UPWARD

MAGAZINE OF THE ISS NATIONAL LAB • UPWARD.ISSNATIONALLAB.ORG • DECEMBER 2019

SPECIAL ISSUE
ADVANCED MATERIALS AND MANUFACTURING

VOLUME 4
ISSUE 3

A COLLECTION OF PREVIOUSLY PUBLISHED
ARTICLES DETAILING RESEARCH SUCCESSES

ISS
U.S. NATIONAL LABORATORY

CONTENTS

ADVANCED MATERIALS AND MANUFACTURING PROGRAM:
Projects that develop next-generation production methods, improve understanding of mechanisms involved in material transformations, advance fundamental materials discovery, or test processes or manufacturing methods of novel design and synthesis pathways.

Published 12/31/2019

The ISS National Lab is managed by the Center for the Advancement of Science in Space, under agreement with NASA.

UPWARD ONLINE. For access on the go, visit: **Upward.ISSNationalLab.org**

THE VIEW FROM THE CUPOLA

BY ERIK SVEDBERG, *National Academies of Sciences, Engineering, and Medicine*

Erik Svedberg is a Senior Program Officer at the National Academies of Sciences, Engineering, and Medicine.

I am very excited to introduce this special issue of *Upward* to you, as its focus is on materials research in space. My work at the Academies is centered on the National Materials and Manufacturing Board and the studies produced under its guidance. The most recent *Frontiers of Materials Research: A Decadal Survey* was published by the Academies this year.

The report provides the nation with advice on how to effectively ensure progress in materials research over the coming decade. The report also highlights much of the exciting materials research being done today in the U.S. and abroad and discusses the benefits of moving forward in this central field. The report touches upon the importance the International Space Station (ISS) U.S. National Laboratory and the exciting materials research being conducted on this unique platform. It is clear that the benefits of materials research in space are closely linked to conditions that are difficult to perfectly reproduce on Earth, such as microgravity, radiation, temperature extremes, and environmental conditions such as atomic oxygen.

This special issue of *Upward* revisits the many ways in which researchers are leveraging these strengths and opportunities for valuable materials research. Gravity is the most obvious difference, and the article "The Little Furnace That Could: Using Space to Improve Radiation Detection" discusses how microgravity is a key player in producing and understanding high-quality crystals. Because many crystals are a complex combination of atomic elements, some in high concentration and others in very low concentration (dopants), gravity tends to prevent uniform distribution and high-quality crystal synthesis here on Earth. These same issues also play a role in the production of materials such as the optical fibers described in the article "Exotic Glass Fibers From Space: The Race to Manufacture ZBLAN." Soon, there will be not only small test samples of such fibers produced in space but fibers up to 100 m long, representing a shift from validation to production of this key optical fiber that is 10 to 100 times better than traditional silica fibers when it comes to signal loss. Gravity is also central to the work described in the article "The ISS & Household Products: How P&G is Using Space to Improve Customer Experience." Procter and Gamble (P&G) used the microgravity environment of the ISS to determine how to create conditions in a liquid that enable the suspension of different-sized particles. The P&G team did this in the form of microscopic nets that can gently suspend particles in a mixture and thus prevent separation, as if gravity had no effect, helping the company enhance its consumer products for all of us on Earth.

Two articles showcase materials research that leverages the extreme space environment. The article "Bringing Motion to Life: Materials Science Research in Space" discusses the use of radiation exposure for the testing of "smart" electroactive polymers that contract in a way that is similar to muscles for use in prosthetic implants in humans. Such materials could also one day help robotic systems clean up radioactive areas or explore space. The article "Tough Enough for Space: Accelerating Materials Testing With a New Permanent Platform" describes a facility available on the exterior of the ISS that allows investigators to analyze the durability of materials in response to temperature extremes and the harsh environmental conditions of space such as atomic oxygen.

Last year, I had the honor of speaking at the first Materials Science in Space Workshop, co-sponsored by the ISS National Lab and the National Science Foundation, held in conjunction with the 2018 ISS Research and Development Conference (ISSRDC). At the workshop, I presented the recommendations from the Academies' *3D Printing in Space* report from 2014, which was the same year the first tool (a ratchet) was designed on the ground, emailed to space, and printed in orbit. Now, the Additive Manufacturing Facility has been a permanent "machine shop" on the ISS for more than three years, bringing us closer to the possibility of designing tools directly for their use in space rather than to withstand launch. An exciting chapter in manufacturing is indeed unfolding, and the article "The New Gold Rush: 3D Printing in Micro-G" further discusses the progress of in-orbit production. This year, the ISS National Lab and NASA's Space Life and Physical Sciences Research and Applications Division held a second Materials Science in Space Workshop at ISSRDC 2019, a telltale sign of the importance of space-based materials research today and in the coming decade. ■

Lenore Rasmussen, Ph. D., checks pressure during the oxygen plasma treatment of titanium metal support mounts

Ras Labs

ORIGINALLY FEATURED IN VOLUME 1, ISSUE 2 ⋮ 2016

CASIS-ISS Synthetic Muscle™ experiment onboard the ISS National Lab

Ras Labs

BRINGING MOTION TO LIFE:

MATERIALS SCIENCE RESEARCH IN SPACE

BY EMILY TOMLIN, *Staff Writer*

Our hands perform dozens, if not hundreds, of tasks for us every day. They wave hello and goodbye. They open jars, doors, and soda bottles. They button our shirts, put on our makeup, and shave our beards. And often unknowingly, they gesture to add emphasis and nuance to our spoken words. For the majority of us, we take for granted the delicate, precise, and constant duties our hands perform on our command.

Now imagine that you are removed of that luxury; the hands that thanklessly performed these tasks are gone. How do you now navigate the world, and what sort of loss do you experience not only in function, but in expression and personality?

Lenore Rasmussen of Boston has devoted her career to science that enables those with lost limbs to overcome this poignant challenge. As a student, Rasmussen became intrigued by the concept of lifelike prosthetics—and for the past two decades, she has worked in the complex field of materials science and polymer chemistry to explore ways to improve prosthetics and robotics. Recently, her work has led her to a somewhat surprising testing platform: the ISS National Lab, onboard which she can study materials science in ways not possible on Earth.

THE PROMISE OF SYNTHETIC MUSCLE™

Rasmussen's passion is her quest to provide amputees with limbs that look and feel human, allowing not only robust function but also form—the artistic and nuanced movement that gives our appendages (especially our arms and hands) the ability to express emotion. Beginning with self-labeled "basement experiments" after graduate school and subsequently navigating her way through the ambitious community of biotech corporations and start-ups, Rasmussen's now 13-year-old company, Ras Labs, currently designs and tests Synthetic Muscle™, an electroactive polymer-based product that seeks to enable such human-like prosthetics.

> *"I thought there must be a way to bridge the gap between form and function," said Rasmussen, "a different way of doing motion rather than a purely mechanical approach."*

So she explored a class of "smart" materials called electroactive polymers, which are not only much lighter than metals but also capable of converting electrical potential energy into mechanical motion without pulleys, gears, or motors.

Previous electroactive polymers have been shown to bend in response to electrical stimuli—but Rasmussen discovered specific formulations and configurations that can actually contract, in a way similar to human muscles. Synthetic Muscle™ uses these specific, patented polymers created by Ras Labs to enable biomimetic motion—lifelike dexterity, contracting, bending, and stretching—with minimal noise and heat.

In addition to contraction, the newest iterations of the Ras Labs polymers also achieve expansion, allowing truly complex motion.

Importantly, Ras Labs seeks to produce these prosthetics without high energy requirements. This feature is critical for their availability and widespread adoption—if a prosthetic can work with a small battery pack instead of a plug-in power supply, the usability for everyday citizens and functionality for military use suddenly becomes a reality instead of science fiction. Moreover, it keeps the cost down—which Rasmussen emphasizes is critical, because the places prosthetics are often most needed globally are places where people cannot afford them.

Perhaps ironically, her quest for human-like motion has made Rasmussen's work attractive to the robotics industry, which also seeks low-power, lifelike function of artificial appendages. Contrary to Hollywood's portrayal of robots and cyborgs that are practically indistinguishable from humans, it is surprising what real-life mechanical and electronic components struggle to do—for example, turn a doorknob.

"In the first experiments testing a robot's ability to open a door, the robots fell over," said Rasmussen. "We take for granted how easy it is, but turning, oblique-type motion with our hands is very complex." The work in diagonal motion Ras Labs is exploring through the use of electroactive polymers lends itself well to solving these kinds of issues in the robotics industry.

The Ras Labs mission has thus become slightly more broad over the years—and as Rasmussen and her team expanded their goals from enabling everyday human tasks to pushing the limits of what their Synthetic Muscle™ can do for a non-human entity, they began to take their materials to the extremes.

A FLY ON THE WALL OF THE ISS

To determine whether Synthetic Muscle™ could function under stresses beyond what would be asked of a human, Rasmussen's electroactive polymers have been through a lot in the past 13 years.

In addition to being zapped by a wide range of electrical shocks, they have been chilled to a cool -271 °C, compressed by extreme G forces and pressures, and assaulted by a radioactive pellet of cesium-137 (at the U.S. Department of Energy's Princeton Plasma Physics Laboratory at Princeton University). And now, most recently, they have been Velcro-ed to the wall of the ISS for more than a year—finally returning home to Boston on June 1 after splashing down on May 11 in a Dragon capsule returning from the ISS.

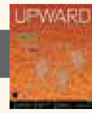
The ISS testing (mainly assessing cumulative radiation exposure effects, which are present at constant low levels even in the interior of the station) will help Rasmussen determine whether robots using Synthetic Muscle™ can be sent into environments that humans either cannot enter for safety reasons or would not want to stay for long. It is obvious to see the benefits of such durability for spaceflight applications—limiting astronaut extravehicular activity would certainly be beneficial for long-term space travel—but the benefits for ground-based use are also compelling. For example, robot emergency response could save many lives in situations too dangerous for humans to act, such as inside nuclear power plants.

RAS LAB'S BUSINESS BREAKTHROUGH

Going into business was not easy for Rasmussen. She patented her discoveries and even authored a book on electroactive polymers, but her goals were always about science, discovery, and patient quality of life. In fact, she originally explored forming a nonprofit instead of a startup LLC—and she may still go that direction someday. But in 2003, she began the difficult journey of taking on partners and navigating her way through the business world as founder and chief technology officer of Ras Labs, LLC.

"In the beginning, I just wanted to see if some of my crazy ideas would work," Rasmussen said. So she started by looking at the bending of electroactive polymers, "zapping" everything she could. True to form for great discoveries, the first example of her polymers contracting instead of merely bending—giving Rasmussen the hope of biomimetic motion—happened in 2007 and was "basically a mistake in the lab," she said. "It was a very picky synthesis, so it took some work to figure out!" Luckily, the later generations of Synthetic Muscle™ are stronger, much easier to produce, and are scalable.

In this initial spaceflight experiment, various investigational additives and coatings related to Ras Labs polymers were passively exposed to the internal ISS environment, which induced changes in the materials. These changes will allow the Ras Labs team to analyze the behavior of the test materials after exposure to the specialized ISS radiation environment. While the bulk of the analyses have just begun (pH testing, material integrity, microscopy, and electroactivity), initial postflight observations and crew photography from in orbit (i.e., changes visible to the naked eye) indicate that the spaceflight results are unique from previous ground-based radiation testing. Further analysis will reveal more specifics, but Rasmussen indicated that the ISS exposure in some cases demonstrated



THE CASIS CONNECTION

Ras Labs' introduction to spaceflight research came in 2013, when Rasmussen entered a competition run by MassChallenge (a global business accelerator that offers both funding and practical support). There, Rasmussen was awarded a grant through a CASIS partnership with MassChallenge—earning her an opportunity to fly her research to the ISS National Lab.

accelerated "aging" or degradation of samples compared with ground controls.

"Being on the ISS was pretty remarkable," said Rasmussen, "And it looks like we'll have some really cool, interesting results."

These results alone could help reveal unknown characteristics, including strengths and weaknesses, of the very specialized polymers Ras Labs creates and tests—which could enable design of new materials with improved features for a number of purposes (including those unrelated to spaceflight). Moreover, Rasmussen has greater plans following this initial foray into spaceflight R&D.

MINIMAL ALLOCATION FOR MAXIMUM RESULTS

The inaugural Ras Labs payload to the ISS was elegant in its simplicity. Additives and coatings for the Ras Labs custom polymers, selected for robustness based on ground-based radiation testing, were placed in tiny containers, sent up on SpaceX-6 in April 2015, and stuck to the interior wall of the ISS—using minimal power, upmass, and crew time by staying inside and requiring minimal manipulation. Two thermoluminescent dosimeters recorded radiation exposure on the ISS and on the ground duplicate controls.

THE POWER OF SPACEFLIGHT RESEARCH

Following on the heels of her promising first experiment in space, Rasmussen seeks to perform more robust spaceflight R&D that takes full advantage of the ISS environment. While passive radiation exposure is expected to yield exciting results for her team, the benefits of performing active interrogations of polymer function in microgravity onboard the ISS platform opens the door to even more revealing inquiries.

The functional absence of gravity onboard the ISS affects the structure, properties, and behavior of materials, including physical, chemical, electrical, thermal, and magnetic characteristics. These effects stem primarily from differences in fluid dynamics in space—removal of sedimentation, buoyancy-driven convection, and other phenomena that dominate fluid motion and behavior on Earth. In the absence of these phenomena, scientists are able to unmask underlying characteristics of materials and critical clues to their behavior and properties that otherwise might never be observed or understood through ground-based studies.

By testing the *function* of Synthetic Muscle™ in future materials science investigations in microgravity, Rasmussen expects to observe expansion and contraction that is more uniform, which could reveal completely new information about Ras Labs' materials. These types of studies will inform the underlying, fundamental basis upon which Ras Labs technology is built, potentially taking the company's product to whole new levels. This brings Rasmussen back to her core goals: innovative science that can improve patient quality of life.

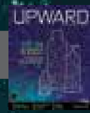
"We need to keep up with the other new, cool developments in the industry," Rasmussen said. For example, "self-sensing," in which mechanical compression can elicit changes in the response and properties of a material. This type of feedback could enable a feature beyond only form and function: a sense of touch. Ras Labs is still working toward the seemingly simple but truly complex prosthetic hand, and Rasmussen believes that an autonomous human-like hand with actuation (including finger movement and grasping functions) is within reach for Ras Labs within five or six years.

> ***"Our hands are close to our face; they define us as humans," said Rasmussen. "It might be a small market, but I didn't go into business to make a million and sit on a beach—I wanted to make something that people can use."***

FINDING THE RIGHT FIT

Along with continuing to explore spaceflight R&D, Ras Labs initiated agreements with the Department of Defense and Department of Energy, and was awarded funding through the Food and Drug Administration for a project administered through the Philadelphia Pediatric Medical Device Consortium and Children's Hospital of Philadelphia that is pushing the first Ras Labs product onto the market: a shape-morphing polymer pad system for prosthetic liners and sockets.

Patient comfort is adversely affected by the common issue of poorly fitting prosthetics, which causes slippage, discomfort, and even breakdown of human tissue. Ras Labs' contracting and expanding polymers are helping to address this issue by improving and maintaining fit, allowing patients to maintain a full active lifestyle.



ORIGINALLY FEATURED IN VOLUME 1, ISSUE 3 | 2016

THE ISS & Household Products:

HOW P&G IS USING SPACE TO IMPROVE YOUR CUSTOMER EXPERIENCE

BY EMILY TOMLIN, *Staff Writer*

In an era of increasing commercial innovation in space, many big-name companies are taking to the skies to explore how microgravity research might enhance their products. But for Procter & Gamble (P&G), a giant among household product providers, spaceflight has been a part of their R&D portfolio for almost a decade—and recently, they have shared exciting progress from their ISS experiments investigating the new science of polydisperse systems.

A common problem in the consumer product world is how to develop new and clever ways of suspending materials in fluids. Consumer foams and gels—such as the familiar products from Gain®, Dawn®, Tide®, Olay®, Gillette®, Pantene®, and many other P&G brands—depend on the stability of such mixtures. This is particularly true for polydisperse mixtures; that is, liquids or gels that contain particles of different sizes in suspension. Unfortunately, how these mixtures move and break down is often not fully understood, which poses a challenge to product designers and manufacturers: ***How to create better, longer-lasting products that maintain all their desired features.***

For example, shampoos contain oils that give the product nice characteristics for a consumer; for example, the oils condition hair and make it easier to brush. But oil droplets suspended in a liquid tend to separate over time, because the oil tends to float to the top. So how does a manufacturer keep these droplets suspended in solution without changing the product so much that it loses its functional and preferable characteristics?

BUILDING MICROSCOPIC NETS

One way to keep droplets suspended is to introduce tiny sticky particulates into a mixture. These micro- and nano-sized particles stick together to create strands that form a net structure within a fluid, stabilizing the movement and dispersity of larger droplets in the mixture. The behavior and effectiveness of such "nets" is the focus of P&G research on the ISS, led by P&G Principal Scientist Matthew Lynch.

> ***"We need overarching mathematical models to describe interactions within these complex mixtures," said Lynch. "We need to build predictability to model, improve, and design for commercial product development."***

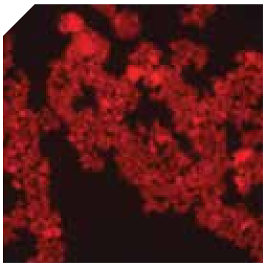


Photo credit: Procter & Gamble

For nets to stabilize a complex mixture, they have to possess mechanical strength. The net must "catch" larger droplets responsible for product benefits (such as oils), keeping the droplets from separating out of solution. But the net also has to be flexible—it must stretch and even break so the mixture can flow like the commercial foams and gels a consumer is used to.

For example, the fluid mixture that makes up a shampoo must flow like a liquid when a consumer squeezes it out of the bottle. However, while the shampoo sits in the bottle, both the manufacturer and the consumer ideally want the solution to behave almost like a solid—keeping the droplets of active materials in place, dispersed throughout the bottle. An ideal product thus acts like a solid as it sits on a shelf in the store or in your home—or even as it is transported down a bumpy road—but under the influence of mechanical force (such as squeezing the bottle), the product flows like liquid.

> ***"We need to get the interactions just right to meet both sets of conditions," said Lynch. "By performing experiments on the ISS, we can ask basic science questions about how these mixtures behave and eventually have a tangible impact on product definition."***

Basic (rather than applied) science works to answer these fundamental questions and build a foundation for new technologies and new ideas. Lynch's team works on "upstream R&D" at P&G, performing investigations in such basic sciences—and eventually improving mathematical models to describe the underlying phenomena responsible for the behavior of fluid mixtures.

ESTIMATING SHELF LIFE

Technically termed complex fluid physics, the basic science P&G is performing onboard the ISS is the study of colloids, or mixtures of particles dispersed in fluids. On the ISS, the complexity of the mixtures in the P&G experiments is somewhat balanced by the simplified elegance of fluid physics in microgravity. Changes in product behavior happen more slowly in microgravity because of reduced buoyancy-driven fluid movement. Moreover, there are fewer confounding factors to studying these systems on the ISS (for example, sedimentation, which is gravity driven).

The ISS has thus allowed P&G to isolate and study the interactions within complex systems under time scales not possible on Earth. Specifically, Lynch's team has been investigating how the nets within fluids keep droplets dispersed and maintain a product's functional characteristics. The ultimate commercial application of this science is something every consumer can appreciate—shelf life, which is dependent on how long these nets stay intact.

Photo credit: Procter & Gamble

"Imagine you have a strand of sticky particles that hold all this stress," said Lynch, "but there's a characteristic time scale for how this strand will change and break down over time." As the many strands within a product break down, the product's structure will eventually collapse, and the various components of the mixture will separate. The product then becomes unusable.

Companies currently have some understanding of the probability of strand breakdown within nets over time, and they use this to predict shelf life. But current models for how this occurs are one-size-fits-all, best describing only simple systems with sticky particles of uniform dimensions. True product chemistry involves polydispersity—interacting particles of many sizes. Breakdown within polydisperse mixtures is complex and difficult to model or predict, let alone to exploit for design of better product formulations.

In other words, current models can give companies indications of how product breakdown will occur, but in the real world, mixtures are not simple, static systems—they are dynamic and complex. Therefore, pragmatic approaches to not only predict shelf life but also improve product design must be driven by a better understanding of the underlying fundamental physics—and the ISS is ideal for this kind of investigation.

PRODUCT BEHAVIOR

For P&G, the robust history of colloid physics investigations onboard the ISS also paved the way for a streamlined, effective R&D experience in space. In collaboration with NASA, CASIS, Harvard, Case Western Research, and service

THE PROBLEM OF POLYDISPERSITY

If a company creates sticky particles of the same size and introduces them into a mixture, the particles organize themselves into strands. These individual strands interact to form the net structure product chemistry seeks to exploit.

But the behavior of sticky particles of varying sizes—the attractive interactions of polydisperse systems—is not well understood. It is these more complex systems that may hold the key to better products with enhanced features and longer shelf life. Polydisperse mixtures behave very differently than the more well-defined systems with uniform particle size.

provider ZIN Technologies, Inc., two series of P&G experiments were conducted over the past decade, with complementary goals and results building a new knowledge base for understanding polydispersity.

> *"Typically, the more complex experiments can have timelines of three years or more," said Christopher Sheehan, area manager at ZIN Technologies, "but in this case we were able to leverage lessons learned from previous NASA experiments to enable flight of multiple payloads within a comparatively short time frame."*

The experiments—one series through NASA sponsorship and the other through CASIS and the ISS National Lab—involved the study of complex fluids at both ends of the spectrum: microscopic and macroscopic.

Photo credit: NASA

In the NASA-sponsored experiments (part of the Advanced Colloids Experiment, or ACE, series on the ISS), P&G studied colloid dispersions—the fundamental physics of how suspended particles move and evolve over time within a fluid. The systems studied not only varied particle size but also differing levels of particle stickiness—which can also be controlled as part of product design.

Basic science knowledge about how these varied mixtures and particles behave will allow manufacturers to predict characteristics, including shelf life, of commercial products that depend on this physics and chemistry.

In contrast, the CASIS-sponsored experiments (part of the Binary Colloidal Alloy Test, or BCAT, series) looked not at micro-structure but rather at the ensemble, over longer time scales. Functionally, this allowed P&G to assess the "aging" of a mixture at a very detailed level, because the separation of mixtures occurs more slowly and evenly within spaceflight samples than on Earth.

BRINGING HOME THE BENEFITS

The parallel approach of P&G's multiple investigations, correlating the microscopic data from ACE with the macroscopic phenomena from BCAT, has allowed the company to see evolving "textures" at the product level that correlate with microscopic events. In this way, the ISS is providing a robust, repeatable platform for P&G to diagnose observable behavior of consumer products on Earth.

"The CASIS model for commercial research lends itself to fast, recurring access to ISS assets," said Sheehan. "This experiment also moved quickly through development and build cycles thanks, in no small part, to previous research and technology investments made by NASA in the colloids field. In both cases, helping get P&G's science to station quickly was very rewarding."

Ultimately, the P&G experiments seek to improve product chemistry—tying the spaceflight investigations back into tangible benefit to consumers on the ground. And the story continues, as future P&G experiments are already scheduled to launch later this year and take advantage of upgraded ISS hardware.

With colloids that improve daily life, from showering to cleaning to caring for a baby, it is estimated that P&G products are used by 4.8 billion people every day—more than half of Earth's population. "The success of the P&G spaceflight experiments is more than just a compelling business impact," Lynch said. "More importantly, what we learn here is going to help a lot of people." ■

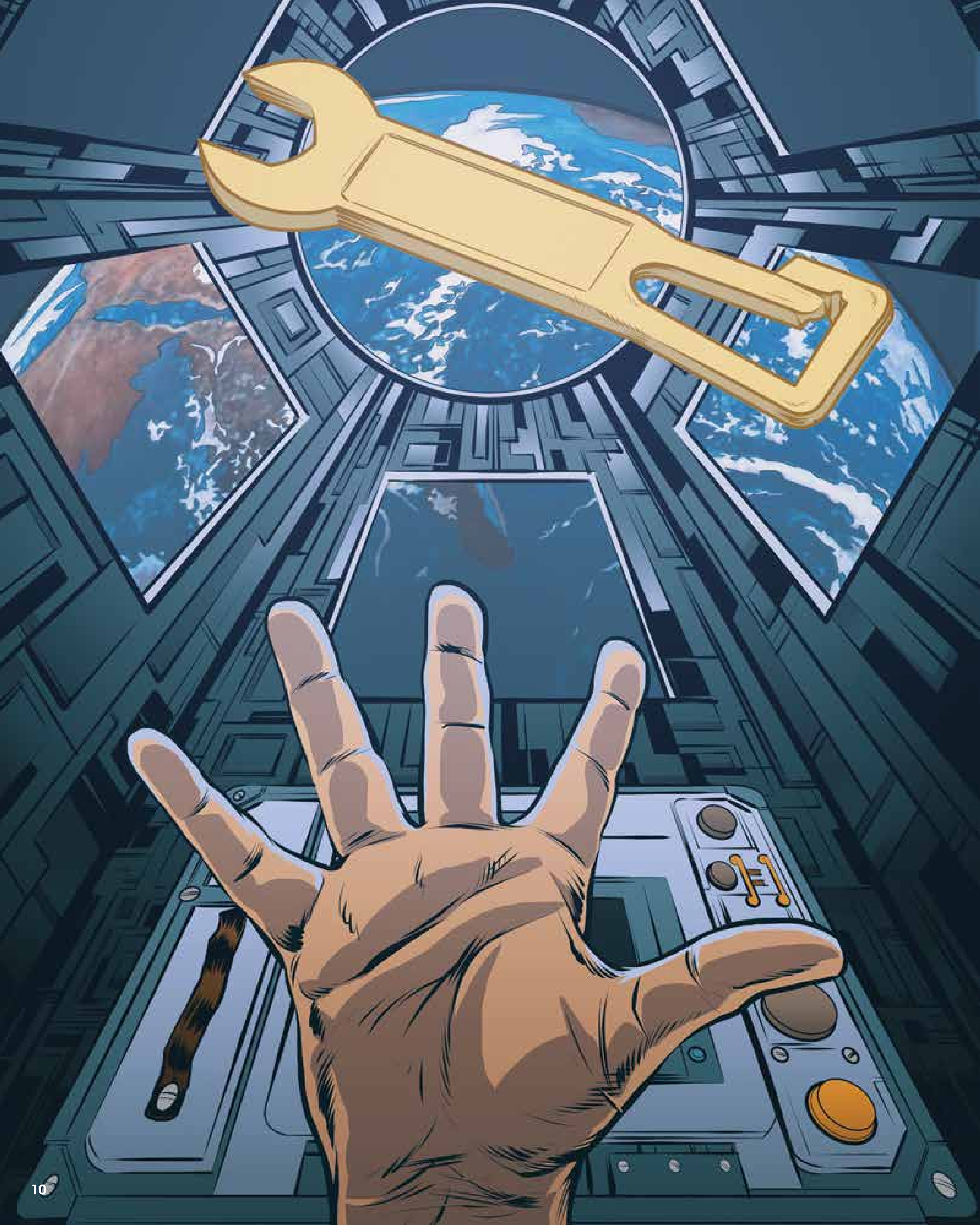
RESULTS: A SNEAK PEAK

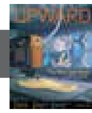
***P&G** The success of P&G products depends on novel and powerful ideas, so the results from their spaceflight experiments are still somewhat confidential—but Lynch and his team intend to publish some of their results to share the details with the scientific community at large.*

Some of the early indications that will be expanded upon in future publications include the fact that smaller particles tend to segregate themselves to the outsides of very sticky strands. Moreover, if the stickiness is decreased, the smaller particles do not join in the net formation at all—only the larger particles form strands. Interestingly, these observed changes appear to be associated not with absolute particle size but rather with the proportionalities of the various sizes.

Understanding these nuances of particle behavior and "ordering" will help scientists create mathematical models to describe the behavior of complex mixtures—which is paramount to improving product design.

Lynch cannot share much more detail at this time, but he did indicate that the ultimate goal of better understanding polydispersity and ordering over long time scales had been greatly aided by the ISS experiments. "We've seen unexpected things and learned a lot of interesting science," he said.





THE NEW GOLD RUSH: 3D PRINTING IN MICRO-G

BY ANNE WAINSCOTT-SARGENT, *Contributing Author*

Until a year ago, commercially printing objects in space was the stuff of science fiction. Not anymore. At any given time onboard the ISS National Lab, a 3D printer receives data files from Earth that it transforms, layer by layer, using plastics, into fully functional tools and parts that ISS crew members can use.

This March marked one year since the Additive Manufacturing Facility (AMF) was launched as a permanent "machine shop" on the ISS, providing in-orbit fabrication services to customers from both the ISS National Lab and NASA.

The AMF, owned and operated by California-based Made In Space, has come a long way from its origins as a proof-of-concept payload launched to the ISS in 2014. That initial prototype proved that 3D printing in microgravity actually works and that there was commercial demand for parts Made In Space. Today, the AMF continues to produce objects on-demand not only for NASA but also for a multitude of commercial companies, fueling the growth of a new economy in low Earth orbit.

Made In Space

SPACE-BASED MANUFACTURING

Ken Shields, director of operations at CASIS, sees several tangible and intangible benefits of being able to manufacture objects off the planet. “Theoretically, you could accelerate completion of end-to-end experimentation in orbit by exchanging out components in near real time as opposed to waiting for results and then sending up parts.”

Before the AMF, any spare parts for the ISS and materials or tools required for experiments on the ISS had to be transported from Earth on a launch vehicle and stowed away onboard until (or if) needed. With the AMF, an ISS crew member or user on the ground can custom design, print, and manufacture an object on demand on the ISS, with the ability to do multiple iterations.

“We can deploy much faster,” said Andrew Rush, Made In Space president and CEO.

As an example, Rush shared how quickly the team designed a ratchet for ISS Commander Barry Wilmore in 2014 using the prototype microgravity 3D printer. The ratchet was the first tool ever to be designed on the ground, emailed to space, and printed in orbit.

> *“We went from idea to part on station in a week. That is an order of magnitude faster than the traditional way of sending things to space,” Rush said.*

The AMF builds upon that first prototype unit. The new commercial facility is larger, modular, and upgradeable. From a capability standpoint, the AMF can both scan and verify the accuracy of the parts it prints with no user involvement.

While the AMF currently uses three types of thermoplastic polymers, it will support other feedstock as demand and applications grow. The plastics available now include: acrylonitrile butadiene styrene (ABS), the same material used to make LEGO® blocks; a high-density polyethylene (HDPE), such as the type found in home food containers; and an aerospace-grade polymer (polyetherimide polycarbonate or PEI-PC). Longer term, Rush and others could see these raw materials eventually recycled from other parts or recovered in situ from the moon or other planets.

Space-based manufacturing eliminates the need to design for the high shock and vibration of launch, which often results in products being over-designed, Rush said. “Making things in space allows us to actually optimize the design for the space environment rather than for the transportation system.”

INDUSTRY INNOVATORS FLOCK TO THE AMF

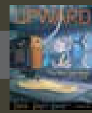
Medical, aerospace, and materials companies are showing the strongest interest in the AMF, Rush said. The medical industry wants to make human spaceflight safer by equipping physicians to print out surgical instruments and perform needed operations when human habitation on the moon or on other planets is realized.

In January, 3D4MD, a Toronto-based 3D printable medical solution provider, became the first company to use a 3D printer on the ISS to create medical supplies in space. The AMF printed a custom mallet finger splint using a laser hand scan saved from the fitting process for spacesuit gloves. The splint has immediate application, given how common hand injuries are for astronauts.

Aerospace companies are studying the design of space-optimized satellites that could be built and launched in orbit. They are also looking into how to make more digital tools for use on the ground and in space.

In the materials arena, Braskem, the largest thermoplastic resin producer in the Americas, is working with Made In Space to fabricate tools and spare parts in space using bio-based resin from sugarcane. Thermoplastic resins are raw, unshaped polymers that turn to liquid when heated and turn solid when cooled. The material can be continually remelted and remolded, allowing parts and scraps to be reprocessed. Thermoplastic resins tend to be recyclable, which adds to their value as a space material.

Made In Space



3D PRINTING IN MICROGRAVITY

How does 3D printing in space work? Like an Earth-based 3D printer, the AMF uses an additive manufacturing method to print objects in layers of plastics, metals, and other feedstock materials. Made In Space relies on a 3D additive manufacturing technology called fused deposition modeling. Heating up the filament to a molten state, the material is precisely deposited through a trigger head in a back-and-forth pattern—layer by layer—until the part takes form.

> ***"There are 3D printers that a lot of people might be familiar with that use this same technique," said Rush. "To make it work in space, you need to eliminate gravity from the equation—everything from positioning of the head and the part, to how the material gets deposited, to making sure it sticks to itself, to managing the heat control."***

Moreover, the free-fall weightless environment of space results in the absence of convection, "so you need to make sure the hot parts stay hot and the cold parts stay cold without the benefit of natural convection," Rush said.

FROM THE EARLY VISION TO PRINTING SPACE-OPTIMIZED TOOLS

Made In Space has come a long way from the early days of proving its design. Initially the founders hoped to "buy a commercial off-the-shelf printer and tweak it until it could turn upside down and function as a space-capable printer," said Rush.

The team spent many sleepless nights testing and retesting their design. They fine-tuned the printer during two weeks of parabolic flight testing, which was critical to proving the design.

The final system, designed to operate from the ground with no ISS crew member involvement, met NASA's requirements for reliability, safety, and self-sustaining performance. The AMF can use a wide variety of materials as feedstock because it regulates temperature and humidity. Its own environmental control system also keeps the materials within appropriate levels of containment, a required safety regulation for ISS hardware and facilities. Interestingly, this containment feature has been incorporated into 3D printers on the ground.

Made In Space engineers on Earth control the AMF's queue of print jobs, while internal cameras allow the company to monitor the printer's operation and notify NASA when an object is printed and ready for retrieval by an ISS crew member.

Made In Space

Since the AMF began full operations this past summer, it has printed more than a dozen objects, including a space-optimized wrench designed by Lowe's Home Improvement Stores for the ISS crew members to clip on their belts to more easily perform repairs. Made In Space has designed numerous other ISS tools, including a sensor adapter, hose adapters, and spacecraft parts.

Made In Space already has a six-month backlog of print orders. Besides NASA, AMF customers include private companies, private individuals, universities, K-12 schools, and other government agencies.

AN UNCOMMON SPACE PARTNER

On the surface, one of the more unconventional partners working with Made In Space is Lowe's, the home improvement company. Look deeper though, and you realize that Lowe's Innovation Labs uses technology, design, and the power of story to help customers and employees innovate and build the future. Lowe's Innovation Labs is developing on-demand manufacturing technologies that will shape our future.

Kyle Nel, the Labs' founder and executive director, regularly works with professional science-fiction writers to use short stories to jump-start the creativity of Lowe's leaders by helping them to better envision the future of hardware retailing.

"We are pursuing a narrative for how technologies, including additive manufacturing, make it possible to get exactly what you need, right when you need it," Nel said.

Many of these futuristic concepts have found their way into Lowe's stores to enhance the shopping experience of customers. They include everything from in-store robots to holograph-based virtual reality and 3D printing. Innovation Labs introduced an experimental 3D printer in one store to allow customers to "print" everyday hardware items. The strong response proved to Nel that Lowe's needed a technology partner to take the 3D printing concept further. Made In Space fit the bill.

"They got what we were trying to do, and we got what they were trying to do—it was this beautiful synergy of space and Earth," Nel said. "Working with uncommon partners like CASIS and Made In Space, we can do things together that we can't do on our own."

Lowe's has helped design everything from 3D-printed ratchets to specialized wrenches for the ISS, as well as other products Nel could not discuss publicly. Nel believes that tools rugged enough to withstand the harsh environment of space and the demands of space operations would more than meet the future needs of a Lowe's customer on Earth.

Nel and Made In Space visionaries also have devised a solution to a common byproduct of 3D printing: plastic waste. Their innovative prototype of a Plastic Recycler, while not yet deployed on the ISS, has the potential to efficiently turn plastic waste into filament that can be used to print new parts.

(L to R) Kyle Nel, Executive Director of Lowe's Innovation Labs, and Jason Dunn, Chief Technology Officer of Made In Space, use a 3D printer on the ground.

Made in Space

A LEO COMMERCIAL SPACE ECONOMY

Given the types of novel ideas already being generated, tested, and printed on the AMF with partners like Lowe's, CASIS's Shields believes the future is bright for the AMF on the ISS and that it will grow to become a critical component of building a sustainable commercial presence in low Earth orbit (LEO).

> ***"The queue of projects and potential customers that want to work with Made In Space indicate there is demand for this on the commercial side," Shields said. "What they are doing is disruptive—it's thinking outside the box. These are the kinds of companies that are going to lead the way in the LEO commercial market."***

According to Shields, hundreds of millions of dollars have been invested to date by commercial players testing the waters for building a business in low Earth orbit, often using the ISS National Lab as their test bed. In the last year alone, approximately $75 million has been invested in LEO projects and activities.

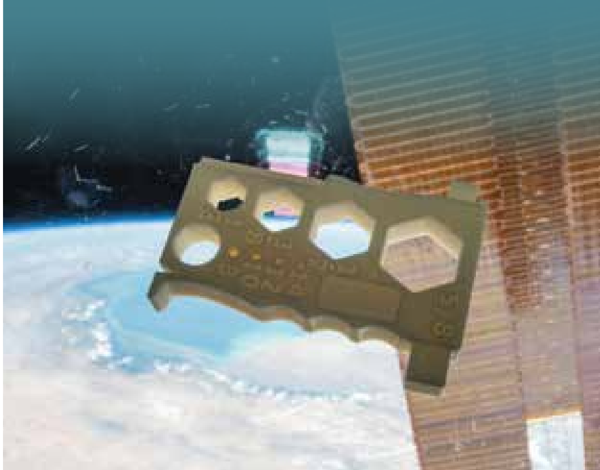
Made In Space is one of five companies now managing in-orbit commercial facilities on the ISS, a service provided by only a couple of companies just five years ago. By 2018, at least nine companies will be managing commercial facilities on the ISS, which together will total $100 million in commercial investments in the LEO space sector. The AMF is a critical part of that future, said Shields.

"The ability to manufacture things in space will be critical for us going beyond low Earth orbit to occupy other regions of space, be it other planets or other orbiting bodies," Shields said. "The applications are endless as far as manufacturing parts and components to sustain oneself in the ultimate remote location."

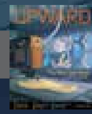
Looking at how far Made In Space has come—from idea to operational manufacturing service in the span of six years—Rush cannot hide his excitement. "I think that's an incredible pace."

Rush and his colleagues have no intention of slowing down. "The design space is so broad, we are just seeing the very first applications of additive manufacturing," he said. "I view the LEO economy, especially in-space manufacturing, as the next gold rush—we aim to expand utilization of space in as dramatic a way as possible through commercial activity on the AMF." ■

The Multipurpose Precision Maintenance Tool, pictured above, was the winning design of the 2014 Future Engineers Space Tool design competition, which gave students the opportunity to design a tool for ISS crew members to be 3D-printed on the AMF. The design was submitted by Alabama high school student Robert Hillan. The AMF can currently print solid objects up to 10 cm x 10 cm x 14 cm, which is slightly larger than a softball. To make larger objects, the AMF can print connection features into parts and have the larger object assembled in space. Made In Space officials say future AMF-printed objects will be significantly larger—the AMF will be able to print objects a foot or more in length on one side.



Made In Space



WHAT'S NEXT FOR MADE IN SPACE?

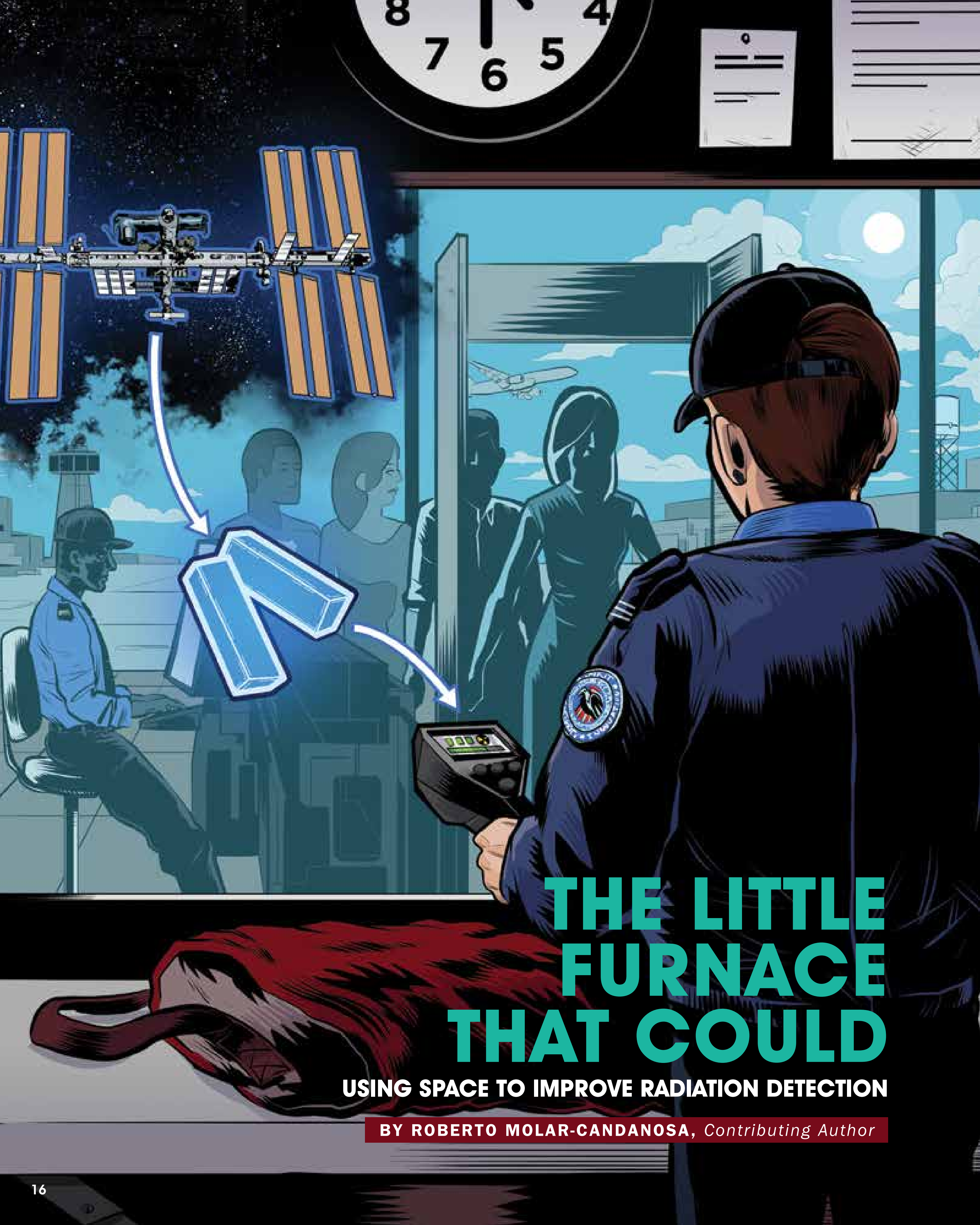
Currently, Made In Space is working with NASA to build larger structures that can only exist in microgravity, said Rush. With in-space additive manufacturing, NASA could print, build, validate, and iterate antennas, trusses, or beams—the building blocks of satellites and future space stations. New satellites printed from space could revolutionize satellite design. One reason is they would be significantly lighter because they no longer would have to support their weight on the ground as satellites made on Earth do.

"We view the AMF as the foundation of a much broader suite of space manufacturing techniques and capabilities," Rush said, "in particular, materials that can only be manufactured and processed in space." He cited a payload Made In Space is building that CASIS will deploy on the ISS National Lab later this year to produce test quantities of ZBLAN optical fiber, building upon the technology operating in the AMF.

Scanning electron microscope images of ZBLAN fibers: at left, processed in unit gravity forming visible crystals; at right, processed with magnetic eliminating crystal formation. NASA

Rush predicted that ZBLAN could potentially replace silica fiber in long-haul telecommunications on Earth by making those communications faster and more reliable. "It has 10 to 100 times lower signal loss than silica fiber, and has a much wider transmission window, which means you can get better bandwidth and get better response time," Rush said.

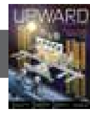
NASA also recently selected Made In Space and its partners to develop a technology platform—the Archinaut—that enables the autonomous manufacture and assembly of spacecraft systems in orbit. Working with Northrop Grumman and Oceaneering Space Systems, Made In Space is designing and building a 3D printer equipped with a robotic arm to operate in low Earth orbit and manufacture space-optimized reflectors and booms, providing next-generation capabilities for government and commercial missions.



THE LITTLE FURNACE THAT COULD

USING SPACE TO IMPROVE RADIATION DETECTION

BY ROBERTO MOLAR-CANDANOSA, *Contributing Author*

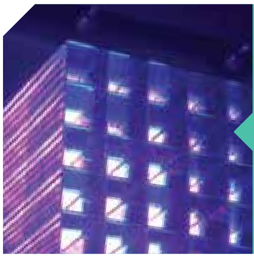


Everything around you emits radiation—from the bananas in your kitchen, to cosmic rays from space, to the piece of paper (or screen) from which you are reading this sentence. Some of these types of radiation are so insignificant that they are harmless. But some can be dangerous. So, how can we better distinguish and detect different types of radiation?

One way is to improve the semiconductor and scintillator crystals used as radiation detectors. Two investigations that launched to the ISS National Lab in April are studying such crystals using the recently refurbished Solidification Using a Baffle in Sealed Ampoules (SUBSA) hardware. A high-temperature furnace roughly the size of a small microwave oven, SUBSA can be used to study how microgravity influences the synthesis of these crystals, which could ultimately enable improved functionality on Earth.

GROWING CRYSTALS ON EARTH

Electronic devices—including computers, medical imagers, and radiation detectors—function thanks to semiconductors: small and specially produced crystals used to conduct electrical signals. Smaller and more powerful semiconductors are the reason our pocket-sized cellphones are so smart these days.



Scintillator crystals used at the Jefferson National Accelerator Facility

Jefferson Lab

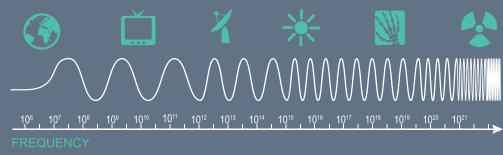
Conversely, scintillators are unique crystals that emit light when exposed to certain types of energy, much like glow-in-the-dark objects. They are mostly used in radiation detection devices for homeland security and defense applications, X-ray security cameras, and medical imaging devices.

To create both semiconductors and scintillators, scientists combine and melt various elements that crystallize after cooling down. The functionality of these crystals depends not only on their composition, but also on their purity and quality and the physical conditions they are exposed to during cooling.

Producing these high-quality crystals is not easy, and many difficulties in the production process can be blamed on gravity. Earth's gravity drives convection, the movement within and between fluids with different temperatures or densities, causing hot fluids to rise and cold or dense fluids to sink while transferring heat.

Aleksandar Ostrogorsky, Illinois Institute of Technology professor and principal investigator of one of the current SUBSA crystal growth projects, said that when crystals are grown on Earth using slow and precise solidification techniques, gravity-driven convection is a problem. It results in variable melt composition, which disrupts the radiation detection properties of the grown crystals.

"There's a continuing mixing in the melt when you grow crystals, as there is when you are boiling a pot of tea," Ostrogorsky said.



RADIATION EVERYWHERE

Matter continuously emits electromagnetic radiation. Visible light and radio waves are examples of harmless radiation, whereas dangerous high-energy waves (such as X-rays and gamma rays) can come from certain gases, radioactive elements in nature, and even outer space. Moreover, in addition to electromagnetic radiation, hard-to-detect neutrons are emitted by uranium or plutonium, elements from which nuclear weapons are made.

These complex dynamics lead to crystals with problematic heterogeneous composition, cracks, bubbles, and other structural imperfections, which disrupt the performance of the crystal in downstream applications.

For example, to activate crystals with radiation detection capabilities, small quantities of a substance known as a dopant must be distributed uniformly throughout the crystal. On Earth, convection causes continuous and unpredictable movement as the melt crystallizes, disturbing dopant distribution.

For many years, scientists have thus aimed to achieve diffusion-controlled growth to grow crystals without the complexities caused by convection. That's where the SUBSA facility on the ISS National Lab could provide a competitive advantage. In space, buoyancy forces are virtually eliminated in the near-absence of gravity. This reduced motion allows for a more homogeneous distribution of dopants, fewer imperfections during crystallization, and ultimately, better crystals.

THE FIRST SUBSA EXPERIMENTS

In 2002, the SUBSA furnace was launched to space to study semiconductors made of indium antimonide. A specially designed transparent section of the SUBSA furnace allowed for observation and video-recording of the melting and crystallization processes onboard the ISS.

Tec-Masters, Inc./NASA

During Ostrogorsky's first SUBSA experiments in 2002, melting and directional solidification was observed for the first time under microgravity conditions. A data downlink from the video-enabled furnace on the ISS allowed Ostrogorsky to coordinate with NASA Astronaut Peggy Whitson to change temperatures, melt times, and other factors, observing how they affected crystallization. These experiments facilitated better understanding of the complex effects of convection in crystallization.

The 2002 successes laid the foundation for a new era of SUBSA utilization kicked off by Ostrogorsky and his former student, Alexei Churilov, who is now a senior scientist at Radiation Monitoring Devices, Inc. (RMD), in Watertown, Massachusetts (see *A New and Improved SUBSA Furnace*). In this round, Ostrogorsky is examining a different semiconductor material that is safe and affordable to produce, and Churilov is examining a scintillator crystal with the powerful ability to distinguish between various types of damaging radiation.

GROWING SEMICONDUCTOR CRYSTALS IN SPACE

The new generation of SUBSA payloads seeks to meet growing technological demands of the U.S. Department of Homeland Security and the U.S. Department of Energy, both of which supported Ostrogorsky's research in the gap period between NASA-sponsored SUBSA experiments. Ostrogorsky's present SUBSA investigation on the ISS National Lab will test indium iodide, which is chemically similar to the indium antimonide samples he used in 2002.

"Indium iodide is an overall promising detector for nuclear radiation," Ostrogorsky said, "and it is the only one I know that is completely benign, meaning it doesn't contain poisonous elements."

Indium iodide can be prepared inexpensively and has a low melting point of 365°C. "That's a relatively easy job for the little SUBSA furnace," Ostrogorsky said. It is also simple to synthesize and reacts to gamma rays, making it suitable for radiation detection.

Ostrogorsky said that his current ISS National Lab experiment, launched on the Orbital ATK CRS-7 in April, will help determine the theoretical limit of the crystal's detection capabilities and other benchmark properties of semiconductors. The experiment is examining de-wetting, which prevents stress-induced imperfections, via separation of the melt from the crystal growth container—a process that has never been directly observed and that Ostrogorsky will watch thanks to the video-enabled SUBSA.

"If at the end this gives us a very good reference for high-quality materials, then we'll have a specific goal to continue this on Earth," Ostrogorsky said. "We could get a really good detector if we manage to control these properties."

Aleksandar Ostrogorsky

A NEW AND IMPROVED SUBSA FURNACE

The SUBSA furnace launched in 2002 allowed scientists to heat samples to approximately 700°C and then precisely cool them down to allow for diffusion-controlled crystallization, all while streaming and recording video.

However, SUBSA's success in 2002 was not enough to overcome NASA funding limitations, and SUBSA was decommissioned shortly after the initial experiments. The hardware was flown back to Earth and sat in storage until 2015, when ISS National Lab customers demonstrated a growing demand for the capabilities of the SUBSA furnace. Through a mutually beneficial partnership, CASIS and NASA worked together to select a variety of payloads that would use the furnace, and NASA committed to refurbishing the hardware.

Upgrading the furnace took complex work to allow for a thermal containment system that could reach increased temperatures as high as 850°C. The upgrade also took care of "a little bit of wear and tear," said Scott Gilley, the SUBSA Payload Developer from Tec-Masters, Inc., who led the original hardware development in 2002 and the refurbishment in 2015.

SUBSA's software and thermal radiation shields were also updated, a larger range of container sizes can now be used, and a higher-definition camera was installed to observe and record the crystal growth process. Also, while SUBSA carries its legacy name, it no longer uses a baffle (a disc-shaped object that reduces fluid motion), because the 2002 experiments demonstrated that microgravity alone was capable of substantially reducing convection.

Hardware refurbishment is one way that NASA and CASIS are working together to maximize utilization of the ISS National Lab and leverage existing resources. Discussions regarding how best to leverage other hardware and facilities in the physical and life sciences under way.

CLYC scintillator crystals under UV excitation

Radiation Monitoring Devices, Inc.

SYNTHESIZING SCINTILLATORS IN MICROGRAVITY

Although semiconductors are a powerful tool for identifying harmful gamma radiation, they cannot detect neutrons, an important type of radiation emitted from objects such as nuclear bombs. However, Cs_2LiYCl_6:Ce (also known as CLYC) scintillator crystals, another set of samples being tested inside the refurbished SUBSA furnace, are capable of detecting this critical signature of nuclear weapons.

Because neutrons do not normally interact with other materials, they are more difficult to detect. The ability to detect neutron radiation is the distinctive quality of CLYC scintillator crystals, said Churilov.

Developed by RMD with support from the U.S. Defense Threat Reduction Agency and Domestic Nuclear Detection Office, CLYC scintillator crystals can detect both gamma rays and neutrons. Furthermore, CLYC scintillators can differentiate between types of radiation. Such dual detection is useful for many applications. For example, CLYC scintillators could help minimize the number and types of detection devices needed for airport security personnel.

"Using one instrument with CLYC scintillators, you could distinguish between harmless sources of radiation versus something like cesium-137 for a dirty bomb," Churilov said. Current technology to detect neutrons is limited, so CLYC scintillator crystals could be game-changers in the field of radiation detection.

To move toward more widespread use of CLYC scintillator crystals for radiation detection devices, RMD is now focusing on scaling up production to grow crystals with larger diameters and fewer physical defects. "But when you scale up the size during crystal growth, defects are much more important," Churilov said. "Crystals crack more easily, they can grow bubbles in them, and so it's much more difficult."

Knowing how the CLYC scintillator mixture behaves and solidifies in microgravity will help Churilov and RMD determine the importance of certain aspects of their production process on Earth. The SUBSA experiments will enable RMD to observe whether convection limits the size and physical quality of CLYC scintillator crystals for improved radiation detection.

"When you eliminate convection, other subtle processes can be directly observed," Churilov said. "This will give us immediate guidance of how significant reducing convection in the melt is for our crystal growth."

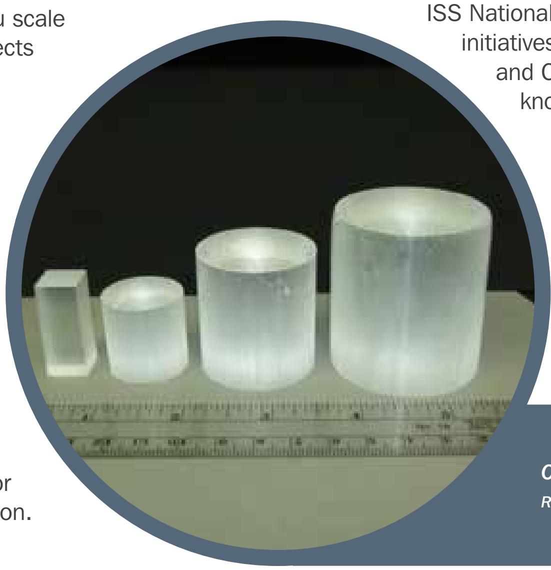
LITTLE FURNACE, BIG BENEFITS

The SUBSA furnace is a relatively small facility, but the advancement in fundamental knowledge about the formation and purity of semiconductor and scintillator crystals may have dramatic impacts in the development of next-generation radiation detectors. Although manufacturing these materials in space may not yet be economically feasible, the knowledge gained by the SUBSA studies will accelerate progress in ground-based production.

> ***"The purpose of our microgravity experiment is not necessarily to grow better crystals in space," Churilov said. "Our ultimate goal is really to understand the formation of defects in these crystals and apply that to our production process back on Earth."***

However, in-orbit manufacturing of materials may not be as far off as one might think. Various companies are currently exploring the possibility of space-based platforms for producing consumer products or commercially important materials. The commercialization of low Earth orbit may include steps toward such next-generation space stations, and current payloads on the ISS National Lab include proof-of-concept initiatives in this realm. But for Ostrogorsky and Churilov, the advancement of knowledge is enough for now.

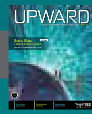
"Trying to think that someday we are going to have crystal production in space is too ambitious, too far away," Ostrogorsky said. "The idea is to do the experiments and get new knowledge so we can do some work on Earth." ■



CLYC scintillator crystals

Radiation Monitoring Devices, Inc.

Exotic Glass Fibers
FROM SPACE



The Race to Manufacture ZBLAN

BY HAYLIE KASAP, *Contributing Author*

Optical fibers are the thread that connects our modern digital world. Smaller in diameter than a human hair, these fibers can transmit light pulses of information at billions of pulses per second and over distances of several thousand kilometers, eclipsing what is possible with electrical cables.

Fiber optic cables used in modern communication.
ISS National Lab

These optical fibers are most commonly made of silica (SiO_2) glass. While silica fibers are easily produced using well-established methods, optical losses in the fiber requires the use of expensive repeaters to boost the signal across long transmission distances.

The fluoride glass optical fiber, ZrF_4-BaF_2-LaF_3-AlF_3-NaF, commonly known as ZBLAN, at its theoretical best can have 10 to 100 times lower signal loss than silica fiber. However, when ZBLAN is produced on Earth, convection and other gravity-driven phenomena can cause imperfections because of the nonuniform distribution of the various chemical components within the fiber. These defects that occur during the process of solidification result in the formation of microcrystals that render the fibers unusable for many commercial applications.

To avoid the adverse effects of gravity, scientists have turned to the ISS National Lab to produce ZBLAN fiber in microgravity.

High-performance ZBLAN fibers would be extremely valuable back on Earth, and several commercial companies such as Fiber Optics Manufacturing in Space (FOMS), Made In Space (MIS), and Physical Optics Corporation (POC) are currently pursuing in-orbit production of ZBLAN fiber. Initial results have been promising, and successful ZBLAN fiber production on the ISS National Lab could pave the way for future large-scale commercial manufacturing of ZBLAN in low Earth orbit.

ZrF_4-BaF_2-LaF_3-AlF_3-NaF

ZBLAN IS FRENCH?

The history of ZBLAN takes us back to 1974 in Rennes, France, when Professor Marcel Poulain of the University of Rennes and his brother Michel accidentally discovered this series of heavy metal fluoride glasses. Four years from their revolutionary find, the brothers formed their own company Le Verre Fluoré, putting the duo at the forefront of specialty fiber production.

However, interest in ZBLAN diminished in the 1980s because no one could pinpoint how to prevent microcrystals from forming in the fiber during production. These crystals greatly reduce the transmission ability of the fiber, making it unsuitable for many applications.

But ZBLAN was too great a revolution to disregard. That is why the U.S. Air Force and the U.S. Naval Research Laboratory started the research back up again in the 1990s, including parabolic arc test flights on NASA's KC-135 aircraft. On these flights, ZBLAN glass experiments were run during the 22-second period of aircraft freefall. Although these few seconds were not enough to produce proper fiber, they were enough to obtain promising preliminary test results.

WHY MICROGRAVITY?

To understand why microgravity is preferable over normal gravity for ZBLAN production, it is important to understand what about Earth's gravity causes defects in the fibers. The production process on Earth involves draw towers that can be up to several stories tall. At the top of the tower is a preform, a large-diameter rod of the glass mixture, which is heated up so that a bead of glass falls, pulling a glass fiber behind it. Reaching the bottom of the tower, the fiber is wound on a spool to continue the draw from the preform. The whole process has been compared to that of pulling taffy.

When scientists talk about defects in ZBLAN optical fibers, they are mainly referring to crystallization and phase separation within the fibers. Due to convection-induced effects in molten ZBLAN glass, as well as other reasons researchers are still trying to determine, ZBLAN optical fibers made in Earth's gravity are prone to having crystals form during the transition from a molten liquid state to a solid-like state.

"ZBLAN is desirable for many applications because it has a very large wavelength transmission window; even the current fibers with defects from ground production are used for transmission of infrared light," said Michael Snyder, chief engineer and co-founder of MIS. "In theory, if you could suppress most or all of the crystallization in ZBLAN, the advantages of ZBLAN fiber, which include repeaterless transoceanic transmission of light, are huge compared to silica fiber."

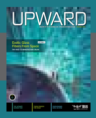
Using estimates for the theoretical loss limit of ZBLAN glass, a 2,000-km length of ZBLAN fiber could have the same optical loss as 10 km of silica fiber, which would be an extraordinary performance gain.

ZBLAN produced in microgravity
NASA

ZBLAN produced in normal gravity
NASA

MADE IN ORBIT. USED ON EARTH.

Diagram courtesy of Made In Space



Because ZBLAN is made of five different elements (zirconium, barium, lanthanum, aluminum, and sodium) while silica fiber consists of only silicon dioxide, phase separation (boundary layers in the micro-structure of a material) is more prevalent due to zirconium, barium, and lanthanum being denser than aluminum and sodium. Microgravity helps minimize this effect as well.

> ***“It’s sort of like your favorite ice cream with a bunch of toppings inside,” Snyder said. “If you let that ice cream melt on Earth, all that heavy stuff sinks and the light stuff floats, and the same thing happens with fiber. In space, those density-related separations don’t happen.”***

THE PATH TO ZBLAN PRODUCTION ON THE ISS

Before taking ZBLAN production to the ISS National Lab, POC used parabolic flight studies to test microgravity’s effects on ZBLAN production and optimize their hardware. “Results were encouraging,” said Ranjit Pradhan, vice president of applied technologies at POC. “The cross section of the glass pulled during parabolic flights was significantly more homogeneous than glass pulled on the ground.”

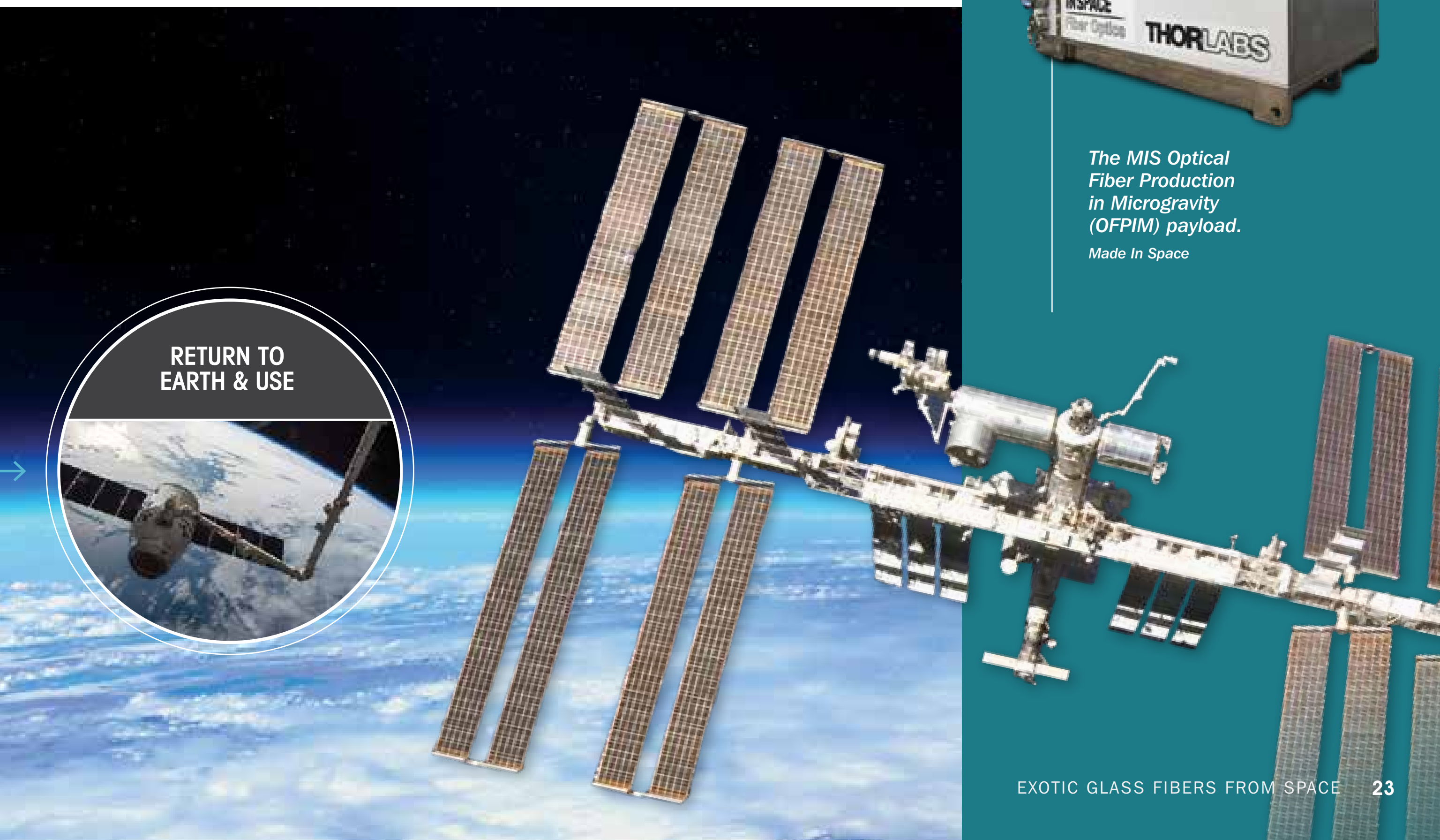
These promising results led to the development of POC’s Orbital Fiber Optic Production Module, which is scheduled for launch to the ISS on SpaceX’s Commercial Resupply Services (CRS)-17 mission in 2019. POC will first operate the system in microgravity to identify any unknown factors that could adversely affect the in-orbit production of high-quality ZBLAN fibers. Once optimization of the system is complete, the company plans commercial operations for in-orbit fiber manufacturing.

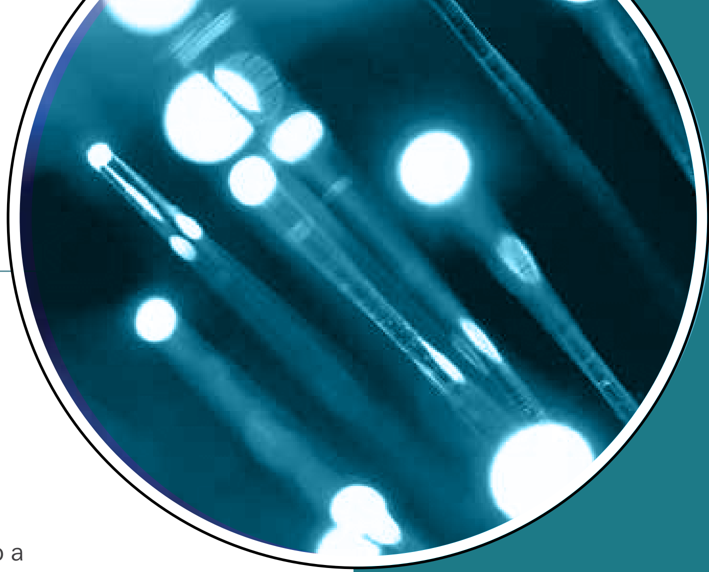
The FOMS Space Facility for Orbital Remote Manufacturing (SpaceFORM) experiment, supported by the ISS National Lab, NASA, the Small Business Innovation Research program, and private funding, is scheduled to launch on SpaceX CRS-17. SpaceFORM, which is covered by an issued U.S. patent, is capable of producing up to 50 km of optical fiber in a single flight.

FOMS

The MIS Optical Fiber Production in Microgravity (OFPIM) payload.

Made In Space





Close-up of optical fiber manufactured in microgravity
NASA

Similarly, FOMS leveraged its knowledge of past studies in the development of ruggedized hardware to develop the Space Facility for Orbital Remote Manufacturing (SpaceFORM), for which the company has an issued U.S. patent. SpaceFORM is intended to serve as not only a proof of concept but also a platform for volume production of optical fibers in microgravity.

"We were able to commercialize the hardware development and scientific development on the materials side even before we were able to bring our hardware and experiments to an orbital platform, which is quite exciting," said Dmitry Starodubov, chief scientist at FOMS. "Our ultimate goal is to scale up production and commercial revenue and to establish a sustainable manufacturing platform in orbit through use of this technology."

SpaceFORM, which is capable of multi-kilometer fiber production, is scheduled to launch to the ISS on SpaceX CRS-17 in 2019, after which FOMS plans to conduct several in-orbit experiments aimed at testing and optimizing their hardware. FOMS hopes to gain insight into the fundamental physics of material processing in microgravity and the improvement pathways for the properties of the fiber produced in orbit. This knowledge will help in operationalizing a commercial in-orbit optical fiber manufacturing facility.

For MIS, successful parabolic flight testing led to the development of the company's initial demonstration optical fiber puller, which launched to the ISS on SpaceX CRS-13 in December 2017. As part of their multi-flight Optical Fiber Production in Microgravity (OFPIM) experiment, this first investigation from MIS focused on evaluating the puller's temperature settings.

The MIS OFPIM payload undergoing acoustics testing.
Made In Space

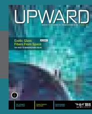
The OFPIM hardware is entirely automated, which holds great promise for long-term commercial use due to the minimal crew time needed for unloading and plugging in samples—but perfecting the operation of the industrial process itself takes iteration. To this end, a second investigation from MIS that launched on SpaceX CRS-14 in April focused on testing several approaches for fiber-pulling techniques, and a third investigation on SpaceX CRS-15 in June further optimized the industrial process settings. A fourth investigation that launched on SpaceX CRS-16 earlier this month seeks to shift from pulling only test-length fibers to pulling fibers reaching up to 100 m in length for analysis.

Michael Snyder (second from right), chief engineer and co-founder of MIS, receives the 2018 ISS Innovation Award in Physical Sciences and Materials Development.
ISS National Lab

INNOVATION AWARD

At the annual ISS Research and Development Conference in July, MIS won the 2018 International Space Station Innovation Award in Physical Sciences and Materials Development for their innovative work on ZBLAN optical fiber production in microgravity.

ISSR&D CONFERENCE



The MIS OFPIM payload atop the Additive Manufacturing Facility with JAXA astronaut Norishige Kanai onboard the ISS.
NASA

The MIS OFPIM mission patch from the SpaceX CRS-13 launch.
Made In Space

This shift from validation to production of fibers for characterization and attenuation is an important step toward optimizing the OFPIM for commercial production of ZBLAN fibers in space for use back on Earth. The fibers pulled in testing so far have not been long enough for critical evaluation, but according to MIS, preliminary visual analysis of the fiber's micro-structure indicates an absence of the level of microcrystallization and flaws typically seen in terrestrially produced fiber.

COMMERCIAL INTEREST AND THE FUTURE OF SPACE MANUFACTURING

The core technology needed to produce commercial quantities of ZBLAN in microgravity is currently in development, and FOMS, MIS, and POC are each fine-tuning their methods of drawing optical fibers in space. For now, the ISS is the ideal platform to support the current level of space-based ZBLAN production. However, depending on the growth of the industry, the future could involve a new ISS module specifically dedicated to fiber pulling or even a new station or other platform for optical fiber manufacturing in low Earth orbit.

> ***"The ISS is a great learning tool for mastering production of ZBLAN fibers," said Pradhan. "It offsets some of the risks in developing these sorts of high-value optical materials for the commercial sector."***

However, before large-scale commercial ZBLAN production in space can really take off, in-orbit manufacturing must become price competitive. "We are thankful to the ISS Commercial Space Utilization Program Office for funding this unique opportunity," said Pradhan. The current round-trip costs of launching cargo to the ISS, performing experiments and procedures, and sending the cargo back down are prohibitive without NASA and the ISS National Lab subsidizing costs. According to Starodubov, though, this may not always be the case.

"The ongoing revolution of the space industry is making orbital processing amazingly affordable," said Starodubov. "The costs will be dropping from the existing space trip cost, which is comparable to the price of platinum per kilogram, by roughly a factor of 10 in the near future."

As costs start to come down, in-orbit manufacturing will become more accessible to smaller companies. And as more companies get involved, whether through the production of ZBLAN or other products, the cost of flying and returning cargo will continue to be driven further down, spurring an expansion of commercial manufacturing of products in space that have high value back on Earth.

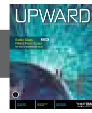
In terms of the future Earth benefits of space-produced ZBLAN, Pradhan said that "given that ZBLAN performs closest to the theoretical best, space fibers could be used to wire up different continents." Trans-oceanic telecommunication lines currently made of silica optical fibers could be replaced with high-performance microgravity-produced ZBLAN fibers.

"With such low optical loss," said Pradhan, "the world could be connected like never before." ■

TOUGH ENOUGH FOR SPACE

Accelerating Materials Testing With a New Permanent Platform

BY ANNE WAINSCOTT-SARGENT, *Contributing Author*



In microgravity, even seemingly indestructible materials degrade. Just look at the Hubble telescope, where its outer layer of insulation and thin layer of aluminum encasing have become so embrittled they are cracking and curling.

Without question, space is a harsh place where radiation, temperature extremes, orbital debris, and atomic oxygen (the presence of highly reactive single-oxygen atoms) flourish.

A new permanent test bed is now available on the exterior of the International Space Station (ISS) that allows investigators to analyze the durability of materials one sample or experiment at a time in the extreme space environment. The remotely controlled platform, the Materials ISS Experiment Flight Facility (MISSE-FF) from in-orbit commercial services provider Alpha Space Test & Research Alliance, LLC, aims to accelerate the testing of materials and components that have utility both in space and on Earth.

MISSE-FF with the zenith MISSE sample carrier open and the samples exposed to space.

NASA

BUILDING ON NASA'S LEGACY OF INNOVATION

MISSE-FF, which launched on the 14th SpaceX commercial resupply services mission in April 2018, builds on two decades of innovation by NASA. When the space shuttle was operating, NASA flew eight MISSE missions to the ISS, the last of which returned to Earth in 2014. The new MISSE design uses carriers to hold the experiments, which are launched and returned with each mission. Carriers from the current mission, MISSE-9, using the new MISSE-FF platform, are currently scheduled to return to Earth in December 2018 and April 2019.

In contrast to earlier MISSE missions, in which astronauts installed MISSE payloads on the outside of the ISS during a spacewalk and then later retrieved the experiments the same way for return to the ground, MISSE-FF is a permanent fixture on the space station. The platform's individual experiment carriers are installed and removed using the robotic Canadarm2. Approximately 40 percent of the platform is reserved for NASA experiments, with the remaining 60 percent available for commercial use.

Robotic transfer of the MISSE-9 MISSE sample carriers from the JEM Airlock to the MISSE-FF platform on ELC-2.

NASA

"Our business model and the MISSE-FF platform significantly broaden access to space and enable commercial enterprises to get to low Earth orbit (LEO)," said Mark Gittleman, president and CEO of Alpha Space. "We make it inexpensive and easy to test new materials, components, and technologies in space with help from NASA and the ISS National Lab, which, together with Alpha Space's great team, enable our business model."

Research and development projects included in MISSE-9 will advance both space exploration and Earth-based innovations in solar technology, remote sensing, telecommunications, and other fields. MISSE-9 includes a suite of investigations, with samples including 3D-printed materials, sensors, sensor components, textiles, carbon-fiber laminates, paints, coatings, polymers, and composites. Within the first few weeks of MISSE-FF operation, Alpha Space had already received 1.2 million data packets (a unit of data made into a single package for transmission), including imagery of samples in various flight orientations.

"We built the MISSE-FF platform in less than three years, and now that it's onboard the ISS, it's running spectacularly," said Alpha Space founder Stephanie Murphy, who brought together a team of engineers with prior MISSE experience to build the platform.

Murphy also leads MEI Technologies, a government contracting firm established in 1992 by Murphy's father as Muñiz Engineering, Inc. MEI Technologies originally won the contract to privatize the MISSE platform, but it was Murphy's idea to spin off Alpha Space into a standalone firm.

(Left) Preflight photos of the MISSE-9 experiment decks in the Alpha Space clean room.

Kim de Groh, NASA's Glenn Research Center

DRIVING NEW UNDERSTANDING AND BREAKTHROUGHS

Results from MISSE-9 investigations will not be fully realized until after the MISSE sample carriers housing the experiments return in winter 2018 and spring 2019 and samples or components are analyzed, but historical MISSE investigations have a legacy of advancing understanding and innovation in several industries on Earth.

For example, research on surface oxidation by atomic oxygen informs the design of fire-retardant and rust-resistant materials on Earth. Interactions between various materials and solar ultraviolet radiation could lead to better protective designs for communications and weather satellites and may help improve terrestrial structures, such as plastic siding for houses.

In addition, because true space environmental conditions are difficult to replicate on Earth, MISSE provides a valuable test platform that enables methods for correlating and extrapolating ground results. "That means that MISSE experiments can make ground testing more accurate and reliable," said MISSE researcher Kim de Groh from NASA's Glenn Research Center.

Most notably, of course, MISSE missions have provided space-environment durability data that enables the design of new, even more reliable spacecraft and innovative new structures for use in harsh environments both on and off Earth. Today's satellites that are relied upon by hundreds of millions of people for Earth observation, weather, and communications were developed with materials tested in space on earlier NASA-led MISSE and related exposure missions.

These established benefits are appealing to a broad customer base. "We've attracted some really diverse initial clients," said Murphy. "We're in a lucky place where we can invite new users to the ISS

Kim de Groh at the NASA Glenn Research Center with the MISSE-9 experiment decks, shortly after sample integration into the MISSE-9 R2 (ram), W3 (wake), and Z3 (zenith) MISSE sample carrier decks.

Kim de Groh, NASA's Glenn Research Center

PROVIDING FOUR SIDES OF EXPOSURE

The MISSE-FF platform, which resembles a futuristic four-sided cube, provides four sides of environmental exposure relative to the space station's orbit—in the wake, zenith, ram, and nadir orientations. This is an important feature that provides advantages beyond the historical MISSE missions by allowing testing related to specific aspects of the external environment.

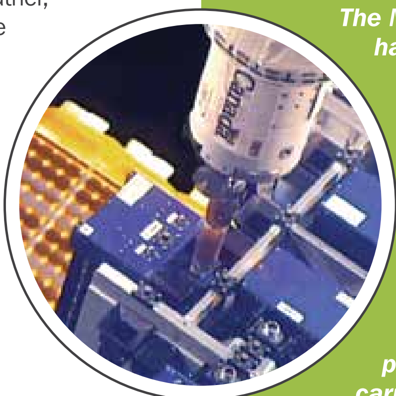
The wake orientation approximates the lunar environment because in this orientation, the facility itself shields the experiments. Materials placed in the MISSE wake orientation would be exposed mostly to the plasma particles in LEO and to solar ultraviolet radiation.

The zenith side faces the sun, and the nadir side is Earth facing. The zenith side supports solar-cell or radiation testing. Significant radiation comes from this view because there's no atmosphere that blocks or slows down radiation. The ram side provides a premium spot for atomic oxygen exposure or analyzing the degradation rate of materials.

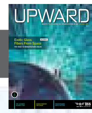
"A big advantage of the new facility is the inclusion of environmental sensors that provide us with information on the amount of exposure in each flight orientation, such as solar exposure, which we didn't have before," said de Groh, who has samples on MISSE-9 in the zenith, ram, and wake orientations.

The MISSE-FF platform itself is permanent. To avoid astronauts having to do spacewalks to retrieve MISSE experiments from the station, NASA required that the platform's plug-in carriers all be robotically re-serviceable. The robotic Canadarm2 special-purpose dexterous manipulator can plug in or remove MISSE-FF sample carriers containing materials or other experiments.

The carriers pick up power and data from the platform, which means that active experiments can be powered and commanded, and data can be read back to Alpha Space's payload operations control center in Houston. Each of the platform's four sides has space for three carriers, and each carrier provides 181 square inches of area exposed to space, offering a large capacity. Each carrier also has more than 270 cubic inches of below-deck space available for experiments and extra electronics.



NASA



National Lab, but our expenses are still being subsidized through the ISS National Lab and NASA. It's a short-term incentive to bring entities and entrepreneurs into the fold that haven't been there before."

Besides traditional materials testing (e.g., paint, coatings, fabrics, and materials for 3D printing), Murphy noted that Alpha Space has had strong interest from customers studying "exobiology," or the behavior of living things in the external space environment; for example, biological firms focused on medical applications.

"We've got people who want to fly biofilms and neurological cells for radiation testing," Murphy said. "Others have interest in flying plants and seeds to test radiation exposures. They want to see if they grow plants on Mars and how radiation will affect their plant growth or seed germination." This diversity of interest has led the company to embrace the slogan: "If it fits, it flies."

***A biofilm** is an assemblage of microbial cells attached to a surface and enclosed in a self-produced matrix of compounds that protect the microbes from the environment.*

AN UNPARALLELED PLATFORM FOR TECH DEMO

Firms wishing to demonstrate or test their space technology components and equipment in LEO are particularly drawn to the MISSE-FF platform. Two such technology demonstration experiments on MISSE-9 involve testing glass-free packaging for solar cells and assessing the robustness of optical receivers for communication in the harshness of space.

One experiment is from New Jersey-based Discovery Semiconductors, Inc., which makes fiber-optic modules and receivers for telecommunications, the military, and now LEO space applications.

"Demand for data bandwidth, which has been strong for terrestrial applications for many years, has started to migrate to space platforms," said Abhay Joshi, owner of Discovery Semiconductors.

Joshi previously flew his fiber-optic components on MISSE-7 and has continued with the current MISSE-9 mission. He hopes the latest tech demo—involving two indium gallium arsenide high-end space receivers—will enhance the technology readiness level (TRL) of his company's components.

***Technology readiness level (TRL)** is a system used to rate the maturity level of a technology on a scale from one to nine, with TRL-1 being observation of basic principles and TRL-9 being proven through successful operations.*

"The MISSE-FF platform is highly desirable because it allows me to get some of my components up in space and see how they withstand vibration, shock, rocket launch, and re-entry, as well as the extreme vacuum and temperatures of space," said Joshi, whose receivers are used for communications and remote-sensing applications. "MISSE-FF is an ideal platform to check the space worthiness of new devices."

An Alta Devices solar cell.
Aarohi Vijh

The materials of the future and the component systems in which they are used are going to need to pass even more rigorous testing in extreme environments in order to operate and remain functional as they shrink in size and power consumption but increase in complexity and capability. The small satellite revolution is driven by advances in material performance and technologies proven in the harshness of space.

Like Joshi, Aarohi Vijh also sees value in the MISSE-FF platform for his technology components. Vijh heads new product definition and technical marketing for Alta Devices, a solar technology company in Sunnyvale, California. The company was founded 10 years ago by two researchers: Harry Atwater, of the California Institute of Technology, and Eli Yablonovitch, of the University of California, Berkeley.

ALTA DEVICES *already supplies its thin and flexible solar cells to the automotive sector and to the unmanned aerial vehicle market, especially for single-junction solar-powered aircraft. Alta Devices holds the world record for solar efficiency, generating very high power per unit area. For small, unmanned systems, Alta Device's AnyLight™ power technology provides unmanned systems as much as five times more daytime endurance, and at one gram per watt of power, it has virtually no impact on weight or aerodynamics.*

Vijh and his team are studying a special kind of solar cell based on gallium arsenide (GaAs). GaAs solar cells were first developed in the early 1970s and have several unique advantages. GaAs is naturally robust to moisture and radiation, making it very durable. It has a wide and direct band gap allowing for more efficient photon absorption and high-output power density.

To create glass-free packaging for these solar cells so that they are lighter, less fragile, and better able to operate in space, Alta Devices tapped into years of NASA performance data on various plastics and polymers flown in space on MISSE missions. “In developing our own packaging solution, it made it a lot easier to look at what had already been done and proven,” Vijh said.

Vijh plans to continue to use the MISSE platform to evaluate his firm’s innovative solar arrays. “It’s a very powerful statement to make to our customers that our solar panels and packaging have actually been on a space flight with a credible provider,” he said.

Vijh sees applications on the ground as well. “The solar cells receive very high environmental exposure in space—ultraviolet rays and temperature cycling,” Vijh said. “The materials and our manufacturing techniques that we’re qualifying on MISSE will carry over to applications on the ground in the automotive industry and near-space applications such as high-altitude aircraft.”

LOOKING TO THE FUTURE

On the NASA side, both de Groh and Sheila Thibeault, a member of the Advanced Materials and Processing Branch in the Research Directorate at NASA’s Langley Research Center, have experiments not only on MISSE-9 but also on MISSE-10, which recently launched to the ISS on Northrop Grumman CRS-10.

Thibeault served as an original founder of the MISSE project back in 1999, building the initial hardware used on MISSE-1 through MISSE-8. She also assisted with the redesign of MISSE to be remotely controlled, eliminating the need for spacewalks, and she and de Groh both advocated for a permanent MISSE platform on the space station.

“I’m really excited about MISSE missions continuing under Alpha Space leadership,” said Thibeault. She recalls how her team often had to take the machining of the carriers to NASA Langley’s machine shop, which was time consuming and involved some cost, and had to oversee quality control for incoming specimens from external partners, which also took time and resources.

“Alpha Space is making our life easier,” Thibeault said. “I can focus on my materials and the science and don’t have to worry about the platform or the specimen holders, which is all being taken care of for me.”

While it is still early in the platform’s performance history, Alpha Space executives believe the future is bright for MISSE-FF as a permanent test bed that will have a lasting impact on the quality of life at home and in space.

THE STEM CONNECTION

MISSE has and will continue to serve as a vehicle for science, technology, engineering, and mathematics (STEM) education, with students collaborating on several NASA MISSE experiments. Under NASA’s two-year MISSE-X project (the predecessor to MISSE-FF), Thibeault and de Groh contributed to the development of a STEM education teacher’s guide (see: nasa.gov/sites/default/files/best_misse-x_workbook.pdf).

“All my prior missions on MISSE-1 through MISSE-8 were collaborative efforts with students at Hathaway Brown, an all-girl high school,” noted de Groh.

Over the last 20 years, de Groh has mentored 31 young women on MISSE projects. The students worked in small teams once a week after school and full time during summer throughout their high school careers.

The MISSE-FF platform, developed by Alpha Space, on the ISS.

Alpha Space/NASA

> ***“Space represents a crucial economic sector for the United States, and Alpha Space is leading the way to help NASA and the country achieve the very important policy of commercializing LEO,” said Gittleman. “We are doing it alongside traditional NASA space science, which I think will enable improvements to the U.S. space-industry supply chain while simultaneously making LEO more accessible than ever before.”*** ■

Synthesizing Gas Separation Membranes in Microgravity

SPOT LIGHT

BY BRIAN GREENE, *Staff Writer*

NASA astronaut Serena Auñón-Chancellor working on Cemsica's investigation onboard the ISS.

NASA

Humankind has made incredible technological advancements over the past two centuries. However, many of these advancements have come at a significant cost to the environment and risk to future generations. Globally, principal human impacts to the environment include accelerated changes to Earth's atmosphere and climate, rising sea levels and increasing ocean temperatures, desertification, shortages of natural resources such as water and food, loss of biological diversity, and widespread pollution.

Now more than ever, it is important to address these issues, and scientists are leveraging the ISS to gain new insights into global environmental challenges and develop new solutions to benefit Earth. Sustainability is a key focus area for research and development onboard the ISS National Lab, which currently has more than 31 sustainability projects in its portfolio. Results from studies conducted onboard the ISS National Lab provide meaningful insights into materials and processes that drive sustainable development.

One such project from the company Cemsica is aimed at synthesizing gas separation membranes in microgravity. Despite many innovations in the energy industry, technology development has been lagging for the removal of gases, notably carbon dioxide, from waste air streams. Cemsica has been working on a potential breakthrough technology that addresses the critical need to reduce greenhouse gas emissions that result from industrial processes.

Cemsica is developing nanoporous membranes that can be tailored to remove specific contaminants, like carbon dioxide, from combustion exhaust gas streams, and the company conducted an investigation onboard the ISS National Lab aimed at improving synthesis of the membranes.

"The carbon dioxide footprint is one of the biggest problems in the energy industry," said Negar Rajabi, founder and chief executive officer of Cemsica. However, carbon dioxide is not always a waste product. It can also be a commodity sold as a feedstock for manufacturing chemicals and beverages—if the carbon dioxide is pure and can be recovered economically.

Commercial methods for capturing carbon dioxide have been around for several years but are complex and very expensive. As such, they have not been successfully implemented on a large scale. Cemsica believes its nanoparticle membranes are a better solution that will reduce operational costs, increase efficiency, and accelerate technological innovations in the industry that benefit the world.

A critical feature of Cemsica's membranes are the nanopores—tiny holes that allow precise separation of carbon dioxide from other gas molecules. Because gravity significantly impacts how particles order themselves on the nanoscale, Rajabi hopes that synthesizing membranes onboard the ISS National Lab will allow Cemsica to overcome some remaining manufacturing challenges in the synthesis and assembly of the membranes—allowing them to produce even lower-cost membranes with improved properties.

> ***One nanometer**—one billionth of a meter—is tens of thousands of times smaller than the width of a human hair. A nanomaterial is a material made up of many nanoparticles, which are 1 to 100 nanometers in size. Nanomaterials can be naturally occurring (e.g., volcanic ash) or engineered by humans.*

Although nanomaterials are not new, Rajabi says there is still much to learn that can enhance nanomaterial properties. She and her team are still in the process of analyzing the data from their ISS National Lab investigation, but preliminary results have shown some improvements in the formation, shape, and size of the particles. Confirming these positive results would provide insights for improving manufacturing of the membranes on the ground and could also open the door for future in-orbit manufacturing in this sector, expanding industrial use of low Earth orbit. ■

This content was abridged and updated from an article that originally appeared in Upward at upward.issnationallab.org/spaceflight-studies-for-a-sustainable-future.

SPOT LIGHT

Materials Science Space Station Investigations: Where Are They Now?

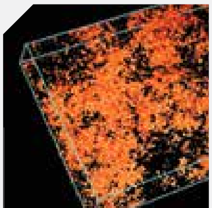
BY HAYLIE KASAP, *Contributing Author*

Research performed on the ISS National Lab isn't one and done—it keeps moving forward. *Upward* has featured several ISS National Lab materials science experiments, including research on Ras Labs' Synthetic Muscle, Procter & Gamble's colloid development, and the synthesis of semiconductor crystals using the high-temperature SUBSA furnace. These researchers have continued to make progress based on the results of their ISS investigations, as highlighted below.

Ras Labs' custom polymers created as Synthetic Muscle™
Ras Labs

Ras Labs Synthetic Muscle

Ras Labs has made several advancements since testing their Synthetic Muscle™ on the ISS. Results from that testing led Ras Labs to develop shape-morphing technology that allows a prosthetic to expand and contract with the body for an improved fit throughout the day. This pressure-sensing technology in the socket of the prosthetic helps to auto-control the fit, reducing the need for manual adjustment. Such pressure sensors have also been used in robotic applications to enable dynamic movements and grippers in automated systems, as well as in products that fit within the ear such as ear buds. Ras Labs' Synthetic Muscle is currently in customer testing, with product development expected within one to two years. The company's eventual goal is to develop a streamlined way to mimic tactile touch, which is still missing in the field of prosthetics. With funding from Breakout Labs and a National Science Foundation Small Business Innovation Research Phase I grant, Ras Labs is continuing to make strides toward advancing their product to market.



Ras Labs' custom polymers created as Synthetic Muscle™
Matthew Lynch with P&G, CASIS, NASA

P&G Colloid Development

Procter & Gamble (P&G) is continuing their fluid physics research, with their most recent ISS National Lab investigations aimed at studying the microscopic behavior of colloids (complex fluid mixtures) in gels and creams. According to Matthew Lynch, principal scientist at P&G, there are currently three patent applications related to product development and shelf life resulting from their ISS National Lab research and development (R&D). Much of P&G's current research pertains to the stability and dispensability of their products, such as cleaning sprays, for their billions of users worldwide. P&G expects that products featuring their new advancements might be released as soon as this year.

CLYC scintillator crystals under UV excitation
Radiation Monitoring Devices, Inc.

Synthesis of Semiconductor Crystals Using SUBSA

Aleksandar Ostrogorsky has continued his research on the crystallization of indium iodide, a type of semiconductor material that can be used to detect nuclear radiation. Ostrogorsky's ground controls produced positive data, with samples responding well to use of the vapor diffusion crystal growth method, producing large crystals with few impurities. Ostrogorsky's flight experiment, currently on the ISS and using the refurbished SUBSA furnace, also uses vapor diffusion, with the added benefit of microgravity crystallization conditions. He expects even better results in microgravity than on the ground, which could lead to important insights about these crystals, which are used to detect radiation in a variety of safety and security applications here on Earth. ■

WHAT IS SUBSA?

Solidification Using a Baffle in Sealed Ampoules (SUBSA) is a high-temperature furnace onboard the ISS. The original SUBSA hardware was launched to the ISS in 2002 and returned to Earth following the completion of initial studies. Because of increasing demand for capabilities provided by SUBSA, NASA refurbished the hardware and worked with the ISS National Lab to identify payloads that could use the renovated furnace.

The SUBSA hardware in the Microgravity Science Glovebox onboard the ISS.
NASA

This content originally appeared in Upward at upward.issnationallab.org/materials-science-space-station-investigations-where-are-they-now.

SPOT LIGHT

Taking Recycling to a New Level

BY AMY ELKAVICH, *Staff Writer*

Over the past 30 years, Earth-based recycling efforts have grown, as more people are routinely recycling plastic bottles, plastic bags, and unwanted mail and other paper. According to the U.S. Environmental Protection agency, more than 67 million tons of municipal solid waste was recycled in 2015. Opportunities to recycle abound, even in space. A unique facility developed by ISS National Lab Implementation Partner Made In Space is striving to turn trash into useful items an astronaut might need in space.

The Made In Space Commercial Polymer Recycling System (CPRS), which launched to the ISS on Northrop Grumman's 12th commercial resupply services mission, aims to demonstrate plastic recycling capabilities in microgravity. The CPRS will take plastic waste, such as expended polymer parts and plastic bags, and process the excess material and plastic waste into uniform feedstock (raw material for 3D printers).

This new recycling system will support Made In Space's existing commercial Additive Manufacturing Facility on the ISS and will create a "regenerative materials" cycle that turns used broken parts and excess packaging into new parts. For example, astronauts might need a new plastic wrench if theirs breaks—with this new recycling system, they could print a new one using the broken pieces of plastic.

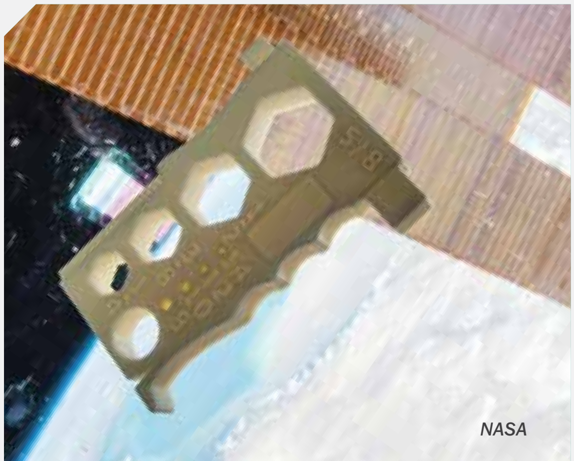
The CPRS project will also include recycling of 3D prints made from Braskem North America's Green Polyethylene (Green PE), a plastic derived from sugarcane. Green PE is ideal for use in a regenerative materials cycle on the ISS because it reduces material waste in orbit without increasing the carbon footprint on Earth.

Feedstock, as well as trash and waste, take up valuable mass and storage volume in an environment such as the ISS that requires optimal resource allocation. The ability to reuse plastic items and transform them into feedstock without need for terrestrial resupply will mean less space required for raw material storage, as well as greater overall printing capacity to produce needed parts and tools.

Back on the ground, terrestrial versions of the CPRS could be used for recycling of 3D printed materials in hardware stores or for expeditionary manufacturing on small surface ships and submarines and on offshore oil and gas platforms.

A space-optimized wrench for ISS crew members 3D-printed onboard the space station using the Additive Manufacturing Facility.

Made In Space



NASA

THE MULTIPURPOSE PRECISION MAINTENANCE TOOL, ***created by University of Alabama in Huntsville student Robert Hillan as part of the Future Engineers Space Tool Challenge, was printed on the ISS. It is designed to provide astronauts with a single tool that can help with a variety of tasks, including tightening nuts or bolts of different sizes and stripping wires.***

This content was abridged and updated from an article that originally appeared on ISS360 at issnationallab.org/blog/taking-recycling-to-a-new-level.

SPOT LIGHT Q&A

Setting Sights on Vision: Taking Flight to Improve Treatment for Retinal Degeneration

BY LYLE SMITH, *Contributing Author*

Nicole Wagner is the president and CEO of LambdaVision, a startup company focused on developing an innovative protein-based retinal implant capable of restoring high-resolution vision and enhancing quality of life for patients with retinal degeneration. The implant technology uses a light-activated protein to stimulate the retina of patients with impaired vision due to age-related macular degeneration and retinitis pigmentosa.

LambdaVision is aiming to use the microgravity environment on the ISS to improve the manufacturing process for their retinal implant. The company's investigation, which launched on SpaceX's 16th commercial resupply services mission, is supported by a "Technology in Space" prize—an award sponsored by the ISS National Lab and Boeing that supports startups associated with the MassChallenge program, one of the leading startup accelerators. LambdaVision was founded in 2009 as a spin-off company from a University of Connecticut research group led by Robert R. Birge, distinguished professor of chemistry. Wagner worked in Birge's research lab both prior to and during the establishment of LambdaVision. Below, Wagner shares her thoughts on LambdaVision's ISS National Lab investigation.

Working in microgravity gives us unique opportunities. Our process is all about having a homogeneous protein solution. In microgravity, we're able to produce a more homogeneous solution and have the proteins adhere in a better way, using less materials and producing a better, higher-quality product.

We want the implant to last the lifetime of the individual receiving it. One of our goals is to increase the life span of the implant. We believe that producing the implant in microgravity will enable a more perfect surface and a better, more stable coating.

There is currently no cure for age-related macular degeneration and retinitis pigmentosa. There are only treatments that will slow the progression of disease. People with these diseases lose the ability to take light and convert that light into a signal that can be sent to the brain. In other words, their eyes become light insensitive. Our retinal implant helps the eye capture light again so that it can be used to generate a neural signal. The protein we use is light-activated and can generate an ion gradient, which will stimulate the remaining cells in the eye.

We're taking more of an organic approach that's very different to what's available otherwise. Competing technologies are all more hardware-driven and often have big goggles or glasses supported by battery packs with wires and cables. They really are engineering marvels, but they are limited in resolution. Our approach provides better pixel density and better resolution for the patient.

We want patients to be able to regain their independence. We want them to be able to make out the shapes of things, navigate a room, open doors, see small things on a computer. Imagine you're about to become a grandparent and you come to a point where you can't read your grandchild a book. Or imagine you've had to give up your career or the

The solutions are being prepared for manufacturing the retinal implant.

Peter Morenus/UConn Photo

LambdaVision President and CEO Nicole Wagner purifying the protein for use in the retinal implant.

Peter Morenus/UConn Photo

success you've built because you can no longer see the computer screen. That's the kind of impact we can have on people's lives by helping them regain their functional vision.

Our goal is not to be a one-and-done operation. If successful, we'd love to continue collaborating with our space partners. Our layer-by-layer approach has real potential for manufacturing a number of different technologies.

The whole experience for us has been incredible. Space Tango was instrumental in helping us miniaturize our device for use on the space station and automate our manufacturing process in a Cube Lab. The entire process can be controlled from Earth, and we're able to communicate if needed with the astronauts onboard the space station. Space Tango has a great team that is not afraid to take on tough challenges.

The work we're doing at LambdaVision is really important. The research we're doing on the ISS is a way to potentially get our implant to patients faster. If this is successful, we'll have a more homogeneous implant to make a positive impact on real people's lives.

This content was abridged and updated from an article that originally appeared on ISS360 at issnationallab.org/blog/setting-sights-on-vision.

Where the Rubber Meets the Sky: Goodyear Paves the Way to Advanced Tire Materials

SPOT LIGHT

BY EMILY TOMLIN, *Staff Writer*

European Space Agency astronaut Luca Parmitano works on the Goodyear Tire and Rubber Company investigation on the ISS.

NASA

The Goodyear Tire and Rubber Company has long demonstrated innovation in space, beginning with the company's key contributions to the lunar landing 50 years ago. Now, onboard SpaceX's 18th commercial resupply services mission to the space station, Goodyear sent a new investigation to space, seeking to develop advanced materials for consumer tires.

Silica is a common material used in consumer tires to help enhance fuel efficiency and traction. While advances in silica technology have been made in many key areas of importance for the tire industry, silica micro-structure still represents an area where research would be beneficial. The ISS National Lab investigation from Goodyear will evaluate the formation of precipitated silica particles in the functional absence of gravity onboard the ISS, where the team may be able to observe novel molecular structures or morphologies of silica not previously observed on Earth.

Such insights could have a clear path to industrial application in the development of unique silica structures—which could result in enhanced tire performance. A breakthrough in the research of the effect of silica morphology on rubber compound properties could lead to not only significant improvements in fuel efficiency and transportation cost savings but also possibly environmental benefits to advance global efforts toward sustainable living.

ISS National Lab advanced materials investigations, such as Goodyear's, have the ability to accelerate applied research, with the potential to bring to market innovative ideas that both demonstrate the industrial capabilities of the ISS to benefit life on Earth and also create a vibrant marketplace in low Earth orbit. Goodyear is one of many private-sector companies helping to pave the way for this exciting future. ■

NASA astronaut Nick Hague working inside the Life Sciences Glovebox for the Goodyear Tire and Rubber Company investigation. NASA

This content was abridged and updated from an article that originally appeared on ISS360 at issnationallab.org/blog/where-the-rubber-meets-the-sky-goodyear-paves-the-way-to-advanced-tire-materials.

2019 ISSRDC Materials Science in Space Workshop Report Released

SPOT LIGHT

BY AMELIA WILLIAMSON SMITH, *Staff Writer*

Optical fibers
NASA

In November, the ISS National Lab and NASA's Space Life and Physical Sciences Research and Applications (SLPSRA) Division released the 2019 ISS Research and Development Conference (ISSRDC) Materials Science in Space Workshop Report.

The 2019 ISSRDC Materials Science in Space Workshop was held on July 29 during ISSRDC in Atlanta, Georgia. This joint workshop brought together government, university, and industry researchers and engineers to discuss how microgravity and the extreme environmental conditions on the ISS could be leveraged for innovative materials science research that meets both NASA's exploration goals and the ISS National Lab's goals to benefit life on Earth.

The first part of the workshop included briefings on high-priority advanced materials topics and new ideas and provided overviews of the latest facilities and instruments on the ISS available for materials research. The second part of the workshop consisted of in-depth breakout sessions, chosen based on responses to a Request for Information issued in advance of the workshop, covering three topics:

1. *Functional Materials*
2. *Materials Characterization, Microstructure, and Process Modeling*
3. *Lunar Infrastructure and Surface Operations*

The goal of the breakout sessions was to discuss potential future investigations, identify gaps in existing research capabilities on the ISS, and recommend follow-on actions.

The Functional Materials session focused on leveraging microgravity conditions on the ISS to develop materials that have improved or tailored properties either for use on Earth or for exploration purposes. Key themes discussed in the session include additive manufacturing and how it can be used to produce materials with improved functionality and performance, materials reuse and the ability to process waste into useful material, high-value materials that can uniquely benefit from studying their production in microgravity, and the acquiring of thermophysical property data to drive machine learning and modeling.

The Materials Characterization, Microstructure, and Process Modeling session centered on use of the ISS for benchmark experiments to study microstructure development and thermophysical properties in microgravity. Such information is needed for the development and validation of physics-based models for a wide variety of fabrication processes. Overarching themes of this session include the use of microgravity to gain fundamental knowledge of additive manufacturing and metal processes and the application of insight gained to the in-space processing, manufacture, and assembly of large-scale systems.

The Lunar Infrastructure and Surface Operations session discussed materials systems and processes necessary for operation in space, lunar, and Martian environments. The focus was on identifying research that could be done on the ISS to examine the effects of microgravity or reduced gravity on materials production and repair processes for long-duration missions on the surface of the Moon or Mars. Key themes from this session include advanced manufacturing, surface infrastructure, in-space assembly, resource prospecting, resource processing and handling, advanced materials development, dust mitigation, and space/lunar environmental compatibility testing.

The workshop report summarizes discussions from the breakout sessions and highlights the resulting key recommendations. For more information about the workshop and to view workshop presentations, visit issnationallab.org/workshops/2019-materials-in-space. Download the full workshop report at issnl.us/2019msw.

This content was adapted from an article that originally appeared on ISS360 at issnationallab.org/blog/2019-issrdc-materials-science-space-workshop-report-released.

SPOT LIGHT

Materials in Microgravity: The ISS National Lab at the Materials Research Society Fall Meeting

BY RYAN REEVES, *Staff Writer*

Uniformity. It is a central concept in materials science. We have all heard about how a chain is only as strong as its weakest link. When metals are not alloyed (or mixed) to uniformity, weak points develop that lead to fracturing of a single link and failure of the entire structure. The uniformity of materials is set during the solidification process. And the nemesis of uniformity during complex solidification processes is gravity.

Access to the persistent microgravity environment on the ISS means freeing researchers from the one-dimensional force of gravity. Microgravity mitigates effects such as buoyancy and sedimentation and can produce materials with a higher degree of uniformity.

The ISS National Lab attended the 2019 Materials Research Society Fall Meeting in Boston to participate in two technical talks discussing the role of microgravity in achieving uniformity during materials manufacturing. The talks focused on complex multiphase materials and high-entropy alloys.

Complex Multiphase Materials

Complex multiphase materials (such as foams, gels, colloids, and microemulsions) exist as a combination of gaseous, liquid, or solid phases that self-assemble into structures. However, gravity can cause solids to fall out of solution (sedimentation) or fluids and gases to phase separate out of solution due to differences in density (buoyancy). And like the layers in the dessert flan, gravity causes the compression of the bottom layers of gels and foams (stratification), creating nonuniform density and material properties. While this nonuniformity, or anisotropy, can be useful for some applications, it is prohibitive in others, such as insulation, wound dressings, and support structures.

ISS National Lab investigations on multiphase materials range from suspended particles in solution (colloids) to foams and gels, emulsions, and liquid crystals. Procter and Gamble (P&G) used the ISS National Lab to explore the transport and stability of gels and colloids in the absence of gravity, which might allow the company to improve the quality and shelf life of consumer products we use every day.

In another investigation, Tympanogen examined the structure of hydrogels polymerized on the ISS and analyzed the release and transport of drugs from hydrogel wound patches. Results from this research can help improve the manufacturing process of wound dressings and better control the release of antimicrobial drugs.

High-Entropy Alloys

High-entropy alloys, a new class of metal alloys composed of five or more elements in near equal proportions, are an exciting area of metals research. The term “high-entropy” describes the energetics of the uniform mixture that are needed for so many components to exist as an alloy rather than distinct phases.

Some high-entropy alloys have higher fracture toughness, strength-to-weight ratios, wear resistance, and corrosion resistance when compared with many existing metal alloys, such as aluminum alloys and steels. However, they are a complex mixture of many elements with varying densities. This leads to the separation of elements in the melt and anisotropy in the solidified high-entropy alloys, which causes poor overall strength and mechanical properties.

The microgravity environment of the ISS could be used to manufacture high-entropy alloys with uniformity in composition (isotropy) throughout the alloy. While the solidification of high-entropy alloys themselves has not been tested in microgravity, numerous studies of metal alloy solidification in microgravity provide evidence of improved uniformity in the solidified product. The manufacture of high-entropy alloys is analogous to in-space manufacturing of complex fluorinated glasses (ZBLAN optical fibers) currently being tested on the ISS.

EXAMPLES OF COMPLEX MULTIPHASE MATERIALS

Aerogels are lightweight, solid structures with a high degree of porosity. Due to the high air content, these materials have low thermal conductivity and very low densities, which leads to high strength-to-weight ratios. Aerogels are used in numerous applications, such as insulation, absorbents, catalyst supports, and battery electrodes.

Hydrogels are polymer networks surrounded by water. These materials are typically soft and flexible with a high moisture content. Hydrogels have been used for applications in cell culturing, tissue scaffolding, and contact lenses, among others.

Procter & Gamble colloidal suspension to be studied for stability in microgravity onboard the ISS.

NASA

This content was abridged and updated from an article that originally appeared on ISS360 at issnationallab.org/blog/materials-research-society-fall-2019-ryan-reeves.

SPECIAL ISSUE
ADVANCED MATERIALS AND MANUFACTURING

Read UPWARD online at **Upward.ISSNationalLab.org**