compared to 2016 AMPR data from the P-3B deployment during the Observations of Aerosols above Clouds and their interactions (ORACLES) campaign, artifacts like along-track striping caused by poor transmissivity were largely eliminated. In addition, the filters eliminated the severe RFI that prevented any useful data collection during Ka-band radar transmit. While some of these issues were corrected in the final 2016 dataset, the radome and filter upgrades have clearly improved overall AMPR data quality.

During CAMP2Ex, two new scanning modes were used. The first, which was the default, provided eight cross-track sweeps before a calibration cycle, twice the usual four sweeps. This increased the repeat frequency of nadir pixels, which will benefit the temporal resolution of planned combined active-passive microphysical retrievals in concert with the JPL radar, a key science priority for CAMP2Ex. The second mode was a nadir-only stare mode rather than cross-track scanning (Fig. 1). This was enabled manually only when passing directly over cloud targets of high scientific value. These data will offer unprecedented, ultra-high-resolution microphysical retrievals in these clouds.

## SUMMARY

In 2019, the AMPR instrument successfully participated in the CAMP<sup>2</sup>Ex field campaign and gathered approximately 140 hours of flight data on tropical maritime clouds and their surrounding environments. The deployment benefited from key technology improvements implemented prior to the campaign. AMPR data from CAMP<sup>2</sup>Ex will enable new scientific insights into how air pollution affects cloud and precipitation processes, a key goal of the recent Earth Science Decadal Survey.

IMAGE CREDIT: TIMOTHY LANG, NASA MSFC



**FIGURE 2.** Approximately 25 min of brightness temperatures for precipitating clouds from both of AMPR's 37.1-GHz channels during ORACLES 2016 (top) and CAMP2Ex 2019 (bottom). The new radome and filters eliminated radome artifacts (horizontal stripes) and RFI (noisy data near beginning and end of ORACLES chart).

**PRINCIPAL INVESTIGATOR:** Timothy J. Lang

**PARTNERS:** University of Alabama in Huntsville, Universities Space Research Association, Aerospace Corporation, ProSensing, University of Utah, Jet Propulsion Laboratory

**FUNDING ORGANIZATION:** Science Mission Directorate

**FOR MORE INFORMATION:** <https://weather.msfc.nasa.gov/ampr/>

# Pixel-Level Smoke Detection with Deep Learning

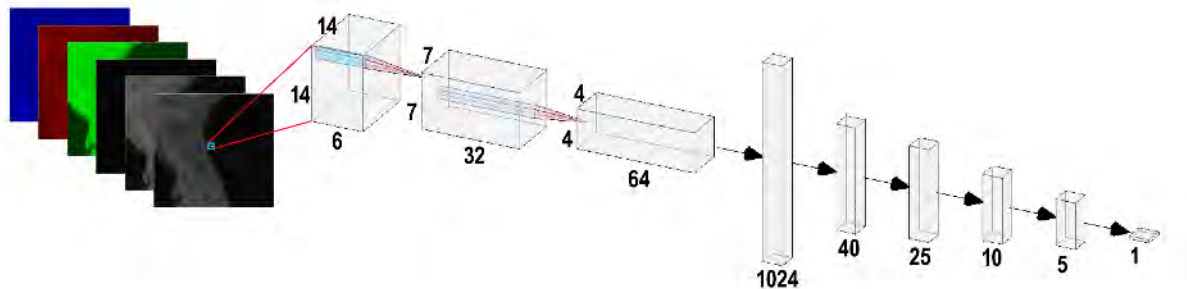
**OBJECTIVE:** To develop a real-time deep learning model for the detection of smoke in the next generation of geostationary satellite imagery.

## PROJECT DESCRIPTION

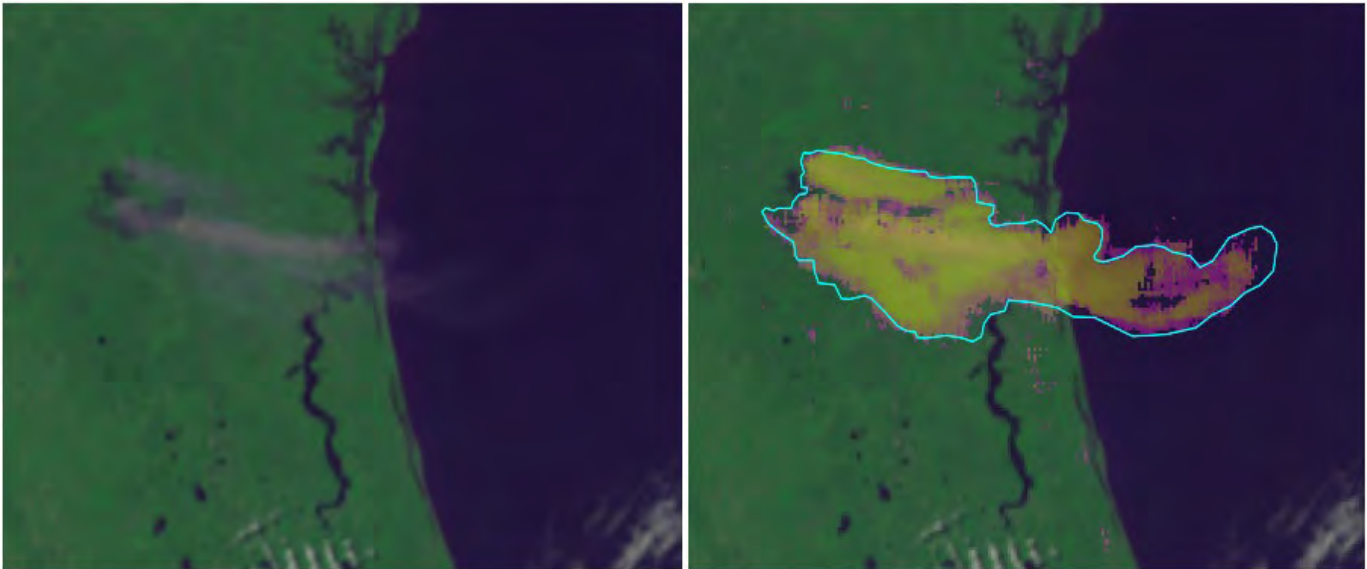
Exposure to smoke from biomass burning negatively impacts human health, has direct and indirect effects on meteorology, and threatens ecological functions. Despite these well-documented impacts, detection and monitoring the evolution of smoke plumes is a challenge for current observation platforms. In-situ observations of biomass burning tracers provide the best indication of smoke in the atmosphere but lack the spatial and temporal coverages required for large-scale, detailed characterization. Satellite remote sensing capabilities provide means of overcoming these limitations but require subjective and intensive manual or multispectral applications analysis limited by large data volumes, class representation biases, and computational costs and efficiency. The spatiotemporal resolution of earth observation data is only increasing with recent technological advances in satellite remote sensing, specifically for geostationary platforms. Thus, there is a need for a scalable, objective method for identifying smoke in this imagery. We have developed a deep learning model for pixel-level smoke detection for satellite imagery to address the need for an automated, high spatiotemporal resolution smoke detection capabilities.

## ACCOMPLISHMENTS

Deep learning is an area of artificial intelligence that consists of multiple layers of artificial neural networks interconnected to progressively learn from input data. The process of learning is designed to mimic the structure and function of the human brain. Convolutional Neural Networks (CNN) are a special type of neural network that is capable of capturing and discriminating features of the inputs using filters. It learns discriminative features without relying on a human expert to identify which features are important. We implemented a smoke detection model by creating a custom CNN architecture (Fig. 1) to capture the spectral properties, texture, and extent of smoke to classify Geostationary Operational Environmental Satellite (GOES) 16 Advanced Baseline Imager (ABI) shortwave reflectance imagery (bands 1–6). A subject matter expert, hand-curated smoke extent truth dataset to train and test the model. This dataset currently consists of 122 plumes identified over North America during 2017–2019 resulting in approximately 1 million smoke pixels. The plume images were split such that 75% of them were used for training, and the remaining 25% were used for testing the model. Figure 2 illustrates an example detection using the model.



**FIGURE 1.** Representation of GOES 16 shortwave reflectance input data and CNN architecture for the smoke detection model.



**FIGURE 2.** GOES 16 pseudo-RGB on of smoke plume on May 2, 2018, in Northern Florida (left) with predictions from the smoke detection model with validation shapefile overlaid (right). Yellow pixels indicate high probability of smoke whereas pink pixels indicate low probability of smoke.

This is the first project that utilizes deep learning to objectively detect smoke in the new generation of geostationary satellite imagery data in real time. A robust truth dataset of smoke plume extents from GOES 16 shortwave reflectance imageries is developed. The smoke detection model is able to identify smoke over a wide range of conditions with some limitations in identifying thin smoke over high reflectance background surfaces. Importantly, the model is able to discriminate smoke from other features with high reflectance in the shortwave range including clouds and snow/ice land cover. Additionally, the model was tested on scenes containing other common atmospheric aerosols including dust storms and volcanic ash with overall success. Currently, the model is being integrated into a production environment for end users. Feedback provided by the community are being incorporated into continued development efforts.

## SUMMARY

We have created a real-time, end-to-end, pixel-based smoke detection model using deep learning for the new generation of geostationary satellite imagery data. A robust truth dataset of smoke plume extents from GOES 16 shortwave reflectance imageries is also constructed. Results show that the model performs with high accuracy in wide range of conditions. The project intends to enable eventual infusion of the smoke detection model as a service at operational centers.

**PRINCIPAL INVESTIGATOR:** Manil Maskey

**PARTNER:** University of Alabama in Huntsville

**FUNDING ORGANIZATION:** Science Mission Directorate

# Design and Analysis of a Slitless X-Ray Spectrograph Using Focusing Critical-Angle Transmission Grating

**OBJECTIVE:** To design a high-throughput, slitless X-ray spectrograph using focusing gratings

## PROJECT DESCRIPTION

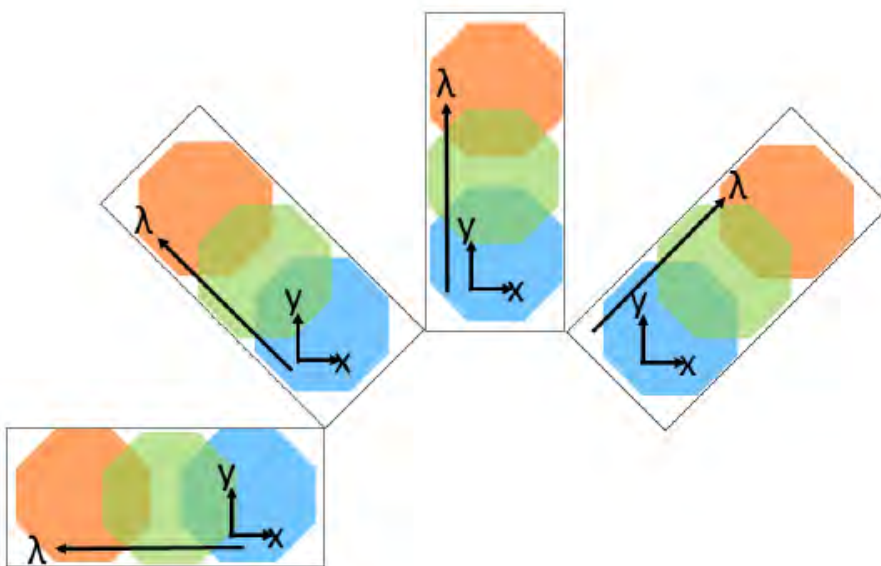
Various science goals require spectroscopic observations in the soft x-ray range. One such goal is to understand the heating mechanism and energy transfer in the solar corona. For this purpose, NASA Marshall Space Flight Center (MSFC) is currently developing the Marshall Grazing Incidence X-ray Spectrometer (MaGIXS) sounding rocket experiment, which consists of a conventional x-ray telescope and a slit spectrograph. While this design produces an unambiguous high-resolution x-ray spectrum, the complexity of the optical system (four grazing incidence mirrors and one reflective grating) results in low throughput, and can only observe along a one-dimensional slit. Even when scaled up to a satellite-based instrument, this design would require several hours to scan the slit over an entire solar active region, and capturing short-lived explosive events is extremely difficult. In this

project, we model the optical properties of a curved critical-angle transmission grating, to investigate the feasibility of a high-throughput slitless spectrograph.

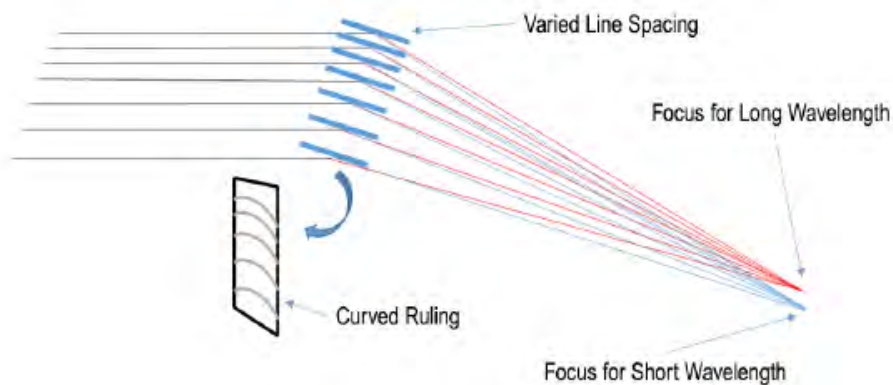
## ACCOMPLISHMENTS

This x-ray spectrograph concept combines several recent innovations. First is the use of multidirectional slitless spectrography to obtain spectral and imaging data simultaneously. A slitless spectrograph produces a 2D image that is dispersed in one direction; this means spectral dispersion is superimposed on the image, so when observing extended targets with complex structures such as the Sun, it is impossible to distinguish between spatial features and spectral features. Montana State University (MSU) is pioneering a multichannel slitless spectrograph in the extreme ultraviolet (UV) wavelengths: by using multiple slitless

spectrographs with different dispersion directions, it is possible to use a computational tomography technique and distinguish between spatial and spectral features. The second innovation is the combination of photon-counting detectors and high-order spectrographs; recent advances in complementary metal oxide semiconductor (CMOS) imager technology allow high-speed readout, making photon-counting a possibility for bright targets such as the Sun. While a CMOS detector has insufficient spectral resolution to resolve emission lines, it is enough to distinguish between multiple diffraction orders of a high-order (5–10) diffraction grating.



**FIGURE 1.** Illustration of the concept of slitless spectrographs. Each rectangle represents the image produced by one slitless spectrograph. Each spectrograph disperses the image in different directions. By combining data from multiple spectrographs, the X, Y and  $\lambda$  components can be separated.



**FIGURE 2.** One possible concept for a slitless spectrograph using a Focusing CAT grating. The curved rulings focus the x-ray in one dimension, and the varied line spacing focuses it in the other dimension. The focus point is wavelength-dependent, making this a spectrograph.

The third innovation, unique to this study, is the concept of a focusing critical angle transmission (CAT) grating. Conventional CAT gratings are transmission grating with extremely deep profiles (i.e. narrow slits cut into a thick substrate at regular intervals). The side wall of each slit reflects light in a specific direction, at a shallow graze angle (below critical angle). This results in a significantly higher efficiency, but the grating otherwise behaves as a standard transmission grating, albeit with a much range of incident and exit angles. By creating a version of the CAT grating with varied line spacing and curved ruling, we believe a simpler slitless spectrograph design can be achieved.

The initial step towards this concept design is to model the optical properties of curved ruling varied-line-space transmission gratings. As such, the goal of this study is to develop a software code for modeling this type of grating, in cooperation with the Smithsonian Astrophysical Observatory (SAO).

## SUMMARY

We have decided on an analytical approach for modeling the focusing CAT grating performance by raytracing with a custom developed module for the Zemax raytracing software. A simpler version of the grating will also be modeled in PCGrate® to verify the Zemax ray-tracing results. The actual software development is ongoing at the time of this report.

**PRINCIPAL INVESTIGATOR:** Ken Kobayashi

**PARTNER:** Smithsonian Astrophysical Observatory

**FUNDING ORGANIZATION:** Science Mission Directorate

# The Chandra X-ray Observatory

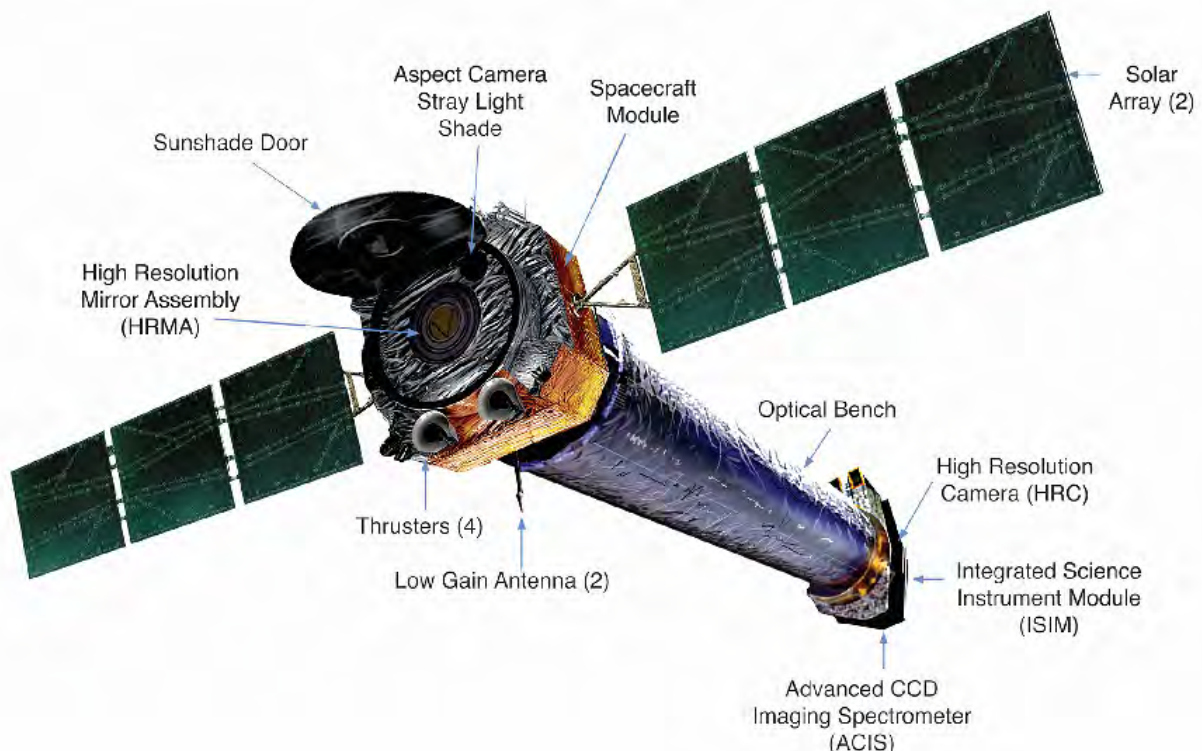
**OBJECTIVE:** *To make fundamental scientific discoveries and contribute to our understanding of the universe.*

## PROJECT DESCRIPTION

The Chandra X-Ray Observatory, one of NASA's Great Observatories, was launched on July 23, 1999. Its unique ability to provide high resolution, subarcsec x-ray images and high-resolution spectra have established it as one of the most versatile and powerful tools for astrophysical research in the 21st century. Chandra explores the hot, x-ray-emitting regions of the universe, observing sources with fluxes spanning more than 10 orders of magnitude, from the x-ray brightest, Sco X-1, to the faintest sources in the Chandra Deep Field surveys. Thanks to its continuing operational life, the Chandra mission also provides a long observing baseline, which is opening new research opportunities. Chandra observations have contributed to all areas of astronomy and astrophysics, including but not limited to deepening our understanding of the coevolution of supermassive blackholes and galaxies, the details of blackhole accretion, the nature of dark energy and dark matter, the details

of supernovae and their progenitors, the interiors of neutron stars, the evolution of massive stars, and the high-energy environment of protoplanetary nebulae, and even the interaction of an exoplanets with their stars.

The key to Chandra's success is the great advance in angular resolution. The mirrors produce images with half-power-diameter  $\approx 0.5$  arcsec for x-ray energies in the range  $0.08 < E < 10$  keV. This angular resolution represents a 10-fold improvement over the two previous best x-ray telescopes, the U.S.-led Einstein X-Ray Observatory (1978–1981) and the German-led Röntgensatellit (ROSAT, 1990–1999). The 10-m focal length, high-resolution mirror assembly (HRMA) consists of four nested pairs (paraboloid-hyperboloid), grazing-incidence, glass-ceramic mirrors coated with iridium to enhance their reflectivity at x-ray wavelengths. The observatory's highly eccentric orbit makes possible continuous observations of up to  $\approx 185$  ks with an observing efficiency ranging from 65% to



**FIGURE 1.** Chandra X-ray Observatory showing major elements. Image credit: James Vaughan/CXC.

75%. The efficiency is limited primarily by the need to protect the instruments from particles, especially protons, during Chandra's passages through Earth's radiation belts.

The observatory (Fig. 1) consists of three principal elements:

- (1) the telescope comprised of the HRMA, two x-ray transmission gratings that can be inserted into the x-ray path, and a 10-m-long optical bench;
- (2) a spacecraft module that provides electrical power, communications, and attitude control; and
- (3) a Science Instrument Module that holds two focal-plane cameras, the advanced charged-coupled device (CCD) imaging spectrometer (ACIS) and the high-resolution camera (HRC), and mechanisms to adjust the camera's position and focus. The observatory is 13.8 m in length, has a mass of 4,800 kg, and the furthest ends of its solar panels are 19 m apart.

## ACCOMPLISHMENTS

The project team accomplished the following in Fiscal Year 2019:



**FIGURE 2.** NASA's Chandra X-ray Observatory 20th Anniversary Collection: Six images of different objects representing the breadth of Chandra science.

- celebrated its 20th anniversary of successful launch and operation on July 23, 2019. (see Figure 2 for image release).
- received 515 General Observer proposals this year from 26 countries requesting including the USA with a factor of 5× more observing time than available.
- continued a steady rate of ≈450 publications in refereed journals per year.
- released 15 science press releases between
- October 1, 2018 and September 30, 2019 (see selected image Fig. 3).

## SUMMARY

The Chandra X-ray Observatory, now in its 21st year of operation, continues to be an indispensable tool for furthering NASA's strategic science goal of expanding the frontiers of knowledge in space. No other observatory has Chandra's capability for high-resolution x-ray imaging of cosmic sources on a sub-arcsecond scale, a critical feature for multiwavelength investigations ranging from planetary atmospheres to clusters of galaxies.

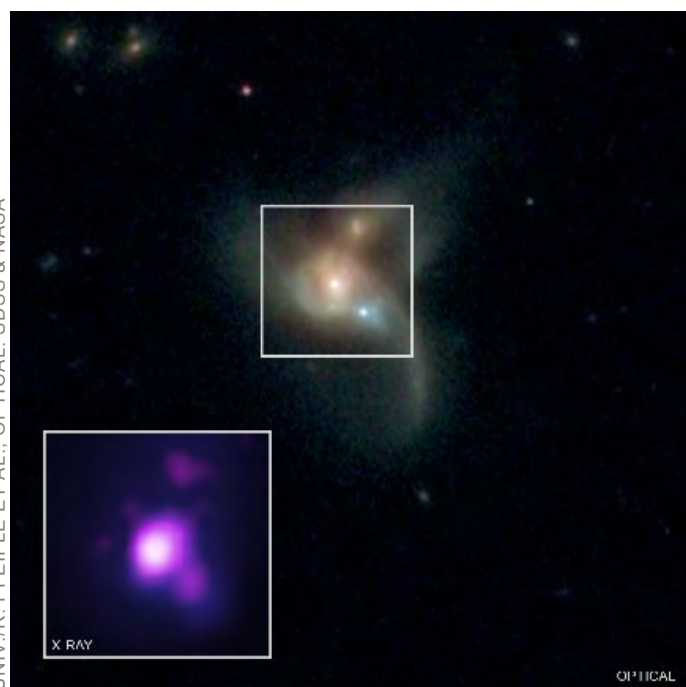
### PROJECT MANAGER AND/OR PRINCIPAL

**INVESTIGATOR:** Martin C. Weisskopf, Project Scientist

**PARTNER:** Chandra X-ray Center, Cambridge Massachusetts

**FUNDING ORGANIZATION:** Science Mission Directorate

**FOR MORE INFORMATION:** <https://chandra.cfa.harvard.edu>



**FIGURE 3:** Black Hole Triplet, a study using data from Chandra and other telescopes provides the strongest evidence yet for supermassive black holes on a collision course.

CREDIT: X-RAY: NASA/CXC/GEORGE MASON UNIV./R. PFEIFLE ET AL.; OPTICAL: SDSS & NASA



# SmallSat Exosphere Explorer of Hot Jupiters (SEEJ)

**OBJECTIVE:** *To measure the extent of exoplanets' atmospheres via measurement of the depth, width and shape of the exoplanet transit x-ray light curve.*

## PROJECT DESCRIPTION

SmallSat Exosphere Explorer of hot Jupiters (SEEJ) will advance our understanding of the physical processes that drive the strong interactions between the outer atmospheres of exoplanets and the coronae of their stellar hosts. Specifically, the SEEJ investigation will determine to what extent stellar high-energy photon fluxes inflate nearby exoplanet atmospheres. The investigation will also determine the bulk composition of the inflated atmosphere and will assess the presence of dense evaporation tails resulting from this interaction. Flux from the star itself is critical to the atmosphere of the planet. Specifically, X-rays can induce both life-enabling and life-threatening photochemistry in planetary atmospheres. Similarly, observed X-ray flares may be harbingers of coronal mass ejections which can aid the development of life by removing primary, hydrogen-dominated atmospheres or threaten its existence by depleting secondary atmospheres.

## ACCOMPLISHMENTS

SEEJ's science objectives will be accomplished using revolutionary Miniature X-ray Optics (MiXO), manufactured at NASA Marshall Space Flight Center (MSFC), that provide near-Chandra collecting area in a low-mass, small-volume, and low-cost package. SEEJ will observe scores of transits of select systems to make detailed measurements of the transit depth and shape which can be compared to out-of-transit behavior of the target system. SEEJ will orbit at an estimated orbit of GEO+10,000 km to mitigate the risk associated with background radiation interfering with the science goals.

SEEJ offers a unique opportunity to study stellar cycles using X-rays in much greater detail and much larger numbers than currently possible. A dedicated X-ray telescope for performing prolonged monitoring observations has never flown.

SEEJ is currently in the final stages of development awaiting the release of the next



FIGURE 1. SEEJ Concept Cutaway Spacecraft Design.

Astrophysics Explorers Mission of Opportunity or comparable NASA solicitation. Ongoing activities include: (a) the revision of the science case in light of the actual targets discovered by TESS and other explorations; (b) expansion of the science team to include more exoplanet specialists; (c) continued investigation and development of detectors at SAO including an investment of internal funds; and (d) completion of funding requirement estimates.

MSFC and Smithsonian Astrophysical Observatory (SAO) performed a comprehensive analysis of all aspects of the SEEJ mission. The results were compiled by SAO in the 2018 Research Opportunities in Space Science Astrophysics Science SmallSat Studies (Awarded Study Contract #18-AS318-0025). These results were reported to NASA Headquarters in both oral and written reports.

## **SUMMARY**

The discovery of exoplanets has fundamentally changed our perception of the universe and humanity's place within it. The first and most easily detected exoplanets were 'hot Jupiters' which are large Jupiter-like planets in close orbits around their host star. For stars with significant x-ray emission, the x-ray flux can alter the structure of the upper atmosphere of the planet, potentially blowing it away. In turn, the angular momentum and magnetic field of the planet may induce even more activity on the star, further enhancing its x-ray emission. X-ray absorption during a transit acts as a unique and valuable probe of the planetary exosphere. SEEJ will advance our understanding of the physical processes that drive the strong interactions between the outer atmospheres of exoplanets and the coronae of their stellar hosts.

**PRINCIPAL INVESTIGATOR:** Mark Stahl, MSFC, and Scott Wolk, Smithsonian Astrophysical Observatory

**FUNDING ORGANIZATION:** Science Mission Directorate



# Global Hydrology Resource Center Migrates its Operations to the Cloud

**OBJECTIVE:** To migrate Earth science data active archive center's data, services and operations to commercial cloud without disrupting existing day-to-day operations.

## PROJECT DESCRIPTION

The current infrastructure of the NASA's Earth Observing System Data and Information System (EOSDIS) will not be able to sustain the annual ingest rate increases from 4 to 50 PB/year due to upcoming large missions (Fig. 1). It will become increasingly difficult and expensive to maintain and improve current system as data volumes and processing demands continue to increase exponentially. This anticipated growth in both the EOSDIS data ingest rate as well as the overall archive volume pose new challenges for distributing and analyzing data that currently are stored and disseminated through physical servers on-premises at EOSDIS Distributed Active Archive Centers (DAACs). To address these challenges, EOSDIS is examining the effectiveness of using a commercial cloud to ingest, archive, process, distribute, and manage the anticipated large volumes of new

mission data. Additional benefits of the cloud include collocation of computations and data to enable new science and application of large-scale analytics and create opportunities for innovation around the new services. In addition, the use of a common infrastructure with cloud native services will reduce redundant tools/services, enable sharing, and enforce the use of community standards as well as uniform policies and processes.

The Global Hydrology Resource Center (GHRC), a NASA Marshall Space Flight Center-managed DAAC, has been an integral part of the EOSDIS effort to examine commercial cloud as a solution to the abovementioned challenges. One of the reasons GHRC was selected as the first DAAC to fully migrate to cloud was due to its history of managing data from a wide variety of sources including satellite missions, field campaigns, and science investigators.



FIGURE 1. NASA's operating and upcoming earth science missions.

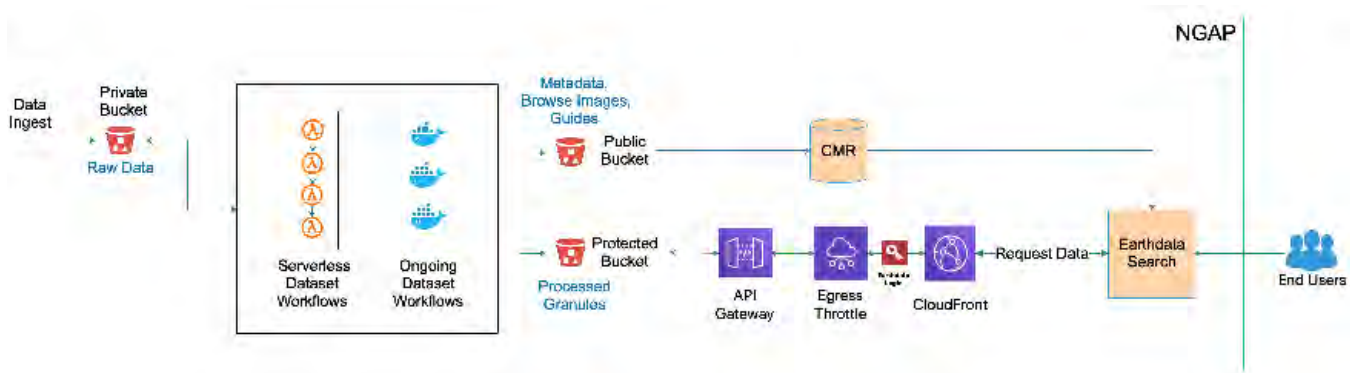


FIGURE 2. A simplified GHRC data publication architecture in the NASA-compliant cloud platform.

## ACCOMPLISHMENTS

In FY 2017, GHRC provided requirements and DAAC expertise for an EOSDIS-developed reusable open source cloud native framework called Cumulus for data ingest, archive, and processing. After a yearlong successful prototype of Cumulus, GHRC was selected to fully migrate to cloud and serve as a pathfinder DAAC. GHRC was involved in providing requirements, planning new features, deploying features, and collaboratively solving issues with the EOSDIS team using the scaled agile framework (SAFe) methodology.

GHRC has fully migrated to the commercial cloud (AWS) on-time and on-budget without disrupting its existing day-to-day operations. All of GHRC data is now being distributed from cloud. GHRC was able to deploy its data publication workflows for backup restoration, ongoing datasets, and upcoming datasets to the NASA-compliant General Application Platform (NGAP), a NASA security compliant platform for hosting EOSDIS applications (Fig. 2). Several members of the GHRC teams are now trained to operate Cumulus hosted in NGAP. Lessons learned as part of the migration has been documented for future DAACs to follow.

## SUMMARY

To address the challenge of managing data from several upcoming large missions, EOSDIS is seeking to utilize commercial cloud. Toward that end, GHRC was selected as the first DAAC to fully migrate to the commercial cloud. At the end of FY 2019, GHRC successfully completed migration of its operations to the cloud on time and on budget. As a result, GHRC began distributing data from the cloud.

**PRINCIPAL INVESTIGATOR:** Manil Maskey

**PARTNER:** University of Alabama in Huntsville

**FUNDING ORGANIZATION:** Science Mission Directorate

# Multi-Mission Algorithm and Analysis Platform (MAAP)

**OBJECTIVE:** To establish a collaboration framework between ESA and NASA to share Earth observation data, algorithms and compute resources in order to foster and accelerate scientific research.

## PROJECT DESCRIPTION

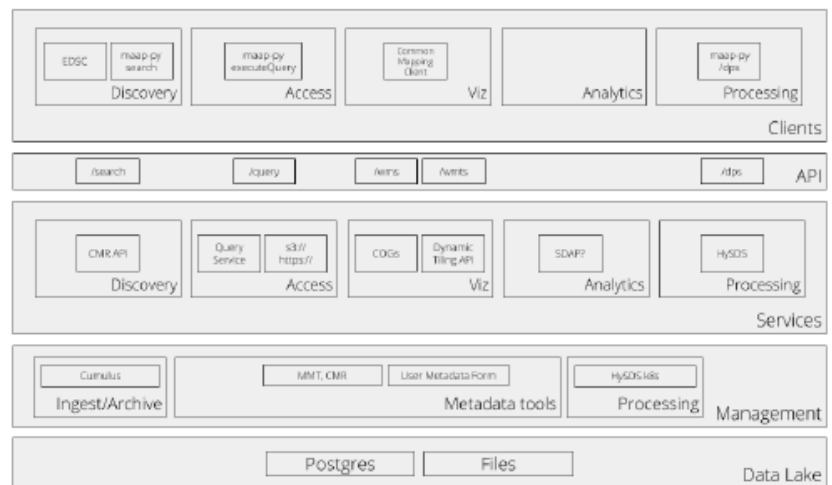
The Multi-Mission Algorithm and Analysis Platform (MAAP) is a collaborative project between NASA and the European Space Agency (ESA). The MAAP will address issues related to increased data volumes from upcoming Earth observation satellite missions and will reinforce open data policies by providing a common platform with compute resources collocated with data as well as a set of tools and algorithms needed to leverage these resources.

The NASA Marshall Space Flight Center (MSFC) MAAP data team supports the MAAP by providing and maintaining a cloud-based data management system. The MSFC team also ensures the ongoing quality of the data, metadata and other information provided in the MAAP.

## ACCOMPLISHMENTS

The MAAP data team is contributing three major innovative approaches to the MAAP project. These approaches include:

- (1) Reusing a data management and stewardship system on the cloud and providing a template for these types of systems for other scientific domains or research groups. During 2019, the MAAP data team built an end-to-end data management system in the cloud which reused existing open source NASA infrastructure components. The MAAP data team also completed prototyping work for supporting nontraditional data sources such as data which is provided and shared by users. While some aspects of the data management process are occurring on the cloud, this effort represents a major step forward



**FIGURE 1.** The MAAP data systems architecture is built on the cloud. The system supports the data management process for the MSFC data team and also supports the discovery and use of data for MAAP users.

in moving the entire process to the cloud. Next steps for this work include supporting the continuous ingest of data in the cloud and documenting various best practices related to this effort.

- (2) Prototyping Analytics Optimized Data Stores (AODS) for Earth observation research applications. AODS support big data analysis for specific scientific user communities. During 2019, the MAAP data team prototyped AODS by providing data via a queryable data storage in the cloud. AODS represent an opportunity to query large amounts of data at scale and are in their infancy in the Earth sciences. Next steps for this work include developing AODS for a high value dataset in MAAP at which to enable analysis.
- (3) Providing a harmonized information model of rich and connected metadata and documentation. During 2019, the MAAP data team expanded the traditional collection and file-level metadata to support search queries needed for the MAAP community. Linked and connected metadata are often discussed within the community, and

the MAAP's efforts provide an opportunity to demonstrate the benefits of linked information. Next steps for this work include deploying both software and documentation metadata in the MAAP in order to document the data product generation process from end to end.

The pilot MAAP development was completed and successfully demonstrated in September 2019. Interoperability with ESA was achieved through both user authorization/authentication and through data and metadata interoperability. To support the data needs of the pilot MAAP users, the MSFC MAAP data team built an end-to-end data publication and management system on the cloud. The MAAP data management system reuses key open source infrastructure components developed by NASA's Earth Science Data and Information System (ESDIS) including the Common Metadata Repository (CMR), the Metadata Management Tool (MMT), the Earthdata Search Client (EDSC), and Cumulus. Using this cloud-based data management system, the MAAP data team made over 30 key datasets available in the MAAP. These data are made available via Amazon's Simple Storage Service (S3) and are discoverable via robust metadata in the CMR. Information provided in the metadata was expanded by the MAAP data team in order to support the unique search needs of the user community. In addition, data visualization and subsetting services were provided for key datasets.

Lastly, over eight key documents defining key interoperability touchpoints were jointly developed between NASA and ESA to support the pilot MAAP. These documents represent a significant contribution towards working collaboratively together.

## **SUMMARY**

The MAAP is a project between NASA and ESA focused on building a collaboration framework between the two agencies in order to share Earth observation data, algorithms, and compute resources which in turn will foster and accelerate scientific research. The high-level contributions by the MSFC data team to date include:

- An end to end data management and stewardship system on the cloud
- AODS prototype for Earth observation research applications
- Expanded metadata and information to support community search needs.

**PRINCIPAL INVESTIGATOR:** Rahul Ramachandran

**PARTNER:** University of Alabama in Huntsville

**FUNDING ORGANIZATION:** Science Mission Directorate



# Short-term Prediction Research and Transition (SPoRT)

**OBJECTIVE:** To transition unique satellite observations and research capabilities to the operational weather community to improve short-term, regional forecasts.

## PROJECT DESCRIPTION

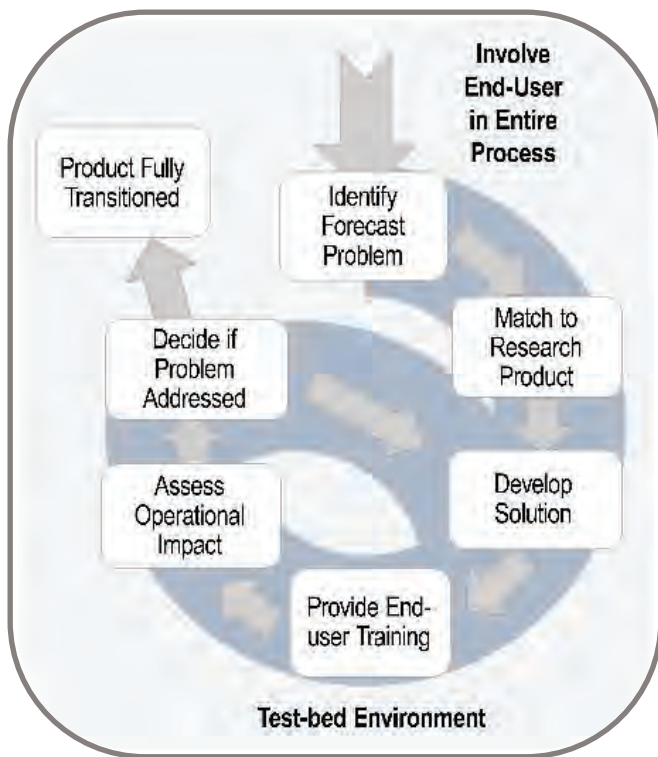
SPoRT is an end-to-end research-to-operations/operations-to-research (R2O/O2R) activity focused on accelerating the use of satellites, nowcasting tools, and advanced modeling and data assimilation techniques to improve short-term weather forecasts. SPoRT partners with universities and other government agencies to obtain near real-time (NRT) data, develop new products, and obtain operational perspective to increase the likelihood of adoption by the operational weather community.

## ACCOMPLISHMENTS

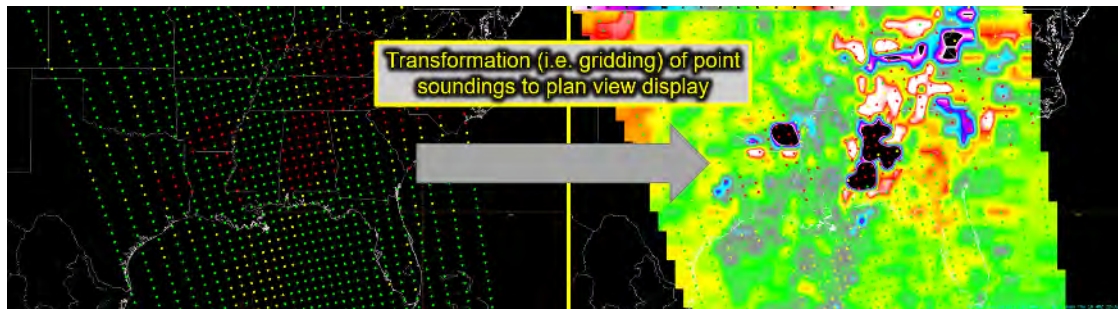
SPoRT incorporates the end user throughout an iterative R2O/O2R feedback process (Fig. 1) by identifying a forecast challenge, incorporating a potential solution into the user's decision support

system (DSS), providing training on use of the product, and assessing the product's impact on their decision-making process. Product iterations continue until a solution is used in regular forecast operations. Collaborative relationships between SPoRT enable honest feedback on product and training value resulting in lasting operational impact of new data products. Often, this feedback includes suggested product changes that lead to significant improvements, increased use of the product, and additional opportunities for research and development. Assessment reports published for the broader community communicate successful product transitions.

SPoRT has been part of a collaborative effort within the Joint Polar Satellite System (JPSS) Proving Ground Sounding Initiative to develop the capability for 2D display of satellite soundings in the NOAA National Weather Service (NWS) decision support system (AWIPS). Cross-track Infrared Sounder/Advanced Technology Microwave Sounder (CrIS/ATMS) temperature and moisture soundings are processed through the NOAA Unique Combined Atmospheric Processing System (NUCAPS) and are good quality in clear-to-partly cloudy regions, but soundings are poor quality where cloud cover is over 85% and when precipitating conditions exist. Currently, NWS offices receive NOAA-20 CrIS/ATMS NUCAPS soundings through the Satellite Broadcast Network for display as vertical soundings and Gridded NUCAPS is the capability to process and view these data horizontally and vertically (Fig. 2). Until now, Gridded NUCAPS has been pre-processed at SPoRT and provided experimentally to Alaska Region NWS offices and the Hazardous Weather Testbed. The team worked with NOAA/CIRA/MDL to create an AWIPS plug-in to grid the soundings upon arrival and ingest in AWIPS. Gridded NUCAPS has been a successful multiorganizational collaborative R2O/O2R project for SPoRT.



**FIGURE 1.** Graphical representation of the SPoRT unique R2O/O2R paradigm



**FIGURE 2.** Left: NOAA-20 CrIS/ATMS NUCAPS sounding availability in AWIPS and right: Gridded NUCAPS plan view display of 700 mb lapse rates. Demonstrates the NUCAPS soundings are gridded for plan view and cross section display.

SPoRT is currently an early adopter for the The Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) satellite, which is a NASA Earth Venture Mission designed for observing tropical cyclones due to launch in 2021. TROPICS presents a unique opportunity in hurricane remote sensing though an unprecedented combination of horizontal and temporal resolution: This mission is expected to provide nearly all-weather observations of 3D temperature and humidity, as well as cloud ice and precipitation horizontal structure, at a mean refresh rate of 30 min. NASA SPoRT is currently assessing the capabilities and applications of the mission with synthetic TROPICS data. Proxy data are designed to mimic the resolution, format, and accuracy of an anticipated project and provide a way to evaluate the potential value of a mission prior to launch.

NASA SPoRT has a long history of creating state-of-the-art multispectral (red, green, blue (RGB)) imagery derived from both polar-orbiting and geostationary imagers RGB imagery is provided to forecasters to allow them to visualize different types of meteorological phenomena and hazards that are sometimes not readily apparent in single channel imagery. Two of the multispectral composites analyzed by forecasters include dust and nighttime microphysics, the latter of which allows for the detection of low clouds and fog. Both blowing dust and fog events can produce a substantial

reduction in visibility, yielding a significant hazard to motorists. As an extension to these products, SPoRT is utilizing machine learning methods to determine if these hazards can be quantitatively identified in remote sensing observations, giving forecasters a probability on whether each pixel contains a certain hazard. This new development can then be used along with the RGB to aid in more accurate visual classification and interpretation.

## SUMMARY

SPoRT is a highly successful project that conducts world-class research and transition activities, with a model that is both sustainable and able to grow with new opportunities. Through collaboration with university and government partners, SPoRT has successfully transitioned value-added observations and capabilities from recently-launched satellites to weather forecasters. These accomplishments further SPoRT's vision to be a 'go-to' project in the applied research community to accelerate the use of next-generation satellite datasets into the operational weather community.

**PRINCIPAL INVESTIGATOR:** Christopher Hain

**PARTNERSHIPS:** NOAA/NWS

**FUNDING ORGANIZATION:** Science Mission Directorate

**FOR MORE INFORMATION:** <https://weather.msfc.nasa.gov/sport/>; <https://nasasport.wordpress.com/>

# Predictive Thermal Control Technology for Stable Telescopes

**OBJECTIVE:** To mature active thermal control technology to enable ultrastable UV to far-infrared (UVOIR) space telescopes.

## PROJECT DESCRIPTION

Exoplanet science via coronagraphy requires ultrastable telescopes for multiple-hour exposures. Predictive Thermal Control Study (PTCS) matures technology to enable active thermally controlled ultra-stable telescopes required to make ultra-high contrast observations of exoplanets.

## ACCOMPLISHMENTS

PTCS HAS THREE OBJECTIVES:

- (1) To validate models that predict thermal optical performance of real mirrors and structures based on their designs and constituent material properties, i.e. coefficient of thermal expansion (CTE) distribution, thermal conductivity, thermal mass, etc.;
- (2) to derive thermal system stability specifications from wavefront stability requirements; and,
- (3) to demonstrate ability of a predictive thermal control thermal system to actively/predictively stabilize a mirror system's thermal environment.

TO ACHIEVE THESE OBJECTIVES, PTC HAS FIVE QUANTIFIABLE MILESTONES:

- (1) To develop a high-fidelity model of the 1.5-m ULE® AMTD-2 mirror;
- (2) to derive specifications for thermal control system as a function of wavefront stability;
- (3) to design and build a predictive thermal control system for a 1.5-m ULE mirror that senses temperature changes and actively controls the mirror's thermal environment;
- (4) to validate high-fidelity model by testing the 1.5-m ULE AMTD-2 mirror in a relevant thermal vacuum environment at the MSFC X-ray and Cryogenic Facility (XRFC) test facility; and
- (5) use validated model to perform trade studies to optimize primary mirror thermo-optical performance as a function of mirror design, material selection, material properties (i.e., CTE) mass, etc.

Previously, PTCS successfully completed goal 1 by accomplishing milestones 1 and 4. In FY 2019, PTCS successfully completed goal 2 by developing

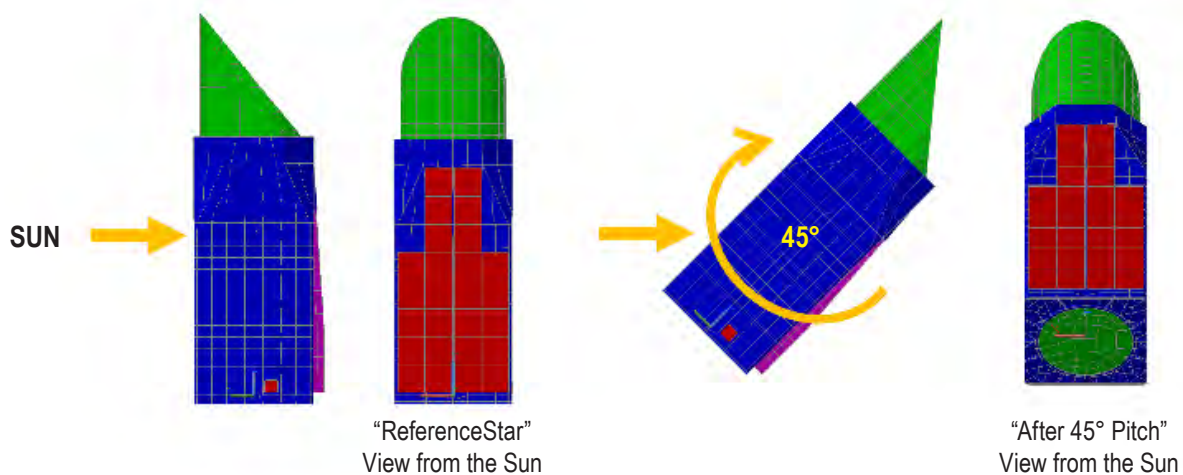
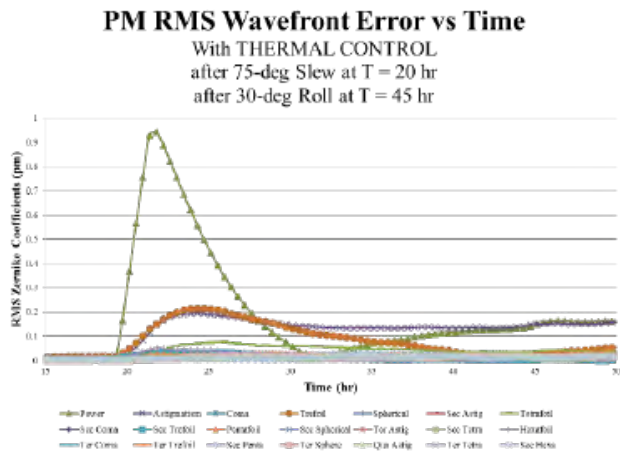


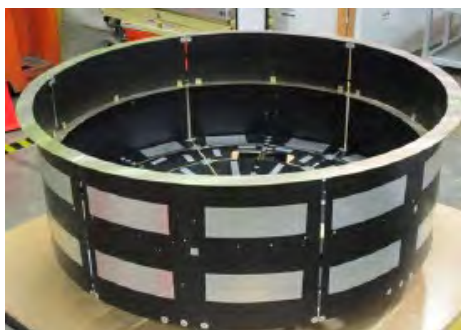
FIGURE 1. Habitable Exoplanet Observatory nominal observing scenario slew for thermal analysis.



**FIGURE 2.** Primary Mirror wavefront error after thermal slew with active zonal thermal control.

a process for defining telescope thermal stability specifications (all Zernike polynomial wavefront error terms need to be less than 2 picometers – except for power, which can be up to 550 pm), and performing trade studies of candidate primary mirror assembly designs, for potential Habitable Exoplanet (HabEx) Observatory study design reference mission (Figure 1), that meet the HabEx thermal-optical performance specification (Fig. 2).

Finally, in FY19 PTCS progressed goal 3 by taking delivery from PTCS Partner Harris Corporation a thermal enclosure with 37 control zones (Fig. 3). Currently the enclosure is being integrated with the PTC control electronics and software and will be tested in FY20 using the 1.5-m AMTD-2 ULE mirror.



**FIGURE 3.** Thermal control system with 37-zone control for AMTD-2 1.5-m ULE© mirror.



**FIGURE 4.** 1.2-m aluminum test mirror.

Because the thermal enclosure prevents direct illumination from the solar lamps, STOP analysis predicts that the 1.5-m ULE mirror—when integrated in the enclosure—will experience only a 7.5 nm rms figure change without thermal control; and, with thermal control this change is reduced to 1.5 nm rms. Therefore, PTCS is procuring a 1.2-m aluminum mirror to serve as a pathfinder test article (Fig. 4). Since aluminum has a larger CTE than ULE, it is expected to provide a 2× larger signature, which can be used to test the PTC control algorithm.

## SUMMARY

PTCS is a multi year effort to mature TRL of technologies needed to enable ultrathermally-stable ultraviolet/optical/infrared (UVOIR) space telescope primary-mirror assemblies for ultrahigh-contrast observations of exoplanets.

**PRINCIPAL INVESTIGATOR:** H. Philip Stahl

**CO-INVESTIGATOR:** Thomas Brooks

**PROJECT MANAGER:** Michael Effinger


**PARTNER:** Harris Corporation

**FUNDING ORGANIZATION:** Science Mission Directorate

# Lightning Imaging Sensor (LIS)

**OBJECTIVE:** *To place a Lightning Imaging Sensor (LIS) on the International Space Station (ISS) to observe global lightning.*

## PROJECT DESCRIPTION



Since 1995, the NASA Marshall Space Flight Center, the University of Alabama in Huntsville, and their partners have developed and demonstrated the effectiveness and value of space-based lightning observations as a remote sensing tool for Earth science research and applications, and in the process, established a robust global lightning climatology free from significant bias. The Lightning Imaging Sensor (LIS) on the Tropical Rainfall Measuring Mission (TRMM) provided global observations of tropical lightning for an impressive 17 years before that mission came to a close in April 2015. Placing an LIS on the International Space Station (ISS) continues the cross-disciplinary, high-value science begun with TRMM LIS and its Optical Transient Detector (OTD) predecessor by creating the opportunity to extend the LIS time series observations, expand coverage to the climatically important mid-latitudes, provide real-time data to operational users, and enable cross-sensor calibration and synergistic observations with other lightning systems. A major science focus of this mission remains to better understand the processes which cause lightning, as well as the connections between lightning and subsequent severe weather events. This understanding is a key to improving weather predictions and saving lives and property here in the United States and around the world.

## APPROACH/INNOVATION

The LIS operating on the ISS is an exact copy—the backup flight space in fact—of the LIS that operated flawlessly for an impressive 17 years on the TRMM mission. To get to the space station, LIS was integrated as a hosted payload on the Department of Defense Space Test Program-Houston 5 (STP-H5) mission, and launched from NASA's Kennedy Space Center to the ISS on 19 February 2017, aboard the SpaceX Cargo Resupply Services-10 (CRS-10) flight. After arriving at the ISS, a robotic installation placed STP-H5 with LIS in a nadir viewing location on the outside of the space station. From its space station vantage point, LIS continuously measures the amount, rate and radiant energy of lightning that occurs within its field-of-view both night and day as it orbits the Earth. It is important to note that its ability to detect lightning during the day is especially unique and scientifically important, since more than 60% of the Earth's lightning occurs during the day. To do this, LIS uses a narrowband near infrared channel and special processing to pull the weak daytime lightning signal from the strong solar background reflected from the cloud tops.

The LIS data handling involves a close partnership between the LIS science team and the Global Hydrology Resource Center (GHRC), one of NASA's Distributive Active Archive Centers (DAAC). The well-established and robust processing, archival, and distribution infrastructure used for TRMM was adapted to the ISS mission to assure that high-quality lightning observations from LIS on ISS can be quickly delivered to science and applications users once routine operations are established.

## ACCOMPLISHMENTS

The LIS has been continuously acquiring global lightning observations since it first powered up on 27 February 2017. Comparisons of the LIS data with observations from three independent reference lightning systems (two from long-range, ground-based networks, one from the new Geostationary Lightning Mapper that traces its heritage to LIS technology) have established that LIS on ISS is working as well as its predecessor on TRMM. Figure 1 shows the annual global lightning flash rate density (Flashes  $\text{km}^{-2} \text{yr}^{-1}$ ) from LIS on ISS during its first two years on orbit. This climatology agrees closely with results from the prior two missions. For the first time since the OTD mission ended in 2000, LIS now observes mid-latitude storms from space, and provides coverage of the full continental United States and Middle and Southern Europe.

## SUMMARY/CONCLUSION

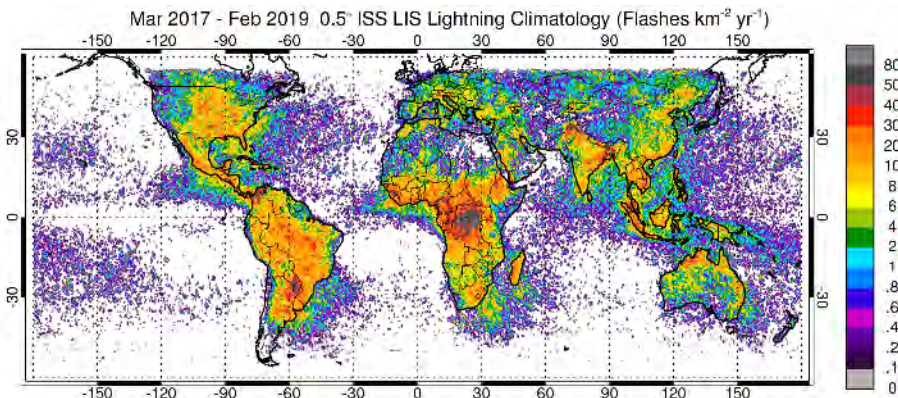
Now into its third year of operation, the LIS on ISS continues to support high-value science and applications activities. In March 2020, project will seek an additional mission extension via the NASA Senior Review process.

**PRINCIPAL INVESTIGATOR:** Richard J. Blakeslee

**PARTNER:** University of Alabama Huntsville

**FUNDING ORGANIZATIONS:** ISS Program Office (preparation, launch and integration), Science Mission Directorate Earth Science Division (mission and science operations)

**FOR MORE INFORMATION:** <https://lightning.nsstc.nasa.gov/index.html>



**FIGURE 1.** Annual global lightning flash rate density during the first two years on orbit. Dashed lines represent the limit of TRMM observations.

# Scintillation Prediction Observations Research Task (SPORT)

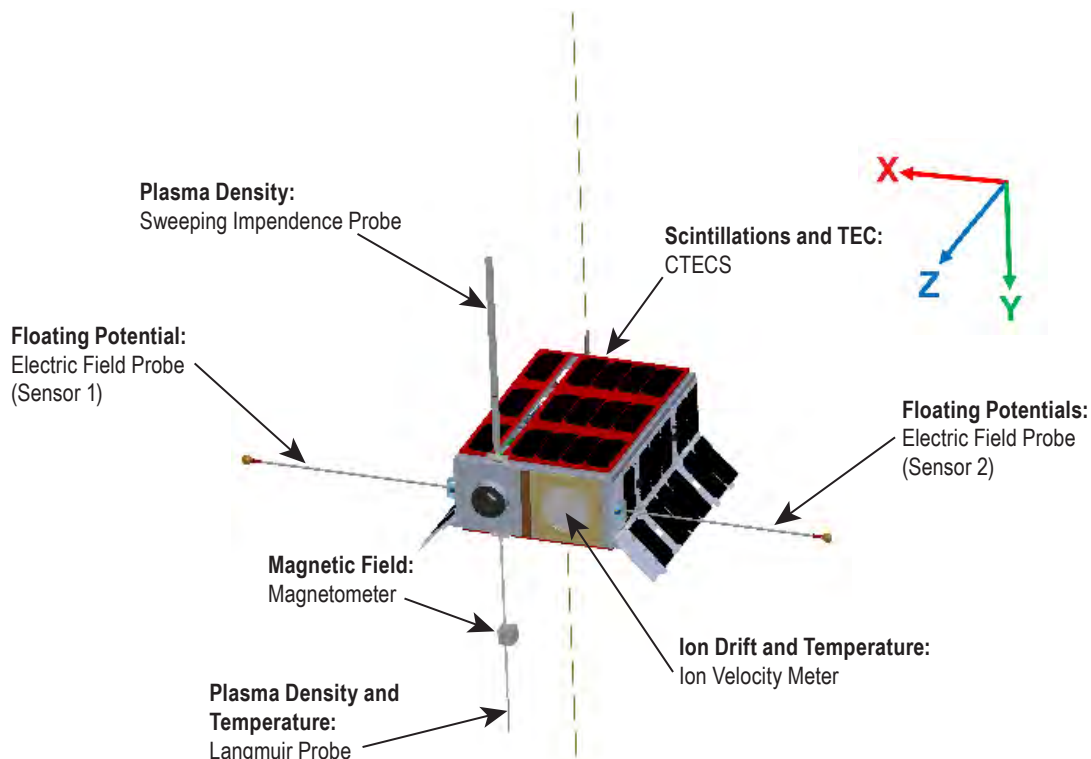
**OBJECTIVE:** *To discover the space weather drivers of ionospheric radio wave scintillation associated with equatorial plasma bubbles.*

## PROJECT DESCRIPTION

The Scintillation Prediction Observations Research Task (SPORT) is a 6U CubeSat satellite mission designed to investigate space weather effects on space-based radio systems. Solar and geomagnetic storms cause the ionosphere to become a turbulent plasma, similar to turbulent water in a Jacuzzi®. Just as turbulent water distorts an optical image, turbulent ionospheric plasma disrupts radio waves as they attempt to propagate through the disturbed medium. The resulting scintillation of ionospheric radio waves routinely causes outages in communication and navigation systems; thus, it is imperative to predict them. The joint U.S.-Brazilian SPORT mission is dedicated to advancing NASA's capabilities in forecasting these ionospheric scintillations.

## ACCOMPLISHMENTS

The SPORT satellite is being developed to fly in circular low Earth orbit at an altitude of  $\approx 400$  km and an inclination of  $52^\circ$  for a nominal 1-year mission lifetime. The satellite is instrumented with the latest space environment sensors available to date. Plasma densities and temperatures, along with electric fields, will be measured by the Utah State University Space Weather Probes. Ion velocities and temperatures will be measured by the Ion Velocity Meter (IVM) developed by the University of Texas at Dallas. Remote sensing of electron density profiles, as well as total electron content and scintillation values on-orbit, will be provided by Compact Total Electron Content Sensor (CTECS) developed by the Aerospace Corporation. Precise 3-axis magnetic fields will be measured by the magnetometer provided by NASA Goddard Space Flight Center (GSFC). Brazilian scientists and



colleagues will provide ground-based observations of the ionosphere, including radio sounding and airglow optical imaging.

By analyzing these data together in a holistic manner, the SPORT Science team will discern the variations in electron densities in the ionosphere. The spatial and temporal scales under investigation are appropriate for studying the effects of irregularities specifically affecting VHF and L-band radio signals. These signals are particularly susceptible to scintillation during solar and/or geomagnetic activity. This investigation will study the statistical distribution of equatorial plasma bubbles as a function of longitude and local time, in addition to seeking the precursor trigger mechanisms for such bubbles.

When developing a satellite with multiple science instruments from multiple institutions, it is imperative that the team tests the communication between the three satellite on-board processors (Payload Data Handling (PDH), Spacecraft Command and Data Handling (CD&H), the Data Storage Unit (DSU)), and all of the instruments. This was accomplished for the SPORT mission during 2019. The so-called ‘Flatsat’ configuration was comprised of the spacecraft processors (avionics) and all of the instruments (note that the IVM consisted of a flight emulator, all other instruments were actual flight-like components) connected together on a clean bench. Command and data handling was tested for all instruments in two campaigns—one where each instrument was tested individually, and the other where all instruments were tested together. Initially, all systems were tested successfully with one exception—the PDH processor failed to accommodate the large volume and rate of data from the CTECS instrument. The team was able to adequately capture the CTECS data by directly linking the instrument with the DSU processor instead of the PDH. Now that the Flatsat testing is complete, the SPORT satellite is considered to be a developmental model.

In August of 2019, the SPORT team underwent a rigorous critical design review. The independent review team did not identify any major findings (i.e., major weaknesses) of the mission development, but it did provide recommendations, concerns, and comments. For example, the attitude

determination and control system (ADCS) modeling and simulation routines need to be updated to incorporate potential feedback of the flexible structures onto the spacecraft body while in orbit. Additionally, it was recommended that the SPORT team explore options for post-processing of star-tracker data on the ground to improve the precision of the attitude determination data. Finally, some recommendations for improvement on the thermal modeling, especially for best- and worst-case scenarios, were provided. These and additional post-CDR activities will be the focus of the work in 2020 as the SPORT team works toward a delivery in early 2021.

## SUMMARY

SPORT is a joint U.S.-Brazilian CubeSat mission to investigate equatorial ionospheric plasma bubbles and associated scintillation on radio signals known to cause outages in communication and navigation systems. By employing the state-of-the-art space weather instruments in space as well on the ground, the SPORT team will use observational data with expert models to advance the ability to forecast space weather effects on these systems. With a 2021 launch, the mission will demonstrate the ability to use a lost-cost mission to do world-class science.



**PRINCIPAL INVESTIGATOR:** James Spann

**DEPUTY PRINCIPAL INVESTIGATOR:** Charles Swenson, Utah State University

**PROJECT MANAGER:** Shelia Nash-Stevenson

**PARTNERS:** Instituto Tecnológico de Aeronáutica; Instituto Nacional de Pesquisas Espaciais, Utah State University, University of Texas at Dallas, University of Alabama at Huntsville, The Aerospace Corporation, and GSFC.

**FUNDING ORGANIZATION:** Science Mission Directorate

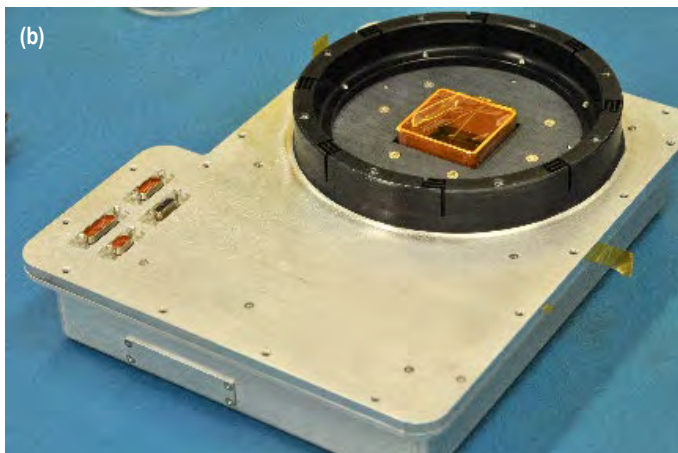
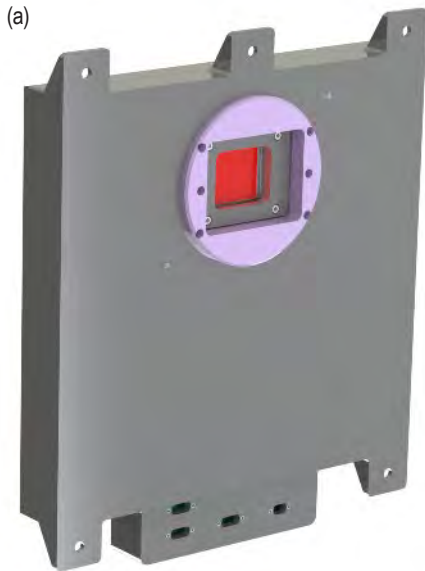
# Low-Noise Extreme Ultra Violet Charge-Coupled Device Camera for the International Space Station: NASA Marshall Space Flight Center Risk Reduction Activity

**OBJECTIVE:** To complete the design modification of the NASA Marshall Space Flight Center (MSFC) Heliophysics sounding rocket charge-coupled device (CCD) camera for use in the COSIE International Space Station (ISS) instrument.

## PROJECT DESCRIPTION

NASA Marshall Space Flight Center (MSFC) has designed, tested, and flown a series of charge-coupled device (CCD) cameras on Heliophysics Sounding Rockets. These cameras are for use in solar extreme ultra violet (EUV) imaging and have

very low noise levels on the order of 10 electrons per pixel per image, enabling high signal-to-noise scientific research. This project sought to modify the existing TRL9 design into one that was suitable for a proposed



**FIGURE 1.** (a) New camera design and (b) Hi-C sounding rocket camera.

instrument, COSIE (Coronal Spectrographic Imager in the EUV), an external ISS solar telescope. Approximately 2 years were needed to design, build, and test a modified camera to achieve TRL6 for this application. This project provided funding for the first project year, which covered design and initial procurement of electronic components. The primary design changes consisted of thermal modifications to allow cooling by radiator instead of liquid nitrogen ( $LN_2$ ), electrical changes for improved radiation tolerance, and redesign of the mechanical housing necessitated by the electrical and thermal changes.

Science-quality cameras for similar applications do exist, but due to customization needs, they can be cost-prohibited for smaller projects of the order of NASA Science Missions Directorate Low Cost Access to Space and Mission of Opportunity solicitations. By completing this work at MSFC, we enable extremely high quality scientific returns with the ability to customize a camera for our needs. In-house work enables the scientific team to work closely with the engineering team to modify the design and/or the requirements in a cost-effective and agile way.

## ACCOMPLISHMENTS

All three design components—thermal, mechanical, and electrical—were worked in parallel, with the main driver of change being thermal performance and stability. To achieve our low-noise requirements, our CCD has to be cooled to  $-55\text{ }^\circ\text{C}$  or lower. External instruments on the ISS face very dynamic thermal conditions due to the constantly changing positions of multiple large sources thermal radiation, namely the Sun, Earth, and the ISS itself. Furthermore, even small changes in the camera

design can dramatically change the head load on the radiator. To work effectively, we designed several thermal models that rely on a set of carefully calculated transient boundary conditions so that we could easily tweak the internal system and re-run with the models with the known boundary conditions with a short turnaround time.

Several important design changes were made as a consequence of the thermal environment. The sounding-rocket dual electrical boards were substituted for a single board with strategic internal thermal breaks to minimize internal radiative and conductive heat transfer. The camera chassis was designed to be a de-facto radiator for the electrical components, allowing the primary radiator to cool a largely thermally isolated CCD sensor.

Electrical work included exchanging parts that had known radiation tolerance when available, and changes related to having a single electronic board instead of two separate boards. The board was optimized with the previously stated thermal breaks while maintaining appropriate ground planes and noise-reduction measures.

We have completed the design of the camera including CAD models, preliminary drawings, a thermal report, and we have all of the components necessary to create the electrical boards. We expect that approximately 1 year is needed from this point to fabricate and test the camera in a thermal-vacuum chamber for camera and thermal performance. While designed for a specific instrument, this camera can be tailored to a range of scientific space-based instruments, and we are exploring several applicable future projects. The thermal models and report include the detailed analysis of the ISS thermal environment, which will be directly applicable to any future proposal for a radiatively cooled instrument at those ISS mounting locations.

The process of working all three engineering design elements simultaneously instead of in series allowed us to explore more options and move forward

swiftly with any potential design changes. The ability to have a modular thermal model with easily access boundary conditions allowed us to rapidly test any modifications, which was key to keeping on schedule. These thermal models have a longer initial setup time, but once that framework is complete, rerunning a model is extremely quick. Our biggest sources of uncertainty resulted from working independently on an instrument subsystem before the interfaces were fully designed; the internal funding allowed our team to progress with the camera during the mission proposal phase.

## **SUMMARY**

MSFC has successfully built and flown a series of low-noise Heliophysics cameras in suborbital sounding rockets. We are now in the process of modifying that camera to operate in space on longer missions. We have completed the initial design to modify the camera for use in an external ISS environment with radiation tolerant components and a passively cooled CCD. The camera design is being used in current and future proposals for space-based Heliophysics missions.

**PRINCIPAL INVESTIGATOR:** Laurel Rachmeler

**PARTNER:** Smithsonian Astrophysical Institute

**FUNDING ORGANIZATION:** Center Strategic Development Steering Group



# Ultralow Density Aerogel Mirrors

**OBJECTIVE:** *To potentially yield ultra-lightweight space-borne reflective optics for spaceborne applications.*

## PROJECT DESCRIPTION

The project aims to investigate the use of aerogels and high-strength aerogel composites as replicated mirror substrates for thin film reflective coatings; thus, potentially yielding unprecedented ultralight weight mirrors for spaceborne applications.

The term aerogel, which is somewhat misleading, refers to the dry, solid, mesoporous (i.e. nanoscale porosity) framework that remains after careful extraction of the liquid component of a gel. A chemical mixture of precursors yields a colloidal system of nanoparticles, called a sol. The replication of aerogels is possible by allowing the mixture to gel in a mold fabricated to a desired shape (similar to molding Jell-O®). If the gel is removed from the mold and exposed to atmosphere, over time, the capillary stress caused by the evaporation of the gel's liquid component would collapse the delicate framework of silica nanoparticles, causing it to shrink, densify, and lose its intended shape. Instead, a clever thermodynamic process called supercritical drying enables the removal of the gel's liquid components without collapsing the delicate framework of silica nanoparticles. The drying process utilizes an autoclave to heat and pressurize the liquid phase of the gel past its critical point. There, the liquid changes phase to become a supercritical fluid in a regime of thermodynamic conditions where capillary stress does not exist. Isothermal depressurization at the critical temperature transforms this supercritical fluid directly to a gas. This process leaves the delicate solid 'skeleton' of the remaining network of silica nanoparticles intact, while air (or vacuum) occupies the remaining 95%–99% of the aerogel's volume, resulting in an ultra-low density solid (i.e.,  $\rho \approx 0.1\text{--}0.5\text{ g/m}^3$ ). Silica aerogels have heritage in space as an insulating material for the Mars rover and used for capturing tiny cometary samples and interstellar dust aboard the NASA Stardust spacecraft. Silica aerogels have high compressive strength for their weight but are much more brittle

than ordinary glass—an undesired property that can restrict their application. Therefore, low-density aerogel composites, called x-aerogels, which rival the strength of aerospace-grade fiber composites, were developed. In particular, as part of this research, we also investigate the potential to use of a high strength novel polyimide x-aerogel developed at NASA Glenn Research Center (GRC) as a lightweight mirror substrate.

## APPROACH/INNOVATION

This project investigates:

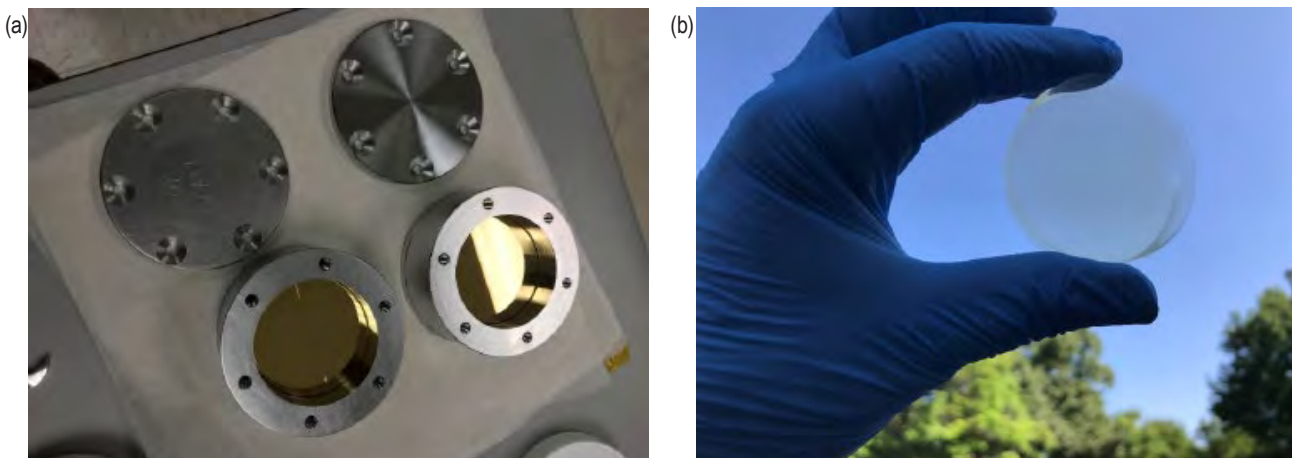
- (1) the replication of flat silica and polyimide aerogels from optical quality molds;
- (2) the figure error of the molded aerogel; evaluated by profilometry/interferometry measurements
- (3) the efficacy of smoothing the aerogel surface by the deposition of carbon (C) and reactively sputtered silica ( $\text{SiO}_2$ ), also known as silicon dioxide; evaluated by atomic force microscopy (AFM) measurements
- (4) the reflectivity of the smoothed aerogel samples after the deposition of a reflective thin film such as iridium; evaluated by x-ray reflectivity measurements at  $\text{CuK}\alpha$ .

This phase of the developed is limited to the replication of flat aerogel samples that were formed from molds containing one optically flat and smooth surface (i.e.,  $\approx 5\text{--}10\text{ \AA}$  surface roughness). Optical flats were fabricated from diamond-turned and polished, electroplated nickel and later replaced by fused silica optical flats that were purchased commercially.

## RESULTS/ACCOMPLISHMENTS

### SILICA AEROGELS

A significant portion of the last fiscal year's development efforts were associated with the design and fabrication of the molds and the replication of the aerogel samples. Different mold



**FIGURE 1.** (a) Fabricated silica aerogel molds with gold coated, electroformed nickel optical flats, and (b) a defect-free, silica aerogel sample molded at Ocellus, Inc.

designs were required for each type of aerogel. For the silica aerogels, it was discovered that portions of the aerogel would stick to the surface of the nickel optical flat and result in a defective sample. We mitigated this problem by coating the nickel flats with gold prior to the replication process; but we later found that superior results were obtained by using uncoated fused silica or Zerodur® optical flats. The molds and optical flats were sent to Ocellus Inc., for molding of six silica aerogel samples. We were able to obtain very high quality (i.e. defect-free, high-clarity) silica aerogel samples by this process. The fabricated mold and a silica aerogel are shown in Fig. 1. Atomic force microscope (AFM) measurement of the as-received samples indicate a surface roughness  $\approx 150 \text{ \AA}$ .

We have also procured the necessary deposition components (i.e., gas flow meters, and other components) needed to carry out the reactive sputtering of  $\text{SiO}_2$  to smooth these samples. Prior to this, we began the deposition process using an  $\text{SiO}_2$  target which, due to its low conductivity, required the use of a radio-frequency (RF), rather than a DC, power supply. Additionally, the films deposited from an  $\text{SiO}_2$  target are inherently sub-stoichiometric and necessitate some flow of oxygen during deposition to obtain fully stoichiometric  $\text{SiO}_2$ . Now that we have the necessary oxygen gas flow components, we are able to reactively sputter  $\text{SiO}_2$  films using a silicon (Si) target and DC power supply, which results in a higher deposition rate of fully stoichiometric films. We are now poised to begin deposition and evaluation of the smoothing effects of depositing various thicknesses of  $\text{SiO}_2$  on these samples.

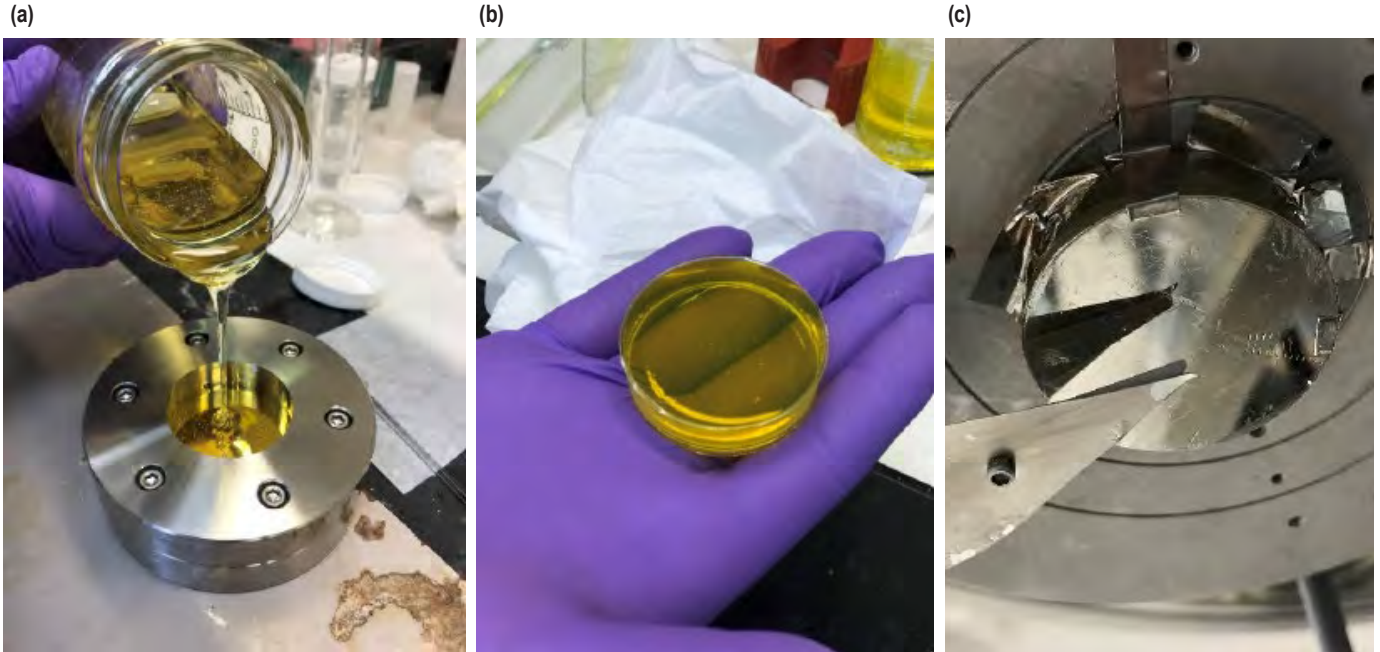
### POLYIMIDE AEROGELS

Another accomplishment relates to the successful mold design, replication, and coating of a flat polyimide aerogel sample(s). The polyimide molding process, a molded polyimide aerogel, and an iridium-coated aerogel is shown in Fig. 2. We obtained an encouraging result after coating one of the as-received samples with  $\approx 100 \text{ \AA}$  of iridium, which resulted in a visibly reflective surface (shown in Fig. 2c). We evaluated the coated sample with AFM and obtained an encouraging surface roughness of  $\approx 16 \text{ \AA}$  without the deposition of a smoothing layer; this is a factor of  $\approx 0.128$  of the roughness we measured on the silica aerogel.

Unfortunately, we were not able to evaluate the figure error or measure the x-ray reflective performance of the coating due to scratches and other defects on the surface; to do so will require molding of additional samples. To expedite this process we have fabricated two additional molds that were received by GRC. Additionally, we have fabricated holders to better protect the samples during shipment and have established a protocol for handling the samples after molding. New samples are expected in early November.

### SUMMARY

We have obtained a number of high-quality  $\text{SiO}_2$  aerogels flats that were successfully molded by Ocellus, Inc. The aerogels were replicated from molds that were designed and fabricated at NASA Marshall Space Flight Center. These as-received  $\text{SiO}_2$  aerogels show a surface roughness of  $\approx 150 \text{ \AA}$



**FIGURE 2.** (a) Molding of a polyimide aerogel, (b) polyimide aerogel after removal from mold and prior to supercritical drying process, and (c) iridium-coated, as received, polyimide aerogel sample. The coating is visibly reflective and has low surface roughness ( $\approx 16 \text{ \AA}$ ), but was damaged due to handling.

according to AFM measurements. Additionally, we have procured and received the necessary components required to configure our deposition system to reactively sputter fully stoichiometric  $\text{SiO}_2$  in an attempt to reduce the surface roughness of the aerogels. Afterward, the samples will be coated and the surface error and reflective x-ray performance evaluated.

We have also obtained polyimide samples from GRC and obtained an encouraging result after coating an as received sample with a  $\approx 100 \text{ \AA}$  iridium thin film. The sample is visibly reflective and has a surface roughness of  $\approx 16 \text{ \AA}$  after coating. The as-received samples, however, have surface damage which likely occurred during the handling and shipping of the samples. Therefore, a second round of sample fabrication is underway and we have fabricated protective holders and established a protocol for handling and shipping of the samples. Two additional molds have been fabricated and delivered to GRC. Defect-free samples are required in order to evaluate the mid spatial frequency figure error and x-ray reflective performance.

**PRINCIPAL INVESTIGATOR:** David Broadway

**PARTNERS:** NASA Glenn Research Center, Ocellus Inc.

**FUNDING ORGANIZATION:** Center Innovative Fund

# Cryogenic Aluminum Mirror Technology

**OBJECTIVE:** *To demonstrate technology for manufacturing cryogenic aluminum mirrors.*

## PROJECT DESCRIPTION

Far-infrared (Far-IR) space telescopes such as the potential Origins Space Telescope (OST) mission concept require a segmented cryogenic primary mirror. Because of James Webb Space Telescope, beryllium (BE) is the incumbent material. But beryllium is expensive. Aluminum (Al) is also a TRL-9 material and has lower cost than beryllium. However, aluminum also has a higher coefficient of thermal expansion (CTE) than beryllium and may not have sufficient thermal stability. The Cryogenic Aluminum Mirror Study (CAMS) will assess the suitability of a 1.2-m aluminum mirror for OST.



FIGURE 1. 1.2-m aluminum mirror.

## ACCOMPLISHMENTS

CAMS has two objectives:

- (1) To characterize thermal stability of a 1.2-m aluminum mirror and
- (2) to demonstrate cryo-null figuring of a 1.2-m aluminum mirror to Far-IR tolerances.

To characterize thermal stability, a 1.2-m aluminum mirror will be cryo-cycled and tested in NASA Marshall Space Flight Center's (MSFC's) X-ray



FIGURE 2. Diamond turning 1.2-m aluminum mirror.

and Cryogenic Facility (XRCF) at least three times to a temperature of 30 K or less. These tests have two purposes: (1) quantify the mirror's cryo-deformation at a temperature relevant for the potential OST mission; and (2) quantify the mirror's thermal stability as a function of cryo-cycling. To demonstrate cryo-null figuring, the measured cryo-deformation will be figured into the mirror. In-process optical testing will quantify MSFC's ability to converge to the desired surface shape. Final optical testing will quantify how well the desired shape was achieved.

In FY 2019, the 1.2-meter mirror (Fig. 1) was machined from a 5083-aluminum billet and stress relieved via heat treatment. 5083 aluminum was selected because it is a cast material with a homogeneous grain structure. A spherical surface has been diamond turned into the mirror and its mount structure designed and fabricated. Unfortunately, diamond turning of the final optical surface necessary for performing the cryo-testing has been delayed into FY 2020 due to the death of the diamond turning technician. Consequently, CAMS has requesting a no-cost extension of the project.

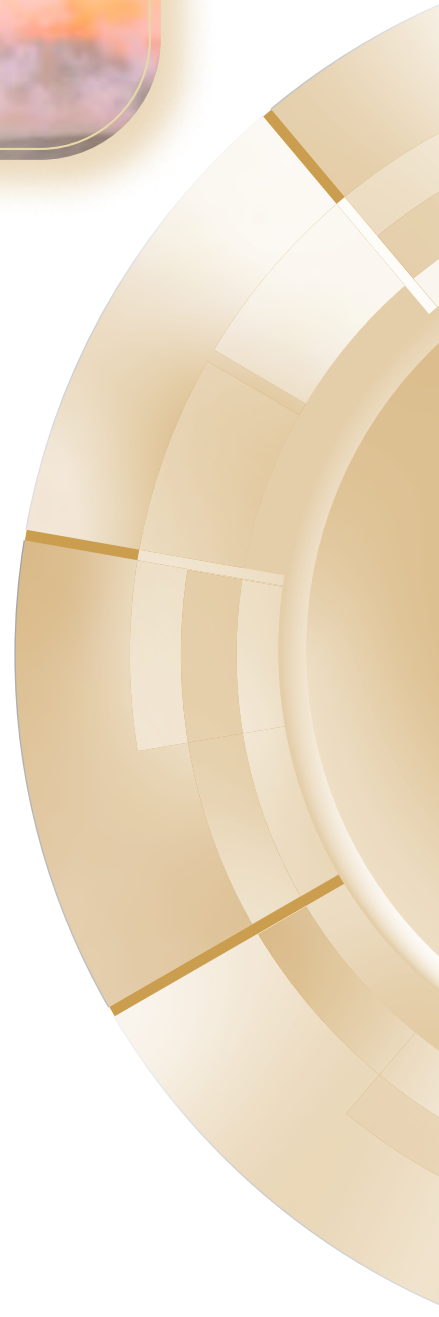
## SUMMARY

CAMS is maturing technologies to manufacture cryogenic aluminum mirrors for a potential Origins Space Telescope missions.

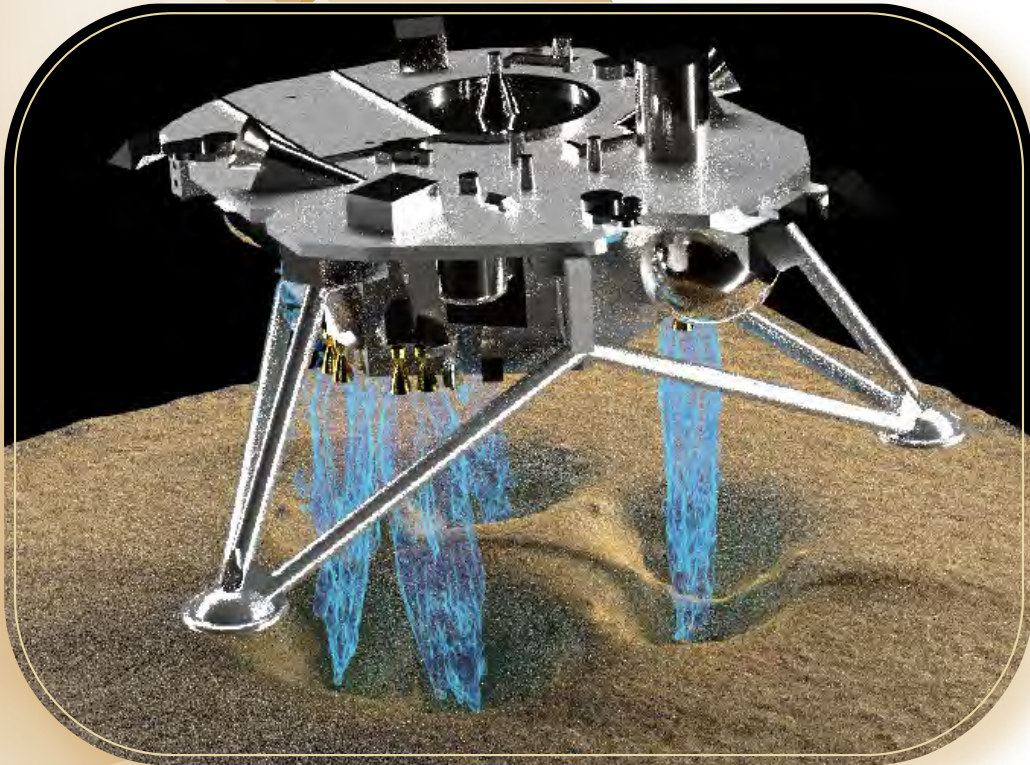
**PRINCIPAL INVESTIGATOR:** H. Philip Stahl

**CO-INVESTIGATORS:** Roy Young and Ron Eng

**FUNDING ORGANIZATION:** Technology Investment Program



# ENTRY, DESCENT, AND LANDING SYSTEMS



# Simulation of Lander Plume-Induced Clouds and Surface Cratering

**OBJECTIVE:** To enhance an existing tool to predict the coupled interaction between lander engines and regolith for two-particle-type, mixed-shape and -size mixtures.

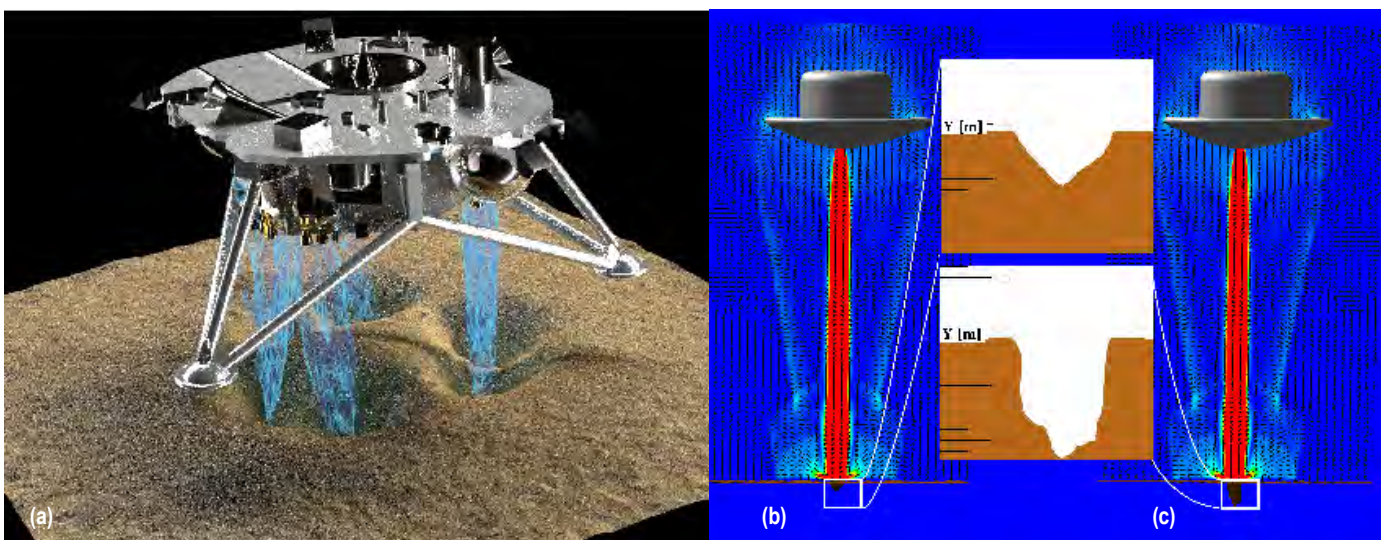
## PROJECT DESCRIPTION

The NASA goal of placing humans on the Moon by 2024 has hastened the pace to select an Entry, Descent, and Landing (EDL) system by as early as 2020. Several of the many risks associated with achieving this goal arise from the interaction between the propulsion system and the soil of the surface below, including: (1) crater formation and surface damage, (2) plume-flow driven regolith particle debris transport, and (3) obscuration from dust particle cloud formation. This project focuses on advancing the unique plume/surface modeling capability developed by the Fluid Dynamics Branch at NASA Marshall Space Flight Center (MSFC) with assistance from CFD Research Corporation to include multiple regolith shapes and sizes, as would be experienced on the Moon, Mars, and other extraterrestrial bodies. With this development, a significant improvement to the physical realism of the modeled plume/surface interaction can be realized, resulting in a higher-fidelity, predictive tool to aid in mitigating risks to the lander.

## ACCOMPLISHMENTS

The plume/surface modeling capability developed through this Technology Investment Program (TIP) project is unique within NASA, academia, and commercial entities with no known equivalent. The fully coupled plume/surface modeling tool allows for high-fidelity plume-induced surface cratering, rock/debris transport and resulting impact damage analysis, and dust particle cloud formation. This development comes with a number of challenges related to the modeling of polydisperse, granular mixtures, including solving two sets of coupled equations, avoiding expensive computations of coefficients for the granular phase conservation equations and keeping memory requirements to a minimum.

The approach to overcoming technical challenges of reducing computational time and memory requirements was to employ an adaptive-tabulation algorithm in a pre-processing step to generate a data lookup table for computing the granular phase equation coefficients. These tables are generated as



**FIGURE 1.** (a) InSight landing reconstruction using single-particle-type Loci/CHEM/GGFS tool with plume flow iso-surface of Mach number equal to 1 at a simulated time of 65 ms. Plume velocity magnitudes and directions as well as cratering shown for 3D simulations with (b) single-particle-type regolith forming a 1 m crater and (c) two-particle-type regolith forming a 2.2 m crater.

a pre-processing step for each granular mixture and used in 2D-axisymmetric and 3D simulations that demonstrate the capability. Such simulations were presented in the TIP midterm report and at the 16th International Planetary Probe Workshop (IPPW-2019) in Oxford, UK, for the Mars InSight lander. Future developments include coupling between continuum and rarefied gas flow solvers to enable the simulation of plume-induced cratering on the lunar surface, where there is no atmosphere and the continuum assumption is no longer valid.

This TIP had four main tasks and associated milestones, all for a representative Mars Lander vehicle and Martian landing. Each task was included to mature and extend the capability through extensive tool development, building, and execution of coupled CHEM/GGFS models, and demonstration of the framework's operation. The four tasks are: (1) port the discrete element model (DEM) database generator to supercomputers at NASA Ames, (2) make DEM customizable on NASA Advanced Supercomputing (NAS) using CHEM equation of state, (3) demonstrate capability for 2D axisymmetric models, and (4) demonstrate capability for 3D models.

Each technology development milestone was met, and results of simulations—both 2D axisymmetric and 3D models—provided useful insight into the capability of the tool. With development of a multiparticle-type regolith mixture, effects of single-versus two-particle-type regolith mixtures were investigated and determined to have a significant impact on crater development. For the conditions considered, the two-particle-type regolith resulted in nearly twice the crater depth as for a single-particle-type mixture. Experiments of jet impingements into various regolith mixtures have shown similar crater shapes. A specific example is the Mars InSight program, where the single-particle-type simulation successfully predicted craters of similar size and shape as those observed from cameras aboard the InSight lander for the

November 2018 landing. The cratering not only presents a risk to landing stability but also has first-order effects on plume-driven debris and dust particle cloud formation that present additional risks.

## SUMMARY

The primary objective of enhancing an existing tool to predict the coupled interaction between lander engines and regolith for two-particle-type, mixed shape and size mixtures was met for both 2D-axisymmetric and 3D simulations. An on-demand, database-generation capability was built to allow for specification of two-particle-type regolith mixtures of different sizes and shapes. More meaningful 3D predictions of plume/surface interactions were performed—the first time that simulations of this scale and fidelity could be accomplished with a two-particle-type regolith mixture.

This TIP considerably advanced the framework functionality and maturity to achieve production-level capability at reasonable expense. The technical readiness level (TRL) at the start of the TIP was a 4, but by the end of the TIP had increased to 6. Development of Gas-Granular Framework Simulation (GGFS) had been achieved through multiple NASA Small Business Technology Transfer (STTR) Phase II, II-X, and III projects, and it continues through STTR Phase II-X project funding. Future work to couple the CHEM/GGFS tool with a rarefied flow solver, Loci/Boltzmann, will pave the way to modeling the plume/surface interaction on extraterrestrial bodies with little to no atmosphere such as the Moon.

**PRINCIPAL INVESTIGATORS:** Douglas Westra, Andrew Weaver

**FUNDING ORGANIZATION:** Technology Investment Program



# Lander Technologies

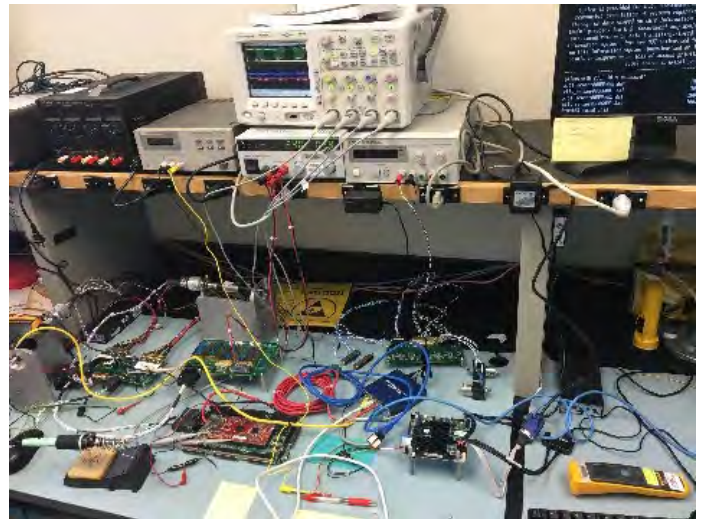
**OBJECTIVE:** *To make a sustainable return to the lunar surface through a combination of participation in and support of commercial lander development, technology development, and risk-reduction activities, and in-house lander design efforts.*

## PROJECT DESCRIPTION

In 2019, the Lander Technologies project saw the completion of the Human Exploration and Operations Mission Directorate's (HEOMD's) Cargo Transportation and Landing by Soft Touchdown (CATALYST) activity and its evolution into and support of the Science Mission Directorate's (SMD's) Commercial Lunar Payload Services (CLPS) program; completed the in-house design of the Volatiles Investigation Polar Exploration Rover (VIPER)—managed by NASA's SMD pallet lander, targeted toward delivery of mobile payloads to the lunar surface, and transitioned into the Human Lander System program formulation activity. During the year, Lander Technologies not only focused on and achieved key technical developments of lunar lander technologies mentioned herein, but also served as a model and incubator for how NASA plans to enable and work with commercial companies to develop future lunar exploration and science landers.

## ACCOMPLISHMENTS

Lander Technologies, as alluded to above, through the CATALYST program, works side by side with three small companies (Astrobotic Technology, Masten Space Systems, Moon Express) on their small, robotic lander designs and their key technical objectives and needs to improve lunar access for each of them, their prospective customers, and NASA. This year, a diverse set of activities were performed to support these companies including: environmental and performance testing of new high-energy density batteries for use by commercial and government spacecraft, development and testing of prototype cryogenic fluid management (CFM) condensation and storage systems, creation of new sensor simulation code for core flight software (cFS), development and test of new MON25-MMH thrusters (refer to TALOS project), demonstration of Fiber Optic Sensing System



**FIGURE 1A.** Integrated Avionics, Flight Software, and GN&C Hardware-in-the-Loop Testing.

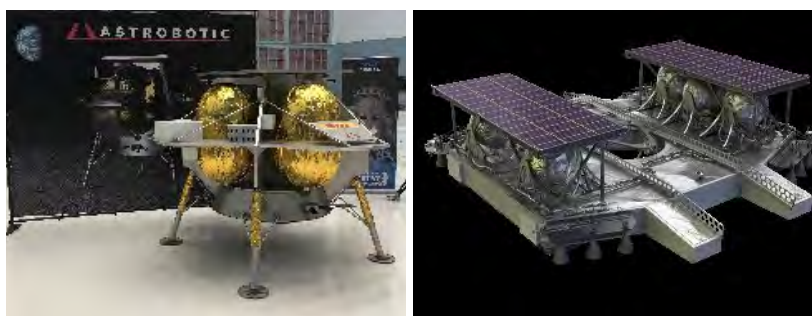


**FIGURE 1B.** Hot fire testing of the 5K LOX/Methane engine; and monoprop test of 3D printed engine.

(FOSS) temperature sensors, integrated, hardware-in-the-loop avionics (see Fig. 1(a)) testing, hot fire testing of an advanced cryogenic engine, plus 3D printing and testing of small thrust chambers, (see Fig. 1(b)), critical structural analysis to solve launch loads issues, extensive thermal analysis at the system and component levels, and other technology development and maturation initiatives like advanced heat pipes for extreme, planetary environments.

With an increased emphasis on lunar exploration and scientific investigation, there is a desire to deliver a wide variety of payloads to the lunar

surface. NASA is leading the effort through the CLPS project, which has already awarded commercial contracts for payload delivery to the surface of the moon. One of the CATALYST companies, Astrobotic Technology, was among those first selected/contracted to be a CLPS commercial lander (Fig. 2) to carry small NASA payloads to the lunar surface. In addition, the NASA in-house designed VIPER pallet lander expands on this emphasis with its ability to land mobile payloads (i.e. rover) on the lunar surface. The work performed under this effort has helped advance critical technologies in the areas of propulsion, navigation, communication, landing, and other subsystems required for a successful lunar lander mission.



**FIGURE 2.** Astrobotic Peregrine Lander and NASA's pallet lander design.

The pallet lander team achieve a preliminary design level of maturity on each of the major subsystems, including power, avionics, communication, structures, propulsion, systems engineering, navigation and thermal. All of this information is captured and documented in two versions of a NASA technical paper; one publically released version and one restricted version for use by government and commercial companies with government contracts (“Volatiles Investigation Polar Exploration Reconnaissance (VIPER) Lander Reference Design,” Technical Paper, August 2019).

Last but definitely not least, the Lander Technologies team, while previously targeted toward robotic landers, refocused its energy toward NASA's new Human Lander System (HLS), which, per the Vice President's pronouncement, is directed to land the first woman and next man on the moon in 2024. The MSFC lander team which is part of a larger multi center team, again with a focus on an innovative and cooperative relationship with the commercial sector, matured NASA's HLS reference design and has helped with commercial efforts to design and evaluate concepts for the

descent, transfer, and refueling elements, all parts of the reference design, working in such areas as advanced cryogenic propulsion fluid management, advanced landing sensors and algorithms, mission planning, and several other discipline areas. More recently the team has lead the development and release of a Broad Area Announcement toward which industry is to propose and deliver their own lander architectures and corresponding flight vehicle systems with NASA technical support, funding and insight. To reach a 2024 human lunar landing requires an all-hands-on-deck approach combining the talents and energies of NASA and our commercial partners.

## SUMMARY

2019 was a busy and exciting year of achievement and transitions for Lander Technologies. CATALYST was successfully completed, providing NASA expertise, resources, and energy to our commercial partners, positioning them to further their development and provide robotic, small payload access to the lunar surface. Some of these partners went on to join CLPS and are slated to carry NASA payloads to Moon. The pallet lander design was matured and will serve as a starting point for the development and inclusion of a medium class mobile payload delivery capability into the CLPS portfolio. In addition to helping foster robotic lunar access, Lander Technologies joined the team that will put humans back on the Moon and seed and strengthen American cis-lunar industry capabilities.

**PRINCIPAL INVESTIGATOR:** Greg Chavers and Jeff Farmer

**FUNDING ORGANIZATIONS:** Science Mission Directorate

# Diagnostic Demonstration of Particle-Laden Jets

**OBJECTIVE:** To develop ultra high-speed diagnostic systems to investigate particle-laden compressible jet flows and provide a unique dataset for ejecta dynamics modeling.

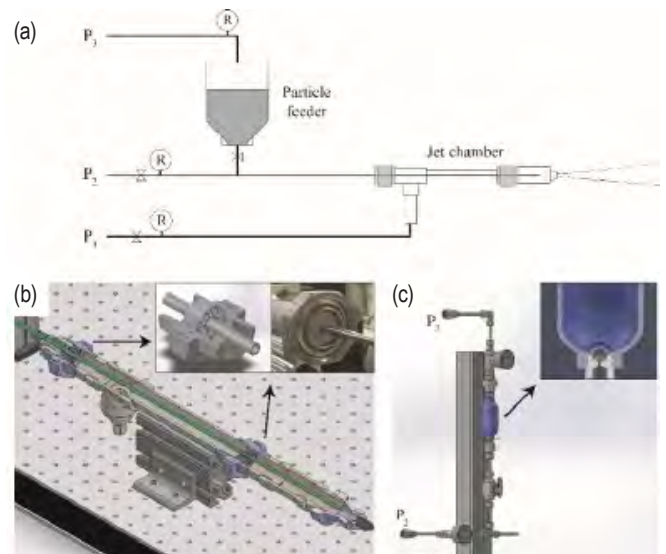
## PROJECT DESCRIPTION

Rocket plumes interacting with the surface regolith can cause significant scouring and particle ejection during a powered descent event. The effects of plume-surface interactions (PSI) and ejecta become more severe as landed mass increases and are likely to damage landers and their payloads. Despite such significance for space mission, PSI and the corresponding ejecta dynamics are still poorly understood due to complexities and challenges in both experimental and numerical works. In particular, there is a dearth of experimental data because of the associated technical challenges, in particular, resolving small micron-sized particles travelling at Mach 1 or above. This Center Innovation Fund (CIF) project provides a feasibility test on ejecta dynamics by leveraging the particle tracking capabilities in the laboratory of co-principal investigator (co-PI) Dr. Rui Ni at Johns Hopkins University. The goal of this project is to develop an ultra-high-speed diagnostic system to provide time-resolved measurements of both gas (jet) and solid (particle) phases. A scaled-down jet facility was constructed to provide a unique dataset of particle dynamics in complex flow environments. At the same time, part of this CIF effort is to help validate and support the development of the Eulerian-Lagrangian simulation of PSI by NASA Jet Propulsion Laboratory (JPL) and University of Michigan team supported by a separate CIF grant.

## ACCOMPLISHMENTS

Throughout this project, Ni's team at Johns Hopkins University developed a state-of-the-art ultra-high-speed diagnostic system for particle-laden underexpanded jet. The key features of this system include: (i) high-speed imaging techniques, (ii) particle injection system, (iii) mass-loading system, and (iv) Lagrangian particle tracking to interrogate particle dynamics interacting with surrounding gas phase. To conduct time-resolved

measurements of micron-sized particle in an underexpanded jet, a high-speed imaging technique were carefully constructed. As the particle velocity approaches sonic speed, the frame rate ( $f$ ) should be high enough to ensure an appropriate particle displacement between frames for tracking, while the exposure time ( $\tau$ ) should be small enough to avoid motion blur. Under the present flow condition, it requires a high-speed camera to have at least 5 million frames per second with the exposure time of less than  $0.25 \mu\text{s}$ . Shimadzu HPV-X2 high-speed camera (10-bit CMOS,  $400 \times 250$  pixel<sup>2</sup>) was chosen because it can reach this ultra-high frame rate at a reasonable spatial resolution. To accompany this extreme frame rate, a mercury arc lamp (150–300 W, Oriel/Newport) was utilized to provide sufficient light to illuminate the field of view. The current system, therefore, successfully captured the dynamics of gas and particle phases with sufficient spatio-temporal resolution by using an inline-type



**FIGURE 1.** (a) Schematic of the particle-laden high-speed jet facility; (b) particle accelerator tube mounted inside the jet settling chamber; inset shows a 3D-printed perforated cylinder inserted inside the chamber to hold the tube and condition the main flow; and (c) particle injector with an orifice at the bottom of the particle chamber (inset); particles are pushed through the orifice by the pressure drop,  $\Delta P = P_3 - P_2$ .

Schlieren imaging and particle shadow tracking technique ( $f=5$  Mfps,  $\tau=110$  ns), respectively.

In addition to the diagnostic system, the Hopkins particle-laden jet rig (see Fig. 1a) was designed to introduce solid particles into gas. This system consists of a particle accelerator (see Fig. 1b) as a long inline metal tube inside the jet plenum and a particle injector (see Fig. 1c) driven by the pressure gradient ( $P_3-P_2$ ). This design allows a separate control on the particle initial velocity ( $U_p$ ) and particle concentration ( $C_p$ ) for a given mass flow rate  $m = C_p A U_p$ , which can be directly quantified using a load cell.

Finally, we employed different types of particles for examination. We have studied the dynamics of particles, including (i) hollow glass sphere with low density; (ii) large particles close to 40–60  $\mu\text{m}$  with a broad distribution in size have also been studied; and (iii) monodispersed PMMA spherical particles at 29  $\mu\text{m}$ . These particles sizes fall within the range of sizes predominantly observed in the regolith of the Moon and Mars. Compared with other earlier studies using glass spheres with a quite large particle distribution (Buchmann et al., 2012; Ingvorsen et al., 2012), the monodispersed particles, herein, help to rule out the possible impact of size distribution on the final results of velocity and acceleration distribution.

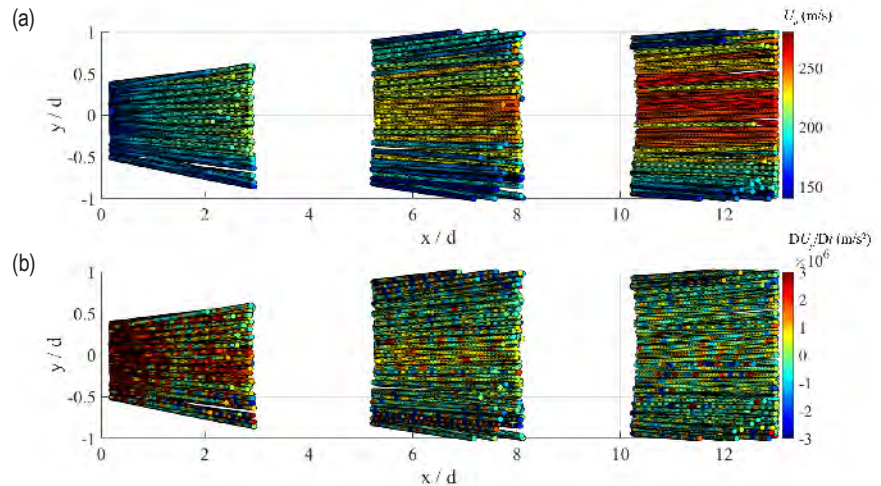
Given the jet facility and high-speed imaging technique described in the earlier section, we accomplished an individual measurement of the gas and particle dynamics based on our initial objectives, and brief results and lessons learned are detailed in the summary section.

Single-phase compressible jet with varying pressure ratios shows an excellent agreement with previous studies (Franquet et al., 2015) in terms of the shock structure (not shown herein for brevity). We also show that the time-resolve Schlieren imaging can provide tracerless particle image velocimetry (PIV) calculation to measure gas velocity.



**FIGURE 2.** Instantaneous snapshot of particle shadow images for different mass loadings: (a)  $\dot{m} = 0.12$  g/s; (b)  $\dot{m} = 0.37$  g/s; (c)  $\dot{m} = 0.94$  g/s.

Particle phase was successfully imaged over time, yielding long and accurate particle trajectories. Figure 2 shows an instantaneous snapshot of the particle shadow imaging results at different mass



**FIGURE 3.** Sampled particle trajectories in different measurement locations ( $0 < x/d < 3$ ,  $5 < x/d < 8$ , and  $10 < x/d < 13$ ). Colormap represents (a) particle velocity and (b) acceleration.

loadings. Images of particles have a consistent size with negligible motion blur. Figure 3 displays sampled particle trajectories in three different measurement locations. Both the streamwise particle velocity ( $U_p$ ) and acceleration ( $DU_p/D_t$ ) were indicated by the color of the track, respectively.



**FIGURE 4.** Instantaneous snapshot of particle shadows overlaid on Schlieren imaging to capture both gas flow and particle dynamics.

Particles particularly close to the jet nozzle experienced a reduced acceleration as passing through the first shock cell even with largely-ballistic trajectories. Figure 4 shows a dual-color Schlieren methodology where particles are overlaid on the Schlieren instantaneous image.

## SUMMARY

Through this CIF, we have shown and demonstrated that an ultra-high-speed particle tracking system is a valuable diagnostic tool for studying ejecta dynamics in plume-surface interaction problem. To show its capability, a particle-laden high-speed jet facility was designed. This facility features a unique high-speed imaging technique as well as a particle injection system coupled with a simultaneous mass-loading measurement. Leveraging these features, the particle mass loading and particle initial velocity were adjusted separately, and micro-sized monodisperse particles were successfully tracked providing the statistics of particle velocity and acceleration. The results obtained from the current facility will help us to understand the solid particle dynamics in plume-surface interaction problem, and it has and will continue to contribute to the development of advanced numerical schemes for predicting plume environments during the powered descent landing phase. The current plan is to implement the Hopkins diagnostic system for investigating ejecta dynamics in NASA unit experiments and large-scale relevant ground test.

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**PRINCIPAL INVESTIGATOR:** Manish Mehta

**PARTNERS: CO-INVESTIGATOR:** Rui Ni, John Hopkins University; Collaborators: Dr. Taehoon Kim, Johns Hopkins University, Dr. Jason Rabinovitch, NASA Jet Propulsion Laboratory, Dr. Jesse Capecelatro, University of Michigan

**FUNDING ORGANIZATION:** Center Innovation Fund



# **NANOTECHNOLOGY**

## **MODELING, SIMULATION, INFORMATION TECHNOLOGY**



# Carbon Nanotube Sensor Using Additive Manufacturing

**OBJECTIVE:** *To produce carbon nanotube based piezoelectric and pyroelectric sensors for structural health monitoring and temperature measurement wirelessly using additive manufacturing.*

## PROJECT DESCRIPTION

This project undertook to produce wireless piezoelectric and pyroelectric materials for use as structural health monitoring sensor and temperature sensors. The advantage of these sensors is twofold: (1) They are wireless and (2) can be made either flexible or stiff depending on the specific application. This allow the sensors to be adhered to the surface of a metal or composite as well as embedded within a composite structure. In structural health monitoring applications, the sensor will report the health of the structure for the lifetime of said structure. Since this material is also pyroelectric, it can be used as a wireless temperature sensor.



**FIGURE 1.** 3D-printed sensor with gold electrodes for testing piezoelectric response.

## ACCOMPLISHMENTS

The approach used was 3D printing a mixture of carbon nanotubes, piezoelectric polymer and piezoelectric nanopowders into a piezoelectric/pyroelectric sensor. The primary innovation is to 3D print a wireless antenna directly onto the sensor. This allows the sensor to be used as both a structural health monitoring sensor as well as

a pyroelectric sensor. It is particularly innovative in that the lack of wires allows it stay in contact with the structure for the life of that structure continuously monitoring the health of the structure.

We have successfully 3D printed piezoelectric/pyroelectric sensors. This involved producing a mixture of carbon nanotubes, piezoelectric polymer and piezoelectric nanopowders of the proper viscosity to enable 3D ink printing. We have successfully designed a wireless antenna but have yet to 3D print onto the sensors. We have tested both piezoelectric and pyroelectric sensors successfully resulting in a final sensor chemistry.

## SUMMARY

In summary, we have successfully produced a 3D-printed sensor which can be uses as both a structural health monitoring sensor and as a temperature sensor. The wireless nature of these sensors will allow them to be used for the lifetime of the application.

**PRINCIPAL INVESTIGATOR:** Dennis S. Tucker

**FUNDING ORGANIZATION:** Technology Investment Program

# Targeted Nanoparticle-Facilitated Delivery of Radiation Countermeasures for NASA Deep Space Missions

**OBJECTIVE:** *To direct countermeasure delivery of graphene-based nanoparticles on specific target tissues using a bimodal application of photothermal and photodynamic therapies.*

## PROJECT DESCRIPTION

A variety of medical countermeasures will be needed to combat the effects of radiation, reduced gravity, and their combination, for NASA deep space missions. In particular, the prolonged exposition to astronauts to different types of radiation (ultraviolet, cosmic, for example) would be conducive to a raise in their expectance to develop cancer-related issues. Therefore, the need of protocols and therapies to face the health-related concerns for human beings experiencing long-time space travels, becomes indispensable. Any nanotechnology-based approach that would identify a biocompatible nanomaterial with the potential combination of both light-induced mechanisms (generation of ROS and localized heating) should represent a breakthrough for the future of space medicine and cancer oncology. Accordingly, this research is focused on the development of novel biocompatible graphene based nano-particles, which can be used as countermeasure agents. Graphene-based nanoparticles are expected to exhibit the capability to be uptaken by cancer cells and release the countermeasure agent (ROS and/or controlled heat) after interacting with near-infrared light, so that countermeasure delivery can be directed to cancer tissues, minimizing delivery to healthy zones. We will synthesize graphene-based nanoparticles (graphene oxide (GO) and reduced graphene oxide (rGO)) and test their uptake into cells and cell viability (cancer and healthy cells) using infrared light, this later in collaboration with NASA. These bi-functional nanostructures could open new avenues to develop space specific therapies as those required in deep space missions, and evidently on Earth.

## INNOVATIVE ASPECT

We propose that nanoparticles be used to help target countermeasure delivery to specific cell types

and tissue types, to minimize the side effects of countermeasures in non-target tissue. We will focus on the optimized synthesis of novel biocompatible graphene-based nanoparticles, which can be used as countermeasure agents. Nanoparticles have the very desirable property that their selective uptake into cells could be enhanced under infrared light irradiation, analogous to photodynamic therapy, so that countermeasure delivery can be directed to specific target tissues, minimizing delivery to non-target tissue. We will develop a modified and short-term synthesis of graphene-based nanoparticles and test their uptake into cells using infrared light. For the second objective, we would carry out preliminary ROS-generation tests and, depending of the results, cytotoxic assessment, in coordination to NASA laboratories. This dual technology will allow for the first to target specific countermeasure agents in cells which will open a new world of space medicaments development for upcoming deep space missions such as going to Mars. In parallel, this technology provides a new, non-invasive and biocompatible way of inducing cancer apoptosis based on biocompatible nanomaterials and biomedical optics applications.

## MILESTONES AND DELIVERABLES

This year, we focused on synthesizing and optimizing the graphene oxide (GO) from starting graphite micro-flakes. Figure 1 shows the different phases of the synthesis. Different synthesis conditions were tested by using the Hummer's Method. The presence of tGO was confirmed by X-ray diffraction and Raman spectroscopy techniques. However, the coexistence of the graphite signal suggests the conversion to be incomplete. To overcome this limitation, a new set of experiments have been designed but now using nanosize graphite powders, instead of micro-flakes. The results from ongoing works suggest the full conversion fC into GO. The results will be presented in a



forthcoming report. In the next step of the research, the graphene oxide will be reduced and tested for their capability to generate ROS and, if successful, move to *in vitro* cytotoxicity experiments. We were trained in *in vitro* experiments to learn the proper aseptic techniques when working with cells. We also started learning how to quantify cell loaded with nanoparticles. Esmarine De León and Kevin Castro (graduate student) took a graduate course in nanomaterials processing with Dr. Oscar Perales to better understand the theory and techniques. Esmarine have also previous experience working with cells from institutions like Harvard University, and have taken classes such as general biology and biochemistry, and all the main chemistry courses from her background in chemical engineering. Her experience in research in nanomaterials have added an ideal expertise in the project. Castro, on his side, is a graduate student pursuing his Master thesis in physics in the field of development and characterization of graphene materials.

#### TECHNICAL/ BUDGET LIMITATIONS

The main challenge we faced during this year was budget limitation. As established in our previous budget plan we estimated a total of \$60,125 (including indirect costs) to fully develop the project. We were awarded \$40,000 from NASA Tech Tank at Marshall Space Flight Center, the rest amount of \$20,125 had been needed to buy materials, pay indirect costs, and covered Kevin and Esmarine research assistantships. At the moment, Kevin had been partially funded. Esmarine had a NASA PR Space Grant Scholarship for the 2018-2019 academic year but the scholarship ended a few months ago, and due to lack of funds it was not possible to cover a stipend for her. We attempted to contact Dr. David Loftus, our research collaborator from NASA ARC to verify if Ames Research Center could help us cover the rest part since it will be mainly used for the *in vitro* studies, which is the center expertise, with no success. We kindly request MSFC to help us get the funds needed to complete the project and our goals. We can perform a new analysis of the budget and discuss based on what we have already used and the future needs including full students' assistantship for one additional January 2020-December 2020 period.

We also faced technical challenges due, mostly, on the effect of Hurricane María. This event affected our research facilities, inhibiting the full access,

and delaying our works. Now, we have regained access to our research laboratories. For the cellular experiments, the main challenge was to define the protocols to be followed at UPRM and NASA. Our team did a depth literature review study and, based on our current experience in cell viability, wanted to confirm it with Dr. David Loftus at NASA. At the moment we need to identify the NASA contact to continue with this part of the research and help boost further technologies for space medicine research for further mission to Mars.

#### ACCOMPLISHMENTS

The Hummers' method (Figure 1), based on the reaction between potassium permanganate and graphite in presence of sodium nitrate and sulfuric acid, was used to synthesize GO. This method consists of: (i) "cold stage", the reactants were contacted at 5 °C under constant stirring; the oxidation step started right after addition of the permanganate. (ii) At the end of the oxidation period, the temperature of reaction was increased

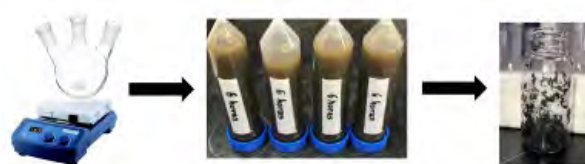
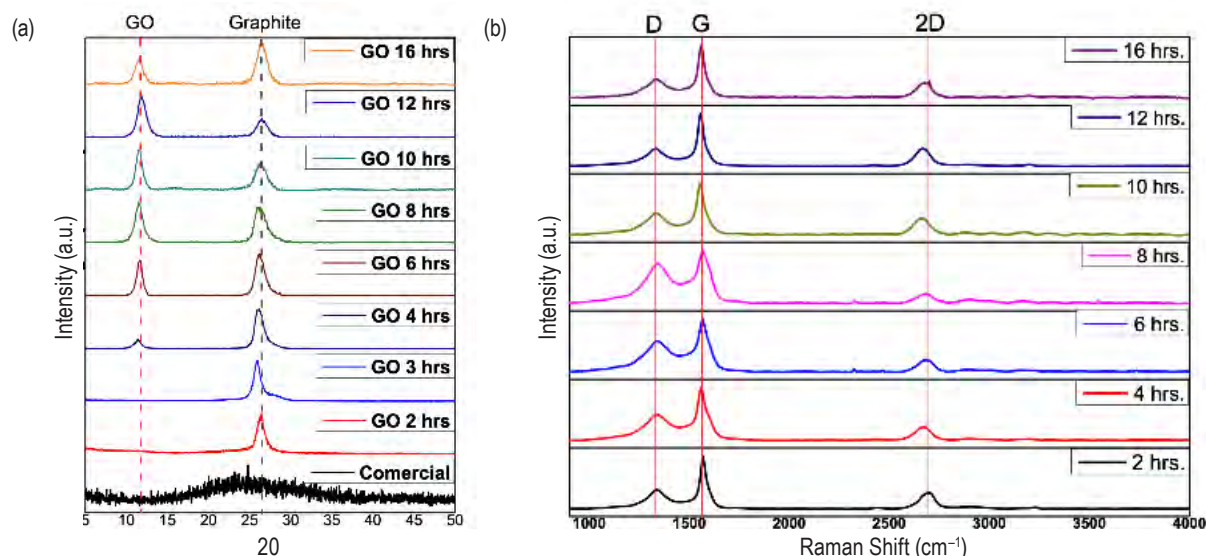


FIGURE 1. Schematic of the three stages of the Hummer's Method.

slowly to 35 °C and maintained for 30 min before the addition of deionized water "intermediate stage." (iii) The "hot stage" began after heating the suspension up to 95 °C (92–98 °C) for 30 min. Finally, deionized water and hydrogen peroxide was added under continuous stirring. Brownish suspensions were obtained at the end of the synthesis route. The powders were recovered by centrifugation at 8K rpm for 15 minutes. Two solid phases were identified. The upper part was discarded since it consisted of unwanted byproducts. The lower part (darker fraction at the bottom) consisted of the GO particles. The black sample was dried at 60°C. X-ray diffraction and Raman spectroscopy techniques (Figure 2) confirmed the development of the GO structure although still co-existing with residual graphite. In order to promote the conversion of C into GO, C-powders have been selected instead of C-flakes by C-powders as GO precursor. Preliminary results



**FIGURE 2.** (a) XRD and (b) Raman Spectroscopy at different oxidation times.

evidenced the complete conversion of C into GO at an overall reaction time as short as 2 hours (when C-flakes were used the reaction time was 16 hours). Current work is focused on the optimization of the oxidation reaction time.

Figure 2(a) shows the corresponding XRD patterns for the samples synthesized at different oxidation times. Graphite showed a characteristic diffraction peak at  $2\theta = 26.7^\circ$ , whereas GO peaks are observed at  $2\theta = 10.3$ . The patterns in the figure shows that the GO structure become evident after 4 hours of oxidation. The rise in the intensity of the GO peak with oxidation time suggests the increased formation of this compound. The corresponding Raman Spectroscopy patterns are shown in Figure 2(b). All kinds of  $sp^2$  carbon materials exhibit a strong Raman mode in the range  $2,500\text{--}2,800\text{ cm}^{-1}$  (the 2D band). This 2D-band is the evidence of

second-order, two-phonon process and exhibits a strong frequency dependence on the excitation laser energy. In turn, the D-mode is caused by disordered structure of graphene. The presence of the D-band around  $1,338\text{ cm}^{-1}$  evidenced the early formation of GO even after oxidations times as short as 2 hours. However, the predominance of the G-band suggests the strong presence of residual graphite.

## SUMMARY

We have successfully synthesized graphene oxide from graphite using the Hummer's method. However, the produced GO co-existed with residual graphite (from starting graphite flakes). Recent work has demonstrated the possibility of achieving a 100% of graphite into GO conversion by using C-powders instead of the flakes. The reaction time went down from 12 hours (using C-flakes) to 2 hours (starting from C-powders). At present, we are evaluating the conversion reaction at reaction times below two hours. Participant students were also trained in the use of a kit to detect ROS in aqueous phase and cell culture protocols for future cytotoxic assessment experiments. Biological expertise and complementary budgetary support, as originally proposed, have been requested.

**PRINCIPAL INVESTIGATOR AND PROJECT MANAGER:** Oscar Perales (PI), and Esmarline De León

**PARTNER:** Ames Research Center

**FUNDING ORGANIZATION:** Center Innovation Fund



**FIGURE 3.** Optical image of GO synthesized after 12 hours of oxidation.

# Delay/Disruption Tolerant Networking

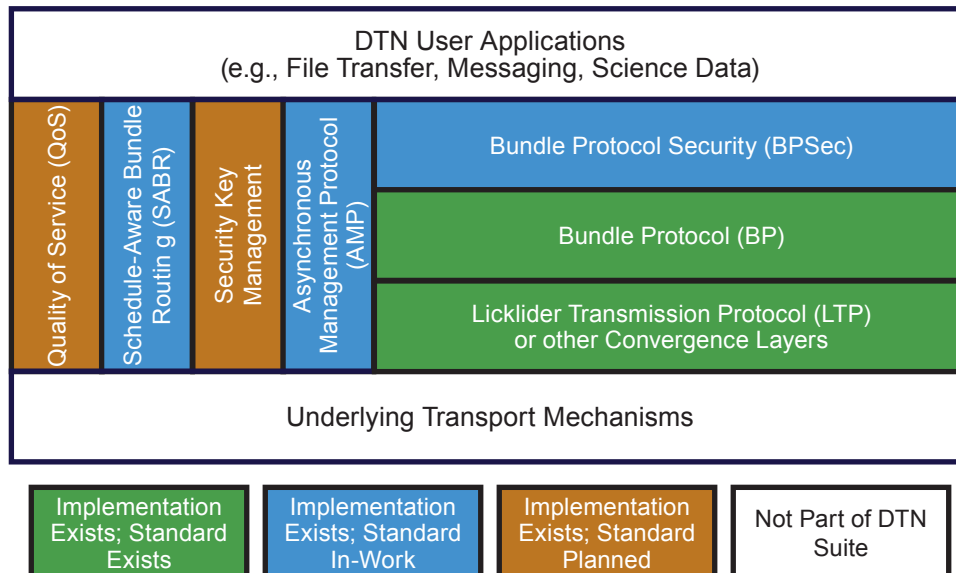
**OBJECTIVE:** To extend Internet-like services to space in support of current and future space missions and as a basis for the Solar System Internetwork.



## PROJECT DESCRIPTION

Delay/Disruption Tolerant Networking (DTN) is a suite of protocols being developed to extend the terrestrial Internet into low Earth orbit (LEO) and deep space to help form the backbone for future space communications. Starting in FY 2020, NASA's Space Communications and Navigation (SCaN) program assumed responsibility for the DTN Project from the Advanced Exploration Systems (AES) Program. SCaN will continue to develop and implement DTN technologies and operations concepts for infusion into the next generation of human spaceflight missions via adoption by SCaN Networks, as part of the Human Exploration and Operations Mission Directorate (HEOMD). HEOMD programs include Orion

Multi-Purpose Crew Vehicle (MPCV), Space Launch System (SLS), International Space Station (ISS) and the Gateway Program. CubeSat Payloads including Lunar IceCube and Lunar Flashlight, and numerous ISS Experiments are utilizing DTN for data transfers as user interest in this capability continues to grow. Emphasis has been placed on developing 'implementation ready' sets of DTN components and operations concepts to support rapid update and infusion of DTN into NASA's space communication architecture. Additionally, emphasis has been and continues to be placed on international standardization of DTN through Internet Research Task Force (IRTF), Internet Engineering Task Force (IETF), and Consultative Committee for Space Data System (CCSDS) standards bodies.



While NASA's DTN-related activity is expected to continue through the operational deployments of DTN on future missions, the focus of the DTN Project is to transition away from a developmental role and into an infusion and mission support role for the technology elements reaching maturity. The DTN protocols being developed benefit NASA human exploration and robotic missions and terrestrial applications.

## ACCOMPLISHMENTS

A key technical challenge over the last year was upgrading the original DTN Gateway Server onboard ISS to another platform. MSFC and NASA Johnson Space Center (JSC) ISS Engineering and Operations teams participated in detailed testing including payload users to ensure the upgraded NASA Interplanetary Overlay Network (ION) DTN implementation as well as the hardware platform and operating system did not introduce issues for existing and new ISS Payload users. The technology upgrade provided the ability to increase the DTN downlink rate from 15 Mbps to 30 Mbps with growth to 50 Mbps expected in FY 2020.

### INFUSION OF DTN TECHNOLOGY ON ISS

The Huntsville Operations Support Center (HOSC) collaborated with JSC ISS flight and ground engineering teams to deploy a DTN architecture supporting ISS operations and payload teams. This activity was started in late 2014 and the hardware and software was deployed to support real-time ISS operations on May 5, 2016. Since initial deployment the ISS onboard DTN Gateway Server was recently upgraded (hardware and Operating System) to provide higher data downlink rates (from 15 to 30 Mbps). Telemetry downlink rate will eventually grow to 50 Mbps in FY 2020. There are many Payloads onboard ISS that are utilizing DTN and many more that plan to utilize this protocol in the near future. By utilizing DTN, an ISS Payload was

able to reduce console time, cut costs associated with telemetry and data downlinks and improve their console support efficiency by reducing the number of hours to retrieve their onboard data.

DTN is part of the planned architecture for the Deep Space Gateway (DSG). In addition, the IETF is preparing to release a new Bundle Protocol Version 7 RFC.

## SUMMARY

DTN allows ISS Payload Developers (PD) the capability to automate and streamline their control center operations. The technology enables automatic retransmission of payload telemetry that may have been disrupted by space link issues. This cuts down on the number of playbacks the payload developers would have to perform to fill these gaps which also helps maximize the bandwidth utilization on the space link between ISS and ground.

### PROJECT MANAGERS AND/OR PRINCIPAL

**INVESTIGATORS:** Brenda Lyons, JSC and DeAnn Bryant

**PARTNERS:** John Hopkins Applied Physics Laboratory, NASA Centers Glenn Research Center, Goddard Space Flight Center, Jet Propulsion Laboratory, and Johnson Space Center

**FUNDING ORGANIZATIONS:** Advanced Exploration Systems, International Space Station

### FOR MORE INFORMATION:

<https://www.nasa.gov/content/dtn>

<http://www.nasa.gov/feature/new-solar-system-internet-technology-debuts-on-the-international-space-station/>

<https://www.ioag.org/public%20documents/sisg%20operations%20concept%20for%20ssi%20-%20final%20version.pdf>



# There's an App for That: Core Flight System Software Development for Mars Ascent Vehicle and Lander Technologies

**OBJECTIVE:** *To enhance MSFC's capability in flight software development using the core Flight System architecture and assess its use for future missions, including the Mars Ascent Vehicle*

## PROJECT DESCRIPTION

The Core Flight System (cFS), developed at Goddard Space Flight Center (GSFC), provides a platform independent, reusable software architecture, which allows projects to focus software development efforts on mission-specific needs in the form of a cFS application, a source code module developed to perform a specific task. These applications can communicate across the cFS architecture to carry out the necessary mission tasks, such as commanding, hardware control, and fault detection. The framework, which has considerable flight heritage across CubeSat missions at NASA, can significantly improve project cost and schedule by decreasing software development time and improving reusability. The goal of this project was to enhance MSFC's expertise in developing flight software using the cFS and by developing prototype applications for new projects, such as the Mars Ascent Vehicle (MAV) and Lander Technologies.

## ACCOMPLISHMENTS

Because many projects are baselining the cFS architecture, expertise in the development of mission-specific flight software that will interface with it is critical to securing flight software development work at MSFC on future missions to support landers, ascent vehicles, habitats and other potential projects. The Software Development Branch at MSFC is well-versed in the development of embedded, real-time software for large and small missions; however, until recently, development using cFS had been limited to prototype or component-level software development for commercial partners in Linux-only environments. The opportunity to work through all the design considerations when

building a flight system using the cFS architecture or work with understanding its performance on relevant flight computers and operating systems has proven extremely beneficial to the Software Development Branch in assessing and understanding cFS for use in a flight project. In this technology development effort, MSFC proposed to use the Sphinx Flight Computer as a hardware platform to run cFS and develop mission-specific application source code that will control a hardware component (i.e. valve, IMU, camera) that could ultimately be used by the MAV and Lander Tech projects.

Completing this project has allowed MSFC to work with the projects to prototype working source code that anticipates future project needs while demonstrating MSFC's expertise. In addition, MSFC has been able to consider cross-project needs and start considering the design elements that could make up more generic sensor applications going forward. This work has allowed MSFC to outline a high-level architecture for MAV using cFS and begin to assess the architecture for use in such a mission, starting with the prototype IMU application.

As part of the 2019 Technology Investment Program, MSFC surveyed the existing specific and high-level cFS applications available across the Agency and worked with the MAV and Lander Tech projects to determine that development of an Inertial Measurement Unit (IMU) application would provide the most benefits. The team then used proven agile software development processes to define high-level requirements and design for the IMU application and develop the associated source code. In light of the MAV design considerations and available IMUs, the team chose to work with

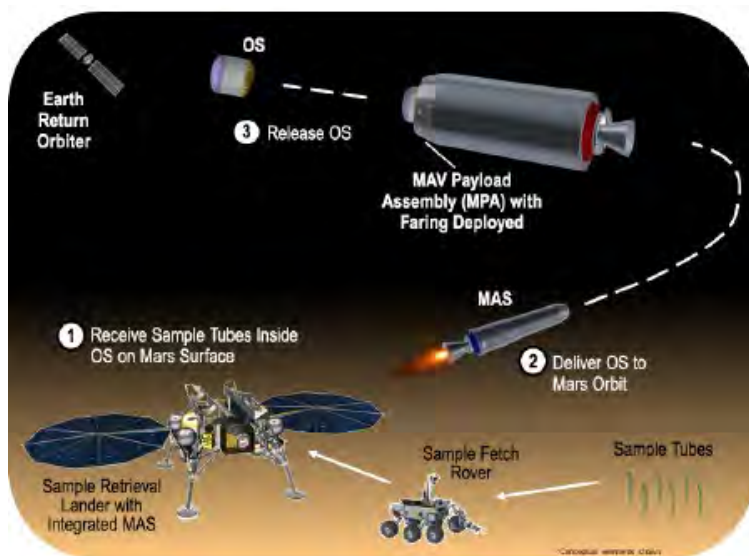
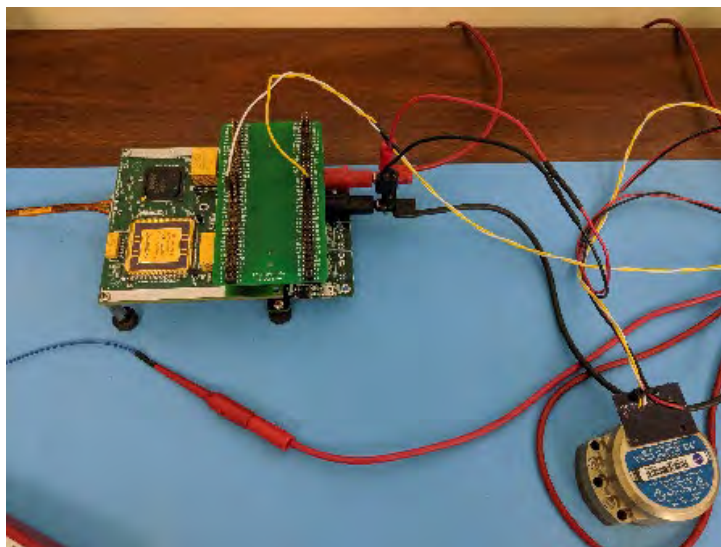
the Honeywell HG4930. The MSFC team developed high-level requirements, design diagrams, and source code for the HG4930 cFS application. The team performed initial testing and troubleshooting of the application in a Linux environment. Next, the team was able to compare results with their application in Linux to results connecting to the HG4930 directly from a PC through the vendor-provided software.

This project also leveraged in-kind contributions from the MAV of two prototype Sphinx flight computers developed at JPL. With the help of the Avionics Hardware Design branch, the two Sphinx boards were set up in the Small Project Rapid Integration and Test Environment (SPRITE) lab at MSFC. The MSFC team performed initial assessment and testing of the Sphinx prototype boards, including running the Real-Time Executive for Multiprocessor Systems (RTEMS) operating system as well as cFS on the boards. These initial tests showed portability of the cFS to the Sphinx flight computer. Once cFS was running on the Sphinx boards, the cFS IMU application was integrated to run on the Sphinx flight computer connected to the HG4930 IMU hardware in the SPRITE lab. Given that the trade space for IMU selection on the MAV project remains open, the team has also used the knowledge gained through this effort as a step toward developing a high-level design for a more generic IMU application. The team also provided high-level documentation of an overall flight software architecture using cFS for consideration by the MAV project.

## SUMMARY

The ability to apply more agile software development solutions leveraging significant code and artifact reuse by using cFS can enable faster and more cost-effective project start up times. This effort enhances MSFC's expertise with both using cFS and assessing it for future projects like MAV. The source code produced through this effort provides prototype flight software that the MAV and Lander Tech projects can use, and it allows MSFC a broader view of developing and implementing mission-specific cFS applications on a representative set of hardware for future projects. The effort also lays the foundation for MSFC to begin considering the development of more generic sensor applications for use across many future

projects and missions. Such generic applications will allow MSFC to contribute to the cFS application catalog, reducing time and cost to develop software for future missions across NASA and the cFS open source community. In addition, the effort positions MSFC to contribute to future projects that will utilize the cFS architecture, either through in-house development or as being a smart buyer of commercial solutions.



**PRINCIPAL INVESTIGATOR:** Stefanie H. Justice

**FUNDING ORGANIZATION:** Technology Investment Program

# Creating a NASA Subject Matter Expert Film

**OBJECTIVE:** *To perform a study in the use of videography equipment for creating NASA Subject Matter Expert (SME) videos, exploring and developing methods, and guidelines for video knowledge capture at NASA Marshall Space Flight Center (MSFC).*

## PROJECT DESCRIPTION

Interns will interview NASA subject matter experts (SMEs) and create an indexed film documenting the technical knowledge learned over the past decades to retain the knowledge for the purpose of passing it on to the younger generation. Interns will explore the use and care of camera and audio equipment to develop a short training video for future knowledge capture videographers. Interns will also experiment with different equipment operations to demonstrate video quality and best practices for creating a file documenting corporate knowledge. The SME video will be featured on NASATube, which is a NASA internal-only version of YouTube. This film may be the first of many covering the entire Agency.

## ACCOMPLISHMENTS

The use of NASATube to collect and distribute corporate knowledge is new to NASA. Video-based knowledge capture provides rich contextual and descriptive information that is not obtainable through written or photographic media. Such video documentation of technical principles and knowledge is increasingly common on commercial YouTube, but has not been developed at NASA for NASA, and especially not at NASA Marshall Space Flight Center (MSFC). Since the objective of video knowledge capture is not for popularity on a YouTube channel but rather, to be useful for conveying technical and programmatic knowledge to an unknown rising generations, films (videos) made by MSFC personnel will likely be most beneficial if the quality of the video is good, and the information captured is indexed and easily discoverable. This project explores the nuances of both basic videography and techniques that are needed to produce good video knowledge capture to meet these objectives. The use of animation as well as live video will be explored. Producing several

films of varying types of knowledge capture and editing those films will provide insight and lessons learned in making good videos. These lessons will be captured on video and in writing to support quality of future knowledge capture.

Following this activity, the video knowledge capture initiative will be deployed across MSFC. The camera use and care video will be used to train employees who will be using MSFC audio/video equipment. Actual knowledge-capture videos will be used to share the knowledge of those topics and will be used to illustrate the different outcomes possible based on different setups of the equipment. This information will be used by employees doing video knowledge capture to plan, set up, and ensure a useful and adequate knowledge capture product, saving time and preserving key information that will be unrecoverable when SMEs retire from MSFC.

**PRINCIPAL INVESTIGATOR:** Jennifer Stevens

**PARTNER:** David Dominguez

**FUNDING ORGANIZATIONS:** Center Strategic Development Steering Group







# MATERIALS, STRUCTURES, MECHANICAL SYSTEMS, AND MANUFACTURING



# Evaluation of Alternative Nickel-Based Superalloys for Additive Manufacturing of Liquid Rocket Engine Components

**OBJECTIVE:** To compare various nickel (Ni)-based superalloys for use in additive manufactured fabrication of liquid rocket engine components.

## PROJECT DESCRIPTION

NASA has a particular and immediate need to evaluate materials and processes for reducing the cost and improving component performance of liquid rocket engines (LRE). This provides an opportunity to insert new materials as well as manufacturing processes such as additive manufacturing (AM) into the engine fabrication or production upgrades. While heritage processing of LRE components relied on stainless steels (SS) and nickel (Ni)-based superalloys, more recent studies have identified the HR-1 as potential game changer since these materials meet the needs of a multitude of LRE component requirements. Thus, by developing fundamental standards for AM fabrication and post build processes specific to this material, the development costs can be greatly reduced by concentrating efforts on one material rather than individual materials for each component.

## ACCOMPLISHMENTS

Various AM processes are being evaluated for liquid rocket engines, including laser powder bed fusion (L-PBF) for printing smaller monolithic components and blown powder directed energy deposition (DED) for other larger components. Common to all these processes is the selection of alloys in powder form. Metal powder is used in both selective laser melting (SLM) and directed energy deposition (DED) AM processes as the feedstock with their complimentary use of 45- $\mu\text{m}$ - and 140- $\mu\text{m}$ -diameter powder, respectively. Thus, development of AM processes and post-processing heat treatments for one given



**FIGURE 1.** Blown powder being deposited through a nozzle onto an additive manufactured build with (a) showing a side view and (b) showing a closeup view of the nozzle exit.

nickel-based superalloy would streamline the development tasks for material development and reduce development costs.

Commonality in the material selection greatly streamlines the qualification testing required, thereby reducing cost and schedule impact. As new materials and processing methods become available, it is imperative to re-evaluate available materials for fabrication LRE components.

Selection of materials for use in LREs consider:

- Increased strength and increased conductivity without loss of ductility.
- Thermo-mechanical fatigue resistant.
- Resistance to hydrogen embrittlement.
- Availability in a variety of forms, which are weldable.
- CTE match with Cu alloys used in the regenerative cooled components (CTE of C18150 = 16.5  $\mu\text{m}/\text{m}-^{\circ}\text{C}$ )

As Table 1 shows, there are improvements to be obtained by switching from the Inconel alloys with their low coefficient of thermal expansion (CTE) to alloys with higher values such as HR-1. This is a critical parameter in bimetallic joints since it drives the localized stresses resulting in low cycle fatigue (LCF) issues.

**TABLE 1.** Properties of various iron and nickel-based superalloys.

	YS (MPa)	%El. (MPa)	CTE ( $\mu\text{m}/\text{m}-^{\circ}\text{C}$ )	K (W/m-K)	T <sub>operational</sub> ( $^{\circ}\text{C}$ )
SS 304L [5]	210/125	58/36	17.3	16.2	800
Nitronic 50 [6]	379	35	16.2	15.6	1066
Inconel 625 [7]	345	50	negligible	9.8	800
Haynes 230 [8]	414	47	11.8	8.9	1149
JBK-75 [9, 10]	745	27	14.98	NA	816
HR-1 [11]	945	24	NA	0.19	650

NA: not available

Initial evaluation will focus on the following objectives:

- (1) Evaluate virgin powder, recycled powder, as-built specimens, and post heat-treated specimens.
- (2) This will validate the stability of the alloying elements during AM processes of both SLM and DED.
- (3) Conduct metallurgical and mechanical evaluation of samples built with SLM and DED. This will include microscopy in addition to tensile testing.

- (4) Evaluate heat treatment parameters on the resulting property and microstructural development.

Powders have been obtained for two nickel-based superalloys of interest, NASA HR-1 and JBK-75. This provides a baseline of the starting powders for evaluation of SLM and DED specimens to determine elemental stability and possible contamination.

This study builds off earlier lessons learned in which minor elements were shown to affect the microstructural evolution doing post AM printing heat treatments and hence mechanical properties. Microstructural characterization of the SLM and DED specimens from HR-1 and JBK-75 will be correlated with tensile testing.

## SUMMARY

Teaming the NASA-MSFC with efforts by Judy Schneider at the University of Alabama in Huntsville (UAH) provides fundamental research for advancing these technologies. Once the material properties and processing are proven and validated, teaming arrangements with commercial business partners can manifest the path for maturation,

commercialization, and insertion into industry. The type of research proposed in this study is needed to advance this technology from its current Test Readiness Levels (TRL) of 1–3 to preproduction TRL of 4. Additional advancements in this technology would be achieved by successful component development and hot fire tests.

**PRINCIPAL INVESTIGATORS:** Judy Schneider and Paul Gradl

**PARTNERS:** STMD Rapid Analysis and Manufacturing Propulsion Technology (RAMPT), RPM Innovations, DM3D, Formally, HMI, Powder Alloy Corporation

**FUNDING ORGANIZATIONS:** SLS Liquid Engines Office, Cooperative Agreement Notice



# Computational Modeling of the Friction Stir Welding Process

**OBJECTIVE:** *To develop and deploy software that provides a high fidelity finite element model of the solid-state friction stir welding process, parameters, geometries and machinery.*

## PROJECT DESCRIPTION

The Welding and Manufacturing Team in the Metal Joining and Processes Branch at NASA Marshall Space Flight Center (MSFC) is funded through the Cooperative Agreement Notice (CAN) mechanism a high-fidelity computational model of the self-reacting friction stir welding (SR-FSW) solid-state welding process by the Computational Fluid Dynamics Research Corporation (CFDRC). This modeling is, in turn, experimentally fine-tuned and is validated by detailed data sets collected by the Welding and Manufacturing Team on the mechanical and thermal behavior of the solid-state FSW process of relevant Space Launch System (SLS) alloys. Making rapid progress, CFDRC has recently been able to predict with reasonable accuracy the as-welded mechanical Vickers Hardness, ultimate tensile strength (UTS) of welded alloy as well as the yield stress (YS) properties. Additionally, CFDRC has been able to show pin-tool/workpiece sensitivities to geometrical detail, modeling pin-tool scroll and reservoir and no-reservoir material flow stagnation and flow zones. This brings us closer to the desired goals of a ‘Welder’s Handbook’ in which weld engineers can input process parameters into the model and predict for the RPM/IPM and alloy and geometry the as-welded mechanical strengths, and that of developing a high-resolution analysis capability for geometry coupling in order to better predict defect free weld quality.



**FIGURE 1.** Small-scale panel level FSW welding. Typically for testing and process development.



**FIGURE 2.** Large-scale FSW welding. From full-scale article development to flight hardware builds and welding. Pictured is MSFC’s Metal Joining and Processes Branch’s south highbay facility.

## ACCOMPLISHMENTS

Key technical challenges include the high complexity of the FSW solid-state welding process. This makes modeling the flow of material that is sheared and simultaneously heated (plasticized) difficult. Add to this an alloy’s multiphase chemistry, this thermomechanically driven towards varying phases. Heat affected zones (HAZs) evolve differently from thermomechanically affected zones, and these are dominated by different aspects of the dynamics. This makes it difficult to predict the after-welded mechanical properties of an aerospace alloy or metal.

CFDRC has, therefore, utilized experimentally validated constitutive models in conjunction with material ‘fluid’ flow at the extreme interface with solid state ‘flow’ in order to extract stresses strains and grain refinement. This experimental data coupling with physics theory coupled with arbitrary Lagrangian-Eulerian (ALE) finite element (FE) has proven to be a very powerful approach. This enabled CFDRC to predict, recently with reasonable accuracy, the from pre-weld process parameters input to as-welded final mechanical properties such as the YS, the UTS, and the Vickers hardness of various SLS relevant alloys, all ahead of the milestones’ deliverables additionally.

CFDRC has recently—and ahead of milestones and deliverables—been able to develop and present a working model. This model is capable of geometric modeling of tool and workpiece details that has, as inputs, process-weld parameters and alloy materials. Then, it is able to predict final-weld mechanical properties.

CFDRC also has been instrumental in corroborating, by their models, the existence of sensitivities to pin-tool weld geometries, specifically highlighting the existence of stagnation zones for flow and therefore susceptibility to defects formation in friction stir welding as well as suggesting avenues for defect formation risk mitigation.

## **SUMMARY**

MSFC's Welding and Manufacturing Team in the Metal Joining and Processes Branch has invested in the goals of fully understanding solid-state welding and in risk mitigation inherent to the solid-state process.

In addition, both NASA Headquarters and MSFC CAN funding has been awarded to optimize NASA's welding capabilities as well as understanding.

CFDRC, as a regular NASA awardee and collaborator, was chosen to provide expertise in developing and deploying a high resolution model of the solid state welding process.

Results of this collaboration have included a rapidly developed predictive model that has been shown to be capable of predicting as-welded final mechanical properties as well as during-weld materials dynamics and sensitivities of the combined weld apparatus and workpiece system. This has contributed significantly to furthering additionally the detailed physical chemical and dynamical understanding of the FSW process.

**PRINCIPAL INVESTIGATORS:** Vernon Cole, CFDRC, and Fredrick Michael, NASA MSFC

**PARTNER:** Computational Fluid Dynamics Research Corporation

**FUNDING ORGANIZATION:** Cooperative Agreement Notice



# Engineering Robust Friction Stir Welds by Using Digital Manufacturing

**OBJECTIVE:** *To use detailed NASA optimal welding test and machine feedback data in conjunction with algorithms to create dynamic feedback controls of welding robotic and large scale equipment in order to consistently weld optimal and defect free structures.*

## PROJECT DESCRIPTION

The Welding and Manufacturing Team in the Metal Joining and Processes Branch at NASA Marshall Space Flight Center (MSFC) has funded, through a Cooperative Agreement Notice (CAN), a Friction Stir Welding (FSW) process feedback control study with partner the University of Alabama Huntsville (UAH). This study seeks to understand, in high-resolution detail, the optimal welding windows for several Space Launch System (SLS) relevant alloys. Moreover, the study seeks to generate a feedback control system approach to FSW where given (determined) optimal welding windows for particular thicknesses and geometries and tooling, the welds are then in real-time feedback controlled to continuously steer the welding system towards said optimal welding windows, by adjusting weld speed, weld tool rotation rate, torques and forge loads and so on.

This modeling is experimentally fine-tuned and will be validated by detailed data sets collected by the Metal Joining and Processes Branch on the mechanical and thermal behavior of the solid-state FSW welding process of relevant SLS alloys. Detailed thermography, tool feedback data of torques and  $x,y,z$  forces feedback (etc.), and have been collected by the Metal Joining and Processes Branch for varied process parameters of rotation rates (RPM), travel speed and forge loads.



**FIGURE 1.** Full-scale welding of development and flight (SLS components, tanks, etc.) hardware.

## ACCOMPLISHMENTS

FSW yet retains sensitivities which are not completely understood. Optimal high-quality welds regions, however, have been determined. In roads toward understanding why optimal weld processes are correlated with as-welded defect-free and high-strength welds are being made.

In addition to the further understanding, there is a desire to implement this understanding towards controlling FSWs continual and real-time optimization of the welding processes and apparatus such that any error potentially caused by drift of the weld away from the optimal welding windows (parameters) is dynamically steered back toward the optimal welding regions.

This dynamics feedback control approach is then the desired goal. It will be implemented utilizing a detailed understanding of the optimal welding coupled with algorithms developed to dynamically perform such real-time feedback control on NASA welding equipment.

The results currently are large detailed data regarding optimal FSW welded articles, these consisting of weld processes and dynamic response as well as as-welded mechanical and metallurgical properties. These are obtained for varied process parameters of welding, therefore obtaining a detailed data matrix describing good or optimal and defect free welding region windows.

These extensive data sets are to be analyzed and combined with algorithms that then dynamically through tool feedback control in real-time steer the welding process to the optimal welding windows improving therefore the consistency and quality of welds performed at NASA.



**FIGURE 2.** Example of 'optimal' weld feedback window(s). Here, this data set has been obscured (Export Controlled).

## SUMMARY

Overcoming scatter and noise between weld-to-weld and machine-to-weld machine can be made by dynamic feedback control. This control requires two things, detailed data on optimal welding windows and then also dynamic algorithms that correct drift and noise such that consistent good quality welding is performed. The UAH team and Welding and Manufacturing Team are, through CAN, developing this capability at Metal Joining and Processes Branch at MSFC.

**PRINCIPAL INVESTIGATORS:** Judith Schneider, UAH;3  
Fredrick Michael, MSFC

**PARTNER:** UAH

**FUNDING ORGANIZATION:** Cooperative Agreement Notice



# Hardened Extremely Long-Life Information in Optical Storage (HELIOS)

**OBJECTIVE:** *To demonstrate stability of innovative storage media in an actual spaceflight situation.*

## PROJECT DESCRIPTION

Can data survive in space over extremely long times and multiple human generations? The possibility of human colonies on other planets may ultimately depend on just such data stability. Hardened Extremely Long-Life Information in Optical Storage (HELIOS) will demonstrate a century-old, tested, archival media for photography in a completely new way for storing high-density computer data in perpetuity. Inherently secure, low-cost technology that cannot be hacked or altered, HELIOS will test whether the media can survive a hostile space environment during long-term space missions, such as the mission to Mars and beyond.

## ACCOMPLISHMENTS

The payload consists of borosilicate slides containing raw data which will be exposed to ionizing radiation on the International Space Station (ISS) for no less than 6 months to determine whether the recording medium is impervious to ionizing radiation. If the media is radiation tolerant, it would be a candidate for storage of core flight software and large volumes of critical data subject to long-term radiation for deep space applications. The media consists of fully processed silver-halide, optically stable photosensitive emulsion which will be impervious to ionizing radiation, static electricity, and electromagnetic interference.

The experimental material will remain packed inside the HELIOS case during ground processing, launch, onboard, and return. Upon arrival to ISS, crew will stow HELIOS into a location that will be determined by the Topology Forum with inputs



**FIGURE 1.** HELIOS case stowed inside the BEAM module on ISS.

from the payload director. A radiation monitor will be pre-positioned inside the case prior to flight. At the end of the experiment duration, the HELIOS case will be removed and stowed for return.

All payload hardware transported to the ISS will be returned to the ground upon completion on the earliest return flight after 6 months on orbit. Early hardware return is required.

The payload was flown to the ISS on board SpaceX Commercial Resupply Service Mission 17 in May 2019. The payload was successfully stowed in the BEAM module. It is currently planned to return on SpaceX 19, likely in early January.

## **SUMMARY**

The payload consists of up to 50 borosilicate slides (recording media) with prerecorded test data on them identical to data on a control group of 50 borosilicate slides in the payload director's lab on the ground. The slides are stored into two interior microscope slide cases, 25 slides in each case. Both microscope slide cases were stored into a HELIOS case that included one radiation sensor. The HELIOS case does not require any manipulation by the crew other than to place the container in a location for no less than six months. After the 6-month period the HELIOS case will be returned to the PD for characterization. If the slides prove as impervious to the space environment as the technology has proved on Earth over centuries, the technology may prove to be a secure write-once, read-forever data storage media that can go with mankind to the stars.

**PROJECT MANAGER AND/OR PRINCIPAL**

**INVESTIGATOR:** Rodney Grubbs

**PARTNER:** Eric Rosenthal, CTech

**FUNDING ORGANIZATION:** Cooperative Agreement Notice



# Fatigue Behavior of Solid-State Additively Manufactured Aluminum-Zinc-Magnesium-Copper Alloy (AA7075)

**OBJECTIVE:** To quantify the microstructural evolution and fatigue behavior of an aluminum-zinc-magnesium-copper Al-Zn-Mg-Cu alloy (AA7075) manufactured via a rapid solid-state deposition process.

## PROJECT DESCRIPTION

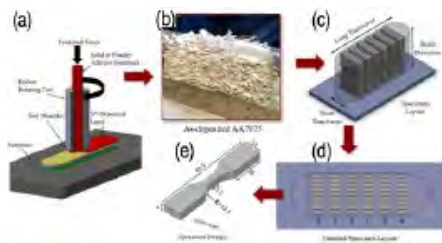
The focus of this study is on determining the mechanisms of fatigue damage and how it relates to the Additive Friction Stir-Deposition (AFS-D) process, and how they differ from the feedstock. In this paper, strain-controlled fatigue experiments were carried out to compare as-deposited and wrought feedstock AA7075 specimens. In addition, microstructural characterization was performed on the as-deposited and feedstock specimens to elucidate fatigue mechanisms.

## ACCOMPLISHMENTS

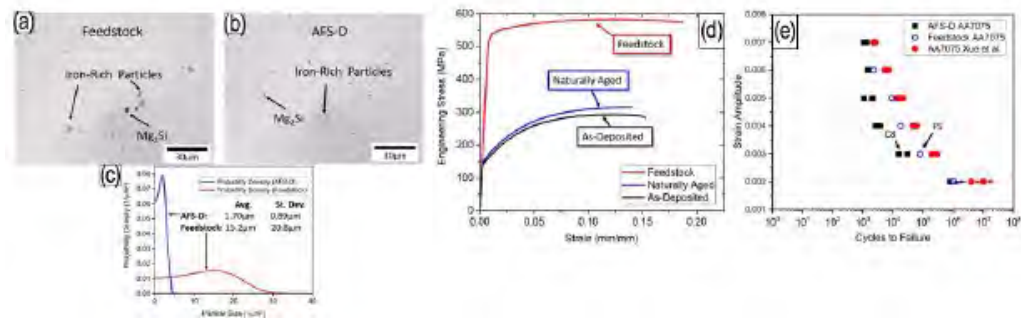
Traditionally, aluminum-zinc-magnesium-copper (Al-Zn-Mg-Cu) alloys have had extensive use within the aerospace industry for flight-critical components due to their high buy-to-fly ratio. However, these components can often be complex and expensive to fabricate. Whereas, additive manufacturing (AM) affords a solution to this problem by providing rapid and cost-effective fabrication of high strength-to-weight materials for complex structural components. Despite increased interest in AM, certain materials have proven to be difficult to effectively manufacture using fusion-based AM technologies. A novel AM

process, additive friction stir deposition (AFS-D), is a solid-state additive manufacturing process that produces fully dense depositions for repair, coatings, and structural components. As illustrated schematically in Figure 1(a), robust, metallurgical bonding is achieved between deposited layers by forcing a metallic powder or solid feedstock through a rotating, nonconsumable cylindrical tool. The AFS-D process provides a path for rapid fabrication of high strength aluminum alloys, without intrinsic microstructural defects typically exhibited in fusion-based AM technologies.

The solid-state AFS-D process is a robust, thermomechanical, AM technique that can rapidly produce fully dense, refined microstructure for AA7075. The as-deposited material exhibited a hardness gradient due to the overaging of the strengthening precipitates  $\eta'$  and  $\eta$ . However, the AFS-D process was able to refine the iron-rich and Magnesium silicide ( $Mg_2Si$ ) constituent particles, while eliminating the iron-rich stringers. Additionally, the coarse granular structure of the wrought AA7075, was refined into equiaxed grains, from 200  $\mu m$  to an average of 5.05  $\mu m$ , a reduction of 97%. Monotonic results revealed that AFS-D AA7075 exhibited a reduction in yield stress, ultimate tensile stress, and elongation to failure. This reduction in mechanical properties is attributed to the increased size of the strengthening phases, that no longer efficiently impede dislocation movement, but increase the strain hardening rate in comparison to feedstock due to dislocation generation in undeformed recrystallized grains. Fatigue results elucidate a similar trend of reduced mechanical response of the as-deposited AA7075.



**FIGURE 1.** (a) Schematic of MELD process with a solid rod extruded through the hollow stirring tool; (b) as-deposited AA7075 sample on an AA7075 substrate; (c) schematic of coupon orientation taken from build; (d) schematic of coupons in build; (e) fatigue specimen geometry used for both as-deposited and feedstock AA7075 specimens.



**FIGURE 2.** (a) Optical micrograph of constituent particles (Iron-rich and Mg<sub>2</sub>Si) found within loading direction of AA7075 feedstock; (b) optical micrograph of constituent particles displayed within loading direction of as-deposited AA7075; (c) constituent particulate distribution for AFS-D and feedstock AA7075; (d) monotonic stress-strain response of feedstock, as-deposited AA7075, and naturally aged (840 hours) as-deposited AA7075; (e) strain-life fatigue results comparing AFS-D, feedstock, and Xue et al. (see ref.1) fatigue results.

## SUMMARY

The AFS-D process provides a path for rapid fabrication of high strength aluminum alloys, without intrinsic microstructural defects typically exhibited in fusion-based AM technologies.

## REFERENCE

1. Xue, Y.; McDowell, D. L.; Horstemeyer, M. F.; et al.: “Microstructure-based multistage fatigue modeling of aluminum alloy 7075-T651,” *Eng. Fract. Mech.*, Vol. 74, No. 17, pp. 2810–2823, Nov. 2007.

**PRINCIPAL INVESTIGATOR:** Omar Rodriguez

**PARTNER:** The University of Alabama

**FUNDING ORGANIZATION:** Technology Investment Program



# Process Development of Rapid Powder Removal for Additively Manufactured GRCop-84 Copper Alloys

**OBJECTIVE:** To develop a self-terminating process to selectively remove the top 50–100  $\mu\text{m}$  of material from a GRCop-84 component fabricated using powder bed fusion (PBF) additive manufacturing (AM) technologies.

## PROJECT DESCRIPTION

The proposed project will demonstrate self-terminating, dissolvable powder removal for GRCop copper-alloy components fabricated using selective laser melting (SLM) additive manufacturing (AM) techniques. This project is specifically designed to address the fact that removing trapped powder from interior passages is the longest lead process in fabricating GRCop-84 copper-alloy components (see example in Fig.1). To overcome this issue, Owen Hildreth at Colorado School of Mines (CSM) recently demonstrated a process to dissolve residual powder and support structures in a self-terminating manner that works independent of component geometry. The process is capable of removing powder and supports from extremely high-aspect ratio channels and integrates seamlessly with existing SLM printing technologies and processes. This project will adapt Hildreth's technology to work with GRCop-84 copper alloys to eliminate the residual powder issues and reduce component lead-time by weeks or months.

## ACCOMPLISHMENTS

This project will support the development of self-terminating etching processes for GRCop-84 components fabricated using SLM AM techniques for applications in removing trapped powder. After printing, the specimens will be submerged in a solution containing either magnesium salts or elemental sulfur. Next, the component will be heated to high temperatures between 300 °C and 500 °C to drive the sensitizing agent into the top 20–100  $\mu\text{m}$  of the component's surface. Since the typical powder bed fusion (PBF) powder diameters range from 20–50  $\mu\text{m}$ , any trapped powder exposed to the sensitizing agent should be completely sensitized. Next, the sensitized region will be dissolved using electrochemical processes designed to selectively remove the sensitized regions while keeping the base component material cathodically protected (Fig. 2(a)). Since only sensitized region are dissolved, the component loses only a small amount of material even over excessively long etch times (Fig. 2(c)). Preliminary tensile data shows no difference when compared to mechanically processed samples.

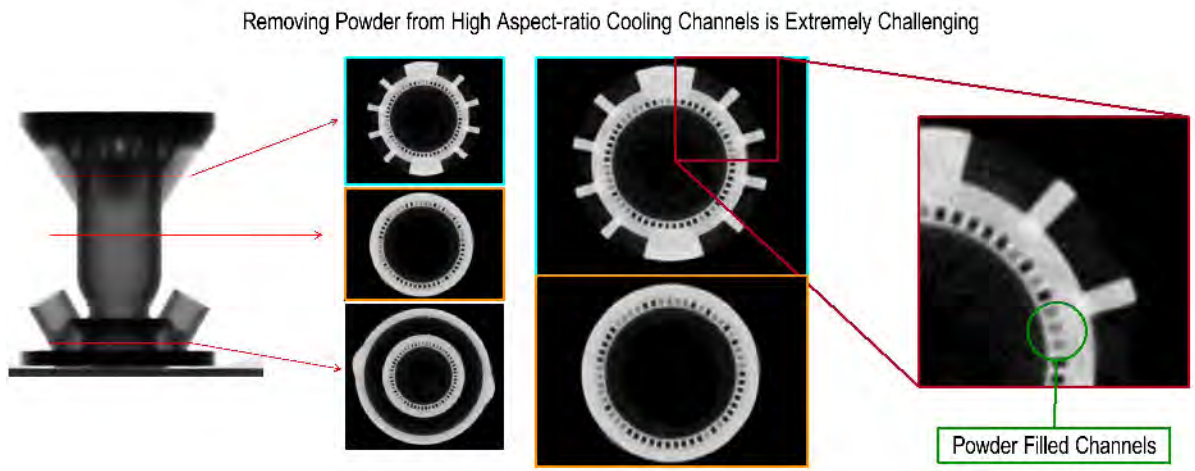
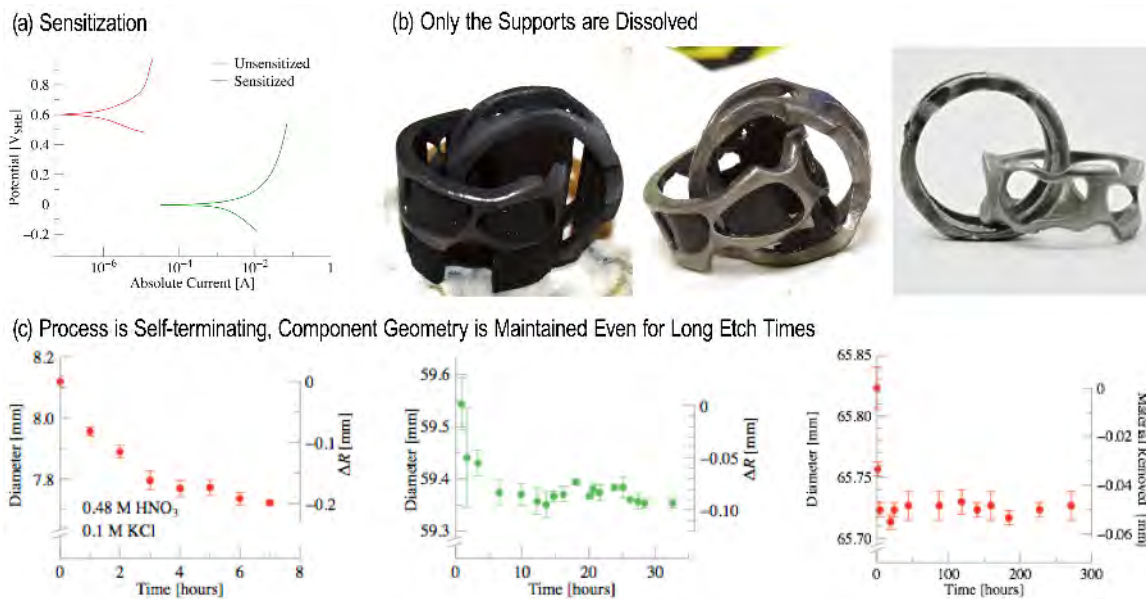


FIGURE 1. This project will address the issue of trapped powder in SLM-processed GRCop-84 components.



**FIGURE 2.** (a) Potentiodynamic polarization curves of the base component material (unsensitized, red) and the sensitized region (green); (b) example showing that the supports are selectively dissolved while (c) the dimensions of the component change minimally (50–200  $\mu\text{m}$  depending on sensitization depth) independent of etch time.

The proposed project will: (1) generate an initial set of processes and chemistries to selectively dissolve trapped powder and support structures for GRCop-84 copper-alloys; and (2) generate data assessing impacts mechanical properties, including tensile strength, and surface finish. These data will be used to identify if and how processing parameters need to be modified along with how much additional research is needed before this technology could be integrated into SLM processing guidelines and used by NASA to improve component performance.

To date, CSM has focused on developing proof-of-principle sensitization and etching processes. Initially, CSM conducted a literature review on the sulfidation of copper alloys in both liquid and vapor-phase sulfur. These studies revealed that two copper sulfides are likely to form depending on temperature, with copper sulfide ( $\text{CuS}_2$ ) forming at temperatures below  $350^\circ\text{C}$  and copper monosulfide ( $\text{CuS}$ ) formed at temperatures above  $400^\circ\text{C}$ . Next, CSM has started testing initial experiments to sulfurize copper samples wet jet cut from a sheet of copper. We tested sulfurization at  $150\text{--}200^\circ\text{C}$  in liquid sulfur to sulfidize between  $660\ \mu\text{m}$  and  $1,990\ \mu\text{m}$  of copper. These experiments verified that copper sulfurizes extremely quickly. This rapid sulfurization of copper makes process control difficult at the temperatures necessary to form the smoother  $\text{CuS}$  films. Instead, CSM is currently testing a two-step sulfurization process where an

initial  $\text{CuS}_2$  film is formed at lower temperatures (below  $200^\circ\text{C}$ ) to better control the sulfur dose followed a high temperature annealing in an inert environment to transform the  $\text{CuS}_2$  to  $\text{CuS}$ . This should allow CSM to control both the sulfurization depth and produce a reasonably smooth surface ( $R_a \leq 5\ \mu\text{m}$  initial target).

## SUMMARY

In summary, CSM has started proof-of-principle sulfurization processes. These initial experiments help bound the processing conditions and informed future process development. Specifically, the high sulfurization rates of copper alloys CSM observed confirms that directly forming a  $\text{CuS}$  film is not feasible from a process control standpoint. CSM is currently testing a two-step sulfurization process to provide increased control and smooth surfaces. CSM will continue developing the sulfurization process and then start developing an etching process to selectively etch stop at the GRCop-84/copper sulfide interface.

**PRINCIPAL INVESTIGATORS:** Owen Hildreth, Colorado School of Mines; Robin Osborne and Paul Gradl, NASA MSFC

**PARTNER:** Colorado School of Mines

**FUNDING ORGANIZATION:** Cooperative Agreement Notice

# Motion Magnification

**OBJECTIVE:** *To develop an imagery system and algorithms that can be used to determine the mode shapes and frequencies of a structure during vibration testing.*

## PROJECT DESCRIPTION

Traditional structural testing relies on accelerometers and strain gages to measure motion from an applied input force. These sensors are accurate and sensitive to small motions, but they have the following downsides:

- They only gather data at discrete locations on the test article.
- The installation of the sensors on large structures is a time-consuming process.
- The sensors add mass that changes the structural dynamics of lightweight structures.

One method of gathering the full-field motion data of the structure without changing the dynamic response is through the use of video cameras. A new technique called motion magnification allows for quick and easy visualization of the dynamic structural response. The goals of this project are (a) to mature the NASA Marshall Space Flight Center (MSFC) software tools that enable the user to measure and easily visualize the motion and b) to use motion magnification as dynamic tests of space structures.

## ACCOMPLISHMENTS

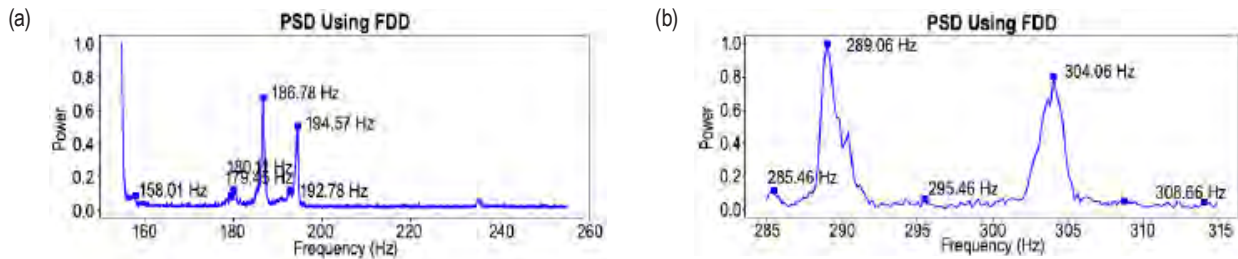
This project uses phase-based motion magnification (REF) to identify the modal frequencies of the system and to amplify the motion associated with the modal frequencies. Phase-based motion magnification uses a complex steerable pyramid to determine the local spatial phase change between images. The local spatial phase is used to determine the motion of the structure, and it can be amplified and added back into the video so that the structural motion is easily visualized.

Motion magnification has been used in the laboratory setting under ideal conditions but has not been used on large space structures prior to this project. This project aims to use phase-based motion magnification to identify the modal frequencies and mode shapes of a structure.

Toward the goal of using motion magnification on large space structures, motion magnification was used on two space structure dynamic tests: the Space Launch System core stage liquid oxygen (LOX) dome modal test and the Imaging X-ray Polarimetry Explorer (IXPE) mirror module assembly (MMA) base excitation test.



**FIGURE 1.** Image of the LOX forward dome during installation of the manhole cover.



**FIGURE 2.** Power spectral density plot showing IXPE resonances from: (a) 155–240 Hz and (b) 285–315 Hz.

For the LOX dome test, an impact hammer was used to excite the structure to collect modal data of the forward dome, particularly in the region surrounding the manhole cover as is seen in Figure 1. Motion magnification predicted the first dome mode frequency to within 0.2% and the second dome mode frequency to within 7% of the accelerometer data. The increased error in the second mode is likely because the type of excitation (impact hammer) does not provide adequate excitation across the frequency band of interest for motion magnification; therefore, outside noise has an oversized influence on the mode frequency prediction.

During the IXPE test, the MMA was excited through base excitation using a sine sweep approach. Figure 2 shows the response of the structure during two sine sweeps: one from 155–240 Hz (Fig. 2(a)) and one from 285–315 Hz (Fig. 2(b)). The peaks show a large structural response during the sine sweep, which is indicative of modal resonances of the structure. The focus of the test was the modes of the mirror shells, which are thin metallic cylinders, and their response would change if accelerometers were added to the structure. Therefore, no accelerometer data was available to compare with the motion magnification results, but the frequencies and mode shapes identified were consistent with those from the pre-test finite element model.

## SUMMARY

Motion magnification has been successfully implemented at MSFC and has been used on two large-scale modal tests: the LOX dome modal test and the IXPE MMA base shake test. Motion magnification was able to accurately identify the first two modes of the LOX dome and many modes of the IXPE structure.

**PRINCIPAL INVESTIGATOR:** Eric C. Stewart

**PARTNERS:** MIT Lincoln Labs

**FUNDING ORGANIZATION:** Seedling Investment Program



# Composite Technology for Exploration

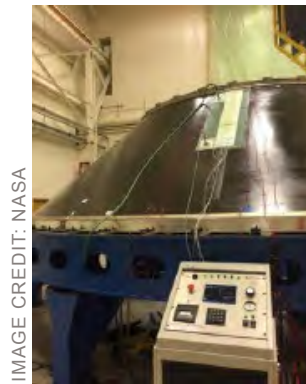
**OBJECTIVE:** *To advance composite technologies with a focus on weight-saving, performance-enhancing bonded joint innovations for heavy-lift launch vehicle-scale applications to support future NASA exploration missions.*

## PROJECT DESCRIPTION

The Composite Technology for Exploration (CTE) project is developing and demonstrating critical composite technologies for future NASA exploration missions with a focus on composite joint technologies for Space Launch System (SLS)-scale composite hardware. CTE is improving the analytical capabilities required to predict failure modes in composite structures. It supports SLS payload adapters and fittings by maturing composite bonded joint technology (longitudinal and circumferential) and analytical tools to enable risk reduction. Composite joints can account for significant increases in cost and weight. Through materials characterization studies, advanced analysis tools, and the design, manufacturing, and testing of lightweight composite bonded joint concepts, CTE is producing weight-saving, performance-enhancing composite bonded joint technologies. CTE is developing and validating high-fidelity analysis tools and standards for predicting failure and residual strength of composite bonded joints. By applying this comprehensive approach, composite technology will progress and improve bonded joint failure load and mode predictions to help reduce knockdown factors and increase overall confidence of bonded joint composite structures.

## ACCOMPLISHMENTS

When properly designed, composite structures have many potential benefits over traditional metallic structures, including lower mass, better fatigue resistance, lower part count, and reduced life-cycle cost. NASA plans to advance composite technologies that provide lightweight structures to support future exploration missions. Due to the large diameter of a heavy-lift type launch vehicle and the unavailability of large autoclaves for curing composite structures, individual large composite panels must be manufactured separately and then



**FIGURE 1.** A longitudinal bonded joint curing on the SLS Payload Adapter (PLA) Manufacturing Demonstration Article (MDA).

joined together. The state-of-the-art method for joining launch vehicle composite panels and structures is metallic joints that are both heavy and labor intensive. Through CTE, NASA is gaining experience on developing lightweight composite joints and analysis techniques specifically applicable to large-scale composite structures. CTE has designed, fabricated, and tested a lightweight bonded joint concept for the SLS Payload Adapter. The project is also developing and validating high-fidelity analysis tools/modeling and analysis standards for the prediction of failure and residual strength of composite bonded joints.

## LONGITUDINAL BONDED JOINTS

After successfully predicting failure in longitudinal joints through analysis and test and demonstrating an out-of-oven manufacturing process for longitudinal bonded joints on the SLS Manufacturing Demonstration Article (MDA), longitudinal bonded joints were baselined by the SLS Payload Adapter to reduce weight and manufacturing time (Fig. 1). Testing included coupon-level specimens and two large-scale panels. All test specimens failed above the CTE point design limit load with a 2.0 factor of safety. For the coupon-level specimens, pre- and post-test correlations were within 8% of the average test data for both pristine and damaged specimens. Large-scale panel buckling tests showed that composite bonded joints are predictable and reliable under buckling load, and both pristine and damaged joints met fracture critical joint performance requirements.

## CIRCUMFERENTIAL BONDED JOINTS

IMAGE CREDIT: NASA



**FIGURE 2.** Infused and cured 36" C-channel.

CTE focused on advancing 3D-woven composites for use in circumferential bonded joints. A circumferential bonded joint includes a C-channel and pi-preform bonded together. Resin-transfer molding (RTM) process

is used to infuse and cure the 'dry' 3D-woven C-channel. Both 12-in and 36-in C-channel parts were manufactured (Fig. 2). From the manufactured C-channels and pi-preforms, circumferential joint subelement concept test articles were designed, analyzed and tested. Each test article was subject to three load cases: bending, tension, and compression. All test articles failed above twice the design limit load. Future work includes understanding and damage in 3D-woven composites, specifically the complex geometry related to C-channels. Continued development of the manufacturing process and testing will support this goal.

## SUMMARY

The potential benefits of CTE's composite joints technology development activities include weight savings, cost savings, and improved performance with increased reliability compared to metallic structures/joints. The project will enable the technology infusion of lightweight composite joints into future exploration missions. CTE is working to achieve these potential benefits by developing and validating high-fidelity analytical tools and standards for predicting failure and the residual strength of composite bonded joints. This allows for a tailored approach to reducing the safety factor for composite discontinuities while still reducing risks and increasing confidence in composite joint technologies.

**PRINCIPAL INVESTIGATORS:** John Fikes and Mallory Johnston

**PARTNERS:** NASA Langley Research Center, NASA Goddard Space Flight Center, NASA Glenn Research Center

**FUNDING ORGANIZATION:** Game Changing Development

**FOR MORE INFORMATION:** <https://gameon.nasa.gov/projects/composite-technology-for-exploration-cte/>



# Rapid Analysis and Manufacturing Propulsion Technology (RAMPT)

**OBJECTIVE:** *To reduce design and assembly schedules while allowing for reduced parts, increased reliability, and significant weight reduction; creating a healthy American supply chain for large-scale, regeneratively cooled liquid rocket engines.*

## PROJECT DESCRIPTION

The Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) project will develop and advance large-scale and lightweight, regeneratively cooled liquid rocket engine components utilizing multimetallic freeform manufacturing and composite overwrap techniques as well as analysis capabilities required to implement them to reduce design and fabrication cycles. RAMPT will reduce design, fabrication, assembly schedules while allowing for reduced parts, increased reliability, significant weight reduction and create a healthy American supply chain.



**FIGURE 1.** 1,200 lbf thrust subscale regen-cooled engine cut-away view showing copper-based alloy TCA, directed energy deposition nozzle, and composite overwrap.

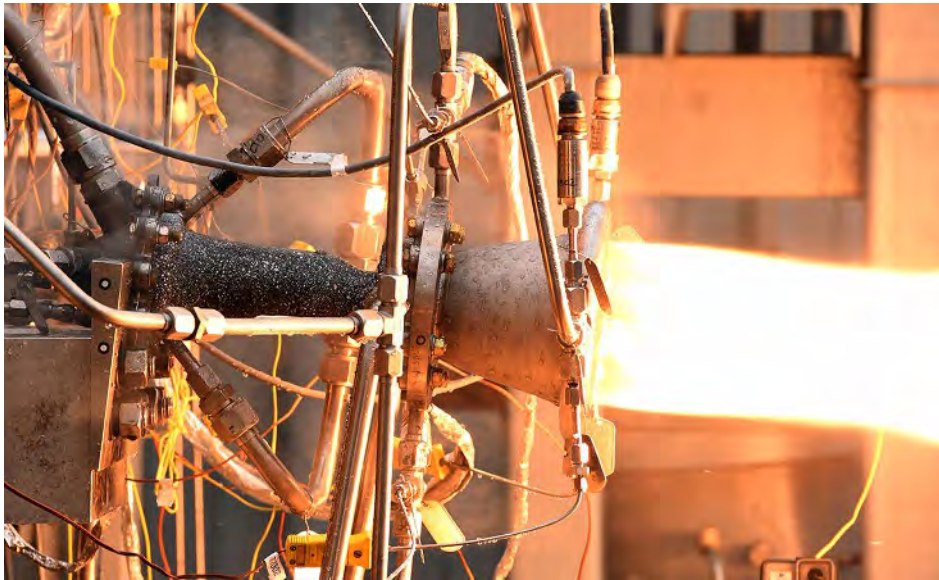
chamber assemblies, 3) to engage manufacturing community organizations in the development effort and facilitate infusion of technology into the commercial industry.

## ACCOMPLISHMENTS

The RAMPT project will focus on advancing the following technical areas: 1) freeform deposition (direct energy deposition (DED)) additive manufacturing techniques to fabricate an integrated regeneratively cooled channel wall nozzle structure, 2) composite overwrap techniques to significantly reduce weight and provide structural capability for a large Thrust Chamber Assembly (TCA), 3) bimetallic and multimetallic additive manufacturing and deposition techniques, including copper-alloy to superalloy transitions to optimize material performance, 4) advance modeling and simulations of large-scale deposition techniques to obtain optimal property predictions, material designs, and develop smart tool-paths to reduce distortion and provide acceptable components, and 5) develop an integrated regen-cooled combustion chamber and nozzle design tool to significantly reduce design cycles and take full advantage of additive technologies.

Along with utilizing NASA's subject matter experts across the agency, public-private partnerships with specialty manufacturing vendors contribute to the success of the project by completing manufacturing process developments to enable a long-term supply chain available to government and commercial rocket industry.

Several milestones were completed that show progress toward meeting overall project goals. Hot-fire testing of 1,200-lbf-thrust-scale engines demonstrated feasibility of a blown-powder DED nozzle, confirmed composite overwrap process development, and helped anchor models and validate new design tools. Blown-powder DED nozzle-onto-copper-chamber process development was carried out, and 1,200-lbf-thrust-scale manufacturing demonstrators were produced at



**FIGURE 2.** Hot-fire testing demonstrated feasibility of blown powder directed energy deposition (DED) with Inconel 625 nozzle with additively manufactured copper-based alloy combustion chamber and additively manufactured injector.

DED process. The HR-1 material is hydrogen resistant and provides high strength.

NASA also has Auburn University under contract to develop and operate the RAMPT public-private partnership with specialty manufacturing vendors to enable a long-term supply chain available to government and commercial rocket industry.

a vendor selected for public-private partnership. The bimetallic interface remained intact after full build of the nozzle and after stress-relief processing indicating a qualitatively good joint. The feature sizes for coolant channels and coolant fabrication processes for coolant inlet and outlet features have been successfully developed and demonstrated. Composite overwrap process development was carried out, and hot-fire testing validated load containment in critical regions. The first iteration of Chamber Design Tool to be developed and used to accommodate and accelerate additive subscale design was completed. The Chamber Design Tool was evaluated by combustion devices experts and data on actively cooled additive parts in a relevant environment was collected in subscale testing. NASA-developed NASA iron-nickel-chromium-cobalt-titanium (HR-1) is the baseline material for the channel-cooled nozzle using blown-powder

## SUMMARY

RAMPT impacts all phases of the engine Thrust Chamber Assembly (TCA) life cycle by addressing the longest lead, highest cost and heaviest component in regeneratively cooled rocket engines. Hot-fire testing of RAMPT's 1,200-lbf composite overwrap combustion chamber demonstrated feasibility of core key technology areas.

**PRINCIPAL INVESTIGATOR:** John Fikes

**PARTNER:** Auburn University

**FUNDING ORGANIZATION:** Game Changing Development



# Ionic Liquid Epoxy for Joining of Cryofluid Handling Plumbing

**OBJECTIVE:** *To investigate the suitability of using a novel epoxy formulation based on ionic liquids as a cryogenic adhesive to bond cryogenic fuel composite feedline components.*

## PROJECT DESCRIPTION

Current cryofluid handling systems use metallic—thus heavy—hardware. The replacement of this hardware with composite structures has met some success but is still limited by the need to use metallic interfaces to join components. One solution to this is to use polymer adhesives to join these structures, but to date, the reliability and mechanical properties of such adhesives in a cryogenic environment are poor. This work evaluated the use of an ionic liquid epoxy (ILE) to bond composite structures. ILEs have previously been shown to possess excellent mechanic properties under cryogenic conditions and to bond to materials that are difficult to bond to such as Kapton® and Teflon™. The elimination of metallic interfaces will significantly reduce the mass of the joints. Additionally, such a joint is less bulky, allowing for easier reliability and verification checks through nondestructive testing (NDT).

## ACCOMPLISHMENTS

A promising alternative to the mechanical joining of cryofluid composite structures is the use of adhesives. As this allows for the pieces to be directly joined, no additional mass is required. The primary obstacle to using this approach is that nearly all commercially available adhesives are not suited for use at cryogenic temperatures. Polyurethane (PU) adhesives are used for the cryogenic handling of liquefied natural gas ( $T_b = -162\text{ }^\circ\text{C}$ ), but this temperature is significantly higher than those required for liquid oxygen ( $T_b = -183\text{ }^\circ\text{C}$ ) or hydrogen ( $T_b = -252\text{ }^\circ\text{C}$ ). Polyurethane adhesives also have low strength—although this increases at cryogenic temperatures—absorb water, and become brittle below their glass transition temperature. This project seeks to meet this need by developing a novel ionic liquid-based epoxy suitable

for use under cryogenic conditions by completing the following objectives; developing the methods and materials for creating adhesive bonds using ILE; and evaluating the performance of the ILE adhesive under cryogenic conditions.

Methods to bond composite to composite and composite to metals (titanium, aluminum, and stainless steel) using ILE were developed, with some examples shown in Figure 1. The ILE readily adhered to all materials, but the geometry of the bond, such as the spacing between the two pieces of tubing, was found to be highly important. Additionally, the material properties of the ILE adhesive were characterized through lap shear testing.

Once the bonded specimens were prepared, they were subjected to liquid nitrogen cryoshock testing, where the pieces were submerged in liquid nitrogen to rapidly cool them and then allowed to slowly heat back to ambient temperature. The quality of these bonds after cryoshock were then evaluated using compressed air and x-ray radiography. The composite-to-composite bonds all passed this testing, as well as the titanium-to-composite bonds. The stainless steel to composite bonds had intermittent delamination, and all of the composite to aluminum bonds exhibited cracking, as shown in Figure 2. These failures are explained by the mismatch in the coefficient of thermal expansion (CTE) for the materials, with higher mismatches correlating to more cracking. Note that the configuration of these first joints, specifically the insertion of metal tubing inside a composite ferrule, may have promoted the delamination of the adhesive. Specifically, the higher CTE of the metals means that these materials shrink more than the composite. Thus, when chilled, the metals pull away from the composite, promoting the formation of

cracks. New bonds, with the metals placed on the outside of the composite ferrule have been prepared. Future work will evaluate the performance of this new bond configuration after liquid hydrogen cryoshock testing and will also study the effect repeated cryogenic cycling has on the bonds.

## **SUMMARY**

The adhesive joining of composite plumbing used for cryofluid handling is an incredibly promising route to reduce the mass of spacecraft, thus enhancing NASA's exploration capabilities. Additionally, the adhesive joining of such structures lends itself well for in space assembly, as the hardware required for such a joining is minimal. However, there are no commercially available adhesives suitable for use in this role. A new class of adhesive, ILE, has been evaluated for use under cryogenic conditions and shown to produce acceptable bonds for both composite to composite joining, as well as composite to titanium joining. Correct design of the joint configuration however is critically important to prevent bond failure due to stresses induced by mismatches in the coefficients of thermal expansion when joining dissimilar materials.

**PRINCIPAL INVESTIGATOR:** Eric Fox

**FUNDING ORGANIZATION:** Center Innovation Fund



# Damage Tolerance Characterization and Environmental Sensitivity of Custom 465 Alloy to Support NASA Technology

**OBJECTIVE:** To characterize the fracture toughness, crack growth rate, and environmental sensitivity of precipitation hardened Custom 465 stainless steel alloy.

## PROJECT DESCRIPTION

Custom 465 is a high-strength, precipitation-hardened stainless steel alloy. Limited data are available that characterize the strength and damage tolerance behavior of the material at ambient and cold temperatures. Damage tolerance characterization includes fracture toughness and crack growth rate performance of a material, which describe how material with a crack responds to static and cyclic loads. In this study, smooth and notched tensile tests, fracture toughness tests, and crack growth rate tests will be conducted at ambient and cold temperatures to evaluate the strength, notch sensitivity, and damage tolerance behavior of the material.

## ACCOMPLISHMENTS

Evaluation of the strength, notch sensitivity, and damage tolerance properties of the alloy will open the design space for the material by providing data that is not currently available in the literature. This data can be incorporated into standard strength and safe life analysis of the hardware. Availability of this data will enable consideration of the alloy for use in fracture critical hardware and for hardware subjected to cold environments. Typically high-strength precipitation hardened stainless steel alloys have limited use at cold temperatures due to loss of ductility. Existing data does not address performance at cold temperatures.

Additionally, fracture toughness test data will be collected over a range of test sample geometries to evaluate the variation in the toughness of the material with constraint conditions. Test data from this portion of the study will be examined

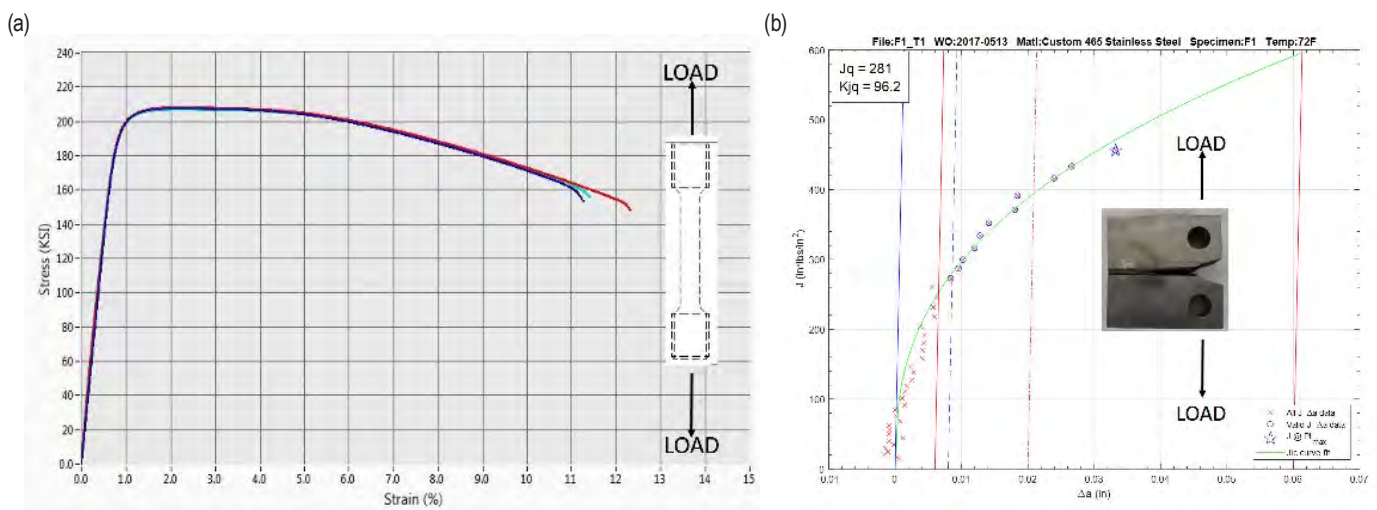


FIGURE 1. (a) Tensile response of Custom 465. (b) Fracture response of Custom 465.

using criteria related to the development of a size insensitive linear-elastic fracture toughness measurement technique being developed by researchers affiliated with ASTM International, an industry standards organization. Data collected in this study will address the applicability of the proposed size insensitive criteria to high strength alloys.

Data collected to date are limited. Smooth and notched tensile tests and a subset of the fracture toughness tests have been conducted at ambient temperatures. Preliminary assessment of the notch testing indicates the alloy at room temperature exhibits notch strengthening behavior. This is atypical of many high strength alloys and suggests favorable material capability in the presence of stress concentrations.

## **SUMMARY**

Test plans have been developed to evaluate the strength and damage tolerance behavior of precipitation hardened Custom 465 stainless steel alloy. Limited data have been collected to date, but preliminary assessment indicates good fracture toughness to strength ratios and favorable notch strengthening behavior.

**PRINCIPAL INVESTIGATORS:** Aaron Adams, Alabama A&M University, Preston McGill, Marshall Space Flight Center

**PARTNER:** Alabama A&M University

**FUNDING ORGANIZATION:** Cooperative Agreement Notice



# Space Environmental Effects

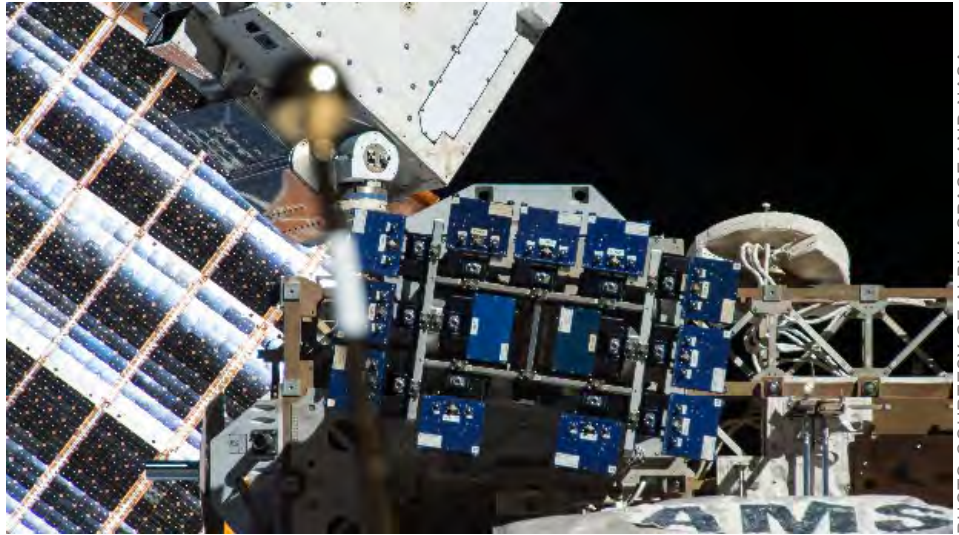
**OBJECTIVE:** *To modify space environment simulators for higher fidelity to actual space environment and characterize the improved performance by testing additively manufactured materials samples. Provide multi-program support by testing innovative materials for durability in the space environment.*

## PROJECT DESCRIPTION

A previous effort had focused on how durable 3D-printed materials might be in the space environment using ground test facilities. During the testing, improved ultraviolet (UV) radiation sensors were also exposed, and the solar UV radiation simulator was better characterized. One of the UV radiation sensor designs and a variety of additively manufactured material specimens were launched in April 2018 as part of the Materials International Space Station Experiment (MISSE)-9 array of experiments. After a year in space, these were returned to Earth.

A duplicate set of additively manufactured material specimens plus polycarbonate samples were launched in November 2018 and flown as part of the MISSE-10 array of experiments. These are on a different face of the MISSE Flight Facility (Fig. 1), therefore in a different orientation and environmental exposure than the MISSE-9 samples.

A new set of materials was put in place of the MISSE-9 3D-printed materials. This experiment, called Materials Experiment for Long Duration Exploration (MELDE) (Fig. 2) is part of MISSE-11 and was launched in April 2019.



**FIGURE 1.** The MISSE Flight Facility on ISS, loaded with blue experiment carriers and avionics boxes.

PHOTO COURTESY OF ALPHA SPACE AND NASA.

## ACCOMPLISHMENTS

The synergistic effects of the various aspects of the space environment, e.g. atomic oxygen, ultraviolet radiation, particulate radiation, thermal cycling, and vacuum are difficult to model and simulate. Flight experiments such as the MISSE series not only provide needed data on spacecraft material durability in the space environment but also reduce risk by improving ground simulations.

Simulated low Earth orbit exposures in this effort included 5 eV atomic oxygen and UV radiation. These tests provided the erosion yield, or the rate a polymeric material is damaged by atomic oxygen, and also changes in thermo-optical properties for these materials. The optical properties of the materials exposed on MISSE-9 were comparable to the changes seen during the simulated UV tests. Mechanical property changes were not available at time of publication.



**FIGURE 2.** MISSE-11 materials experiment.

The MISSE-9 and MISSE-10 experiments raise the TRL of manufacturing in space and give needed data on the behavior of additively manufactured materials in different aspects of the space environment. The improved UV sensors were successfully flown on the ram, wake, and zenith sides of the MISSE Flight Facility.

Other additively manufactured materials were identified for space environmental effects testing, mostly for electrical components and thermal control. The MISSE-11 experiment MELDE incorporated these and other needed materials such as ionic liquid epoxies, radiation shielding, multi-layer insulation materials, and environmentally-friendly protective coatings.

## **SUMMARY**

This project provided data on the durability of additively manufactured materials in the space environment, to help develop in-space manufacturing capabilities and advance towards more sophisticated parts. At the same time, laboratory simulators were improved for better fidelity to the space environment. Work is continuing on materials needed for long duration exploration of space.

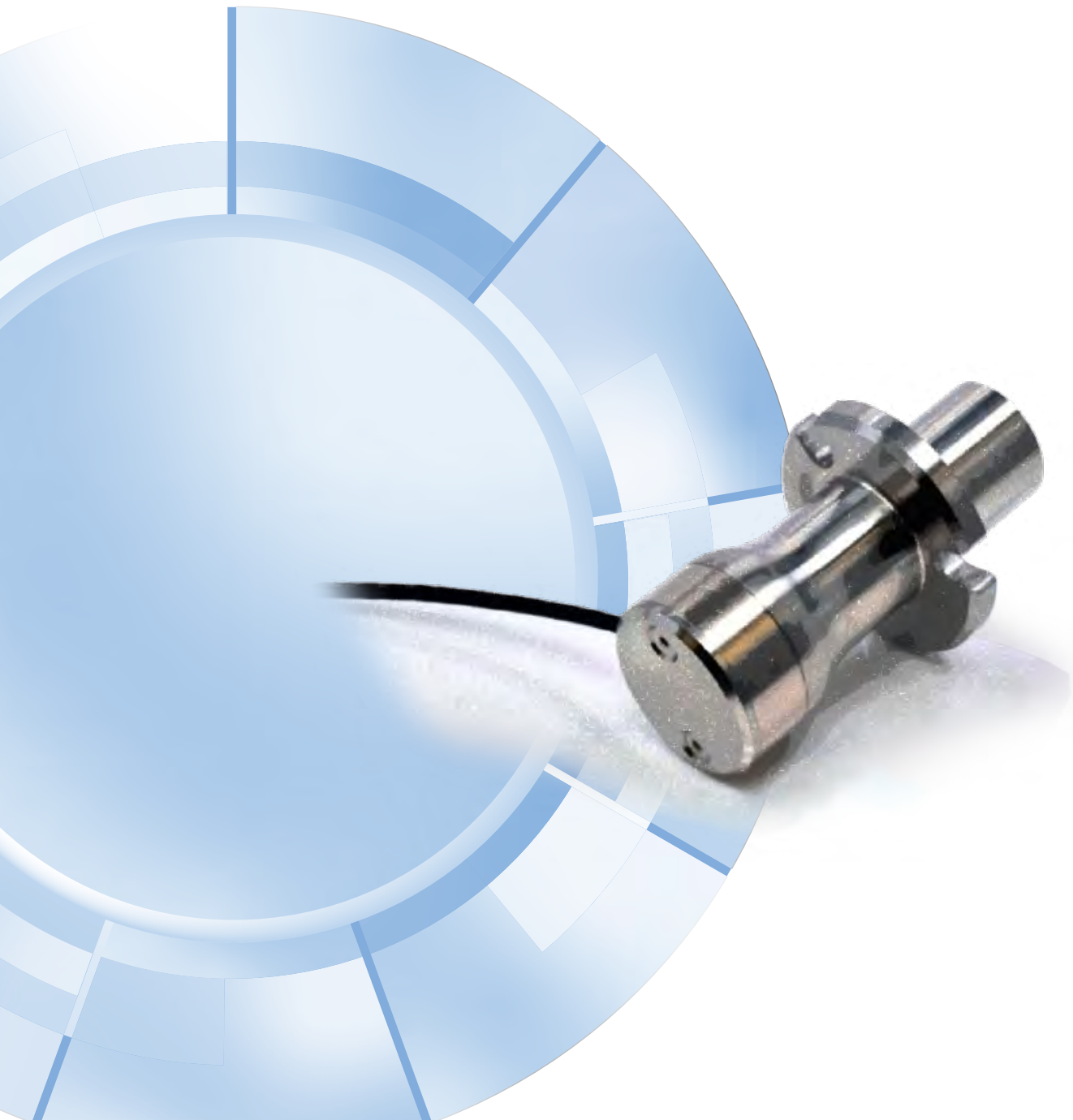
**PROJECT MANAGER:** Miria Finckenor

**FUNDING ORGANIZATION:** Center Strategic Development Steering Group





# THERMAL MANAGEMENT SYSTEMS



# Hot Gas Facility Skin Friction Measurements

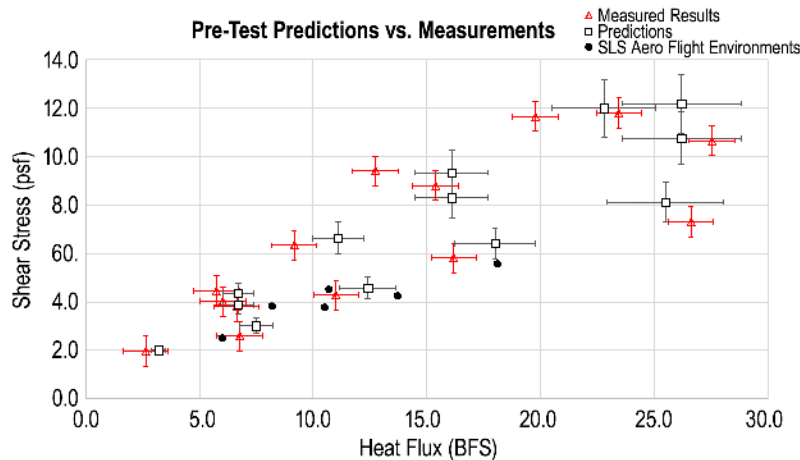
**OBJECTIVE:** To design, integrate and test new skin friction gauges to measure shear stress in the Hot Gas Facility.

## PROJECT DESCRIPTION

This project's plan was to determine if shear stress (skin friction) gauges could be employed in the Improved Hot Gas Facility (HGF) at NASA Marshall Space Flight Center. This is vital for future work because previous HGF tests have indicated that ignoring the impact of shear stress leads to thick and heavy thermal protection system (TPS) designs for launch vehicles. TPS recession rates observed in the HGF are significantly overestimated compared to the recession rates observed in flight (Space Shuttle flights). This results in additional thermal protection being required to meet safety standards and reduces the potential available payload mass. The overarching goal is to more accurately predict TPS recession for launch vehicle ascent environments, adequately define the environments and to minimize conservatism. More specifically, this is to adequately inform the Space Launch System (SLS) where vehicle performance may be enhanced.

## ACCOMPLISHMENTS

The primary technical challenge and risk of this project was to obtain a method to accurately measure shear stress in the high enthalpy environment of the HGF. Traditionally measuring shear stress accurately has proven to be extremely challenging, and when combined with the high enthalpy conditions of the HGF, it becomes significantly more difficult. Many past attempts for measuring shear have been inconclusive or otherwise unreliable.



**FIGURE 1.** (Top) shear stress versus heat flux measurements from shear stress gauges and predictions and compared to SLS environments; (Bottom) picture of the Ahmic skin friction gauge.

The research plan involved was to (1) design and acquire new shear stress gauges, (2) integration into the existing HGF calibration plate and data acquisition system, (3) conduct calibration runs and (4) reduce and analyze the data to determine gauge performance.

The primary results are raw data outputs from the sensors, which can then be analyzed, filtered, and compared to the predictions made based on Reynold's Analogy and oblique shock theory. This new data provided

(1) a more complete HGF environment (shear and heating rates) envelope and (2) performance of the gauges. This could be valuable to other organizations that desire to better understand the flow and shear conditions inside their test facility or to compare with their computational fluid dynamics models using the HGF. In continuing this research, the intent is to acquire more shear stress gauges and perform exhaustive analysis of the HGF and to use the same gauges in the Hyperthermal Test Facility to determine how the gauges perform in much lower shear environments. This near-term follow-on work and a more extensive TPS recession characterization test program will allow to populate recession data in high and low shear environments in which more accurate correlation models can be developed and representative ascent environments obtained. This will significantly move the state of the art forward within the launch vehicle TPS discipline.

Six shear stress gauges were obtained and operated in the HGF. Four of these gauges were unidirectional, and two gauges were bidirectional to provide flow direction. The measurements, as shown in Figure 1, showed good agreement with predictions indicating that the gauges performed well despite the adverse conditions of the HGF. Spectral analysis helped to ensure that the data was valid despite applying filtering algorithms. Filtering the raw data was necessary because the HGF as a Mach 4 combustion driven wind tunnel has significant vibrations, which cause false readings of shear stress on the gauges due to their sensitivity.

## **SUMMARY**

The skin friction gauges were successfully employed at the HGF to measure shear stress. This indicates that continuing this research to develop an improved and more accurate shear-dependent recession rate equation is possible. Accurately measuring shear stress within HGF, having been identified as one the primary technical risks, has been mitigated due to this Technology Investment Program (TIP).

**PRINCIPAL INVESTIGATORS:** David Brewer, Manish Mehta

**FUNDING ORGANIZATION:** Technology Investment Program



# Ultralight Thermal Protection System

**OBJECTIVE:** *To develop a field applied lightweight thermal protection solid film that displaces cork-based ablative applications.*

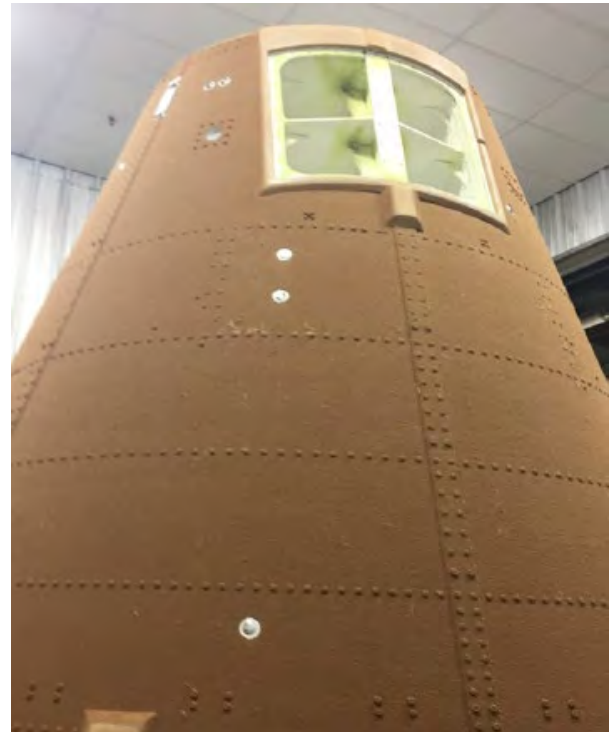
## PROJECT DESCRIPTION

The objectives of this project were to formulate a revolutionary high-temperature Thermal Protection System (TPS) and perform a limited evaluation of the performance. TPS material advancements support cross-cutting applications including launch vehicle ascent; manned and unmanned missions; propulsion and space transport; lander systems and space habitats; cryogenic fluid storage and transport TPS. This TPS is targeted to be suitable to protect heat sensitive components exposed to high temperature transient environments by maintaining substrate temperatures below 200 °F. The primary objective was to generate formulations that are lighter than traditional cork-based ablatives while allowing sprayable application of the coating.

### APPROACH/INNOVATION

During formulation, the first screening point was for weight reduction. While it is obvious that a reduction in density will result in weight savings, it is also true that insulation efficiency will increase as thermal conductivity is decreased. Low thermal conductivity requires less thickness of material to achieve a required level of insulation even at the same density. The formulation desire was to achieve improvement in both these properties thereby producing significant weight reduction. The resultant coating formulations are insulating sprayable ablators (ISA). Potential applications range from sprayable insulation to weight saving high temperature protection through the ablation mechanism.

Sprayable coatings have many production advantages. One key advantage is that they can cover a large surface area of complex geometry in a relatively short time. Therefore, another key approach was to evaluate whether these formulations were compatible with spraying equipment. The coatings were sprayed onto test panels using a batch process and commercially available spray equipment. This provides an entry

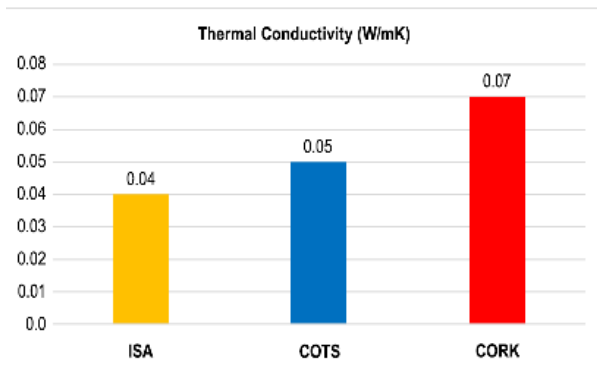


**FIGURE 1.** Example of ultra-lightweight TPS coating applied to a structure.

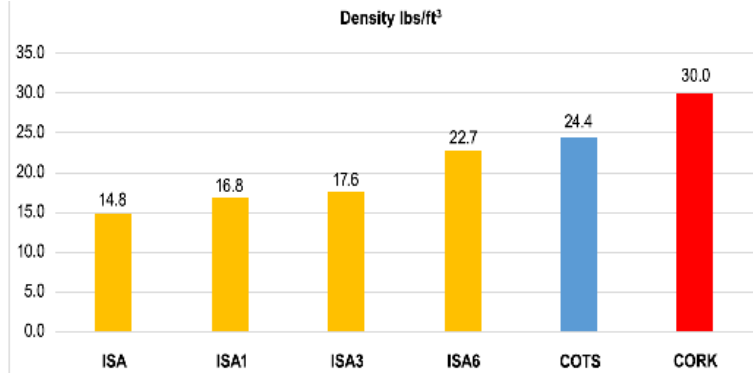
investment advantage over sprayable cork ablators that utilize the convergent spray process that requires complex spray equipment. Additionally, by being sprayable, this coating maintains the advantage of complex 3D shape conformity which is difficult to achieve with bonded on cork sheets.

A challenge with sprayable coatings is environmental compliance. Volatile organic compound (VOC) limits are imposed by the Environmental Protection Agency, state agencies and local communities. This coating utilizes a water-based resin system that avoids these limitations and resulted in ‘as applied’ formulations less than 50 g/l VOC.

This next step for this project is to partner with industry or government organizations in need of further developing the technology for specific applications.



**FIGURE 2.** Thermal conductivity for environmentally friendly spray formulation.



**FIGURE 3.** Density for environmentally friendly spray formulation.

## ACCOMPLISHMENTS

This revolutionary high-temperature cork-ablative replacement TPS is significantly lighter than cork-based ablatives, while also being an environmentally friendly spray able formulation. Figures 2 and 3 compare the results of measured thermal conductivity and density for these formulas (ISA). The ISA formulas are compared to a commercially available insulation coating (COTS) and traditional cork. As can be seen, the ISA coatings have the lowest thermal conductivity and density. It therefore takes less of this coating to achieve the same insulation value of the COTS or cork materials.

Performance was also evaluated for simulated launch or descent environments. The coatings were subjected to 450 BTU/ft<sup>2</sup> heat loads at Mach4 airflow plus heating rates of 5 BTU/ft<sup>2</sup>s and 10 BTU/ft<sup>2</sup>s. The effect of this exposure to the ISA2 formulation is shown in the figure to the right. It can be seen that the surface has minimal damage but has begun to char and ablate. The resultant weight losses were 7.2% and 10.9% respectively. This shows

the mechanism of ablation was helpful to further protect the substrate from the extreme exposure environment beyond the insulation impact of this ultra-low thermal conduction material.

## SUMMARY

The ISA developed through this effort show promise for cross-cutting applications within aerospace and general industry. The coatings have excellent insulation capability due to their low density and low thermal conductivity. This TPS is capable of protecting low temperature substrates such as aluminum or composites from exposure environments in excess of 500 °C. These low VOC coatings can be applied with commercially available batch process spray equipment thereby opening access of this technology to a wide variety of users and application scenarios.

**PRINCIPAL INVESTIGATOR:** John Bloyer

**PARTNER:** NASA Glenn Research Center

**FUNDING ORGANIZATION:** Center Innovation Fund

ISA2 Formulation Ascent Thermal Performance.



**FIGURE 4.** Visual comparison of TPS before and after exposure to heat.



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