National Aeronautics and
Space Administration

NASA/TM—20230000685

Marshall Space Flight Center

2022

Research & Technology Report

NASA/TM—20230000685
Marshall Space Flight Center
Research & Technology Report
2022

NASA/TM–20230000685

Marshall Space Flight Center

Research and Technology Report 2022

J.W. Dankanich, R.L. Frederick, 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, Rebekah Frederick, and Heather Morris. The MSFC Office of Center Chief Technologist recognizes Jason Shoemate, Kathleen Hotchkiss, 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 Rebekah Frederick provided the support, insights, and decisions required for the compilation of this TM.

Trademarks

For additional copies of this report contact:

NASA STI Information Desk
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681–2199, USA

757–864–9658

This report is available in electronic form at
<http://www.sti.nasa.gov>

Foreword

This year, we accomplished so much at Marshall Space Flight Center and across the Agency. The Artemis I mission grabbed the headlines with a successful November launch and splashdown of Orion. Along with the historic Artemis I mission completion, there were so many other milestones that our center was critical to making happen. From managing the Imaging X-ray Polarimetry Explorer (IXPE) and seeing its groundbreaking scientific discoveries to developing the foundational technology solutions, skills, and capabilities for a sustained lunar presence, our diverse technology teams at Marshall never cease to amaze me.

One of the biggest missions NASA will accomplish in the coming years is sending humans back to the Moon and helping enable the first human missions to Mars. None of that will be possible without Marshall's scientists and engineers that are developing the technologies to make those visions a reality. Sustainable lunar exploration and pushing the boundaries of science and technology will require the best of our talented workforce.

Teams at Marshall are at the forefront of advancing capabilities for the most challenging missions to explore the Moon, Mars and beyond. I'm proud to say that we have subject matter experts in technology areas that will be among the most critical to NASA's Moon to Mars missions. The scientists and engineers at our center are world-leaders in innovation and continue to be the reason Marshall is integral to the success of NASA's boldest missions.

As we explore more of the Moon and prepare for Mars, we will need their expertise more than ever to perform the science and technology development required for deep space exploration. Whether it's developing the habitation and life support systems to live and work in space or advancing the technologies that will allow us travel to deep space destinations, everything we do here is because we have a determined team of people making it happen.

Jody Singer

Jody Singer

Center Director
NASA Marshall Space Flight Center

Introduction

The 2022 Research and Technology Annual Report represents what is hopefully the *"new normal"* for portfolio execution. The portfolio took advantage of the best features of the virtual work environment with collaborations across the nation without any geographical constraints. This allowed key partnerships between NASA Marshall Space Flight Center (MSFC) and other NASA centers, other government agencies, industry, and academia. Also, because there were no longer any constraints on laboratory and test capabilities, we were able to make significant progress with hands-on technology development, fabrication and testing that is critical to validating the efficacy of advanced technology.

The return on investment of our 2022 projects is already yielding dividends and will continue to do so for many years. This year, the portfolio highlights Early Career Initiatives (ECIs) with teams of early career employees and external partners that identified novel solutions to enduring NASA challenges. These include lunar thermal design challenges with surviving the lunar night; navigation on the Moon without the use of a Global Positioning System (GPS), in partnership with a Department of Defense contractor; and fundamental materials advancement for mechanisms in the lunar environment. Past ECI investments are now delivering flight hardware with new enabling capabilities. Also, MSFC successfully completed Center Innovation Fund (CIF) projects achieving the most significant breakthroughs in chemical propulsion in decades, which graduated to a new ECI project for rotating detonation rocket engine (RDRE) development.

I am once again humbled and honored to represent a vast team of innovators that often go beyond expectations and take individual initiatives to both advance our state of knowledge and enable new capabilities for NASA and terrestrial applications with tangible results.

John W. Dankanich

Center Chief Technologist
NASA Marshall Space Flight Center

Table of Contents

Technology Area 01: Propulsion Systems **1**

Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) 2

Development of the Fast-Acting, Deep-Throttling Hybrid Motor 4

Development of Ultra-High-Performance Additively Manufactured Injector Elements 6

Composites in Braided Experimental High-speed Rotation (CiBEHR) Coupling . 9

Improved Actuator for a Pyroless Isolation Valve 12

Adaptable Fluid Dynamometer for Electric Motors (AIDEM) 15

Electromagnetic Solar Sail Coupling (ESSC) 18

Process Development and Characterization of Ruthenium-Based Monolithic Metal Foam Catalyst for Monopropellant Thruster Applications 20

Near-Earth Asteroid Scout 22

Technology Area 03: Power and Energy Storage **25**

All-Printed Flexible Biofuel Cells for Energy Harvesting from Human Sweat 26

The Lightweight Integrated Solar Array and anTenna (LISA-T) Pathfinder Technology Demonstrator 28

SIBatt-3D: In-Space/on-Surface 3D Printing of Sodium Ion Batteries Using In-Situ Materials 30

Technology Area 04: Robotic Systems **33**

ISS Deployment and High-Altitude Descent Drone Landing Using SVGS 34

Technology Area 06: Human Health, Life Support, and Habitation Systems **37**

Parabolic Flight Demonstration of Fluid Dispensing Tube Performance Limits for Drop Delivery 38

Structured Sorbents: Rapid Cycle Temperature Swing Adsorption (RC-TSA) 41

Investigating Autonomous Healing of Cracks in Lightweight, Aerospace-Grade Materials Systems 44

Printable, Molecularly Imprinted Polymers for Cortisol Sensing 48

Early Biofilm Detection in ISS Water Supply Systems Using Impedance Microbiology 50

Investigating the Performance Characteristics of Auxetic Foams in Neuropathy Treatment Applications 52

Development of Non-Platinum Group Metal Catalysts for Hydrogen Resource Recovery 54

Bioremediation of Microgravity Biofilms and Water Processor Health 56

Additive Manufacturing of Fire Retardant and Repairable Composite Structures Based on Lunar Regolith and Vitrimer Epoxy under Lunar Conditions 58

Technology Area 07: Exploration Destination Systems 61

Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) Project 62

Demonstration of a Prototype Design for a Multipurpose Lunar Habitat 65

Extraterrestrial Marangoni Mining 68

Cellular Fabrication (C-Fab©) Materials for In-Situ Lunar Additive Manufacturing and Outfitting 72

Duneflow Lunar Gravity Suborbital Flight 74

Parametric Study of Additive Manufacturing using Martian Regolith Metal Recovered with Ionic Liquids 76

Trichloride Ionic Liquid-Mediated Metal Extraction from Regolith 78

Technology Area 08: Sensors and Instruments 81

Viability Assessment of Printed Powerless Sensors Structures for Aerospace Environments 82

SERVIR ... 85

Advanced Microwave Precipitation Radiometer (AMPR) ... 88

International Space Station Lightning Imaging Sensor (ISS LIS) ... 90

Segmented Mirror Telescope Program (SMTP) ... 92

$CeBr_3$/NaI Phoswich Scintillator Detector Technology ... 94

Moon Burst Energetics All-Sky Monitor (MoonBEAM) ... 96

Scintillation Prediction Observations Research Task (SPORT) ... 98

Extreme-Ultraviolet Stellar Characterization for Atmospheric Physics and Evolution (ESCAPE) Phase A Concept Study ... 100

Materials Development for Additive Manufacture of Radiation Sensors and Shielding ... 102

Technology Area 09: Entry, Descent, and Landing ... 103

Exploring High-Performance Additively Manufactured Rotating Detonation Rocket Engines ... 104

Additively Manufactured Fluidic Diode Injectors for Rotating Detonation Rocket Engines ... 107

Precision Landing of a Hexacopter Drone by Smartphone Video Guidance Sensor ... 110

Technology Area 11: Software, Modeling, Simulation, Information Technology ... 113

BERT-E: Artificial Intelligence-Driven Language Model for Earth Science ... 114

Earthdata Publication Tool ... 116

The Management Office of the Satellite Needs Working Group ... 118

Artificial Intelligence-Driven Reverse Image Search System for Earth Science ... 120

Visualization, Exploration, and Data Analysis (VEDA) ... 122

Machine Learning for Agriculture Crop Damage Identification and Assessment from Intense Thunderstorms ... 124

Technology Area 12: Materials, Structures, Mechanical Systems, and Manufacturing **127**

Metallic Environmentally Resistant Coatings Rapid Innovation Initiative (MERCRII) 128

Rapid Process Development of Aerospace Alloys Using Small Punch Test 131

Additively Manufactured Passive Wireless Sensors with Printed Electronics 134

On-Demand Structural Health Monitoring Sensor Manufacturing for NASA Applications 136

On-Demand Manufacturing of Electronics in Space 138

In-Space Additive Nanomanufacturing and Dry Printing of Multimaterials Electronics 140

Polymer Coatings with Glass Bubbles for Thermal Radiation Control in Space 143

Cost-Effective, High-Temperature Materials Testing 146

Alloy Design for Additive Manufacturing of Crack-Free Tungsten Alloys via Laser Powder Bed Fusion Process 149

Coupling In-Situ Data Analysis with Machine Learning for Characterization of Additively Manufactured Parts 152

Modeling of Self-Reacting Friction Stir Welding to Correlate Predicted Phenomena with Weld Quality and Hardness 154

Advanced Tooling Demonstration for Friction Stir Welding of Heat Resistant Materials 156

Realizing Spatially Resolved, Real-Time Temperature Measurements in Friction Stir Welding Using Ultrasonic Thermometry 158

High Strength Aluminum Scalmalloy® Laser Powder Bed Fusion Additive Manufacturing 160

Software Tools for Effective Use of Additive Manufacturing In-Situ Diagnostic Data 162

Additive Construction at Drake State: Developing the Future Advanced Workforce 165

Additive Manufacturing of Outfitting Components for Lunar Habitat Interior and Exterior 168

Development of Radioluminescent Tritium Material for High Visibility Applications 172

Enhanced Equipment Isolation in Extreme Vibratory Environments Using Rotational Inertial Devices 174

Cavitation Effects on the Structural Dynamics of Turbomachinery Components: Modeling and Experiment 177

In-Situ Synchrotron Characterization of Levitated Aerospace Alloys Under Dynamic Processes for Optimization of Advanced Manufacturing Methods ... 180

On-Demand Manufacturing of Multimaterials 182

Development and Testing of Recyclable and Antimicrobial Materials for Additive Manufacturing 184

Extended-Stroke, Reverse-Operation, Differential-Thermal-Expansion Thermal Switch for Extreme Variable Environments 187

Technology Area 13: Ground Test and Surface Systems 191

Plasma Rapid Oxidation Technique for Extending Component Tenability (PROTECT) 192

Technoloy Area 14: Thermal Management Systems 195

Advanced Thermal Control System Architecture for Exploration 196

Advanced Cryogenic Fluid Management Devices Using Large Scale Additive Manufacturing (AM4CFM) 198

Low-Melting-Point Metallic Suspension Nanocomposite Phase Change Material as a Thermal Management Solution for More Electric Systems 200

Lunar TheRMiS – Lunar Thermal Regulation for Mission Sustainability 202

Technology Area 01

PROPULSION SYSTEMS

Rapid Analysis and Manufacturing Propulsion Technology (RAMPT)

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

PROJECT GOAL/DESCRIPTION

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

APPROACH/INNOVATION

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

RESULTS/ACCOMPLISHMENTS

RAMPT has advanced manufacturing and integration of various scales of hot-fire hardware. The progression of scale allowed for incorporating lessons learned into larger scale hardware with increasing chamber pressures and more challenging thermal and structural loads. With temperatures ranging from –400 °F to 450 °F, hot-fire testing was completed on both the 2k-lbf and 7k-lbf thrust-class decoupled and coupled hardware, which included composite overwrap chambers and LP-DED nozzles with integrated channels. The 40k-lbf decoupled hardware completed hot-fire testing in August 2022. Fabrication of the AM 40k-lbf coupled hardware is complete and is currently undergoing application of a composite overwrap structural jacket over the chamber.

RAMPT printed one of the largest AM nozzles NASA has produced by utilizing LP-DED. With a diameter of 58 in and a height of 72 in, the nozzle was 65% scale of the Space Launch System (SLS) Core Stage RS-25 engine and included integrated cooling channels. RAMPT also printed a full-scale RS-25 nozzle

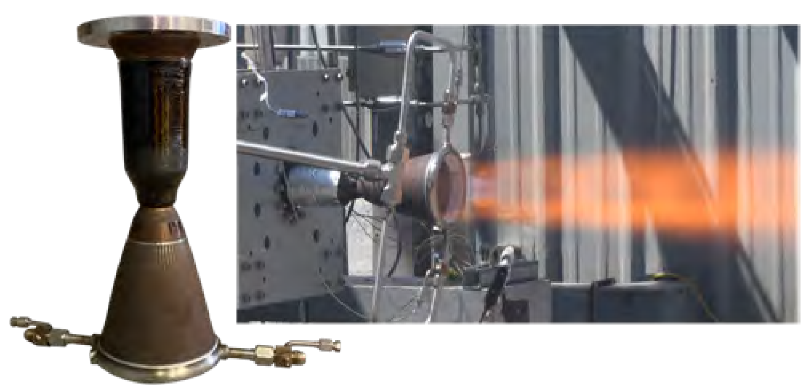


FIGURE 1. 2k-lbf coupled bimetallic AM chamber with composite overwrap completed testing in 90 days.

FIGURE 2. 7k-lbf coupled hardware testing completed.

liner (without channels) with a diameter of 96 in and a height of 111 in. NASA is working with commercial partners and the SLS program on additional work.

Simulations and modeling played a key role in the deposition of the full-scale nozzle liner by informing build strategies that control distortion during print. Computational models predicted residual stresses and distortion, and results were compared across multiple simulation codes. Bimetallic AM material characterization studies are comparing cold spray, LP-DED, and laser hot wire DED cladding processes for manifolds; structural jackets; and coupled chambers and nozzles. Composite overwrap developments have included processing techniques and resin advancements for filament winding and braiding.

PARTNERSHIPS

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

SUMMARY

RAMPT has impacted all lifecycle phases of the regeneratively cooled rocket engine by addressing the longest-lead, highest-cost, and heaviest components. The LP-DED process has completed a series of large-scale manufacturing demonstrators and hot-fire test hardware. Various composite overwrap chamber configurations have evolved. Process development and mechanical testing has advanced bimetallic technology. Modeling has aided critical manufacturing decisions.

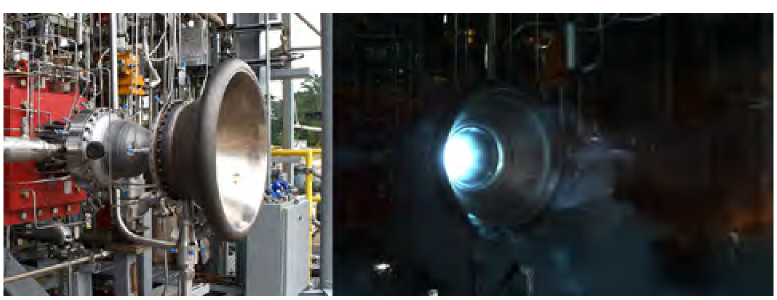


FIGURE 3. 40k-lbf decoupled hardware testing completed.

PRINCIPAL INVESTIGATORS: Paul Gradl, Chris Protz

PARTNERS: Auburn University

FUNDING ORGANIZATION: Game Changing Development

FOR MORE INFORMATION: https://www.nasa.gov/directorates/spacetech/game_changing_development/projects/RAMPT/
https://doi.org/10.1016/j.aime.2022.100084
https://doi.org/10.1007/s11665-022-06850-0
Patent #11333105, Thrust chamber liner and fabrication method therefor: https://patents.justia.com/inventor/paul-r-gradl

Development of the Fast-Acting, Deep-Throttling Hybrid Motor

OBJECTIVE: *To combine NASA Marshall Space Flight Center Valves, Actuators, Lines and Ducts Group's Fact-Acting Digital Valve with Utah State University's Deep-Throttling Hybrid Motor to develop a Fast-Acting, Deep-Throttling Hybrid Motor and determine the thrust response sensitivity to rapidly changing oxidizer flow rates.*

PROJECT GOAL/DESCRIPTION

Hybrid motors have several key advantages over other propulsion systems, such as their inherent safety and environmental friendliness, their system simplicity, and their ability to deeply throttle. The goal of this project is to utilize NASA Marshall Space Flight Center's (MSFC's) Fast-Acting Digital Valve concept in conjunction with Utah State University's Deep-Throttling Hybrid Motor to create a hybrid motor that is capable of rapid full-scale throttling transients. Several concepts within a closed-loop control, such as step inputs, sine wave profiles, and feed-forward control, are to be explored. If successful, this project could have several applications within required spaceflight thrust profiles that enable hybrid motors to be utilized as an equivalent performance alternative to historically used solutions that do not have the key advantages of hybrid motors.

APPROACH/INNOVATION

The MSFC Digital Valve design is capable of achieving throttle commands to all setpoints within its full flow coefficient scale within 10–20 ms and ≈0.75% accuracy of any desired setpoint. A valve with this level of speed and fidelity has, to the best of the collaborators' knowledge, never been tested in conjunction with a hybrid motor. The Utah State University gaseous oxygen (GOX)/acrylonitrile butadiene styrene (ABS) hybrid motor architecture scaled well with the already developed valve, and hot-fire results have shown significant potential with this concept, which could be used for in-space maneuvering and landing efforts as both a main propulsion system and reaction control system with the same motor. Future work includes fabricating a digital valve component with a flightlike mass and volume.

RESULTS/ACCOMPLISHMENTS

A total of 30 open-loop control hot-fires have been completed at Utah State University in 2022. These hot-fires have shown the Fast-Acting, Deep-Throttling Hybrid Motor to be capable of achieving linear throttle control, rapid full scale stepped throttle, and accurate sine wave thrust response at 1 Hz. Hot-fire tests have provided model input data that have shown that the motor should be able to respond to oxidizer throttle inputs up to 8 Hz, which the digital valve system can provide.

PARTNERSHIPS

This project was a collaborative effort between MSFC in Huntsville, Alabama, and Utah State University in Logan, Utah. The Digital Valve was designed and fabricated at MSFC and then shipped to Utah State University for hot-fire testing. MSFC's Valves, Actuators, and Ducts Design and Development Branch and Solid Propulsion and Pyro Devices Branch (Solid and Hybrid Propulsion Team) met biweekly with Utah State University faculty and students to discuss desired hot-fire thrust profiles, test data results, and control concepts. MSFC would like to thank the Utah State University Propulsion Research Laboratory for their interest in the project and for the excellent hot-fire testing campaign and test data analysis.

FIGURE 1. Fast-Acting, Deep-Throttling Hybrid Motor hot-fire test at Utah State University.

SUMMARY

Hybrid motors have several key advantages over other propulsion systems, such as their inherent safety and environmental friendliness; their system simplicity; and their ability to deeply throttle. Historically, quick full-scale throttling of hybrid motors has not been achieved. MSFC's Valves, Lines, and Ducts Design and Development Branch reached out to and formed a collaboration with Utah State University's Propulsion Research Laboratory to test the Fast-Acting, Deep-Throttling Hybrid Motor concept. MSFC provided Utah State University with their Digital Valve component, which is capable of achieving throttle commands to all setpoints within its full flow coefficient scale within 10–20 ms and within ≈0.75% accuracy of any desired throttle position. Utah State University integrated the Digital Valve into their well characterized Deep-Throttling Hybrid Motor test setup. Initial test results show a significant improvement in thrust response. The Digital Valve is capable of adjusting the oxidizer flow rate quickly enough to compensate for a hybrid motors chemical time constant. A total of 30 open-loop control hot-fires have been completed at Utah State University thus far, which have shown that the Fast-Acting, Deep-Throttling Hybrid Motor is capable of achieving linear throttle control, rapid full scale stepped throttle, and accurate sine wave thrust response at 1 Hz. These preliminary hot-fire tests have provided model input data that have shown that the motor should be able to respond to oxidizer throttle inputs up to 8 Hz, which the Digital Valve system can provide. Future work includes hot-fire testing feed-forward control concepts; testing a variety of fuel and oxidizer combinations; and designing and manufacturing a flightlike Digital Valve.

PRINCIPAL INVESTIGATOR: Andrew Smith

PARTNER: Dr. Stephen Whitmore, Utah State University Propulsion Research Labratory

FUNDING ORGANIZATION: Center Innovation Fund

Development of Ultra-High-Performance Additively Manufactured Injector Elements

OBJECTIVE: *A collaborative effort between Auburn University and NASA Marshall Space Flight Center is underway to identify design parameters which will guide the design for future additively manufactured injector element schemes for higher engine theoretical characteristic velocity.*

PROJECT GOAL/DESCRIPTION

Traditionally manufactured (TM) liquid rocket injectors often achieve 90–97% of theoretical characteristic velocity (C*), depending on propellants. However, this still leaves potential performance gains of 3–10% on the table. With the advent of metal additive manufacturing (AM), new injector element schemes not previously possible with TM techniques could reduce these losses in C* performance and simultaneously reduce hardware mass and length requirements. Well atomized and mixed liquid propellants yield high overall combustion efficiency in all types of combustion devices, particularly liquid rocket engines (LREs) and rotating detonation rocket engines (RDREs). The goal of this effort is to enhance and enable NASA Marshall Space Flight Center (MSFC) propulsion system and AM capabilities. To accomplish this, several novel, additively manufactured (AMed) injector elements were designed and produced via laser powder bed fusion (L-PBF) to yield high combustion performance. The spray effectiveness is then characterized via cold flow atomization and mixing experiments. These AMed injector concepts have been printed in collaboration with MSFC and experimentally studied alongside legacy propellant injectors to identify potential performance improvements. In addition, an optically accessible spray test facility was constructed at Auburn University for experimental testing of prototype AMed propellant injectors. This facility integrates MSFC-specific test requirements and can be fully augmented to support future investigations of interest for NASA.

APPROACH/INNOVATION

Production of high-performance AMed injectors face two key challenges: (1) currently, no single culminating effort exists documenting the design and development of novel high-performance AM injector elements; and (2) there exists no standardized methodology for 3D, instantaneous visualization of AM injector spray fields. The experiment, developed in collaboration with MSFC, will provide a major resource to cost-effectively assess AMed injector performances through cold flow spray field characterization without the need for expensive hot-fire testing. The current measurements will, for the first time, provide MSFC with critical data and a new design methodology for additive specific injectors to identify build capability, limitations of build, and design recommendations for future full-scale AM hardware development.

Current injector studies have primarily been assessed qualitatively and require further studies to acquire desired quantitative data. Qualitative results thus far have allowed for injector scheme comparisons of effective atomization and mixing; penetration depth; and liquid jet degeneration depth. Current quantitative results are limited to liquid core identification and dilute spray detection limits. The resulting 3D point cloud will provide information on spray characteristics such as spreading angle, spray field evolution, droplet size, droplet position, and droplet velocity. This will provide a comprehensive characterization of AMed injector

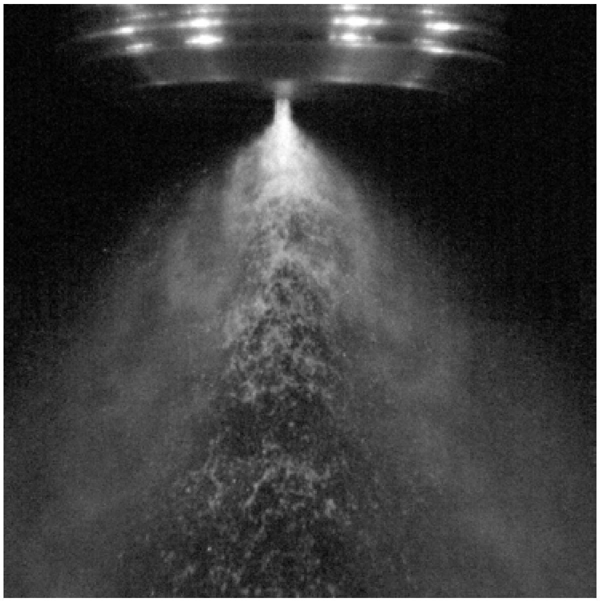


FIGURE 1. Spray testing of high-performance additively manufactured injector element.

spray performance in comparison with traditional injectors. The diagnostic techniques developed here will be applicable to future injector designs for performance mapping.

RESULTS/ACCOMPLISHMENTS

The facility constructed at Auburn University consists of a pressurized water and air system capable of delivering independently varied pressures from 50 – 1,000 psi to an injector ‘plate,’ and an optically accessible ‘combustion’ chamber. The AMed injectors are mounted in the injector plate and supplied with air and water as surrogates for fuel and liquid oxidizer, respectively. Water is contained within a pressure vessel, which is pressurized using compressed nitrogen and plumbed to an injector nozzle situated within an optically accessible spray chamber. Compressed air is provided to a fuel plenum attached to the nozzle. The nozzle spray field is issued into an optically accessible chamber that allows for visualization of the spray field by the stereophotogrammetry imaging system (fig. 1). Stereo imaging provides the capability of reconstructing a 3D image field from 2D image data from two high-speed cameras. A dual-pulse neodymium-doped yttrium aluminum garnet (Nd:YAG) laser (New Wave Solo III, 50 mJ/pulse) with a 20 ns pulse duration eliminates the blur effect caused by rapidly moving droplets. Research scheme injectors have been designed and additively manufactured based on the manufacturing limits of L-PBF AM and are not designed to any specific flow area balance or specific operating conditions.

Novel additive optimized injectors and L-PBF AM non-circular orifice injectors have been compared to conventional coaxial injectors in the liquid-gas-liquid (LGL) and gas-liquid-gas (GLG) condition. The additively manufactured injectors have a thinner, more focused stream in comparison to the conventional coaxial injectors. This implies that orifice geometry is essential to injector mixing and can dramatically affect intra-injector interactions as well as flame holding location. An injector that has a more penetrative stream will hold a flame farther off the face, while injectors with a shallow, wide stream may interact more with those around it. The additive optimized injectors appear to perform similarly to the conventional injectors. Relative droplet size and density can be determined qualitatively from these sample image sets and used to compare effective spray atomization of the different injector schemes. The pentad orientation is seen with the highest effective atomization, creating a uniform cloud of barely perceptible droplets (fig. 2). By comparison, the triplet’s droplets are larger and more distinct,

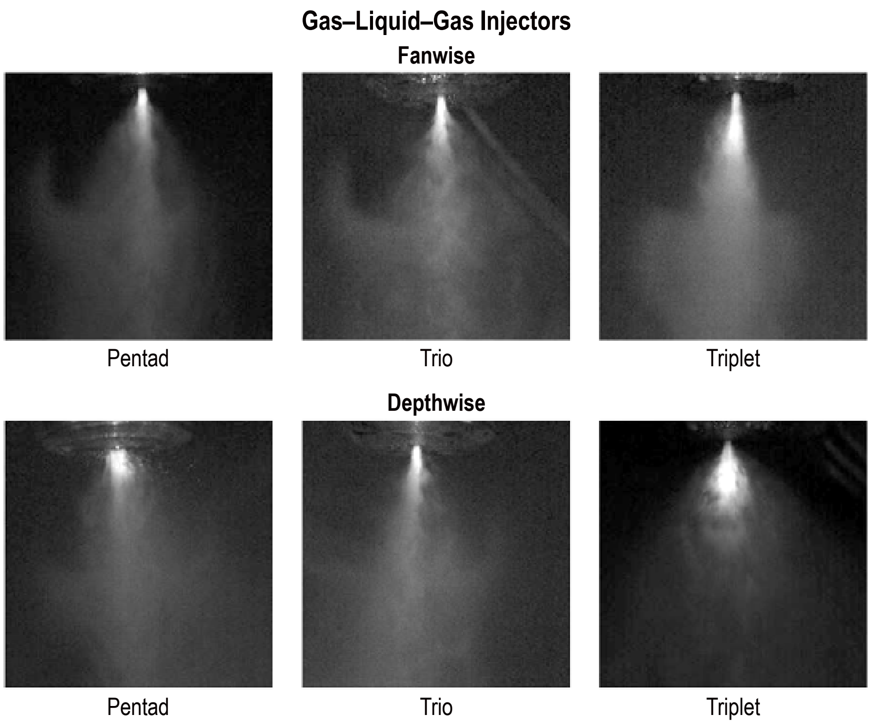


FIGURE 2. Spray pattern comparison of different additively manufactured injector element schemes.

and the field is not uniform, but rather retaining the geometry of the orifice. This suggests a lower level of atomization.

PARTNERSHIPS

Auburn University is the primary collaborator for the work outlined in this report. The spray facility and diagnostic equipment is setup at the Auburn Combustion Physics Laboratory on Auburn's campus. Dr. David Scarborough, an assistant professor, and Ari Goldman, Alabama Space Grant Fellow graduate researcher, are the primary collaborators at Auburn University. They have significantly advanced the technology research level (TRL) of this work for NASA and will continue this collaborative effort toward hot-fire testing in Fall 2022.

SUMMARY

This effort represents an important first step in developing high-performance propellant injectors for LREs and RDREs and in developing an important diagnostic tool for understanding the 3D structures of injector atomization and mixing. This capability will substantially benefit MSFC by providing a resource for future performance enhancement designs of AMed liquid rocket injectors. Next steps will proceed along the following two paths: First, the lessons learned from this initial development of ultra-high-performance injectors will provide critical information about the propellant injector additive manufacturing process and the resulting atomization and mixing field that can be achieved from these designs. Lessons learned and best practices will be developed, which will enable the development of the next generation of AMed propellant injectors aimed at achieving high C* performance over a broad range of operating conditions. Second, stereographic capabilities developed during this effort provide a first step toward gaining a better understanding of the details of the atomization and mixing process.

PRINCIPAL INVESTIGATORS: Thomas Teasley, NASA Marshall Space Flight Center; Dr. David Scarborough, Auburn University

PARTNER: Auburn University

FUNDING ORGANIZATION: Cooperative Agreement Notice

Composites in Braided Experimental High-speed Rotation (CiBEHR) Coupling

OBJECTIVE: *To develop a low cost soft mechanical coupling for cryogenic turbomachinery components by optimally braiding advanced fibers for torsional rigidity.*

PROJECT GOAL/DESCRIPTION

This project aims to develop a cryogenic-rated cord, named the Composites in Braided Experimental High-speed Rotation (CiBEHR) Coupling, which is capable of transmitting torque at high speeds by strategically braiding strands of advanced fiber together. The goal operating capabilities are 6 N·m of torque and 50,000 RPM, which come from a 45 kW electric pump being developed for Additively Manufactured Propulsion E-pump Demonstrator (AMPed), an electric cycle liquid rocket engine. This novel soft coupling will offer a competitive solution to mating technology of high-speed turbomachinery components and test rigs. A braided coupling allows for higher tolerances of misalignment; protects hardware in event of failure; and offers control of independent environments for pump and drive components. The materials considered will have favorable metrics in size, cost, strength, stretch, abrasion resistance, and cryogenic resistance. Ropes and braids are extremely difficult to model and analyze conceptually; therefore, this project aims to experimentally develop the CiBEHR Coupling in an evolutionary process. Initial prototypes will be baselined on a 50 N·m static test bench in order to determine their torsional and axial rigidity in ambient and liquid nitrogen (LN_2) environments. Leading candidates will then be tested on a 12 kW/50,000 RPM dynamic test stand to verify dynamic performance.

APPROACH/INNOVATION

The CiBEHR Coupling is a function of length, diameter, material, braid configuration, and termination design. The first CiBEHR Couplings are made of off-the-shelf rope and smooth collet shank terminations. Two fiber materials of varying sizes were selected to be compared: ultra-high molecular weight polyethylene (UHMWPE) and liquid crystal polymer (LCP), also known as Dyneema® and Vectran™ respectively. Nylon is a favorite in the rope industry for its abrasion

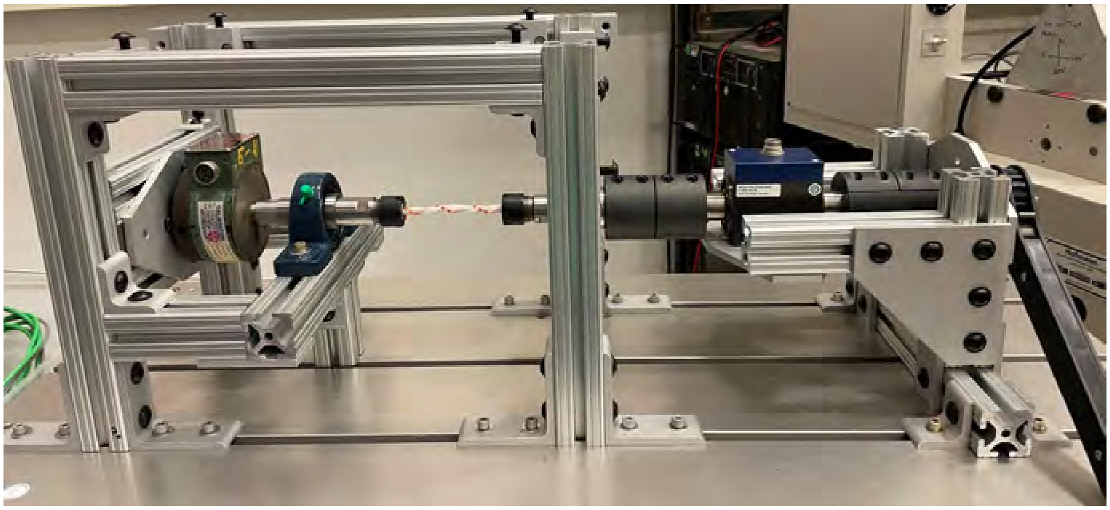


FIGURE 1. The CiBEHR static test rig is capable of testing prototype braided couplings to 50 N·m and 500 lbf.

resistance and shock absorbing characteristics, but fails to meet CiBEHR Coupling requirements for strength and cryogenic resistance. Polybenzobisoxazole (PBI or Zylon), aramid, and carbon fiber were ruled out for being too abrasive and costly. Initial braids are made of a symmetric 12-strand core and some are double braids containing an outer sleeve. The symmetric braid is necessary for torque transmission both clockwise and counterclockwise. Braids are typically configured for equal axial load transfer to the fibers, but the CiBEHR Coupling fibers must strategically interact with each other for torque transfer.

The component which integrates the braid ends to the shaft are called terminations. In the case of initial prototypes, CiBEHR terminations must be axisymmetric and accept a variety of cord sizes. Clamp chucks, such as one the end of a drill, and serrated collets were considered but ruled out due to size and complexity of assembly. The smooth collet and chuck design was selected as they allow for high-speed rotation, adaptable coupling size, and simple test bench installation. However, initial static tests exposed an issue as the braid outer diameter would shrink as torque increased causing the rope to slip inside of the smooth collet. This was mitigated with an epoxy injection into the braid and collet, which provided a significant increase in the torque transmission under static testing. Future static tests will utilize metallic pins that stab through the rope and lock in the collet, preventing slippage.

Static tests characterize torsional and axial rigidity, which offer insights in how the CiBEHR Coupling might scale to meet varying applications. Torque transfer is the goal, but braids also result in axial loads when twisted. This spring-like load exhibited by the CiBEHR Coupling must be evaluated and deemed acceptable in future systems. Static test measurements taken are twist angle, axial force, and torque via a 2,000 pulse per revolution (PPR) rotary encoder, 500 lbf load cell, and 50 N·m torque transducer. Dynamic tests are planned with a 12 kW eddy-current dynamometer and 30,000 RPM brushless DC motor. Upon completion, test results will verify fiber braids as competitive coupling technology.

The NASA Marshall Space Flight Center (MSFC) Turbomachinery (ER13) group is also developing a high-speed test bench called Adaptable Fluid Dynamometer with Electric Motors (AIDEM). AIDEM will be able to characterize lander class cryogenic electric motors with a series of strategically sized liquid nitrogen brakes. Once drive motors are established, the test bench will then be able to test cryogenic inducers, impellers, and bearings. This modular system would benefit from a misalignment-tolerant and simple-to-install cryogenic coupling. This laboratory environment seems to be the perfect application of the CiBEHR Coupling, which offers a low-cost sacrificial method to protecting the drive and load side of the test bench from each other — allowing for peace of mind that research and development tests hardly offer.

RESULTS/ACCOMPLISHMENTS

The CiBEHR Team — made up of MSFC Engine Components Development and Technology Branch (ER13) and Structural & Dynamics Analysis Branch (ER41) engineers — has formed relationships with fiber technology leaders and kickstarted the project by consulting with companies such as Whitehill and Teufelberger. While this torsion application of braids has been met with skepticism, the CiBEHR Coupling has continued to prove itself. Prototypes have been tested up to 12 N·m which is double the target torque of 6 N·m. Under a LN_2 drip, one 11 mm LCP rope was found to double its torsional rigidity while only increasing its axial rigidity by 10%; meaning that this braid pulled on the shaft at

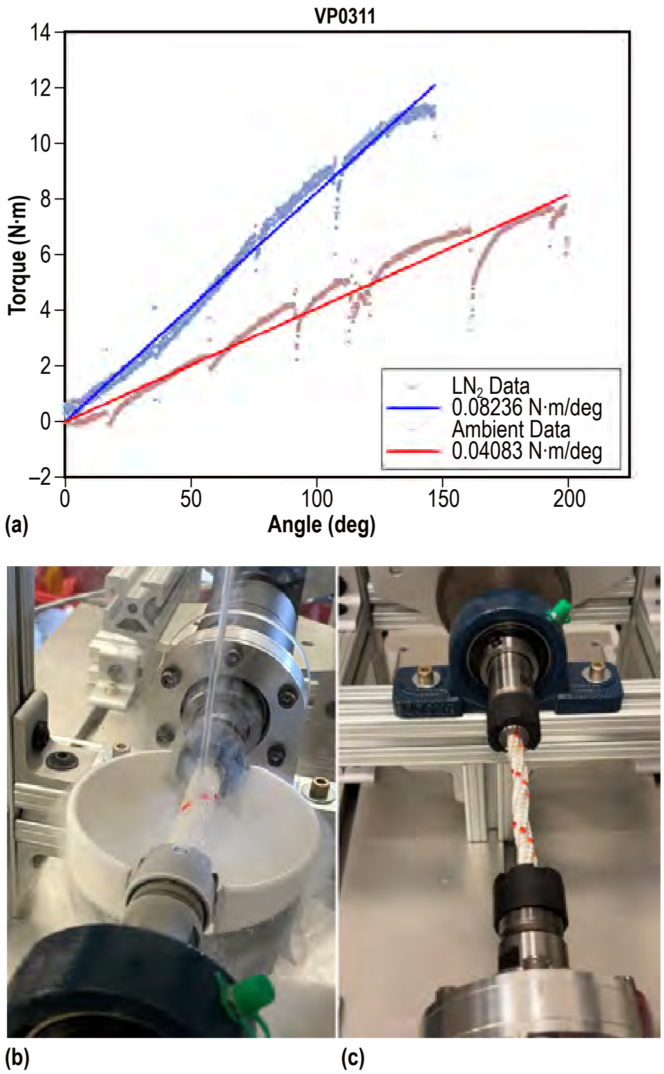


FIGURE 2. A 3-in-long, 11-mm-diameter liquid crystal polymer braid (a) doubled its torsional stiffness when (b) exposed to LN_2 temperatures as compared to (c) ambient temperatures.

57 lbf at ambient temperature and 129 lbf at LN_2 temperature while transmitting the same 6 N·m torque. These results demonstrate the required torque capabilities and cryogenic operation of the CiBEHR Coupling. A dynamic test stand has been designed and the team is awaiting funding for a necessary dynamometer to build it. As for lessons learned, the termination was continuously the weakest element in static testing and needs to be matured to increase grip strength. While epoxies and pins offer quick fixes, the forward path for termination design is to customize a serrated clamshell collet design that will allow for better compression and lateral interaction of the fibers. The goal is to increase termination efficiency and prevent slipping of what could be a commercial mechanical coupling product.

SUMMARY

Prototype CiBEHR Couplings were assembled with various ropes and mill collet shank terminations. Some of these have been successfully tested on a newly-developed static test bench which measures twist, torque, and axial load. Cryogenic operation of the CiBEHR Coupling is favored, as it increases torsional rigidity and lowers the resulting axial load. Static tests are still ongoing to evaluate braid capabilities by size, material, misalignment, and temperature. A dynamic test stand has been designed and will be built soon. This project has helped the CiBEHR team build up a lab space for electric motor testing as well, complete with a new electronics workspace and electric motor drive system. This is seen to be a successful first effort in the greater goal to develop AIDEM.

PRINCIPAL INVESTIGATORS: Zachary Standridge and Adam Willis

FUNDING ORGANIZATION: Center Innovation Fund

Improved Actuator for a Pyroless Isolation Valve

OBJECTIVE: *To design and build a new actuation system based on a sear release system for a pyroless isolation valve that NASA Marshall Space Flight Center designed for a previous Center Innovation Fund.*

PROJECT GOAL/DESCRIPTION

The goal of this proposal activity is to design and build a new actuation system for the pyroless isolation valve that NASA Marshall Space Flight Center (MSFC) Valves, Actuators, and Ducts (ER14) engineering team designed for a previous Center Innovation Fund (CIF) project in fiscal year (FY) 2014. That solenoid-based actuator was prone to jamming and could be difficult to reset when in the test mode. The use of hermetic isolation valves in satellite and spacecraft propulsion systems has typically been accomplished using pyrotechnic devices that have the inherent risks that all pyrotechnic devices possess. Use of a mechanism that eliminates these risks can improve the system's overall safety, but it would need to be as reliable as the pyrotechnic devices. As shown with the work done previously, an additively manufactured (AMed) valve element can be made that is reliable, but testing showed the release actuator was prone to hang and was difficult to check out. This work designed a sear system, as found in a rifle or climbing equipment, to release the loads and allow the pressure to rupture the hermetic seal, rather than a solenoid latch system as was previously used. Sear-based systems are used for critical systems such as firearms and heavy-load handling equipment, as they are safe and reliable. Incorporation of this type of release system into the prototype AM hermetic valve improved its reliability and thus made this device a better fit for satellite and spacecraft use.

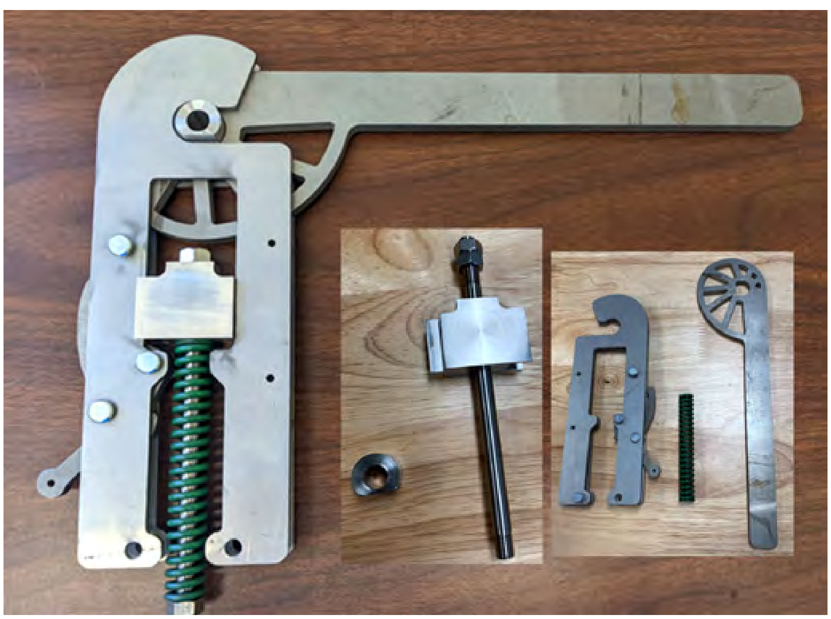
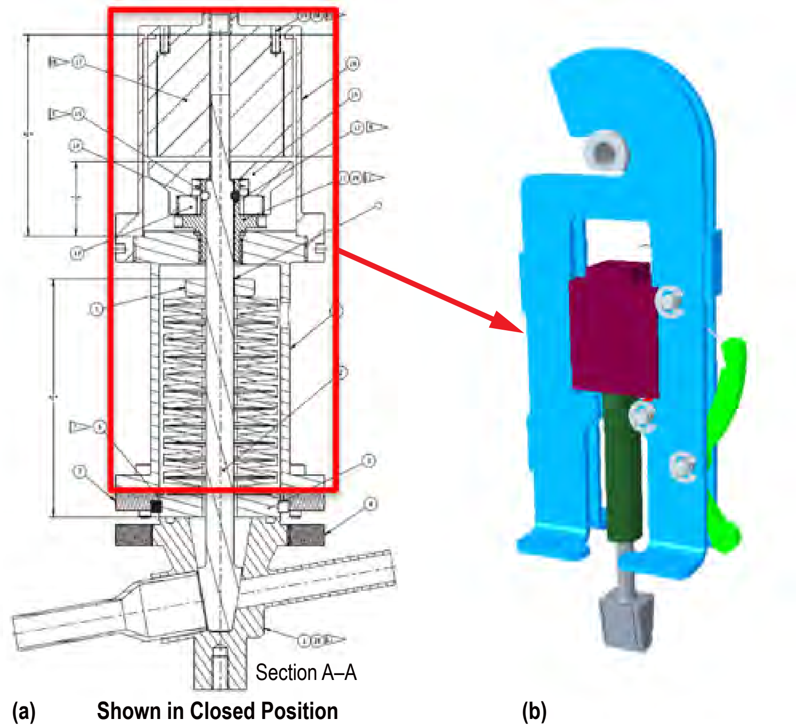


FIGURE 1. Sear release mechanism parts ready for assembly.

APPROACH/INNOVATION

Hermetic isolation of propellants from the rest of the propulsion system is a common requirement for long duration satellites, interplanetary probes and to provide ground safety for upper stage reaction control systems (RCS). To accomplish this task, pyro valves are used in just about every application where storable propellants are used. However, those valves are all operated with pyrotechnic devices making ground operations hazardous and prone to risks to the ground crew safety and damage to the spacecraft if inadvertently actuated on the ground. The pyroless approach was designed to improve ground operations as the actuator could

FIGURE 2. (a) Rendering of the sear release mechanism and (b) the spring loaded actuator on the previous design that it was intended to replace.



be fully tested without rupture of the flight hardware, reducing risk to crew safety while offering the same hermetic protection of the pyrotechnic-based valves. In FY 2014, MSFC designed and built valves using additive manufacturing methods and a solenoid latch type actuator. Although the valve was shown to be very effective, the solenoid latch was not robust. It would not release or would only partly release. It also proved to be difficult to prepare to test and to reset after testing. As the use of rapid actuated pyro-type valves are being considered for ground-based water hammer and surge testing, ER14 proposed a redesign of the AMed isolation valve using a more robust sear release system to improve on the valve's operational performance.

The old release system used a release actuator based on a ball and groove method like a quick release coupler and a solenoid to pull the coupler ball retainer. This low power solenoid limited the size of the balls that could be used, and thus the balls would sometime jam in the coupler. A new test system, which is being developed for ground testing of water hammer and surge systems that have been proposed, needs fast acting hermetic isolation valves and the use of pyrotechnics would be restrictive for this facility. Therefore, ER14 redesigned the AMed hermetic valve using a sear release system instead of the old ball/solenoid method. If this could be made to work for the ground system, then use of these AMed valves for flight would be more likely considered and a new generation of spacecraft possible with no pyrotechnics used. MSFC had several remaining AMed valve units from the project in FY 2014 and used those valves as a starting point for this effort. The valves were modified to accept the sear-based release system and tested to demonstrate the needed reliability. Realizing that a lower-risk and higher-reliability AMed valve with sear-type actuators enable more versatile interplanetary science, commercial satellites, and upper stage missions, this component could change the way spacecraft are built. Specifically, this component would reduce the risk of ground operations while maintaining the reliability of the spacecraft. This sear-based actuator could have the potential of eliminating pyrotechnics from future spacecraft.

RESULTS/ACCOMPLISHMENTS

The AMed valve design was updated to accept the new sear release actuator concept. This required only minor changes to the bonnet of the valve. A concept for the actuator was generated with the thought of reuse and cost in mind. The mounting brackets and the majority of the sear release mechanism were fabricated from sheet metal via waterjet. There were two parts that required machining and the remaining fasteners and springs were procured as off the shelf items. A functional, 3D-printed prototype was fabricated and demonstrated operation of the sear release mechanism. Since the first use of this valve and actuator would likely be in ground-based water hammer and surge testing, a method to quickly reset the sear lease mechanism would be desired. A handle was designed and fabricated from sheet metal via computer aided manufacturing that could be used to manually compress the main spring and reset the actuator for the next test or actuation. A test plan was completed for the actuator assembly and test conducted showed and cycles were completed, showing promise for the concept as an actuator.

There is still forward work to be completed to further demonstrate this actuator concept and increase the technology readiness level (TRL) beyond TRL 4. Though the actuator was demonstrated on a desktop, mounting it on an operational valve and demonstrating the two subassemblies as one unit needs to be completed. The prototype sear releaser actuator is also bulky and not optimally packaged. MSFC is working to package the actuator in a lighter, more flight-like arrangement. Further testing would be required beyond that, including those that would demonstrate how the mechanism stands up to vibration and thermal environments. This is all out of scope for this effort but work that MSFC has planned for future development of the concept.

SUMMARY

A pyroless isolation valve was developed by MSFC a few years ago and the valve was a huge success. The use of additive manufacturing allowed for a body that was easy to fabricate and low in cost when compared to traditional pyro valves, and it could be serviced on the ground to allow for easy testing prior to launch or during subsystem testing. However, the actuator portion of the MSFC valve was problematic and stiction or binding of the actuator was noted multiple times. To improve reliability of these types of valves, an actuator system that uses a sear like that found in a quick-release or firearm trigger was designed to replace the highly loaded ball and sleeve design of the previous version. The concept was designed to be manually reset after actuation, but the release activation force could be a simple pneumatic cylinder for ground systems to a small solenoid for a flight rated system. It was thought the use of the sear-based mechanism could improve the reliability of the valve and allow the full potential of these pyroless isolation valves to be realized. A prototype unit was fabricated and successfully bench tested to demonstrate operation. Successful actuation, rapid movement of the valve stem, and manual reset capability of the actuator were all achieved. To fully realize this concept for a flight application, further testing to demonstrate robustness to environments and optimization for weight and packaging needs to be completed.

PRINCIPAL INVESTIGATORS: James Richard (retired) and David Eddleman

FUNDING ORGANIZATION: Center Innovation Fund

Adaptable Fluid Dynamometer for Electric Motors (AIDEM)

OBJECTIVE: *To design an adaptable turbomachinery test bench capable of testing high-speed and high-power cryogenic electric motors for rocket engine applications.*

PROJECT GOAL/DESCRIPTION

There is significant development needed before electrical rocket engine components can become competitive in propulsion system trade spaces. Electric motors and generators, while wildly popular in the automotive industry, lack maturity in cryogenic, high-speed, and high-power applications. The few vendors who would bid on such components struggle to meet the high speed (>20,000 RPM) and extreme environment (e.g., liquid hydrogen (LH_2), liquid oxygen (LOX), and liquid methane (LCH_4)) requirements for them. This lack of market solutions drives up costs and even when prototypes are created, there are no easily available testing solutions. Existing power dissipation technologies focus on low-speed and high-torque machines and are typically lubricated. Therefore, the NASA Marshall Space Flight Center (MSFC) Turbomachinery and Combustion Devices Branch (ER13) wants to develop a dedicated cryogenic, high-speed, and high-power test bench for electric engine components called Adaptable Fluid Dynamometer for Electric Motors (AIDEM). The aim is to significantly increase MSFC's electric motor/pump testing capabilities by designing a modular cryogenic fluid dynamometer system that provides a full range necessary for speed, torque, and power for rocket engine applications.

APPROACH/INNOVATION

The challenge in developing a rocket engine electric motor test bed capable of cryogenic temperatures is providing both high speed and a high power load to the motor. Industry solutions are cost prohibitive and are best suited for single operating point analysis. Research and industry input have pushed testing needs towards a fluid brake dynamometer solution as it has the best potential to meet the requirements of speed, power, and cryogenic temperatures. This solution would provide the capability to characterize an electric motor across the entire intended operation range for rocket engine applications.

A NASA-developed modular fluid brake would use multiple impellers to maximize the test envelope and adapt to motor operation conditions. Using multiple impellers while varying flow rate provides the desired torque and power characterization for a given shaft speed. This data is then used to generate efficiency curves

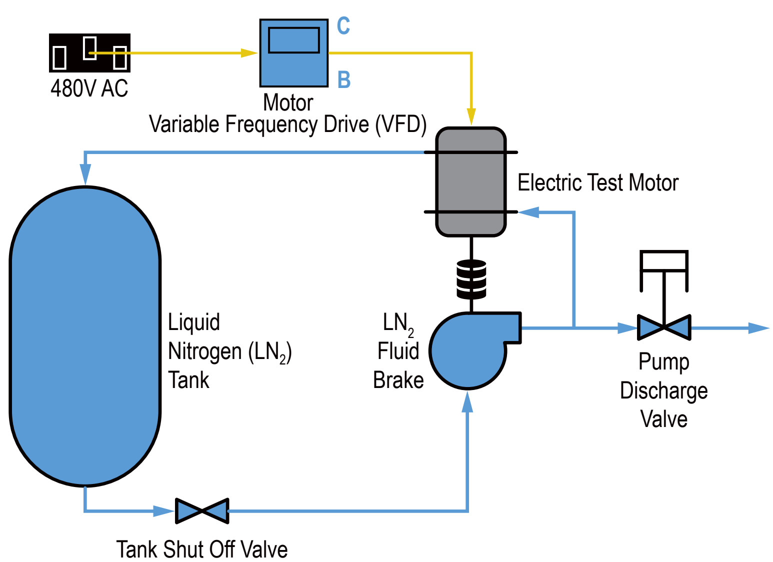


FIGURE 1. This simplified AIDEM schematic shows it only requires control input to motor speed and discharge valve position to characterize high-speed electric motors.

for the motor at each operating point. The hydrodynamic design philosophy is to reduce cost and manufacturing time while accommodating a wide operating range. This leads us towards additively manufactured solutions with Barske type impellers (i.e., radial straight vanes). Barske impellers reduce pump complexity while meeting the performance criteria needed.

The immediate goal of AIDEM is to test the Additively Manufactured Propulsion E-pump Demonstrator (AMPed) 55 kW cryogenic electric motor. The desire is to characterize operational performance, but this motor also has control sensitivities to coolant temperature because of back EMF control logic which needs to be better understood. If controller programming needs to vary during operation, this is best calibrated in the test environment offered by AIDEM. Electric machines often have unique operating criteria like this, and AIDEM will be able to adapt to meet any test objectives.

Designs for a water brake dynamometer prototype and cryogenic dynamometer will be completed under a fiscal year (FY) 2022 Technology Investment Program (TIP). Additionally, by utilizing hardware from a previous effort to build a water brake, the prototype will be built and tested. The multiyear plan for AIDEM can be broken down into the following objectives:

- Water Prototype: Build and assemble test bench for water dynamometer prototype for dynamic testing of motor couplings.
- Cryogenic Test Bench: Procure hardware and modify prototype test bench for cryogenic compatibility using liquid nitrogen in a characterization test of the AMPed 55 kW motor.
- LH_2 Electric Motor: Partner with electric motor vendor to create AIDEM owned hardware aimed at conducting studies on inducer performance in the expected operational environment.

RESULTS/ACCOMPLISHMENTS

One of the first steps to developing AIDEM was establishing the methodology of which an electric motor can be fully characterized with a fluid dynamometer. Designing fluid impellers to one operating point is simple, but electric motors will need to be characterized in as much of their operating envelope as possible. This can be accomplished by driving strategically sized impellers across flow resistance sweeps while measuring electrical power, shaft power, and fluid power. AIDEM will need a collection of impellers which can be easily switched out. Since efficiency is not a design priority, these impellers can be rapidly manufactured at low costs. One idea is to additively manufacture a collection of constant diameter impellers and grind them to size when needed. The only machining necessary would be a shaft interface bore and any balancing holes. After running through 3 or 5 impellers, an electric motor efficiency map could be generated on a torque-speed chart.

Once AIDEM has characterized a motor, that machine can be used to drive development components like pump heads or bearing rigs. So, while AIDEM will be created for electric motor testing, a resultant capability will be rapid turbomachinery component testing. This is relevant for numerous technology development efforts. One example is nuclear thermal propulsion technologies, as LH_2 inducers are being driven towards two-phase pumping and AIDEM can provide development enabling test capabilities. Another area AIDEM could benefit is long-life shaft support technologies. Turbines will eventually run out of drive gas in ground tests, but electric drive motors will be able to run until bearings fail.

In partnership with Composites in Braided Experimental High-speed Rotation (CiBEHR), AIDEM has developed a water brake capable of coupling to an existing 12 kW, 30,000 RPM electric drive motor. This is a contingency plan for

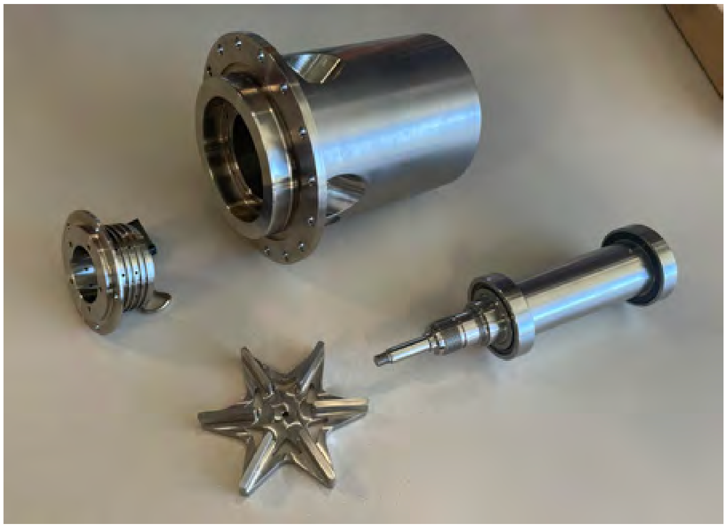


FIGURE 2. Hardware manufactured for a 30,000 RPM AIDEM water brake prototype.

dynamically testing a novel soft mechanical coupling which uses advanced fibers strategically braided to transfer torque. This highlights a current development effort where a lack of high-speed test capabilities impacted project schedule. AIDEM intends to fulfill that role with a prototype system, where a successful test would benefit both teams. Hardware shown in figure 2 will be used to assemble the water brake.

PARTNERSHIPS

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

SUMMARY

AIDEM was awarded a FY 2022 TIP to complete the design for a water brake dynamometer prototype and a cryogenic dynamometer to characterize electric motor/pump systems for rocket engine applications. Near-term efforts are focused on building the water brake dynamometer prototype, then using the lessons learned to finalize the cryogenic dynamometer design. Once the cryogenic system is complete, testing of the 55 kW electric motor will be completed. Follow-on efforts will be focused partnering with electric motor vendors to create AIDEM owned electric motor hardware. This will lead to testing and studying turbomachinery components such as inducers for electrically driven boost pumps, cryogenic bearing alternatives, additively manufactured impellers with varying polishing techniques, along with other experimental pump technologies. Lastly, an adaptable test bench like AIDEM also increases NASA's workforce knowledge of designing, building, and testing turbomachinery hardware by providing a hands-on environment for engineers to work.

PRINCIPAL INVESTIGATORS: R. Zach Taylor and Zachary Standridge

FUNDING ORGANIZATION: Technology Investment Program

Electromagnetic Solar Sail Coupling (ESSC)

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

PROJECT GOAL/DESCRIPTION

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

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

Magnetic coupling also lets the solar sail rotate independently of the bus, allowing for the construction of larger, rotating solar sails that may support much higher mass or enable more complex spacecraft capable of executing science missions to more distant and difficult-to-reach targets. The objective of this project is to advance this novel tethering technology from technology readiness level (TRL) 3 to TRL 4 through the construction and testing of a mock sail and Bluetooth-controlled spacecraft.

APPROACH/INNOVATION

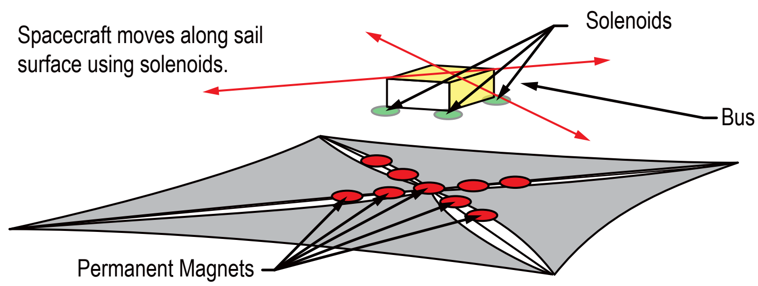
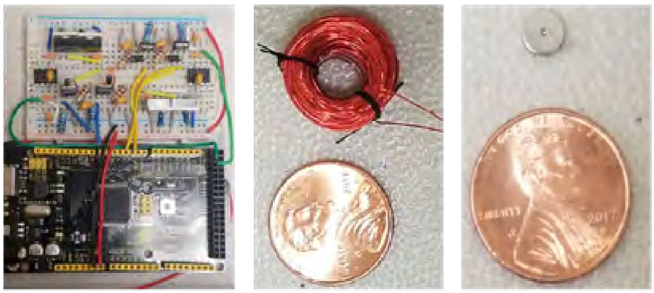


FIGURE 1. Conceptual overview of electromagnetically coupled solar sail.

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

In addition to the novel technology concept of using electromagnets and permanent magnets to wirelessly tether solar sails, the team employed several innovative ideas through use of commercial-off-the-shelf (COTS) components (e.g., Raspberry Pi computers, cameras, bench power supply, air



(a) (b) (c)

FIGURE 2. Prototype hardware.

hockey table, etc.). The extensive use of COTS components allowed for the rapid development of a low budget prototype. Through the development of video signal processing algorithms, tracking and control algorithms were developed based on the detection of color-coded bands on the satellite bus.

RESULTS/ACCOMPLISHMENTS

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

SUMMARY

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

PRINCIPAL INVESTIGATOR: Manuel J. Diaz
FUNDING ORGANIZATION: Center Innovation Fund

Process Development and Characterization of Ruthenium-Based Monolithic Metal Foam Catalyst for Monopropellant Thruster Applications

OBJECTIVE: *This project will develop a lower cost ruthenium-iridium (90/10) alloy catalyst alternative to the current iridium-based catalyst.*

PROJECT GOAL/DESCRIPTION

Iridium is one of the most important materials currently used in monopropellant thrusters. Therefore, the total cost of a thruster is heavily dependent on the iridium price. Recently, there has been a dramatic spike in material cost, driving a dramatic increase in the cost of monopropellant thrusters.

The goal of this project is to develop of a ruthenium-iridium alloy catalyst to replace the current 100% iridium catalyst, thereby reducing the overall cost for monopropellant thrusters. This ruthenium-iridium catalyst also offers technical advantages over the current state of the art, including (1) reduction of overall catalyst weight, and (2) reduction of catalyst density to enable the more rapid heating of the catalyst, thus improving catalyst performance.

APPROACH/INNOVATION

Ruthenium is a light-weight metal with excellent oxidation resistance and catalytic properties amongst the best of platinum group metals. Unfortunately, ruthenium alone has a lack the mechanical strength needed in catalyst disks Alloying ruthenium with iridium will improve its mechanical strength and oxidation resistance. This project will produce a set of catalyst samples to evaluate specific catalyst parameters in comparison with current baseline iridium data. If successful, this could represent a >80% cost reduction in raw material costs, signifying a potentially disruptive innovation in monopropellant thruster catalyst cost.

This project has four primary tasks, including:

(1) Development of ruthenium-iridium electrolytes.

(2) Development of deposition parameters (i.e., catalyst sample manufacturing).

(3) Materials analysis of samples via scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), and Brunauer–Emmett–Teller (BET) analysis.

(4) Final Reporting.

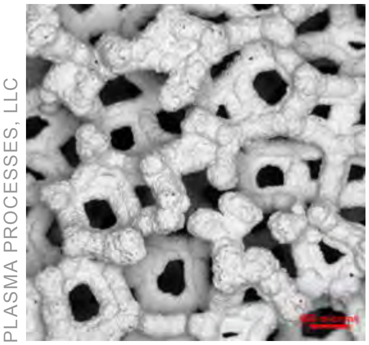
The results of the proposed tests will provide empirical insight into the viability of the proposed ruthenium-iridium catalyst. If shown viable, this activity would lead to thruster level testing (e.g., thermal vacuum chamber and hot-fire) using the ruthenium-iridium catalyst.

RESULTS/ACCOMPLISHMENTS

Task 1 was completed in March 2022. However, the team experienced delays due to availability of a dedicated deposition unit. Once a unit became available, the monolithic catalyst was deposited with its an underlayer material for structural support. Deposition of the ruthenium-iridium layer is anticipated to be completed by end of the first quarter of fiscal year 2023, followed by materials analysis.

COURTESY OF PLASMA PROCESSES, LLC

FIGURE 1. Monolithic iridium foam disk.



COURTESY OF PLASMA PROCESSES, LLC

FIGURE 2. Scanning electron microscopy image of Iridium foam showing the unit cell.

PARTNERSHIPS

Plasma Processes, LLC is the prime contractor for this activity, and nearly all work will be performed by Plasma. Plasma Processes will be lead author on any papers. The MSFC Center Innovation Fund (CIF) team awarded the sole-source contract and will serve as Contracting Officer's Representative (COR), will provide technical insight/oversight of the activities, and will co-author any papers with Plasma.

SUMMARY

This project intends to develop a ruthenium-iridium alloy catalyst as an alternative of the current 100% iridium-based catalyst. This proposed catalyst offers potential increased performance while reducing the overall cost of monopropellant thruster manufacturing. Despite schedule delays, the project team continues to make progress toward completing manufacturing of catalyst samples. Once complete, the sample will be evaluated and compared to the current state of the art.

PRINCIPAL INVESTIGATOR: Carlos Diaz
PARTNER: Plasma Processes, LLC
FUNDING ORGANIZATION: Center Innovation Fund

Near-Earth Asteroid Scout

OBJECTIVE: *To demonstrate the use of a small spacecraft propelled by a solar sail to obtain important images and scientific measurements of a near-Earth asteroid.*

PROJECT GOAL/DESCRIPTION

After its deployment from NASA's Space Launch System (SLS) on the Artemis I flight, the Near-Earth Asteroid (NEA) Scout mission will travel to and image an asteroid during a close flyby using an 86 m^2 solar sail as its primary propulsion. Solar sails are large, mirror-like structures made of a lightweight material that reflects sunlight to propel the spacecraft. The continuous solar photon pressure provides thrust with no need for the heavy, expendable propellants used by conventional chemical and electric propulsion systems. Developed by NASA Marshall Space Flight Center (MSFC) and NASA Jet Propulsion Laboratory (JPL), the NEA Scout is based on the industry-standard CubeSat form factor. The spacecraft measures 11 × 24 × 36 cm and weighs less than 14 kg. Following deployment from the SLS, the solar sail will deploy and the spacecraft will begin its 2- to 2.5-year journey. About one month before the asteroid flyby, NEA Scout will search for the target and start its Approach Phase using a combination of radio tracking and optical navigation. It will then perform a relatively slow flyby (10–20 m/s) of the target.

APPROACH/INNOVATION

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 × 10 × 10 cm cubes. Each cube is called a 'U' and is typically allocated about one kg of total mass. Previous year innovations were the design, development, test of a solar sail system to provide the propulsion required for the mission. In 2021, the completed spacecraft was integrated into the launch vehicle. Since then, the team has focused on the flight control system that will manage the sail's continuous low thrust throughout the flight, up to and including the slow flyby of the target asteroid.

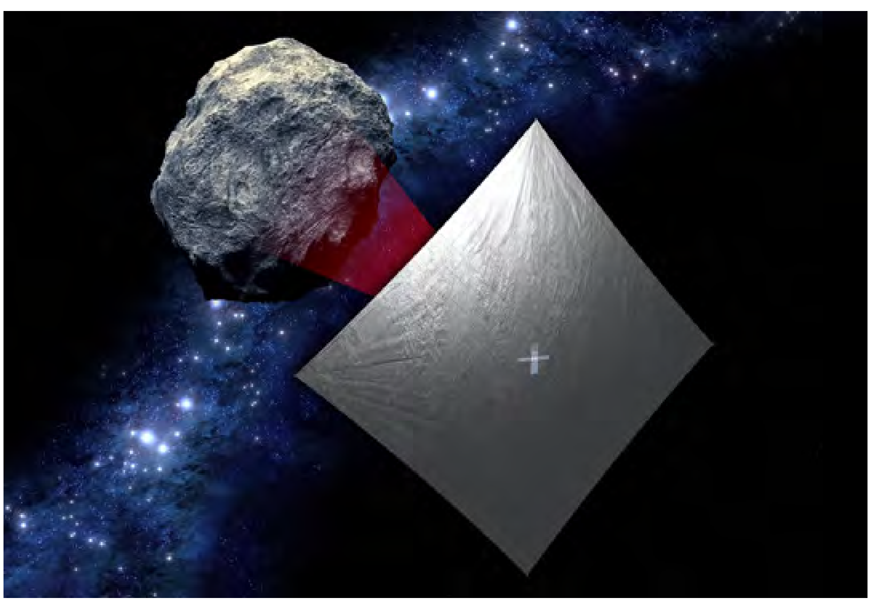


FIGURE 1. Artist concept of the solar-sail-propelled NEA Scout imaging the target asteroid during its flyby.

NEA Scout will be different from all previously flown solar sail systems in that its objective is to use the sail for controlled flight to affect a close flyby of the target asteroid. Given that the solar sail is a single sheet deployed on four booms from the center 2U of the 6U 3-axis-controlled spacecraft, any asymmetries between the center of pressure (CP) of the sail with the spacecraft system center of mass (CM)

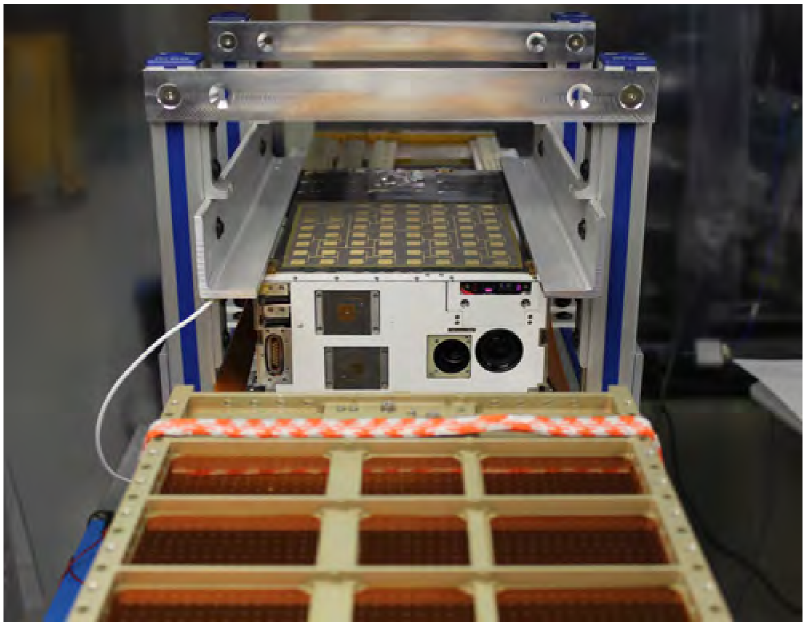


FIGURE 2. The NEA Scout was successfully loaded into the flight dispenser, which will deploy it once the Orion Stage Adapter has separated and is on its way to the Moon.

will result in a torque on the system that must be carefully managed to maintain attitude and thrust control. To manage the CP/CM offset and other solar pressure induced torques, NEA Scout will use an active mass translation (AMT) device, reaction wheels, and a small onboard cold gas thruster system.

RESULTS/ACCOMPLISHMENTS

The NEA Scout spacecraft was integrated into the flight dispenser from which it will be deployed in space. The dispenser was then integrated into the SLS Orion Stage Adapter. To meet the flight control and momentum management challenges during flight, the NEA Scout team spent much of the last year running simulations of nominal and off-nominal spacecraft and sail operations; assessing the adequacy of the planned contact times and durations with NASA's Deep Space Network; and troubleshooting potential solutions to minor and worst-case off-nominal operation.

PARTNERSHIPS

JPL performs the Mission Design and Navigation functions for NEA Scout, which are critical for developing and maintaining a trajectory design in orbit. JPL works in tandem with the Guidance and Control (G&C) team at MSFC. The Mission Design team delivers a trajectory design that the G&C team implements as specific spacecraft attitudes, and the Navigation team uses multiple radionavigation methods to precisely determine NEA Scout's position in space, assessing what, if any, trajectory corrections are necessary. The collaboration with JPL will continue throughout the mission, concluding when the spacecraft is decommissioned.

SUMMARY

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

PRINCIPAL INVESTIGATOR: Les Johnson

PARTNERS: NASA Jet Propulsion Laboratory; NASA Langley Research Center; NeXolve

FUNDING ORGANIZATION: Advanced Exploration Systems, Exploration Systems Development Mission Director

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

Technology Area 03

POWER AND ENERGY STORAGE

All-Printed Flexible Biofuel Cells for Energy Harvesting from Human Sweat

OBJECTIVE: *To develop a flexible printed biofuel cell platform which allows in-situ energy harvesting at high efficiency toward achieving self-powered sensors and systems.*

PROJECT GOAL/DESCRIPTION

Wearable electronics have tremendous potential for monitoring astronaut performance and would be an ideal solution to NASA's future diagnostic needs. Renewable and sustainable power sources are highly desired for space healthcare applications. The goal of this project is to develop a flexible printed biofuel cell (BFC) platform, which allows in-situ energy harvesting at high efficiency (–1 mW/cm^2 level) toward achieving self-powered sensors and systems.

The nanomaterial ink suspension and the laser-engraved graphene substrate will be prepared by the California Institute of Technology (Caltech). The nanoengineered flexible BFC electrodes will be prepared using both an inkjet printer as well as an nScrypt 3Dn-300 multimaterial 3D printer system. The integrated BFCs were evaluated by principal investigator Dr. Wei Gao's group at Caltech.

It is expected that the proposed printed biofuel cells could allow for the development of self-powered, battery-free wearable electronics for continuous human performance and health monitoring. With further development, this biofuel cell-based energy harvesting technology could serve as a highly attractive approach toward self-powered wireless personalized health monitoring for both in-space and on-earth applications.

To that end, the project team established the following four objectives:

(1) Prepare and characterize the printed flexible enzymatic nanoengineered bioanode for efficient catalytic lactate oxidation.

(2) Prepare and characterize the printed flexible nanoengineered cathode for efficient oxygen reduction.

(3) Characterize the electrochemical and mechanical performance of fully printed flexible BFCs in lactate solutions and in collected biofluids.

(4) Develop and evaluate the self-powered wearable system for direct energy harvesting and storage, and for electronic load powering.

APPROACH/INNOVATION

There are several significant innovations related to this research. First, the development of an on-demand 3D-printed biofuel cell is significant; even more so is the fact that the power generated by the biofuel cell will provide power for a range of on-demand printed electronics and sensors. Ultimately, this technology could free astronauts and sub-systems from the constraints of external power or batteries.

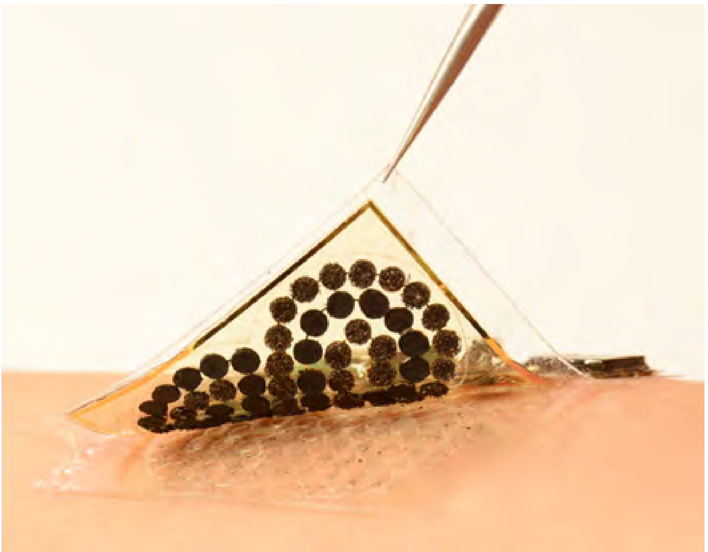


FIGURE 1. Printed biofuel cell for harvesting energy from human sweat.

RESULTS/ACCOMPLISHMENTS

During this first year of the Cooperative Agreement Notice (CAN) project, Caltech has made significant progress in the development of this wearable fuel cell technology. The following tasks have been accomplished:

- Preparation of the printed enzymatic nanoengineered bioanode, including testing and selection of appropriate binder/vehicle systems for desired rheological properties of bioanode ink.
- Optimization of 3D print settings upon a treated substrate and comparison of both thick- and thin-film print quality post-curing.
- Characterization and optimization of the electrochemical performance (current density and stability) of the printed bioanode for lactate oxidation optimized in lactate solutions by nanomaterial film thickness, curing conditions, and enzyme concentrations.
- Preparation of the nanoengineered biocathode. Carbon nanotubes (CNTs) were mixed with carbon nanofibers as the conductive ink for biocathode materials. Printed silver oxide (Ag_2O) or printed platinum (Pt)/CNT were tested in preparation of the BFC cathode.
- Characterization and optimization of the electrochemical performance (current density and stability) of the printed devices for efficient oxygen reduction of the printed cathode by nanomaterial film thickness, curing conditions, and enzyme/Pt concentrations.
- Preparation of the dielectric layer and assembly of the BFC. Printing of BFC bioanode, cathode, dielectric layer on the same flexible substrate to obtain the fully assembled BFC.

Additional tasks that are in process for the remainder of the project include the following:

- Characterization of the electrochemical behaviors (e.g., power density, polar curves, onset potential, and the stability) of the fully printed and assembled BFCs in lactate solutions and in collected sweat samples.
- Evaluation of the mechanical performance of the printed flexible BFCs during and after repetitive bending cycles (under physiologically relevant strains).
- Development of the integrated self-powered wearable electronic system consisting of bioenergy harvesters, power management & storage module, and electronic load powering and wireless communication module.
- On-body evaluation of the wearable system's energy harvesting efficiency.

PARTNERSHIPS

Dr. Gao at Caltech is a nationally known researcher in the areas of biosensing, energy storage, printed energy storage, and molecularly imprinted polymers. The On-Demand Manufacturing of Electronics (ODME) team is continuing to work with Dr. Gao on follow-up research projects in the areas of printed biosensors and other printed electronics.

SUMMARY

Caltech's research into printed biofuel cells is innovative and has great potential for on-demand 3D printing of these devices in space for future exploration missions. This project showed the potential for printed biofuel cells as an enabling technology for astronaut crew health wearable sensors as well as self-powered sensor networks. Ultimately, this technology could also form the basis for development of a new class of on-demand printed power generating and energy storage devices that would be critical for long-range space missions.

PRINCIPAL INVESTIGATORS: Dr. Wei Gao, California Institute of Technology; Curtis Hill, MSFC

PARTNER: California Institute of Technology

FUNDING ORGANIZATION: Cooperative Agreement Notice

The Lightweight Integrated Solar Array and anTenna (LISA-T) Pathfinder Technology Demonstrator

OBJECTIVE: *To demonstrate the deployment, operation, and environmental survivability of the LISA-T power generation and communication array in a representative operational environment.*

PROJECT GOAL/DESCRIPTION

Satellite miniaturization continues to create lower cost, faster paced, and higher risk-tolerant options for space missions. Small spacecraft continue to grow in popularity and are becoming of interest to scientific, exploratory, and commercial missions alike. The large body of research and development within government, academia, and industry has greatly advanced small spacecraft technologies and, as a result, mission capabilities. However, electrical power systems have not commensurately increased in capability, creating a bottleneck in bus design and, ultimately, payload capability. This bottleneck is driving the need for advanced power generation, storage, and distribution designs. The Lightweight Integrated Solar Array and anTenna (LISA-T) is being developed, in partnership with NeXolve Holding, LLC (Huntsville, AL), to fill the power generation portion of this technology gap.

LISA-T provides a compact, lightweight, efficient, and affordable power generation system with an integrated antenna for small spacecraft missions. LISA-T generates >300% more power per mass and volume than state of the art options, vastly improving electrical power availability on small spacecraft. The technology will enable both highly capable, near-Earth small spacecraft missions as well as the capability for small spacecraft to operate deeper into space than currently possible. This is essential for science applications such as space weather monitoring concepts, national defense applications, as well as small spacecraft flagship mission support such as communication relays or ancillary spacecraft to capture additional science during the mission.

To date, LISA-T has been developed through technology readiness level (TRL) 6. Prototype arrays have been fabricated and tested in a comprehensive set of relevant space environments. To prepare the array for mission infusion and ubiquitous use, an in-space technology demonstration is currently being prepared. The LISA-T Pathfinder Technology Demonstrator (PTD) is a payload comprising of a LISA-T array along with supporting electronics, data collection systems, and other hardware that will fly on a 6U CubeSat as part of NASA's Small Spacecraft PTD series of rapid demonstration missions. LISA-T PTD will demonstrate the deployment, operation, and environmental survivability of LISA-T in a low-Earth orbit. The mission will prove out the LISA-T technology, achieving TRL 7 and ensuring the power generation array is ready for mission designers to take advantage of the >300% higher power generation for small spacecraft.

APPROACH/INNOVATION

To fill the technology gap, LISA-T utilizes thin-film materials—to do more, from less. The use of thin-film-based solar arrays for spacecraft applications has long been recognized as an advantageous power generation option; however, the materials, cells, and deployment systems have not been available to make them a reality. Thinner materials yield both mass and volume savings, enabling more power to be generated from the same mass and volume allocation. Perhaps just as important for small spacecraft, the mechanical flexibility of thin films

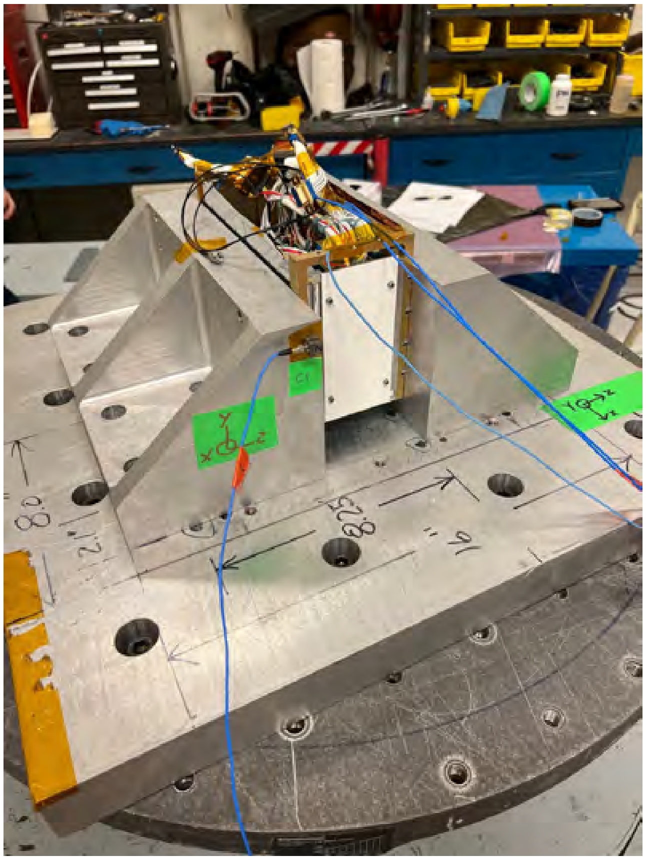


FIGURE 1. LISA-T flight payload under vibrational test.

lends itself well to stowage and deployment schemes, allowing novel folding of the array into the spacecraft for launch as well as unfolding of the array once in space. LISA-T is utilizing advanced solar cells being developed in industry (e.g., inverted metamorphic multifunction cells) coupled with advanced, space-rated polyimide materials manufactured by NeXolve to form the basis of LISA-T. These cells and core materials are backed by a novel multifunction mechanical system, which provides both the structural backing as well as deployment (unfolding) forces for the array.

The array is being combined with avionics and other critical elements to former a flyable payload. This payload will be integrated to the Terran Orbital PTD platform: a 6U CubeSat with ≈3.6U of standard subsystem (e.g., battery, communication, flight computer, etc.) and ≈2.4U of open payload space. The integrated PTD and LISA-T payload will fly in fiscal year (FY) 2023 to low-Earth orbit for between 2 to 6 months. This flight will demonstrate the array capabilities and reduce risk for future infusion.

RESULTS/ACCOMPLISHMENTS

Several accomplishments have been made over the last year to prepare the LISA-T technology for the PTD mission. In FY 2022, the LISA-T team successfully passed critical design review and fabricated flight hardware shortly thereafter. The flight hardware has been integrated to form the payload and has been tested to the thermal and vibrational flight environments. This testing is supported by multiple analyses alongside comprehensive benchtop functional testing. Early in FY 2023, the completed payload will be integrated to the Terran Orbital PTD CubeSat and prepared for flight.

SUMMARY

The LISA-T array will enable both highly capable, near-Earth small spacecraft as well as the capability for small spacecraft to operate deeper into space through both improved power generation and communication capabilities on the same deployable array. The LISA-T PTD mission will demonstrate this array, proving it out for future mission use. The deployment, operation, and environmental survivability of LISA-T will be tested. This mission, combined with ground-based testing, parabolic flight testing, and international space station material exposure testing will enable LISA-T to provide >300% improved power generation to small spacecraft and usher in a new class of low cost, fast paced, risk tolerant missions.

PRINCIPAL INVESTIGATOR: Dr. John A Carr

PARTNERS: NeXolve Holding, LLC; Terran Orbital

FUNDING ORGANIZATION: Early Career Initiative

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

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

PROJECT GOAL/DESCRIPTION

Right now, rechargeable batteries are being used in many space applications from exploration robots to crew health monitors; and at the moment, all of these batteries must be brought from earth though a lengthy and expensive process. The SIBatt-3D project is focused on in-space manufacturing of shape-conformable batteries using in-situ resources from lunar and martian regolith. 3D-printed batteries allow for complex electrode geometries that lead to improved performance and are shape-conformable, so they can be co-designed with a system to minimize the dead volume and mass. Sodium ion batteries are of interest due to their improved safety and the relative abundance of materials that can be used as

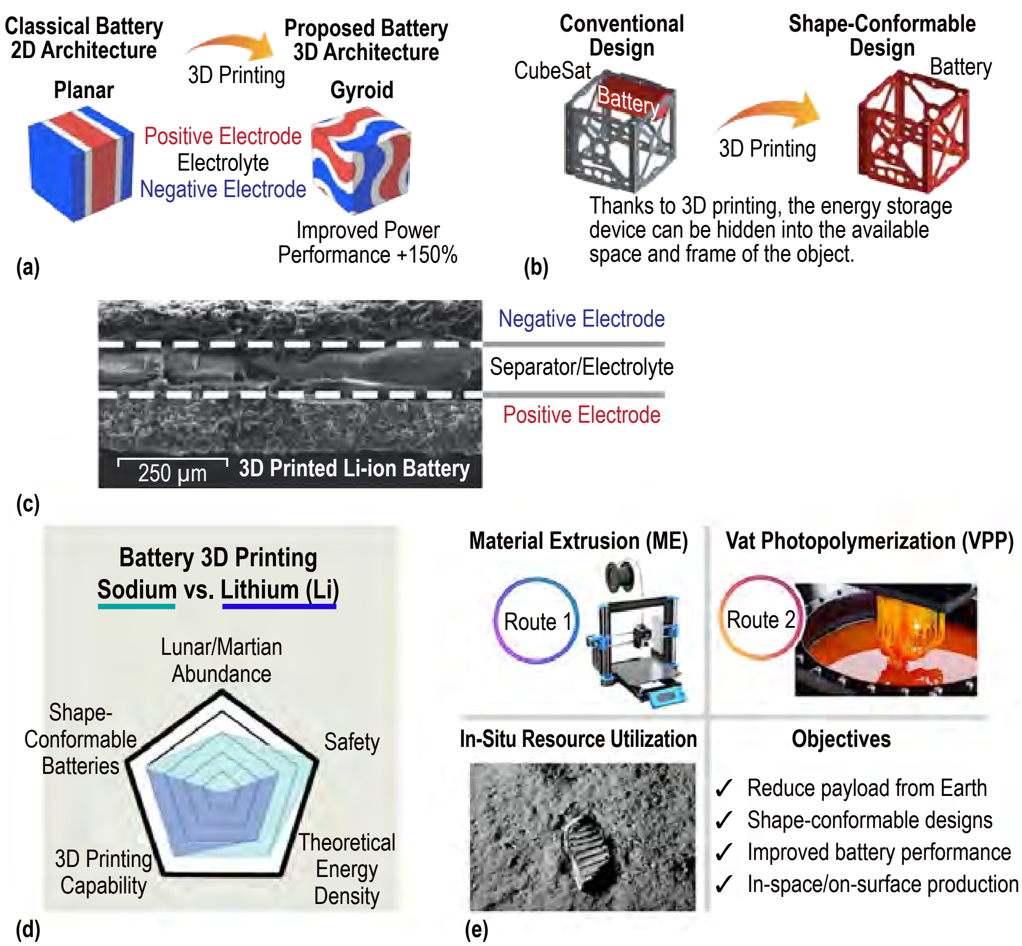


FIGURE 1. 3D printed architectures allow for complex electrode geometries and shape-conformable deigns as this team has previously demonstrated with printed lithium-ion batteries. This project pursues two printing routes, ME and VPP, with a focus on sodium-ion chemistries due to their improved safety and higher availability in-situ on the Moon and Mars.

printing feedstocks found on the Moon and Mars. These novel geometries have the potential to improve performance and rival traditionally manufactured batteries despite the usual losses associated with additive manufacturing and 3D printing. This project paves the way towards in-space/on-surface development of freeform energy storage devices that will fill unique volumes and save dead space for applications like small spacecraft, portable power devices, robots, and lunar/martian habitats.

APPROACH/INNOVATION

The SIBatt-3D team is pursuing two printing methods, material extrusion (ME) and vat photopolymerization (VPP), to develop the most efficient and reliable method for in-space and on-surface shape-conformable sodium-ion battery printing. The electroactive materials were selected based on the availability on the Moon and Mars. Tailored ionic liquid extraction processes to obtain sodium-ion battery materials and precursors from regolith are being developed in tandem with the printing methods. For both printing types, adequate printable materials (i.e., loaded inks/slurries and UV-curable resins) corresponding to each battery component were developed, printed, post-processed, and characterized separately by the end of the first year. This effort is one of the earliest among 3D printing of sodium-ion batteries and contributes greatly to the state of the art required for next-generation battery development. During year two, SIBatt-3D will continue to work on printing independent battery components and integrating one into a printed wall segment made by commercial partner ICON.

RESULTS/ACCOMPLISHMENTS

SIBatt-3D began with the evaluation of potential electroactive materials based on the relevant electrochemical data and their in-situ availability on the moon and mars. After the review of the candidate electroactive materials, sodium iron oxide

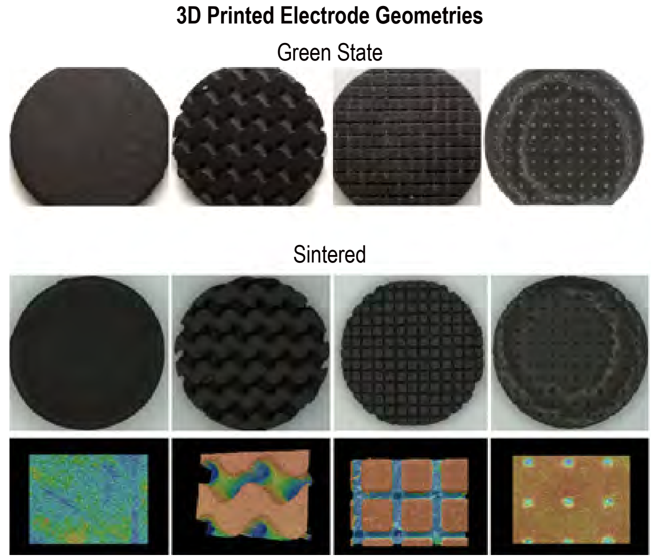


FIGURE 2. Photographs showing four of the printed electrode geometries currently being tested before and after the sintering and debinding process. The electrodes pictured are to be the battery anodes and are printed using a custom hard carbon resin.

($NaFeO_2$) and sodium manganese oxide ($Na0.44MnO_2$) were identified for the positive electrode while titanium oxide (TiO_2) and hard carbon were selected for the negative electrode. These materials have been added to a commercial resin or to our lab-made resin for VPP printing, and also formulated into inks suitable for direct ink writing. Different ratios of electroactive material and conductive additives to resins and specific ink formulations are continuing to be tested to maximize printability. Our results showed that printability is improved if the conductive additives are incorporated in the form of a coating on the electroactive materials instead of as powder additives.

For the custom resin printing route, the team is using the Admatec Admaflex 130, a digital light processing (DLP) 3D printer with a unique material delivery system that avoids sedimentation in the feedstock material. Seven electrode designs have been printed from the team's custom resins. Half-cell batteries using these electrodes as working electrodes were assembled and galvanostatically tested. The two best performing designs are disks with a gyroid infill and a larger grid infill, due to their inherent surface macro and microporosity that allowed liquid electrolyte impregnation.

Other shape-conformable shapes are envisaged to be produced during year two. For the ME route, the Voltera V-One direct ink write printer is currently being used. The electrode inks that were prepared by this team were printed in an interdigitated design for initial printability and performance tests. A specific electrochemical cell has been developed for the electrochemical testing of these electrodes in a half cell configuration, and the results are underway. A different configuration that will fit inside of a coin cell battery is also under investigation.

As for the electrolyte, evaluations of gel and solid polymer electrolyte, as well as ceramic and composite electrolytes are still in progress, with the current front runner being sodium perchlorate ($NaClO_4$)-based compositions. For the moment, a liquid electrolyte is being used to test independently the electrodes; however, in the near future, 3D-printed electrolytes developed by the research team will be employed instead.

PARTNERSHIPS

The University of Texas at El Paso (UTEP) is known for its leadership in the advanced manufacturing field. During both years, UTEP's role is developing resins for each part of the battery and performing electrochemical testing and evaluation of the printed parts. Youngstown State University (YSU) provided invaluable expertise in printing ceramics and other custom materials. During both years YSU worked with the project to optimize printing and postprocessing of the batteries and their components. Formlabs, one of the top consumer 3D printing organizations in the US, provided the project with access to customize print setting and consultation on resin formulation during year one. ICON, NASA's main partner for additive construction on the lunar surface, will work with SIBatt-3D to demonstrate a printed battery embedded in a printed wall during year two.

SUMMARY

The SIBatt-3D ECI project's goal is to develop methods to 3D print sodium-ion batteries in-space/on-surface from in-situ resource utilization (ISRU) materials. SIBatt-3D has identified potential electroactive materials for each battery component based on the in-situ availability of materials on the moon and mars along with their theoretical performance. The identified electrode materials have been printed through two different methods—digital light processing, using loaded resins; and direct ink writing, using custom inks—to determine the preferred method for future manufacturing efforts. The printed battery components have been evaluated individually through cycling in the half-cell configuration. The project has just completed year one of its two-year timeline. During year two, the SIBatt-3D ECI will work to assemble full 3D-printed batteries using the materials and methods developed during year one and to demonstrate a fully printed battery embedded in a printed wall in partnership with ICON.

PRINCIPAL INVESTIGATOR: Cameroun Sherrard

PARTNERS: University of Texas at El Paso; Youngstown State University; Formlabs; ICON

FUNDING ORGANIZATION: Early Career Initiative

Technology Area 04

ROBOTIC SYSTEMS

ISS Deployment and High-Altitude Descent Drone Landing Using SVGS

OBJECTIVE: *To demonstrate the Smartphone Video Guidance Sensor for robotic intra-vehicular activity on the Astrobee vehicles inside the International Space Station for precision descent and landing via high-altitude outdoor drone landing.*

PROJECT GOAL/DESCRIPTION

The Smartphone Video Guidance Sensor (SVGS) was developed as a sensor for rendezvous, proximity operations, and docking (RPOD) for small spacecraft. Previous development work demonstrated SVGS exclusively in a 1-g environment, limiting its performance to just three degrees of freedom (3DOF). Integration with the Astrobee vehicles and demonstrating inside the International Space Station (ISS) enabled the first six-degrees-of-freedom (6DOF) demonstration in the microgravity environment of space. Successful demonstration on Astrobee inside ISS also proves SVGS's viability as a sensor for robotic intra-vehicular activity (IVA) inside the lunar Gateway, Mars Transit Habitat, or other lunar habitats. Outdoor high-altitude (>100 m) drone descent and landing testing seeks to build off previous development of indoor landings from an altitude of ≈1 m. The drone landings from the 100-m altitude much more closely resemble the concept of operations for a lunar landing scenario and will prove SVGS's viability as a sensor for precision lunar descent and landing. It is anticipated that the outdoor drone landings could prove SVGS-aided landings could be accurate to within 20 m.

APPROACH/INNOVATION

The SVGS uses a cluster of four light emitting diodes (LEDs) in a prescribed configuration as targets for an optical navigation methodology. A camera records an image of the four LEDs, and image processing and photogrammetry software estimate a 6DOF state between the camera reference frame ant the target reference frame. That 6DOF state can be used by a robot such as Astrobee inside a habitat like the ISS to perform IVA within the habitat. If the targets are facing upward on the surface of the Moon, a lander could utilize the 6DOF state to guide its precision landing to a repeating landing site. SVGS provides highly accurate and deterministic 6DOF state estimates with a very robust and proven algorithm.

For robotic IVA, the approach is to fabricate and deploy four sets of SVGS LED targets of different colors on the ISS. The SVGS software was loaded on the Astrobee's High Level Processor (HLP) and would use Astrobee's own cameras to image the targets and then compute the 6DOF state. The HLP would then send the 6DOF state down to Astrobee's guidance, navigation, and control (GN&C) function to command the vehicle. For descent and landing, the approach was to fabricate long-range and short-range targets of different color, facing upward on the ground. A drone would be equipped to carry a smartphone running the SVGS software. The drone's GN&C function would receive the 6DOF state from the smartphone to autonomously command and land the vehicle near the targets.

RESULTS/ACCOMPLISHMENTS

The SVGS ISS deployment marked several successful accomplishments in the past year. Four LED target sets were flown up to the ISS on the Crew-3 mission in October 2021. In early 2022, SVGS software was successfully tested in the Astrobee granite table test facility at NASA Ames Research Center.

FIGURE 1. Single Astrobee maneuver using SVGS.

This testing verified SVGS software integration with Astrobee and the maneuvers to be performed on-orbit. In June 2022, Astrobee successfully completed the first maneuvers inside ISS with SVGS in the loop. The first set of maneuvers comprised the Astrobee moving in a prescribed pattern around a single set of wall-mounted SVGS targets (fig. 1). In July 2022, Astrobee vehicles Queen and Bumble performed a leader-follower maneuver around a wall-mounted SVGS target. In this proximity operations demo, the leader Astrobee moved in a prescribed pattern around the wall-mounted targets. The follower Astrobee followed a set of SVGS targets mounted on the backside of the leader Astrobee (see figure 2). For robotic IVA, the entry technology research level (TRL) was 4. Upon completion of these maneuvers inside ISS, end TRL for robotic IVA is now 7.

The high-altitude drone descent and landing was not completed in fiscal year (FY) 2022 but is making steady progress toward a demonstration targeted for Spring 2023. Thus far, a drone has been procured to satisfy the requirements of the descent and landing concept of operations. Short-range and long-range SVGS targets have been designed and manufactured for the outdoor descent. Preliminary modifications have been made to the SVGS software to utilize the long-range and short-range targets as well as perform the transition between targets during descent. Entry TRL for lunar landings is 3. TRL 4 is expected to be achieved after the outdoor demonstrations are completed in FY 2023.

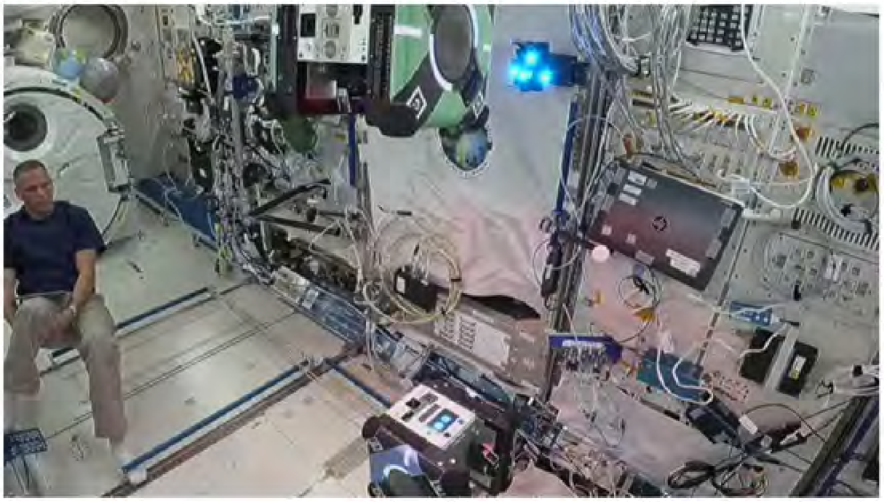


FIGURE 2. Astrobee leader-follower maneuver using SVGS.

PARTNERSHIPS

Dr. Hector Gutierrez at the Florida Institute of Technology (FIT) has been a valuable partner in this work. FIT manufactured and delivered the SVGS targets for ISS deployment. FIT also integrated the SVGS software with the Astrobee flight software and is assembling the drone and integrating SVGS with the drone for the outdoor descent and landing demo. Dr. Gutierrez's team has been a dedicated partner in SVGS development since 2017 and will continue to partner with MSFC in pursuing robotic IVA and lunar descent and landing applications.

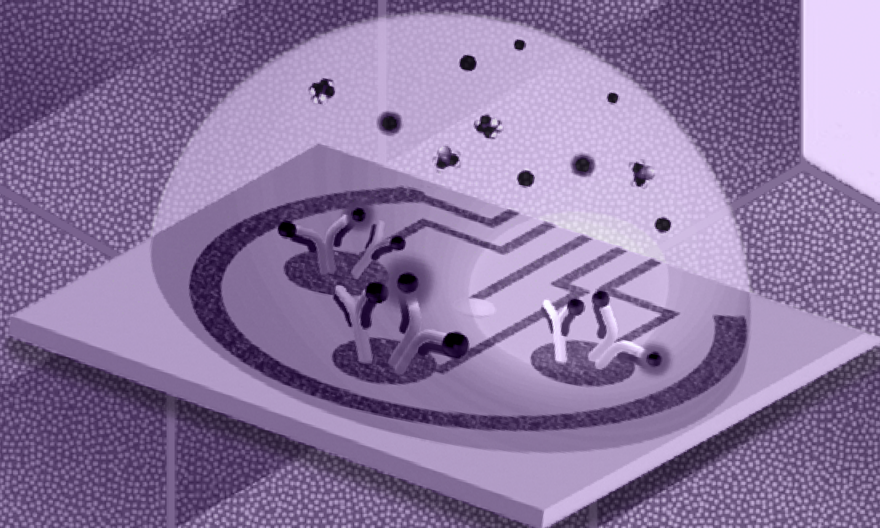
SUMMARY

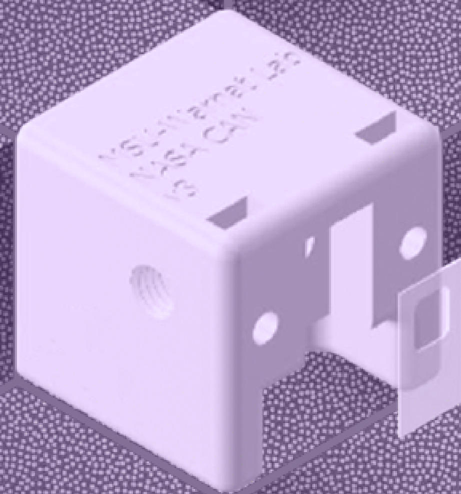
The SVGS, an evolution of the MSFC-developed Advanced Video Guidance Sensor (AVGS), originated through the Center Innovation Fund (CIF) in 2013. Originally intended to apply to small satellite RPOD, it is now seeing opportunities for diverse applications for space exploration such as robotic IVA and lunar descent and landing. This project proved SVGS's potential to be a navigation sensor for robotic IVA in future space habitats through maneuver demonstrations on the Astrobee vehicles inside the ISS. This project also set out to prove SVGS's viability as a lunar descent and landing sensor via autonomous outdoor drone landings. The outdoor drone landings are expected to be completed in the FY 2023 timeframe.

PRINCIPAL INVESTIGATOR: John Rakoczy

PARTNER: Florida Institute of Technology

FUNDING ORGANIZATION: Cooperative Agreement Notice





TECHNOLOGY AREA 06

HUMAN HEALTH, LIFE SUPPORT, AND HABITATION SYSTEMS

Parabolic Flight Demonstration of Fluid Dispensing Tube Performance Limits for Drop Delivery

OBJECTIVE: *To design and verify the capabilities of a new fluid dispensing system for the delivery and pinning of a 1-in liquid bubble between two pinning rings in the microgravity environment for subsequent scientific investigation.*

PROJECT GOAL/DESCRIPTION

In 2016, initial parabolic flight experiments were conducted on commercial carrier ZeroG, which tested the growth and pinning of 1-cm diameter liquid drops under simulated microgravity. Data gathered from these initial parabolic flight investigations provided sufficient confidence in our ability to develop International Space Station (ISS) flight hardware to pin much larger 1-in liquid drops in the microgravity environment, without implementing undue modifications to initial designs. A Biological and Physical Sciences (BPS) Program-funded ISS investigation of insulin amyloidogenesis required the development of ring shear drop (RSD) flight hardware capable of delivering a liquid drop to a stable 1-in size with predictable constraint of the drop between two pinning rings. Amyloidogenesis is the formation and growth of amyloid structures considered detrimental in diseases, including Alzheimer's, Parkinson's disease, etc. However, lack of predictability of fluid behavior at the pinning edge of a blunt syringe delivery tube (fig. 1) led to failures in the pinning of a 1-in liquid drop that prevented the study of amyloidogenesis, which can only be properly conducted in the microgravity environment of ISS. Hence a delivery or dispensing tube ('D-tube') capable of delivering a stable liquid drop over a range of possible flow rates to enable pinning between two rings is desired. As parabolic flight opportunities became available to NASA personnel in 2020, the goal was then to develop more robust designs and verification approaches for new D-tubes that would enable the delivery of a 1-in liquid bubble constrained between two rings, as required by the BPS-funded ISS flight experiment.

APPROACH/INNOVATION

The technological concepts for designing a new delivery system that can grow and pin a 1-in liquid bubble are based on the contact angle formed when a liquid comes in contact with a given substrate. To ensure the delivery of a sufficiently large bubble of fluid, the contact angle formed at the end of the delivery mechanism must not exceed a critical angle, which can be determined from measurements performed on Earth. The blunt edge 10-gauge needle design for delivery of this large bubble of fluid failed due to the following issues: (1) the pinning contact angle exceeded the critical angle at the tube wall; and (2) the pinning contact angle was destabilized by the

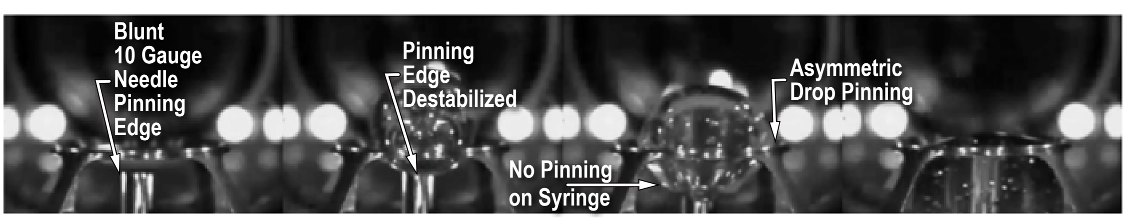


FIGURE 1. A series of images demonstrating the loss in integrity of the liquid pinning edge as it is dispensed from a 10-gauge blunt edge needle (left to right), until the liquid is no longer pinned at a contact ring. Pinning edge at the needle surface needs to be maintained for the delivery of the required 1-in liquid bubble between two contact rings.

violent asymmetric process of liquid attaching to a pinning ring. Advancements in the design of new D-tubes must account for the above known or observed physical processes of pinning and must also limit the surface area of contact between the liquid and D-tube to allow for the successful execution of RSD experiments on ISS.

Several designs for a D-tube were considered capable of dispensing a stable liquid drop at rapid flow rates to enable pinning between two rings. These new designs were subjected to performance tests in November 2020 by making use of a series of 60 parabolic flight profiles that offer near-microgravity environments of limited duration (≈25 s). To assess further the suitability of the selected designs, 60 additional parabolic flights were utilized in March 2021 to deliver and pin 1-in liquid bubbles of protein solutions to be investigated on the ISS flight experiment. The approach utilized in design and testing of the functional characteristics delivery and pinning of various liquids ensured the successful investigation of amyloidogenesis of insulin.

RESULTS/ACCOMPLISHMENTS

Parabolic flight experiments provided an opportunity to obtain data on fluid flow exiting delivery tubes of several specific designs. The parabolic flights thus made possible the determination of functionality of various designs to deliver 8 – 10 ml of water to form large liquid bubbles in a near-zero-gravity environment. From data gathered in these initial flights (fig. 2), a single design was determined to be most appropriate for application in the ISS flight experiment. The parabolic flight experimental data were much needed to select the final design to be implemented in the RSD flight hardware for the execution of ISS amyloidogenesis investigations. The NASA Marshall Space Flight Center Team worked to resolve know failures of previous designs making use of much needed microgravity environment afforded by parabolic flight profiles:

Upon determination of a single best design, the test cells for RSD hardware were incorporated with the newly designed D-tubes and manifested for flight on NASA Commercial Resupply Mission NG-16, which arrived at ISS on 8/12/2021. The test cells were utilized within the RSD flight hardware and functioned flawlessly for all test and protein solutions, delivering a 1-in liquid bubble pinned between two rings for subsequent amyloidogenesis investigations. The Rensselaer Polytechnic Institute (RPI) investigative team lead by Prof. Hirsa processed several protein solutions in their ISS investigative efforts that are currently under publication.

FIGURE 2. A series of images demonstrating the ability of a new delivery tube design to dispense a liquid bubble while maintaining integrity of the pinning edge. As shown from left to right, the asymmetric process of a moving liquid front stabilizes or pins at the edge of the delivery tube and proceeds to grow symmetrically as a large bubble.

PARTNERSHIPS

MSFC's partners included CFD Research Corporation, Jacobs, and RPI.

MSFC and CFD Research will continue collaborative efforts to extend the applicability of investigated designs in exploration systems as well as ISS business ventures.

SUMMARY

A number of conservative and elegant designs for a delivery mechanism capable of dispensing a 1-in bubble of liquid were tested using the near-microgravity environment provided by parabolic flights. Parabolic flights offered by a commercial carrier (ZeroG) provided microgravity environments for sustained durations of 15 to 20 s on each parabolic flight profile. Although limited in duration, results obtained from the effort were invaluable in determining a design solution for the RSD hardware used in amyloidogenesis investigations of ISS. Absent such services, the design and construction of hardware to be used in microgravity environments would be fraught with uncertainty and failure in execution of expected tasks, as experienced in the RSD investigation.

PRINCIPAL INVESTIGATOR: Sridhar Gorti

PARTNERS: Rensselaer Polytechnic Institute; CFD Research Corporation; Jacobs

FUNDING ORGANIZATION: Flight Opportunities

Structured Sorbents: Rapid Cycle Temperature Swing Adsorption (RC-TSA)

OBJECTIVE: *To design, build, and test a new subscale rapid cycle temperature swing adsorption carbon dioxide adsorption bed.*

PROJECT GOAL/DESCRIPTION

Current state-of-the-art (SOA) carbon dioxide (CO_2) removal systems, such as the Carbon Dioxide Removal Assembly (CDRA) currently in use on the International Space Station (ISS), utilize packed beds filled with pelletized sorbent material. By contrast, this research team is developing new CO_2 removal technology using sorbent-coated metal sheets. This form factor allows for rapid thermal cycling, and thus, smaller beds. The end goal of this work is a smaller, more energy-efficient CO_2 removal process for crewed spaceflight missions. NASA is interested in adsorption-based CO_2 removal systems that cycle quickly, as these accomplish CO_2 removal with less sorbent (i.e., lower mass/volume). However, many sorbent form factors are limited by slow heating and cooling. This new design increases heat transfer efficiency by placing the sorbent material directly in contact with a liquid heated/cooled metal plate.

APPROACH/INNOVATION

In fiscal year (FY) 2021, the Environmental Control and Life Support System (ECLSS) Development Branch (ES62) of NASA Marshall Space Flight Center (MSFC) designed the first-generation rapid cycle temperature swing adsorption (RC-TSA) CO_2 removal bed that utilized a commercial off-the-shelf (COTS) plate heat exchanger. This design has two separate wetted pathways: one for air and one for a heat transfer fluid. The parallel channels for air are coated with a thin layer of sorbent material, zeolite 13X. This concept is depicted in figure 1. Utilizing a COTS product in the first-generation design allowed for a timely proof of concept test. However, the temperature limit of the gaskets used in the heat exchanger is 120 °C, which is

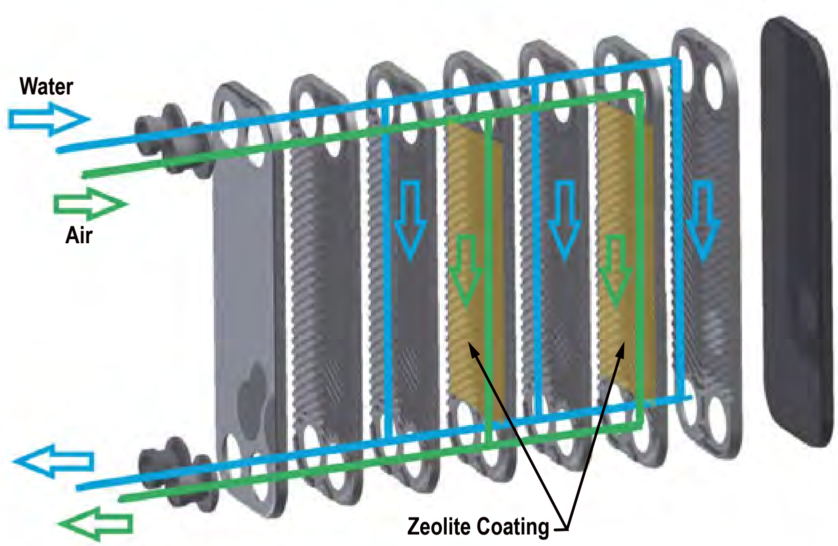


FIGURE 1. Schematic showing the wetted pathways of the RC-TSA bed design.

TABLE 1. Summary of results from heating tests.

	Heating Low Flow	Heating Mid Flow	Heating High Flow
Water flow rate (gal/min)	0.5	1.0	1.5
Water inlet temp at t=0 (°C)	22.5	24.1	23.1
Water inlet temp at critical point (°C)	64.6	67.5	65.5
Water outlet temp at critical point (°C)	52.9	52.4	41.1
Time at critical point (seconds)	46	22	11
Heating rate to critical point (°C/s)	0.9	2.0	3.9

below the zeolite's regeneration temperature of 200 °C. To address this problem, the next-generation metal substrate bed is being manufactured at MSFC and will utilize Dupont™ Kalrez® O-rings, whose temperature limit is 326 °C. Additionally, the thickness of the zeolite layer will be increased to allow for higher CO_2 adsorption capacity. In FY 2022, the next-generation bed was designed and is currently being machined. It is planned to have the next-generation plates coated with the zeolite layer and tested by end of FY 2023.

RESULTS/ACCOMPLISHMENTS

In FY 2022, testing of the first-generation bed began. This involved getting the vacuum characterization test stand (VCTS) operational and certified with the pressure systems and industrial safety groups. Modifications were made to the VCTS to allow for testing of a bed with a new form factor and separate wetted pathway for a heat transfer fluid. What sets this design apart from SOA CO_2 removal systems is its ability to rapidly heat and cool the bed. Heating and cooling tests were performed to get some data on the time it takes to heat and cool the bed. The VCTS utilizes a Julabo heating and refrigerating circulator to send either hot or cold fluid to the bed. The heating tests started with an ambient temperature bed and had a fluid temperature set point of 85 °C. The fluid was circulated out to the bed at three different flow rates: 0.5, 1.0, and 1.5 gal/min. It was found that at a certain point, the heating of the bed was limited by the rate at which the Julabo could heat the fluid back up to the set point. A critical point was defined as the time at which the inlet and outlet liquid temperatures experienced local maxima, at which point further heating was limited by how quickly the Julabo could heat the fluid. A summary of the results is shown in table 1. Eventually this data will be used to refine and validate the thermal model that was created for this design back in FY 2021.

In FY 2022, the next-generation bed was designed. Initially, a design using copper gaskets and a knife edge seal was considered. This would remove the low temperature limit, but it was determined that it would require quite a bit of force to crush the copper gaskets to make an airtight seal. In terms of functionality, this design would be challenging to assemble and dissemble when needed. Additionally, this design would require thicker metal plates to effectively use the knife edge seal without distorting or bending the plates resulting in a heavier weight design. To minimize mass and improve ease of machinability and functionality, a new design was considered: O-ring and Kalrez gaskets. The plates for this design are currently being manufactured and will be sent to Precision Combustion, Inc. (PCI) for coating once complete.

PARTNERSHIPS

PCI developed and optimized the zeolite 13X coating process and application on the first-generation plates. The project has an open contract with PCI to coat the next-generation plates with a thicker coating that can allow for higher temperature operation. The goal is to have them develop a ≈1-mm-thick coating that can withstand operation at up to 300 °C. It is beneficial to the project to have the same vendor coat the next-generation plates to avoid having to relearn the properties and behaviors of a new zeolite coating. Successful zeolite coatings are difficult and using another vendor would increase the risk of the zeolite coating's having poor adhesion, poor mass transfer behavior, or poor mechanical properties.

SUMMARY

RC-TSA for life support CO_2 removal has the potential to be smaller, lighter, and more efficient than SOA CO_2 removal systems. All crewed spaceflight missions require CO_2 removal, so this technology could impact future flight applications such as short- and long-term crewed space flight, Gateway, and Moon and Mars habitation. In FY 2022 the first-generation RC-TSA bed was tested, and the next-generation bed was designed.

PRINCIPAL INVESTIGATORS: Emily Klee and Timothy Giesy

PARTNER: Precision Combustion, Inc.

FUNDING ORGANIZATION: Center Innovation Fund

Investigating Autonomous Healing of Cracks in Lightweight, Aerospace-Grade Materials Systems

OBJECTIVE: *To fabricate and study a UV-curable shape memory polymer matrix reinforced by hybrid shape memory alloy (Flexinol) wires, glass fibers and carbon fibers for the autonomous healing of cracks in lightweight, aerospace-grade materials systems to support advanced manufacturing of structures and materials.*

PROJECT GOAL/DESCRIPTION

It has been well-known that laminated composites have been widely used in lightweight aerospace structures due to their high specific strength and stiffness, adjustability, and corrosion resistance. However, laminated composites are vulnerable to out-of-plane impact damage, and even low velocity impact events could undermine them. Various types of damage can be created under a low velocity impact, with delamination being the most common. If the delamination is not healed, significant reduction of in-plane mechanical properties will be induced. Z-pins have been widely used to help in resisting delamination. While this method can mitigate delamination, it cannot fully eliminate it. Therefore, delamination self-healing is highly desired. Based on the biomimetic close-then-heal (CTH) strategy patented by the investigators, this project is studying the use of sinusoidal shape memory alloy (SMA) z-pins to assist in delamination closing, using a multifunctional thermoset polymer developed by the investigators as the polymer matrix. This polymer has high strength, high stiffness, and excellent shape memory effect; it is ultraviolet (UV)-curable, self-healable, recyclable, and 3D-printable. The role played by the sinusoidal SMA z-pins is threefold: (1) Reducing delamination, (2) closing delamination by shape memory effect, and (3) heating the laminate by electricity during the healing process. The goal is that the combination of the sinusoidal SMA z-pins and the multifunctional polymer will achieve the enumerated objectives.

Four tasks have been identified as essentials in this project: (1) Selection of raw materials (e.g., polymer, fiber, and SMA); (2) fabrication of sinusoidal SMA z-pinned composite laminates; (3) low velocity impact tests and compression after impact (CAI) tests; and (4) self-healing and healing efficiency tests. Success of this project will benefit specific NASA objectives for space exploration by providing lightweight structures with damage self-healing capability. Furthermore, this work will benefit the research mission of Southern University and further the value of existing intellectual property, including issued and pending U.S. patents covering self-healing of polymer composite structures. It will also enhance the education mission of Southern University by directly involving minority graduate and undergraduate students in related research.

APPROACH/INNOVATION

There is one key challenge of fabricating aerospace-grade, self-healing fiber-reinforced polymer composite laminates: using the conventional autoclave method presents a difficulty in maintaining the programmed recovery stresses in a hybrid composite laminate. For instance, making a hybrid composite laminate using shape memory polymer (SMP) and SMA with the motivation of yielding a high recoverable stress to effect healing is difficult to achieve, since most of the available SMPs require an elevated temperature curing. As a result, embedding an SMA material in such an SMP will lead to premature recovery happening during the manufacturing process. The objective of using hybrid multifunctional shape memory materials is to exploit the synergetic recovery stress contribution from each segment. The research team has designed an out of autoclave (OoA) curing process that readily enables the inclusion of sinusoidal SMA z-pins to SMP and glass fiber at room temperature. This mechanism makes it flexible to obtain a hybrid composite laminate with stored recovery stresses that can be used to effect healing when damage occurs.

The methodology involves creating a simple reusable mold from a 2-in-thick aluminum plate with a cutout of 8 × 8 in. This open mold has two plain glass coverings to complete the mold. The function of the cut-out aluminum plate is to hold the laminate and the sinusoidal z-pins in place, while the plain glass coverings help to impose pressure on the laminates to get rid of trapped air and to allow the passage of UV radiation to cure the laminates. The sinusoidal z-pins are electrically conductive and will be heated by resistive joule heating to recover the SMA as well as to heat up the SMP for the thermoreversible reaction to take place. Figure 1 gives a schematic of the setup. In the current study, tasks 1 and 2 have been completed. Tasks 3 and 4, which involve low velocity impact tests and CAI tests, and self-healing and healing efficiency tests on manufactured laminated specimens with the sinusoidal z-pins, have been initiated.

RESULTS/ACCOMPLISHMENTS

Highlighted in figure 1 are the key steps in the vitrimer matrix hybrid composite fabrication process. The laminate was cured by UV light and the healing was achieved via electricity. The following experimental work has been carried out:

(1) Instron® Dynatup 8250 HV impact tester was used to carry out low velocity impact tests on the laminates according to American Society for Testing and Materials (ASTM) standard D3763-18.

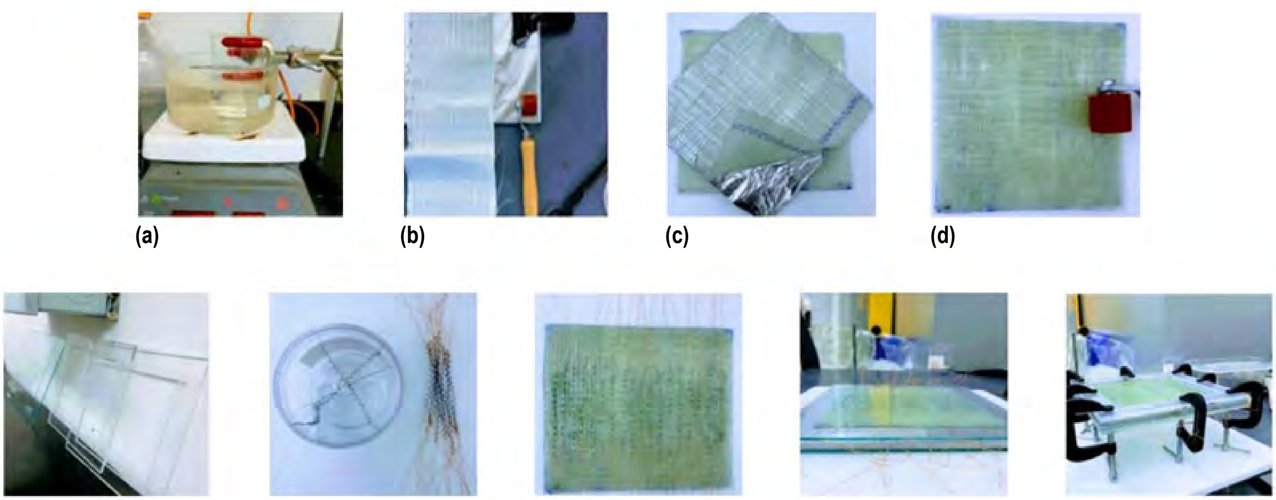

(a) (b) (c) (d) (e) (f) (g) (h) (i)

FIGURE 1. Composite Fabrication Procedure (a) vitrimer preparation, (b) laying of Saertex unidirectional glass fiber, (c) rolling of sandwiched vitrimer wetted glass fiber in thin sheets of aluminum foil to enhance surface finish, (d) rolled out laminate with good surface finish and orderly aligned plies. (e) sinusoidal z−pinned SMA and copper wire connections to be embedded in laminate, (f) embedded sinusoidal z−pinned SMA in laminate, (g) glass sheet and frame to hold laminate for curing, (h) laminate sandwiched in aluminum mold with glass ware covering, (i) C-clamps used to exert pressure on laminate.

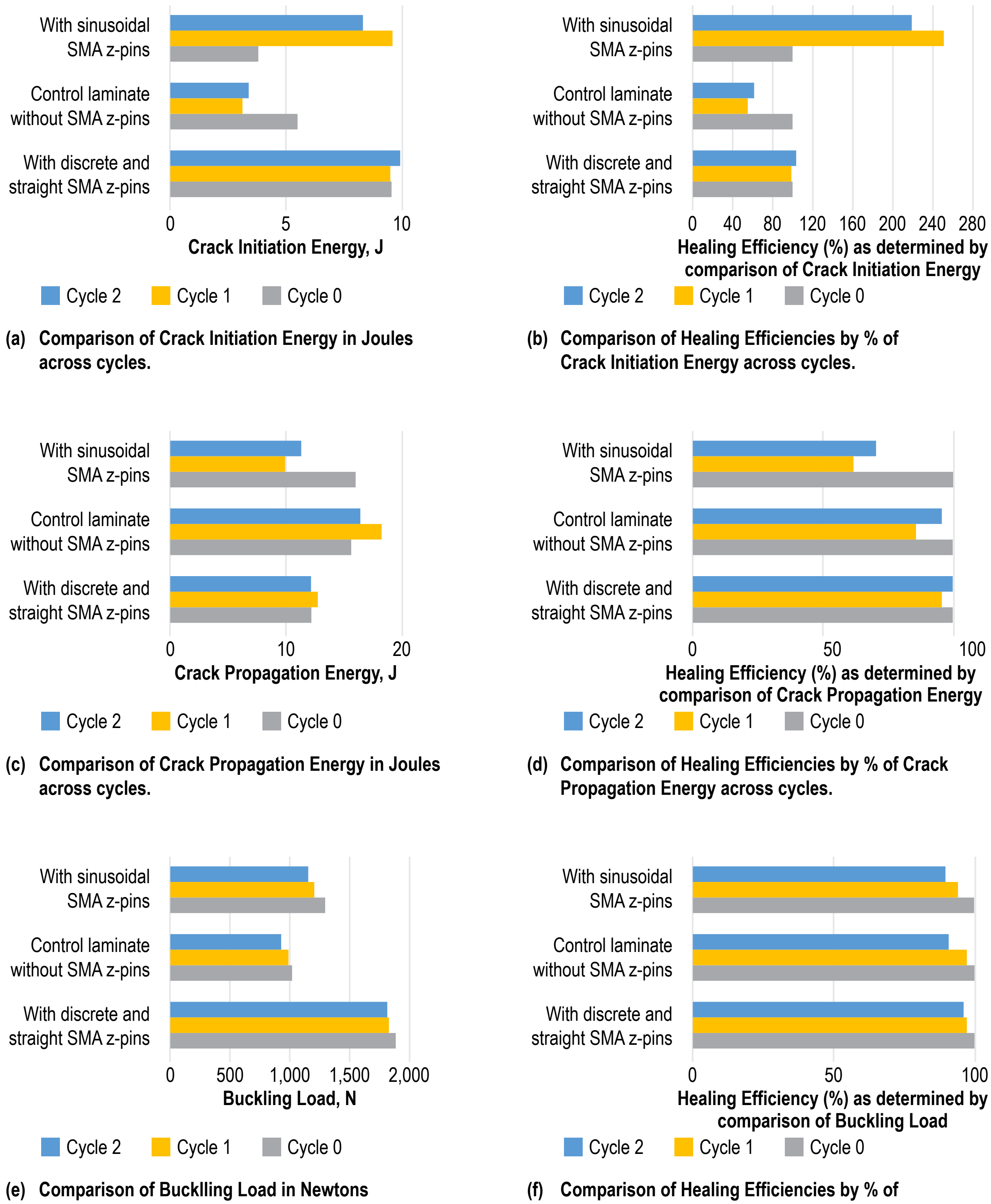


FIGURE 2. Charts representing summary of test results.

(2) Healing efficiency of the laminates with the SMA sinusoidal z-pins is compared with that of the straight SMA z-pins and the control laminates without SMA z-pins.

(3) In addition to the crack initiation energy of the composite laminate as a basis for computing the healing efficiency, the crack propagation energy and the critical buckling loads recorded during CAI testing were also used to ascertain the healing efficiency.

CAI test results are shown in figure 2.

PARTNERSHIPS

Guoqiang Li collaborated of experimental methods for fabrications vitrimer matrix hybrid composite laminate, and Samuel Ibekwe collaborated of mechanical characterization of laminates.

SUMMARY

The Southern University team has developed a new laminated composite with enhanced impact tolerance and self-healing capability. The laminate was manufactured by using vitrimer as matrix, continuous glass fiber as reinforcement, and sinusoidal SMA z-pins as transverse reinforcement, delamination closing device, and conductor for joule heating. The laminate was cured by ultraviolet light, and the healing was achieved by electricity. Overall, the CAI strength of the sinusoidal SMA z-pinned composite laminate is better than the control laminate without SMA z-pins.

PRINCIPAL INVESTIGATOR: Patrick Mensah, Southern University

PARTNERS: Southern University; NASA Marshall Space Flight Center

FUNDING ORGANIZATION: Cooperative Agreement Notice

Printable, Molecularly Imprinted Polymers for Cortisol Sensing

OBJECTIVE: *To develop an on-demand 3D-printable sensor for detection of cortisol to determine the level of stress in astronauts.*

PROJECT GOAL/DESCRIPTION

Printed electrochemical sensors functionalized with synthetic and inherently temperature- and time-stable capture probes would be an ideal solution to NASA's future diagnostic needs. This project aims to develop a novel cortisol sensing strategy based on a judicious combination of molecularly imprinted, polymers-based 'artificial antibodies;' nanoparticle functionalization for on-demand ink-based printing; and in-situ regeneration technology.

APPROACH/INNOVATION

The In-Space Manufacturing (ISM) On-Demand Manufacturing of Electronics (ODME) project is developing on-demand 3D printing capability for the International Space Station (ISS) and other space applications. An area of significant need is on-demand sensors for astronaut crew health, so that replacement sensors, upgrades, or new sensors can be printed as needed. The need for a printed sensor to measure astronaut stress is one of the highest needs for the NASA flight surgeons, so ODME has partnered with the California Institute of Technology (Caltech) to develop these novel, innovative sensors.

ODME is incorporating the results of this project into the overall development of a wireless, wearable crew health sensor platform. The design concept is to incorporate replaceable, wearable stress sensors with a flexible sensor controller board that are in contact with the skin. The wearable stress sensors would be able to be peeled off and replaced as necessary, similar to an adhesive bandage. This is a novel concept that can eventually be a sensor platform for multiple biosensors and environmental sensors to provide advanced feedback to flight surgeons on the health and well-being of the astronauts. Wireless communication with these sensors means real-time feedback on the astronaut crew and environmental conditions.

RESULTS/ACCOMPLISHMENTS

The project had three objectives for developing the molecularly imprinted polymer (MIP) stress sensors: (1) prepare and characterize the MIP nanoparticles for stress hormone recognition; (2) prepare and characterize printed stress hormone sensors in buffer and biofluids; and (3) wirelessly integrate the printed MIP sensor.

Electrochemical cortisol and noradrenaline sensors were fabricated and characterized, including characterization of each sensor type in human sweat. The concentration levels to be detected were set at 20–100 nM for noradrenaline and 0–150 nM for cortisol. The fabricated sensors worked extremely well and the results were excellent, as very small concentration detection will be necessary for monitoring astronaut stress in extremely small volumes of human sweat. A significant result was that the noradrenaline sensor actually sensed beyond the nanomolar range, which is remarkable.

Finally, the Caltech team was successful in developing a Bluetooth Low Energy wireless communications module for the sensor output. The module was tested with the printed noradrenaline sensor,

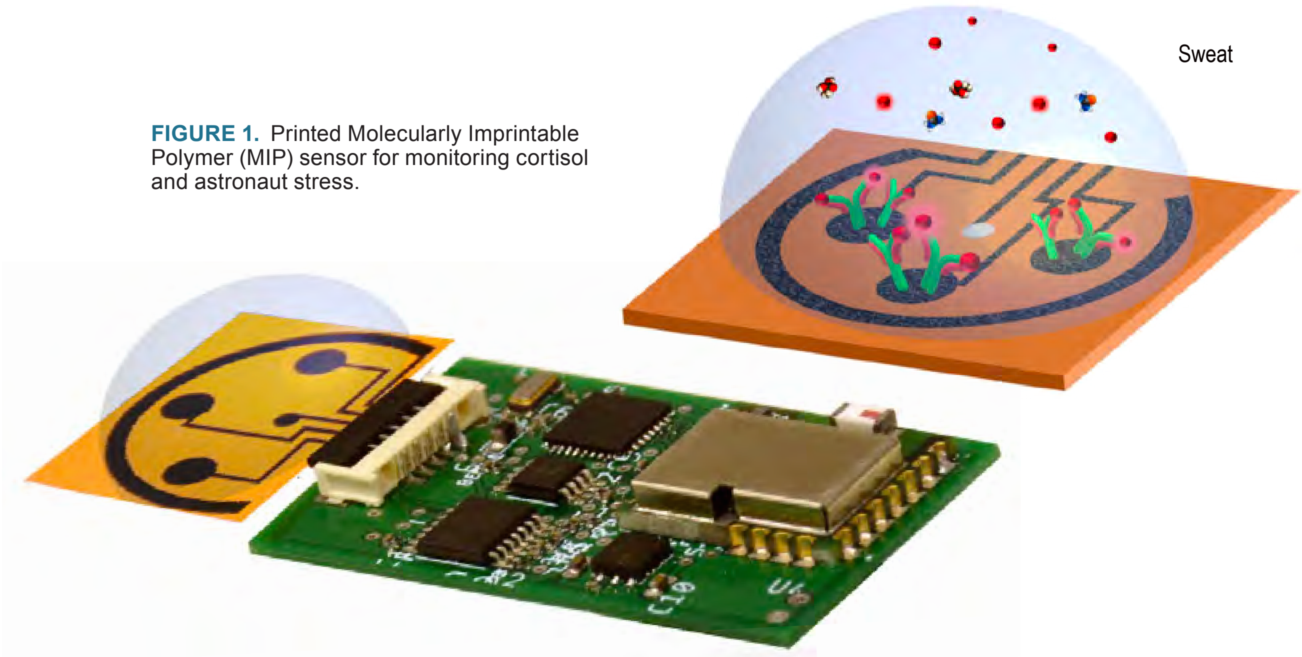


FIGURE 1. Printed Molecularly Imprintable Polymer (MIP) sensor for monitoring cortisol and astronaut stress.

and it worked very well. This integration of wireless communications with a flexible biosensor accomplished all of the objectives of the project.

PARTNERSHIPS

Dr. Wei Gao at Caltech is a nationally known researcher in the areas of biosensing, energy storage, and molecularly imprinted polymers. ODME is continuing to work with Dr. Gao on a follow-up project to this one, jointly developing an on-demand printed biofuel cell to provide energy for biosensors and other printed electronics.

SUMMARY

The Caltech research into molecularly imprinted polymers for biosensing of astronaut crew health is innovative and has great potential for on-demand 3D printing of biosensors in space for future exploration missions. This project showed the potential for MIPs for two different biosensor approaches to sensing astronaut crew health, and both cortisol and noradrenaline sensors performed very well in sensing very small concentrations in human sweat. The development of biosensors such as this that can be manufactured as needed in space will enable future NASA missions to be much safer and efficient for the astronauts.

PRINCIPAL INVESTIGATORS: Dr. Wei Gao, California Institute of Technology; Curtis Hill, NASA Marshall Space Flight Center

PARTNER: California Institute of Technology

FUNDING ORGANIZATION: Cooperative Agreement Notice

Early Biofilm Detection in ISS Water Supply Systems Using Impedance Microbiology

OBJECTIVE: *To design an impedance microbiology sensor for biofilm detection in ISS-relevant environments.*

PROJECT GOAL/DESCRIPTION

Water supply systems on the International Space Station (ISS) and future extended space exploration missions are critical elements of the primary life support system. Microbes in the water can lead to biofilm growth inside the water supply or recovery systems, which may clog lines and harm astronauts. An in-situ sensor capable of detecting biofilm formation would help protect astronaut health, inform maintenance decisions, and eliminate costly shutdowns. The research team's sensor is based on impedance microbiology principles and detects electrochemical changes caused by biofilm formation.

APPROACH/INNOVATION

Electrochemical impedance spectroscopy sensors were used in this study to detect early biofilm formation. The transducer principle is based on detecting a change in the electrochemical double layer capacity of an electrode system under an electrical alternating current (AC) field (electrical amplitude and frequency) perturbation. Interdigitated electrodes (IDEs) with active physical dimensions of 10 µm electrode width and 15 µm spacing were repeated 50 times. This minimized sensor configuration has the advantage of detecting initial microbial attachment and biofilm growth. Attached microorganisms on the electrode change the double layer capacity and consequently the measured electrical impedance of the entire electrochemical cell. The change in impedance as a function of time indicates growing biofilms. The sensor fabrication utilizes matured technologies adapted from the semiconductor industry and is robust, reproducible, lightweight, and highly sensitive. An innovative leak-free mechanical sensor housing for sensor integration within the ISS water supply system was developed to allow crew members to efficiently replace sensors.

RESULTS/ACCOMPLISHMENTS

The sensor platform was fabricated at the Montana Microfabrication Facility and includes two impedance sensors and one temperature sensor, as shown in figure 1a. The accomplishments and technological

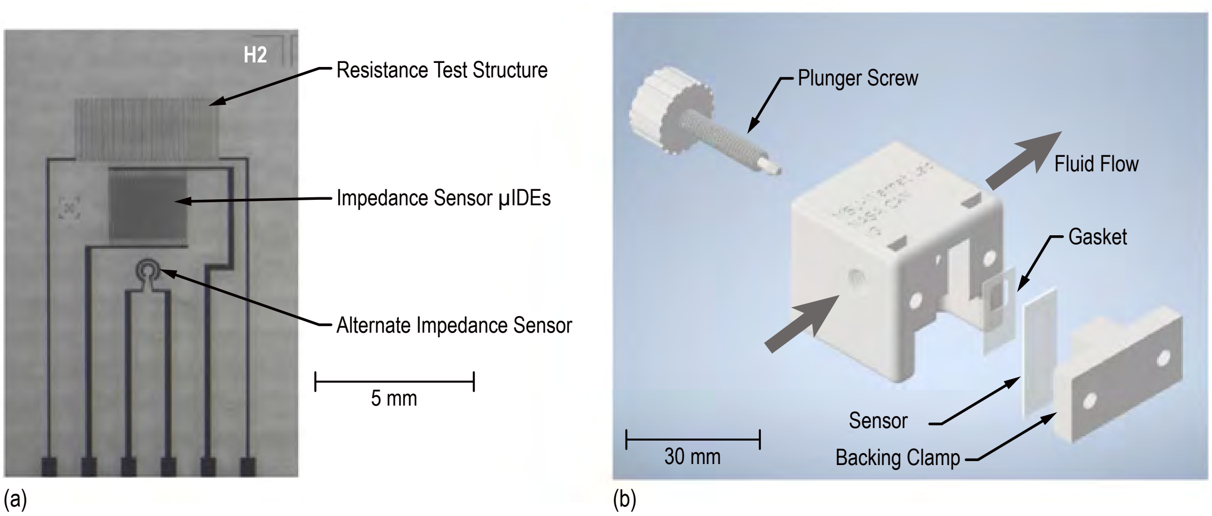


FIGURE 1. (a) Montana State University's biofilm sensor includes two impedance sensors and one temperature sensor; (b) Sensor housing with an integrated plunger to replace the sensor that allows fluid flow during sensor replacement.

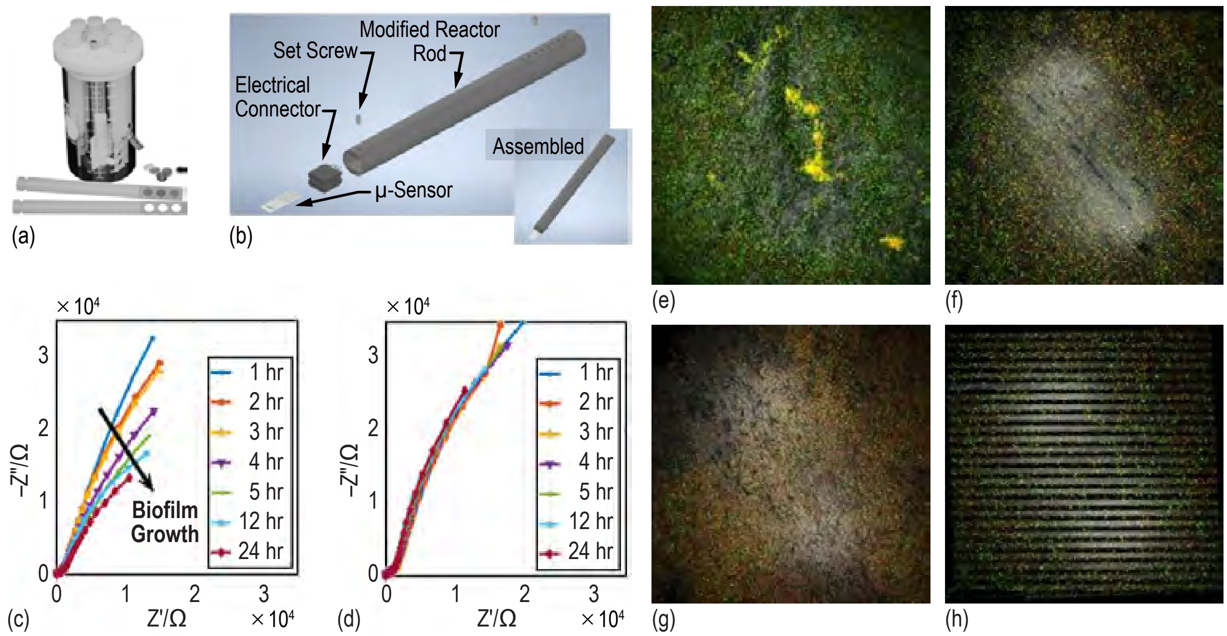


FIGURE 2. (a) CDC biofilm reactor showing deployable rods and coupon surfaces for monitoring biofilm formation; (b) Exploded view of modified reactor rod with integrated impedance spectroscopy microsensor used in biofilm growth experiments under gravity conditions; (b insert) detailed view of assembled reactor rod ready for deployment into CDC reactor; (c) Nyquist plot (real (Z') vs. imaginary (–Z") impedance) of sensor response from *P. aeruginosa* biofilm growth; (d) Nyquist plot of abiotic control experiment; (e–h) Live/dead imaging of *P. aeruginosa* biofilm on Teflon, stainless steel, Inconel, and microfabricated sensor, respectively; removed at 24 h of growth under gravity conditions. Scale bars represent 150 µm.

development milestones reached in 2022 are as follows:

- Sensor stability was initially evaluated by operating the system in microbial ersatz media for 40 d. Sensor signal drift was <1%, indicating no material corrosion and high system reliability.
- Mechanical sensor housing with an integrated plunger, as shown in figure 1b, enables leak-free sensor replacement in under 1 min.
- A standard biofilm reactor (CDC biofilm reactor) was modified to accommodate removable rods with integrated microfabricated sensors and material coupons of stainless steel, Inconel® nickel alloy, and Teflon™. Samples of *Pseudomonas aeruginosa* PAO1 with initial concentrations of approximately 1×10^9 colony forming units (CFUs)/mL^{-1}, 1×10^7 CFUs/mL^{-1}, and 1×10^5 CFUs/mL^{-1} were tested against sensor responses. Biofilm growth was measured by the change in impedance and confirmed using confocal microscopy on the sensor and material coupon surfaces, as shown in figure 2.

PARTNERSHIPS

This project was undertaken in partnership with Layne Carter and Yo-Ann Velez Justiniano at NASA Marshall Space Flight Center.

SUMMARY

The impedance microbiology sensor system has been demonstrated to monitor biofilm growth and can be an asset to control water remediation on the ISS and future space missions. The sensor technology is now being applied in a collaborative project with NASA Program to Stimulate Competitive Research (EPSCoR) entitled *"Integrated Biofilm Control Strategies for Water Systems during Extended Space Flight"* at the Center for Biofilm Engineering at Montana State University.

PRINCIPAL INVESTIGATORS: Dr. Stephan Warnat and Dr. Christine Foreman, Montana State University Center for Biofilm Engineering

PARTNERS: Layne Carter and Yo-Ann Velez Justiniano, NASA Marshall Space Flight Center

FUNDING ORGANIZATION: Cooperative Agreement Notice

Investigating the Performance Characteristics of Auxetic Foams in Neuropathy Treatment Applications

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

FIGURE 1. Ground reaction forces and neuropathy testing utilizing force plate technology.

PROJECT GOAL/DESCRIPTION

Technologies geared toward the health, muscular longevity, and Earth applications of returning astronauts are important but currently scarce at NASA. Astronauts in space are exposed to ten times more radiation than on Earth and are much more susceptible to degenerative muscular and nerve diseases and conditions, such as neuropathy and limited mobility. In fact, Scott Kelley, a former astronaut during NASA's Shuttle Discovery mission, suffered from posture and balance deficiencies upon his return to Earth. Technologies in the sustainment of health of returning astronauts are underdeveloped and are a necessity to ensure that astronauts are supported by NASA even after they return from space. Moreover, more than 20 million Americans suffer from limited mobility and neuropathy, inclusive of returning astronauts. Developing such technologies would also create significant positive impact on society in general.

Auxetic foams are foams with negative Poisson's ratios. They expand when stretched and shrink when compressed. This is contrary to almost all naturally occurring or synthetic materials, whose Poisson's ratios are positive. Auxetic foams exhibit many desired properties (e.g., significantly improved cushioning and pressure relief; superior shape conformity; optimal dynamics; enhanced toughness; shear resistance; bending stiffness; improved impact and indentation resistance; etc.). This research supports the investigation of the performance characteristics of auxetic foams and the evaluation of their efficacy as a neuropathy aid. Additionally, this research supports the investigation of the material characteristics of the auxetic foam for potential applications in astronaut's suits and in structures for deep space exploration systems.

APPROACH/INNOVATION

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

Additionally, the auxetic foam material was also investigated. Dynamic mechanical analysis (DMA) testing was performed utilizing a TA Instruments DMA 2980 compression clamp with 15-mm-diameter plates, as well as a TA Instruments Q800 DMA-RH accessory clamp. Strain sweeps and humidity vs. temperature testing were conducted via DMA.

FIGURE 2. Expansion of auxetic foam material in transverse direction, after being stretched.

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

RESULTS/ACCOMPLISHMENTS

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

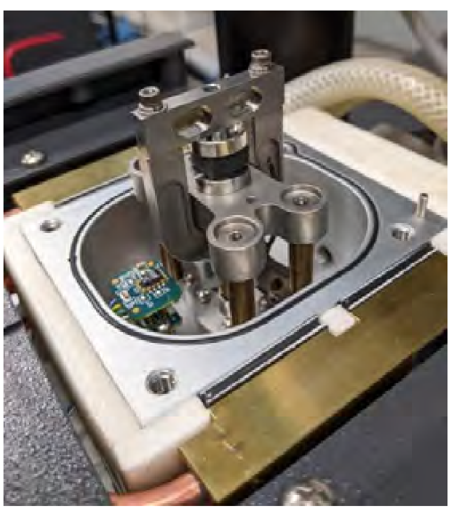


FIGURE 3. A square sample of auxetic foam mounted between two circular platens (each 15 mm diameter) in the DMA 2980 compression clamp.

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

PARTNERSHIPS

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

SUMMARY

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

PRINCIPAL INVESTIGATOR: LaBreesha Batey

PARTNER: Florida A&M University–Florida State University College of Engineering

FUNDING ORGANIZATION: Cooperative Agreement Notice

Development of Non-Platinum Group Metal Catalysts for Hydrogen Resource Recovery

OBJECTIVE: *To demonstrate at least 85% hydrogen recovery from a nominal Plasma Pyrolysis Assembly (PPA) by developing a non-platinum group metal catalyst utilized in a single-cell electrochemical hydrogen separator.*

PROJECT GOAL/DESCRIPTION

Currently on the International Space Station (ISS), approximately 50% oxygen (O_2) is recovered from metabolic carbon dioxide (CO_2). NASA is currently targeting technologies that achieve 75–90% oxygen recovery. One approach to achieve additional recovery is to recycle hydrogen (H_2) by adding a methane (CH_4) postprocessor downstream of the Carbon dioxide Reduction Assembly (CRA) that is part of the Atmosphere Revitalization architecture on the ISS. NASA has been exploring the use of the Plasma Pyrolysis Assembly (PPA) for this purpose. The PPA converts the CH_4 produced by the CRA into a mixed gas stream of mainly H_2 and acetylene (C_2H_2). Secondary reactions also occur that result in a PPA effluent mixture containing product H_2, C_2H_2, and unreacted CH_4, as well as trace quantities of water (H_2O), carbon monoxide (CO), ethylene (C_2H_4), ethane (C_2H_6), and solid carbon (C).

In order to recycle H_2 back to the CRA, the hydrocarbon and carbon byproducts must be removed to prevent fouling of the Sabatier catalyst. NASA collaborated with Skyre to develop an electrochemical-based H_2 separation technology for this application. In 2018, two subscale electrochemical H_2 separation systems were delivered to NASA that employed alloyed platinum catalysts to preferentially separate H_2 from the PPA effluent. The platinum-alloyed catalyst showed improvements over traditional platinum in terms of lowering acetylene hydrogenation; however, the resulting performance was not satisfactory to meet the requirements of a sustainable H_2 recovery/recycling solution. The focus of this project is to develop a non-platinum group metal (PGM) catalyst that is electrochemically active to the hydrogen oxidation reaction (HOR) to enable effective H_2 separation while catalytically preventing the C_2H_2 hydrogenation reaction.

APPROACH/INNOVATION

A key aspect of this technology approach is the requirement to separate and purify H_2 from the PPA product stream while preventing C_2H_2 hydrogenation to achieve the desired H_2 recovery rates, which will increase O_2 recovery. During the H_2 separation process, the PPA effluent stream is fed to the cell anode. The H_2 is oxidized to protons and electrons and the protons migrate across a proton exchange membrane (PEM) from the anode to the cathode due to the imposed electrical field. The electrons are pumped by a direct current power supply to the cathode, where they combine to form gaseous H_2. The membrane only transports protons, leaving the remaining constituents in the anode exhaust stream. A schematic is depicted in figure 1.

Carbon monoxide is present in the PPA effluent stream, which is a known poison to platinum catalysts with low-temperature PEM cells. The subscale units delivered to NASA were built with polybenzimidazole (PBI)-based membranes. PBI membranes allow high-temperature operation, which inhibits adsorption of CO. However, these membranes use phosphoric acid for proton conductivity, which corrodes cell hardware and can potentially migrate and negatively impact downstream hardware.

This project is focused on achieving the desired H_2 recovery rates through the development of non-PGM catalysts for the HOR that achieve increased H_2 recovery rates, tolerant to CO, and reduce

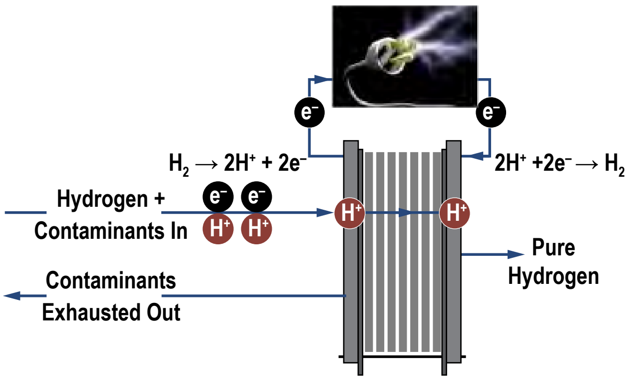


FIGURE 1. Electrochemical hydrogen separator.

hydrogenation of C_2H_2. To ensure desired outcomes, three approaches have been implemented while investigating the use of non-PGM. The first is to prevent C_2H_2 adsorption onto the catalyst by providing inert surfaces; the second is to prevent the reaction of C_2H_2 with H_2 by separating the different active sites for C_2H_2 and H_2 adsorption; and the third approach is to poison the active catalyst sites. Low-temperature PEMs were utilized rather than PBI-based materials to mitigate corrosion and acid migration issues identified in previous program activities.

RESULTS/ACCOMPLISHMENTS

Efforts were made to advance the development of the electrochemical hydrogen separator membrane technology. Three non-PGM catalyst candidates (one metal oxide and two metal sulfides) were synthesized, characterized, and evaluated. Subscale catalyst testing was limited to 5 cm^2 hardware to identify the best performing catalyst. The results indicated that the metal oxide catalyst outperformed the metal sulfide catalyst candidates and the baseline platinum-alloyed catalyst. The optimal catalyst selection was completed, and work began generating large batches of the catalyst for construction of the single-cell electrochemical unit. Test results from the downselected catalyst demonstrated poor/no H_2 recovery due to high electrical conductivity and HOR activity, despite its selectivity in the PPA effluent stream.

Another non-PGM catalyst was investigated to use as a bifunctional catalyst to tolerate CO efficiently by oxidizing to CO_2. Utilizing this new catalyst yielded increased H_2 recovery of greater than 80% while operating at significantly low voltage. However, the catalyst displays less tolerance to C_2H_2 and required high potential operation along with low H_2 recovery due to C_2H_2 hydrogenation. Future work to continue development of the membranes for electrochemical H_2 separation from acetylene is still required.

PARTNERSHIPS

Skyre, Inc. located in East Hartford, CT has partnered with NASA to develop technologies to recover hydrogen for increased oxygen recovery. Through Skyre's partnership with the University of Connecticut, they continue their work to further close the oxygen recovery loop for life support systems as well as recovering hydrogen and helium from rocket engine testing.

SUMMARY

It is imperative that a H_2 separation technology is identified for the use of the PPA, as it is a viable solution to increase O_2 recovery for long-duration manned missions. It was observed that the platinum-alloyed catalyst in previous builds of the separator contributed to degraded performance and that performance could be increased by employing a non-PGM catalyst. Efforts focused on synthesizing, characterizing, and testing candidate non-PGM catalysts to identify the optimal candidate for an electrochemical H_2 separator solution. The candidate catalysts did not perform as expected yielding less than required H_2 recovery due to CO poisoning and C_2H_2 hydrogenation. Future work will involve investigating other tolerant catalysts with the PEM membrane.

PRINCIPAL INVESTIGATORS: Cara Black, NASA Marshall Space Flight Center; Dr. Trent Molter, Skyre, Inc.; Dr. Steven Suib, University of Connecticut

PARTNERS: Skyre, Inc.; University of Connecticut

FUNDING ORGANIZATION: Cooperative Agreement Notice

FOR MORE INFORMATION:
https://www.skyre-inc.com/project-7-breathe

Bioremediation of Microgravity Biofilms and Water Processor Health

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

PROJECT GOAL/DESCRIPTION

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

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

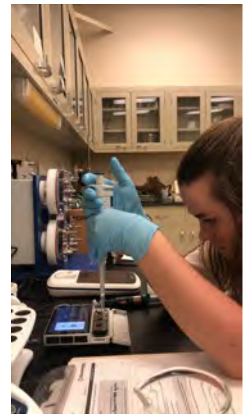


FIGURE 2. Sequencing capabilities were established to support plasmid engineering verifications. Molecular biologist intern inserts samples into sequencing apparatus to investigate use in this format.

APPROACH/INNOVATION

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

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

RESULTS/ACCOMPLISHMENTS

Relevant strains were gathered and short- and long-read sequencing was performed on the genome samples. The whole genomes were obtained via hybrid assembly by using the Unicycler pipeline. Pangenome analysis was performed using existing pangenome analysis tools like OrthoMCL and Anvi'o utilizing all hybrid assemblies in order to have all potential shared genes aligned. The pangenome analysis provides data for in-silico analysis of function overlaps at the DNA level. Once overlapping DNA was determined, it was used as a target sequence. If not found, a mixture of targeted plasmids was suggested to account for a mixture of targets. Plasmids were developed to contain target regions and parts necessary for insertion/deletion.

PARTNERSHIPS

The research team included internal partners from NASA Johnson Space Center and NASA Ames Research Center, as well as external partners from Texas State University and the University of Alabama in Huntsville.

SUMMARY

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

PRINCIPAL INVESTIGATOR: Jonathan P. Wilson, NASA Marshall Space Flight Center

PARTNERS: Texas State University; University of Huntsville in Alabama; NASA Johnson Space Center; NASA Ames Research Center

FUNDING ORGANIZATION: Center Innovation Fund

Additive Manufacturing of Fire Retardant and Repairable Composite Structures Based on Lunar Regolith and Vitrimer Epoxy under Lunar Conditions

OBJECTIVE: *To design and characterize a multifunctional lunar regolith/vitrimer epoxy-based composite suitable for extrusion additive manufacturing to print regolith structures with enhanced mechanical properties.*

PROJECT GOAL/DESCRIPTION

This research aims to significantly lower the cost involved in building architectural habitats and manufacturing spare parts in long-term space exploration visits. Due to the extremely higher cost associated with transporting masses from the earth, in-situ resource utilization (ISRU) of lunar regolith is strongly desired for structural applications. In this project, a compatibility study of lunar regolith simulant with different vitrimer epoxies that are fire retardant and repairable has been undertaken. Vitrimer-based regolith composites are also being designed and characterized for additive manufacturing (AM). In addition, an extrusion AM system for vitrimer/regolith slurry is under development which will be optimized for the printing process to print high performance regolith/vitrimer composites for structural components.

Thus, in this project, four specific tasks have been planned: (1) compatibility testing of different vitrimer epoxies with lunar regolith simulant; (2) designing vitrimer epoxy/lunar regolith composite slurry for extrusion additive manufacturing; (3) developing custom extrusion AM system for regolith composite; and (4) optimizing and computationally analyzing the printing process. Successful completion of this proposed project will directly benefit NASA's space exploration initiatives by providing capabilities to print structural components on the Moon using abundant lunar regolith. Therefore, the end goal of this project is to design and characterize a multifunctional lunar regolith/vitrimer epoxy-based composite suitable for extrusion AM to print regolith structures with enhanced mechanical properties.

APPROACH/INNOVATION

As a result of compatibility testing of different vitrimer epoxies with lunar regolith simulants, a curing process for regolith/vitrimer epoxy composite has been developed and implemented. Experiments were conducted with different weight fractions of regolith in composite matrix. The mixing process involves manually stirring the printable ink constituents (i.e., bisphenol A diglycidyl ether (DGEBA), fatty acid, zinc acetate ($Zn(Ac)_2$), and nanoclay) with regolith powder in an oven-safe container, then heating and cooling the mixture within a tube furnace from the pre-crosslinking phase to the fully cured phase. The heating program was 130 °C for 90 min (pre-crosslinking), 60 °C for 20 h (pre-curing), and at 180 °C for 6 h (fully curing), as shown in figure 1. Elevating the curing temperature and lowering the curing time compared to the published literature was found to improve the curing process. This process was conducted under vacuum due to the volatile components produced by the DGEBA once heated. A vacuum trap was employed to protect the vacuum pump and the testing environment. The incorporation of nanoclay facilitated the curing process and resulted in cured, solid components of regolith/vitrimer composite, as shown in figure 2.

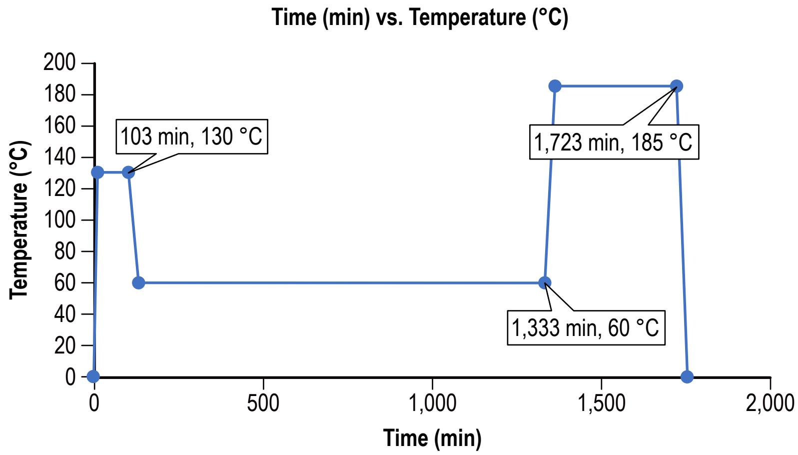


FIGURE 1. Temperature profile for curing rectangular sheet for tensile test coupons.

The change in regolith/polymer composition resulted in different degrees of mechanical stiffness, as proven in the preliminary qualitative experiments. As the percentage of regolith increased from 38% to 64%, the stiffness of the cured composite decreased.

Further, experiments revealed that the thermal curable vitrimer epoxy temperature program must be modified according to the equipment and sample size being used. Curing tests were ran in the tube furnace using custom molds made of Teflon™ bars, Teflon sheets and steel plates. The control sample was tested in all trials to be able to verify the results with literature. For dissolving the cured regolith-composites, the samples were submerged in ethylene glycol (EG) and heated at 180 °C for 6 h. The material did not dissolve completely, and various methodologies were considered to complete the dissolution such as increasing the dissolution time. A review of literature informed that, instead of using a $Zn(Ac)_2$ catalyst, triazabicyclodecene (TBD) can facilitate the dissolution process. Therefore, it was decided to test the dissolution experiment with TBD.

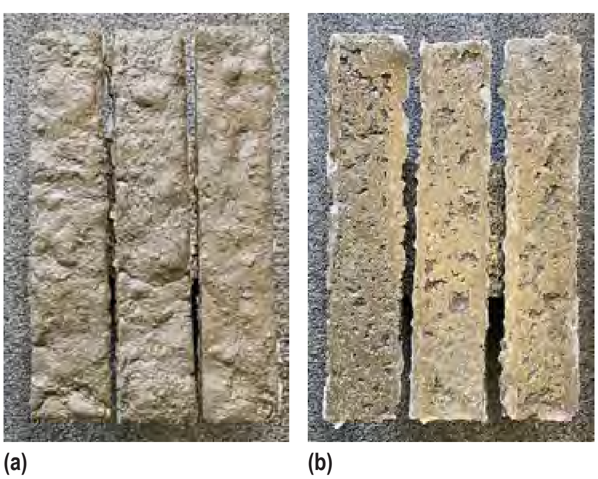


FIGURE 2. Front and back view of pristine, cured regolith samples (64% regolith simulant).

RESULTS/ACCOMPLISHMENTS

Currently, a number of regolith-composite samples are being fabricated as 8-mm-thick rectangular cured sheets with varying regolith compositions. These sheets will be cut using water-jet cutter to prepare tensile test samples following Type III coupon of American Society for Testing and Materials (ASTM) D638 standards. In a separate study, which falls outside of the proposed project, regolith powders mixed with tap water were subjected to a sintering process that showed promising results, indicating a new future work that could potentially

(a) (b) (c)

FIGURE 3. (a) Completely sintered LMS at 1,100 °C for 4 hours, (b) partially sintered LHS at 1,100 °C for 5.33 hours, and (c) broken samples indicating incomplete sintering.

benefit manufacturing of regolith-based structural components. In this sintering project, a sample of 80% regolith and 20% water successfully sintered at 1,100 °C for 4 hours using an oven furnace. The sintering studies showed that changing the type of regolith simulant altered the effect of sintering. Sintering Lunar Mare Simulant (LMS) for 4 h (fig. 3a) yielded a completely sintered solid, whereas sintering Lunar Highland Simulant (LHS) for 5.33 h (fig. 3b and 3c) exhibited a partially sintered sample. These tests were run as preliminary experiments and systematic analysis is to follow.

PARTNERSHIPS

Dr. Mohammad Khondoker collaborated on development of experimental methods and procedure as well as analysis of results. Dr. Khondoker plans to continue collaborating in this project.

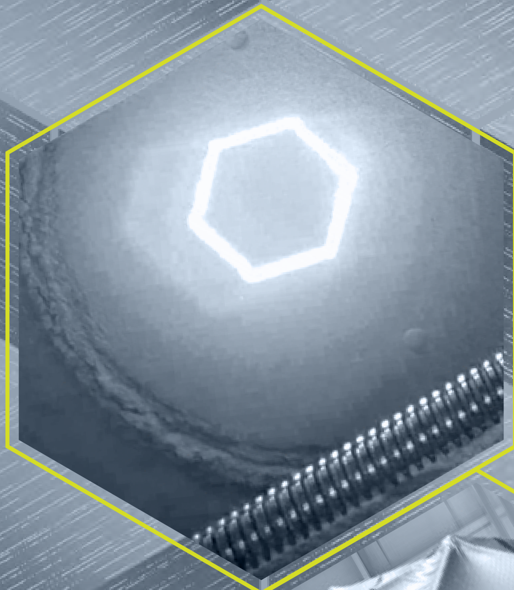
SUMMARY

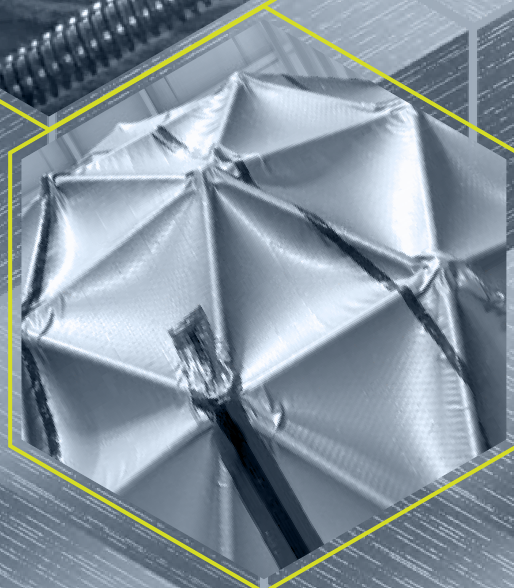
In this project, a regolith composite consisting of vitrimer epoxy DGEBA, fatty acid, $Zn(Ac)_2$, and nanoclay was developed through a curing process by heating the samples 130 °C for 90 min (pre-crosslinking), 60 °C for 20 h (pre-curing), and at 180 °C for 6 h (fully curing). Custom molds made of Teflon bars, Teflon sheets and steel plates were designed and fabricated to prepare tensile test coupons of the cured regolith composites. The cured samples were also tested in ethylene glycol to dissolve, which showed that a different catalyst is necessary for complete dissolution. In a separate attempt to fabricate structurally competent regolith-based materials, the regolith mixed with water was found to have huge potential when sintered at a significantly higher temperature (i.e., 1,100 °C) for ≈4 h.

PRINCIPAL INVESTIGATOR: Patrick Mensah, Southern University

PARTNERS: Southern University; NASA Marshall Space Flight Center

FUNDING ORGANIZATION: Cooperative Agreement Notice





TECHNOLOGY AREA 07

EXPLORATION DESTINATION SYSTEMS

Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) Project

OBJECTIVE: *To develop, deliver, and demonstrate on-demand capabilities to protect astronauts and create infrastructure elements on the lunar surface via construction of landing pads, habitats, shelters, roadways, berms, and blast shields using lunar regolith-based materials.*

PROJECT GOAL/DESCRIPTION

NASA needs the capability to consolidate and stabilize regolith on large scales, including microwaves and additive manufacturing-based construction or additive construction, and to mitigate dust via in-situ manufacturing and repair, in order to sustain a long-term human presence on, and utilization of, the Moon (NSP Objective 2.2). The same capability provides a thermal heater for volatile extraction from regolith, a heating source, and ultimately radiation protection structures for habitats. This capability currently does not exist.

APPROACH/INNOVATION

The Lunar Surface Innovation Initiative (LSII) Formulation Planning Guidance for Lunar Construction identified the following capability needs that are addressed within the Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) project:

Material and construction requirements and standards:

MMPACT is partnered with ICON and many other members of industry and academia to support construction requirements and standards development. Additionally, MMPACT is partnered with materials experts within NASA, industry, and academia to support material requirements and standards development.

Increased autonomy of operation:

MMPACT is partnered with ICON, the Defense Innovation Unit (DIU);

IMAGE USED WITH PERMISSION FROM ICON.

FIGURE 1. Illustration of a permanent base under construction near the south pole of the Moon.

the Air Force Civil Engineering Center (AFCEC); and the Texas Air National Guard (TANG) to increase autonomy of operations and remote operations capabilities for construction systems.

Scale of construction activities:

MMPACT is leveraging current technology elements at ICON and NASA Marshall Space Flight Center (MSFC) to mature construction materials and processes to a technology readiness level (TRL) of six. The team is targeting a lunar surface technology demonstration in fiscal year (FY) 2027 for a construction proof of concept on a Commercial Lunar Payload Services (CLPS) lander.

Hardware operation and manufacturing under lunar environmental conditions:

The materials and construction process candidates will be evaluated, down selected, then performance tested in a thermal vacuum (TVAC) chamber. Resulting materials will be characterized for properties used in structural models. This portion of the effort leverages (1) MSFC's expertise and experience in microwave and additive manufacturing construction materials and technologies, (2) industry advances made from the 3D Printed Habitat Centennial Challenge, and (3) extensive partnering with the Air Force.

Long-duration operation of mechanisms and parts:

The MMPACT payload will be designed for dust mitigation, leveraging LSII programmatic element linkages/interfaces and a dust ditigation technology survey completed by yet2. The materials will be selected based on their ability to perform in lunar environmental conditions. The technology will be designed for robustness, robotic field reparability, and assessed for vulnerabilities in the lunar environment.

RESULTS/ACCOMPLISHMENTS

The MMPACT team developed a lunar construction roadmap that identifies the path through two demonstration missions and two qualification missions to establish a full construction capability on the lunar surface. The first lunar demonstration mission (DM-1) is planned for FY 2027. The team refined technology gaps and closure plans in support of the Space Technology Mission Directorate (STMD) Strategic Implementation Plan and incorporated them into the MMPACT demonstration and qualification mission goals. Towards those goals, the elements of MMPACT have several accomplishments to report:

Cementitious Construction Technology:

The Cementitious Construction Technology material processing element achieved notable accomplishments in support of MMPACT in FY 2022. Lunar ISRU-based cementitious material processes were characterized, including low pressure cure tests and early set performance testing. A prototype environmental enclosure in support of cementitious materials processing at reduced pressure was fabricated and demonstrated. Finally, both static and dynamic electrical impedance tests, demonstrating the capability to detect voids as small as 0.07% of the measured volume, were demonstrated on a cementitious process flow.

ICON:

The MMPACT project's primary partner, ICON, demonstrated successful laser melting and fabrication of 100% regolith (simulant) samples in a vacuum environment; and extrusion of molten 100% regolith (simulant) samples using a thermal profile to achieve the same microstructure as the laser deposition system. ICON also completed mobility system trade studies for DM-1.

IMAGE USED WITH PERMISSION FROM ICON.

FIGURE 2. ICON's terrestrial vacuum laser direct energy deposition testbed.

Construction Materials Development:

The FY 2022 focus of the Construction Materials Development team has been in the design, procurement, and characterization of regolith simulants for MMPACT's construction material down select, to be completed in the first quarter of FY 2023, and for future large-scale hardware testing. Additionally, the team is working on Duneflow, a lunar gravity suborbital flight payload that will characterize gravity-dependent properties of simulants, ultimately quantifying the differences in the simulants and the geotechnical properties of lunar regolith. Future simulant designs will incorporate lessons learned from the Duneflow payload mission operations. Another project within the element involves geopolymers made with regolith simulants; MMPACT's partner Pennsylvania State University has a geopolymer experiment flying to the International Space Station in FY 2023 to obtain information on geopolymer in microgravity to bound the effect of gravity on cement crystallization.

Microwave Structure Construction Capability:

The Microwave Structure Construction Capability team established a useful bakeout procedure for three regolith simulants: NU-LHT-4M, JSC-1A, and CSM-LHT-1G. The team was further successful in the development and benchtop demonstration of multimode (vacuum) and near field coupler (benchtop air) applicators; cryogenic and broad frequency range dielectric testing; and development and benchtop demonstration of a site preparation tool.

PARTNERSHIPS

ICON and their partners are developing the laser directed energy deposition (DED) process and the lunar construction system for flight on DM-1. Additional partners include other NASA centers, other government agencies, industry, and academia.

SUMMARY

The MMPACT project has made significant strides in both strategic planning and accomplishing specific work in FY 2022. The project is on track to meet all requirements for a successful first lunar demonstration mission in FY 2027.

PRINCIPAL INVESTIGATOR: Dr. Raymond G. "Corky" Clinton, Jr.

PARTNER: ICON

FUNDING ORGANIZATION: Game Changing Development

FOR MORE INFORMATION:
https://www.nasa.gov/oem/surfaceconstruction

Demonstration of a Prototype Design for a Multipurpose Lunar Habitat

OBJECTIVE: *To demonstrate the capability of a deployable structure to provide a 0.6 atm ΔP to support an environment suitable for mixing and extrusion of a water-based concrete on the lunar surface while maintaining structural integrity of the concrete during curing.*

PROJECT GOAL/DESCRIPTION

It is known that curing a water-based concrete in the low pressure environment of the Moon or Mars will cause excess water in the concrete (needed for flowability) to vaporize, generating porosity and reducing mechanical properties and overall structural integrity. A prior series of low pressure integrity tests had been performed on two water-based lunar concrete compositions and it was determined that structural integrity could be maintained in the samples during curing in an atmosphere as low as 0.6 atm.

Therefore, the goal of this project was to design, fabricate and demonstrate a deployable structure, also known as an environmental enclosure (EE), with both fabric and structural elements that could be used to provide a 0.6 atm differential pressure (ΔP) inside the structure during extrusion printing of a water-based concrete. A flight design EE could be used on the Moon at 0.6 atm in the vacuum of the lunar surface and could also be tested in a large vacuum chamber on Earth. For this effort, it was determined to pull a vacuum to 0.4 atm internal to the EE while in the 1 atm Earth environment to demonstrate the required 0.6 atm ΔP. It is believed that this sort of EE at material-specific complimentary pressure could also prevent formation of porosity in other deposition technologies, including ‘waterless’ lunar concretes, molten regolith extrusion, and laser or microwave sintering. It was assumed that results of this Cooperative Agreement Notice (CAN) effort would feed directly into selection of cementitious materials as the deposition technology on the planned Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) demonstration mission (DM)–1 mission in 2026.

APPROACH/INNOVATION

The state of the art for deployable, inflatable space structures originated with the TransHab project at NASA Johnson Space Center (JSC) and now resides with Bigelow Aerospace in Las Vegas, NV. Their Bigelow Expandable Activity Module (BEAM) is currently deployed on the International Space Station (ISS). Launched in 2016, it is intended to remain on the ISS until at least 2028, although Bigelow is apparently now out of business.

BEAM is an inflatable structure with essentially a 1.0 atm ΔP. It was not designed for multiple deployments, so has relatively thick walls. The approach on this project was to design a structure that could be deployed, pressurized (or depressurized, for ambient Earth testing), and then de-pressurized after structure printing and moved to a new location for subsequent printing.

Kappler’s goal was to bond varying layers of fabric together to provide a strong, tough, flexible material that could also provide some radiation and micrometeorite protection for a large-scale 3D printer and the structure being printed. Segments of this fabric would be sewn together with gas-tight tape at the seams. In addition, the fabric would include gas-tight zippers to support installation and removal of the fabric from the structure. For Earth-based-testing of a prototype, it was determined to use a commercial-off-the-shelf (COTS) geodesic dome structure.

RESULTS/ACCOMPLISHMENTS

After selection, and while the COTS geodesic dome structure was being procured, Kappler designed and fabricated a fabric template to ensure the design of the fabric element would allow integration with the structural elements. Once the geodesic dome was delivered, the fabric was fit-checked on the dome prior to cutting actual fabric element segments. The geodesic dome and checkout of the fabric template can be seen in figures 1 and 2.

FIGURE 1. Geodesic dome structure used for EE testing.

FIGURE 2. Fabric template during fit check on geodesic dome structure testing.

During early tests, some deformation of structural elements was observed at ΔPs of approximately 0.3 atm. Some internal aluminum beams were replaced with equivalent steel beams, but in subsequent tests, the 0.3 atm ΔP could not be exceeded due to multiple leaks at zipper seals and fabric seams. The EE during low pressure testing can be seen in figure 3. After multiple tests, even with the addition of more pressure tape on the seams, the team could not achieve higher than an 0.3 atm ΔP and the project was terminated.

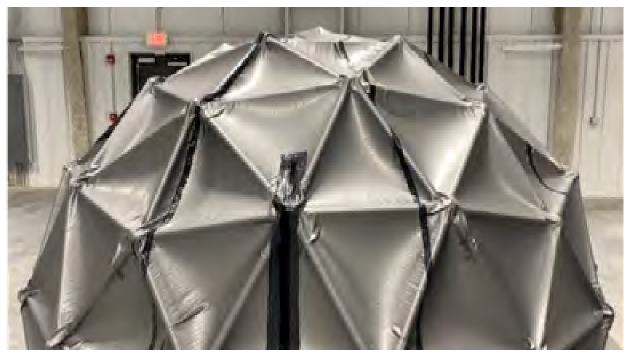


FIGURE 3. Prototype EE low pressure testing at ΔP of 0.3 atm.

The frame system design was inadequate to reduce stresses/forces that occurred by incorporating a flat floor strut design in lieu of a geodesic or spherical shaped floor. This required the addition of a center beam to prevent inversion of the floor. Even though the smaller volume of approximately 200 ft^3 was utilized in the prototype, the forces induced by the vacuum were much greater than expected. The design of frame bottom edge could have been modified to provide a smooth surface for the zipper to set against to prevent twisting around the bottom circumference of the frame. The end stop compression seal design for the separating zippers was not adequate to prevent inward leakage at about 3 in Hg vacuum and below. The surface profiles of the zipper end stops and slider contributed to the inability to seal.

Even though single layer materials were used for the pressure boundary, the research of existing and future material layups show the increased complexity of a temporary shelter to support the additive manufacturing of the lunar regolith into a permanent structure. It is understood that achieving and maintaining the pressures and vacuum levels required to support the additive manufacture of cementitious materials would require structural support and sealing techniques to the lunar surface that may be design-restrictive for a temporary structure. Consideration should be given to evaluation of alternative cementitious materials that would not require the use of a water-based binder. An alternative binder may be required. Another consideration for follow up work would involve further investigation and development of a liner material for the completed concrete structure. Liner candidate development and design integration with access points of the structure would be beneficial. It is evident the pressurization required on the lunar surface will preclude the use of a floor system that would not be spherical and/or rigid in design. Further work is needed to determine the efficacy of a sealed edge approach to a temporary structure.

PARTNERSHIPS

Kappler was selected for this CAN based on their unique capabilities and relevant experience. In 2006–2007, Kappler teamed with Auburn University to produce a prototype ballistic shelter for a lunar rover. The design concept was to produce an arch shaped structure containing multiple individual pockets that could be filled with regolith to create a self-supporting structure. Woven Kevlar fabric was used for construction of the pockets. The project was funded and managed through NASA Marshall Space Flight Center (MSFC).

In 2006, Kappler teamed with Quick Protective Systems (QPS) to produce fifty integrated respirator hoods for protection against ammonia in the event of a leak on the International Space Station. It was designed to fit a 3M respirator currently used on the ISS. The project went from concept to flight in nine months. The project was funded and managed through JSC.

Since 1994, Kappler has manufactured over 11,000 fielded life support systems and components and is one of the leading manufacturers of Chemical and Biological Collective Protection (ColPro) Life Support Systems for the U.S. Government and the world.

SUMMARY

MSFC and Kappler teamed to try to develop an EE that could meet the requirements of 3D printing of water-based concretes on the lunar surface. At least for the selected combination of structural and fabric elements, the ΔP was sufficient to preclude the ability of the structure to prevent damage. Alternative designs are being considered, as well as development of ‘waterless’ lunar concretes.

PRINCIPAL INVESTIGATORS: Philip Mann (Kappler); Jennifer Edmunson (NASA/MSFC); Michael Fiske (NASA/MSFC/Jacobs)

PARTNER: Kappler

FUNDING ORGANIZATION: Cooperative Agreement Notice

Extraterrestrial Marangoni Mining

OBJECTIVE: *To demonstrate the feasibility of thermal-driven mining and extracting metals, alloys, and oxygen (O_2) from extraterrestrial soil without mechanical excavation/transportation or terrestrial precursors via two coupled thermal-driven phenomena, the Marangoni effect and fractional decomposition.*

PROJECT GOAL/DESCRIPTION

Two coupled thermal-driven phenomena, the Marangoni effect and thermal fractional decomposition under high vacuum, could lead to an extraterrestrial mining operation that would significantly reduce mechanical operation and allow in-situ product extraction directly from the mineral without the necessity of either mineral beneficiation or use of terrestrial precursors. A vertical-tubular thermal high vacuum chamber (THVC) equipped with a camera mounted on a blue-laser-illuminated viewport and a residual gas analyzer (RGA) was designed and built to conduct the study and characterization of both thermal-driven phenomena on molten extraterrestrial simulant samples.

APPROACH/INNOVATION

Extraterrestrial mining will require an operational approach completely different from the terrestrial one, which heavily relies on not only mechanical excavation/transportation but also separate extraction/refinery of the mined materials. An in-situ, nonmechanical all-in-one process might be feasible by coupling the Marangoni effect with fractional decomposition under high vacuum. A solar concentrator would be used to scan and melt the asteroid's or lunar surface, while a ceramic-based band in contact with the melt would allow its upward migration and nonmechanical transport of the molten material from the surface to the containment. Additional heating would then be supplied to drive the fractional decomposition of the melt as it continues its upward migration through a number of trays, where multiple products would be fractionally decomposed/withdrawn without the necessity of terrestrial precursors and mechanical transportation.

The key objective of this research is to advance the technology readiness level (TRL) of this novel, sustainable, and nonmechanical thermal-driven approach for extraterrestrial mining that could be coupled with in-situ production and storage of the different component products, including gaseous byproducts that might be used as propellant for the product's containment or power generation. The key milestone of this project is to be able to corroborate as well as to characterize both coupled phenomena, upward migration (thermal Marangoni effect) and fractional decomposition, on three different lunar regolith simulants along the wall of tall tubular crucibles.

RESULTS/ACCOMPLISHMENTS

Figure 1a depicts three different views of the THVC's test stand designed and built in-house at NASA Marshall Space Flight Center (MSFC). The test stand is mainly equipped with a vertical alumina tube with an outer diameter (OD) of 3.25 in, an inner diameter (ID) of 3 in, and a length of 40 in; a high vacuum system (turbo-rough on the top and diffusion-rough on the bottom); sixteen silicon carbide (SiC) heating rods; top/bottom inner insulation; a heating controller; eight thermocouples; a camera mounted on a viewport illuminated with a blue-laser emitter; and an RGA. Figure 1b depicts the material domains and selected outputs of the comprehensive 3D THVC model built to determine the optimal location of the tubular crucible housing the sample to

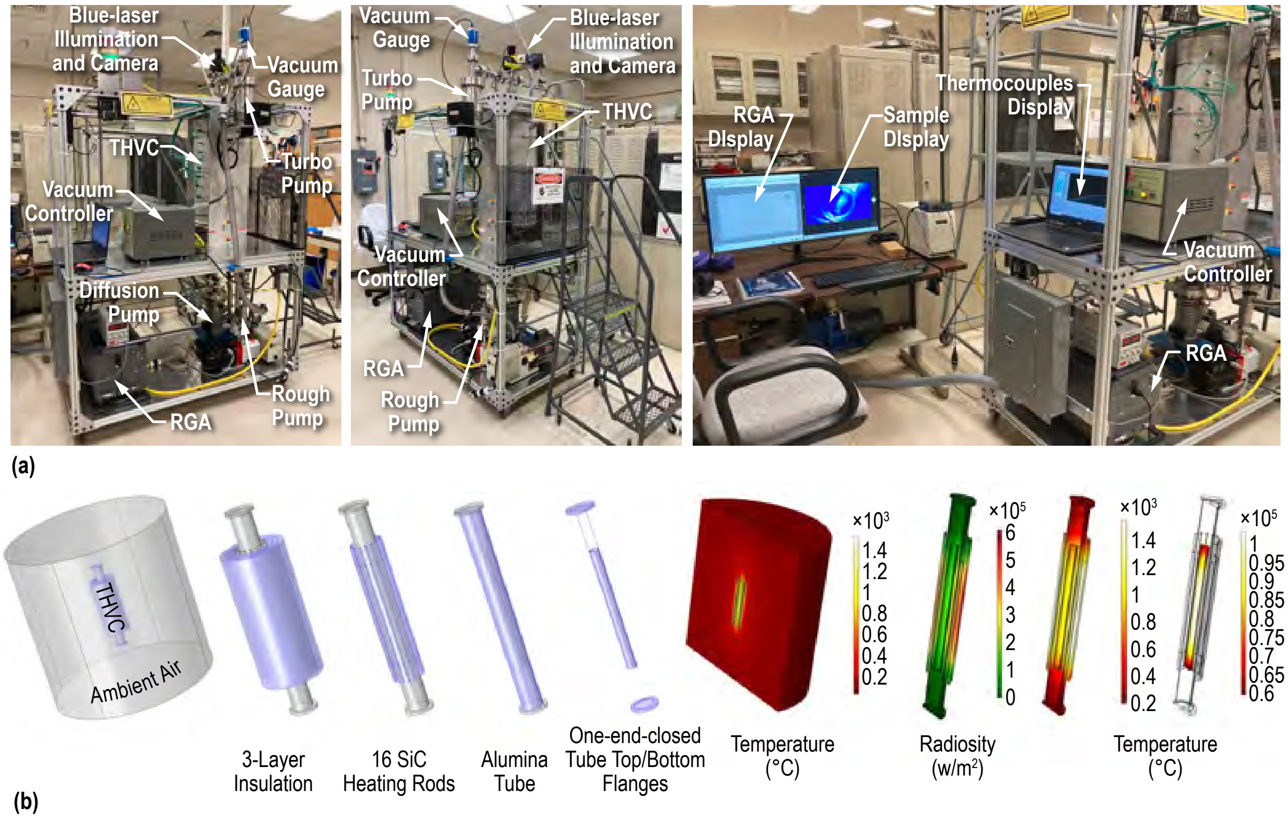


FIGURE 1. (a) Three different views of the THVC's test stand designed and built in-house at MSFC. (b) Material domains and results of the comprehensive 3D THVC's model built to determine the optimal location of the one-closed-end tube housing the sample to obtain the largest temperature gradient along the tube's wall to boost thermal Marangoni effect.

obtain the largest temperature gradient along the tube's wall as the driving force of the thermal Marangoni effect is temperature gradient. The 3D model is at scale, includes all the THVC's elements, and has a comprehensive approach as heat fluxes derived from surface-to-surface thermal radiation and free convection flow are rigorously estimated.

150 g of JSC-1A lunar regolith samples were housed in a tubular crucible with an OD of 2 in, ID of 1.75 in, and length of 16 in. The 150 g of simulant occupied 1.25 in of the 16-in wall length, leaving 14.75 in of bared inner wall. At 1,300 °C and 0.0037 torr of vacuum the melt did not decompose, as the RGA did not detect any O_2 and elemental oxygen (O) peaks; however, it formed a meniscus on the surface in contact with the crucible's wall and uniformly migrated upwards, climbing 13 in of the 14.75 in of originally bared wall. At 1,400 °C and 0.0012 torr of vacuum, the melt's metal oxides mildly decomposed as the RGA registered small peaks of O_2 and O and also formed a meniscus on the melt's surface in contact with the crucible's wall that led to not only shorter upwards migration than previously observed (10 in instead of 13 in) but also different coloration (brown instead of black) and texture (mostly shiny on the bottom section with dendritic spots instead of

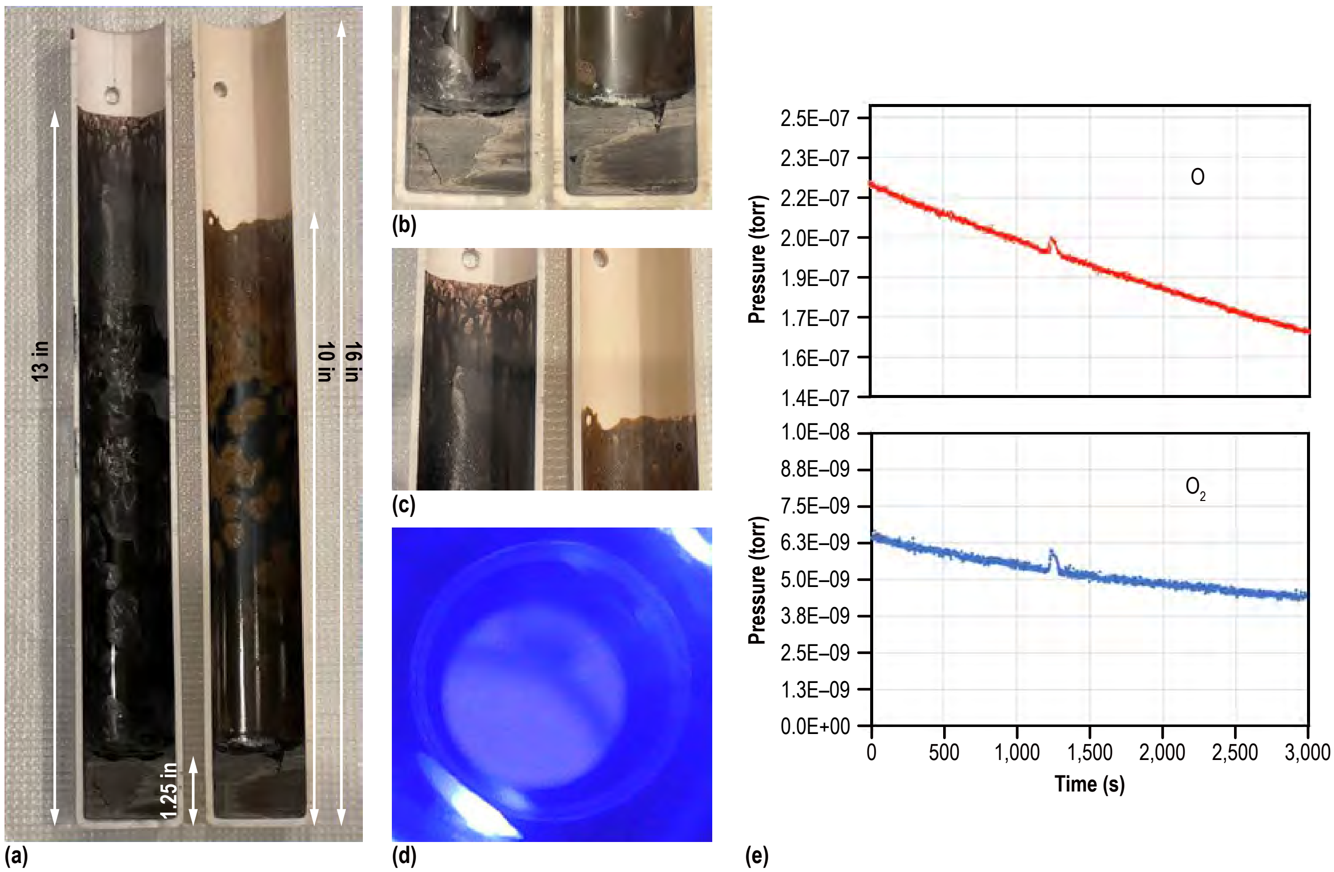


FIGURE 2. (a) Interior of two tubular crucibles housing the same amount (150 g) of JSC-1A lunar regolith simulant melts generated at 1,300 °C (0.0037 torr) and 1,400 °C (0.0012 torr) cases respectively. (b) Magnified section of the meniscus formed in both cases on the surface of the melt in contact with the wall. (c) Front end of the upward migration: in both cases, a ring of clear melt, near the top of the front end, is formed and from which streaks drop back into the melt. (d) Image of the melt taken by the camera mounted on the top of the THVC under blue-laser illumination at 1,400 °C. (e) O and O_2 partial pressure peaks detected by the RGA at 1,400 °C.

spotted shiny surfaces without dendritic spots). Figure 2 summarizes the outcome on these two cases, Figure 2a depicts the interior of two tubular crucibles housing the same amount (150 g) of JSC-1A melts generated in both cases. Figure 2b depicts a magnified section of the meniscus formed in both cases on the surface of the melt in contact with the crucible's wall. Figure 2c depicts the front end of the upwards migration in both cases, a ring of clear melt, near the top of the front end, is formed and from which streaks dropped back into the melt. Figure 2d depicts the image of the melt at 1,400 °C under blue-laser illumination taken by the camera mounted on the top of the THVC. Figure 2e shows O_2 and O partial pressure peaks, measured by the RGA, due to the decomposition of some metal oxides present in the melt.

Self-transportation due to Marangoni effect, without fractional decomposition that would be required in the non-mechanical extraterrestrial mining approach, was witnessed along 13 in of length in the first case. Additionally, self-transportation coupled with fractional decomposition of the melt at higher temperature that would be required for sustainable extraction/refinery and all-in-one extraterrestrial mining approach was also witnessed along 10 in of length in the second case. The authors consider that the TRL has been increased from 2 to 3 after obtaining the outcome reported here.

PARTNERSHIPS

The authors plan to pursue further work by searching for funding sources and potential collaboration teams to keep maturing the technology and scaling its TRL.

SUMMARY

Thermal Marangoni effect alone and coupled with fractional decomposition of metal oxides releasing O_2 have been corroborated on molten JSC-1A lunar regolith simulant through long upward migration paths, 10 in and 13 in respectively; validating further the proposed approach for extraterrestrial mining. These two coupled phenomena, thermal Marangoni effect and fractional decomposition, will be more prominent on extraterrestrial surfaces under much higher vacuum and reduced gravity.

The test stand designed and built by the authors can operate at temperatures as high as 1,600 °C and house longer and wider tubular crucibles to carry larger samples with lengthier self-transportation path. The comprehensive 3D model built by the authors demonstrated to be a crucial tool to determine the optimal location of the tubular crucible to obtain the largest temperature gradient along the crucible's wall to boost the thermal Marangoni effect. In future tests, scanning electron microscopy and energy dispersive x-ray analysis will be conducted on the melt sample along the upward migration path to quantify the fractional decomposition of the melt. This novel approach might be an alternative to pursue sustainable and environmentally friendly production of metals, such as aluminum that generates less CO_2 by weight than than traditionally manufactured aluminum.

PRINCIPAL INVESTIGATOR: Jesus A. Dominguez (Jacobs/ESSCA)

PARTNER: NASA Marshall Space Flight Center; Jacobs

FUNDING ORGANIZATION: Center Innovation Fund

Cellular Fabrication (C-Fab©) Materials for In-Situ Lunar Additive Manufacturing and Outfitting

OBJECTIVE: *To enable outfitting via C-Fab©, regolith-based biopolymer-bound soil composites material science, and outfitting application design research.*

PROJECT GOAL/DESCRIPTION

Outfitting is how one *"makes a house into a home."* It includes mechanical, electrical, and plumbing systems, as well as hatches and seals, furniture, room dividers/partitions, countertops, air ducts, sinks, cabinets, etc. To produce outfitting components for an off-Earth human base, it is important to have a system capable of manufacturing at a relatively large scale that uses as little material as possible for fabrication and utilizes in-situ resources, including recyclable waste and materials that can be grown onsite. Branch Technology, with architectural firm Foster + Partners, Stanford University, and NASA Ames Research Center (ARC), are working toward enabling outfitting technologies to complement emplacement of infrastructure on planetary surfaces, with the initial target being the lunar surface.

APPROACH/INNOVATION

A key aspect of this technology approach, Branch Technology's C-Fab, is a freeform fabrication technique which allows the fabrication of so-called latticework 'cells' in free space. The technology uses significantly less material than other traditional 3D printing techniques to produce relatively large structures, which makes it ideal for the new area of planetary surface infrastructure outfitting. Branch has partnered with Stanford University and ARC to research biopolymer-bound soil composites (BSCs), which are biologically produced polymers with lunar regolith (simulant) mixed in as aggregate.

A goal of this effort is to see if the C-Fab technology can print with the BSC material. Architectural firm Foster + Partners is contributing designs and human factors into the study.

Deliverables to date have included a project kickoff meeting with relevant stakeholders; presentation of the selected material compositions and target performance criteria; arrival of coupon samples at NASA Marshall Space Flight Center for testing; and the design of the final artifact demonstration geometry (3D model). In the very near future, the final artifact demonstration event will showcase an internal wall partition concept geometry and the multifunctional nature of the design, envisioned by Foster + Partners and manufactured by Branch Technology. Beyond the Cooperative Agreement Notice (CAN), further demonstrations of outfitting, involving NASA, are planned by Branch and their partners.

RESULTS/ACCOMPLISHMENTS

Through the CAN effort to date, there are a few outstanding accomplishments by the team. The first is the ability of C-Fab freeform fabrication to be completed with a biologically produced polymer. The second is the numerous multifunctional capabilities of the partitions designed by Foster + Partners, as well as the incorporation of color for the aesthetics of the partition. The third is the combination of simulated beneficiated lunar regolith with the BSCs to produce colorful tiles to offset the grayscale lunar surface for the sensory benefit of the crew.

PARTNERSHIPS

Branch Technology is leading the CAN effort and is using their C-Fab technology to produce a multifunctional room partition that would be suitable for an inflatable or constructed habitat. Foster + Partners is providing the design of the multifunctional room partition, as well as a taxonomy for outfitting items. Stanford and ARC are providing BSC for testing, characterization, and demonstration. Plans for future collaboration include involvement in the Lendlease Milan Innovation District, where an outfitted planetary habitat will be constructed to serve as an analog for habitat use.

SUMMARY

A sustainable human presence in deep space will require the technologies to fabricate items of different sizes, from the smallest gear to the largest habitat, out of resources found in situ. These resources could be regolith, waste, volatiles, biological byproducts, or a combination of these materials such as BSCs. Stanford University's work in BSCs has shown the material warrants further study in deep space applications. The CAN work, led by Branch Technology, explored the use of BSCs for outfitting. Outfitting is required to *"make a house a home."* That is, a habitat must have furniture as well as mechanical, electrical, and plumbing systems. The CAN activity to date has shown the potential for using a combination of C-Fab and BSCs in outfitting applications. Complementary design work for modular room dividers/partitions by Foster + Partners demonstrates and highlights the C-Fab technology.

PRINCIPAL INVESTIGATOR: Jennifer Edmunson

PARTNERS: Branch Technology, Foster + Partners, Stanford University, NASA Ames Research Center

FUNDING ORGANIZATION: Cooperative Agreement Notice

Duneflow Lunar Gravity Suborbital Flight

OBJECTIVE: *Duneflow will investigate the flowability of lunar regolith and regolith simulants, and the stability of artificial slopes constructed in a lunar gravity field.*

PROJECT GOAL/DESCRIPTION

Project Duneflow addresses the flowability of lunar regolith and the stability of artificial slopes constructed in lunar surface material. Both flowability and stability have to do with the angle of repose (i.e., angle of internal friction), which is gravity dependent. Lunar regolith simulants, and ideally an Apollo regolith sample or two, will have their own separate volumes in a flight locker on a suborbital flight. During the lunar gravity portion of the flight, the materials will be rotated in an hourglass-like container and will flow through an orifice. The volume will continue to rotate; the angle of the grain pile's surface will be measured and the flow of the grains during rotation of the volume will be observed via camera. This experiment allows the quantification of the geotechnical properties of multiple (6) regolith simulants/samples using existing optical video capture technology and post-analysis with velocimetry of particles in motion through the orifice during rotation. In addition to acquiring data that is key to excavation and construction in reduced gravity, the results of the experiment will guide the design and development of more accurate geotechnical (mechanical) simulants for the lunar surface technology development community.

IMAGE PROVIDED WITH PERMISSION FROM ICON TECHNOLOGY

FIGURE 1. Different types of hourglass container shapes investigated by the Duneflow team to optimize image and data capture.

APPROACH/INNOVATION

The state of the art for studying the geotechnical properties of both simulated and real lunar regolith is experiments done in terrestrial gravity, followed by computer modeling to extrapolate to lunar gravity. Additionally, most regolith simulants do a poor job replicating the flow behavior and slope stability of lunar regolith. For example, measurements in vacuum (in terrestrial gravity) have shown that Apollo regolith samples have nearly twice the angle of repose of commonly used terrestrial simulants like JSC-1A. There are two potential approaches to better replicate the flow behavior and therefore geotechnical properties of lunar regolith: (1) A high-fidelity, high-cost approach using synthetic agglutinates; and (2) a low-cost, simple material that simulates flowability, but not other properties like composition. However, these approaches have not previously been evaluated under realistic conditions. Duneflow allows evaluation of simulant materials and lunar regolith under lunar gravity and vacuum conditions. Results from Duneflow will influence simulant designs and technology development testing for years to come.

The Duneflow hardware consists of avionics, lighting, cameras, and six vacuum-capable cells with hourglass-shaped containers that are rotated with motors at a specific spin rate during the two minutes of lunar gravity of the suborbital flight. Cameras and lighting will allow visualization of the flowability and angle of repose of the simulant materials and regolith. The Duneflow flight is currently scheduled to occur in January 2023.

RESULTS/ACCOMPLISHMENTS

To date, the team, which includes ICON Technology, Inc. (ICON), has received funding for the mission; has passed the Preliminary Payload Data Package (PDP) Review with the lunar gravity suborbital flight provider Blue Origin; has finalized the design; and has provided test cells to the Colorado School of Mines (CSM), who have selected the materials to fly inside the flight cells. Upcoming events include final assembly, flight acceptance testing, launch, operation, data analysis, and publication of results.

PARTNERSHIPS

- ICON provides hardware and software engineering and integration, hardware, materials, documentation, operations during testing, operations during flight, and post-flight data analytics.
- CSM provides graduate students and faculty time, as well as materials, documentation, operations during testing, operations during flight, and final publications.
- NASA Marshall Space Flight Center (MSFC) provides flight acceptance testing, PDP test package documentation, and participation of subject matter experts in the Payload Readiness Reviews.

ICON will integrate lessons learned from Duneflow directly into their design for the Moon to Mars Planetary Autonomous Construction Technology (MMPACT) Project's Demonstration Mission 1, a proof-of-concept of surface construction on the Moon with construction materials fabricated from regolith. The CSM will integrate lessons learned into the fabrication of new lunar regolith simulants.

SUMMARY

MSFC, ICON, and CSM are developing lunar gravity suborbital flight hardware to address the flowability of lunar regolith/simulants and the stability of artificial slopes constructed from lunar surface material in lunar gravity. Some geotechnical properties, such as the angle of repose, are gravity dependent. The lessons learned will guide the development of more accurate geotechnical simulants for testing during technology development, as well as provide data that will directly affect the design of the MMPACT lunar surface construction technology demonstration.

PRINCIPAL INVESTIGATORS: Jennifer Edmunson (NASA/MSFC); Evan Jensen (ICON); Kevin Cannon (CSM)

PARTNERS: ICON Technology; Colorado School of Mines (CSM)

FUNDING ORGANIZATION: Game Changing Development

Parametric Study of Additive Manufacturing using Martian Regolith Metal Recovered with Ionic Liquids

OBJECTIVE: *To demonstrate additive manufacturing of a metal alloy produced from simulated martian regolith simulant metals and Environmental Control and Life Support System Bosch carbon.*

PROJECT GOAL/DESCRIPTION

Under a previous Cooperative Agreement Notice (CAN) with NASA Marshall Space Flight Center (MSFC), Mississippi State University created metal alloys (e.g., ductile iron/steel) from (1) metals extracted from martian regolith simulant using ionic liquid extraction, and (2) carbon from the Bosch process, under investigation by MSFC's Environmental Control and Life Support Systems group, as a method to remove carbon from carbon dioxide to regenerate breathable oxygen. The work in the current Center Innovation Fund (CIF) expands that research to 3D printing of in-situ resource utilization (ISRU)-based metal powders. Ultimately, this work will show an end-to-end process from in-situ resource to manufacturing feedstock to printed part. This work directly addresses the technology gap that exists between metals extracted through the ISRU process and the on-demand manufacturing capability necessary for a sustainable human presence off-Earth.

APPROACH/INNOVATION

A key aspect of this technology approach The CIF effort involves alloying steel powder composed of the regolith simulant metals and Bosch carbon, then transforming it into additive manufacturing feedstock to be used in an additive manufacturing (laser) system. Printing of the material will be optimized by experimentally varying parameters in the printing process. Measurements of density, porosity, and the mechanical properties of the printed material will be made, as well as a characterization of the printed material's microstructure.

RESULTS/ACCOMPLISHMENTS

The composition of the material to be transformed into the steel powder has been determined and manufactured. Delivery of the metal powder from the subcontractor to Mississippi State University is in work. The work was to be completed by the end of fiscal year (FY) 2022; however, supply chain issues led to a delay in acquiring the materials necessary to simulate the ionic liquid metal composition. Further delays occurred due to the nature of the material in that it was difficult to transform into the metal powder. The issues with the metal powder have recently been overcome, and the lessons learned will be documented and publicly released.

PARTNERSHIPS

This effort is through a partnership with Mississippi State University's Department of Mechanical Engineering and Center for Advanced Vehicular Systems. The preceding CAN work was the focus of a doctoral student's dissertation in which ISRU-based ductile iron was cast into parts; this work expands his research into additive manufacturing of the final parts, which negates the need for a mold. The MSFC team plans to continue collaboration in the development of ISRU-based metal alloys and manufacturing feedstock for a variety of applications.

SUMMARY

For humans to live off-Earth, and to be truly Earth-independent, on-demand manufacturing is critical. Spare parts must be produced from in-situ resources, including recycled materials and regolith. The CIF work with Mississippi State will demonstrate an end-to-end process for manufacturing parts from available in-situ resources through alloying, making additive manufacturing powder feedstock, and dialing in the parameters to make strong parts via laser-based additive manufacturing.

PRINCIPAL INVESTIGATORS: Jennifer Edmunson (MSFC); Hongjoo Rhee (Mississippi State University)

PARTNER: Mississippi State University

FUNDING ORGANIZATION: Center Innovation Fund

Trichloride Ionic Liquid-Mediated Metal Extraction from Regolith

OBJECTIVE: *To evaluate an unexplored low-temperature process to extract metals from lunar regolith.*

PROJECT GOAL/DESCRIPTION

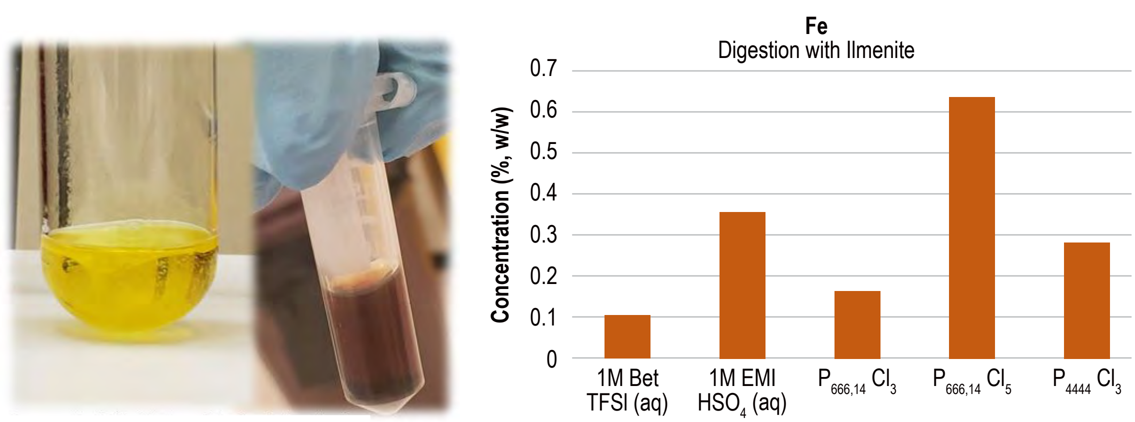
Sustainable lunar and martian infrastructure will require the local production of metallic feedstock for in-space manufacturing processes. Currently, there is no process that can produce these feedstock materials, which represents a major gap for in-situ resource utilization (ISRU) technology development. This study investigates a novel metal extraction process that oxidatively dissolves the metal found in lunar regolith, which then can be electrochemically purified into metal feedstocks for in-space manufacturing processes.

APPROACH/INNOVATION

Trichloride ionic liquids (TCILs) store chlorine as molten salts at room temperature by forming polyhalide anions. This property allows TCILs to oxidatively dissolve many metals into solution as room temperature ionic liquid salts. The solvated metal is extracted electrochemically at the cathode and the trichloride (Cl_3) anion is regenerated at the anode, which enables a closed-loop reaction pathway.

The temperature required for this electrochemical reaction is hundreds of degrees Celsius less than contemporary molten salt electrolysis processes (traditional molten salt processes ≈900 °C, compared to <100 °C for TCILs). This reduction in temperature would significantly lower the required process power and would likely improve the service life of molten salt electrolysis reactors. Additionally, the challenges of working with corrosive chlorine gas are greatly reduced by storing the chlorine as a nonvolatile ionic liquid (IL) salt.

The TCILs were synthesized through gravimetric addition of chlorine until the desired molar ratio between chlorine and chloride IL was obtained. Thermal stability of the TCIL was evaluated using thermogravimetric analysis/Fourier-transform infrared (TGA/FTIR) spectroscopy. The extraction of metals from lunar regolith was evaluated using ilmenite and an anorthosite simulant (GreenSpar). The metal concentration after dissolution was determined using inductively-coupled plasma optical emission spectroscopy (ICP-OES).



(a) (b)

FIGURE 1. (a) Image of ionic trihexyl(tetradecyl)phosphonium pentachloride ($P_{666,14}Cl_5$) before (left) and after (right) ilmenite digestion. (b) Comparison of iron (Fe) extraction from ilmenite with selected ionic liquids.

FIGURE 2. Image of tetrabutylphosphonium trichloride ($P_{4444}Cl_3$) digestion with GreenSpar anorthosite simulant.

RESULTS/ACCOMPLISHMENTS

Several Cl_3 and polychloride ILs were successfully synthesized and evaluated for this study using their chloride-based precursors. This study revealed a new IL having a chlorine content consistent with the formation of a pentachloride (Cl_5) anion. These compounds have not been reported outside this study and were found superior to that of the Cl_3 anion in terms of metal extraction. Furthermore, the nature of the cation determined the final chlorine loading capacity as the larger cations were able to absorb more chlorine than their smaller analogues. All ILs demonstrated high thermal stabilities corresponding to that of the parent cation precursors.

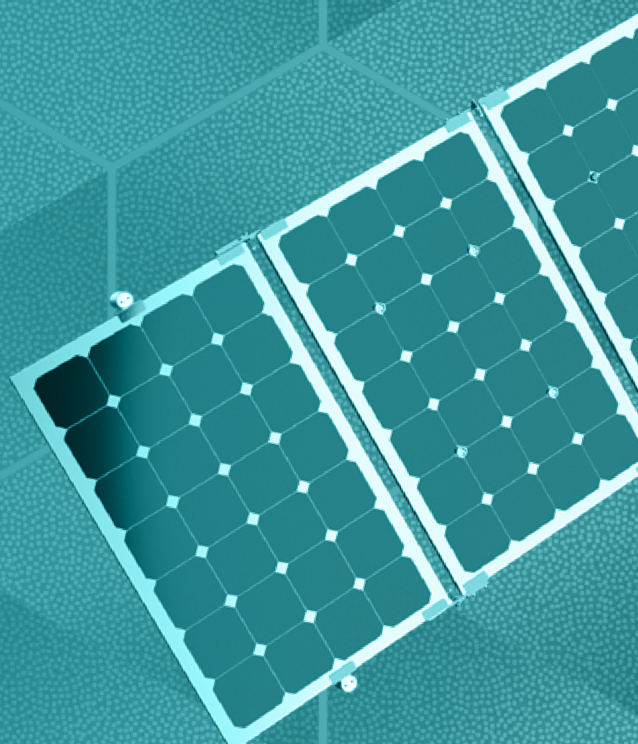
Elemental analysis showed that Cl_5 ILs have the highest metal extraction capacity of the TCILs evaluated in this study. The TCILs were able to solubilize the metals found in both the GreenSpar anorthosite and ilmenite simulants. The amount of iron (Fe) extracted from ilmenite was found to be especially high in concentration. However, the ILs were not able to chlorinate carbon and form the anticipated intermediate carbon tetrachloride under the reaction conditions.

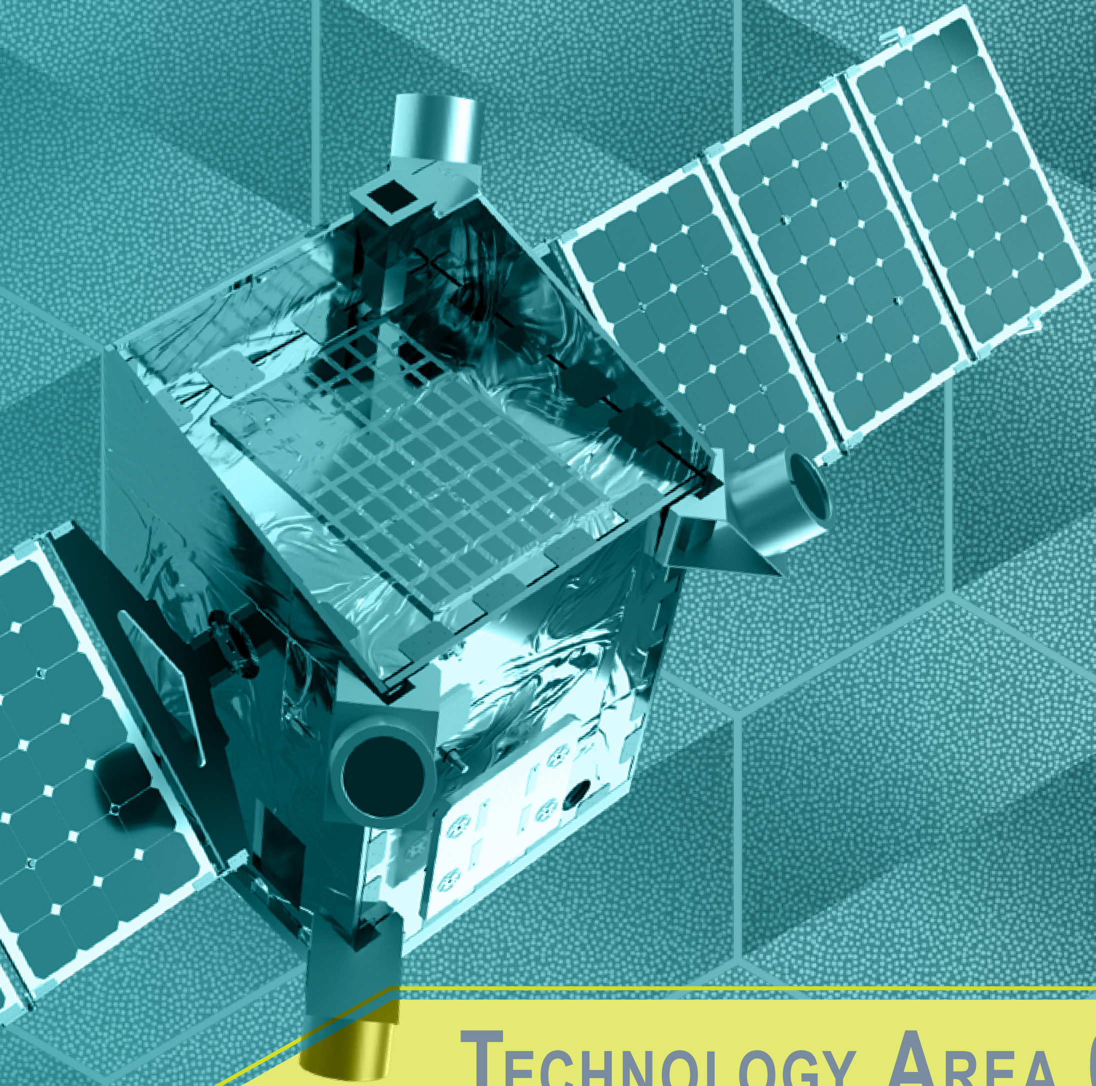
SUMMARY

TCILs were investigated for metal extraction from lunar regolith using ilmenite and GreenSpar anorthosite as simulants. The TCILs demonstrated excellent thermal stability and the ability to extract metals from lunar regolith forming a room temperature molten salt. Higher orders of chlorine anions were demonstrated for the first time and improved the metal extraction capability of the ILs studied.

The data and methods developed during this study provide a solid basis for future work focused on the development of electrochemical parameters required for breadboard demonstration reactors and infusion into higher technology readiness level oxygen extraction processes. Partnerships with oxygen extraction stakeholders are anticipated in this future work. Additionally, this technology has clear infusion paths into terrestrial recycling technologies supporting efforts such as the Department of Defense's Precious Metal Recovery Program and could lead to greener terrestrial metal refining processes.

PRINCIPAL INVESTIGATOR: Christopher Henry
FUNDING ORGANIZATION: Center Innovation Fund





Technology Area 08

SENSORS AND INSTRUMENTS

Viability Assessment of Printed Powerless Sensors Structures for Aerospace Environments

OBJECTIVE: *To create a simple, integrated, and cost-effective embedded sensor system capable of real-time and on-site damage detection in 3D-printed aerospace structures.*

PROJECT GOAL/DESCRIPTION

The project pursues the study of additive manufacturing for the development of a hybrid/3D manufacturing of in-situ triboluminescent optical fiber (ITOF) sensors for structural health monitoring of aerospace structures. Integrating a 3D-printed additive manufacturing technique and real-time damage detection sensing will create new robust technology for further space exploration missions. In order to make these expeditions, it is pertinent that the technologies and aerospace structures that are sent out are safe, operational, and cost effective. The integration of ITOF sensors in advanced thermoplastic structures can contribute to the development of robust smart structures for space applications. The manufacturing process is illustrated in figure 1.

APPROACH/INNOVATION

The ITOF sensor can detect real-time damage in large composite structures. Using additive manufacturing, the ITOF sensor and structure can be printed layer by layer, optimizing system integration. This project will investigate incorporating the sensor into a 3D-printed acrylonitrile butiadene styrene (ABS) structure with carbon fiber (ABS-CF). ITOF sensors will be tested mechanically, and their sensitivity measured in a simulated space environment during impact strikes. However, integrating the sensor into the printed structure is difficult. Intelligent materials require sensors and composite. Warping and poor layer adhesion are problems for additively manufactured structures. New technologies should be developed to improve 3D-printed sensor structures. By optimizing printing parameters that affect sensor/composite integration, the system's interfacial mechanism can be improved. Future research aims to simultaneously print the composite structure and the sensing system, an innovative approach to developing the structural health monitoring (SHM) system with huge potential for the future use of composite structures in space exploration.

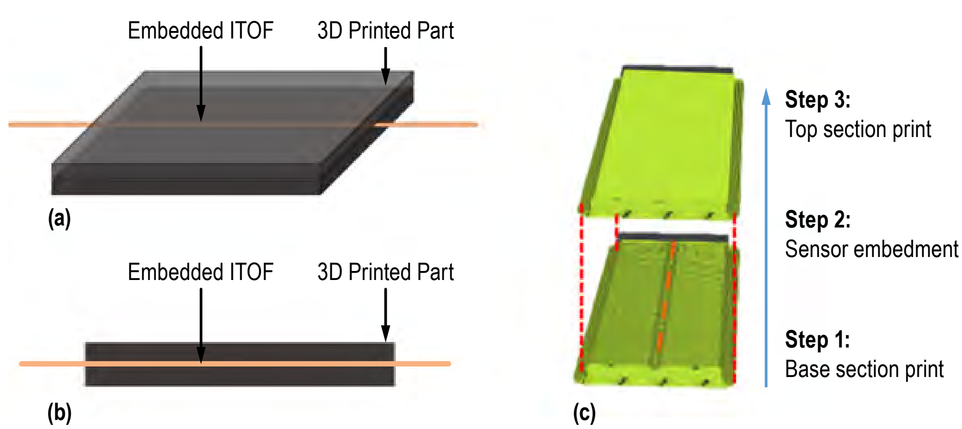


FIGURE 1. Schematic representation of the (a) embedded ITOF in a 3D-printed ABS composite, (b) cross-sectional view, and (c) manufacturing process.

RESULTS/ACCOMPLISHMENTS

Failure modes and damage propagation were determined using impact tests. The sample received 9.7 J of impact energy, but there was no visible damage or indentation. At 20 J, the sample barely affected site damage. The impact site was measured with a Heidenham indentation measurement. Scanning electron microscopy (SEM) assessed internal damage. The optical fiber sensor was still intact. To study the performance of the sensor for impact damage sensing, a data acquisition (DAQ) box was connected to the thermoluminescent (TL)-coated sensor to acquire signal data. This process converts light into an electrical signal to quantify data. The sensor was connected to a Hamamatsu DAQ amplifier and National Instruments 6210 USB connector. MATLAB code processes signals. The initial impact was performed with less than 0.57 J of energy to test each sensor's sensitivity. The 1 mm sensor produced the strongest signal at 0.032 a.u. The 0.25 mm sensor produced a weak impact signal, but the 0.5 mm sensor responded well. When 10 J of impact energy was applied to the composite sensor system, the 1 mm sensor showed a 0.2780 a.u. TL peak. The sensor system can detect composite loads and damage. The 0.5 mm and 0.25 mm sensors produced less signal than the 1 mm sensors. Signal rise ($\tau rise$) and decay time ($\tau fall$) after impact can indicate sensor performance. When hit or stressed, TL material emits light. The $\tau rise$ and $\tau fall$ times of an ITOF sensor are the time it takes to reach 90% and 10% of steady-state values, respectively, and are related to the sensor's ability to respond to fast input signals. The 1 mm sensor had a 6 ms $\tau rise$ and 15 ms $\tau fall$, which is comparable to some semiconductor photodetectors. The sensor system is suitable for SHM and other high-speed optical applications.

Dynamic mechanical analysis (DMA) was used to examine the viscoelastic behavior of composite samples with different-sized ITOF sensors (1,000 mm, 500 mm, and 250 mm). ABS-CF 3D-printed samples with and without (baseline) sensors were analyzed for storage modulus, loss modulus, and tan delta. The DMA test used a double cantilever fixture, a –50 °C to 170 °C temperature range, and a 5 °C/min temperature ramp. Sensor embedding can change the composite's mechanical properties. Baseline sample had typical DMA storage, loss, and tan delta curves. Other reports on ABS-CF predicted the samples' glass transition temperature (*Tg*) to be 100 °C. When an ITOF sensor is embedded in a structure, DMA results change, regardless of sensor size. The *Tg* is predicted to be 55 °C. Additionally, it is possible to observe two peaks in the tan delta results for specimens with an embedded sensor, indicating that the composite system is experiencing two *Tg*, and this early degradation.

PARTNERSHIPS

This technology development project has the collaboration of Dr. Enrique Jackson, Rebecca Farr, and Ian Small from NASA. Dr. Jackson is the primary collaborator in the evaluation and characterization of the performance of 3D ITOF sensors in extreme conditions. The performance of sensors will be evaluated under simulated extreme space conditions (low temperature, low pressure) at NASA Marshall Space Flight Center (MSFC) by Dr. Jackson. This work will utilize NASA MSFC thermal analysis and laboratory facilities.

SUMMARY

This project is intended to satisfy NASA's need for embedded sensors for structural health monitoring. The proposed sensor must improve performance, environmental durability, mass, power consumption, and size. This project focuses on developing a high performance, powerless sensor for structural monitoring using mechanoluminescent (triboluminescent) materials. The research team designed and produced ITOF sensors for monitoring the health of aerospace structures, and established repeatable 3D printing parameters and identified technical difficulties with ABS carbon fiber matrix. Different-sized ITOF sensor systems were tested. The sensor system showed repeatable impact tests. 3D-printed structural health monitoring systems are feasible for use on aerospace vehicle structures using the 1 mm embedded ITOF sensor. To advance our research, we intend to continue optimizing the 3D printing materials, parameters, conditions, and ITOF sensor quality.

PRINCIPAL INVESTIGATOR: Dr. Okenwa Okoli, Florida A&M University – Florida State University College of Engineering

PARTNERS: Florida A&M University – Florida State University College of Engineering; NASA Marshall Space Flight Center

FUNDING ORGANIZATION: Cooperative Agreement Notice

SERVIR

OBJECTIVE: *To connect space to village by enabling local decision makers in Africa, Asia, and Latin America to apply Earth observations and geographic information technology to make informed decisions regarding issues like agriculture, land use change, water resources, climate, and disaster.*

PROJECT GOAL/DESCRIPTION

In 2005, SERVIR-Mesoamerica—first known as the Mesoamerican Regional Visualization & Monitoring System—was established and operated until 2011 in Panama City, Panama, through the joint effort of NASA, the U.S. Agency for International Development (USAID), and other partners. By late 2008, the SERVIR model, through the support of NASA and USAID, had been expanded to East Africa in partnership with the Kenya-based Regional Centre for Mapping of Resources for Development, creating the SERVIR-Eastern and Southern Africa hub. SERVIR's global expansion continued in late 2010, when SERVIR-Hindu Kush Himalaya was established at the International Centre for Integrated Mountain Development in Kathmandu, Nepal.

In 2014, global expansion continued into Southeast Asia with the establishment of SERVIR-Mekong by the Asian Disaster Preparedness Center and consortium partners. In 2016, SERVIR-West Africa became the fourth SERVIR hub, implemented by the Agrometeorology, Hydrology and Meteorology Regional Center in Niamey, Niger, and its consortium partners, with support from Tetra Tech, Inc. In 2019, USAID and NASA announced a fifth hub, SERVIR-Amazonia. The newest SERVIR hub is located in Cali, Colombia, and implemented by the International Center for Tropical Agriculture and consortium members. A new hub in Central America is under development and expected to launch in 2023.

APPROACH/INNOVATION

Building and relying upon a network of collaborators is fundamental to SERVIR. In addition to the sponsorship and participation of NASA and USAID, the SERVIR network of partners and collaborators includes other U.S. federal agencies, government agencies in SERVIR's target regions, universities, non-governmental organizations, and other specialized groups. This network actively participates in co-developing and implementing geospatial services, and supporting educational events and training workshops.

CREDIT: NASA JET PROPULSION LABORATORY/CALTECH.

FIGURE 1. NASA and Indian Space Research Organization (ISRO) Synthetic Aperture Radar (NISAR) satellite artist's concept.

FIGURE 2. NASA Earth Observatory images by Joshua Stevens, using Suomi NPP VIIRS data from Miguel Román, NASA Glenn Space Flight Center.

SERVIR partners with countries and organizations in its five hub regions to address critical challenges including climate change, food security, water disasters, land use, and air quality. Using satellite data and geospatial technology, such as the upcoming NASA and Indian Space Research Organization (ISRO) Synthetic Aperture Radar (NISAR) satellite mission scheduled to launch in 2023 (fig. 1), SERVIR collaboratively develops innovative solutions to improve resilience and sustainable resource management from the local to the international level.

SERVIR increases awareness and access to geospatial data and technology to help communities make sustainable, proactive, and socially inclusive decisions. With activities in more than 50 countries, SERVIR has already improved its capacity to address local issues by developing over 40 custom services, collaborating with over 600 institutions, and training more than 10,000 individuals. Because of its unique approach, SERVIR is the flagship of international applied sciences outreach, enabling and training decision-makers and scientists to develop solutions and continue training other local personnel.

RESULTS/ACCOMPLISHMENTS

SERVIR's hubs plan and launch services within four thematic areas: (1) Agriculture and Food Security, (2) Land Use and Land Cover Change, (3) Water and Water-Related Disasters, and (4) Weather and Climate. In 2022, SERVIR hubs have launched several new services, including a mangrove monitoring service in Amazonia, a land cover service for West Africa, a gender equality monitoring tool for the Mekong region, and more. Additionally, some of these tools were handed over to be run, updated, and improved by the hubs. One notable example is the handoff of the landslide monitoring system, Landslide Hazard Assessment for Situational Awareness (LHASA), to the Mekong regional hub.

In May 2022, the United Nations asked SERVIR's Eastern and Southern Africa hub to provide a drought impact analysis to inform international humanitarian aid decisions for the ongoing drought and food insecurity in the Horn of Africa. SERVIR used climate models and satellite-based vegetation information (e.g., Visible Infrared Imaging Radiometer Suite (VIIRS), Landsat, and Moderate Resolution Imaging Spectroradiometer (MODIS)) to provide this information (fig. 2). Additional uses include news outlets in Burkina Faso distributing SERVIR-West Africa rainfall forecasts to millions of farmers across the country and the adoption of four SERVIR-Mekong services by the Mekong River Commission into their decision-making process.

SERVIR hubs also trained people from over 40 countries—from private corporations, the government, and research institutions—to use geospatial products and tools. New countries reached included Zimbabwe, Togo, Trinidad and Tobago, and more. Outreach opportunities extended to schools in the Hindu Kush Himalaya region and Eastern Africa. The U.S. Embassy in Dhaka, Bangladesh also hosted an outreach event for local university students.

SUMMARY

SERVIR's unique network of research institutions, governmental organizations, and other stakeholders around the world enables a breadth and diversity of satellite applications that would not otherwise be possible. By listening to, promoting, and building the capacity of local stakeholders, the use of Earth observations and geospatial information tools in these areas has grown exponentially in the last decade and is allowing regional, national, and local experts to make crucial decisions for the people who live there.

PRINCIPAL INVESTIGATOR: Dan Irwin

PARTNER: U.S. Agency for International Development

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 GOAL/DESCRIPTION

The Advanced Microwave Precipitation Radiometer (AMPR) is an airborne, polarimetric, passive microwave radiometer producing brightness temperatures at 10.7, 19.35, 37.1, and 85.5 GHz. These frequencies are sensitive to the emission and scattering of precipitation-sized 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 horizontally (H)- and vertically (V)-calibrated polarized microwave brightness temperature values need to be determined. This is accomplished by deconvolution of polarization-variable measurements from two orthogonal channels per frequency.

APPROACH/INNOVATION

During fiscal year (FY) 2022, AMPR was deployed for a NASA field campaign called Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS). The January/February 2022 deployment saw AMPR integrated on the NASA ER-2, which is a high-altitude aircraft that serves in a *"satellite simulator"* role for providing remote sensing observations of snowstorms. When not flying, additional development occurred on AMPR's new data system, called Marshall Space Flight Cnter (MSFC) Instrument Data Architecture for Science (MIDAS), as well as on a new power distribution unit (PDU) for AMPR. Lab- and sky-focused testing of the instrument occurred throughout in support of this maintenance and instrument development.

RESULTS/ACCOMPLISHMENTS

In figure 1, observations from AMPR during IMPACTS 2022 are shown. On the 85 GHz channels, significant ice scattering (shown in the yellow-to-orange range) can be seen due to heavy snowfall. However, mixed in with this is surface emission signal, including the Hudson River visible as a thin curve with very cold brightness temperatures (shown in greens). On the lower frequency channels (i.e., 10, 19, and 37 GHz), brightness temperatures mostly indicate surface emission. AMPR gathered dozens of hours of data on precipitation systems and other notable features during IMPACTS 2022.

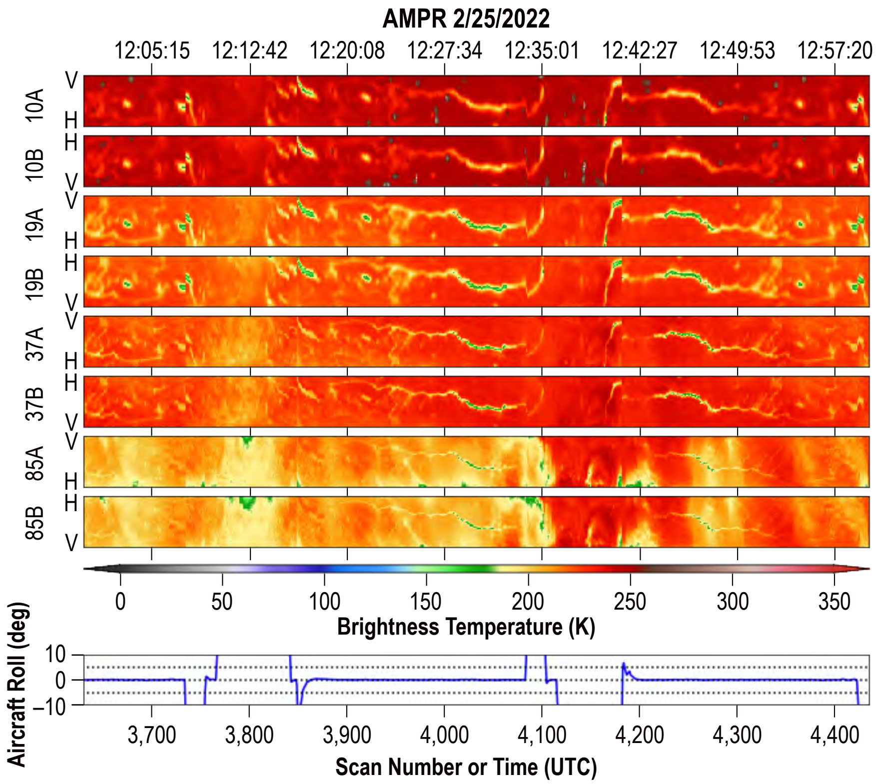


FIGURE 1. Strip chart showing one hour of data from an AMPR flight on 25 February 2022. Shown are brightness temperatures from each of AMPR's 8 channels, as well as a time series of aircraft roll angles. When roll angle is near 0° AMPR data are useful for scientific analysis.

PARTNERSHIPS

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

SUMMARY

AMPR provided useful scientific data on snowstorms during a field campaign in FY 2022. These data are being analyzed now while instrument development continues in order to maintain operational readiness. AMPR will fly again in IMPACTS 2023.

PRINCIPAL INVESTIGATOR: Timothy Lang

PARTNERS: University of Alabama in Huntsville; The Aerospace Corporation

FUNDING ORGANIZATION: Science Mission Directorate

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

International Space Station Lightning Imaging Sensor (ISS LIS)

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

PROJECT GOAL/DESCRIPTION

NASA Marshall Space Flight Center (MSFC) has long been a world leader in the detection of lightning from space. This leadership culminated with the launch of the International Space Station Lightning Imaging Sensor (ISS LIS) in 2017. ISS LIS has now operated for more than 5.5 years on orbit and continues to extend the multidecadal global climatology of lightning not only in time but also to higher latitudes (55° vs. 38°) than the previous LIS instrument on the Tropical Rainfall Measuring Mission (TRMM; 1997–2015).

APPROACH/INNOVATION

During fiscal year (FY) 2022, ISS LIS continued to operate nominally on orbit. This stability has been accomplished mainly through the use of an automated Timeliner script, which enables rapid recovery from single event upsets (SEUs) that often occur when the ISS is over high latitudes or passing through the South Atlantic Anomaly (SAA). In order to deconflict with another incoming mission, the host payload containing ISS LIS, called the 5th Space Test Program–Houston (STP–H5) mission, was relocated in July 2022 to another site on the 1st EXpedite the PRocessing of Experiments to Space Station (ExPRESS) Logistics Carrier (ELC-1) ISS platform.

RESULTS/ACCOMPLISHMENTS

The relocation of STP–H5 with ISS LIS (fig. 1) was successfully accomplished via use of the ISS robotic arm. Deactivation of the payload prior to the relocation occurred normally and there were no significant issues with reactivating the payload at the new site. Analysis is ongoing to adjust ISS LIS data for the new location and new field of view. We expect to release updated datasets with full corrections in FY 2023. ISS LIS data are being made available from the Global Hydrometeorology Resource Center (GHRC) Distributed Active Archive Center (DAAC), which provides both science-quality data as well as near-realtime data suitable for operational applications.

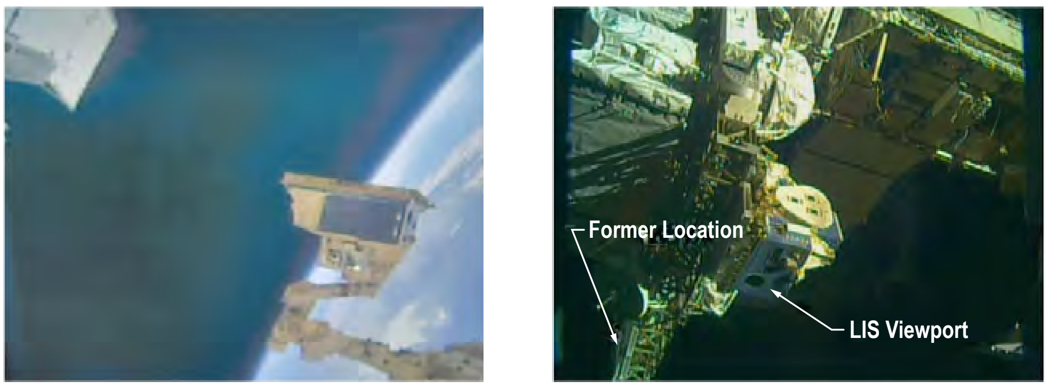
PARTNERSHIPS

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

SUMMARY

In FY 2022 ISS LIS continued to operate nominally and relocation of the instrument on ELC-1 was successful.

ISS LIS Relocation — 7 July 2022



STP-H5/LIS being carried by robotic arm during relocation.

STP-H5/LIS in new site on ELC-1 (site 3).

FIGURE 1. Photographs from the relocation of STP–H5 with ISS LIS.

PRINCIPAL INVESTIGATOR: Timothy Lang

PARTNERS: Space Test Program; University of Alabama in Huntsville; Universities Space Research Association

FUNDING ORGANIZATION: Science Mission Directorate

FOR MORE INFORMATION:
https://ghrc.nsstc.nasa.gov/lightning/data/data_lis_iss.html

Segmented Mirror Telescope Program (SMTP)

OBJECTIVE: *To reduce risk by maturing technologies resident in industry to enable large aperture space telescopes.*

PROJECT GOAL/DESCRIPTION

Large telescopes are needed to accomplish NASA's highest priority astrophysics science objectives. Starting in 2016, in advance of the National Academy's *Pathways to Discovery in Astronomy and Astrophysics for the 2020s Decadal Report*, NASA initiated an end-to-end study to identify technology gaps, to inventory technologies in industry which might close those gaps, and to invest in technologies with the greatest potential to enable future large-aperture, ultra-stable space telescopes—for a potential mission to directly image and characterize Earth-like planets around Sunlike stars via a coronagraph.

APPROACH/INNOVATION

The Segmented Mirror Telescope Program (SMTP) is an industry-led study with insight and oversight from NASA Marshall Space Flight Center (MSFC), NASA Goddard Space Flight Center (GSFC), NASA Jet Propulsion Laboratory (JPL) subject matter experts, and the NASA Headquarters (HQ) Astrophysics Division, including the Cosmic Origins/Physics of the Cosmos and the ExoPlanet Exploration Program offices. SMTP Phase 1 conducted a systematic, science-driven systems engineering study to identify technology gaps for enabling a potential large-aperture, ultra-stable ultraviolet/optical (UVO) space telescope. SMTP Phase 2 is investing in technologies, resident in industry, to understand and retire specific gaps. SMTP is a precursor activity in support of the Astro 2020 National Academy Decadal Report, which recommended a Great Observatories Mission and a Technology Maturation Program. SMTP Phase 2 (including contract extension) is scheduled to complete in fiscal year (FY) 2023.

RESULTS/ACCOMPLISHMENTS

SMTP is currently in Phase 2 with two industry led studies: Ultra-Stable Large Telescope Research and Analysis (ULTRA) and Technology Maturation of Astrophysics Space Telescopes (TechMAST).

The ULTRA study, led by Ball Aerospace, matures key component-level technologies via hardware testbeds and targeted simulations. ULTRA is studying active and passive technologies in the following five areas: (1) Mirror segment edge sensing and actuation at the picometer level with path-to-flight properties; (2) thermal sensing and control in the millikelvin range; (3) low distortion mirror mounting and segment radius-of-curvature matching; (4) increased large composite structures damping; and (5) improved composite material property metrology for higher stability and accurate integrated modeling. These technology development activities are informed by performance allocations flowed down through a system stability budget, which is anchored by coronagraph simulations traceable to science goals.

The TechMAST study, led by Lockheed Space Systems, matures four technologies related to large stable space telescopes:

(1) Integrated modeling to develop predictions for telescope performance, as measured by stability of wavefront error (WFE) and line-of-sight (LOS) pointing. These analyses incorporate the dynamic interaction of flexible structures, realistic disturbances and noise, interface control and linear optical models.

(2) Design of a disturbance-free payload (DFP) CubeSat demonstration payload and cable harness test bed experiments.

(3) Development of heterodyne metrology using photonic integrated circuits (PICs) to improve an existing testbed and develop models and error budgets.

(4) Advancement of tracking frequency gauge (TFG) metrology at Illinois Institute of Technology and University of Florida through parallel efforts on optical testbed improvements and electronics design development to improve metrology performance and create a path to flight.

PARTNERSHIPS

SMTP is a management collaboration between the NASA HQ Astrophysics Division and MSFC with subject matter experts from MSFC, GSFC and JPL. SMTP has two industry teams.

ULTRA study is led by Ball Aerospace Corporation (Boulder, CO) with contributions from KBR Wyle, LLC (Houston, TX), Kratos SRE (Birmingham, AL), L3Harris Technologies (Rochester, NY), Northrop Grumman Space Systems (Redondo Beach, CA), Smithsonian Astrophysics Observatory (Cambridge, MA), and Space Telescope Science Institute (Baltimore, MD).

The TechMAST study is led by Lockheed Martin Space (Sunnyvale, CA) with contributions from Lockheed Martin Space Advanced Technology Center (Palo Alto, CA), the University of Florida (Gainesville, FL), the Illinois Institute of Technology (Chicago, IL), and Endless Frontiers Associates (Boulder, CO).

SUMMARY

SMTP is an industry-led study with insight and oversight from MSFC, GSFC, JPL subject matter experts, and the NASA HQ Astrophysics Division. SMTP is currently in Phase 2 with two industry lead studies: ULTRA and TechMAST. SMTP Phase 2 is investing in technologies resident in industry to understand and close specific gaps. SMTP is a precursor activity in support of the Astro 2020 National Academy Decadal Report, which recommended a Great Observatories Mission and a Technology Maturation Program. SMTP Phase 2 is scheduled to complete in FY 2023.

PRINCIPAL INVESTIGATOR: Philip Stahl

PARTNERS: Ball Aerospace; Lockheed Martin

FUNDING ORGANIZATION: Science Mission Directorate

$CeBr_3$/NaI Phoswich Scintillator Detector Technology

OBJECTIVE: *To characterize the performance of a novel phoswich design for a wide field-of-view gamma-ray detector.*

PROJECT GOAL/DESCRIPTION

The field of astronomy currently requires more sensitive all-sky monitoring at keV photon energies to enable the detection of astrophysical sources with multiple cosmic messengers. Phoswich detector technology, which couples two different scintillating materials to a single photosensor, addresses this need by providing improved off-axis sensitivity relative to existing single scintillator designs for wide field-of-view instruments in the keV energy range. This project characterizes the performance of a novel cerium bromide ($CeBr_3$)/thallium-doped sodium iodide (NaI(Tl)) phoswich detector design for future satellite missions.

APPROACH/INNOVATION

Traditional wide field-of-view gamma-ray instruments in the keV energy range, such as Burst And Transient Source Experiment (BATSE) and Fermi–Gamma-ray Burst Monitor (Fermi–GBM), have used sets of 0.5-in-thick single crystal scintillation detectors for both the detection and localization of astrophysical transients. The wide (≥5 in) diameter of each detector is designed to produce a large amplitude signal for on-axis events and a much smaller signal for off-axis events. This provides the asymmetric response needed to reconstruct the location of an astronomical event, but yields reduced sensitivity to events viewed off-axis. The reduction in off-axis sensitivity for this type of detector can prohibit all-sky coverage on SmallSat spacecraft designs where mass constraints limit the number of detectors.

Thia approach using phoswich technology couples two different scintillating materials, $CeBr_3$ and NaI(Tl), with distinct decay times (fig. 1). This allows the research team to construct a single detector using both a thin forward scintillator and a thicker secondary scintillator with only a minimal mass increase per detector. Doing so produces significantly better sensitivity for off-axis sources when compared to a single scintillator design. Localization accuracy is maintained since photons interacting in the forward scintillator can be distinguished based on the decay timescale of the signal.

Furthermore, the combination of $CeBr_3$ and NaI(Tl) represents an innovation upon existing NaI(Tl) and sodium-doped cesium iodide (CsI(Na)) phoswich designs with flight heritage. This is because $CeBr_3$ has both a higher light yield and faster response time than either NaI(Tl) or CsI(Na), resulting in a lower energy threshold, improved energy resolution, and lower trigger dead time.

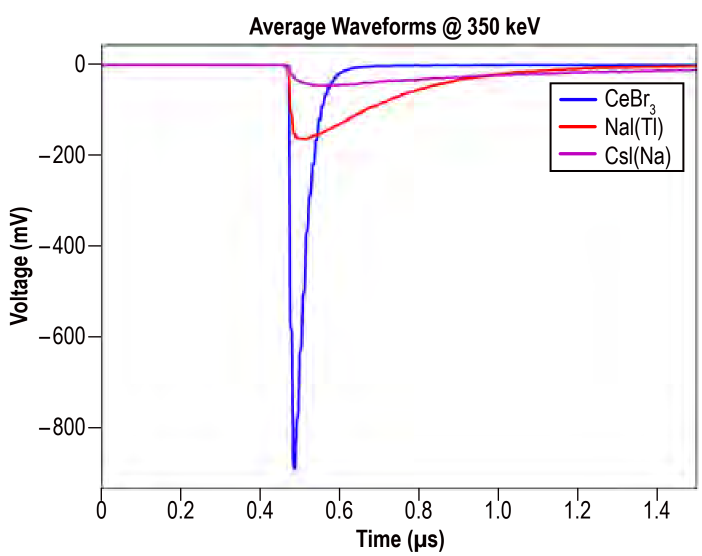


FIGURE 1. Pulse amplitude versus time for 350 keV photon signals in three scintillator materials.

The objective of this work is to quantify the energy threshold, energy resolution, and trigger dead time of this design in the laboratory. The research team plans to further advance the technology readiness level (TRL) of this technology through a STMD Early Career Initiative proposal in preparation for its inclusion in future SmallSat designs.

RESULTS/ACCOMPLISHMENTS

The research team successfully quantified the energy threshold, energy resolution, and trigger dead time of the $CeBr_3$/NaI(Tl) phoswich design relative to an equal mass NaI(Tl)/CsI(Na) phoswich unit (Table 1). These results were obtained using a charge integrating amplifier with a 50 μs integration timescale and a RC-CR2 filter for digital triggering. The energy thresholds are estimated by extrapolating the amplitude of 30 keV photon signals down to the noise floor of the trigger filter. In practice, the actual threshold below 10 keV will depend on the material choice for the detector housing.

The team finds that the energy thresholds of the scintillators in thr $CeBr_3$/NaI(Tl) design are well matched, with the extrapolated 3.5 keV threshold of $CeBr_3$ representing a 100% improvement over the 9 keV threshold of CsI(Na). The trigger dead times are similarly well-matched, with $CeBr_3$ representing a 100% improvement over CsI(Na) for the same trigger settings. This proves the innovation of this design over the NaI(Tl)/CsI(Na) combination with flight heritage. The only downsides for this design appear to be worse energy resolution at 30 keV, which is not critical for typical astrophysical spectra at these energies, and manufacturing constraints that limit $CeBr_3$ crystal diameters to 5 in or less.

SUMMARY

The investigators have verified that the $CeBr_3$/NaI(Tl) phoswich detector design notably improves upon the performance of existing NaI(Tl)/CsI(Na) designs. Additionally, this design has more off-axis sensitivity relative to traditional, single crystal scintillation detectors used for all-sky monitoring at keV photon energies. It is therefore a highly valuable technology for use in future wide field-of-view instruments at keV photon energies.

TABLE 1. Measured performance data for two equal mass phoswich detectors with 2-in diameter. Each cell contains two entries corresponding, respectively, to the primary and secondary scintillator materials used in the phoswich construction.

Phoswich Unit Thickness	Energy Threshold	30 keV Resolution	662 keV Resolution	Trigger Dead Time
0.4" $CeBr_3$ / 1.5" NaI(Tl)	3.5 keV / 3.5 keV	26% / 17%	5% / 6%	0.8 μs / 1.1 μs
0.5" NaI(Tl) / 1.25" CsI(Na)	3.5 keV / 9.0 keV	17% / 20%	6% / 8%	1.1 μs / 1.6 μs

PRINCIPAL INVESTIGATOR: Michelle Hui; Dan Kocevski; Joshua Wood)

FUNDING ORGANIZATION: Technology Investment Program

Moon Burst Energetics All-Sky Monitor (MoonBEAM)

OBJECTIVE: *Moon Burst Energetics All-Sky Monitor (MoonBEAM) is a gamma-ray mission concept in a cislunar orbit to observe the entire sky instantaneously for relativistic astrophysical explosions. The mission would probe the extreme processes in cosmic collision of compact objects and facilitate multi-messenger time-domain astronomy to explore the end of stellar life cycles and black hole formations.*

PROJECT GOAL/DESCRIPTION

The Moon Burst Energetics All-Sky Monitor (MoonBEAM) project is designed to explore the behavior of matter and energy under extreme conditions by observing the prompt emission from gamma-ray bursts (GRBs), identifying the conditions capable of launching transient relativistic jets, and determining the origins of high-energy radiation from the relativistic outflows. It provides essential gamma-ray observations for multimessenger astronomy by reporting on the prompt emission and providing rapid alerts to the astronomical community for contemporaneous and follow-up observations. In this era of multimessenger astronomy, simultaneous broadband observations of relativistic transients are needed to construct a comprehensive picture of stellar explosions. These joint observations are crucial to study the central engines that power the explosions, to provide insights into the composition of relativistic outflows, and to enable strict constraints on the timescales for jet formation and propagation.

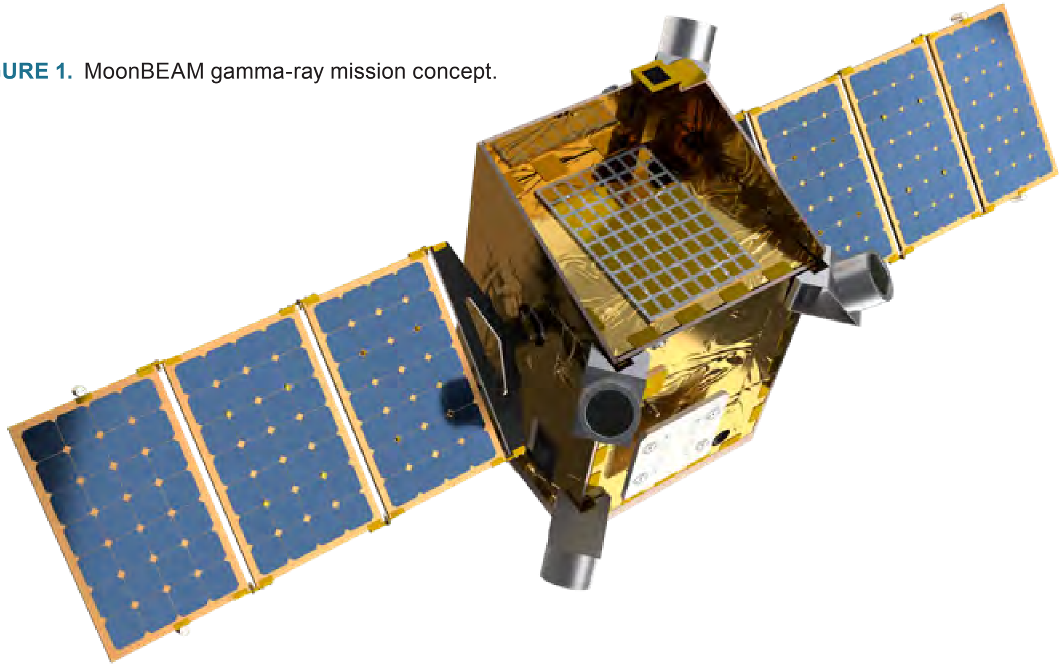
APPROACH/INNOVATION

MoonBEAM achieves instantaneous all-sky coverage with a near-continuous observing duty cycle based on its instrument design and its cislunar orbit. The instrument consists of six thallium-doped sodium iodide (NaI(Tl))/sodium-doped cesium iodide (CsI(Na)) phoswich detectors, positioned on corners of the spacecraft to achieve all-sky coverage. The phoswich design allows simultaneous dual mode analysis: refined localizations from the NaI(Tl) crystal with the thicker CsI(Na) crystal serving as an active shield to reduce the background, while increasing the effective area over a wide field of view (FOV) and extending the sensitivity to higher energies using the signals from both crystals.

The cislunar orbit minimizes Earth blockage to the FOV and variation in the background radiation environment compared to the low-Earth orbit that is typical of science missions. It also provides a longer baseline from Earth for localization refinement using the timing-triangulation technique with other gamma-ray instruments. When a gamma-ray transient is detected by multiple instruments in different orbits, the difference in detection times will constrain the arrival direction to an annulus on the sky and aid in reducing the localization area.

MoonBEAM will reach the cislunar science orbit from an Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) Grande rideshare to any standard geosynchronous transfer orbit. The spacecraft is a Lockheed Martin small satellite bus with a high-heritage deep space propulsion system. Rapid GRB alerts will be downlinked and distributed with dedicated ground stations provided by the Near Space Network.

FIGURE 1. MoonBEAM gamma-ray mission concept.



RESULTS/ACCOMPLISHMENTS

The MoonBEAM concept development was initially enabled by Independent Research and Development (IRAD) and selected for a one-year mission design study by the Astrophysics Science SmallSat Studies program in 2020.

The MoonBEAM mission proposal was submitted to the 2021 Astrophysics Explorers Mission of Opportunity (MO) in December 2021 and was one of two MOs selected for a nine-month Phase A concept study starting September 2022. Downselection is targeted in the first quarter of 2024 after the submission of the concept study report and site visit.

PARTNERSHIPS

Lockheed Martin Space is the spacecraft bus provider. The University of Alabama in Huntsville is co-developing the detector and instrument software. Universities Space Research Association is co-developing the science operations and data analysis. The scientific collaboration includes University of Alabama in Huntsville, Universities Space Research Association, Louisiana State University, NASA Goddard Space Flight Center, University of Western Australia, Cornell University, and Deutsches Elektronen-Synchrotron (DESY) Zeuthen.

SUMMARY

Moon Burst Energetics All-Sky Monitor (MoonBEAM) is a gamma-ray mission in a cislunar orbit to observe the entire sky instantaneously for relativistic astrophysical explosions. It will provide the sensitive high-energy all-sky observation that is critical to transient and multimessenger astronomy and will address the time domain priority identified by the National Academy's *Pathways to Discovery in Astronomy and Astrophysics for the 2020s Decadal Report*.

PRINCIPAL INVESTIGATOR: C. Michelle Hui

PARTNERS: Lockheed Martin; University of Alabama in Huntsville; Universities Space Research Association; Louisiana State University; NASA Goddard Space Flight Center; University of Western Australia; Cornell University; Deutsches Elektronen-Synchrotron (DESY) Zeuthen

FUNDING ORGANIZATION: Bid and Proposal

Scintillation Prediction Observations Research Task (SPORT)

OBJECTIVE: *The Scintillation Prediction Observations Research Task (SPORT) is a 6U CubeSat mission to advance the scientific understanding of the preconditions and triggering mechanisms leading to equatorial plasma bubbles.*

PROJECT GOAL/DESCRIPTION

The Scintillation Prediction Observation Research Task (SPORT) is a joint mission between the United States and Brazil using a 6-Unit (6U) CubeSat. The science goals of this space weather mission are to investigate the conditions that lead to the formation of plasma bubbles.

FIGURE 1. SPORT logo.

SPORT addresses two specific science questions to provide a better understanding of the preconditions leading to equatorial plasma bubbles and scintillation:

(1) What is the state of the ionosphere that gives rise to the growth of plasma bubbles that extend into and above the F-peak at different longitudes?

(2) How are plasma irregularities at satellite altitudes related to the radio scintillations observed passing through these regions?

Answers to these questions can improve the ability of researchers to predict the formation of plasma bubbles and to understand the conditions under which anomalies develop in the ionosphere at low latitudes near the equator, leading to scintillations on radio signals.

APPROACH/INNOVATION

The SPORT satellite addresses the first science question by measuring the state of the ionosphere when the satellite is in the region where plasma bubbles are thought to be triggered. On the next satellite orbit, the Earth's rotation moves that longitude sector eastward and later into the night, where fully formed bubbles might be present. A GPS receiver is used to detect whether bubbles have occurred by looking for scintillations on GPS signals coming from that direction. The data from many periods are compared to look for patterns of why bubbles occur or don't occur at different longitudes around the Earth's equator.

The second science question is addressed by using measurements at the SPORT satellite altitude of the plasma density produced at higher sample rates than have previously been obtained. This process permits the characterization of turbulence created by plasma bubbles with scale sizes down to 200 m. Radio receivers on the ground in Brazil record the scintillation pattern on waves that pass through the ionosphere, and these are compared to the satellite measurement of the turbulent plasma. Once verified using available data in the Brazilian sector, the same procedures can be applied at other longitudes to produce a global description of scintillation due to plasma bubbles.

RESULTS/ACCOMPLISHMENTS

SPORT assembly, integration, and testing (AIT) was completed earlier this year. Battery issues encountered during AIT were resolved and environmental testing of SPORT began. Environmental testing was successfully completed. SPORT was shipped to the U.S. and delivered to the

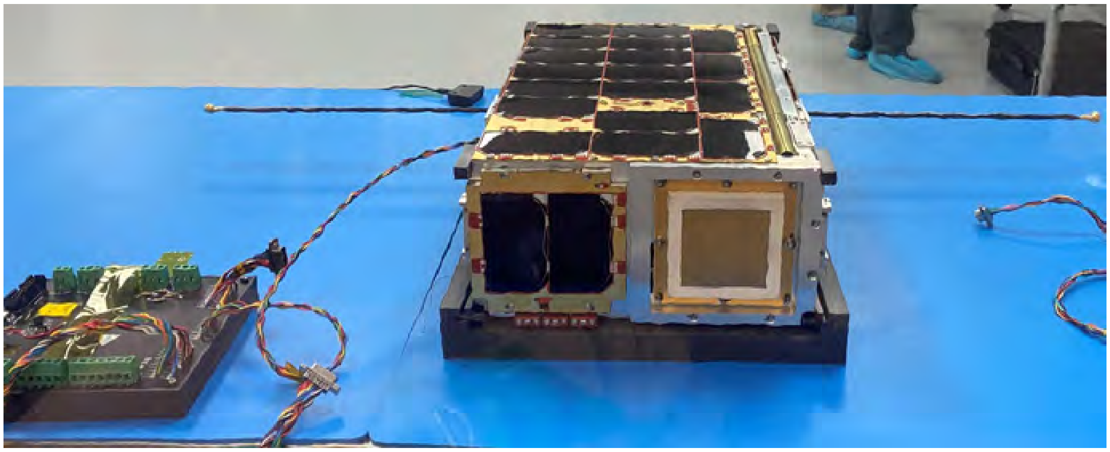


FIGURE 2. Final functional test of the SPORT CubeSat.

Nanoracks facility. The Brazilian Technical Aeronautics Institute (ITA) team arrived shortly afterwards and performed post-shipment functional tests; SPORT was functioning as expected. The official handover to the launch provider, Nanoracks, took place in July. The Mission Readiness Review was completed in October 2022. SPORT was manifested on SpaceX Commercial Resupply Mission 26 (SpX-26), which launched on November 26, 2022.

PARTNERSHIPS

SPORT is a partnership between NASA and the Brazilian Space Agency (AEB). Through AEB, two Brazilian institutes contribute to the mission: the National Institute for Space Research (INPE) is handling operations and ground network and ITA is providing the spacecraft. In addition to NASA Goddard Space Flight Center (GSFC), the University of Texas at Dallas, Utah State University, and the Aerospace Corporation provided the scientific instruments. U.S. Department of Defense entities, including U.S. Southern Command and six other combatant commands; Combat Capabilities Development Command: Aviation & Missile Center; and U.S. Space Force Air Force Research Laboratory Space Vehicles Directorate (AFRL/RV) will provide technology validation and technology transfer. SPORT is managed by NASA Marshall Space Flight Center (MSFC) in Huntsville, Alabama.

SUMMARY

The Scintillation Prediction Observations Research Task (SPORT) is a 6U CubeSat mission to advance the scientific understanding of the preconditions and triggering mechanisms leading to equatorial plasma bubbles. The scientific literature describes bubble preconditions in both the ionospheric drifts and the density profiles as being related to bubbles forming several hours later in the evening. What is unknown is how these triggering mechanisms vary with longitude around the equatorial region of the Earth. SPORT provides a systematic study of the state of the pre-bubble conditions at all longitudes sectors to enhance understanding of the interaction between geography and magnetic geometry.

PRINCIPAL INVESTIGATOR: Dr. Charles Swenson, Utah State University

PARTNERS: Brazilian Space Agency (AEB); the Technical Aeronautics Institute (ITA); the National Institute for Space Research (INPE); NASA GSFC; the University of Texas at Dallas; Utah State University in Logan, Utah; the Aerospace Corporation; Department of Defense U.S. Southern Command, Combat Capabilities Development Command: Aviation & Missile Center; and U.S. Space Force: Air Force Research Laboratory Space Vehicles Directorate

FUNDING ORGANIZATION: Science Mission Directorate

FOR MORE INFORMATION: https://www.nasa.gov/mission_pages/sport/index.html

Extreme-Ultraviolet Stellar Characterization for Atmospheric Physics and Evolution (ESCAPE) Phase A Concept Study

OBJECTIVE: *Design and analysis of X-ray mirror mount system for NASA Astrophysics Small Explorer mission concept study report.*

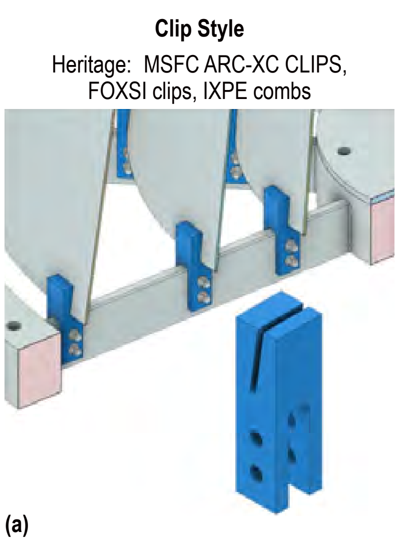
PROJECT GOAL/DESCRIPTION

NASA Marshall Space Flight Center (MSFC) was a partner institution on the proposal entitled Extreme-Ultraviolet (EUV) Stellar Characterization for Atmospheric Physics and Evolution (ESCAPE), submitted by the University of Colorado's Laboratory for Atmospheric and Space Physics (LASP) to the NASA Astrophysics 2019 Small Explorer (SMEX) competition. MSFC's task on ESCAPE was to design and fabricate grazing-incidence mirror shells, and to mount those mirror shells into mirror module assemblies (MMAs). The MMAs needed to withstand vibration loads expected during launch of the ESCAPE observatory while protecting the fragile mirror shells from stresses that would cause deformation or loss of optical alignment.

APPROACH/INNOVATION

Two fundamentally different telescope designs were considered: the first called for multiple (e.g., 3 or 4) nested mirror shells, and the second (and final) configuration included just a single shell. The nested-shell approach necessitated that the mirrors be supported at their ends and cantilevered from the so-called mounting 'spider.' The mounting system needed to provide adequate support to prevent mirror deformation and maintain alignment, while the fraction of light blocked by the mounting attachments had to remain small so as not to significantly impact the effective area of the telescope.

Two different approaches were designed and analyzed for the nested-shell system: clip-style mounts, and button-style mounts. The clip style features a slot to



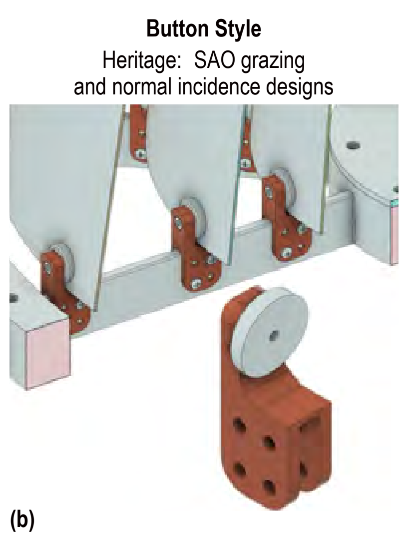


FIGURE 1. (a) Clip-style and (b) button-style mounts for nested mirror shells.

receive the end of the mirror shell, and a pair of legs to straddle the spokes of the spider. This type of mount has significant flight heritage and is similar to that used on the Imaging X-ray Polarimetry Explorer (IXPE) mirrors. The button-style mount is based on a pad that attaches to the outer surface of the mirror, and then is supported by a flexible standoff which, in turn, straddles the spider spokes. While the slot of the clip mount allows epoxy to adhere to both sides of the mirror shell, the button mount only adheres to one surface. Tradeoffs include the double adhesion of the clip-style, compared to the potential for greater flexibility offered by the standoff of the button mount.

In contrast, the single-shell design allowed the mounts to be placed on the outside surface of the shell, at the center of gravity. With no requirement to cantilevering from the end, and thus no concern about obscuring the collecting area of the mirrors, the mounting attachments could be made larger. The button-style mount was adapted to use blade-shaped flexures, which then attach to a mounting flange circumscribing the mirror shell. This approach has heritage from the Chandra X-ray observatory and is similar to mounting systems used for the Marshall Grazing Incidence X-ray Spectrometer (MaGIXS) and normal-incidence glass mirrors.

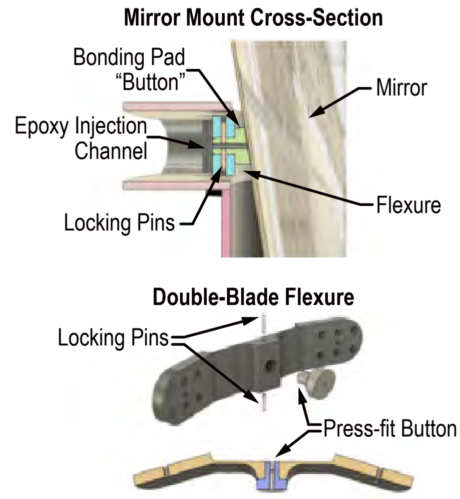


FIGURE 2. Single-shell mirror mounting design diagrams showcasing double-blade flexure.

RESULTS/ACCOMPLISHMENTS

For each of the designs, we constructed finite-element models and analyzed the performance in flightlike dynamic environments. All three showed promise and may be adapted for future proposals. The ESCAPE design converged on the single-shell approach, and thus the double-blade flexure approach was submitted in the Phase A Concept Study Report.

SUMMARY

The design and analysis work executed for this project allowed the team to evaluate three different approaches for mounting thin metallic shells for grazing-incidence mirrors. All three concepts have strengths, and a range of variables that can be adjusted for future mission design proposals.

PRINCIPAL INVESTIGATORS: David E. McKenzie and Patrick R. Champey

PARTNER: University of Colorado Laboratory for Atmospheric and Space Physics

FUNDING ORGANIZATION: Science Mission Directorate (SMD)

Materials Development for Additive Manufacture of Radiation Sensors and Shielding

OBJECTIVE: *To create in-situ resource and resistance-based radiation detectors (RRDs) that are compatible with Earth- and space-based additive manufacturing technologies.*

PROJECT GOAL/DESCRIPTION

Radiation is one of the most significant hazards in the space environment. It can destroy electronics, degrade materials, and produce irreparable damage to biological organisms. Current detectors, called dosimeters, are not capable of real-time readouts and therefore cannot warn crewmembers of significant exposure events. Current detectors are also not producible by 3D-printable methods, and therefore would not lend themselves to on-demand fabrication using in-space manufacturing. Under a Cooperative Agreement Notice (CAN) with NASA Marshall Space Flight Center (MSFC), Georgia Institute of Technology is developing neutron radiation detection devices that will produce real-time exposure data and have the capability of being fabricated off-Earth using in-situ resources.

APPROACH/INNOVATION

The approach involves demonstrating the sensitivity of resistance-based radiation detectors (RRDs) to neutron radiation and to measure the effect of irradiation on the RRDs. Then, the team will demonstrate how RRDs can be fabricated using additive manufacturing technologies. Finally, the team will investigate the fabrication of RRDs using in-situ (i.e., lunar and martian) resources.

Multilayered printed electronics will be used in the design of the RRDs, which integrates well with the roadmap for in-space manufacturing technology development. Next steps after this year's work include incorporating RRDs into the test print lineup for future in-space manufacturing efforts, as well as perfecting the design for reduced-gravity printing.

RESULTS/ACCOMPLISHMENTS

Highly conductive polymer composite materials were produced and integrated with layers of a radiation-sensitive material. Growth of crystals of the radiation-sensitive material was accomplished; however, the initial manufacturing technique attempted did not achieve the conductive thin films necessary for RRD production. Thus, inkjet printing of conductive ultrathin layers was investigated. Optimization of this technique is in work.

PARTNERSHIPS

This work in RRDs that can be manufactured in situ is possible through a partnership with Georgia Institute of Technology. Future collaboration opportunities include additional sensor types, radiation monitor deployment techniques for surface construction, and further testing.

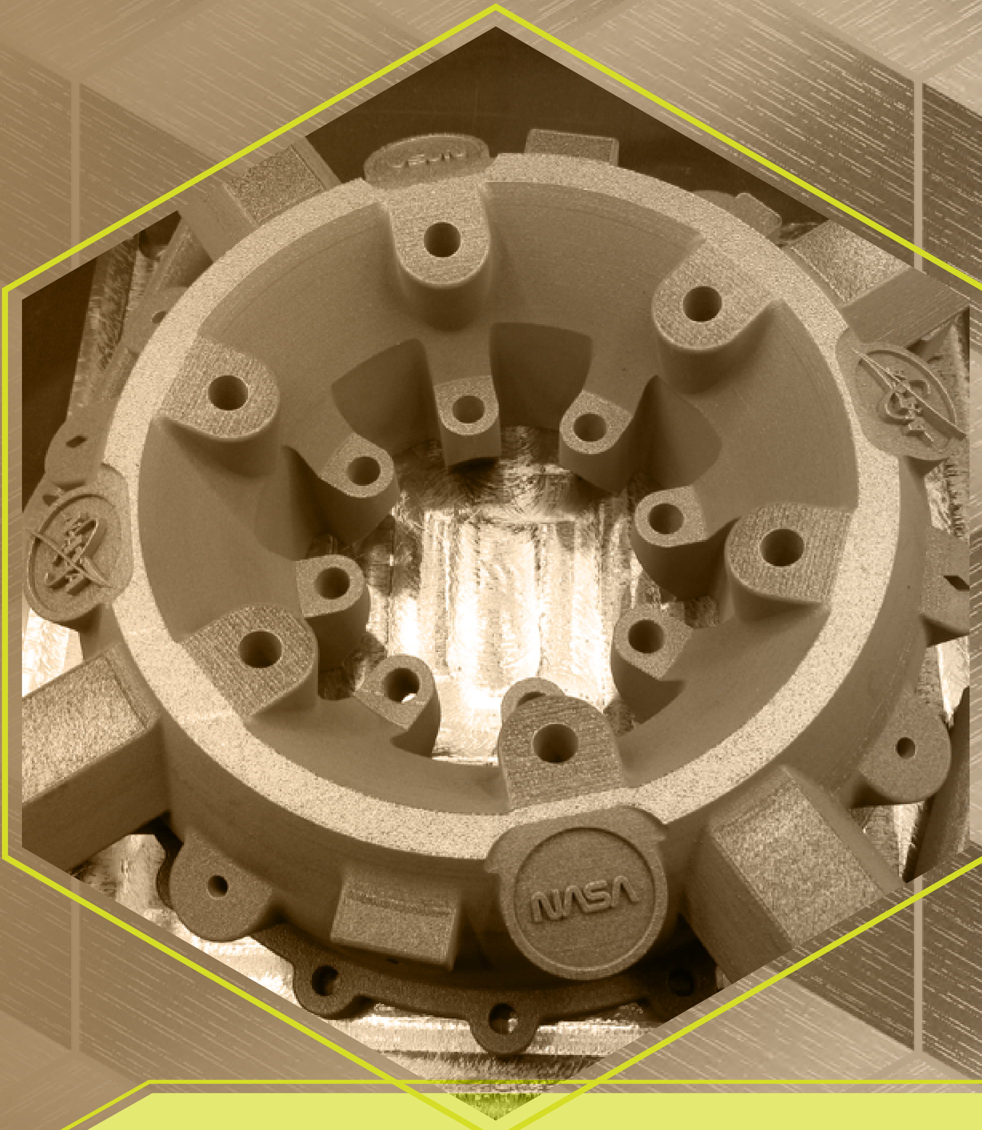
SUMMARY

Establishing a sustainable human presence in deep space requires the on-demand production of necessities, such as real-time readout radiation sensors, from in-situ resources. Georgia Institute of Technology partnered with MSFC to investigate fabrication of RDDs using techniques that are possible with in-space manufacturing.

PRINCIPAL INVESTIGATORS: Curtis Hill (MSFC/ESSCA); Jennifer Edmunson (MSFC); Phillip First, Thomas Orlando, and Zach Seibers from Georgia Institute of Technology

PARTNER: Georgia Institute of Technology

FUNDING ORGANIZATION: Cooperative Agreement Notice



Technology Area 09

ENTRY, DESCENT, AND LANDING

Exploring High-Performance Additively Manufactured Rotating Detonation Rocket Engines

OBJECTIVE: *To develop cooling and injection strategies for continuously rotating detonation rocket engine hardware using additive manufacturing techniques and materials.*

PROJECT GOAL/DESCRIPTION

The primary focus of this Center Innovation Fund (CIF) work was to identify novel injection and cooling strategies using additively manufactured hardware for use with rotating detonation rocket engines (RDREs). These include injectors, chambers with integral coolant channels, and channel wall nozzles. Ultimately, RDREs could produce higher performances than the state-of-the-art (SOA) liquid rocket engines. Higher performances can be defined in several ways: part cost reduction; effectiveness of cooling; higher thrust or specific impulse (Isp); or robustness and reusability of hardware. The primary additive manufacturing (AM) technique leveraged in this work is the laser powder bed fusion (L-PBF) process. The primary AM materials utilized are two copper alloys developed at NASA Glenn Research Center, GRCop–42 and GRCop–84. The focus of this work has been developing design and integration strategies for advanced cooling channel geometries along with transpiration mesh geometries for effective cooling of hardware.

APPROACH/INNOVATION

Additive manufacturing now allows for the production of complex integrated structures, such as transpiration meshes and coolant channels directly within the component. For example, the face of an injector and the wall of a chamber. This allows a designer to produce a single component in a significantly shorter time period without the need for multiple development steps as traditional manufacturing would require. An injector with transpiration cooling can now be produced within the span of a few weeks

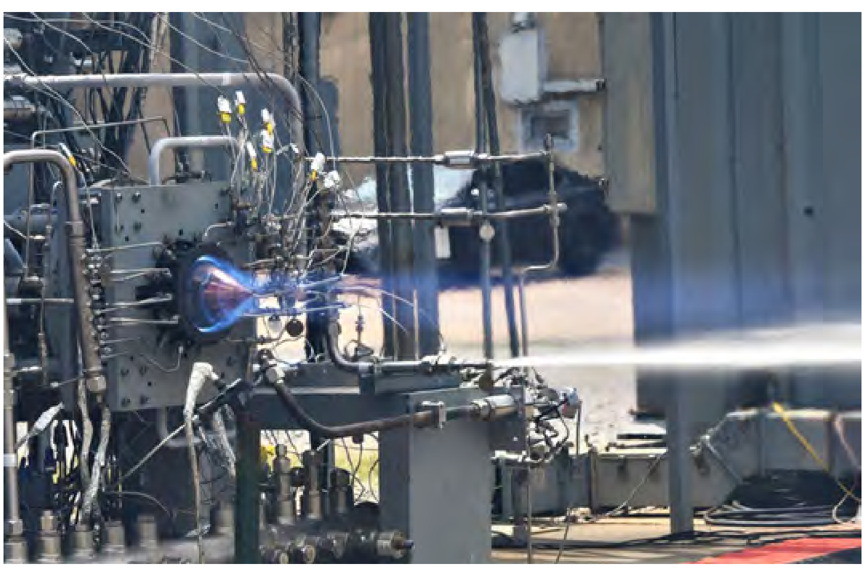


FIGURE 1. NASA additively manufactured GRCop–42 RDRE firing with liquid oxygen (LOX)/methane (CH_4).

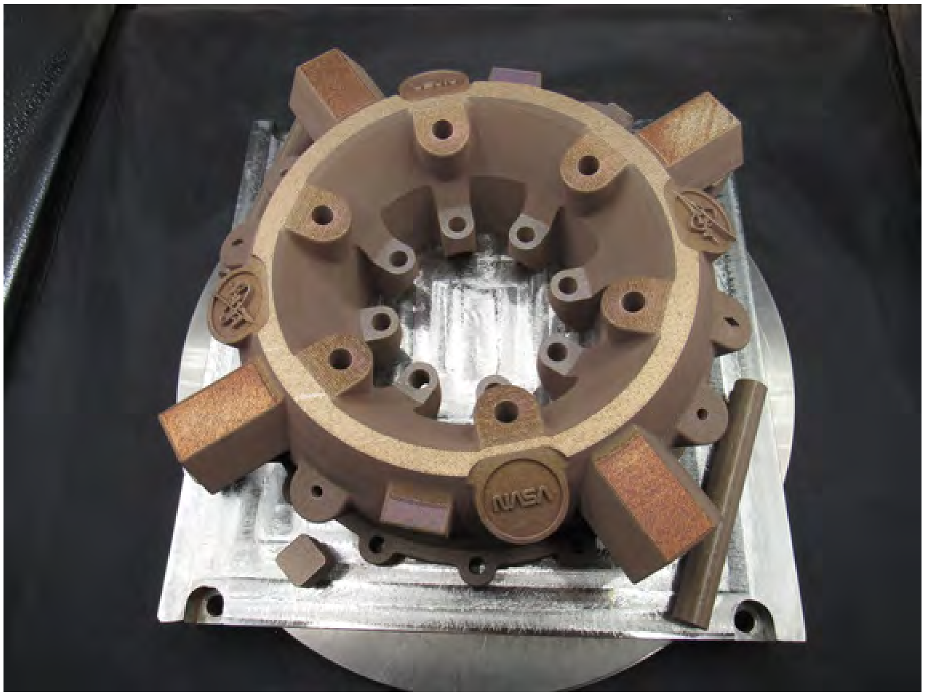


FIGURE 2. NASA RDRE powder bed fusion GRCop–42 injector.

as opposed to several months or years. However, these transpiration structures still have significant structural challenges that require innovative design strategies to reinforce their base design. Cooling channels can now be tailored to the exact heat flux profile but suffer from significant pressure losses due to wall roughness from the additive process. Industry can now leverage these mesh structures and channel design practices within their own flight hardware to effectively cool components that would experience the most extreme of combustion environments.

This is why this technology was developed and tested with NASA's first RDRE during Summer 2022 at NASA Marshall Space Flight Center (MSFC). Detonations produce the highest temperature and pressure environments that rocket hardware could experience. Images of hardware that were piggyback tested under an announcement for collaborative opportunity (ACO) test program are included with this writeup. The next step is to further demonstrate integral cooling channels at elevated detonation engine mean pressures and novel injection strategies that directly integrate mesh into the injection scheme. Now that cooling performance has been successfully demonstrated, other engine performances such as combustion efficiency, thrust, and design compactness will now also be demonstrated.

RESULTS/ACCOMPLISHMENTS

Several print demonstrators were originally produced to identify if the injection schemes were viable without build failure. All original samples printed successfully on the first attempt. Next, full-scale injectors were produced for a constant pressure engine and an RDRE for direct comparison of performances between engine cycles. Both injectors printed successfully with one being shown in the attached image. This injector was successfully tested with many key lessons learned documented. In addition, the injector integrated a new ignition scheme dubbed multi-point augmented spark ignition and was successfully demonstrated to ignite the engine reliably. All hardware survived the extreme combustion environments while showing significant increases in combustion efficiency, all with only a 3-in combustion chamber. The constant pressure injector is anticipated to be tested in October 2022 and a more direct comparison of engine performances can be made after testing.

PARTNERSHIPS

Purdue University was the primary partner, with Elementum 3D and Quadrus Corp. being the primary additive hardware vendors. Dr. Stephen Heister's lab at Purdue was instrumental in the development of RDRE technology, and they are continuing to the next phase of the technology development in Spring 2023. Valuable data from the Phase 1 testing at MSFC has been used to design new chamber and injector geometries optimized for detonation cycle engines. These designs are currently under production and will be tested under Phase 2. Future partnership opportunities are anticipated with future work aiming for flight demonstration of the engine system.

SUMMARY

Substantial progress has been made to date on the development of extreme environment injection and cooling strategies for RDREs. Phase 1 testing will be completed in October 2022 and Phase 2 testing is anticipated to take place in Spring 2023. A major highlight for the CIF thus far is the successful production of a single high performance transpiration injector and hot-fire demonstration at MSFC in Summer 2022. This injector demonstrated detonation wave activity with realistic propellant combination, liquid oxygen with liquid methane fuel, gaseous methane fuel, and gaseous hydrogen fuel. Future hardware is already under development at MSFC under a Space Technology Mission Directorate (STMD) Early Career Initiative (ECI) project and anticipated to be tested in Summer 2023.

PRINCIPAL INVESTIGATOR: Thomas Teasley
PARTNER: Purdue University – Dr. Stephen Heister
FUNDING ORGANIZATION: Center Innovation Fund

Additively Manufactured Fluidic Diode Injectors for Rotating Detonation Rocket Engines

OBJECTIVE: *To design and test novel liquid-gas injector elements to improve the performance of rotating detonation rocket engines and hinder backflow via manipulation of injector diodicity.*

PROJECT GOAL/DESCRIPTION

This project has two main objectives:

(1) Design, model, and fabricate additively manufactured (AMed) liquid/gas rocket injector elements with integrated fluidic diode structures. Assessment of component build and build failure modes were assessed for the benefit of Marshall Space Flight Center's (MSFC) AM capability.

(2) Cold flow test the injector elements and test with simulated detonation waves that are propagated across the injector face. The rates of recovery for liquid and gas phase propellants and variable responses of integrated diode structures have been characterized. This will directly benefit ongoing MSFC rotating detonation rocket engines (RDREs) and deep-throttled lander development efforts.

APPROACH/INNOVATION

This work takes an innovative approach to designing injectors for detonation and deep throttle devices by incorporating fluidic diodes in injector elements to combat the effects of propellant flow halting and/or backflowing prevalent in many RDRE experiments. Steady state backflow tests, traditional cold flow tests, and simulated detonation wave tests were all studied in this work.

Technical Approach and Deliverables:

Activity 1: Design, modeling, and AM of fluidic diode injectors.

Activity 2: Injector cold flow and spray characterization.

Activity 3: Injector backflow tests with simulated detonation wave to study transient diodicity, backflow, and refill.

Following the approach outlined above, full scale hot-fire tests are planned with the best performing injectors using an RDRE at The University of Alabama in Huntsville (UAH). The UAH RDRE is a racetrack style combustor with optical access to identify critical performance metrics such as detonation structure. Direct observation of the detonation wave/injector interaction is a critical next step in the technology development path.

FIGURE 1. Experimental demonstration of passing detonation wave with liquid jet.

RESULTS/ACCOMPLISHMENTS

Using ANSYS simulation software, forward and reverse simulations of a 2D diode structure ranging from one to four diodes in series was performed to determine diodicity. Diodicity was shown to increase as the number of diodes increased, with arguably minimal added gain past three diodes. Once a steady diodicity was reached as mass flow rate increased, it was found the diodicity ranged from about 0.98 to 1.22 in the simulations. More diodes required finer mesh resolution and therefore convergence quality began to degrade. All simulation results are steady state flow with air.

Spray tests, along with forward and reverse cold flow tests using water and air simulants, were conducted on a wide range of injectors either printed in Inconel® or resin. The resin printing allowed for rapid prototyping of injector designs such as triplet and pentad impingers, shear and swirl coaxial, and pintle injectors; but there are material properties of the AM process that affect injector performance (e.g., porosiyt) that cannot be captured with resin prints. Straight channels with varying numbers of diodes were tested to determine any diminishing gains in diodicity with each addition of a diode. High speed imaging and pressure drops were measured on each injector.

Experiments showed that the single diode had better diodicity than two or three diodes, with the worst being the double diode case. All experimental diodicities were under, one which means there was more restriction in forward flow than in backflow — an undesired outcome in these types of injectors. The best mixing was found in the triplets and pintle injectors, followed closely by a swirl-impinge hybrid injector. Mixing was determined qualitatively by looking at high speed images of the spray field.

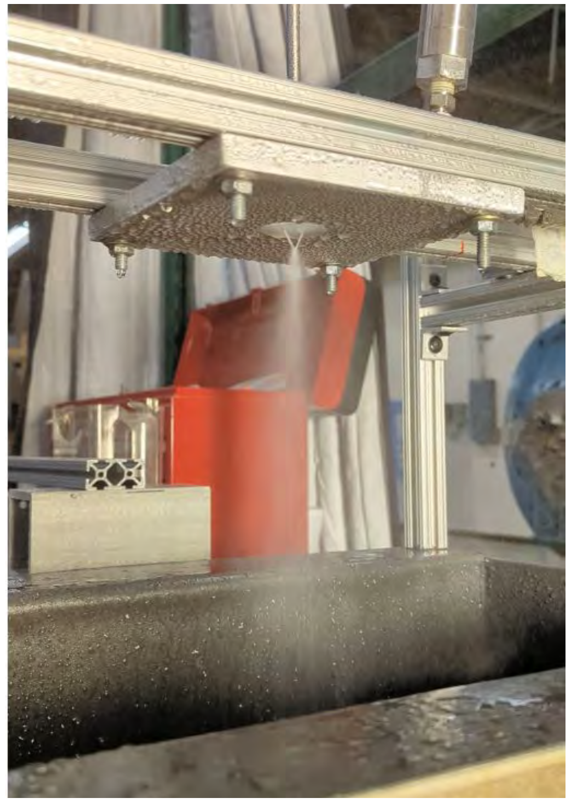


FIGURE 2. Spray testing of fluidic diode integrated injector element.

A resin printed detonation channel was constructed to allow transient recovery testing in atmospheric and pressurized conditions. Preliminary atmospheric transient behavior of the impingement injectors has been tested on the UAH test stand and high-speed imaging was able to capture the initial flow, detonation passing, and recovery of simulated propellants. Simulant pressure versus recovery time has been determined for these injectors and found that with high enough mass flow rate, the detonation didn't seem to disrupt the flow enough to prevent impinging, only to effect the mixing. The simulated propellants used were low pressure air and water.

PARTNERSHIPS

Dr. Gabe Xu's laboratory at the University of Alabama in Huntsville is the primary collaborator for the work outlined in this report. The cold flow and detonation experiments were conducted at UAH facilities. This work was primarily conducted by NASA Space Technology Graduate Research Opportunities (NSTGRO) fellow and graduate research assistant Michaela Hemming. They have significantly advanced the technology readiness level (TRL) of this work for NASA and will continue this collaborative effort toward hot fire in fiscal year (FY) 2023.

SUMMARY

Rapid prototyping of liquid-gas propellant injectors intended for RDRE applications were designed; simulated; and underwent experimentation with propellant simulants, water, and air to determine steady state and transient performances. Simulations mainly focused on steady state diodicity while experiments focused on mixing and transient performance with a passing detonation wave.

PRINCIPAL INVESTIGATORS: Thomas Teasley, Marshall Space Flight Center; Dr. Gabe Xu, University of Alabama in Huntsville

PARTNER: University of Alabama in Huntsville

FUNDING ORGANIZATION: Cooperative Agreement Notice

Precision Landing of a Hexacopter Drone by Smartphone Video Guidance Sensor

OBJECTIVE: *To demonstrate the viability of the Smartphone Video Guidance Sensor (SVGS) as a sensor for lunar descent and landing via an autonomous drone landing in a laboratory environment.*

PROJECT GOAL/DESCRIPTION

NASA's Human Landing System (HLS) program aspires to perform precision landing on the lunar surface to an accuracy of 100 m or better. Simulations and analyses predict that the baseline HLS navigation system, if supplemented by the Smartphone Video Guidance Sensor (SVGS), could potentially reduce that landing accuracy to better than 20 m. As an inexpensive and low-risk proof-of-concept of this analysis, Marshall pace Flight Center (MSFC) and its partner at the Florida Institute of Technology (FIT) set out to integrate the SVGS on a drone and show that an autonomous precision landing can be achieved.

APPROACH/INNOVATION

SVGS was developed in 2013 under the Center Innovation Fund (CIF) as a sensor for rendezvous, proximity operations and docking (RPOD) for small spacecraft. SVGS uses a cluster of four targets, either retroreflectors or light emitting diodes (LED), in a prescribed configuration as targets for an optical navigation methodology. A camera records an image of the four targets, and image processing and photogrammetry software estimate a six-degrees-of-freedom (6DOF) state between the camera reference frame and the target reference frame. That 6DOF state can be used by a chase vehicle trying to rendezvous with a target vehicle carrying the targets (see figure 1). If the targets are facing upward on the surface of the Moon, a lander could utilize the 6DOF state to guide its precision landing to a repeating landing site. SVGS provides highly accurate and deterministic 6DOF state estimates with a very robust and proven algorithm.

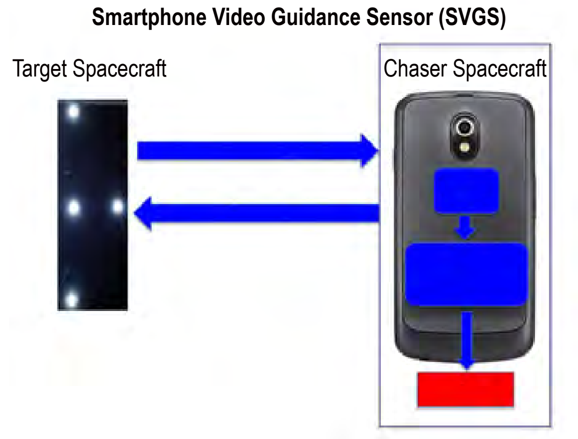


FIGURE 1. SVGS concept of operations.

The original plan was to integrate a Samsung Galaxy S8 smartphone with FIT's laboratory hexacopter. The drone would carry the smartphone underneath it with the smartphone's camera facing the LED targets on the laboratory floor. The smartphone's SVGS software would estimate the 6DOF state between the drone and the ground LED targets. The smartphone would transmit the 6DOF state to the drone's control computer to execute the landing maneuver. Preliminary integration work and airworthiness assessments revealed that FIT's own hexacopter was not robust enough to perform the mission. A new quadcopter was procured and successfully integrated with the S8 smartphone. FIT fabricated blue LED targets, which faced upward on the laboratory floor. FIT constructed a mesh landing platform and placed it

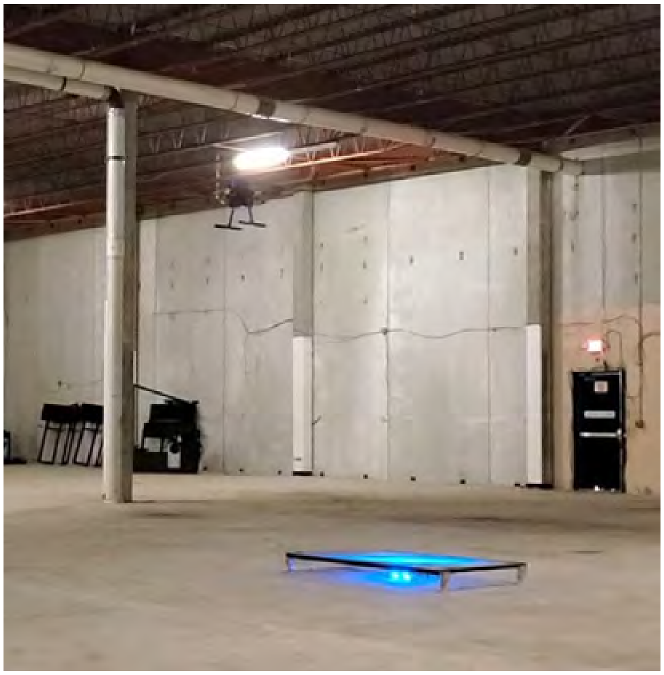


FIGURE 2. Indoor drone landing demonstration.

over the targets in such a manner that the S8's camera could see the targets and the mesh platform could support the drone's landing.

RESULTS/ACCOMPLISHMENTS

The SVGS software was successfully integrated with the hexacopter drone. LED targets were fabricated and placed beneath a mesh landing pad in FIT's laboratory. Hexacopter drone maneuvers were performed to enable an autonomous descent from approximately 1.5 m inside FIT's laboratory. From the 1.5-m altitude, autonomous descent and landing using SVGS was executed (see figure 2). In May 2021, successful landing was achieved on the mesh landing pad within ten cm of the LED targets. This demonstration proved the feasibility of using SVGS as a descent and landing sensor in autonomous operations.

PARTNERSHIPS

Dr. Hector Gutierrez at FIT has been a valuable partner in this work. FIT procured and assembled the quadcopter and performed integration with the smartphone version of SVGS. FIT manufactured the LED targets and conducted all the flight tests in their laboratory. FIT has been a dedicated partner in SVGS development since 2017 and will continue to partner with MSFC in pursuing SVGS implementation for descent and landing in both space and terrestrial applications.

SUMMARY

Evolved from the MSFC-developed Advanced Video Guidance Sensor (AVGS), demonstrated in space on the Orbital Express mission for spacecraft RPOD, SVGS was originally conceived to support small satellite RPOD. In response to the goals of the HLS program, SVGS is being repurposed for entry, descent, and landing (EDL). Exploiting the inexpensive and low-risk research platform that terrestrial drones provide, MSFC and FIT set out to prove the feasibility of using SVGS in an EDL application. Successful autonomous landings from a 1.5-m altitude were performed by a quadcopter drome carrying a smartphone running the SVGS software. By landing within 10 cm of the targets, the SVGS EDL architecture promises enormous potential for aiding precision landing to repeating landing sites on the Moon. Future work will aspire to work out the details of lunar landing scenarios from more realistic starting altitudes around 100 m.

PRINCIPAL INVESTIGATOR: John Rakoczy
PARTNER: Florida Institute of Technology
FUNDING ORGANIZATION: Cooperative Agreement Notice

Technology Area 11

SOFTWARE, MODELING, SIMULATION, INFORMATION TECHNOLOGY

BERT-E: Artificial Intelligence-Driven Language Model for Earth Science

OBJECTIVE: *To develop an Earth science-specific language model using the corpus of scientific literature.*

PROJECT GOAL/DESCRIPTION

Earth science research generates an ongoing stream of valuable data. A large amount of this data is structured (e.g., satellite observation measurements, airborne measurements, ground station measurements, etc.). Robust and well-tuned methodologies exist that shape these structured data streams into scientifically actionable resources. The other category of data generated by Earth science research is unstructured data. Some of the largest sources of this type of data are journal articles, conference papers, documentation, and reviews.

The Earth science domain is home to highly specialized mathematical models, science data, and scientific principles. Less appreciated is the fact that Earth science research depends upon language that is just as specialized. To solve today's problems, Earth science researchers need to find and bring together concepts frequently developed in isolation from each other. Language is an indispensable tool for finding those concepts. Whether in data keyword tags, contextual metadata, or journal articles, the ability to accurately apply descriptive words to research concepts and data and to quickly search for those words is essential to the advancement of Earth science.

APPROACH/INNOVATION

The current generalized language models are not as well suited for domain-specific tasks, such as those in Earth sciences, due to the fact that they haven't been exposed to a corpus pertaining to the domain and, therefore, lack meaningful connections between domain concepts. Fortunately, these transformer models adapt easily when trained with domain-specific corpus. They are great few-shot learners—meaning they can learn domain relations quickly from a handful of examples as opposed to hundreds—and they can self-adjust their internal representations rather than having to be trained from scratch.

Bidirectional Encoder Representations from Transformers (BERT) is one such general purpose language model, which makes use of transformers to understand the context of a given text with respect to what is to the left and right of it in a

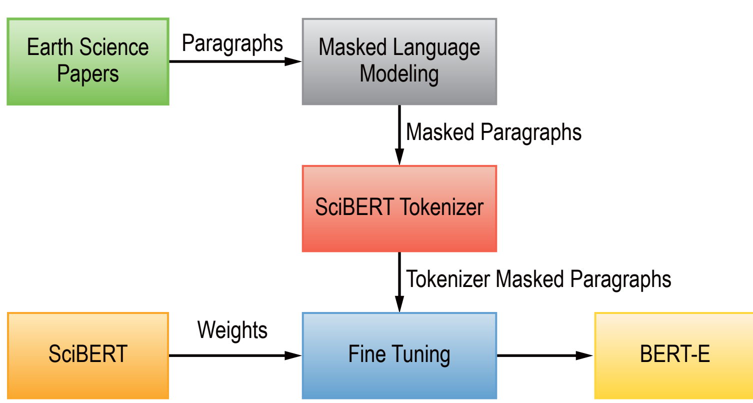


FIGURE 1. Architecture for BERT-E.

sentence. The Interagency Implementation and Advanced Concepts Team's (IMPACT) machine learning team has fine-tuned a BERT model pre-trained on science articles (SciBERT) with an additional layer to create a transformer-based, domain-specific language model for Earth science called Bidirectional Encoder Representations from Transformers – Earth Science (BERT-E).

RESULTS/ACCOMPLISHMENTS

BERT-E can be used for a myriad of downstream tasks such as question answering, recognizing named entities (e.g., United States or NASA), and next sentence prediction (which seeks to understand dependencies across sentences). One such task is the automated generation of metadata keywords that accurately describe Earth science datasets. NASA's Global Change Master Directory (GCMD) contains a hierarchy of keywords that form a controlled Earth science vocabulary set. The more accurately the keywords describe the datasets that they tag, the more search tools can provide consistent and precise results. IMPACT has used BERT-E to develop the GCMD Keyword Recommender, also called GKR, that provides data curators with suggested GCMD keywords using predictions based on existing descriptions of datasets.

SUMMARY

General language models are trained on large and varied natural language text over the internet. BERT-E extends these models into the Earth science space through fine tuning using over 270,000 Earth science articles with a total of almost 6 million paragraphs. BERT-E is especially effective because it understands the context of a word using the neighboring words and the domain knowledge learned during the pre-training phase. As a result, the pre-trained BERT-E model can be fine tuned with just one additional output layer to create state-of-the-art models for a wide range of tasks, such as question answering and language inference. This means substantial task-specific modifications are not necessary.

PRINCIPAL INVESTIGATOR: Rahul Ramachandran

PARTNER: University of Alabama in Huntsville

FUNDING ORGANIZATION: Science Mission Directorate

Earthdata Publication Tool

OBJECTIVE: *To develop a cloud-native Earthdata Pub (EDPub) tool to support NASA's Earth science data publication process.*

PROJECT GOAL/DESCRIPTION

NASA's Earth science Distributed Active Archive Centers (DAACs) face the challenge of dealing with an increasingly diverse number of publishable data products from various data producers. Data producers, on the other hand, experience difficulties when interacting with DAACs to deliver and publish their datasets. The Earthdata Publication Tool (EDPub) is an enterprise-level tool that provides a front-end interface with common terminology for data producers. From the DAAC data management perspective, EDPub is designed to streamline internal processes by allowing DAACs to create and manage customized publication workflows and to develop and integrate their own modules, such as preferred metadata editors. From the data producer perspective, EDPub provides a common interface for requesting acces to datasets at a DAAC or DAACs, providing data product information, uploading sample files, communicating with DAAC staff to verify metadata, and monitoring the status of requests in the EDPub dashboard. EDPub tracks the publication process from multiple user perspectives and reduces publishing time.

APPROACH/INNOVATION

EDPub consists of three front-end applications—Forms, Dashboard, and Overview—connected by an application programming interface (API). The API includes a notification handler, metrics handler, workflow action handler, and database. EDPub differs from other data publication tools in that it allows users

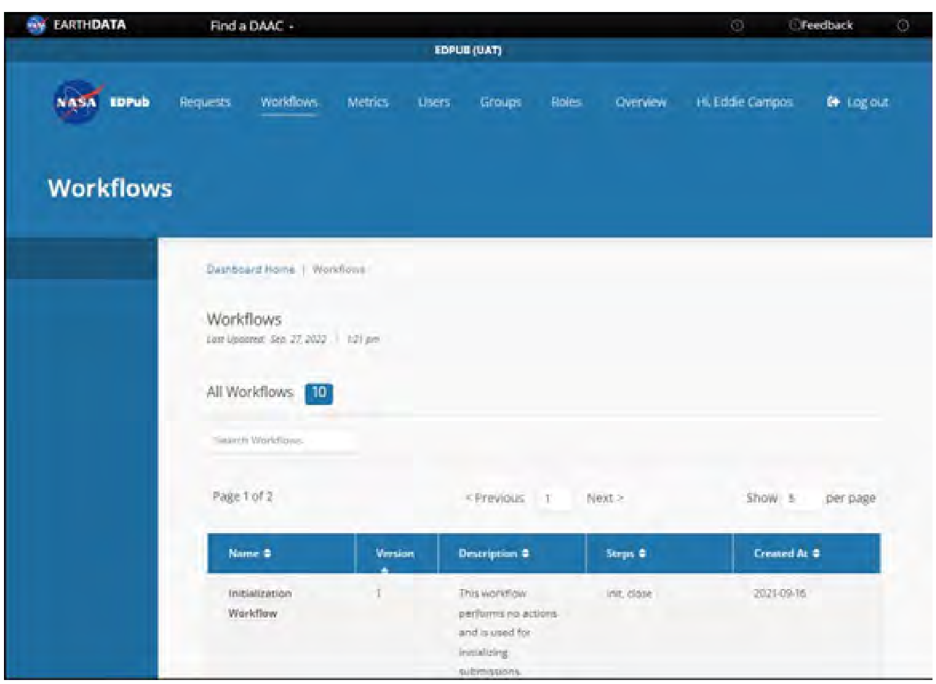


FIGURE 1. Earthdata Publication Tool Interface.

freedom to choose a metadata editor. This feature requires that EDPub integrates into existing metadata editors rather than implementing its own internal metadata editing and publication. This preserves existing metadata editing and publication tooling and shortens onboarding times, as DAACs have more freedom to use a familiar metadata editor. Next steps include integrating the metadata management tool developed by the Earth Science Data and Information System (ESDIS) project as another metadata editing and publication option for DAACs.

RESULTS/ACCOMPLISHMENTS

The minimum viable product (MVP) version of EDPub was released in early 2022, followed by a user interface/user experience (UI/UX) evaluation to guide further user-centered development and ensure alignment with other Earthdata enterprise tools. EDPub integration with mEditor, NASA Goddard Earth Sciences Data and Information Services Center's metadata editor, was completed as a module in EDPub (i.e., available to use in a DAAC data publication workflow). This integration allows responses from data producers in the EDPub forms to be mapped into common metadata for mEditor, which DAAC data management staff can then use as a plugin to edit metadata and submit to the Common Metadata Repository (CMR).

PARTNERSHIPS

EDPub is a cross-DAAC collaboration, with a project management and development team comprised of members of the Global Hydrometeorology Resource Center DAAC and the Oak Ridge National Laboratory DAAC, under the guidance of NASA ESDIS project technical leads. A multi-DAAC EDPub information team also serves in a content advisory role for the application's overview pages, dashboard, and forms. The EDPub development team collaborates with other DAAC and ESDIS software teams to build pluggable modules that will expand customization options for DAAC data publication workflows in EDPub.

SUMMARY

Earthdata Pub (EDPub), an enterprise-level cloud-native system, supports the DAAC data publication process in NASA's secure Earthdata Cloud by providing a primary point of interaction and common data publication experience for data producers and DAAC data management staff.

PRINCIPAL INVESTIGATOR: Manil Maskey

PARTNERS: University of Alabama in Huntsville; Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center; Global Hydrometeorology Resource Center (GHRC) Distributed Active Archive Center

FUNDING ORGANIZATION: Science Mission Directorate

The Management Office of the Satellite Needs Working Group

OBJECTIVE: *The Satellite Needs Working Group (SNWG) provides services that address Earth observing needs of federal agencies; the SNWG Management Office at NASA Marshall Space Flight Center supports all phases of the SNWG lifecycle.*

PROJECT GOAL/DESCRIPTION

The President's 2016 budget recognized NASA's responsibility for the space segment of all civilian and U.S. Government-owned Earth-observing satellites (excluding National Oceanic and Atmospheric Association (NOAA) weather satellites). It also acknowledged that federal agencies' growing needs for Earth observations should inform NASA's decisions about transitioning observation projects from experimental to sustained. The Satellite Needs Working Group (SNWG) was established as the first whole-government approach to assist NASA in making such decisions. SNWG efforts are based on a biennial survey of agency needs. Survey results inspire new services and solutions that leverage existing or upcoming missions. The SNWG Management Office is essential to the effort; responsibilities include survey formulation, assessment of surveyed needs, solution implementation management, and agency engagement and training.

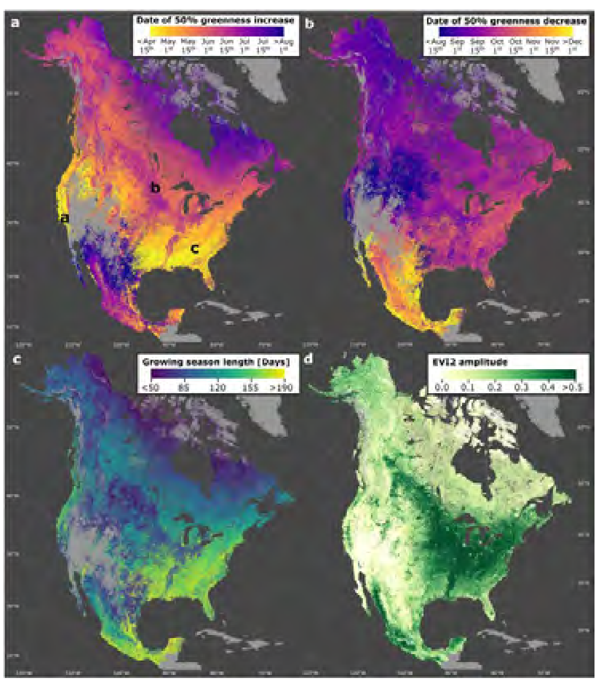


FIGURE 1. The HLS data product is a service from the 2016 SNWG cycle.[1]

APPROACH/INNOVATION

Several aspects of the SNWG effort make it innovative and unique: (1) The inter-agency and interdisciplinary approach that enables collaboration across a wide array of Earth sciences; (2) the stakeholder-driven agenda aimed to facilitate the day-to-day job of Federal agencies; and (3) the rapid response to surveyed needs by formulating and implementing solutions with clearly defined deliverables and dates. These characteristics distinguish SNWG from the annual Research Opportunities in Space and Earth Sciences (ROSES) research announcements by the NASA Science Mission Directorate. ROSES grants research funding to multiple types of organizations—domestic and foreign, government and private, for-profit, and not-for-profit—after a rigorous review process by the science community. The elements of the research programs supported by the Science Mission Directorate cover a wide range of basic and applied research in space and Earth sciences. Conversely, the SNWG is driven by stakeholder needs with an emphasis on the implementation of solutions and services and stakeholder engagement.

RESULTS/ACCOMPLISHMENTS

While solution implementation and survey assessment are currently underway for the 2020 and 2022 SNWG cycles, respectively, the 2016 and 2018 cycles generated several high-impact solutions. For example, the Observation Products for End-Users for Remote Sensing Analysis (OPERA) are deliverables in response to needs identified in the 2018 cycle: global product suites of (1) Surface Water Extent and (2) Surface Disturbance, and (3) a North America Displacement product suite. The latter is generated from complex radar data products that serve as a set of secondary deliverables: (4) a North America land coregistered single-look complex product, and (5) a global land-surface radiometric terrain-corrected product.

The global Surface Water Extent and Surface Disturbance suites are produced using Harmonized Landsat 8 and Sentinel-2 (HLS) data—a service from the 2016 SNWG cycle that combines data from the NASA/U.S. Geological Survey (USGS) Landsat 8 satellite with the Sentinel-2A and Sentinel-2B satellites of the European Space Agency. The Landsat satellite system has generated an invaluable data record of Earth with global and consistent acquisitions since 1982; while the more recent Sentinel-2 satellites have a higher spatial and temporal resolution. By harmonizing these data streams into a single product, an unpresented temporal resolution of two days is achieved. While initially created to address Federal needs identified in the 2016 cycle, the HLS data is used extensively by the research community; a search for HLS in Google Scholar returns over 4,000 hits.

Examples of other SNWG solutions include the Commercial Smallsat Data Acquisition Program (CSDA), which provides researchers and Federal agencies access to commercial land surface imagery acquired by NASA; the Catalog of Archived Suborbital Earth Science Investigations (CASEI), which facilitates quick access to detailed information about NASA's Earth science airborne and field investigations; and near real-time air quality products from the upcoming NASA Tropospheric Emissions: Monitoring Pollution (TEMPO) mission.

SUMMARY

The Satellite Needs Working Group (SNWG) addresses the Earth observing needs of U.S. Federal agencies by leveraging existing and upcoming satellite assets. The SNWG Management Office at NASA Marshall Space Flight Center formulates the biennial surveys, assesses agencies' needs, and manages solution implementation and stakeholder engagement.

Reference

1. Bolton, D. K.; Gray, J. M.; Melaas, E. K.; et al.: "Continental-scale land surface phenology from harmonized Landsat 8 and Sentinel-2 imagery," *Remote Sensing of Environment*, Vol. 240, p. 111685, April, 2020.

PRINCIPAL INVESTIGATOR: Pontus Olofsson

PARTNER: University of Alabama in Huntsville

FUNDING ORGANIZATION: Science Mission Directorate

Artificial Intelligence-Driven Reverse Image Search System for Earth Science

OBJECTIVE: *To use artificial intelligence to provide search capabilities across NASA's Earth science image archive.*

PROJECT GOAL/DESCRIPTION

Before embarking on a scientific study involving Earth science phenomena, scientists must collect numerous examples to build a dataset. Such effort can yield a valuable trove of data, but manually searching is cumbersome and laborious. Making large amounts of data more discoverable and usable for specific parameter extraction is a difficult problem to overcome. The Interagency Implementation and Advanced Concepts Team (IMPACT) developed a self-supervised, learning-based reverse image search system that allows users to provide a sample image as a query to retrieve similar images from the NASA Global Imagery Browse Services (GIBS) image archive.

APPROACH/INNOVATION

IMPACT partnered with the SpaceML initiative, an international artificial intelligence (AI) accelerator for citizen scientists, and a branch of Frontier Development Lab to develop the prototype model for reverse image search. The prototype model utilized the self-supervised learning-based approach, which generates vector information features called embeddings. Such an approach utilizes the concept that an image, and transformations of the same image, should have the same feature representation. Embeddings are created across the archive and stored as indices. When a query image is submitted, the system creates an embedding for that image and uses the nearest neighbor search algorithm to find the best matching images. The prototype model was scaled and entered into production by the Development Seed team.

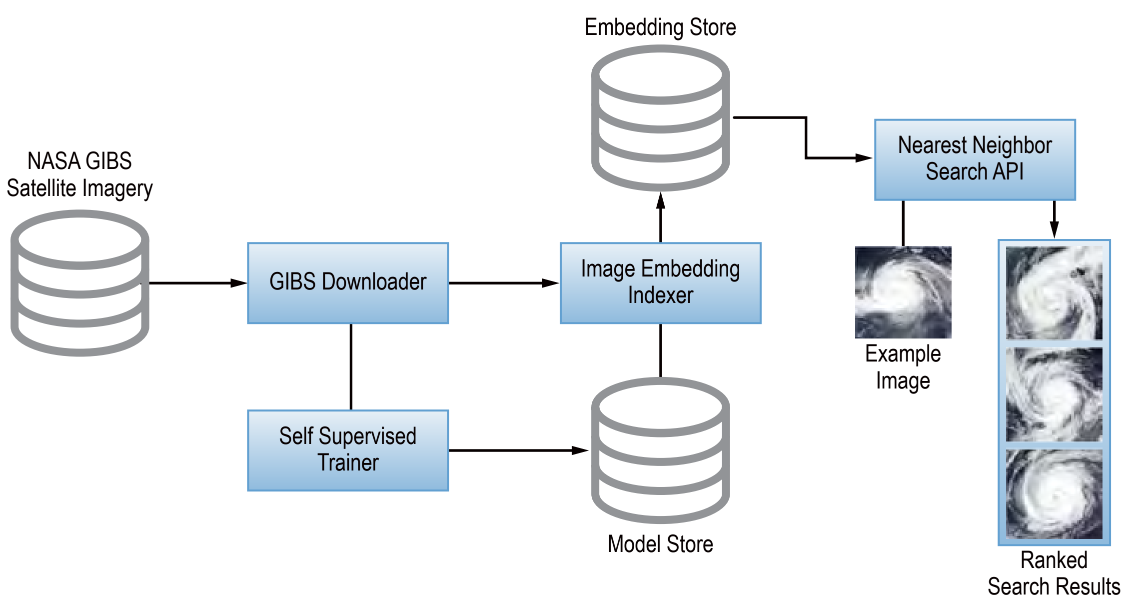


FIGURE 1. Overview of the self-supervised learning-based approach for the Earth science image archive.

RESULTS/ACCOMPLISHMENTS

This is the first project that provides reverse image query services for NASA Earth science. The results of this effort are an easy-to-use interface for data search at scale, a set of open-source tools that simplify using NASA's Earth science archive for machine learning, and cross-domain utilization of a similar approach for space observation data (fig. 2). Using the production interface, the team plans to solicit community feedback and continuously evolve the system.

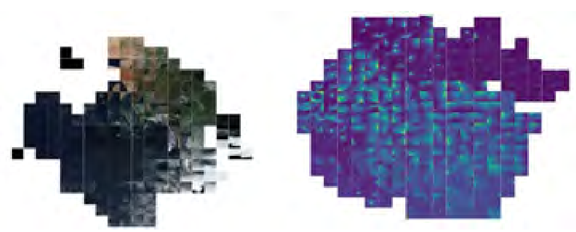


FIGURE 2. Leveraging self-supervised learning for multiple domains: (left) clustering of similar images in the Earth science image archive; and (right) clustering of images from Hubble telescope.

SUMMARY

The research team has created a reverse image search system for NASA Earth science. This system allows users to submit a query image and retrieve similar images from the archives, reducing the burden of downloading data from multiple archives and manually comparing images. The team envisions scientists using this system to identify use cases for event studies and to study those events over time.

PRINCIPAL INVESTIGATOR: Manil Maskey

PARTNERS: SpaceML; Frontier Development Lab; Development Seed; University of Alabama in Huntsville

FUNDING ORGANIZATION: Science Mission Directorate

Visualization, Exploration, and Data Analysis (VEDA)

OBJECTIVE: *To provide unified open-source science cyberinfrastructure for data processing, visualization, exploration, and geographic information system capabilities (re-)using the ecosystem of tools and services with NASA science data on the cloud.*

PROJECT GOAL/DESCRIPTION

NASA Earth science needs sustained support to advance interactive visualization, exploratory visual data analysis, geographic information systems, and data processing for analysis capabilities that are enabled through data migration to the cloud computing environment. To that end, the Visualization, Exploration, and Data Analysis (VEDA) project focuses on three main areas: visualization and interactive exploration (VizEx), data analysis and processing (DPP), and geographic information systems (GIS). VizEx provides data analysis on the browser and storytelling platform; and DPP establishes an interactive, collaborative platform and cloud-native environment for simulation modeling and data assimilation. The GIS component creates an enterprise-wide, cloud-native GIS service, consolidating many of the varied and disconnected delivery mechanisms now supporting the community.

APPROACH/INNOVATION

VEDA is being designed as a scalable, interactive system for science data, and it draws from an ecosystem of mostly existing services and analysis clients. The tools and services are modularized and interoperable so that any new data system's needs can be addressed by selecting a set of components from the ecosystem rather than from VEDA as a whole. Openness and reusability are pillars of VEDA's development, and predominantly community-backed software stacks are selected for implementation. VEDA is being built in the Amazon Web Services (AWS) cloud platform primarily because

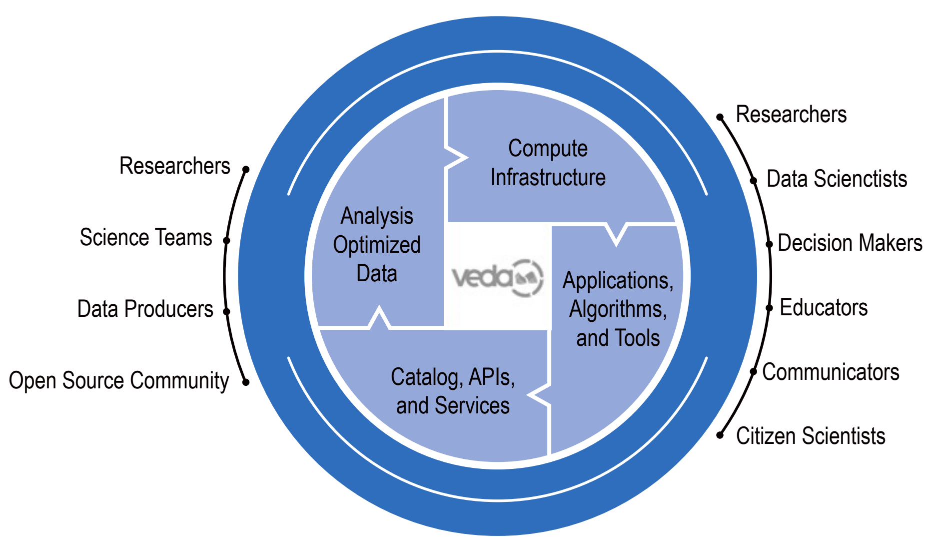


FIGURE 1. VEDA components and users.

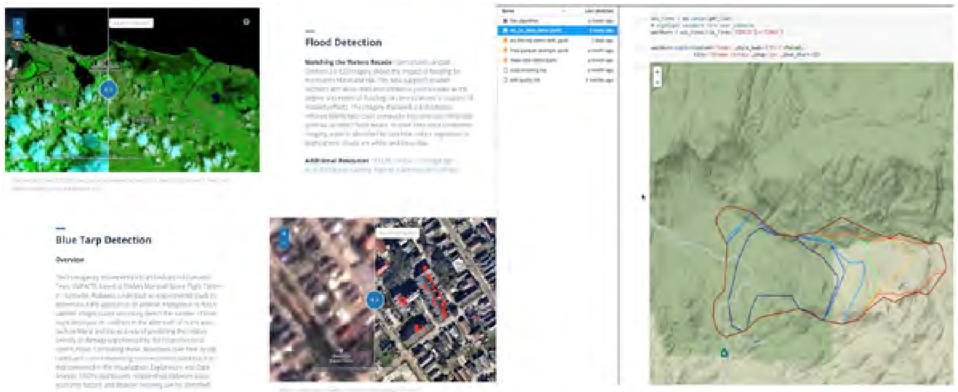


FIGURE 2. VEDA interfaces: (left) interactive stories and (right) analysis.

NASA archives its data in AWS. The DPP component of VEDA provides data-proximate computing to minimize data movement and reduce cost. The current components of VEDA implementation are all deployed in AWS and include (1) federated data stores; (2) data processing for extraction, transformation, and loading; (3) data services including application programming interfaces (APIs); and (4) visualization, exploration, and analysis clients.

RESULTS/ACCOMPLISHMENTS

VEDA has already established the following five results: (1) Data systems to transform and publish datasets for Earth Information System (EIS) thematic areas; (2) a cloud-based data processing platform; (3) an interactive dashboard to publish data-driven stories about findings; (4) a dataset catalog; and (5) a standards-based API of external applications to access data and information.

SUMMARY

VEDA establishes a novel approach to organizing, processing, and featuring NASA Earth science data sets on the cloud by providing a suite of exploratory tools. Designed as an ecosystem of services and analysis clients that are modular and interoperable, VEDA addresses several priorities of the agency including the Earth Information System (EIS) and the international dashboard on environmental change. Initially, the EIS will be VEDA's primary focus.

PRINCIPAL INVESTIGATOR: Manil Maskey

PARTNERS: Development Seed; University of Alabama in Huntsville

FUNDING ORGANIZATION: Science Mission Directorate

FOR MORE INFORMATION: https://www.earthdata.nasa.gov/dashboard/

Machine Learning for Agriculture Crop Damage Identification and Assessment from Intense Thunderstorms

OBJECTIVE: *To develop machine learning models for automated identification of severe weather damage to agricultural crops using NASA land surface remote sensing imagery.*

PROJECT GOAL/DESCRIPTION

Each year during the prime warm growing season, intense and severe thunderstorms bring damaging winds and large hail to agricultural crops across the Great Plains and Midwest. On occasion, these storms produce large swaths of damage that can measure hundreds of kilometers long and tens of kilometers wide, which are visible from satellite imagery. These swaths are frequently identified on a case-by-case basis through satellite remote sensing imagery and manual analysis. Two members of this project team have experience in developing techniques for analysis and extraction of these damage swaths through quantitative analysis of vegetation indices from optical remote sensors, radar remote sensors, and thermal remote sensing instruments. This project focused on improving capabilities for detecting these damage swaths through the use of machine learning (ML)-based approaches as the amount of remote sensing data to analyze continues to grow at an exponential pace. This fiscal year (FY) 2022 Center Innovation Fund (CIF) project sought to develop a new technology through innovative applications of modern ML approaches that utilize daily, globally available satellite imagery from NASA Moderate Resolution Imaging Spectroradiometer (MODIS) to develop severe storm damage swaths and provide an initial first estimate of the damaged areas. The project focused on the linear characteristics of the reduced vegetation surrounded by healthy vegetation for the ML extractions.

APPROACH/INNOVATION

The project utilized a 21-year hail damage swath database that was developed at NASA Marshall Space Flight Center (MSFC) to serve as the training and validation datasets. This 21-year hail damage swath database was finalized during the project by Bell and Molthan. The database included relevant metadata to the damage swaths and provided geospatial outlines of confirmed damaged areas to be matched with MODIS True Color imagery that was accessed via NASA Global Imagery Browse Services (GIBS). This project adopted previous ML approaches that team members were familiar with and that had proven successful with other atmospheric phenomena (i.e., smoke detection and high-latitude dust detection).

The project leverages U-Net, a neural network-based segmentation model for crop damage identification. This network consists of a contracting path and an expansive path. The contracting path resembles a typical convolutional neural network, where the input is downsampled consecutively by use of convolutions to obtain features of the image. The expansive path then gradually upsamples the features to obtain a mask of the class targets, where the pixel intensity represents the hail damage. The model is trained using a customized version of Tversky loss function due to high data imbalance observed in the dataset (the number of pixels labeled as *"hail damage"* < number of pixels labeled as *"no damage"*). A diagram of the ML workflow is given in figure 1.

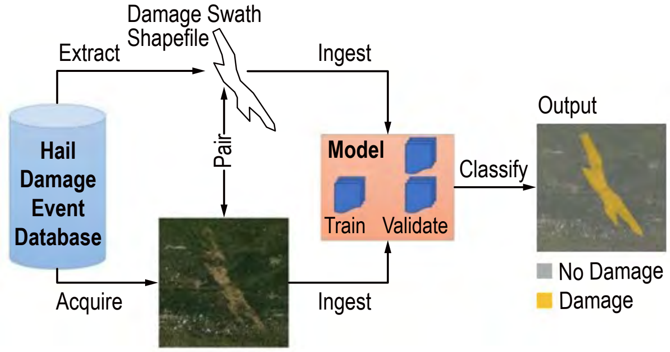


FIGURE 1. Workflow of ML approach to identify hail damage swaths.

As a first step, the investigative team processed the MODIS True Color imagery and damage outlines into an ML-compatible format. Then, the U-Net model was trained to identify pixels subject to damage in the imagery and tested for accuracy using a held-out test set. The model was further tweaked for performance by iteratively optimizing the neural network parameters.

RESULTS/ACCOMPLISHMENTS

The final results after tuning show capability in identification of damaged areas (fig. 2a) in the imagery, but false positives remain a problem to tackle (fig. 2b). On testing the model with a held-out test set, the model shows good overall accuracy (97.5%) but needs improvement in eliminating false positives as indicated by the precision of the predictions, which currently is at 23.1%.

Some areas of improvement have been identified to reduce false positives and are being considered for future work. This includes incorporating baseline imagery to compare to each MODIS True Color scene. This would allow for the identification of permanent land features that are contributing to the high false positive rate. Another consideration is utilizing additional NASA satellite datasets that are available via NASA GIBS, such as land surface temperature (LST). Previous work by Bell and Molthan has shown that these damaged areas can have a higher LST than the LST of nondamaged surrounding areas.

PARTNERSHIPS

NASA Interagency Implementation and Advanced Concepts Team (IMPACT) and The University of Alabama in Huntsville utilized their machine learning expertise to help develop a machine learning approach to try to identify severe weather damage to agricultural areas. There are plans to continue working on this problem.

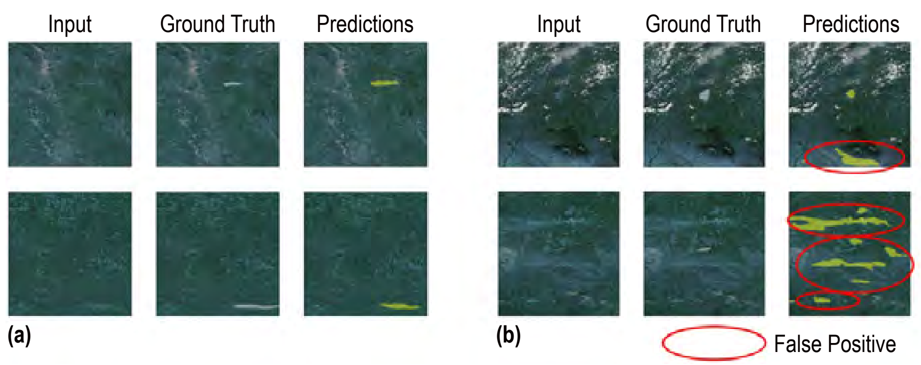


FIGURE 2. (a) Example of ML model accurately identifying the hail damage swath in two separate events; (b) Example of ML model output with a large number of false positives.

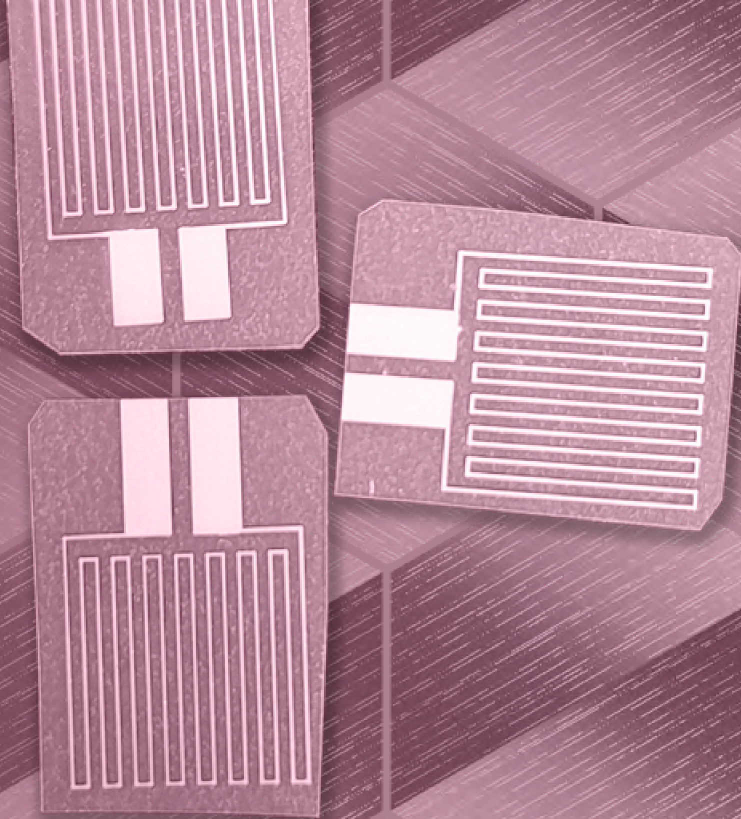
SUMMARY

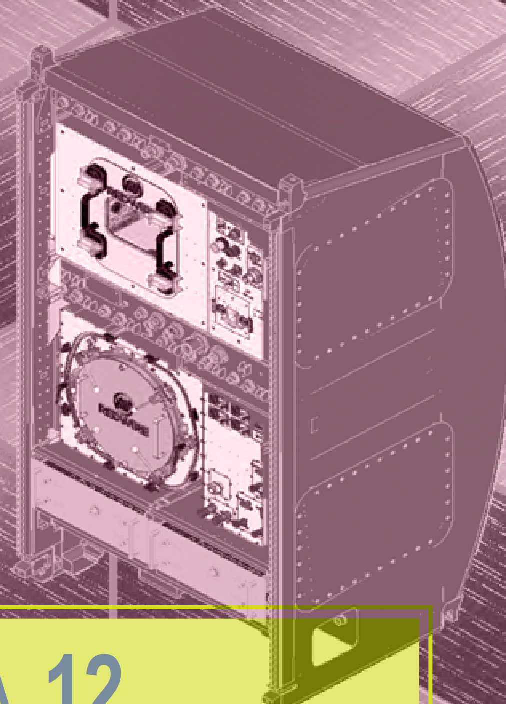
Intense and severe thunderstorms impact agricultural areas during the prime warm growing season. In certain instances, swaths of damage left behind from these thunderstorms can be visible to satellite remote sensing instruments. A 21-year database of the hail damage swaths was constructed at MSFC. This database was used to train and validate machine learning approach to identify these damage swaths. This projected used a neural network segmentation model in an attempt to identify these damage swaths. The initial run of the machine learning model yielded an accuracy of 97.5%, but the precision of the model was significantly lower at 23.1%. This was due to permanent land surface features and other phenomena generating too many false positives.

PRINCIPAL INVESTIGATOR: Jordan Bell

PARTNERS: Dr. Andrew Molthan (ST11); Dr. Brian Freitag (ST11); Muthukumaran Ramasubramanian (UAH); Iksha Gurung (UAH)

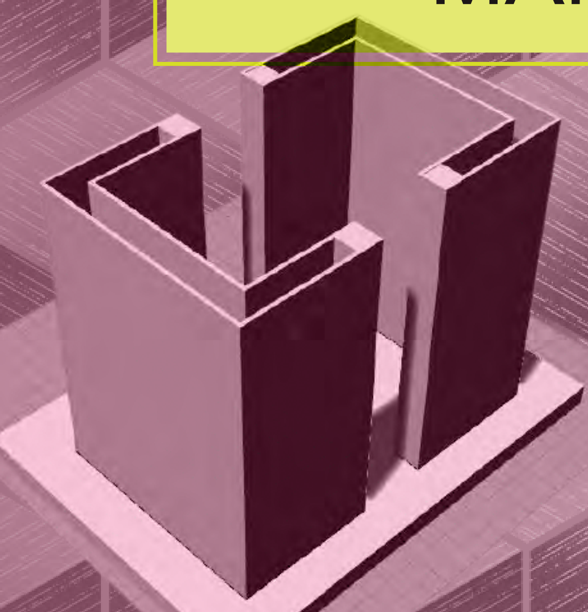
FUNDING ORGANIZATION: Center Innovation Fund





Technology Area 12

MATERIALS, STRUCTURES, MECHANICAL SYSTEMS, AND MANUFACTURING



Metallic Environmentally Resistant Coatings Rapid Innovation Initiative (MERCRII)

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

PROJECT GOAL/DESCRIPTION

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

APPROACH/INNOVATION

Two coatings will be developed for the ubiquitous core spacecraft materials: BN-based coatings and NiTi-based coatings. Both coatings exhibit high wear resistance, and the BN-based coatings are expected to provide additional radiation shielding improvement. BN-nanomaterials are well known for their excellent mechanical and thermal properties, high impact resistance, low friction coefficient, chemical inertness, corrosion resistance, and good interfacial adhesion with Al and Ti metals. It has been observed that coatings that perform best in sliding are not always the hardest, but rather those with a high hardness/elastic modulus (H/E) ratios NiTi-based materials offer a unique combination of high hardness, low modulus, and extensive elastic deformation range resulting in superior static indentation load capability.

Based upon laboratory static load tests performed at NASA Glenn Research Center (GRC), bearings made with NiTi alloys provide up to ten times higher tolerance to denting damage compared to conventional steel bearings. This novel bearing material has the potential to be highly resistant to damage caused by lunar and martian dust. The coatings will be applied through two process technologies: atmospheric plasma spray (APS) and vacuum plasma spray (VPS). The coatings will be exposed to thermal cycle and radiation environments and subjected to tribological tests in the presence of lunar dust after exposure, to guarantee the survival of the coatings to the extreme space environment. The coating technology will be demonstrated to enable the use of both conventionally manufactured (CM) as well as additively manufactured (AM) mechanisms. The coatings will be applied to three mechanisms of action (joint, torsional, and sliding), which will be fabricated from Al and Ti, both CM and AM. These mechanisms of action encompass commonly utilized mechanisms and will enable this technology development effort to create optimized advanced wear coating options that will protect an array of future mechanisms for the Moon, Mars, and beyond.

RESULTS/ACCOMPLISHMENTS

Wear Testing:

The first downselection eliminated several coatings as candidates.
All remaining coatings are BN-based Ti64 metal matrix composites. All of these will be wear tested again, this time at vacuum, during the next downselection (Phase 2).

The BN-based Al coatings were eliminated in an early stage of the project because high wear was observed during testing with no regolith simulant present. For tests with regolith simulant, the wear was reduced but the regolith particles were embedded in the soft coating, creating a very abrasive surface that caused severe wear of the stainless steel balls that were in sliding contact with it. The NiTi coating was eliminated, because it showed the lowest wear resistance among the coatings that were tested.

All wear tests for the first downselection (Phase 1) were completed. Wear rate comparisons for the various BN-based coatings with no environmental exposures (Virgin) and with exposures to particle radiation (Radiation), to thermal extremes (Thermal), and to both particle radiation and thermal extremes (Combined) were completed. All BN-based coatings deposited on Al6061 substrates show wear rate improvements of more (and in most cases much more) than 100% compared to uncoated Al6061 substrates. A comparison of BN-based coating wear rates to the minimum key performance parameter (KPP) level ($3.12E^{-6}$ mm^3/Nmm for Al6061) for the project shows a similar result — the wear resistances for the coatings are generally much greater than the minimum KPP level for Al6061. A comparison of BN-based coating wear rates to the desired KPP level shows that the Ti–10 vol.% hexagonal boron nitride (hBN) APS wear performance is worse than the desired KPP ($5.19E^{-7}$ mm^3/Nmm) for several of the comparisons. Given this result, this coating was eliminated from further consideration to Phase 2. The Ti–2 vol.% hBN APS, Ti–2 vol.% hBN VPS, and Ti–10 vol% hBN VPS coatings showed good to very good performance in all comparisons.

Radiation Shielding Testing:

The neutron radiation shielding testing was conducted at NASA Langley Research Center (LaRC) for various plasma spray coated samples for the Early Career Initiative (ECI) project. Two sample sets were studied for neutron shielding effectiveness: virgin samples and combined exposure samples.

Some desirable trends were observed with the presence of hBN with both Al and Ti substrates. Increasing hBN content from 2% to 10% improved the shielding effectiveness for most cases. The improvement was more prominent for the Ti substrate cases. The APS coatings generally exhibited better shielding effectiveness than VPS coatings for both Al and Ti substrates. It is concluded that the presence of hBN in the wear resistant coating tends to improve shielding effectiveness for both Al and Ti substrates despite its miniscule quantity.

The combined Al and Ti samples without coating showed lower shielding effectiveness than the virgin samples, by 21% and 10% respectively. This indicates that combined space environment (radiation and thermal) exposure might degrade the samples and lower the shielding effectiveness. More structural, morphological, and chemical analyses are needed to understand the relevance. On the other hand, all Ti–hBN coated samples showed improved shielding effectiveness for both Al6061 and Ti64 substrates. The shielding effectiveness of the combined exposure samples is even greater than that of the virgin samples for all cases. This indicates that the thin Ti–hBN coating provided not only neutron shielding effectiveness, but also greater sustainability under extreme space environments (radiation and thermal cycles).

PARTNERSHIPS

Dr. Park and Dr. Chu serve in this ECI as the LaRC team leads to develop optimized BN-based metal matrix composites and radiation studies both experimentally (i.e., neutron) and computationally (i.e., galactic cosmic ray (GCR) and solar particle event (SPE)). They will provide mentorship to LaRC's early career and will serve as technical mentors for the project.

Dr. Howard, Dr. Jimenez, and Dr. Dellacorte from GRC will provide technical mentorship and input for space mechanisms, serve as mentors for the development of new tribological materials and solutions for aerospace mechanisms (testing design, forensic engineering).

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

Plasma Processes, LLC will provide NiTi intermetallic coatings and BN-based coatings on AM and CM Al and Ti alloy test panels as fabricated by NASA Marshall Space Fligt Cemter (MSFC). Coatings will be applied using existing cold spray and plasma spray equipment at Plasma Processes.

Plasma Processes is in charge of providing a vacuum chamber for simulated space environment to test the mechanisms in the presence of lunar dust. Plasma Processes brings 27 years of aerospace coating production experience to the team. Additionally, Mr. Tim McKechnie and Mr. Michael Renfro are key technical personnel available to support this work. Upon technology maturation, Plasma Processes is interested in working to license the technology for commercial use.

SUMMARY

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

PRINCIPAL INVESTIGATOR: Sara Rengifo

PARTNERS: Plasma Processes, LLC; Florida International University; NASA Langley Research Center; NASA Glenn Research Center

FUNDING ORGANIZATION: Early Career Initiative

FOR MORE INFORMATION: https://nasa.sharepoint.com/sites/STO_jamboree/SitePages/Development-of-Coated-Additively.aspx

Rapid Process Development of Aerospace Alloys Using Small Punch Test

OBJECTIVE: *To design and fabricate a high-throughput small punch test capability and test a variety of additively manufactured metal samples for direct comparison with tensile stress-strain data.*

PROJECT GOAL/DESCRIPTION

For this project, a high-throughput small punch test (SPT) system was designed to rapidly assess bulk material mechanical property data at a low cost. The combination of a small sample size, direct sample preparation, and rapid testing allowed for accelerated mechanical testing of metallic materials produced by advanced processes. Existing state-of-the-art (SOA) prototypes for SPT both at Georgia Institute of Technology (Georgia Tech) and NASA Marshall Space Flight Center (MSFC) allow for a single SPT to be performed at a time, and initial test results from these prototypes have exhibited excellent accuracy. This work resulted in a prototype multisample testing apparatus used to gather stress-strain predictions, positioning MSFC a step closer to developing a high-throughput, automated SPT system. The primary need that is addressed by high-throughput SPT is rapid materials development with material or process classes that incur great expense to obtain test data.

APPROACH/INNOVATION

The work performed under this Center Innovation Fund (CIF) project improved upon the SOA of small-scale mechanical testing by designing and fabricating a high-throughput fixture prototype so SPT samples could be tested more rapidly than the prior SOA. The alignment of the fixture with the punch posed the greatest technical challenge to the project because alignment relied on precision machining. This risk was mitigated by imprinting a rubber mold with the punch to quantify the centering of the punch with respect to the fixture. This imprinted mold was then optically inspected and SPT simulations were performed to assess the effects of the punch being off-center. The work performed under this CIF is complementary to work performed at a variety of national labs and universities, such as the National Institute of Standards Technology (NIST) and Georgia Tech. The work performed under this CIF built upon assertions of prior researchers that SPT is highly conducive to high throughput and tested out advanced analysis protocols currently being developed by Georgia Tech.

The primary objectives of the research performed under this CIF were to design and fabricate a high-throughput SPT setup, and to test and analyze a variety of metal samples produced via advanced manufacturing processes. The project started by completing a design review and machining the fixture prototype. This prototype was used to test more than 150 SPT samples. The majority of the samples had known strength values and were used to build a compliance correction function, while approximately 70 of the tested samples had unknown mechanical properties. The primary deliverables for this project were the new high-throughput SPT prototype owned by the MSFC Processes and Manufacturing Branch (EM32) and the analyzed test data for the samples with unknown mechanical properties. The next step for this research is to test more refractory alloys in support of the Refractory Alloy Additive Manufacturing Build Optimization (RAAMBO) project. Additionally, an effort to build an advanced machine prototype, informed by lessons learned from this CIF, would be a great next step to improve the rate and fidelity of new SPTs.

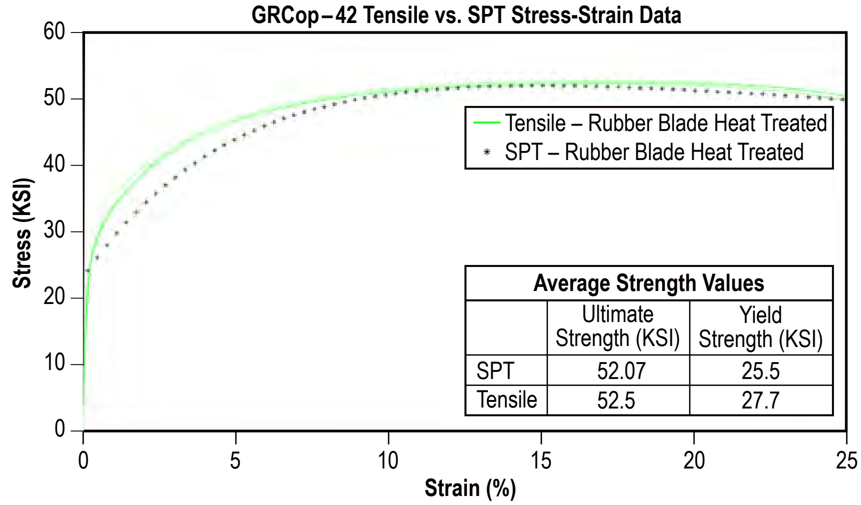


FIGURE 1. GRCop–42 small punch test stress-strain predictions vs corresponding tensile stress-strain.

RESULTS/ACCOMPLISHMENTS

The work performed under this CIF resulted in a new semiautomatic SPT capability for EM32 and the MSFC Materials & Processes (M&P) lab. This SPT prototype was created by retrofitting an existing EM32 load frame, and tests performed on the load frame were carried out by MSFC Materials, Testing, Chemical Containment Control Branch (EM22) personnel. In parallel with testing, metallographic examination was performed on remnant material from which SPT specimens were extracted. Between the microscopy performed by the MSFC Materials Science and Metallurgy Branch (EM31), the testing performed by EM22, and the project management performed by EM32, this project helped to strengthen working relationships in the M&P lab. With the new SPT capability, samples of several metal alloys (e.g., copper alloy GRCop–42, nickel-based alloys, and a tungsten-molybdenum alloy) were tested. The SPT stress-strain results from each material have been compiled, and in cases where corresponding tensile data exists, it was compared for accuracy. Microscopy data was also compiled with the SPT data, but the limited number of sample conditions for a given material class prevented the formation of a structure-property linkage model (this will be pursued further in follow-on studies).

Multiple lessons learned were gathered from this CIF study. First, initial studies indicate that SPT sample preparation requires the removal of the electrical discharge machining (EDM) recast layer to properly expose the specimen for testing. Removal via conventional polishing methods can be time consuming, and

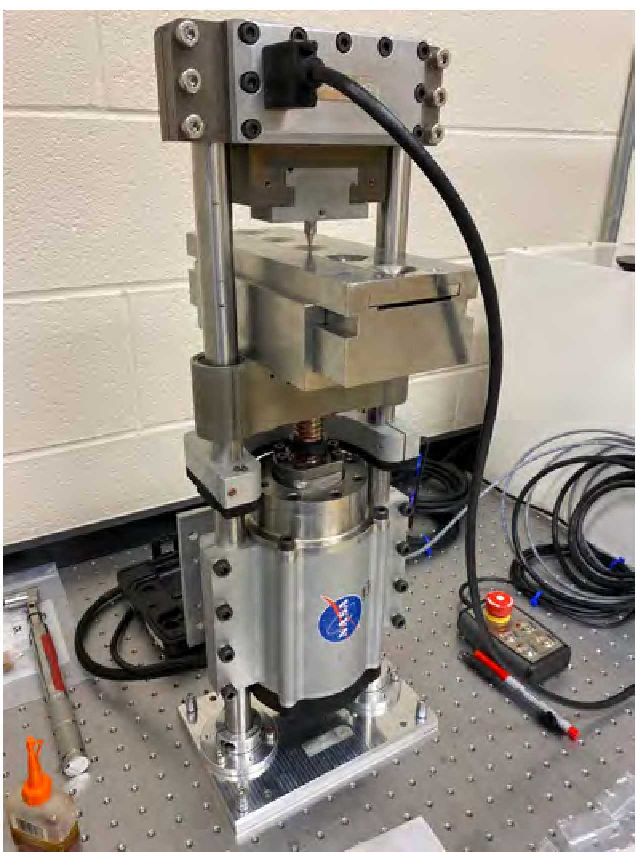


FIGURE 2. Retrofitted Psylotech µTS load frame for high-throughput small punch test.

future studies should focus on testing in the unpolished condition or automating the removal process. Another lesson learned is that mechanical alignment of the fixture and punch is not an ideal practice. A slight misalignment due to manual fixture positioning was observed during testing. To better understand the effects of misalignment, the displacement between the punch and fixture was measured. Numerical simulations were run to better understand the effects of misalignment, and ultimately, the alignment was found to be sufficient to extract test results. Follow-on prototypes should utilize a more accurate alignment method (e.g., optical alignment or calibrated machine alignment).

PARTNERSHIPS

Georgia Tech provided data analysis support for this CIF. Their expertise was valuable for the interpretation of SPT results and with establishing a protocol to compare microstructure characteristics to SPT results. Continued collaboration with Georgia Tech will greatly benefit future efforts to automate SPT and define protocols to utilize SPT results to inform the design of parts built with advanced manufacturing processes. The principal investigator plans to continue periodic communication with Georgia Tech and will consider a follow-on CIF or a Technology Investment Program (TIP) grant to continue the research established by this CIF.

SUMMARY

This CIF study has been met with challenges, but ultimately delivers on the proposed product. It has resulted in the fabrication of a new capability for the M&P lab and opened the doorway to rapid low-cost mechanical testing. Building the prototype has given early career MSFC personnel the chance to build cross-organization relationships and learn how to collaborate outside of MSFC. The insights gained from this project have the potential to mature into new automated mechanical testing capabilities. The next steps to advance towards automated SPT include the submission of a New Technology Report (NTR), proposing for Technical Excellence, and potentially proposing for a TIP. Future work using small-scale mechanical testing will also support the RAAMBO project through the development of C103 Laser-Powder Bed Fusion (L-PBF) build parameters and heat treatment schedules.

PRINCIPAL INVESTIGATOR: Zachary Stephen Courtright

PARTNER: Georgia Institute of Technology

FUNDING ORGANIZATION: Center Innovation Fund

Additively Manufactured Passive Wireless Sensors with Printed Electronics

OBJECTIVE: *To develop and evaluate additively manufactured passive wireless sensors for remote sensing applications to structural health monitoring. Additive manufacturing is being demonstrated as a possible replacement for printed circuit boards and even for impedance sensors such as capacitive interdigitated electrode sensors.*

PROJECT GOAL/DESCRIPTION

The ability to manufacture replacement or new sensors and electronics is critical for future manned lunar and deep space missions. Without this capability, even what would be simple repairs on Earth may be impossible on these missions and would likely result in mission failure and potential health risks to astronauts. Traditional fabrication techniques for electronic devices and assemblies are impractical, if not impossible, for these missions. Additive manufacturing (AM) has been demonstrated as a suitable replacement for many types of traditional machining. With the development of new conductive and nonconductive inks, AM is being demonstrated as a possible replacement for printed circuit boards (PCBs) and even for impedance sensors such as capacitive interdigitated electrode (IDE) sensors.

Recently, semiconductor inks have become commercially available, allowing the realization of simple electronic components such as diodes and transistors. Auburn University has expertise in developing low cost sensors based on PCB technology that can be produced with AM techniques. A small business partner, EngeniusMicro, LLC has expertise at integrating these sensors into passive wireless tags for remote sensing; and NASA Marshall Space Flight Center (MSFC) On-Demand Manufacturing of Electronics (ODME) engineers have expertise at AM printing of electronic assemblies. This effort seeks to merge these activities to develop and evaluate AM-produced passive wireless sensors for remote sensing applications to structural health monitoring. Auburn and EngeniusMicro designed the sensor tags and MSFC OMDE manufactured the tags. The tags will be evaluated at Auburn University against similar passive wireless sensor tags manufactured with traditional fabrication techniques.

FIGURE 1. Printed passive wireless sensors for remote sensing applications.

The project's goals are as follows:

- Auburn designed the printed Schottky diode and the passive wireless sensor tag for capacitive structural health monitoring applications, with input from EngeniusMicro.
- MSFC will fabricate the Schottky diode and the passive wireless sensor tags.
- After fabrication, the Schottky diodes and the complete sensor tags will initially be evaluated by Auburn University. Additional sensor testing regarding structural health monitoring will be performed at MSFC.
- At the conclusion of this project, a useful AM-printed Schottky diode will not only be realized as a discrete device, but it will be successfully integrated into a functioning passive wireless sensor system for structural health monitoring.

APPROACH/INNOVATION

Traditional fabrication techniques for electronic devices and assemblies are impractical—if not impossible—for International Space Station (ISS), lunar, and future long-range missions. Additive manufacturing has been demonstrated as a suitable replacement for many types of traditional machining. With the development of new conductive and nonconductive inks, AM is being demonstrated as a possible replacement for PCBs and even for impedance sensors such as capacitive IDE sensors.

The project also seeks to develop printed Schottky diodes, semiconducting devices, with additive manufacturing fabrication techniques. This effort, integrated with the development of sensing tags, is very innovative, and is a first effort at MSFC for printing semiconductor electronics.

RESULTS/ACCOMPLISHMENTS

During this year, Auburn University, EngeniusMicro, and NASA MSFC have collaborated to develop designs and fabricated prototype devices for passively sensing a range of different applications.

So far, the project has achieved the following benchmarks:

- A wireless communications base station PCB was designed and fabricated.
- The new base station board was also evaluated using passive diode tags and is operating correctly.
- An additional partner, Appalachian State University, was added during the year to do work on function testing and additional materials characterization.

Additional tasks still in progress for this year include:

- Continue to evaluate the harmonic detection tag/base station configuration.
- Design wireless tags with larger IDE sense capacitors to mitigate the diode capacitance issue.
- Design and order new sensor tags and a base station using the spiral planar inductors.

PARTNERSHIPS

Partners with MSFC for this project include Auburn University, EngeniusMicro, and Appalachian State University.

SUMMARY

The development of novel additive manufacturing processes and materials for the in-space fabrication of passive wireless sensors is a technology with many potential NASA and commercial applications in the coming years. Not only would these sensors be much smaller and lighter, but they can be produced as needed for crew health monitoring, environmental monitoring, and structural health monitoring applications.

PRINCIPAL INVESTIGATOR: Curtis Hill

PARTNERS: Auburn University; Appalachian State University; EngeniusMicro

FUNDING ORGANIZATION: Cooperative Agreement Notice

On-Demand Structural Health Monitoring Sensor Manufacturing for NASA Applications

OBJECTIVE: *To explore technology to provide on-demand and affordable structural health monitoring (SHM) solutions through additive manufacturing approaches. SHM sensors are needed by NASA for a wide range of structural integrity monitoring, and additive manufacturing of these sensors would allow their fabrication on demand in the environment in which they are needed.*

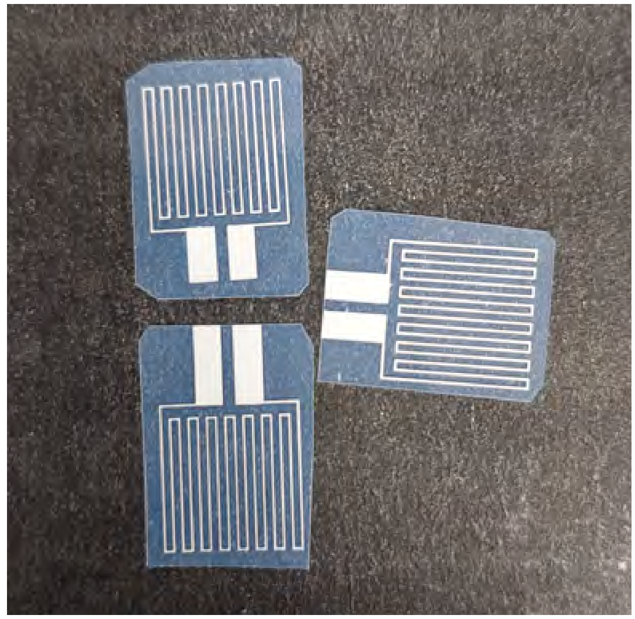


FIGURE 1. Printed strain sensor for monitoring of vehicle Structural Health.

PROJECT GOAL/DESCRIPTION

Structural health monitoring (SHM) is critically important for safety and liability of space exploration. In the past, various sensor techniques including fiber Bragg grating (FBG) sensor, ultrasonic transducer, pressure transducer, thermometry, and direct current analysis were used for SHM applications in metal and composites structures; but each of them had limitations. For instance, one of the most important barriers in using these sensors is their invasiveness to the composite structure. This incompatibility can create a weak link, delamination, or partial or complete part failure. Furthermore, limited choices of sensor types and sizes and complexity of preparing sensor networks to cover large areas, are also among the major challenging issues for aerospace industries to widely adopt SHM for real-world engineering applications. This research is exploring technology potentially to provide on-demand and affordable SHM solutions through additive manufacturing (AM) approaches. Building upon high sensitivity and low profile networks of carbon nanoparticles, including carbon nanotubes (CNTs) and graphene, researchers from Florida A&M University-Florida State University (FAMU-FSU) College of Engineering have demonstrated high performance strain sensing due to piezoelectrical and capacitive mechanisms of the networks and achieved a large range of gauge factors varying from tens to hundreds for SHM applications. This research is focused on the study and transfer of promising initial studies into AM technologies to realize on-demand structural health monitoring sensor manufacturing.

The objective of the project is to study and develop on-demand manufacturing technology of strain sensors by optimizing ink materials, the additive manufacturing printing process and post processing strategies. This includes optimizing ink formulations, sensor geometry design and printing parameters for on-demand manufacturing of high performance (20 – 50-gauge factor), low profile, and compatible single-strain sensors or sensor arrays. These materials can potentially be used for both surface and embedded SHM applications in materials and structures for space exploration. These three tasks are being accomplished in the project: (1) Ink selection, modification, and printing process study;

(2) sensor design study and optimization of percolation network microstructure for high gauge factor; and (3) compatibility and sensor performance study and demonstration.

The project's current goals are as follows:

- Evaluation of commercial and NASA Marshall Space Flight Center (MSFC) custom electronic inks for the fabrication of these SHM sensors by FAMU-FSU.
- Development of optimized 3D printing parameters for the nScrypt multimaterial printer by FAMU-FSU in their labs. This is the same printer used by MSFC in their On-Demand Manufacturing of Electronics (ODME) research.
- Design of SHM sensors for evaluation. Conduct performance studies on the SHM sensors and conduct a study of potential compatibility with various composite materials.
- Finalization of a performance study and composites evaluation for SHM printed sensors demonstration.

APPROACH/INNOVATION

Traditional fabrication techniques for electronic devices and assemblies are impractical, if not impossible, for International Space Station (ISS), lunar, and future long-range missions. Additive manufacturing has been demonstrated as a suitable replacement for many types of traditional machining. With the development of new conductive and nonconductive inks, AM is being demonstrated as a possible replacement for a wide range of sensors, including crew health monitoring, environmental, and structural health monitoring. This research is specifically focused in optimizing the on-demand manufacturing of SHM sensors, which are needed in a wide range of NASA mission applications.

Since FAMU-FSU has the same nScrypt multimaterial 3D printer as MSFC, the techniques and materials developed in this research will be directly portable to MSFC and the ODME project.

RESULTS/ACCOMPLISHMENTS

During 2022, FAMU-FSU has accomplished a significant amount of research on AM of SHM sensors. A number of commercial electronic inks were evaluated for the 3D printing process with characterization of the printed sensors. Initial designs of a SHM strain sensor were developed, fabricated, and characterized. FAMU-FSU is using this project as a seed project for graduate students to introduce additive manufacturing of electronics and sensors.

For the remainder of the year, the project team is continuing to fabricate and characterize new designs for SHM sensors. FAMU is also developing a process for laser processing/curing of the electronic inks on the nScrypt printer. This research will directly benefit the ODME project as ODME plans to use this process on an eventual ISS demonstration of printed electronics and sensors.

PARTNERSHIPS

The partner with MSFC for this project is the FAMU-FSU College of Engineering.

SUMMARY

The development of novel additive manufacturing processes and materials for the in-space fabrication of structural health monitoring sensors is a technology with many potential NASA and commercial applications in the coming years. Not only would these sensors be much smaller and lighter, but they could be produced as needed for crew health monitoring, environmental monitoring, and structural health monitoring applications. The new AM 3D printing processes being developed will also allow specialized fabrication laboratories, or 'FabLabs,' to be located on ISS, Gateway, lunar surface, and long-range NASA missions for on-demand fabrication of electronic devices and sensors as required.

PRINCIPAL INVESTIGATOR: Curtis Hill

PARTNERS: Florida A&M University-Florida State University

FUNDING ORGANIZATION: Cooperative Agreement Notice

On-Demand Manufacturing of Electronics in Space

OBJECTIVE: *To develop a manufacturing system capable of printing a range of electronic devices and sensors in a microgravity environment.*

PROJECT GOAL/DESCRIPTION

The availability of on-demand manufacturing of electronic devices is a critical element for NASA's future in-space and planetary expeditions. Electronic devices such as sensors, communication electronics and infrastructure (e.g., cabling), printed energy storage devices, and power generation elements will all need to be manufactured on-demand in an orbital or extraterrestrial habitat environment in order to replace failed components or manufacture new systems on long duration, Earth-independent missions. Currently, many devices that fall into these categories have been demonstrated using ground-based processes by NASA and commercial partners; but the systems used to make these devices (e.g., printers) cannot be readily flown and the processes and materials have not been demonstrated in microgravity. The primary goal of this project is to create a deposition system or manufacturing suite as a demonstration on the International Space Station (ISS) that is capable of manufacturing a set of selected electronic devices on demand in microgravity. This will require integration and miniaturization of several different materials deposition technologies, new processes and materials for multilayer circuit stacking, post-processing technologies, and development of in-situ functional verification methods for manufactured devices.

APPROACH/INNOVATION

The limitations of in-space manufacturing of electronics include the lack of space for normal ground-based manufacturing systems, challenging extreme environments, lack of available power for thermal processing, and a need for manufacturing operations to run autonomously as much as possible. The On-Demand Manufacturing of Electronics (ODME) project is developing a multimaterial 3D printer with optimized deposition tools for printing a wide range of electronic materials in microgravity. These tools will also allow for very precise deposition of high-density circuitry down to 100 microns of feature size.

In addition, ODME is developing novel directed energy curing processes for the electronic inks and materials that will be printed. Directed energy postprocessing means very low power requirements; increased processing speed; and the elimination of bulky, heavy thermal ovens for postprocessing. ODME incorporates a great deal of collaborative research to accomplish the objectives of the project. During 2022, ODME collaborated with seven NASA Centers and seventeen research universities.

RESULTS/ACCOMPLISHMENTS

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

- Evaluation of thin film (<25 μm) deposition systems for microgravity. Two different deposition systems were evaluated during the year, with a total of four parabolic flight campaigns utilized to evaluate these systems in zero gravity. One system was downselected for incorporation on the FabLab ODME Flight Printer.
- ODME and Auburn University have collaborated to develop new materials and processes for multilayer fabrication of electronic circuits on flexible

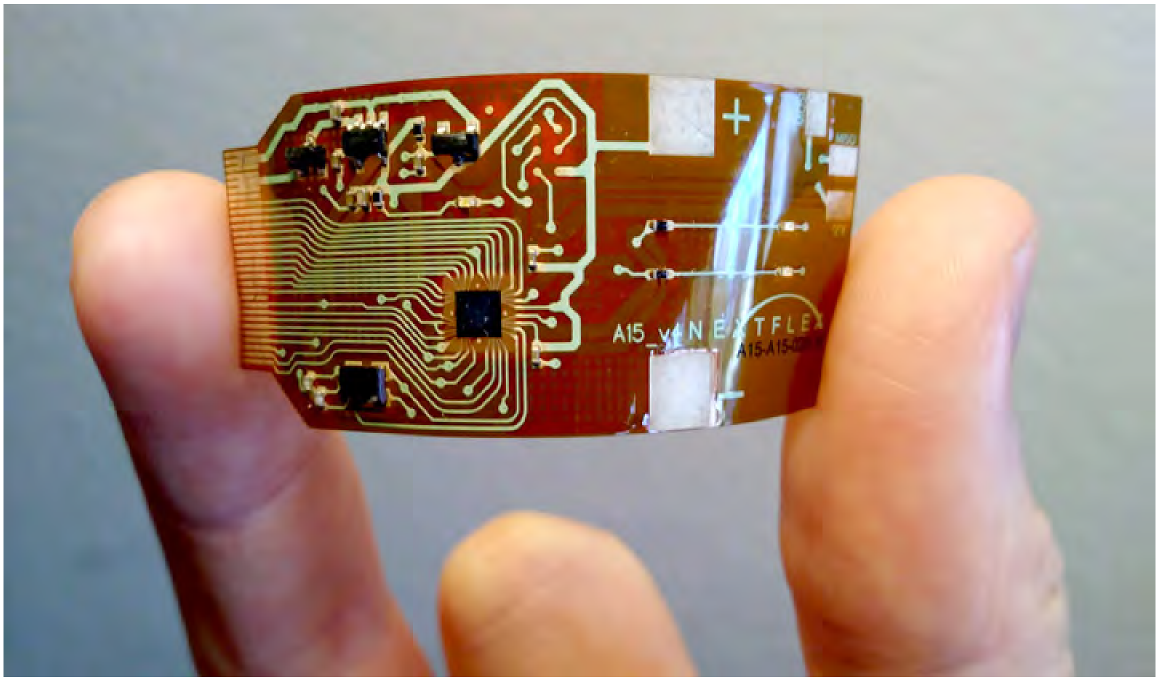


FIGURE 1. Flexible wireless printed circuitry for sensor networks.

substrates. This research will enable the in-space fabrication of wearable, flexible wireless sensors for astronaut crew health monitoring.

- New on-demand printing technologies have been developed for power generation and energy storage devices to support ODME fabricated devices. These technologies will eliminate the need for external power or batteries for printed sensor networks and wearable electronic devices. These technologies include printed thermoelectric devices, printed power generation antennas for harvesting power from wi-fi electromagnetic radiation, and supercapacitors for storing energy.
- Several new on-demand printed sensor technologies have been developed by ODME and its collaborative partners this year. These include printed humidity and temperature sensors, printed carbon dioxide sensors, printed radiation sensors, and printed structural health monitoring sensors.

PARTNERSHIPS

As previously mentioned, ODME partnered with seven NASA Centers, 17 universities, and six small businesses during the year to accomplish the objectives of the project.

SUMMARY

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

PRINCIPAL INVESTIGATOR: Curtis Hill

PARTNERS: Multiple NASA Centers and Universities including Auburn University

FUNDING ORGANIZATION: Cooperative Agreement Notice

In-Space Additive Nanomanufacturing and Dry Printing of Multimaterials Electronics

OBJECTIVE: *To develop a liquid-free system capable of dry printing various functional materials under the microgravity environment for the high-resolution fabrication of printed electronics and sensors.*

PROJECT GOAL/DESCRIPTION

A laser-based additive nanomanufacturing (ANM) method is a very promising approach that can enable the high-resolution in-space printing of electronics. Currently, almost all printed electronic deposition systems utilize nanoparticle inks that are deposited on a wide range of substrates for the fabrication of printed devices. Subsequent thermal curing postprocessing is required to complete the process.

The key advantage of the ANM system is the generation of a stream of dry nanoparticles on demand, with a tunable speed that can readily move in microgravity and even work in antigravity environments. When these nanoparticles are directed toward a substrate placed on an X-Y stage, they can be sintered in real time, forming desired electronic circuits. This deposition system has a number of advantages, including faster overall manufacturing of devices, very high feature resolutions, and no need for post processing operations.

To enable the future in-space ANM of electronics, this project consists of four specific objectives:

(1) Demonstrate the dry printing of multimaterial and functional hybrid electronics (FHE) by an ANM method that enables the future space manufacturing mission.

(2) Support NASA On-Demand Manufacturing of Electronics (ODME) project experts to ensure the compatibility and use of the proposed system in the space environment.

(3) Design a closed-loop gas flow system that can capture and reuse the inert gas to minimize the use of gas in space.

(4) Identify the potential pathways for making the ANM printer deployable by reducing its footprint and investigating the integration on an ODME demonstration printer.

APPROACH/INNOVATION

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

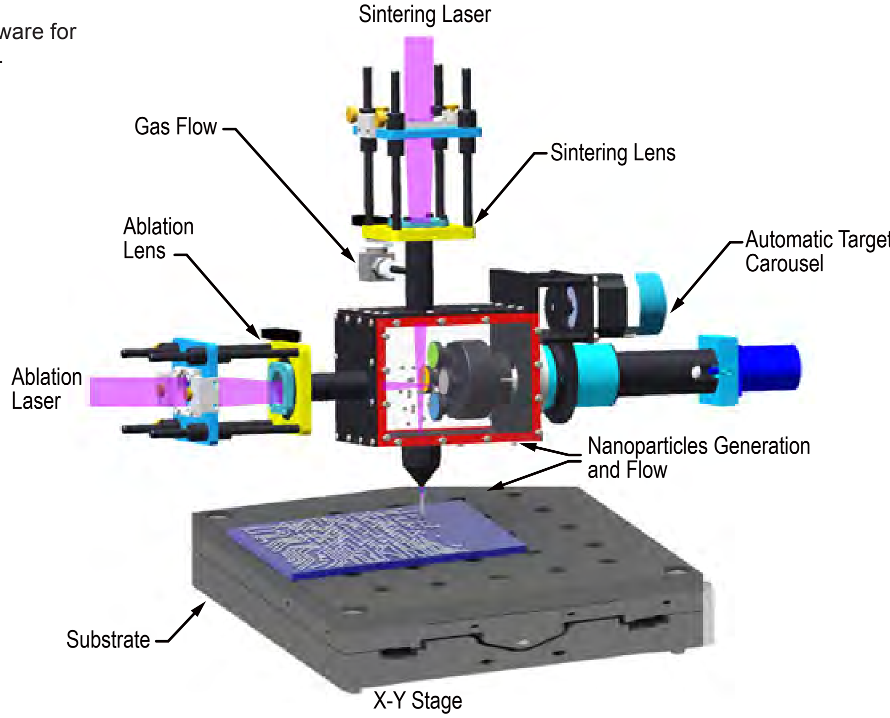
This ANM process fulfills these requirements with the potential for integration into future lunar and long-range missions for on-demand manufacturing of electronics and sensor systems. Since the system does not use liquid inks or other external feedstock materials, the logistics support of this system is also minimal. This system does have a lot of potential for future NASA electronics manufacturing.

RESULTS/ACCOMPLISHMENTS

During this partial first year of the Cooperative Agreement Notice (CAN) project, Auburn University has made significant progress in the development of this ANM deposition technology. The following tasks have been accomplished:

- Development of a standalone ANM printer system has been accomplished. This system incorporated the horizontal ablation laser for generation of the target nanoparticles, and the vertical deposition and sintering laser and inert gas transport system.

FIGURE 1. Overview of hardware for dual laser dry printing system.



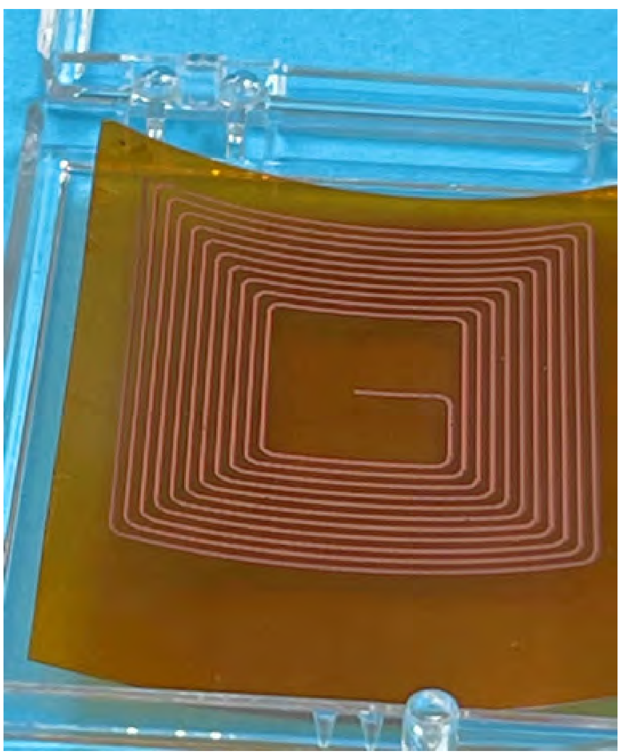


FIGURE 2. Printed copper antenna pattern on flexible substrate.

- A range of materials and test patterns have been printed to show the performance of the system. After characterization of these devices, the system is exceeding the anticipated performance for finished printed feature resolution and electrical properties performance.
- A working prototype system at Auburn University has produced printed silver conductive traces for printed electronics down to 100-micron resolution with extremely high electrical conductivity. The robustness of these deposits has been tested for adhesion and repeated flexion on flexible substrates, with excellent results.

Additional tasks that are in process for the remainder of the project include further characterization of the printed devices for long term reliability in differing environments, and deposition and testing of additional materials to enable manufacturing of a wide range of potential electronic devices and sensors.

PARTNERSHIPS

Dr. Masoud Samini at the Auburn University is a nationally known researcher in the areas of electronic manufacturing, electronics, mechanical systems, and lasers. ODME is continuing to work with Dr. Samini on follow-up research projects for a range of ODME application areas, including the manufacturing of electronics on the lunar surface.

SUMMARY

The ANM dry deposition system has great potential for on-demand 3D printing of electronics devices and sensors in space for future exploration missions. This project showed the performance potential of this system to produce complex printed electronics with high performance characteristics. Ultimately, this technology could revolutionize the fabrication of printed electronics for terrestrial as well as space manufacturing applications for electronics.

PRINCIPAL INVESTIGATORS: Dr. Masoud Samini, Auburn University; Curtis Hill, NASA Marshall Space Flight Center

PARTNER: Auburn University

FUNDING ORGANIZATION: Cooperative Agreement Notice

Polymer Coatings with Glass Bubbles for Thermal Radiation Control in Space

OBJECTIVE: *To develop a lightweight, flexible, and scalable polymer composite coating for thermal radiation control in space by integrating hierarchical hollow glass microspheres and surface texture.*

PROJECT GOAL/DESCRIPTION

The main goal of this project is to develop a lightweight, flexible, and scalable polymer composite coating, which serves as a selective emitter for thermal radiation control in space by integrating hierarchical hollow glass microspheres, or glass bubbles, and microscale pyramidal texture (fig. 1). Glass bubbles allow a higher degree of structural hierarchy, substantially lower weight, and larger interface density compared to other designs such as solid spheres; and the large interface density is important for selective optical control. The pyramidal texture further improves the optical properties through geometrically induced interference and confinement effects. A polymer matrix based on polydimethylsiloxane (PDMS) not only provides flexibility and conformal coating capabilities but also compatibility with a cast molding process to create microscale texture in a scalable manner.

APPROACH/INNOVATION

The samples were prepared by integrating a controlled volume fraction (vol.%) of microscale silicon dioxide (SiO_2) glass bubbles from 3M within a PDMS matrix by mixing silicone elastomer and curing agent. After stirring and degassing, the PDMS film was applied to a textured mold and put into a vacuum oven for heated drying. After a full dry, the PDMS film was peeled off from the mold. Following sample preparation, the optical properties were characterized by ultraviolet (UV)-visible (VIS)-near infrared (NIR) spectroscopy in wavelengths of 0.4–2.5 μm and Fourier-transform-infrared (FTIR) spectroscopy in wavelengths of 2.5–16 μm. Surface texture effects on optical properties were investigated using rigorous coupled-wave analysis (RCWA) and finite-difference time-domain (FDTD) simulations. The geometric parameters of the surface structures, mainly the aspect ratio (i.e., height/pitch), were varied to optimize

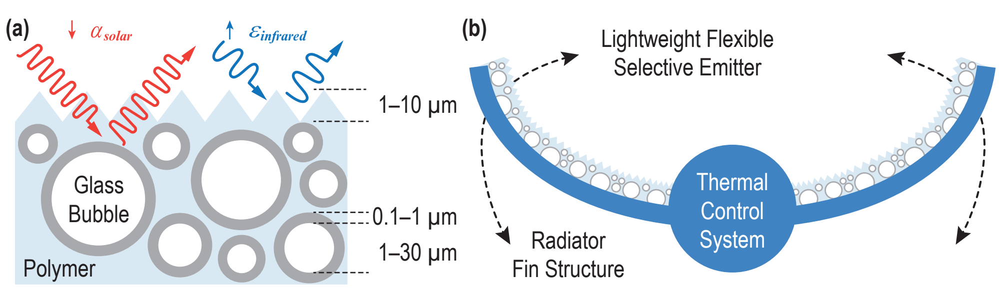


FIGURE 1. Proposed material and concept system designs. (a) The combination of glass bubbles and surface texture allows selective optical control that minimizes solar absorption and maximizes infrared emission; (b) The lightweight flexible selective emitter could be integrated with radiator fin or inflatable habitat structures and enable breakthroughs in thermal control of deployable and flexible systems.

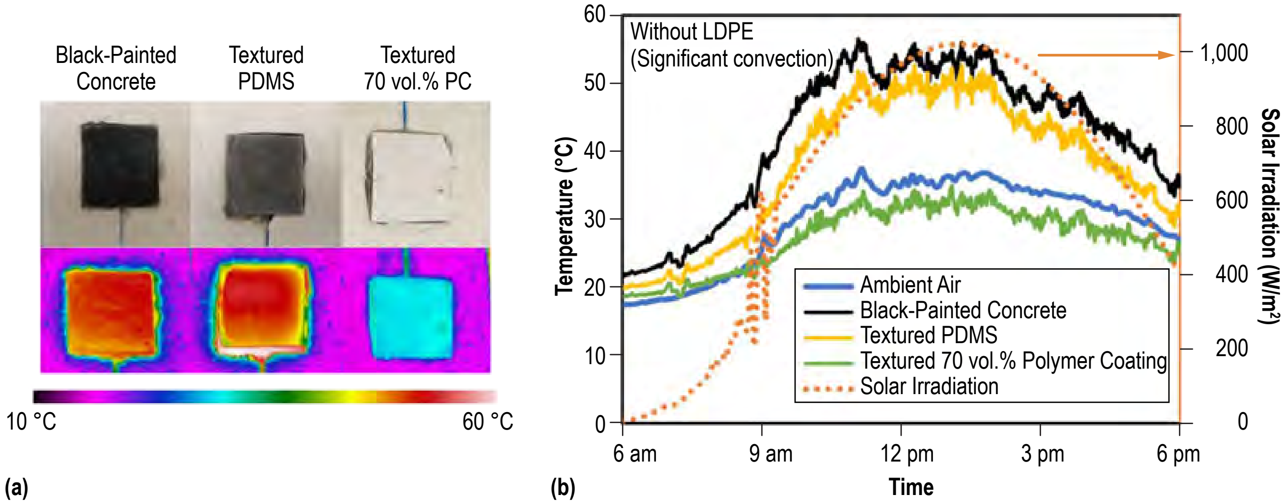


FIGURE 2. Thermal characterization of polymer coatings. (a) Optical and infrared images of black-painted concrete, textured PDMS on black-painted concrete and textured polymer coating with 70 vol.% glass bubbles on black-painted concrete. (b) Outdoor temperature measurements of black-painted concrete (black curve), textured PDMS on black-painted concrete (yellow curve) and textured polymer coating with 70 vol.% glass bubbles on black-painted concrete (green curve). Ambient air temperature (blue curve) and solar irradiation (orange dotted line) are plotted for comparison.

the current design. The predicted optical properties were used to generate theoretical temperature profiles for the textured and flat samples under ambient temperature and various heat transfer boundary conditions. The computational results were then validated by experimental data obtained through established outdoor temperature measurements. The project also used Mie theory and FDTD computations to investigate and understand the driving mechanism for optical properties of solar reflectors or selective emitters composed of hollow microspheres with uniform and varying diameters.

RESULTS/ACCOMPLISHMENTS

The optical measurements of the samples show that as the vol.% of glass bubbles increases from 0% to 70%, the average reflectivity in the VIS region and NIR region is enhanced from 0.14 to 0.94 and from 0.13 to 0.84, respectively. The research team then studied the optical properties of glass bubbles in polymer composites and identified ideal design parameters. Outdoor measurements revealed that textured polymer coating enable an additional 1.8 °C reduction in temperature compared to the flat variants when coated on common building material surface under limited convection and 0.63 °C reduction with significant convection at peak solar intensity (fig. 2). Compared to polymer coatings with no glass bubbles, the textured polymer coating with 70 vol.% glass bubbles show a significant temperature reduction on a concrete surface even when directly exposed to a peak solar intensity of around 1,000 W/m^2. The results indicate the cooling performance of textured polymer coatings with glass bubbles is promising for spacecraft and building surfaces.

PARTNERSHIPS

NASA Marshall Space Flight Center partnered with the University of California, Irvine to complete this project under a Cooperative Agreement Notice (CAN).

SUMMARY

The research team has successfully prepared lightweight, low-cost, and scalable polymer coatings for thermal radiation control by integrating 70% volume fraction of glass bubbles within a PDMS film with surface texture. This polymer coating demonstrated a high solar reflectivity of 0.92 and high mid-infrared (MIR) emissivity of 0.85. The measurement results suggest that the polymer coatings can achieve a subambient cooling and reduce the temperature significantly. The team has also studied the solar reflectivity of solid and hollow microspheres within a PDMS matrix using Mie theory and FDTD simulation method. The result shows that hollow microspheres with a thinner shell are more effective in scattering light and lead to a higher solar reflectivity. The high scattering efficiency, owing to the refractive-index contrast and large interface density, in hollow microspheres allows low-refractive-index materials such as SiO_2 to have a high solar reflectivity of 0.77, when the thickness of the film is 100 μm.

Testing has shown that the randomly distributed 0.5 – 1 μm SiO_2 hollow microspheres provide the largest solar reflectivity of 0.84 among all studied designs and the effect of varying diameters is supported by the backscattering ratio. The team has also identified that materials with a low extinction coefficient in the solar spectrum are promising for solar reflection. Further testing demonstrated that surface texture enhances emissivity in infrared wavelengths and greater cooling capabilities compared to flat polymer coatings.

PRINCIPAL INVESTIGATORS: Jaeho Lee, University of California, Irvine; Enrique Jackson, NASA Marshall Space Flight Center

PARTNER: University of California, Irvine

FUNDING ORGANIZATION: Cooperative Agreement Notice

FOR MORE INFORMATION: https://lee.eng.uci.edu

Cost-Effective, High-Temperature Materials Testing

OBJECTIVE: *To define a concept for high-temperature testing of mesoscale tensile samples and small punch test samples, and to identify a path forward to develop such a capability.*

PROJECT GOAL/DESCRIPTION

This Cooperative Agreement Notice (CAN) project sought to establish a viable path to heat small-scale mechanical test samples to extract high-temperature mechanical properties at a lower cost than current high-temperature mechanical testing procedures. Localized heating was identified in the proposal as an ideal manner to reach elevated temperatures of up to 2,500 °C with a relatively small amount of thermal energy compared to conventional methods for high-temperature testing. The goal was to identify means to localize heating so testing can be performed more quickly and at a lower energy consumption rate. The project focused on the goal of reaching 2,500 °C because current high-temperature testing capabilities at NASA Marshall Space Flight Center (MSFC) are not capable of reaching that temperature and because that temperature will enable high-temperature testing of refractory metals. Environmental benefits, through efficient heating of samples, were also identified as a benefit to the technology developed in this CAN.

APPROACH/INNOVATION

To enable localized heating of samples, laser heating was identified as an ideal candidate. However, laser heating poses technical challenges related to sample emissivity and reflectivity. While this project focused specifically on identifying areas for development and creating preliminary designs, many of the technical challenges were addressed. Investigators performed a detailed literature review and reached out to relevant authors, which led to a joint discussion with the Air Force Research Laboratory (AFRL) on laser heating. This discussion helped Psylotech determine challenges to laser heating and ultimately led to the discovery of the company PulseRay, which has laser heating technology that Psylotech is considering licensing so they may add high-temperature testing to their repertoire. At the conclusion of the project, Psylotech indicated that this work helped them identify new partnerships and a new market in high-temperature testing.

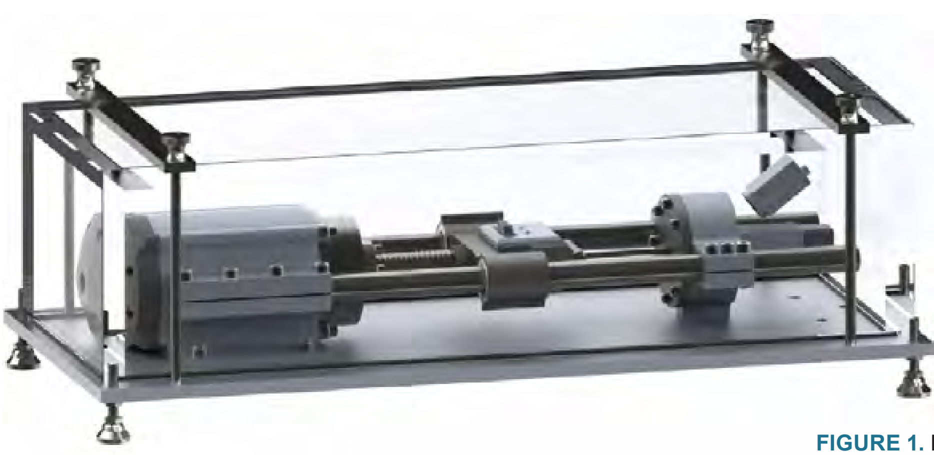
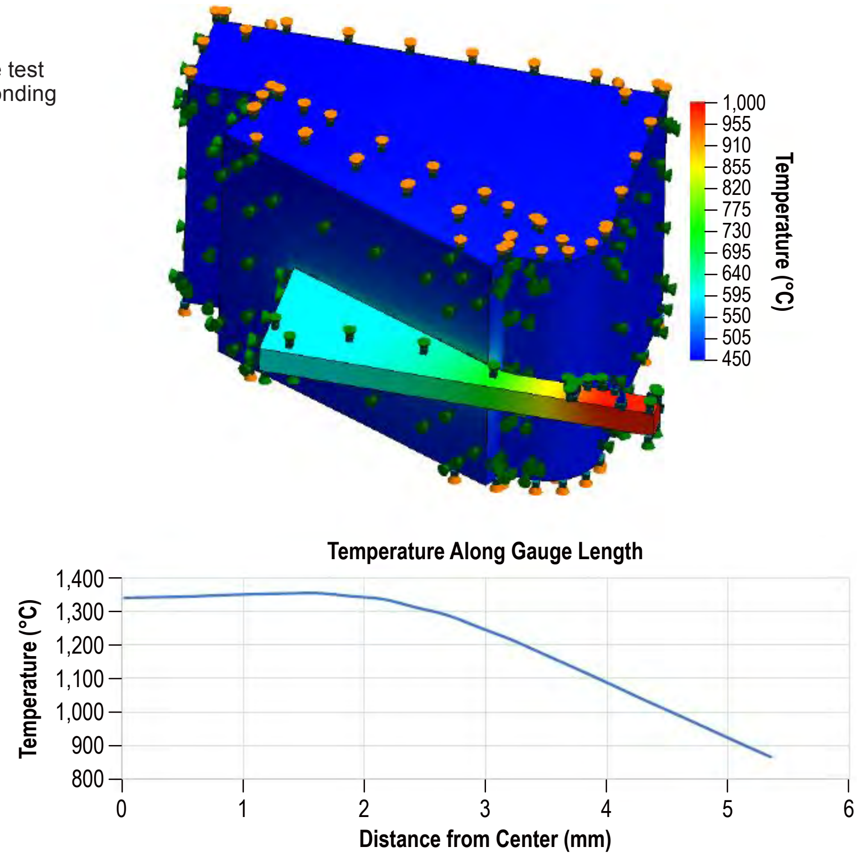


FIGURE 1. Model of the Psylotech 10 kN μTS load frame within a vacuum chamber.

FIGURE 2. Simulated micro-tensile test (axisymmetric model) and corresponding thermal gradient.



The work pursued in this CAN was complimentary to a Center Innovation Fund project, which focused on retrofitting a NASA-owned load frame manufactured by Psylotech to perform small punch testing (SPT). Other complimentary work is being pursued by Georgia Technical University (Georgia Tech), the National Institute of Standards and Technology (NIST), and a variety of other national laboratories and universities. Georgia Tech is pursuing research to improve the throughput of experimentation and analysis using SPT. They are also seeking to begin work on performing SPT at elevated temperatures. NIST has published multiple journal articles recently on the application of SPT, or other small-scale mechanical tests, to develop additive manufacturing processes. Sandia National Lab has performed similar work to develop mesoscale tensile testing. The next step beyond this CAN is to maintain communication with Psylotech as they license laser heating technology and produce a system that can test samples at elevated temperature using efficient heating methods. A partnership between NASA, Psylotech, and the University of Illinois was discussed as an avenue to perform research using Psylotech's potential new system prior to procurement of a system for exclusive NASA use.

RESULTS/ACCOMPLISHMENTS

This CAN resulted in a very detailed literature review on the potential of laser heating for high-temperature mechanical testing. The literature review helped to identify potential laser systems, materials, and sensors for the prospective high-temperature mechanical testing machine. Emissivity requirements, laser safety considerations, laser options, and laser optics were all subjects of interest for the literature review. Preliminary designs of the fixture have been produced, including plans to enclose part of the system in a vacuum chamber to protect samples from oxidation at elevated temperatures. Simulations were also performed using the fixture designs to identify heat flow and stresses that the system would experience at extremely high temperatures.

The most significant accomplishments of this CAN were the new connections that Psylotech was able to establish with PulseRay and AFRL. These relationships, along with existing partnerships that Psylotech has developed, greatly increase the chances that the need identified in this CAN will be addressed and that NASA will have access to an efficient high-temperature testing capability. Lessons learned from this CAN include:

- Monthly communications are the best way to keep the partner engaged without meeting too often.
- The CAN mechanism provides a company with more than just NASA resources; it also allows a company to benefit from the NASA legacy so they can build the relationships necessary to produce a product that is of interest to NASA.
- Choosing a challenging subject for a CAN is great way to encourage the partner to come up with unique solutions, both technically and with respect to relationships.

PARTNERSHIPS

Psylotech is a small business located in Evanston, IL. They focus on providing small-scale mechanical testing solutions with an emphasis on digital image correlation. Their relationships with their customers and collaborators across industry, academia, and government allow them to identify areas of research that have growing markets. This partnership helps NASA find other entities that share a common goal and has the potential to enable NASA to secure new technologies without significant internal development. The current plan moving forward is to maintain bimonthly communications with Psylotech on their development of the high-temperature testing capability.

SUMMARY

This CAN allowed NASA and Psylotech to collaborate on literature review, partnership building, and design for a cost-effective, high-temperature testing machine. It invigorated Psylotech as they identified other customers with similar needs to NASA. The relationship built through this CAN will help NASA remain in the loop as Psylotech moves forward with developing high-temperature testing capability for subscale mechanical test samples.

PRINCIPAL INVESTIGATOR: Zach Courtright

PARTNER: Psylotech

FUNDING ORGANIZATION: Cooperative Agreement Notice

FOR MORE INFORMATION: https://www.psylotech.com/loadframe

Alloy Design for Additive Manufacturing of Crack-Free Tungsten Alloys via Laser Powder Bed Fusion Process

OBJECTIVE: *To demonstrate additive manufacturing of near-fully-dense and crack-free tungsten alloy specimens with improved high-temperature mechanical properties and acceptable room-temperature ductility.*

PROJECT GOAL/DESCRIPTION

The focus of this project is to support materials and process development for additive manufacturing (AM) (i.e., laser powder bed fusion (L-PBF)) of high-temperature materials for space propulsion and nuclear fusion applications. The technology of this project aims to validate successful production of a high-temperature application component in laboratory environment. The primary accomplishment/deliverable of this project is successful AM of crack-free tungsten (W)-based alloys with improved high-temperature mechanical properties and acceptable room temperature ductility.

APPROACH/INNOVATION

The approach is based on an integrated computational materials engineering (ICME) framework. The ICME or systems approach quantitatively establishes the connections among composition-printability-microstructure-properties-performance (CPMPP). The effort begins by conducting Scheil solidification simulations in Thermo-Calc Calculation of Phase Diagrams (CALPHAD) software to determine the constituent phases after rapid solidification, along with calculations of cracking susceptibility coefficient (CSC) values and solidification range (ΔT). This step is used to design alloys with the best printability characteristics for AM. The optimal composition is then selected based on the best combination of anticipated mechanical performance and 3D printability. The experimental work involves production of the AM-qualified prototype powder

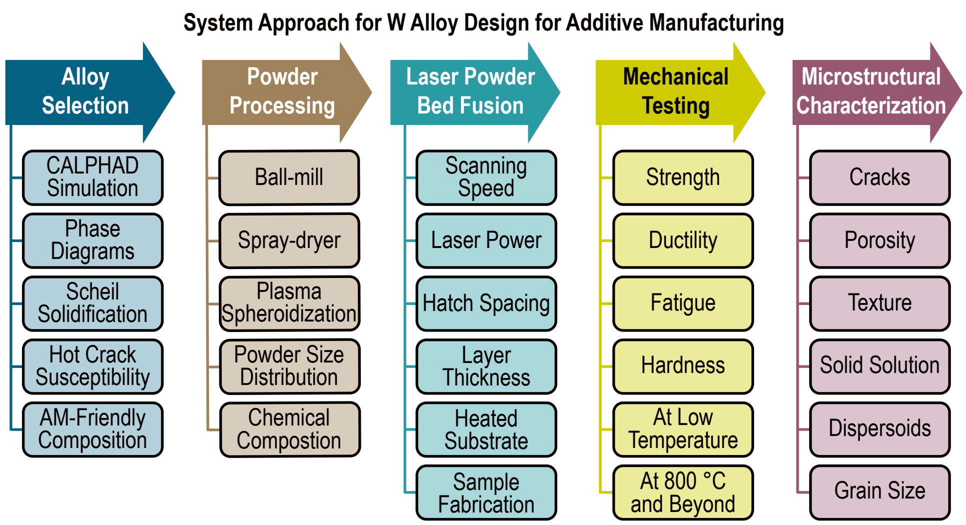


FIGURE 1. The iterative process under the overarching ICME umbrella, from materials discovery through advanced manufacturing and testing.

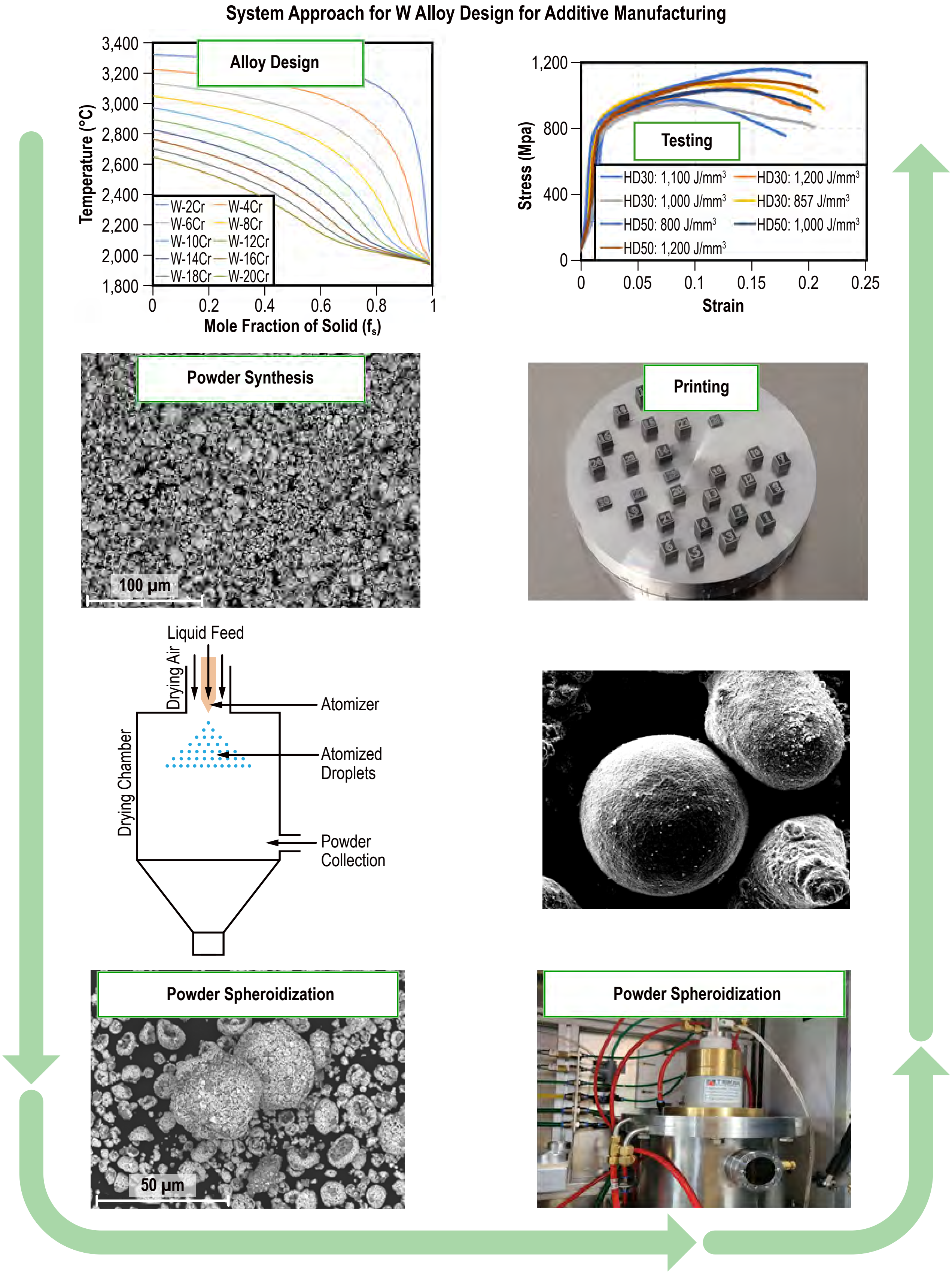


FIGURE 2. The specific refractory alloys-based ICME process for this project at the University of North Texas.

as the feedstock for L-PBF. Process parameter development for the designed alloy was conducted through a factorial design of experiment (DOE) scheme to obtain maximum relative density and desired microstructural features. Density measurements and microstructural characterization using scanning and transmission electron microscopy (SEM and TEM) will provide feedback to improve process parameters. Mechanical performance will be evaluated by mechanical testing with focus on room temperature ductility, and high temperature yield and ultimate tensile strength.

RESULTS/ACCOMPLISHMENTS

This study focused on composition selection for 3D printability of W-based alloys starting with CALPHAD simulations. Simulations were conducted for the compositions ranging from 2–14 wt.% chromium (Cr), vanadium (V), and tantalum (Ta) as binary, ternary, and quaternary systems in increments of 1 wt.% step size. Hafnium carbide (HfC) phase has been selected to promote heterogeneous nucleation in the melt pool. HfC has a high melting point (3,900 °C), thus tuning process parameters to avoid melting these particles would be plausible. HfC has also been widely used in W and molybdenum (Mo) alloys for particle strengthening with a great degree of success.

Chromium was chosen as a binary alloying element because of its low density and high affinity for oxygen. Scheil's solidification simulation also showed that adding Cr helps in eutectic solidification. Eutectic solidification allows the liquid to backfill cracks during the end of solidification, preventing microcracking. Powder manufacturing was done for the first binary system. The W-Cr powders were mixed in a 1% polyvinyl alcohol (PVA) slurry and spray-dried so that the powders could agglomerate. Then, the agglomerated powders were plasma spheroidized into spherical alloyed powders. The Trumpf 1000 series AM machine was used to print the first set of compression coupons. Compression tests revealed ultimate compressive strength above 1,100 MPa. Further printing, mechanical testing and characterization will be performed in the coming year.

SUMMARY

The results obtained from the CALPHAD Scheil simulations show that the addition of Cr supports the 3D printability of W. The alloyed powder manufactured via plasma spheroidization process were spherical. Printability evaluation has started. Crack-free printability of W-based alloys will enable design freedom and manufacturing flexibility by eliminating the need for conventional processing steps of pressing, sintering, thermomechanical processing, and machining.

PRINCIPAL INVESTIGATOR: Fredrick Michael
PARTNER: University of North Texas
FUNDING ORGANIZATION: Cooperative Agreement Notice

Coupling In-Situ Data Analysis with Machine Learning for Characterization of Additively Manufactured Parts

OBJECTIVE: *To investigate image processing and machine learning methods for identifying defect signatures from in-situ monitoring data of additively manufactured components.*

PROJECT GOAL/DESCRIPTION

The goal of this project is to advance efforts in developing certification logic for laser powder bed fusion (L-PBF) additive manufacturing (AM) parts through analyzing and correlating defect indications collected from in-situ process monitoring to their final as-built condition. This work includes comparisons to nondestructive evaluation (NDE) data (e.g., computed tomography (CT), radiography, etc.) and metallurgical data to enable quantifiable determination of how well the in-situ defect signatures correspond to actual defects and the anomalous indication rate. The results include implementing convolutional neural networks (CNNs) and other machine learning algorithms to identify defect layers in the build that can be used to screen parts for abnormalities that could affect their safe use.

APPROACH/INNOVATION

The NASA Marshall Space Flight Center (MSFC) Nondestructive Evaluation Team partnered with faculty and graduate students from the Southern Illinois University in Carbondale (SIUC) to tackle this effort. The approach was broken down into three tasks. In task one, samples were designed with seeded defects and then fabricated by L-PBF while being monitored layer by layer with an in-situ thermal imaging technique. The finished samples then underwent CT and radiographic NDE to characterize the build; and finally serial sectioning and imaging was performed to get the final as-built defect state. The in-situ data, and portions of the ex-situ data, were provided to SIUC for analysis.

The second task involved SIUC investigating novel methods for defect feature identification and extraction. They investigated and applied several frameworks for developing machine learning algorithms, comparing classification accuracy, and for automating the trial-and-error approach to determining optimal CNN architectures. In the final task, SIUC investigated numerous machine learning frameworks using a variety of CNN architectures to provide an automated, combined approach for processing, analyzing, and correlating multiple NDE datasets for a single AMed component.

RESULTS/ACCOMPLISHMENTS

L-PBF AM samples with seeded defects were produced with corresponding in-situ monitoring data. Subsets of the in-situ monitoring data were included in training datasets for CNN classifiers. Various preprocessing and class balancing approaches were employed to generate multiple datasets. Binary CNN classifiers belonging to a well-defined range of CNN architectures were trained and tested on the generated datasets.

Multiple sets of in-situ L-PBF image data were generated with different degrees of class balancing, and various preprocessing schemes were applied to evaluate the performance of various binary image classification models, with a primary focus on CNNs.

The binary CNN classifiers were trained and tested in both MATLAB and Python environments. Experiments performed in MATLAB achieved testing accuracies greater than 90%. Accuracies meeting or exceeding 95% were shown to be repeatable. A variation of the Hyperband algorithm, available in the Keras Tuner Python library, was used to perform hyperparameter tuning over the well-defined range of CNN architectures. The procedure employed by the Hyperband tuner illuminates the best performing architecture among the vast number of possible CNN architectures.

Overall, results showed that testing accuracies exceeding 80% are easily achieved with the range of CNN architectures studied and datasets included. X-ray CT results revealed a tendency for the seeded defects to 'heal,' meaning that indications present in the in-situ optical tomography data could not be found through ex-situ NDE or metallurgical analyses. This outcome prevented correlation of defect indications from in-situ imaging with those from ex-situ NDE and metallurgical analyses.

PARTNERSHIPS

This work was performed by members of the NASA MSFC Nondestructive Evaluation Team in conjunction with faculty and graduate students from SIUC. The research effort was a follow on to a series of internships by those students working various aspects of the same venture. NASA and SIUC are seeking additional follow-on activities to take this technology to fruition as a potential inspection process for additive manufactured hardware.

SUMMARY

The NASA/SIUC partnership has provided a huge leap forward in being able to understand the process for using in-situ monitoring data to verify, or certify, part quality during L-PBF additive manufacturing. With the processes developed and demonstrated during this effort the groundwork for using machine learning to screen for defects in a finished part, collected layer-by-layer as it is built, were established. The basis for conducting probability of detection statistical evaluations of that data were also established which will play a large part in being able to certify the inspection process.

The work overcame many technical hurdles, including developing ways to overcome the training-testing bias where an unbalance between the two skews the training vector. This led to ways to create artificial 'defect' data from actual defect data. The work created processes for reducing the noise bias on the images providing a stable data form that the machine learning algorithms could work from and learn. Methods for classifying accuracy of the machine learning algorithms was created that will allow the next step of determining statistical probability of detection to be determined. And finally, the work established ways to rapidly evaluate large parameter sets to come up with efficient models for defect detection.

PRINCIPAL INVESTIGATOR: James Walker

PARTNER: Southern Illinois University at Carbondale, Dr. Tsuchin Chu

FUNDING ORGANIZATION: Cooperative Agreement Notice

Modeling of Self-Reacting Friction Stir Welding to Correlate Predicted Phenomena with Weld Quality and Hardness

OBJECTIVE: *The objective of this effort is to further refine and validate the previously developed CFD Research Corporation's thermomechanical model of self-reacting friction stir welding, and its associated models linking predicted thermal and stress-strain history to weld properties, while extending the models to address additional lightweight aluminum alloys; and to transfer the resulting capability to NASA Marshall Space Flight Center.*

PROJECT GOAL/DESCRIPTION

There is a recognized need for better analytical tools to support advanced manufacturing of metallic structures, with a special emphasis on understanding friction stir weld processes and lightweight alloys. CFD Research Corporation, in partnership with NASA Marshall Space Flight Center's (MSFC) Metallic Materials & Processes (EM32) branch, has further matured, validated with experimental data, and delivered an accurate self-reacting friction stir welding (SR-FSW) modeling and simulation software tool. This tool allows users to predict the effects of process parameters, pin tool design, and welded material with a particular focus on Space Launch System (SLS)-relevant alloys, such as aluminum alloys AA2219 and AA2050.

APPROACH/INNOVATION

The challenges faced by MSFC-EM32 when developing SR-FSW weld schedules during transitions between working materials and tooling are motivating factors for developing predictive models of the process. The modeling approach utilized by the team builds on prior work and complementary efforts in academia for predicting the outcome of similar friction stir welding processes. The predicted thermal and strain rate history experienced at multiple points across the weld are extracted from the model results and provide inputs for metallurgical process models to predict mechanical properties of the weld.

RESULTS/ACCOMPLISHMENTS

Analysis of experimental data for the effects of a weld thermal cycle representing the predicted SR-FSW temperature-time history indicated that these calibrated semi-empirical models overpredicted the softening of the workpiece at high temperatures, with an unrealistic hardness recovery after cooling to room temperature. Therefore, a physics based Kampmann and Wagner (KWN) numerical metallurgical process model formulation was implemented. The KWN formulation is based on a discrete precipitate size distribution and includes dissolution of strengthening precipitates (i.e., transitions between precipitate phases),

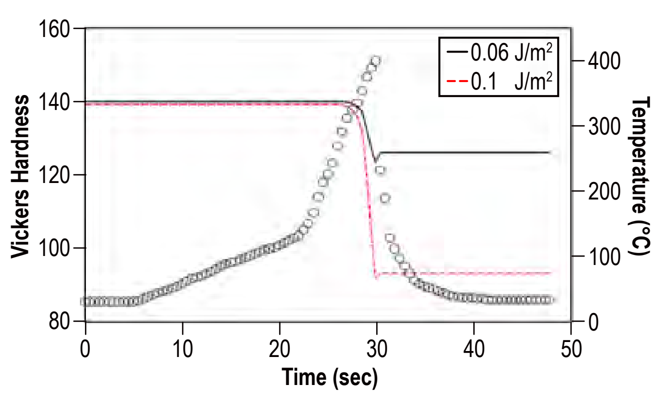
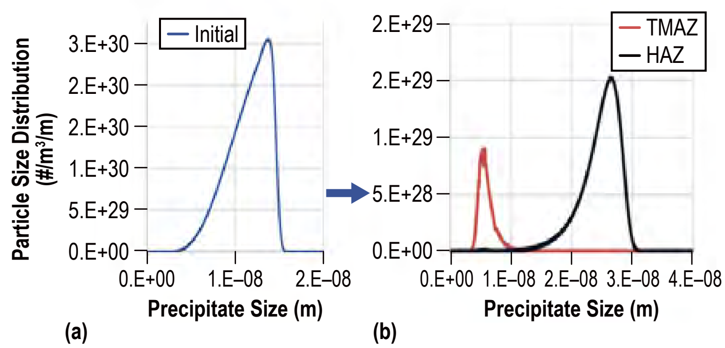


FIGURE 1. KWN predicted evolution of the hardness of AA2219-T87 during a simulated SR-FSW thermal cycle interrupted at 400 °C, with varying interfacial energy.

FIGURE 2. (a) Initial prediction of precipitate size and particle size distribution; (b) Prediction of particle size distribution and precipitate size in TMAZ and HAZ.



precipitate regrowth during cooling after thepin tool has passed, and the resulting effects on the workpiece strength (or hardness) distribution across the weld. The software implementation for a single precipitate phase was verified against published results for effects of a weld thermal cycle on an aluminum (Al)-magnesium (Mg)-silicon (Si) alloy; model parameters were estimated using Calculation of Phase Diagrams (CALPHAD) and published AA2219 quench sensitivity studies; and the model was tuned to predict, for example AA2219 strength from the SR-FSW thermal cycling.

Applying the KWN model to the varying time-temperature histories (fig. 1) allows for prediction of the final particle size distribution. Full dissolution of the precipitates is predicted in the thermomechanically affected zone (TMAZ) with some recovery due to nucleation of new precipitates. Precipitate coarsening is dominant in the heat affected zone (HAZ), which reduces strength and is not expected to recover (see figure 2).

PARTNERSHIPS

Under Cooperative Agreement Notice (CAN) funding from MSFC, CFD Research has continued to mature the SR-FSW models and apply them to meet MSFC needs by improving simulation capabilities for rapid analysis across changing process conditions and weld geometry. It is expected that the CFD Research thermal and viscoplastic flow simulations will complement experiments to provide insight into material and weld behavior that cannot be directly observed.

SUMMARY

The goal of this project was to progress towards a model-based ‘Welder’s Handbook’ for SR-FSW that can provide the welding team bounds on the desirable process window when workpiece thickness, tool design, and workpiece materials are changed. The model formulations and software have been further improved and validated, and are being actively applied at MSFC to support process development and troubleshoot the root cause of process instabilities.

PRINCIPAL INVESTIGATOR: Vernon Cole, CFD Research Corporation

PARTNER: CFD Research Corporation

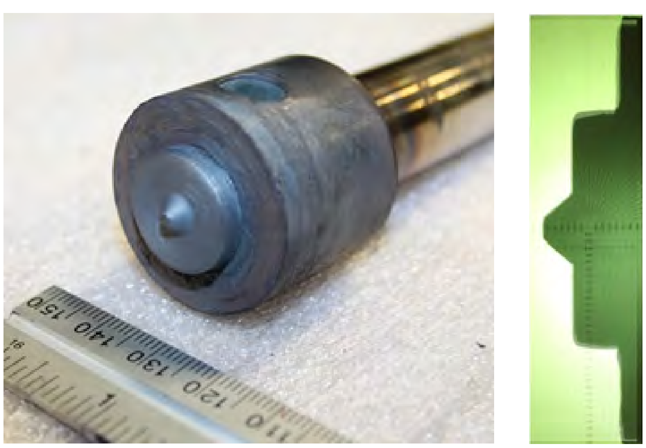
FUNDING ORGANIZATION: Cooperative Agreement Notice

Advanced Tooling Demonstration for Friction Stir Welding of Heat Resistant Materials

OBJECTIVE: *To improve the reliability and robustness of solid-state friction stir weldments, advanced materials are being investigated for use as the tooling material.*

PROJECT GOAL/DESCRIPTION

Development of advanced high-strength and high-temperature tool materials are required for solid-state friction stir welding (FSW) not only for the Space Launch System (SLS) and Artemis program, but also for various commercial and industrial applications. Due to the large scale and long durations of these welds, tools that are fatigue- and wear-resistant are required to ensure the production of high quality FSW weldments. Of equal importance to advancing the FSW process is the parallel development of advanced FSW tool materials. The tool must be able to survive at the temperatures experienced in the FSW weldment under the high mechanical loading. Thus, improving the durability of FSW tool materials is critical to producing robust weldments, not only in the current aluminum (Al) alloys, but also in materials that retain their strength at elevated temperatures such as Inconel®, nickel alloys, titanium (Ti) alloys, and steels. Figure 1 shows the newly developed tool after FSWing in steel and figure 2 shows the corresponding FSW weldment.



(a) (b)

FIGURE 1. (a) FSW tool after 35 cm of weldment and (b) overlay showing no appreciable change from original tool geometry.

APPROACH/INNOVATION

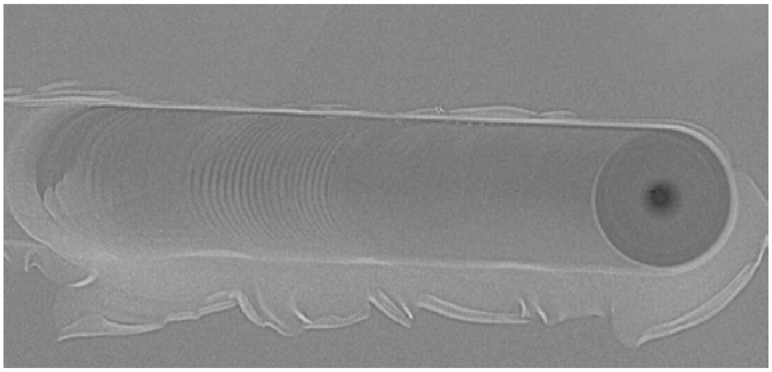
Table 1 summarizes current materials used for FSW tooling. Empirically obtained temperatures for the weldment in the FSW process are in the homologous temperature range of 0.7 to 0.9. Thus, while tool steel is suitable for joining Al alloys, other materials with higher melting temperatures require more advanced tooling. These options are either brittle ceramics (i.e., polycrystalline cubic boron nitride (PCBN)), or tungsten (W)-based refractory alloys.

TABLE 1. Candidate FSW tool materials.

	Operational Temperature Limit (°C)	Machinable	Room Temperature Hardness (HRC)
MP159	600	Yes	56
PCBN	950	No	60–62
W–25%Re–2%HfC	1,050	Yes	48–50
W–25%Re–4%HfC	1,050	Yes	53–55

As noted in table 1, the refractory alloy tungsten-rhenium (Re)-hafnium carbide (HfC) (W-25%Re-HfC) is able to operate at the highest temperature in addition to retaining ductility to enable its machinability. Using the processing methods developed under an earlier Cooperative Agreement Notice (CAN) project, the addition of 4% HfC was shown to be optimal in terms of the resulting metallurgy. The tools previously produced using spark plasma sintering (SPS) demonstrated a cost of roughly $1,000 per tool. This is in contrast to the $10,000 to $50,000 price for the brittle PCBN

(a)



(b)

FIGURE 2. (a) Overview of FSW segment in 1018 steel and (b) corresponding NDE RT showing clean weldment.

tooling. The current CAN is demonstrating their ability to survive under FSW conditions in metals such as steel and Ti alloys.

RESULTS/ACCOMPLISHMENTS

Figure 1a shows the FSW W-25%Re-HfC tool after completing the initial FSWs. Images from an optical comparator captured the pin profiles before and after the FSWs, which are overlaid in figure 1b. No appreciable tool wear was noted, and the pin appeared clean and lacked any signs of erosion due to wear. A clean surface can be observed in a segment of the FSW shown in figure 2a with the corresponding nondestructive evaluation (NDE) radiographic testing (RT) x-ray inspection in figure 2b. The x-ray shows a fully consolidated weldment without any inclusions that might arise from tool wear.

After completing the FSW in 1018 steel without auxiliary heating, the tool is currently being adapted to the FSW equipment located at NASA Marshall space Flight Center (MSFC) where it will continue to conduct welds in various steels and Inconel nickel alloys.

Three FSW W-25%Re-HfC tools are available for continued studies. To date, 35 cm of FSW weldment has been completed in 1018 steel. Postweld inspection verified that there was no significant wear of the pin tool. Radiographic testing x-ray inspection verified a clean weldment with no evidence of voids or inclusions present from pin tool wear. Metallurgical specimens were also prepared to ensure the weldments were fully consolidated. The tool is currently being adapted to MSFC equipment to continue wear studies.

PARTNERSHIPS

To produce the W-25%Re-HfC tool, the University of Alabama in Huntsville (UAH) has teamed with Rhenium Alloys. This collaboration will accelerate the time to market once the long term duration has been demonstrated.

SUMMARY

By using a novel processing route to consolidate the W-25%Re-HfC tools used in this study, the cost per tool is lowered to $1,000 each. This represents a substantial savings over its closest competitor, PCBN. The W-based tools are also machinable and have higher fatigue life than the ceramic PCBN.

Some delays have been experienced at UAH due to COVID-19 and equipment issues and no-cost extensions have been filed. Adapting the tool to equipment at MSFC will enable the welding group to have firsthand exposure to the results of this improved tool material.

PRINCIPAL INVESTIGATOR: J.A. Schneider, University of Alabama in Huntsville

PARTNERS: University of Alabama in Huntsville; Rhenium Alloys

FUNDING ORGANIZATION: Cooperative Agreement Notice

Realizing Spatially Resolved, Real-Time Temperature Measurements in Friction Stir Welding Using Ultrasonic Thermometry

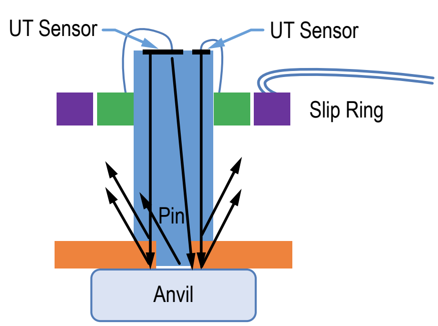
OBJECTIVE: *This study is demonstrating the use of ultrasonic thermometry to remotely obtain real-time, spatially resolved temperature profiles within friction stir weld zones with a newly developed 'smart tool.'*

PROJECT GOAL/DESCRIPTION

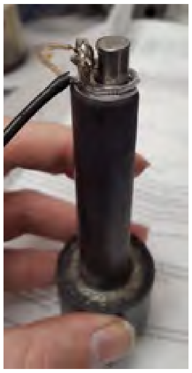
Friction stir welding (FSW) is a solid-state joining technique patented in the 1990s and first implemented at NASA Marshall Space Flight Center (MSFC) in 1995. It was successfully used in the joining of heavily alloyed aluminum panels on the external fuel tank for the Space Shuttle main engine (SSME) and has been baselined for the Space Launch System (SLS). While the fuel tanks for the SSME used thinner workpieces since they did not provide structural support, the fuel tanks on the SLS provide structural support and therefore require thicker workpieces. As the workpiece increases in thickness, maintaining a constant temperature throughout the weldment becomes more difficult. With any joining process, knowing and controlling the temperature is fundamental to quality control and production of robust, high-quality joints. Thus, having a method to monitor—and ultimately control—the real-time temperature during FSW is required. However, in FSW, the temperature is not directly controlled, but rather empirically correlated with the process control parameters of tool rotation and travel.

APPROACH/INNOVATION

By making use of ultrasonic wave propagation, transducers can be installed remotely and used to monitor the workpiece material through temperature dependent changes in time-of-flight of the signal. Installation of the transducers on the backside of the tool allows the 'smart tool' to be adapted to any existing FSW equipment. Figure 1a shows the transducer mounted on a FSW tool and figure 1b shows the tool in the FSW equipment with a slip ring installed to transmit the signal. The remote attachment does not influence the thermal transport in the weld zone, nor subject the transducers to a harsh thermal environment. Use of this methodology will assist in understanding the occurrence of random variations in the properties of FSW weldments, especially with varying material alloys and their corresponding process parameters. Ultimately, this proposed methodology would support various feedback control schemes to maintain constant temperature in the FSW zone and ensure the production of repeatable, robust, high quality weld joints.



(a)



(b)

FIGURE 1. (a) Schematic of the transducer mounting and signal propagation through the FSW tool and (b) the transducer installed on FSW tool.

TABLE 1. FSW Temperature (˚C) in 6 mm Al 2219 panels.

	Step 1	Step 2	Step 3	Average
275 RPM 6 in/min	560 ± 3.6	500 ± 17.7	376 ± 3.7	485 ± 8.3
300 RPM 6 in/min	584 ± 15.6	479 ± 3.0	395 ± 8.8	494 ± 9.4
350 RPM 6 in/min	621 ± 13.2	487 ± 16.7	405 ± 27.7	514 ± 10.8

RESULTS/ACCOMPLISHMENTS

Table 1 summarizes the temperature measurements made using the 'smart tool' during FSW of 6-mm-thick aluminum (Al) alloy 2219 panels. Empirical data for FSW estimates the temperature to be in the homologous temperature range of 0.7 to 0.9. For Al alloys, this would correspond to temperatures in the range of 380 to 567 °C. From the literature, the temperature is expected to be highest near the shoulder (step 1), decreasing toward the backing anvil (step 3) (see figure 2). Also, the temperature is strongly dependent on the tool rotation, increasing as the rotation is increased. Table 1 shows the correlation between the spatially resolved temperature and the expected trends.

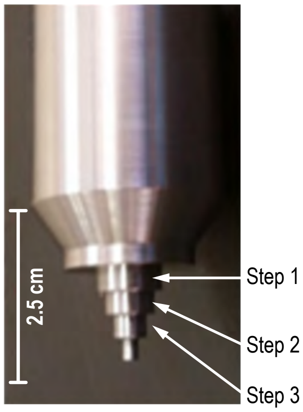


FIGURE 2. Close-up of the FSW tool showing the shoulder (step 1) and backing anvil (step 3).

PARTNERSHIPS

The University of Alabama in Huntsville (UAH) is continuing to work with Don Yuhas at Industrial Measurement Systems, Inc. to adapt this technology to transient applications.

SUMMARY

Some delays have been experienced at UAH due to COVID-19 and equipment issues, and no-cost extensions will be filed. To overcome the equipment issues at UAH, it is planned to migrate the technology to the equipment located at the MSFC welding group to accelerate benefits to the FSW process.

PRINCIPAL INVESTIGATOR: J.A. Schneider, University of Alabama in Huntsville

PARTNERS: University of Alabama in Huntsville; Industrial Measurement Systems, Inc.

FUNDING ORGANIZATION: Cooperative Agreement Notice

High Strength Aluminum Scalmalloy® Laser Powder Bed Fusion Additive Manufacturing

OBJECTIVE: *To develop laser powder bed fusion additive manufacturing Scalmalloy for propulsion and cryogenic fluid management applications.*

PROJECT GOAL/DESCRIPTION

The aluminum (Al)–silicon (Si)–magnesium (Mg) alloy AlSi10Mg is a baseline additive manufacturing (AM) aluminum alloy, but mechanical properties are below that of other Al alloys such as 6061-T6 and required heat treatments add four weeks to manufacturing schedules for projects. High strength AM Al alloys are critical to propulsion and cryogenic fluid management (CFM) components. The objectives of this effort were to source APWorks Scalmalloy® Al alloy powder that meets AM specifications; to conduct laser powder bed fusion (L-PBF) AM parameter development; to investigate optimal heat treatments; to characterize microstructure and mechanical properties; and to qualify domestic supplier(s).

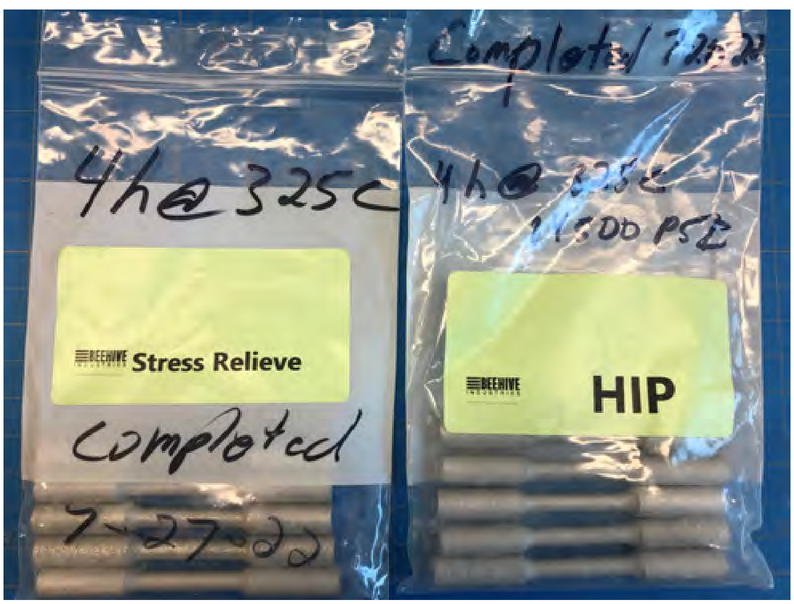


FIGURE 1. L-PBF AM Scalmalloy mechanical test specimens after heat treatment.

APPROACH/INNOVATION

Development began with Scalmalloy powder procurement and characterization to ensure it met L-PBF AM specifications. Parameter development was conducted by Beehive on an Electro Optical Systems (EOS) M290 L-PBF AM platform and resulted in an as-built relative density of 99.9 %. Microstructure characterization was conducted by IMR Test Labs and NASA Marshall Space Flight Center (MSFC). Heat treatment investigations, trial stress relief and hot isostatic press (HIP) schedules were conducted by MSFC. Multiple mechanical specimen builds were completed on the M290 and specimens underwent heat treatment, room-temperature tensile testing, and low cycle fatigue (LCF) testing at IMR Test Labs. An MSFC CFM component design was provided to Beehive to AM a Scalmalloy demonstration article, which underwent x-ray microcomputed tomography (μ-CT) nondestructive evaluation at MSFC in anticipation of testing. Parameters, metallographic, heat treatment, and mechanical property results are used to qualify commercial vendors to meet qualification requirements and publication to socialize with the broader aerospace AM community.

RESULTS/ACCOMPLISHMENTS

A domestic supplier of high strength aluminum AM Scalmalloy is now qualified for immediate use for turbomachinery, CFM, and optimized structures for Human Landing System (HLS), Space Nuclear Propulsion (SNP), robotic missions, etc. Domestic Scalmalloy AM services are now available to MSFC, other NASA centers, commercial aerospace partners, the U.S. Department of Energy (DOE), and the U.S. Department of Defense (DOD). Scalmalloy property data was made available for use in AM Scalmalloy design guidance.

PARTNERSHIPS

This project was completed in partnership with Beehive Industries (formerly Volunteer Aerospace, LLC), which sourced the Scalmalloy powder and conducted L-PBF AM parameter development, and which now offers Scalmalloy L-PBF AM services domestically.

SUMMARY

Scalmalloy L-PBF AM parameter development, heat treatment, and mechanical testing was completed. Metallographic and mechanical property data show a significant improvement compared to standard Al L-PBF AM alloys. These results will enable a greater degree of choice when requiring high strength propulsion components produced using L-PBF AM from Al-based alloys.

PRINCIPAL INVESTIGATOR: Omar Mireles
PARTNER: Beehive Industries
FUNDING ORGANIZATION: Cooperative Agreement Notice

Software Tools for Effective Use of Additive Manufacturing In-Situ Diagnostic Data

OBJECTIVE: *To develop a robust software solution for automated analysis and anomaly detection in additive manufacturing in-situ process monitoring data.*

PROJECT GOAL/DESCRIPTION

CFD Research Corporation (CFDRC) in Huntsville developed software tools for automated analysis and postprocessing of additive manufacturing (AM) in-situ process monitoring data, linking the diagnostic data to potential flaws in as-built parts. Previously, time-intensive manual review of in-situ monitoring data was required to assess the potential impact on part quality. As a result, the in-situ diagnostic data was not being fully leveraged to diagnose process outcomes and direct postbuild analysis. CFDRC leveraged their experience in image analysis to identify indications of potential part anomalies. Machine learning is used to automate the identification of process disturbances that impact material quality by linking the data to nondestructive evaluation (NDE) results. This met an immediate existing need to process the large volumes of in-situ monitoring data that are generated with each AM build. It complements other efforts to enable the use of in-situ monitoring data for defect detection and part certification. Large, complex AM parts may not be inspectable using computed tomography (CT) or other NDE methods, so there is an urgent need to assess the effectiveness of in-situ monitoring as a tool for quantifying part quality and enabling certification.

APPROACH/INNOVATION

CFDRC began with a literature review to contextualize the state of the art and promising approaches for processing in-situ monitoring data. A supervised convolutional neural network is a common approach, but requires a substantial library of trained (i.e., labeled) images to draw from. Any supervised learning approach requires identifying defect locations and labeling them to build a training set. These are the types of approaches CFDRC has used in the past for detecting changes in remote imagery.

Unsupervised learning can learn and recognize structure and patterns in raw data without labeled information. One major obstacle to overcome in the analysis of in-situ monitoring data is the presence of features that will appear as anomalies between build layers but are an expected feature of the build process, such as the change in orientation of

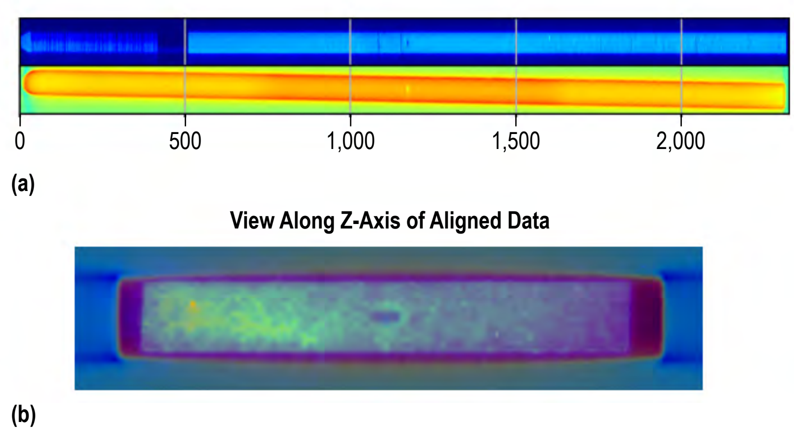


FIGURE 1. Registration and alignment of (a) thermal in-situ monitoring and (b) computed tomography data.

laser pass overlaps due to the chosen scan strategy. There are also variations in thermal emission that occur during a build, but do not result in any detriment to the part. Using CT scan data to determine locations where a defect was formed is a useful way to identify in-situ monitoring signatures that affect build quality.

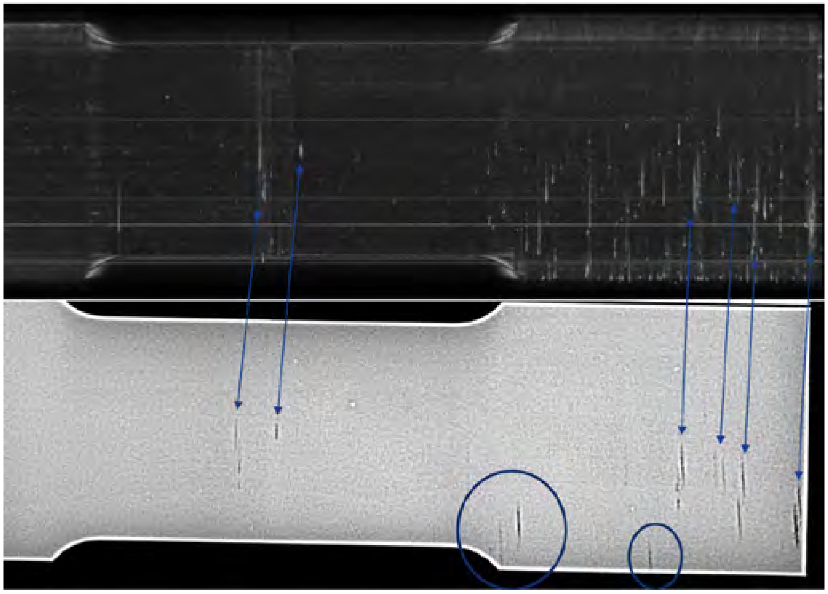


FIGURE 2. Comparison of thermal in-situ monitoring indications with an x-ray image of the part.

Edge detection and object extraction enabled individual analysis of multiple parts in an AM build and removal of background noise. Histogram analysis of the isolated build objects revealed major outliers that needed to be corrected, such as dead pixels and empty space around the parts. This led to the idea to generate synthetic nominalbuild data to use as a baseline for comparison. Partial synthetic data sets were generated from three build objects and the true data from another build object was used as a test set for an autoencoder approach. This neural network consists of encoder and decoder layers that reconstruct the image to highlight outliers. Two additional postprocessing steps have been employed to reduce noise: an exponentially weighted moving average filter to remove single-layer indications, and a median pooling filter to remove smaller spatial artifacts. Different statistical thresholding approaches were considered and tested, but in the end a three sigma threshold effectively highlights the areas of interest when combined with the postprocessing filters. This processing software has been delivered to NASA Marshall Space Flight Center (MSFC) and is being used to analyze in-situ monitoring data sets after a build is complete. The current in-situ monitoring system at MSFC requires the images to be exported after the build. For different monitoring systems that produce image files during the build, this software could be used for real-time analysis.

RESULTS/ACCOMPLISHMENTS

CFDRC has written an image segmentation algorithm in Python that is adaptable to different data sets. This is useful for isolating build objects for individual analysis and reducing data volume. This script has been delivered to MSFC and has been tested on different data sets with different object shapes and sizes with good results. This script could be implemented to reduce data volumes or to facilitate image analysis.

They also tested different image analysis methods and settled on an effective approach. Adding filters improved results for reliable detection of defects with reduction of noise. They refined and improved this approach by testing it on build data and delivered user-friendly scripts for implementation at MSFC. In addition to the script that crops the image data, generates a 3D volume, and trains the variational autoencoder; there is another script that processes the data, as well as a script to visualize indications.

The team has also accomplished the registration of CT data to in-situ monitoring data. These disparate data sets have differences in resolution and orientation that need to be reconciled before they can be compared side by side. These have been rotated to align within 0.1 degree, registered based on common features, and scaled appropriately to enable comparisons. A currently funded follow-on effort is expanding this capability to align, visualize, and analyze CT, in-situ monitoring, and serial sectioning metallography data.

PARTNERSHIPS

The CFD Research Company in Huntsville has completed many projects with NASA and other government entities. Many of these projects involve the processing of large image data sets and the development of user-friendly analysis software. They are currently on contract developing more advanced image visualization and analysis tools for in-situ monitoring data.

SUMMARY

The goal of this project was to develop a turnkey software solution for processing in-situ monitoring data. This met an immediate need in the MSFC AM lab to analyze large volumes of in-situ monitoring data produced with each AM build. The final image analysis scripts have been delivered to MSFC. These can be used on the data once it has been copied to another computer and exported as image files. Integration in line with the AM equipment manufacturer's in-situ monitoring software and sensors could be a potential area of future work. A complementary follow-on effort with CFDRC developing visualization and analysis software for in-situ, CT, and metallography data is ongoing. This work is a key part of NASA's efforts to characterize the flaw detection capability of in-situ monitoring systems to aid in AM part certification.

PRINCIPAL INVESTIGATOR: Dr. Vernon Cole, CFD Research Corporation

PARTNER: CFD Research Corporation

FUNDING ORGANIZATION: Cooperative Agreement Notice

Additive Construction at Drake State: Developing the Future Advanced Workforce

OBJECTIVE: *Drake State Community and Technical College, a Historically Black College (HBC), proposes to address the need for a diverse, qualified, knowledgeable pool of large-scale 3D printer technicians by creating a robust technician training that is tailored to the need of the existing and future NASA as well as commercial research and project implementation needs.*

PROJECT GOAL/DESCRIPTION

The project contributes to addressing a defined NASA need in the area 2.1.2 Advanced Manufacturing, Structures, and Materials. Specifically, NASA has identified a need in developing technologies that enable additive manufacturing of large-scale, nonmetallic 3D structures (2.1.2). The development of these needs requires maintenance and operation of 3D printers by experimental researchers who are engaged in fundamental research aimed at solving complex scientific research questions. As research teams experiment with new technology, materials, and concepts, they need qualified technicians who are knowledgeable about utilizing the complex equipment such as 3D printers. During the design and implementation stage or in the event of breakage, maintenance and problem troubleshooting for additive manufacturing equipment, such as large-scale 3D printers, can significantly delay a research project or detract valuable research team time and resources. Skilled additive manufacturing technicians are a valuable asset to research and development teams working on NASA research projects. The proposed project/technology development partnership will benefit a specific NASA need in advancing knowledge and technical readiness levels in additive manufacturing at NASA Marshall Space Flight Center (MSFC); will benefit NASA's goal of creating a pipeline of qualified diverse workforce; and will develop Drake State's strategic and development needs in large-scale printer design, printing processes, and printing structures. The training program will include a practical building project utilizing the 3D printer.

FIGURE 1. Assembled research printer robotic arm.

APPROACH/INNOVATION

MSFC released an annual call seeking outcome-based proposals for Research and Technology (R&T) Cooperative Agreement Notice (CAN) projects. The Minority University Research and Education Program (MUREP) provides funds for work with Historically Black Colleges and Universities (HBCUs) and Minority Serving Institutions (MSIs) to support education opportunities with those institutions. Using the CAN, Marshall awarded a contract to Drake State Community and Technical College for Additive Construction at Drake State: Developing the Future Advanced Workforce.

To achieve the project's goals and objectives, five outcomes were highlighted, and a work plan was developed with project deliverables that showed progress and real success for an HBCU, its students meeting a NASA need.

The established project outcomes are as follows:

(1) Increase the overall body of knowledge associated with additive construction for both terrestrial (i.e., on-earth) and planetary (i.e., in-space) applications.

(2) Advance the technology readiness level (TRL) associated with large-scale printers designed for terrestrial applications from TRL 2 to 4.

(3) Advance the TRL associated with large-scale construction printing processes for terrestrial applications from TRL 2 to 5.

(4) Advance the TRL associated with full scale printed structures for terrestrial structures from TRL 2 to 4.

(5) Create a ready, trained, and ready diverse workforce of 3D printer technicians.

The deliverables associated with these outcomes and their status are listed below in the results section. The HBCU, NASA Center, industry partner ICON, and the Frontiers Research Program Advisory Board members made the cooperative agreement project the success it is today. The final report results documenting the demonstration in November 2022 comes at the conclusion of the project. Results will be published in the 2023 Research and Technology Report.

RESULTS/ACCOMPLISHMENTS

As part of the CAN, the research group developed a set of defined research tasks with defined data collection protocols. The defined research tasks include: the fiber puller design; a series of tests for measurement of concrete viscosity (flowability) during mixing, pumping, and construction; the curing process and the measurement processes that involved breaking the test coupons to collect data.

Initial data was collected by the interns and NASA technical team that included the safety protocols; viscosity measures; concrete mixing protocols used; and compression test results. This data was compiled into a database with metadata.

A 3D printing center was set up on the Drake State campus. The preliminary building permitting process was initiated. Safety protocols that pertained to the 3D printing processes were discussed and incorporated into intern training. The 3D printer was acquired and is being set up for the first test run.

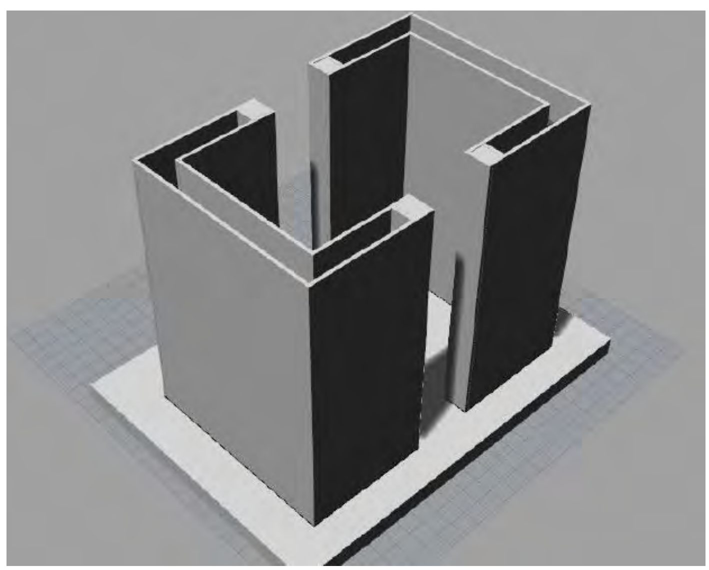


FIGURE 2. CAD 3-D Design rendering of experimental structure.

Two training certificates were approved and added to the state-wide list of curricula. Drake State is offering the courses, such as Rheology (ADM 158) from the curriculum in Fall 2021 semester. The goal is to train at least 20 students in additive manufacturing through these courses.

A goal was set to train four additive manufacturing interns, with at least 30 hours of 3D printer access, and four individual reports with training observations from each intern. These four interns participated in field trips to ICON facility and had access to the 3D printer. The first cohort of the interns completed their observation reports in February 2021. The second cohort will complete their observation reports pending the completion of the program.

Two of three progress reports have been completed, including the finalized fiber puller design and the results of the first series of tests at the ICON facility. The third interim report is pending the complete analysis of results from tests of sample coupons.

PARTNERSHIPS

Drake State worked in partnership and collaboration with NASA Marshall Space Flight Center and ICON, a leading construction firm in advanced construction technology out of Austin, TX. Advising Drake State was the Frontiers Research Program Advisory Board made up of local leaders in government, education, and industry.

SUMMARY

Drake State has established a successful partnership between an HBCU community college, a NASA center, and a business. NASA cooperative agreement can be utilized to develop qualified and diverse workforce that can address the future technology needs. Through cooperation, a community college can successfully participate in research and technology development activities that serve both the government and communities.

PRINCIPAL INVESTIGATOR: Robert N. Grissim; Karen Ray

PARTNERS: Drake State Community and Technical College; ICON

FUNDING ORGANIZATION: Cooperative Agreement Notice

Additive Manufacturing of Outfitting Components for Lunar Habitat Interior and Exterior

OBJECTIVE: *To develop Drake State additive manufacturing of outfitting components for lunar habitat interior and exterior with NASA Marshall Space Flight Center.*

PROJECT GOAL/DESCRIPTION

This project contributes to addressing a defined NASA Marshall Space Flight Center (MSFC) technology focus area A.4.1 in advanced manufacturing. Specifically, NASA identified a need in developing technologies supporting advanced manufacturing, structures, and materials (4.1.2). The development of these needs requires solutions for in-space manufacturing using polymers as feedstock as well as understanding of the effects of microgravity on materials used for additive manufacturing in space. Drake State Community and Technical College, a Historically Black College (HBCU), proposes to manufacture 3D-printed outfitting components for lunar habitat interiors and exteriors in a simulated microgravity environment utilizing its 3D printer with a robotic arm. This project will contribute to the understanding of the behavior of polymer and polymer-mix materials in microgravity. The project will print and test a subset of items up to 152 cm^3 in volume. This research agenda will be integrated in the training curriculum for Drake State's Additive Manufacturing program, which trains skilled technicians in additive manufacturing. The proposed project will contribute to enhancing technology readiness levels (TRLs) and enhancing the body of knowledge in additive manufacturing in microgravity, additive manufacturing of polymers, and printing parts for planetary structures. This project builds on the existing Cooperative Agreement Notice (CAN) in additive manufacturing of large-scale, nonmetallic 3D structures awarded to Drake State in August 2020. The proposed project is being carried out in cooperation with Kappler, Inc. on the construction of the structure for microgravity simulation, and with technical consultation from Made In Space, Inc.

FIGURE 1. Test structure.

APPROACH/INNOVATION

Solving the problem of manufacturing parts and tools in space is one of the key components of successful sustainable space exploration and establishing a sustained presence first on the Moon and later on Mars. Additive manufacturing technology has proven successful in enabling the capability to manufacture needed structures, tools, and parts with flexibility and limited feedstock availability using in-situ materials. As a part of the Artemis project, NASA is working on developing a space-based

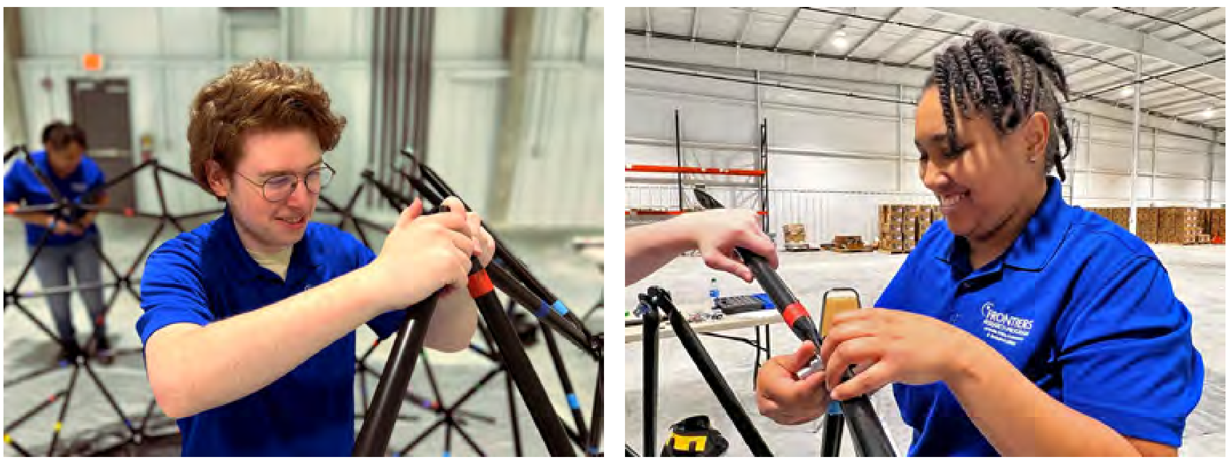


FIGURE 2. Interns working on assembling the structure at Kappler.

habitat construction system to sustain lunar exploration. In order to be habitable, structures must be outfitted with structural components, furniture, and tools. Given that delivering one kilogram of material from Earth is costly and the total load is limited, lunar habitats must be able to create processes for acquiring or recycling materials for manufacturing the required parts on site. These parts, such as but not limited to the wall penetrations, brackets, environmental enclosure structure components, furniture items, racks, storage containers, and more, can be manufactured utilizing plastic feedstock or recycled plastic materials in order to minimize waste and reduce supply payload required for delivery from Earth. Thus, achieving seamless logistics of producing the necessary tools and equipment in space is one of the key prerequisites of successful long-range space exploration missions.

The existing research on 3D printing in space includes successfully printing and testing polymer-based small tools and samples on the International Space Station (ISS) in 2014–2016. The first printed items manufactured in microgravity were produced in two phases in 2016, thus successfully completing the 3D Printing in Zero G Technology Demonstration Mission. Current research efforts include investigating the effects of microgravity on additive manufacturing and establishing protocols for recycling feedstock material, such as polymers, for use as feedstock in multiple manufacturing cycles. The ISS Refabricator Technology Demonstration project will test whether recycling of plastics can produce successful fabrication of items from polymer-based materials.

To date, samples manufactured in microgravity have been produced during the 3D Printing in Zero G Technology Demonstration Mission. During the mission, items were manufactured with a print volume of 1,400 cm^3 ($14 \times 10 \times 10$ cm). To add to the existing body of knowledge, Drake State proposes to manufacture a subset of items for outfitting of lunar habitat. These items will be produced using the fused deposition modeling (FDM) printer with an attached robotic arm. The print volume of the printer with robotic arm is approximately 5×5 ft (152×152 cm). Additional sample size variations will be explored by manufacturing samples that range up to 8 ft (243 cm) in height by mounting the robotic arm onto a gantry crane. The samples will be printed using polymer feedstock. For the experiments, the 3D printer will be housed inside a Kappler-made structure that will enable the simulation of microgravity. This project will create synergy with the existing Drake State CAN for additive manufacturing of a building. Drake State plans to test the proposed samples, such as building fixtures or furniture items, by using them for outfitting the 3D-printed concrete structure.

RESULTS/ACCOMPLISHMENTS

The CAN team worked on the creation of a database with samples, drawing from the ISS database. To date, there are 50 items in the database, with 14 items test printed.

Drake State's team worked closely with Kappler Inc to coordinate the manufacturing of the testing enclosure. The enclosure was built and the interns traveled to Guntersville on three occasions to learn how to assemble and disassemble the structure. On July 14, 2022, the Kappler primary investigator reported that the structure is not able to withstand the pressure that is specified in the task order. Given that the test structure is unable to maintain structural integrity, it was advised by the NASA Technical Advisor to not place the robotic arm inside the structure.

FIGURE 3. Dr. Bruce Peters of Torch Technologies mentoring the intern on training the robot.

Two interns were selected and trained: Sharde Tate and Luke Thomas.

The CAN team is working with Dr. Bruce Peters from Torch Technologies on the tasks of integrating the robotic arm with the MakerBot extruder. Tasks are:

(1) Contact the manufacturer of the robotic arm to obtain a plugin for DobotSCStudio to obtain the parameters for the developed 3D models from GCODE.

(2) Code the robot manually through the script terminal provided within DobotSCStudio.

(3) Dial the robot in within the Teach Trajectory mode; set up a grid; and, in teach mode, do the same path as a 3D printer would (X and Y planes only).

Currently, the intern is working on sending a digital output signal to the extruder to be able to begin the first print.

PARTNERSHIPS

The proposed project is expected to be carried out in cooperation with Kappler, Inc. on the construction of the structure for microgravity simulation and in technical consultation with Torch Technologies on the integration of the robotic arm with a 3D printer extruder.

SUMMARY

Drake State respectfully requests approval for the no-cost extension of the CAN given that the project timeline crept due to the delays in the fabrication of the Kappler structure that led to the delays in the structure testing. Drake State's project timeline was tied to the Kappler timeline. Additionally, the process of integrating the robotic arm with the 3D printer extruder, requires additional time, given the tasks of setting up communication between the extruder and the robot. The current CAN balance is 67% of the funds spent or encumbered. The extension is requested for one year.

PRINCIPAL INVESTIGATOR: John Ellis, Drake State University

PARTNERS: Drake State Community and Technical College; Torch Technologies; Kappler Inc.

FUNDING ORGANIZATION: Cooperative Agreement Notice

FOR MORE INFORMATION: https://drakestate.edu/career-pathways-programs/frontiers/

Development of Radioluminescent Tritium Material for High Visibility Applications

OBJECTIVE: *To develop a radioluminescent tritium material capable of surviving multiple space environments to fulfill visibility requirements levied on space flight hardware and to facilitate additional long term internal and external lighting needs.*

PROJECT GOAL/DESCRIPTION

The project goal is to identify, synthesize, and test a radioluminescent tritium polymer material that can emit enough light to meet visibility requirements for optical recognition, imagery tracking, and other internal/external lighting needs. Such materials could provide illumination for the portable life support system for the Exploration Extravehicular Mobility Unit (xEMU), for the Human Landing System (HLS), and for rovers. The materials are being designed to meet mission illumination levels, such as those for remote sensing of the Mars Ascent Vehicle (MAV) (400 – 900 nm wavelength and 0.5 surface reflectance) and for Smart Video Guidance Sensors (SVGS) (475 nm wavelength and 2.5 W radiant flux).

Tritium is radioluminescent, meaning that radioactive decay of the nucleus results in the emission of beta particles. These high-energy, high-speed electrons will fluoresce and give off light when striking a phosphor, such as zinc sulfide. The combination of contained tritium gas and a phosphor is referred to as a gaseous tritium light source (GTLS). A GTLS provides a sustainable light source requiring no electrical energy, which provides light for 10 to 20 years on average.

APPROACH/INNOVATION

MB-Microtec AG Trigalights®, a brand of GLTS, were purchased in a variety of colors, shapes, and sizes. The lights will be mixed with four different silicone adhesives: Dow Corning DOWSIL™ 93-500, Avantor® NuSil® CV-2289, NuSil CV-1144-0, and Master Bond® MasterSil® 971-LO. The light/adhesive mixture will then be applied to a substrate or allowed to cure in an aluminum dish. After completely cured, the samples will be viewed in a light box in both light and dark conditions to observe the brightness of each coating/substrate system. Photometric measurements of intensity, luminance, flux, and illuminance will be taken. Additional mechanical and environmental testing will be carried out to assess temperature and pressure effects, darkening of the polymer, viscosity, ease of application, etc.

This effort is complementary to work being done at NASA Marshall Space Flight Center (MSFC) with SVGS. Light-emitting diode (LED) targets are currently being used to measure distance via photogrammetry. Tritium material could replace the illuminated targets.

The next steps are preparing the material samples for testing at MSFC and for the 18th Materials International Space Station Experiment (MISSE – 18) mission.

RESULTS/ACCOMPLISHMENTS

Milestones:

- Meeting all radiation safety requirements to properly handle and store the GTLS, including proper Nuclear Regulatory Commission (NRC) licensing, radioactive material signage, and safety training.
- Purchasing and receiving GTLS.
- Identifying four silicone adhesives for the experimental polymer binders.
- Purchasing a BYK-Gardner byko-spectra® standard 115 V light booth for observing the material and lights.
- Being selected for the MISSE – 18 mission.
- Securing fiscal year (FY) 2023 Center Innovation Fund continuance funding.

SUMMARY

GTLS will be combined with silicone adhesives to create a radioluminescent tritium polymer material that can meet visibility requirements for optical recognition, imagery tracking, and other internal/external lighting needs. The materials are being designed to meet mission illumination levels such as those for remote sensing of the MAV (400 – 900 nm wavelength and 0.5 surface reflectance) and for SVGS (475 nm wavelength and 2.5 W radiant flux). Test specimens of these materials will receive mechanical and environmental tests and their optical quantities will be measured and recorded. The lights and specimens will also be flown on the International Space Station as a part of the MISSE – 18 mission. The results will be used to determine the optimal candidate for further testing and to identify additional areas of use for radioluminescent tritium materials.

PRINCIPAL INVESTIGATOR: Lauren Fisher

FUNDING ORGANIZATION: Center Innovation Fund

Enhanced Equipment Isolation in Extreme Vibratory Environments Using Rotational Inertial Devices

OBJECTIVE: *To develop a vibration mitigation device (VMD) that combines passive isolation and a rotational inertial device into a single VMD.*

PROJECT GOAL/DESCRIPTION

NASA hardware is subject to extreme vibratory environments. These environments can cause damage to avionics boxes and other equipment that is difficult to mitigate. This problem is of particular importance when using legacy hardware in new systems with higher predicted environments, such as the Space Launch System and Orion Spacecraft. A traditional solution to these vibration concerns are low-stiffness isolation mounts. The isolated system's low stiffness, and thus the low isolation frequency, effectively controls the acceleration response of the equipment it is attached to when considering a broadband loading. However, this decreased stiffness and low isolator natural frequency would cause the equipment to be subjected to excessive displacement and acceleration response at low frequencies due to transient excitation. The objective of this collaborative project between the University of Tennessee (UT) and NASA Marshall Space Flight Center (MSFC) is to provide a proof of concept for, and assess the feasibility of, an equipment vibration isolation system for NASA hardware that features rotational inertial devices. As this project is an intermediate step toward further development, the research team only considered loading and response in one direction. Analytical and numerical modeling was performed to model the behavior of different configurations of a rotational inertial device. The research team designed, fabricated, experimentally tested simulated flight hardware with an isolation system featuring rotational inertial devices.

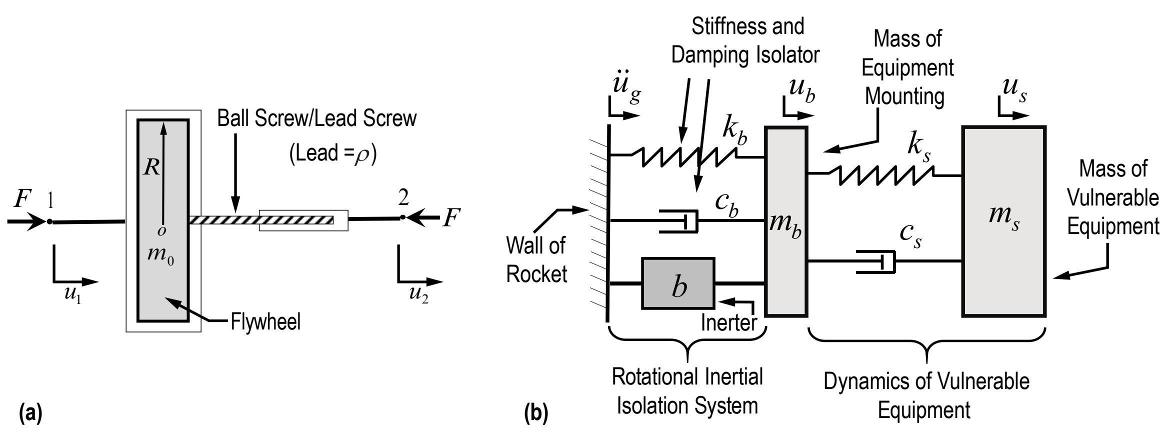
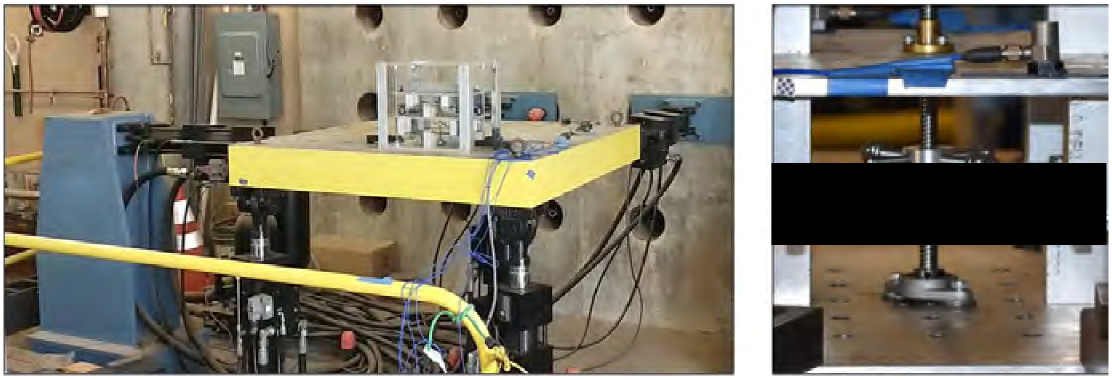


FIGURE 1. (a) Example diagram of an inerter and (b) example configuration of an isolated system with a rotational inertial device.



(a) (b)

FIGURE 2. (a) Shake table testing of system that includes a rotational inertial mechanism in its isolation layer and (b) Rotational intertial mechanism in isolation layer.

APPROACH/INNOVATION

This work sought to leverage recently developed rotational inertial devices and to combine them with isolation systems. While these rotational inertial devices have taken various forms, their common feature is a mechanical device called an inerter. The inerter is a two-terminal mechanical device that produces a rotational inertial mass proportional to the relative acceleration between its two terminals. Realizations of the inerter include the rack and pinion mechanism and ball screw mechanism. Through the transformation of linear motion to rotational motion, the inerter can provide a large effective inertial mass through a physically small flywheel mass.

Inerter-based isolation systems combine devices featuring inerters with traditional low-stiffness isolation systems. In general, studies on inerter-based isolation systems have found that they are capable of significantly reducing the displacement response of the isolated system without increasing their peak acceleration response. While previous studies of inerter-based isolation systems have shown promise in leveraging these mass effects for vibration control, these studies have largely not considered the experimental realization of these devices.

RESULTS/ACCOMPLISHMENTS

The research team's accomplishments in 2022 include shake table testing of the hardware developed in the past year (i.e., the isolated system testbed with a rotational inertial device) and the development, manufacturing, and testing of the mass lever inerter, which is a new way to realize the effects of rotational inertial devices. Furthermore, the lessons learned from the experimental design and testing portions of the entire project have been documented to assist in the group's subsequent development effects.

The results from these experimental studies serve as a proof of concept and show that the inclusion of an inerter in an isolation system reduced the magnitude and frequency of the isolation mode, but that a rise in the high-frequency vibrations transmitted was observed. The influence of this transmission likely depends on the system being isolated. These phenomena were previously seen in the numerical frequency response results and increase with increased size of the inerter.

Efforts to disseminate the results of this project include the following conference presentation/paper and poster presentation:

- Abolghasemi, S.S.; Wierschem, N.E.; and Knight, J.B.: *"Vibration mitigation using an inerter-based isolation system,"* Engineering Mechanics Institute Conference 2022 (Dynamics Committee Student Paper Competition), Baltimore, MD, May 31 – June 3, 2022.
- Shell, J.; and Wierschem, N.E.: *"Passive Structural Control Achieved with a Mass Lever Inerter,"* Exhibition of Undergraduate Research and Creative Achievement, University of Tennessee, April, 2022 (poster presentation, won an award).

PARTNERSHIPS

This project was executed by partners Nicholas Wierschem and his research group at UT and Brent Knight at NASA MSFC. In this partnership, the UT group was primarily responsible for analysis, design, and experimental efforts. Through regular meetings, Mr. Knight helped to ground the project with the concerns and limitations of its application with NASA, as well as resolve issues that were identified and plan the next steps of the project. This partnership is exploring ideas for continued collaboration on projects involving structural dynamics, dynamic loads, and vibration mitigation.

SUMMARY

This project sought to provide a proof of concept for an equipment vibration isolation system for NASA hardware that features a rotational inertial device. Simulated flight hardware with an isolation system featuring two options for rotational inertial devices has been manufactured and experimental testing of this hardware has been completed at the UT shake table facility. Data from this project, including the experimental tests, have served to validate part of the numerical models of these devices and support further study of rotational inertial isolation systems, including those systems that consider intentional nonlinearities in the rotational inertia device. This project concluded in March 2022.

PRINCIPAL INVESTIGATOR: Dr. Nicholas Wierschem, University of Tennessee

PARTNER: University of Tennessee

FUNDING ORGANIZATION: Cooperative Agreement Notice

Cavitation Effects on the Structural Dynamics of Turbomachinery Components: Modeling and Experiment

OBJECTIVE: *To develop and experimentally validate a computational modeling tool for predicting the effects of cavitation on the structural dynamic properties of turbopump inducer and impeller blades.*

PROJECT GOAL/DESCRIPTION

The structural dynamic characteristics (e.g., natural frequencies, mode shapes, and damping) of a structure can be greatly changed when the structure is in contact with dense fluids. This phenomenon is inherent in many systems, such as fluid pumps and naval propulsion. While some empirical, analytical, and experimental data exists examining fluid-structure interaction, it is generally limited to simple geometries and in well-behaved flow regimes. Components of liquid rocket engine turbomachinery have complex geometry and operate in a variety of extreme flow conditions. One of the most complicated and destructive flow phenomena present in turbomachinery is cavitation where vapor bubbles form in the fluid, as seen in figure 1. The presence of the cavitation bubbles adds a level of complexity to the structural dynamic characteristics.


FIGURE 1. Cavitating inducer.

A cooperative research program has concluded between NASA Marshall Space Flight Center (MSFC) and the University of Georgia (UGA) to measure and predict the dynamic structural response of inducer bladelike geometries in the presence of cavitation. UGA used their high-speed water flow facility to measure the dynamic response of submerged cavitating plates. MSFC in turn has used this experimental dataset to validate numerical models that predict the natural frequency, damping, and response of submerged structures. This computationally efficient and test-validated modeling tool will be used in the development and analysis of liquid engines for NASA and its commercial space partners.

APPROACH/INNOVATION

MSFC is developing a computationally inexpensive alternative to full-order fluid-structure interaction (FSI) simulations of cavitating flows. This will be accomplished by validating the recently developed nonlinear fluid modal method (NFMM) with experimental data of a cavitating flow case. MSFC will use FSI simulations of a representative 'unwrapped' inducer test article to construct the NFMM model; this can then be used in place of traditional computational fluid dynamics to predict the structural dynamic behavior, thereby increasing simulation speed by orders of magnitude. UGA fabricated and fine-tuned the test article, mounted it in a state-of-the-art high-speed water tunnel, ran test flow cases with induced

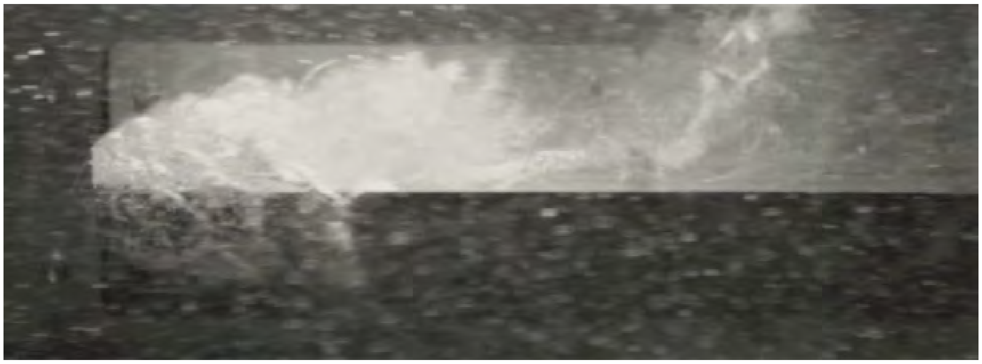


FIGURE 2. Cavitating plate in UGA water tunnel.

cavitation, and measured the structural dynamic response. UGA also reduced the data and reported it to MSFC for code validation. The deliverables from UGA included a detailed test description, including instrumentation; test parameters and conditions; results summary; and digital copies of all test data.

RESULTS/ACCOMPLISHMENTS

UGA constructed a notional test article to verify time history and high-speed video data capture. Several iterations to the test article and leading-edge geometry were completed, resulting in a configuration that controllably produced large cavitation, shown in figure 2. UGA also reinforced their test facilities in order to increase the range of the operating pressure. This resulted in greater control of cavitation onset and magnitude, which allowed for a broadening of the original test matrix. Additionally, measurements were taken under two excitation mechanisms: (1) A pneumatically actuated plunger and (2) self-excitation due to a combination of vortex shedding and cavitation. The improvements UGA made greatly increased the amount of usable data gathered from this test campaign and postprocessing at MSFC is still ongoing due to the size of the dataset.

From the data that has been examined, a counterintuitive phenomenon was observed. As cavitation increases, it is expected that the natural frequency of the structural article will increase due to less 'heavy' fluid being present in its vicinity. The UGA data repeatedly showed that the natural frequency decreased for certain flow conditions (see fig. 3). It is hypothesized that this occurs due to a flutter instability or lock-in effect of the structure and flow, but this hypothesis has yet to be confirmed analytically. Numerical predictions of the plate response and hydrodynamic damping are ongoing.

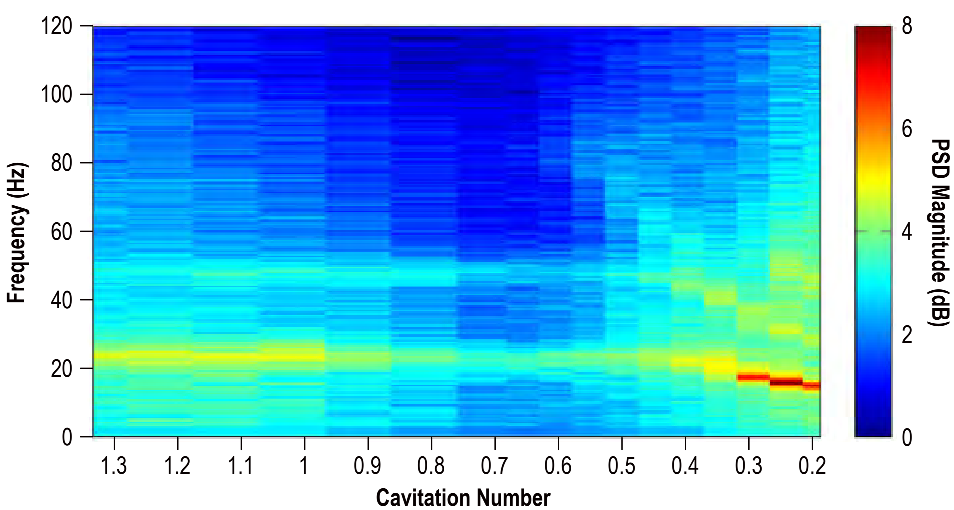


FIGURE 3. Effect of cavitation on natural frequency.

PARTNERSHIPS

MSFC is partnering with UGA on this project, utilizing their high-speed water flow dynamics facility and their wealth of knowledge to further research on developing advanced turbomachinery components.

SUMMARY

A Cooperative Agreement Notice technology development program between MSFC and the University of Georgia to study the effect of cavitation on the structural dynamic response of turbomachinery components has been completed. UGA has completed an extensive test series in their water flow dynamics facility. This data is being used at MSFC to validate a numerical code in development for the prediction of the structural dynamic response of components in the presence of cavitation. This prediction capability has proven to be critical for the accurate structural dynamic analysis of pump-side structures such as inducers and impellers.

PRINCIPAL INVESTIGATORS: Timothy Wray; Andrew Brown

PARTNER: Dr. Benjamin Davis, University of Georgia

FUNDING ORGANIZATION: Cooperative Agreement Notice

In-Situ Synchrotron Characterization of Levitated Aerospace Alloys Under Dynamic Processes for Optimization of Advanced Manufacturing Methods

OBJECTIVE: *To support NASA's vision of developing for-space manufacturing and in-space manufacturing capabilities by providing in-situ chemical and structural material characterization of dynamic processes for optimizing processing parameters and validating computational models, progressing toward qualified metallic components.*

PROJECT GOAL/DESCRIPTION

The investigation of dynamic structural evolution is vital in the comprehensive study of the rapid melt and solidification processes undergone in additive manufacturing (AM) processes and their effect on the resulting microstructure of the solid part; and, in turn to understand the impact of microstructure on macroscale material behavior. Improving understanding of solidification mechanisms will assist in process optimization and support phase field simulation efforts that can then be expanded into larger ranges of temperature and composition measurements for material evolution prediction. This research will utilize the synchrotron light source at the Louisiana Center for Advanced Microstructures and Devices (CAMD), which offers the opportunity to study both dynamic sintering and melting processes and the resulting structural and compositional evolution.

APPROACH/INNOVATION

This project proposes to utilize the NASA Marshall Space Flight Center (MSFC) mobile electrostatic levitation (ESL) instrument for integration at the CAMD synchrotron facility, to enhance and couple the materials science and engineering expertise of MSFC's ESL Laboratory with the CAMD synchrotron radiation facility's in-situ characterization capabilities. This will provide data on the time sequence of phase transformations during different processing temperature profiles. In-situ synchrotron x-ray diffraction testing will provide tangible data to help understand the mechanisms for processing under specific temperature profiles and gas environments. The synchrotron beam source will allow the investigation of both the in-situ structural and chemical dynamics of the alloy systems via x-ray absorption and diffraction studies, providing support for the development of improved AM simulation, and processing and control strategies. Deliverables include optimized in-situ experimental processes for extraction of the properties of interest, data supporting AM process optimization, and modelling of AM processes for targeted alloys.

X-ray absorption and spectroscopy measurements of levitated samples will provide quantitative data relating to

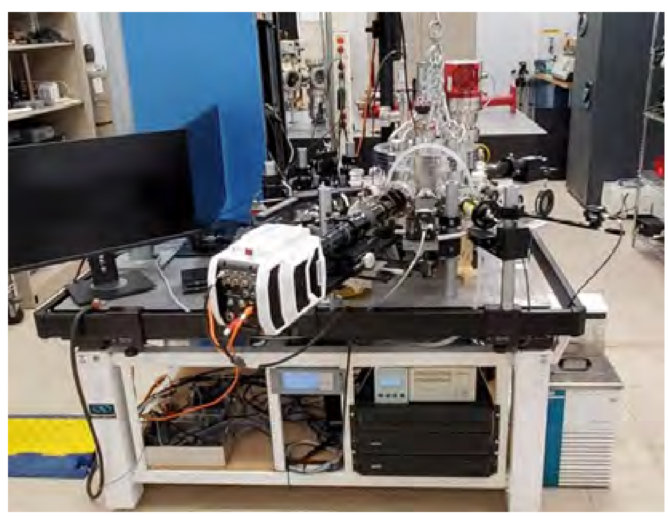


FIGURE 1. Portable electrostatic levitator.

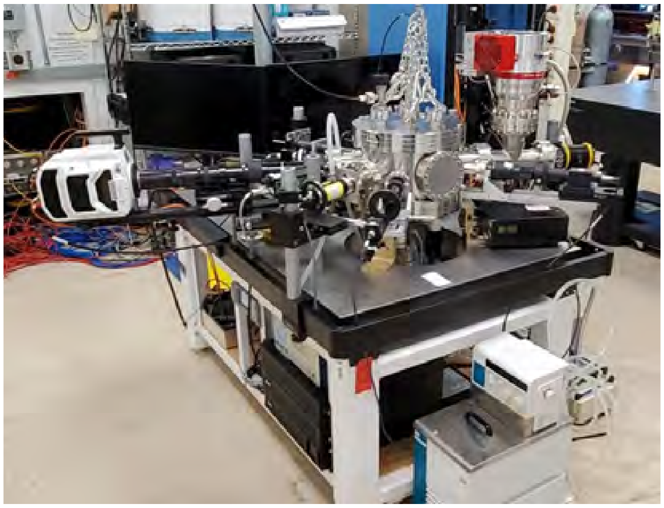


FIGURE 2. Portable electrostatic levitator.

characterization of surface composition, segregation, and diffusion of the targeted material systems, including nickel alloys, titanium alloys, and stainless steel. Energy dispersive diffraction measurements of levitated samples will provide quantitative data related to microstructural evolution, including during the melting and solidification transition of levitated samples.

To complement the in-situ spectroscopy and diffraction studies, ex-situ characterization will combine focused ion beam scanning electron microscopy, electron backscatter diffraction, and transmission electron microscopy. The chemical diffusion of alloying species, the grain size and shape distribution, and phase distribution in processed samples and as-built parts will be investigated. The goal will be to optimize the experimental procedure and determine the complete set of characterization modes to benefit future ESL tests.

RESULTS/ACCOMPLISHMENTS

Unfortunately, due to a window failure at the CAMD synchrotron and retiring supporting test personnel at MSFC, the testing has been postponed into the next calendar year. However, the research team is using the additional time to allow for improved optimization and conditioning of the new hardware at CAMD, as well as doing some pre-characterization of samples on the mobile ESL at MSFC and training new personnel to allow for testing in 2023.

PARTNERSHIPS

This work is in collaboration with Dr. Jonathan Raush (University of Louisiana at Lafayette) and Dr. Phil Sprunger (Louisiana State University). The data generated by these experiments will support phase field simulation efforts at University of Louisiana at Lafayette. Another objective of this work is the development of a sustainable collaboration for conducting future ESL beamline studies with the data directly impacting AM process and simulation improvements that are relevant to NASA.

SUMMARY

This collaborative research effort will study additive manufacturing processes using aerospace metal alloys of interest in both for-space manufacturing and in-space manufacturing applications. The goal of this project is to utilize the MSFC mobile ESL system for integration at the CAMD synchrotron facility to investigate both the in-situ structural and chemical dynamics of the alloy systems via x-ray absorption and diffraction studies.

The investigation of dynamic structural evolution is vital in the comprehensive study of the rapid melt and solidification processes undergone in AM processes and their effect on the resulting microstructure of the solid part; and, in turn to understand the impact of microstructure on macroscale material behavior. The synchrotron light source at CAMD offers the opportunity to study both dynamic sintering and melting processes and the resulting structural and compositional evolution.

PRINCIPAL INVESTIGATOR: Brandon Phillips
PARTNER: University of Louisiana at Lafayette
FUNDING ORGANIZATION: Cooperative Agreement Notice

On-Demand Manufacturing of Multimaterials

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

PROJECT GOAL/DESCRIPTION

The On-Demand Manufacturing of Multimaterials (ODMM) project provides a solution toward sustainable, flexible missions through on-demand fabrication, replacement, and recycling capabilities to support critical systems, habitats, and mission logistics and maintenance. These capabilities can provide tangible cost savings by reducing launch mass; can reduce risk by decreasing dependence on spares; can enable design systems for maintainability; and can enable crew to respond to unanticipated scenarios.

APPROACH/INNOVATION

The current International Space Station (ISS) logistics model is heavily dependent upon orbital replacement units (ORUs) for system-based repair and maintenance. Logistics support and habitat outfitting is a significant challenge for sustainable, extended human operations in space, especially for missions beyond low-earth orbit where timely resupply or abort in the event of emergency would not be possible.

The ODMM project has partnered with Techshot, Inc. and Redwire, Inc. to develop a system capable of demonstrating the manufacturing of metal, polymer, and electronic components aboard the ISS. Following the demonstration of feasibility, similar systems will be used for habitat outfitting and logistics reduction aboard transit vehicles. While a prototype system was demonstrated in in previous years, the project primarily focused on the reduction of power necessary to consolidate metallic parts, and on

FIGURE 1. In-Space Manufacturing project portfolio graphic.

the design of a revised furnace module. These efforts complement a sister project within the NASA In-Space Manufacturing portfolio (On-Demand Manufacturing of Electronics) as well as academic research at the University of Louisville on the bound metal additive manufacturing (BMAM) process. The next fiscal year (FY) will be focused on the maturation of the system toward critical design review (CDR) with an emphasis on the printer module.

RESULTS/ACCOMPLISHMENTS

The ODMM project is pursuing the commercial development of hybrid (i.e., additive-subtractive) manufacturing prototype units for demonstration aboard the ISS. Two distinct approaches were considered. Techshot, Inc. has developed a fully integrated ground-based prototype system using bound metal deposition (BMD) known as the Fabrication Laboratory (FabLab), which can produce titanium parts. Redwire, Inc. developed a wire-arc additive manufacturing (WAAM) system called Vulcan to produce aluminum components. During 2022, the Vulcan system conducted a preliminary design review (PDR) and phase I safety review. Following the conclusion of the PDR, a downselection study was conducted. The FabLab facility was selected for further maturation towards CDR.

The FabLab payload's furnace module was redesigned to accommodate the requirements of the EXpedite the PRocessing of Experiments to the Space Station (EXPRESS) rack. The hot zone size was altered to $4.5 \times 4.5 \times 7$ in while additional insulation was added to reduce the thermal load. These changes, in conjunction with lowing the process temperature, resulted in a preliminary analysis indicating that the revised furnace design will meet engineering margins. Hardware for the qualification unit is currently underway with an expected delivery date in the first quarter of FY 2023.

FIGURE 2. Diagram of the Techshot FabLab system.

Recycling and reuse technologies were also matured. In partnership with Cornerstone Research Group, the ODMM project successfully formed a batch of reversible thermoset polymers with approximately 15% flame retardants added.

An outfitting subproject under ODMM is currently being scoped. Within the past year, the project has partnered with NASA Crew Health and Performance Exploration Analog (CHAPEA) to provide a 3D printer and handheld scanner for the crew analog mission. Data on how the crew interacts with the system and outfitting needs will be used to develop an infusion plan for in-space manufacturing technologies.

PARTNERSHIPS

Techshot, Inc. is the prime contractor for the development the FabLab payload. The contractor provides a wealth of experience as a payload developer and is currently on contract to mature the payload through a CDR in 2024.

Redwire, Inc. is the prime contractor for the development of the Vulcan payload. Although Vulcan was discontinued in favor of the FabLab facility, it should be noted that Techshot is a subsidiary of Redwire. Continued partnership with Redwire on subsequent payloads is anticipated.

SUMMARY

The ODMM project aims to develop and demonstrate systems for manufacturing goods in a reduced gravity environment to address logistics challenges associated with long duration missions and a sustainable presence on the lunar surface. During the past year, the project matured the FabLab furnace module to fit within the EXPRESS rack resource requirements and started the manufacturing of a engineering development and qualification unit. The payload is anticipated to conduct a CDR within the next calendar year. Additionally, ODMM matured recycling and reuse technologies and started to scope the inclusion of a subproject for habitat outfitting.

PRINCIPAL INVESTIGATOR: Christopher Roberts
PARTNERS: Techshot, Inc.; Redwire, Inc.
FUNDING ORGANIZATION: Game Changing Development

Development and Testing of Recyclable and Antimicrobial Materials for Additive Manufacturing

OBJECTIVE: *To develop and test a recyclable and antimicrobial polymer for additive manufacturing for use on long duration missions.*

PROJECT GOAL/DESCRIPTION

To achieve NASA's goals for maintaining and sustaining a human presence in space, on-demand manufacturing will be required. Under the current paradigm, the International Space Station (ISS) is constantly resupplied from Earth; for long-duration missions, however, this logistical model is not feasible. For building outposts on both the lunar and martian surfaces, for example, logistics reduction will be necessary, making in-situ resource utilization through in-space manufacturing a prerequisite. If waste streams are diverted from disposal and instead converted into functional parts or tools, considerable amounts of time, energy, and money could be saved and logistical support requirements can be significantly reduced.

Moreover, the immune response in astronauts has been shown to be altered in just six months on board the ISS. This could in turn result in increased susceptibility to illness during long-term missions and limit our capabilities for human space exploration. The ability to print on-demand medical devices and implants with inherent biocidal properties will enable long-term space flight to be conducted safely. Furthermore, logistics studies show that the implementation of on-demand manufacturing in conjunction with recycling will create adaptable or reconfigurable systems that can adapt to unforeseen scenarios and mitigate crew risks. The primary focus of this research is to understand how the material properties of two biocidal plastics change with multiple recycling loops.

APPROACH/INNOVATION

The first aim is the development of high-strength, recyclable, and biocidal polylactic acid (PLA)-based and thermoplastic polyurethane (TPU)-based materials. The manufacture of PLA begins with the fermentation of corn to form lactic acid, which is condensed to lactide and polymerized to PLA. The addition of copper microparticles in differing concentrations may impart varying levels of antimicrobial properties to the material. PLA was chosen as it is a common material in 3D printing with well-known material properties and because it is biocompatible. The material shows promise for making casts and other medical devices

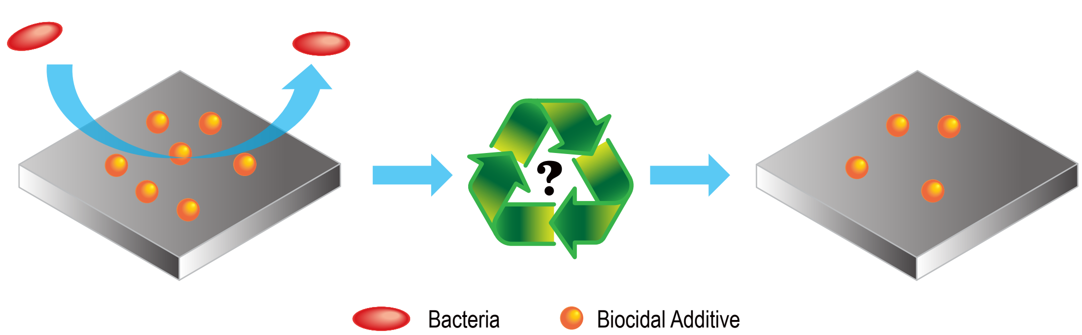


FIGURE 1. Mechanical properties and antimicrobial effectiveness of polylactic acid and thermoplastic polyurethane-based 3D prints will be tested after each recycling loop with a minimum of three cycles attempted.

and is probably most known as the material used in absorbable sutures. TPU was chosen because it is a flexible and biocompatible material that has shown promise in medical devices such as artificial heart components, blood plasma bags, and personal protective equipment (PPE). These antimicrobial characteristics coupled with the ease of recycling will allow for the manufacture of recyclable medical devices in austere environments such as future lunar and martian habitats or the ISS.

While antimicrobial plastics are not novel, this study will examine the retention of antimicrobial effectiveness after repeated recycling. These materials will be made into filament suitable for additive manufacturing. The intent is to measure the bacterial count of *escherichia coli* (*E. coli*) and methicillin-resistant *Staphylococcus aureus* (MRSA) after a 24 h incubation period of unrecycled biocidal PLA and TPU in addition to material that has been recycled once, twice, and three times. Tensile and compressive testing will be conducted to determine if material properties degraded with each repeated cycle. This work will contribute to the growing body of work in recycling, additive manufacturing, biomedical devices, and logistics reduction. Follow-on work may include additional materials development and testing the limitations of recyclability of these materials.

RESULTS/ACCOMPLISHMENTS

This work is ongoing, but current results show promise. The material was still capable of being printed after one and two recycling loops involving regrinding

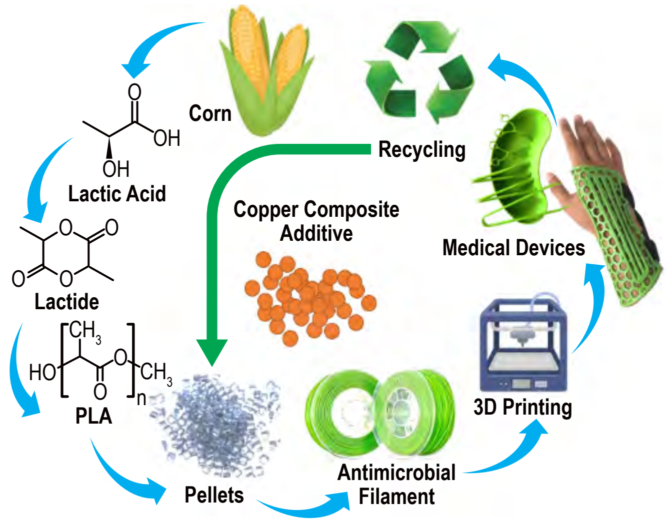


FIGURE 2. Manufacturing process of antimicrobial medical devices using a biodegradable antimicrobial 3D printing filament.

and extruding of the material. PLA was easier to grind and extruded with minimal clogging. TPU, however, was more difficult to grind and extrude due to its elasticity, and tended to clog the machine during extrusion. This clogging issue was overcome by adding a mechanical agitator to the hopper, reducing the rate that the material entered the auger. Aerating the material gave smooth and consistent filament that printed well.

The antimicrobial effectiveness was tested against MRSA showing that the native state (i.e., unrecycled) PLA material was 99.99% effective before aging (1-year simulated heat-based aging) and 90.86% effective after aging. The native state TPU showed 99.95% efficacy before aging and 98.91% efficacy after aging. After one recycling loop, PLA was 99.99% effective before and after aging while TPU was 98.91% effective before aging and 0% effective after aging.

The mechanical test data is not yet available for evaluation; however, the printability of the material after two cycles may indicate the material suffered minimal degradation of mechanical properties.

SUMMARY

This work aims determine the antimicrobial effectiveness and mechanical properties of PLA and TPU embedded with a copper additive after repeated recycling loops. The work is ongoing; however, mechanical testing of the ultimate tensile strength and compressive loads for each recycling loop will indicate either a retention or degradation of mechanical properties. In addition, antimicrobial effectiveness will be tested by counting the bacterial colonies of MRSA after 24 hours of incubation to determine the retention of microbial resistance. Some promising initial data indicates retention of biocidal properties after one recycling loop and preservation of material printability. Follow-on experiments will determine to what degree the material has been degraded and if there is an increase in bacterial growth on further recycling cycles.

PRINCIPAL INVESTIGATORS: Dr. Jorge Zuniga, University of Nebraska at Omaha

PARTNERS: University of Nebraska at Omaha

FUNDING ORGANIZATION: Cooperative Agreement Notice

Extended-Stroke, Reverse-Operation, Differential-Thermal-Expansion Thermal Switch for Extreme Variable Environments

OBJECTIVE: *To raise the technology readiness level of the extended-stroke, reverse-operation, differential-thermal-expansion (DTE) thermal switch from four to six through vibration testing, pre- and post-vibration thermal cycle vacuum testing, and long-duration thermal cycle vacuum testing.*

PROJECT GOAL/DESCRIPTION

NASA Marshall Space Flight Center (MSFC) and the NASA Jet Propulsion Laboratory (JPL) collaborated to design, build, and test a high-efficiency thermal switch (TSW) for extreme thermal conditions. A thermal switch creates a variable thermal contact between a component and a cold sink: when the component is hot, the switch creates a strong thermal contact through which heat is transferred to the cold sink (on); and when the component is cold, the thermal contact is greatly reduced and heat is conserved (off). This variable heat transfer is crucial to enabling survival in both extreme hot and extreme cold temperatures, such as on the lunar surface, where temperatures can fluctuate between 95 K and 390 K.

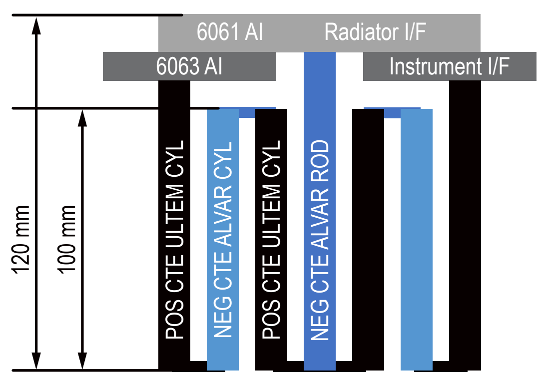


FIGURE 1. Cross sectional diagram of the TSW showing positive and negative CTE materials.

The TSW was designed, built, and functional benchtop tests performed at JPL by Dave Bugby, Jose Rivera, and their team. The goal of this Technology Investment Program (TIP)-funded project is to perform relevant environmental testing on the TSW to increase the technology readiness level (TRL) from 4 to 6. The tests include vibration testing, pre- and post-vibration thermal cycle vacuum testing, and long-duration thermal cycle vacuum testing. The vibration test shakes the TSW to General Environmental Verification Standards (GEVS) protoflight levels to demonstrate survival of potential launch and landing loads. The pre-vibration thermal cycle test demonstrates the nominal TSW performance prior to vibration testing and the post-vibration thermal cycle test provides a comparison to verify the performance after vibration testing. The long-duration thermal cycle test demonstrates the TSW performance in a relevant environment.

APPROACH/INNOVATION

The TSW uses materials with both positive and negative coefficients of thermal expansion (CTE) in multiple stages to improve thermal isolation when off and thermal conductance when on, increasing the turndown ratio (i.e., on/off conductance). Previous switch versions were single stage and used conventional positive CTE material. This TSW is unique because of the high turndown ratio and longer stroke length, which creates a larger gap between interfaces when off and thus increases effectiveness in both vacuum and non-vacuum applications.

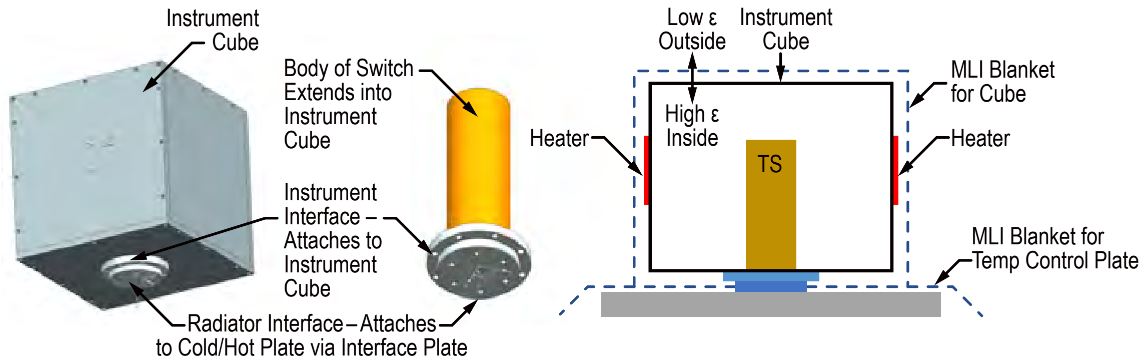


FIGURE 2. Diagrams of test set up for all thermal cycle tests.

To test the performance of the TSW, the instrument interface disk is mounted to an aluminum instrument cube with two heaters to represent instrument heat dissipation. The TSW radiator interface disk is mounted to a temperature control plate that cycles between hot and cold plateau temperatures. Each thermal cycle of the pre-vibration, post-vibration, and long-duration cycle tests includes a hot and cold plateau of 313 K and 100 K, respectively. Each test transitions between temperature plateaus no faster than 2 K/min. The pre- and post-vibration thermal cycle tests are identical. Each is in vacuum and consists of three cycles, with hot and cold plateau lengths of 2 h. The long-duration thermal cycle test is also in vacuum and consists of six cycles, with hot and cold plateau lengths of 20 h. A representative thermal model will also be correlated to the test data.

RESULTS/ACCOMPLISHMENTS

Accomplishments as of September 2022 include a completed test plan, special test equipment designed and purchased, additional test materials purchased, and the test set up readied. The TSW within the instrument cube has been designed, built, and assembled; and the vacuum chamber, temperature control plate, interface plates, thermocouples, and interfacing hardware and software are ready for testing. A thermal model of the TSW and test set up has been built using C&R Technologies® Thermal Desktop® and has been used to make test predictions and aid in the test design. The test data will be used to correlate this model, which will be able to predict the TSW performance in future applications. All testing will be completed and results reported by the end of the 2022 calendar year.

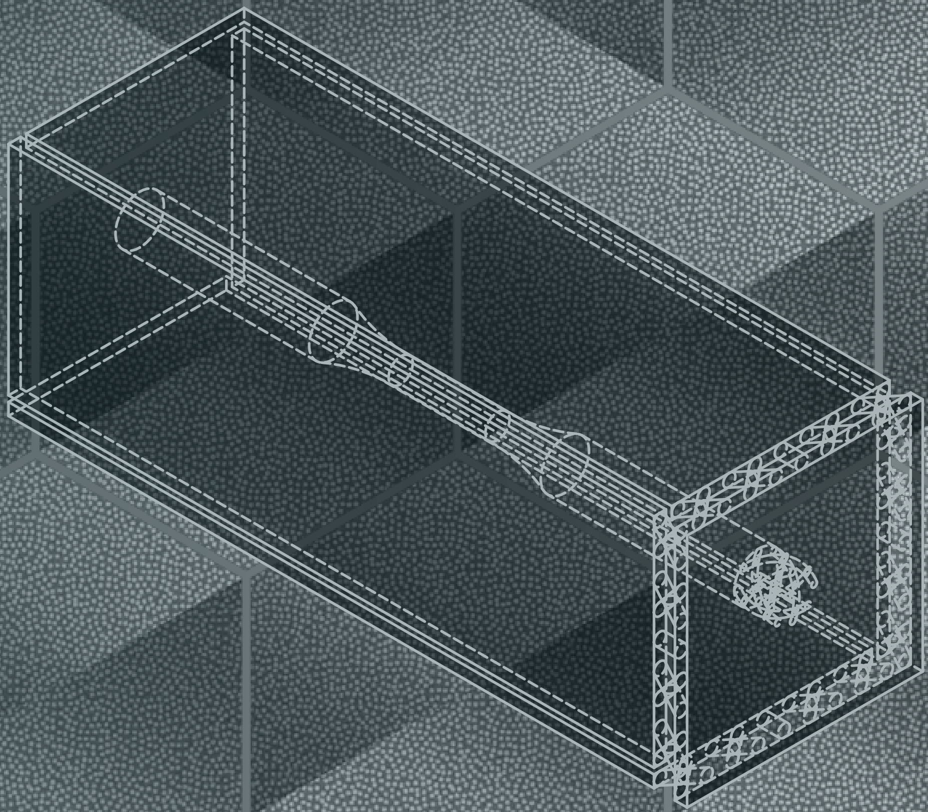
PARTNERSHIPS

MSFC partnered with JPL to design, build, and test the TSW. Dave Bugby, Jose Rivera, and their team at JPL conducted the design, build, and functional benchtop testing of the TSW. This TIP consists of the relevant environment testing and detailed thermal modeling of the TSW performed at MSFC. The partnership is valuable to increase collaboration across NASA centers, share knowledge of thermal control for extreme environments, and further NASA's objective of long-duration survival in extreme environments such as the lunar surface.

SUMMARY

JPL and MSFC collaborated to design, build, test, and qualify a high-efficiency TSW to enable continuous, long-duration operation in vacuum and non-vacuum extreme temperatures encountered on the lunar surface, the martian surface, and in deep space missions. The variable heat transfer path created by the TSW is essential to enabling the survival of components in both extreme hot and extreme cold conditions. The technology is unique because it uses both positive and negative CTE material in stages to create a larger gap when off and higher conductance when on, which increases the total turndown ratio and enables use of the TSW in both vacuum and non-vacuum environments. JPL has succeeded in designing and building a prototype of the TSW. MSFC has succeeded in planning the vibration and thermal vacuum testing in relevant conditions to qualify the technology. Testing will be complete by the end of the 2022 calendar year with an expected final TRL of 6.

PRINCIPAL INVESTIGATORS: Stephanie Mauro; Jeff Farmer
PARTNER: NASA Jet Propulsion Laboratory
FUNDING ORGANIZATION: Technology Investment Program



Technology Area 13

GROUND TEST AND SURFACE SYSTEMS

Plasma Rapid Oxidation Technique for Extending Component Tenability (PROTECT)

OBJECTIVE: *To demonstrate a novel plasma electrolytic oxidation surface finishing technique that uniformly reduces surface roughness of additively manufactured parts, including the interior of parts, to allow more intricate design capability and increased component life.*

PROJECT GOAL/DESCRIPTION

Metallic parts are routinely produced by additive manufacturing (AM), also known as 3D printing, for use on spacecraft and launch vehicles. Additive manufacturing allows for on-demand production and new design capabilities, potentially reducing weight, power and cost requirements for spacecraft and launch vehicles. Post-processing surface finishing techniques, such as media blasting or vibratory polishing, are often required prior to component use. However, traditional surface finishing techniques limit the design capability because surface finishing on the interior of intricate parts cannot be accomplished. Plasma electrolytic oxidation (PEO) is a surface coating technology that produces ceramic layers on the surface of light metals and their alloys to improve their performance characteristics. These ceramic coatings for light alloys are tailored to provide a combination of characteristics such as corrosion protection, wear resistance, thermal management, extreme hardness, and fatigue performance. The metallic part is immersed in a solution allowing surface treatment of even the most intricate interiors of the part, which may be especially beneficial in fatigue-limited applications.

APPROACH/INNOVATION

Plasma Rapid Oxidation Technique for Extending Component Tenability (PROTECT) will demonstrate a 10% improved fatigue performance and a 70% improvement in corrosion characteristics on the interior of AM-produced titanium-aluminum-vanadium alloy (Ti–6Al–4V) specimens when compared to nontreated AM specimens. While other PEO techniques have a detrimental impact on fatigue performance, preliminary fatigue data for the PEO parameters selected for PROTECT are encouraging. Fatigue performance improvements are expected because the PEO process reduces surface roughness by creating a thin ceramic coating that is itself too thin to reduce fatigue properties. Utilization of these novel PEO parameters is expected to create a protective oxide that reduces corrosion susceptibility, which will promote longer component lifetimes, increased reliability, improved safety, and decreased costs.

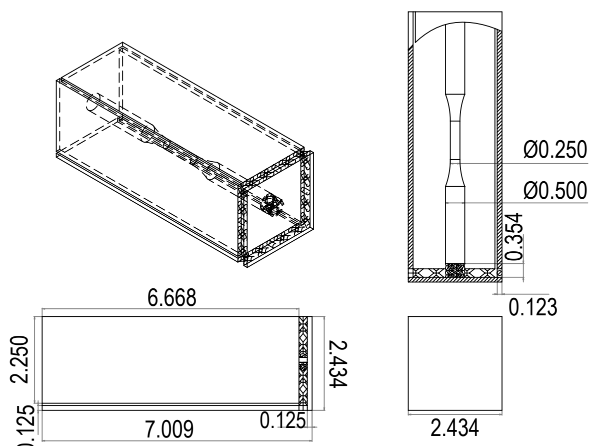


FIGURE 1. Drawing of the PROTECT specimen.

While Ti–6Al–4V does not typically corrode under normal service conditions, the surface roughness inherent in AM component builds can promote corrosion. Complementary work from Nieto et al. at the Naval Postgraduate School demonstrated corrosion of additively manufactured Ti–6Al–4V in a salt fog chamber simulating environments of Naval interest. Typical postprocessing can treat the exterior of components to reduce surface roughness that impacts fatigue and corrosion characteristics, but would not be able to access the interior of complex designs. PEO utilizes a liquid medium and can access the interior of components. A key technical challenge was designing an AM specimen that mimicked the interior of a complex component, but provided an adequate number of corrosion and fatigue specimens for testing. Through an iterative design process involving all the stakeholders, ten specimens were successfully designed and delivered. A Kennedy Space Center fiscal year (FY) 2022 Center Innovation Fund (CIF) grant provides for the corrosion and fatigue testing of these specimens through May 2023.

RESULTS/ACCOMPLISHMENTS

Specimens were designed to contain a shrouded fatigue specimen to mimic the interior of a complex AM component. The internal fatigue specimen was designed per American Society for Testing and Materials (ASTM) standard E466. The corrosion test specimens will be prepared by cutting the shroud into 2×2-in squares or 2×4-in rectangles. The original test specimen design contained pegs at each of the corners of the base; however, early polymer prints of the test specimen were unsuccessful. The design was updated to contain a crosshatch in order to provide stability for the vertical build. This design allows the fatigue test specimen to be liberated from the shroud with one wire electrical discharge machining (EDM) cut along the crosshatched area at the base.

The specimens were printed in Ti–6Al–4V via laser powder bed fusion (L-PBF) AM on an EOS M290 metal 3D printer. Samples were depowdered and underwent hot isostatic pressing (HIP) utilizing standard NASA HIP parameters. Samples were subsequently evaluated by computed tomography (CT) to verify there were no concerning manufacturing defects. A Kennedy Space Center FY 2022 CIF provides for the PEO treatment and corrosion and fatigue testing of these specimens through May 2023.

PARTNERSHIPS

- Marshall Space Flight Center: Brian West contributed expertise in Ti–6Al–4V AM specimen design, build parameters and postprocessing.
- Kennedy Space Center: Jennifer Williams, Ph.D., Christopher Williams, and Eliza Montgomery, Ph.D. KSC plans to continue testing through May 2023 via a FY 2022 CIF. Christopher Williams provided Ti–6Al–4V AM expertise. Dr. Eliza Montgomery provided corrosion expertise. Dr. Jennifer Williams serves as principal investigator.
- Syracuse University: Alexander Callo is a mechanical engineering major and provided specimen drawings, experimental design, data analysis, and literature review.
- Union College: Srihari Balaji is a mechanical engineering major and provided experimental design, data analysis, and literature reviews.
- West Virginia University: Travis Allen is an aerospace engineer major/graduate and provided experimental design, specimen drawings, flow simulations, data analysis, and literature review.
- Old Dominion University: Catherine Fischer is mechanical engineering major and provided experimental design, data analysis, and literature review.
- Virginia Tech University: Gabriel Chester is mechanical engineering major and provided experimental design, data analysis, and literature review.

SUMMARY

The application of PEO to AM postprocessing for Ti–6Al–4V aerospace applications will improve component design flexibility. Unlike traditional AM postprocessing, PEO can utilize specialize parameters to reduce the surface roughness of the interior of components, which will improve fatigue and corrosion characteristics allowing for novel AM designs.

PRINCIPAL INVESTIGATOR: Jennifer Williams

PARTNERS: MSFC, KSC, Syracuse University, Union College, West Virginia University, Old Dominion University, Virginia Tech

FUNDING ORGANIZATION: Center Innovation Fund

Technoloy Area 14

THERMAL MANAGEMENT SYSTEMS

Advanced Thermal Control System Architecture for Exploration

OBJECTIVE: *This project will provide a demonstration of an advanced hybrid thermal control system architecture that combines the benefits of an internal pumped fluid loop system with external loop heat pipe heat rejection.*

PROJECT GOAL/DESCRIPTION

Human-rated and high-heat-rejection exploration thermal control system (TCS) architectures typically employ separate internal and external pumped fluid loops (PFLs) to acquire, transport and reject heat with the internal fluid loop utilizing a nontoxic water-based coolant. In a conventional architecture, the external PFL coolant is isolated from the crew and is chosen for thermal performance (e.g., heat capacity, freezing point, etc.). An external loop heat pipe (LHP) radiator may offer substantial improvements over an external PFL in reliability and performance for extreme thermal environments like those being researched by the Commercial Lunar Payload Services (CLPS) Survice the Night program as well as providing potential resource savings. The goal of this effort is to demonstrate a hybrid TCS architecture utilizing a representative internal crew-friendly PFL coupled with an external LHP thermal radiator, leveraging hardware from previous Small Business Innovation Research (SBIR) projects.

APPROACH/INNOVATION

A hybrid PFL/LHP TCS architecture has not been demonstrated in space for large-scale heat rejection. The individual technologies are high technology resource level (TRL), but not as an integrated system. This investment would provide a TRL 5 breadboard demonstration of the integrated hybrid technology against a projected current TRL of 3. The key performance parameters (KPP) are a system turndown ratio greater than 10:1 (PFL ≈4:1) and power consumption less than that of an equivalent PFL system. NASA's exploration missions necessitate high reliability for long term operations lasting up to 15 years (with dormancy). LHP TCS radiators have no moving parts and better micrometeoroid orbital debris (MMOD) redundancy than similar PFL systems. LHP systems offer low freezing point fluids (such as propylene, –302 °F),

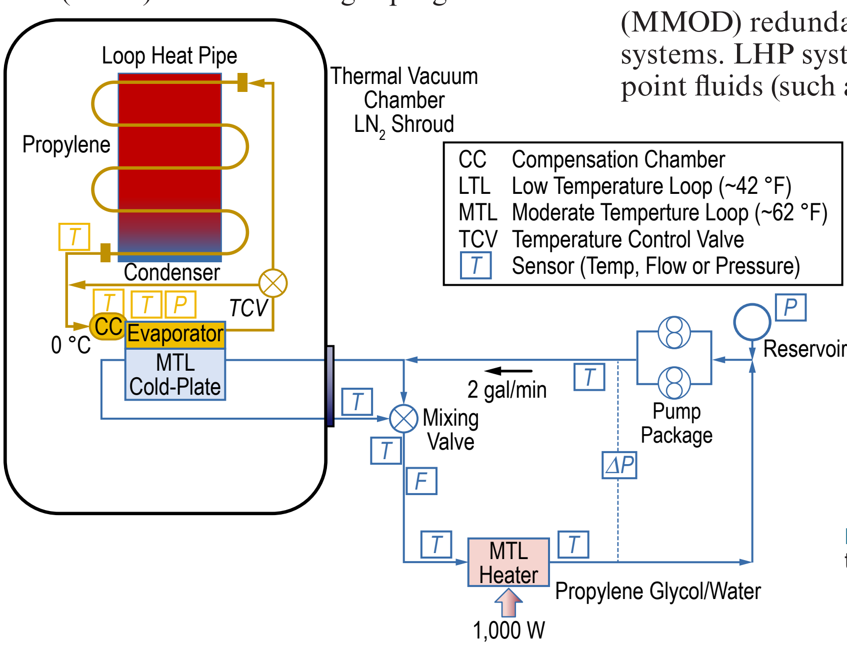


FIGURE 1. Notional loop heat pipe test configuration.

which are ideal for extreme lunar environments like those being researched by the CLPS Survive the Night program.

The overall approach is to design, procure, and fabricate an integrated PFL/LHP breadboard TCS architecture for experimental evaluation inside of a thermal vacuum chamber. The breadboard test setup with the LHP inside of a thermal vacuum chamber (to simulate the lunar environment) coupled to a representative PFL is shown in figure 1.

Evolution of this innovation would consider the development and test of more advanced systems with higher capacity LHPs and multiple LHPs to meet the temperature and high-heat-rejection demands of human-rated systems in extreme thermal environments.

RESULTS/ACCOMPLISHMENTS

The breadboard system has been designed and procured with fabrication in progress. Test evaluations of the integrated system are anticipated to begin in November 2022. The propylene LHP was fabricated by Advanced Cooling Technologies (ACT) and has been received by NASA Marshall Space Flight Center (MSFC). The breadboard LHP is shown at the vendor facility in figure 2. The LHP compensation chamber, evaporator with cold plate and thermal control valve are visible on the right side of the LHP as oriented in the picture.

FIGURE 2. Breadboard loop heat pipe at ACT.

Several tests are planned to assess the hybrid TCS performance over a range of expected Lunar thermal environments. The LHP will be tilted slightly to simulate performance in lunar gravity and sink temperatures representative of both lunar day and night operations will be imposed. TCS operation during a survival scenario like the CLPS Survive the Night will also be assessed. It is anticipated that this investment would provide a TRL 5 breadboard demonstration of the integrated hybrid technology against a projected current TRL of 3.

PARTNERSHIPS

This investment will support ongoing NASA Next Space Technologies for Exploration Partnerships (NextSTEP) Moon-to-Mars Habitation studies to assess hybrid TCS architectures for lunar surface or Mars transit applications. The MSFC Habitation Systems Development Office (HP40) provided funding in support of this research. The investigative team has also discussed possible collaboration with the United States Space Force (USSF) and the Air Force Research Laboratory (AFRL) Space Vehicles Thermal Lead.

SUMMARY

A breadboard hybrid TCS architecture, utilizing a representative internal crew friendly PFL coupled with an external LHP thermal radiator, has been designed and procured with fabrication underway. Experimental evaluations of the system under relevant thermal environments are expected to commence in November 2022. Results from the testing will provide valuable insight for the application of hybrid TCS architectures to future lunar surface or Mars transit applications.

PRINCIPAL INVESTIGATOR: Kayla Daniel
PARTNER: NASA Habitation Systems Development Office
FUNDING ORGANIZATION: Technology Investment Program

Advanced Cryogenic Fluid Management Devices Using Large Scale Additive Manufacturing (AM4CFM)

OBJECTIVE: *To design and analyze additively manufactured vane-type propellant management devices for use in cryogenic applications and characterize the material properties of additively manufactured aluminum alloy 2319.*

PROJECT GOAL/DESCRIPTION

As NASA looks to return to the Moon and to put humans on Mars, innovative methods of storing cryogenic propellants will be essential to support long-duration spaceflights. Additive manufacturing (AM) can aid in this effort by enabling engineers to make clever design changes to storage tanks and increase their efficiency at maintaining cryogenic conditions. This effort specifically focuses on designing and analyzing vane-type propellant management devices (PMDs), which passively direct propellant in microgravity toward the outlet of the tank where it is needed. Additionally, since it has been noted that AMed parts have different material properties compared to conventionally manufactured components, funding was obtained to characterize the structural and thermal properties of the aluminum alloy to be used in the construction of the tank, known as aluminum (Al) alloy 2319.

APPROACH/INNOVATION

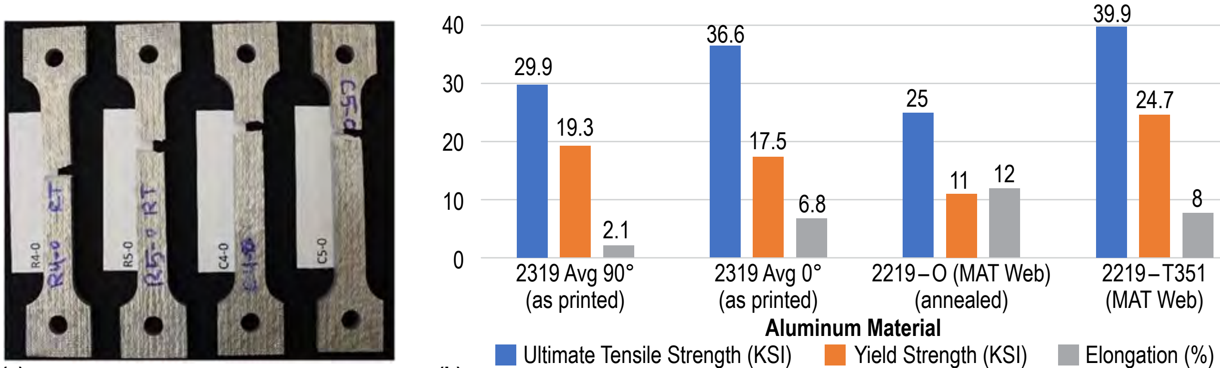
The approach to completing this effort is twofold. The first fold is performing design and analysis work to optimize the thermodynamics of the vane. The first step toward this is to develop a model in C&R Technologies® Thermal Desktop® program to estimate the baseline conditions inside the tank. Once the model is complete, different vane shapes will be added to the model and compared to the baseline results, which will help to optimize a vane shape based on mass, flow characteristics, and heat transfer efficiency. These idealized vanes will be documented for future tank builds and demonstration articles will be printed in plastic and metal.

The second fold of the project is the material characterization of directed energy deposition (DED) Al 2319. DED is an AM process that uses thermal energy to fuse material together as it is being deposited. The Al 2319 stock material in this application is in the form of wire, which is melted as it is being laid down by either an electrical arc or a laser, similar to welding. Because of this novel heating and fabrication process, the grain structure of the material is fundamentally different than a traditionally manufactured material, which can cause it to have different thermal and structural properties. In an effort to characterize these material properties, samples of both laser wire directed energy deposition (LW-DED) and arc wire directed energy deposition (AW-DED) materials will be obtained and analyzed.

The AW-DED samples have been obtained from a company called Big Metal Additive (BMA). The LW-DED samples will be created in-house from a Meltio Laser Wire system currently being installed at NASA Marshall Space Flight Center (MSFC). Once the Meltio installation is complete, parameter development will be performed to print Al 2319 and generate the samples needed for thermal and structural testing.

RESULTS/ACCOMPLISHMENTS

So far, the thermal model of the tank has been created, and cases are being run to establish its baseline performance. Once this baseline is established, a generic



(a) (b)

FIGURE 1. (a) AW-DED Al 2319 0° test specimens; (b) Comparison of AM 2319 test data to wrought 2219.

vane will be added to the model and different vane length increments will be run to optimize the size and mass of the vane for the system. When a roughly optimized vane size has been determined, different vane shapes will be analyzed based on printability, flow characteristics, and heat transfer efficiency.

The material testing portion of the project has procured all the samples needed for characterizing AW-DED Al 2319 and has provided those samples to the groups/companies that are going to perform the tests (fig. 1a). The room temperature structural tests have already been completed and are compared to traditionally manufactured Al 2219 in figure 1b. The data for the cryogenic structural tests and the thermal characterization is still in progress. As previously mentioned, MSFC is currently working to bring the Meltio system online. Once that has been completed, LW-DED samples will be generated and tested.

The major milestones of the project are as follows: (1) Create a thermal model of the Sierra Lobo Inc. (SLI) cryogenic tank; (2) perform a trade study to determine the optimal size/shape of the vanes; (3) procure AW-DED and LW-DED material samples; and (4) perform structural and thermal material characterization tests on the samples. Milestone 1 has already been completed and significant progress has been made on the other three milestones. All the milestones are expected to be completed by the conclusion of the project and further funding will be sought to continue this work.

PARTNERSHIPS

Sierra Lobo Inc. (SLI) and BMA are currently working a Phase II Small Business Innovation Research (SBIR) grant to fabricate and test an AM cryogenic tank. The team has been working in conjunction with SLI/BMA to help develop their current tank design, as well as provide input for future tanks that may need to incorporate PMDs. In the future, further funding will be sought to continue raising the technology readiness level of this technology and include SLI/BMA in a formal partnership.

SUMMARY

The goal of this project is to take the first steps in designing and optimizing PMDs for use in an AM cryogenic tank. This will be accomplished using thermal modeling, as well as characterization of the Al 2319 material that will be used to print the tank. The team is working in conjunction with SLI and BMA on their Phase II SBIR to build and test an AM cryogenic tank. Progress has been made toward all the significant milestones of the project and is expected to be completed by the end of calendar year 2022. Once this effort has been completed, further funding will be sought to continue to develop this technology for use in future deep space missions.

PRINCIPAL INVESTIGATOR: Travis Belcher

PARTNERS: Sierra Lobo Inc.; Big Metal Additive

FUNDING ORGANIZATION: Technology Investment Program

Low-Melting-Point Metallic Suspension Nanocomposite Phase Change Material as a Thermal Management Solution for More Electric Systems

OBJECTIVE: *Development of a model to aid in the design of a nanocomposite phase change material as a passive thermal management solution for electronics.*

PROJECT GOAL/DESCRIPTION

For years, thermal management in electronic packaging has been geared toward the use of forced air cooling; and more recently has changed to liquid cooling with emphasis on enhancing the convective heat transfer coefficient by a myriad of novel solutions. However, all these technologies require overdesigning the cooling system to tackle the thermal spikes, thus resulting in bulky and heavy energy consumption solutions. These go against the tendency of electronics' miniaturization, efficiency, and weight reduction, which are crucial for NASA needs. Due to the reasons described, this work is aimed at the development of a computational model to aid in the downselection of efficient phase change material (PCM) configurations. Any downselected PCM can be directly deposited in contact with the heat source (i.e., the case of the semiconductor) so that when it undergoes a phase transition (e.g., solid-liquid), it will passively absorb thermal energy in the form of latent heat while keeping the electronics at a nearly isothermal condition.

APPROACH/INNOVATION

Serving as a tool to guide the design process, a thermal conductivity model that incorporates the phase change was developed as an enabler for analytical simulations of heat transfer during energy peaks, using nanofluid as a so-called 'thermal paste.'

The current work documents the formulation of a finite element simulation and compares it with the solutions of the developed analytical MATLAB model. This study aims to be used as a guide for the power electronics packaging of power densities lower than 109 W/m^2. The most important parameter in composites is to accomplish a mass ratio that provides suspension stability and uniform dispersion.

RESULTS/ACCOMPLISHMENTS

The development on the proposed model builds upon the work originally proposed by T.J. Lu;[1] however, equations were modified to add the effects of a composite mixture as well as temperature gradients within the phase change material. This model works for lower power densities (<109 W/m^2) and assumes a quasi-steady-state condition, thicknesses less than 1 mm, and a convection coefficient near 10 W/m^{2}K. The model intends to find critical time parameter regimes to separate composite behaviors.

This is the first design tool developed to help guide the designer on selecting an efficient PCM for known application conditions. Under all conditions evaluated the melting energy equation works effectively and gives accurate results, which is in agreement with literature.

SUMMARY

The current work completed the implementation of a computational model that focused on the thermal response of an electronic system to aid in future design of PCM nanocomposites.

There exists a lack of microscopic thermal conductivity models for PCM behavior. For PCM applications, when phase change occurs, the effective thermal conductivity also changes. The existing models work for the time range where the PCM is in a solid state, but when the phase change occurs Maxwell's model is limited. For that reason, a modified Maxwell thermal conductivity model was completed and validated, which incorporates the phase change of the composite. The modeling effort, included an energy balance approach, built upon a previous work by the principal investigator (P. Quintero) and T.J. Lu.[1] The model will serve as a tool for predicting thermal behavior and potential design of application for specific PCM nanocomposite alternatives. This effort was completed under the guidance of Dr. Quintero together with students from the University of Puerto Rico Mayaguez.

Reference

1. Lu, T.J.: "Thermal management of high power electronics with phase change cooling," *International Journal of Heat and Mass Transfer*, Vol. 43, No. 13, pp. 2245–2256, July 1, 2000, doi: 10.1016/S0017-9310(99)00318-X.

.

PRINCIPAL INVESTIGATOR: Pedro Quintero

PARTNER: University of Puerto Rico Mayaguez

FUNDING ORGANIZATION: Cooperative Agreement Notice

Lunar TheRMiS – Lunar Thermal Regulation for Mission Sustainability

OBJECTIVE: *To leverage both NASA Marshall Space Flight Center and partner capabilities to develop the Lunar TheRMiS — a validated collection of design and technology information for spacecraft and payload designers of systems that need to survive extreme lunar environments.*

PROJECT GOAL/DESCRIPTION

In recent years, there has been a push to return a human presence to the Moon, with an increased focus on sustainability. Part of this sustainability will be reusable and long-duration vehicles as Apollo-style single-use vehicles are too expensive and impractical. Numerous engineering challenges exist when developing such vehicles, one of which is designing a thermal control system (TCS) that can survive the extreme cold of the lunar night. Currently, the state of the art is to use radioisotope heating; however, this is difficult to sustain. Nuclear material has large cost, socio-political concerns, and integration challenges, making its use impractical for many missions. The Lunar TheRMiS team is developing an advanced TCS solution using non-nuclear components that will allow a 50–500 kg-class lander to survive the lunar night. This capability will enable scientific missions to close lunar human exploration strategic knowledge gaps as well as sustainable lunar presence architectures that depend on survivability through the lunar night. The team is collaborating with Astrobotic, an innovator in commercial lunar landers, who will be providing their Peregrine lander as a testbed for analysis and eventual flights to the Moon. This effort will advance the TCS technology through system-level thermal vacuum testing and culminate in the delivery of flight-ready hardware to Astrobotic. In addition, the effort will result in a validated toolbox

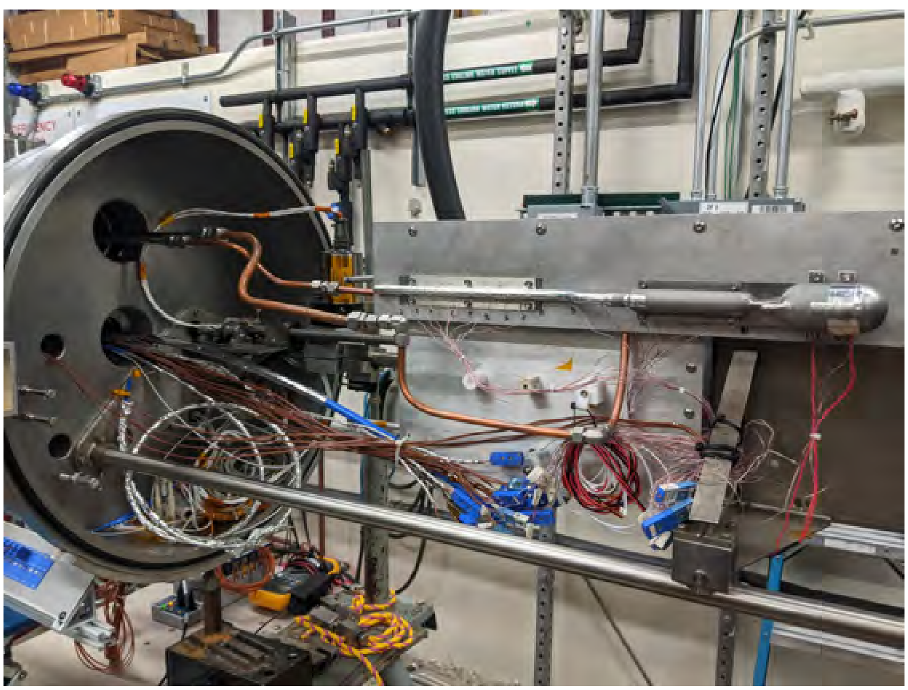


FIGURE 1. Warm-reservoir variable conductance heat pipe in thermal vacuum chamber.

of thermal modeling techniques that can provide a set of TCS solutions for broad application to lunar landers, and can help identify solutions to future thermal challenges faced by NASA and its commercial partners.

APPROACH/INNOVATION

The Lunar TheRMiS team utilized a fast-paced, test-focused approach to complete the year's objective—readying a key thermal control technology for flight. Prior to hardware delivery, the team held numerous stand-up meetings each week to address little issues head-on and ensure progress was always moving forward. Once hardware was delivered, the team transitioned to meeting in the lab several days each week to complete predetermined test objectives. This approach allowed for the team to complete qualification testing of protoflight hardware with limited resources and budget. By completing this testing and gaining the flight data that is to come, the team has made progress towards validating the technology for use in extreme environment systems. This more general approach complements the focused approach in industry for specific systems.

RESULTS/ACCOMPLISHMENTS

Several major hardware, testing, and analysis accomplishments happened this year. The first major accomplishment was protoflight qualification testing of a warm-reservoir, hybrid-wick variable conductance heat pipe (VCHP). This VCHP has several advantages over traditional cold-reservoir VCHPs that will be beneficial to survival in extreme lunar environments. The most critical advantage is the warm reservoir, which reduces the amount of heater power needed to control the VCHP. A cold-reservoir VCHP requires heater power on the reservoir to turn off the heat transfer. The warm-reservoir VCHP, however, does not typically require the same amount of heater power—invaluable when heater power must be minimized in the coldest environments. The Lunar TheRMiS team successfully completed a protoflight qualification campaign before delivering the VCHP to Astrobotic for integration into the Peregrine 1 lander.

The team initially performed benchtop thermal characterization testing to become familiar with operating the VCHP. Once this was completed, a series of dynamic vibration tests were performed. Both random and sine vibrations were tested in all three axes. The VCHP physically passed the vibration tests, but another round of thermal characterization was required to ensure it still operated as designed. The successful completion of this test led to final thermal vacuum qualification — all passed without issue (fig. 1).

Further benchtop testing occurred this year for promising thermal control technologies. One such test was a loop heat pipe (LHP) with an additively manufactured evaporator (fig. 2). This LHP was subjected to a battery of characterization tests — steady state at different power levels, dry-out tests, and rapid cycling. By testing technologies such as these, the Lunar TheRMiS team has been validating the matrix of candidate technologies for surviving in extreme lunar environments.

FIGURE 2. Benchtop testing of additively manufactured loop heat pipe.

PARTNERSHIPS

The major partner for this Early Career Initiative (ECI) project was Astrobotic. They provided key insight into industry and payload needs for surviving in extreme environments. They also integrated and will fly the warm-reservoir VCHP on Peregrine mission 1. The ECI partnership has completed, but they remain a partner with the Lunar TheRMiS team and others at NASA Marshall Space Flight Center (MSFC) through various Small Business Innovation Research (SBIR) and Tipping Point activities.

Advanced Cooling Technologies (ACT) is another valuable partner for the work of surviving extreme lunar environments. ACT has furthered the fundamental research for advanced thermal control technologies. MSFC partners with them via numerous SBIR activities of various phases—most of which finish with new thermal control hardware delivered to MSFC, including the protoflight VCHP.

SUMMARY

The Lunar TheRMiS team has completed the ECI work, but will continue to push towards enabling payload and spacecraft designed to survive in extreme lunar environments. The work performed by the team has established several critical technologies that can be vital for the design of extreme environment systems, while also identifying candidate technologies that require further study. The Lunar TheRMiS team will pursue new funding opportunities to continue studying and testing advanced thermal control technologies that will enable future lunar surface architectures.

PRINCIPAL INVESTIGATOR: Will Johnson

PARTNERS: Astrobotic; Advanced Cooling Technologies

FUNDING ORGANIZATION: Early Career Initiative

FOR MORE INFORMATION: William.e.johnson-1@nasa.gov

Index by Funding Source

Advanced Exploration Systems, Exploration Systems Development Mission Director

Near-Earth Asteroid Scout, 22–23

Bid and Proposal

Moon Burst Energetics All-Sky Monitor (MoonBEAM), 96–97

Center Innovation Fund

Bioremediation of Microgravity Biofilms and Water Processor Health, 56–57

Composites in Braided Experimental High-speed Rotation (CiBEHR) Coupling, 9–11

Development of Radioluminescent Tritium Material for High Visibility Applications, 172–173

Development of the Fast-Acting, Deep-Throttling Hybrid Motor, 4–5

Electromagnetic Solar Sail Coupling (ESSC), 18–19

Exploring High-Performance Additively Manufactured Rotating Detonation Rocket Engines, 104–106

Extraterrestrial Marangoni Mining, 68–71

Improved Actuator for a Pyroless Isolation Valve, 12–14

Machine Learning for Agriculture Crop Damage Identification and Assessment from Intense Thunderstorms, 124–126

Parametric Study of Additive Manufacturing using Martian Regolith Metal Recovered with Ionic Liquids, 76–77

Plasma Rapid Oxidation Technique for Extending Component Tenability (PROTECT), 192–193

Process Development and Characterization of Ruthenium-Based Monolithic Metal Foam Catalyst for Monopropellant Thruster Applications, 20–21

Rapid Process Development of Aerospace Alloys Using Small Punch Test, 131–133

Structured Sorbents: Rapid Cycle Temperature Swing Adsorption (RC-TSA), 41–43

Trichloride Ionic Liquid-Mediated Metal Extraction from Regolith, 78–79

Cooperative Agreement Notice

Additive Construction at Drake State: Developing the Future Advanced Workforce, 165–167

Additively Manufactured Fluidic Diode Injectors for Rotating Detonation Rocket Engines, 107–109

Additively Manufactured Passive Wireless Sensors with Printed Electronics, 134–135

Additive Manufacturing of Fire Retardant and Repairable Composite Structures Based on Lunar Regolith and Vitrimer Epoxy under Lunar Conditions, 58–60

Additive Manufacturing of Outfitting Components for Lunar Habitat Interior and Exterior, 168–171

Advanced Tooling Demonstration for Friction Stir Welding of Heat Resistant Materials 156–157

Alloy Design for Additive Manufacturing of Crack-Free Tungsten Alloys via Laser Powder Bed Fusion Process, 149–151

All-Printed Flexible Biofuel Cells for Energy Harvesting from Human Sweat, 26–27

Cavitation Effects on the Structural Dynamics of Turbomachinery Components: Modeling and Experiment, 177–179

Cellular Fabrication (C-Fab©) Materials for In-Situ Lunar Additive Manufacturing and Outfitting, 72–73

Cost-Effective, High-Temperature Materials Testing, 146–148

Coupling In-Situ Data Analysis with Machine Learning for Characterization of Additively Manufactured Parts, 152–153

Demonstration of a Prototype Design for a Multipurpose Lunar Habitat, 65–67

Development and Testing of Recyclable and Antimicrobial Materials for Additive Manufacturing, 184–186

Development of Non-Platinum Group Metal Catalysts for Hydrogen Resource Recovery, 54–55

Development of Ultra-High-Performance Additively Manufactured Injector Elements, 6–8

Early Biofilm Detection in ISS Water Supply Systems Using Impedance Microbiology, 50–51

Enhanced Equipment Isolation in Extreme Vibratory Environments Using Rotational Inertial Devices, 174–176

High Strength Aluminum Scalmalloy® Laser Powder Bed Fusion Additive Manufacturing, 160–161

In-Situ Synchrotron Characterization of Levitated Aerospace Alloys Under Dynamic Processes for Optimization of Advanced Manufacturing Methods, 180–181

In-Space Additive Nanomanufacturing and Dry Printing of Multimaterials Electronics, 140–142

Investigating Autonomous Healing of Cracks in Lightweight, Aerospace-Grade Materials Systems, 44–47

Investigating the Performance Characteristics of Auxetic Foams in Neuropathy Treatment Applications, 52–53

ISS Deployment and High-Altitude Descent Drone Landing Using SVGS, 34–36

Low-Melting-Point Metallic Suspension Nanocomposite Phase Change Material as a Thermal Management Solution for More Electric Systems, 200–201

Materials Development for Additive Manufacture of Radiation Sensors and Shielding, 102

Modeling of Self-Reacting Friction Stir Welding to Correlate Predicted Phenomena with Weld Quality and Hardness, 154–155

On-Demand Manufacturing of Electronics in Space, 138–139

On-Demand Structural Health Monitoring Sensor Manufacturing for NASA Applications, 136–137

Polymer Coatings with Glass Bubbles for Thermal Radiation Control in Space, 143–145

Precision Landing of a Hexacopter Drone by Smartphone Video Guidance Sensor, 110–111

Printable, Molecularly Imprinted Polymers for Cortisol Sensing, 48–49

Realizing Spatially Resolved, Real-Time Temperature Measurements in Friction Stir Welding Using Ultrasonic Thermometry, 158–159

Software Tools for Effective Use of Additive Manufacturing In-Situ Diagnostic Data, 162–164

Viability Assessment of Printed Powerless Sensors Structures for Aerospace Environments, 82–84

Early Career Initiative

Lightweight Integrated Solar Array and anTenna (LISA-T) Pathfinder Technology Demonstrator, 28–29

Lunar TheRMiS – Lunar Thermal Regulation for Mission Sustainability, 202–204

Metallic Environmentally Resistant Coatings Rapid Innovation Initiative (MERCRII), 128–130

SIBatt-3D: In-Space/on-Surface 3D Printing of Sodium Ion Batteries Using In-Situ Materials, 30–32

Flight Opportunities

Parabolic Flight Demonstration of Fluid Dispensing Tube Performance Limits for Drop Delivery, 38–40

Game Changing Development Program

Duneflow Lunar Gravity Suborbital Flight, 74–75

Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) Project, 62–64

On-Demand Manufacturing of Multimaterials, 182–183

Rapid Analysis and Manufacturing Propulsion Technology (RAMPT), 2–3

Science Mission Directorate

Advanced Microwave Precipitation Radiometer (AMPR), 88–89

Artificial Intelligence-Driven Reverse Image Search System for Earth Science, 120–121

BERT-E: Artificial Intelligence-Driven Language Model for Earth Science, 114–115

Earthdata Publication Tool, 116–117

Extreme-Ultraviolet Stellar Characterization for Atmospheric Physics and Evolution (ESCAPE) Phase A Concept Study, 100–101

International Space Station Lightning Imaging Sensor (ISS LIS), 90–91

Management Office of the Satellite Needs Working Group, 118–119

Scintillation Prediction Observations Research Task (SPORT), 98–99

Segmented Mirror Telescope Program (SMTP), 92–93

SERVIR, 85–87

Visualization, Exploration, and Data Analysis (VEDA), 122–123

Technology Investment Program

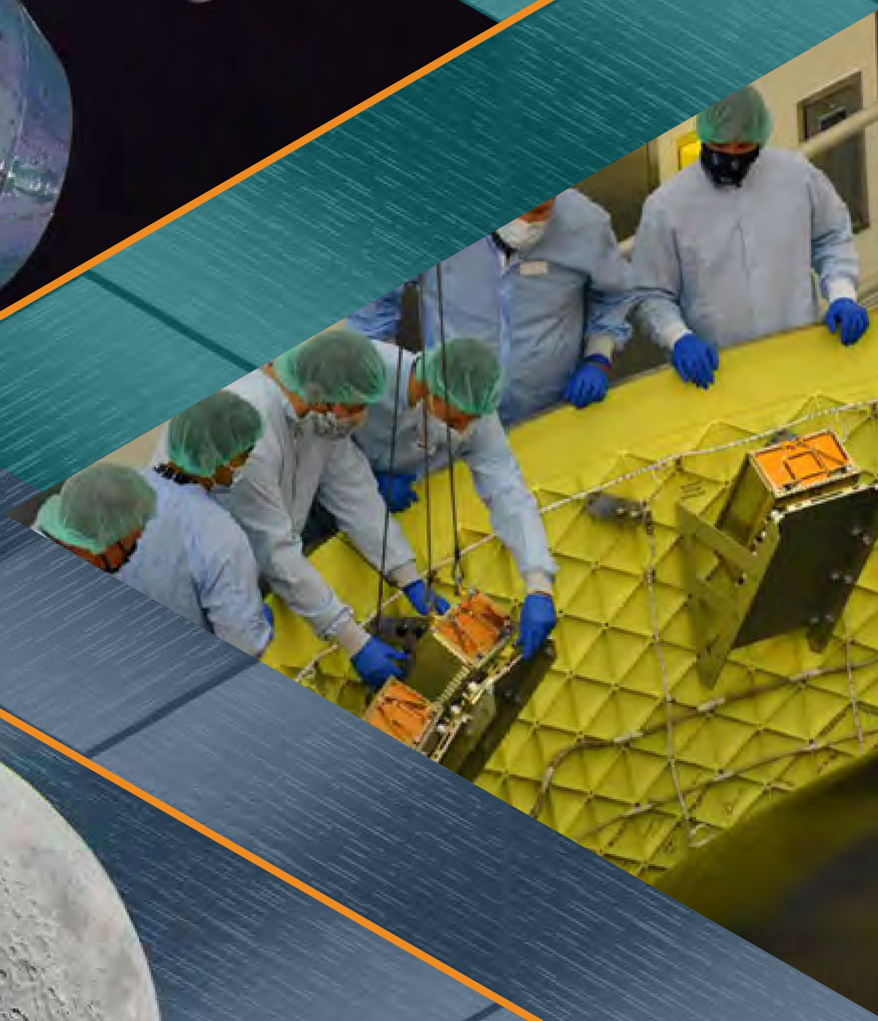
Adaptable Fluid Dynamometer for Electric Motors (AIDEM), 15–17

Advanced Cryogenic Fluid Management Devices Using Large Scale Additive Manufacturing (AM4CFM), 198–199

Advanced Thermal Control System Architecture for Exploration, 196–208

CeBr3/NaI Phoswich Scintillator Detector Technology, 94–95

Extended-Stroke, Reverse-Operation, Differential-Thermal-Expansion Thermal Switch for Extreme Variable Environments, 187–189



NASA/TM—20230000685

Marshall Space Flight Center

Research & Technology Report

2022

National Aeronautics and Space Administration

George C. Marshall Space Flight Center
Huntsville, AL 35812
www.nasa.gov/marshall

www.nasa.gov