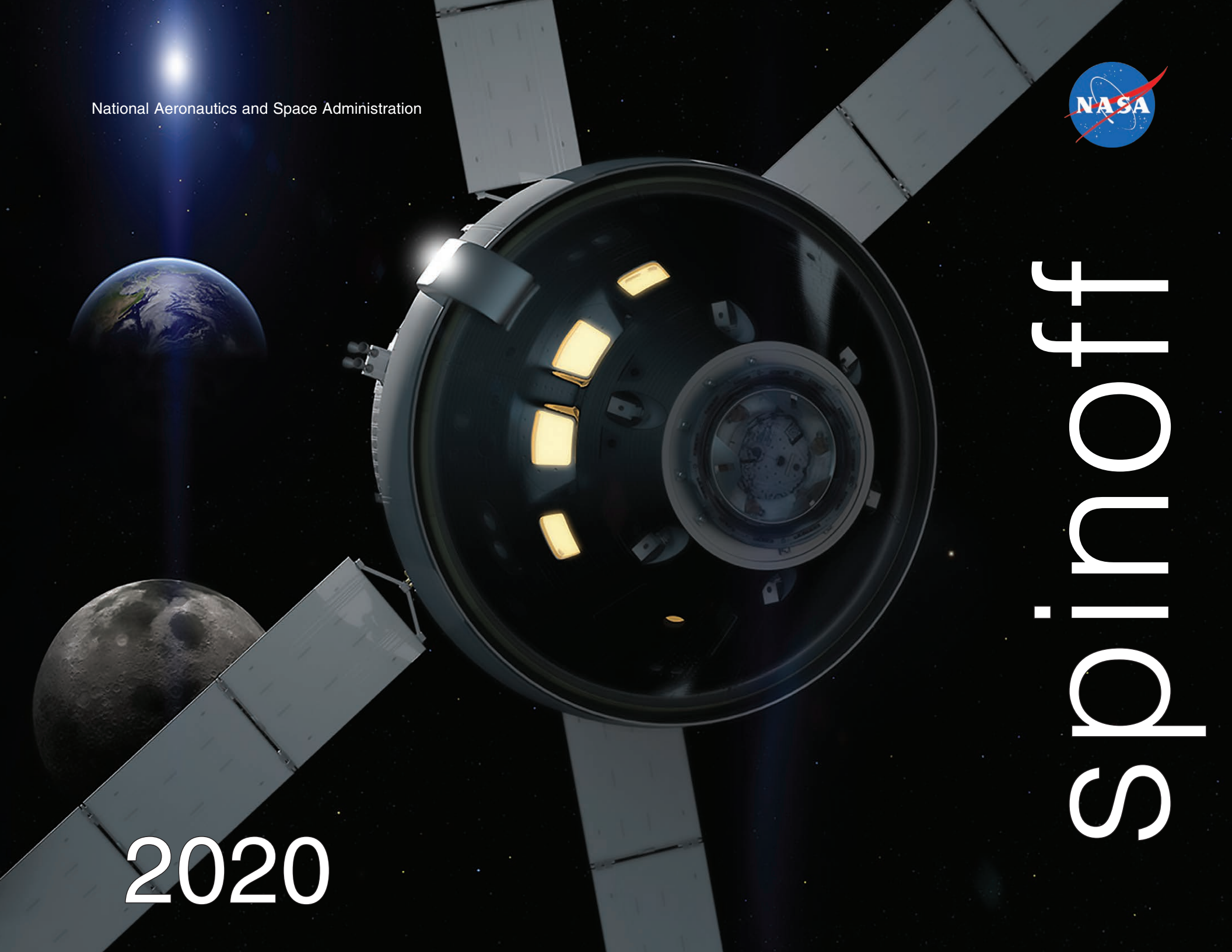
National Aeronautics and Space Administration



spinoff

2020

SPINOFF

2020

Technology Transfer Program

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By 2020, there could be as many as 400,000 commercial small drones registered in the United States, along with some 2 million for recreational use. Many jobs—those too dirty or dangerous for people—are already emerging for drones. And there is an increasing need, especially in an urban environment, to keep all that activity in the air running safely and smoothly. In 2019, NASA conducted field demonstrations of small drones navigating urban landscapes in Reno, Nevada, and Corpus Christi, Texas.

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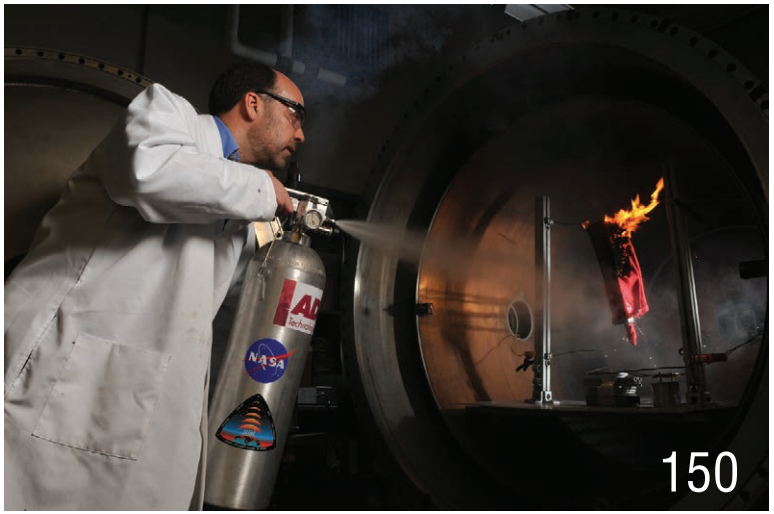

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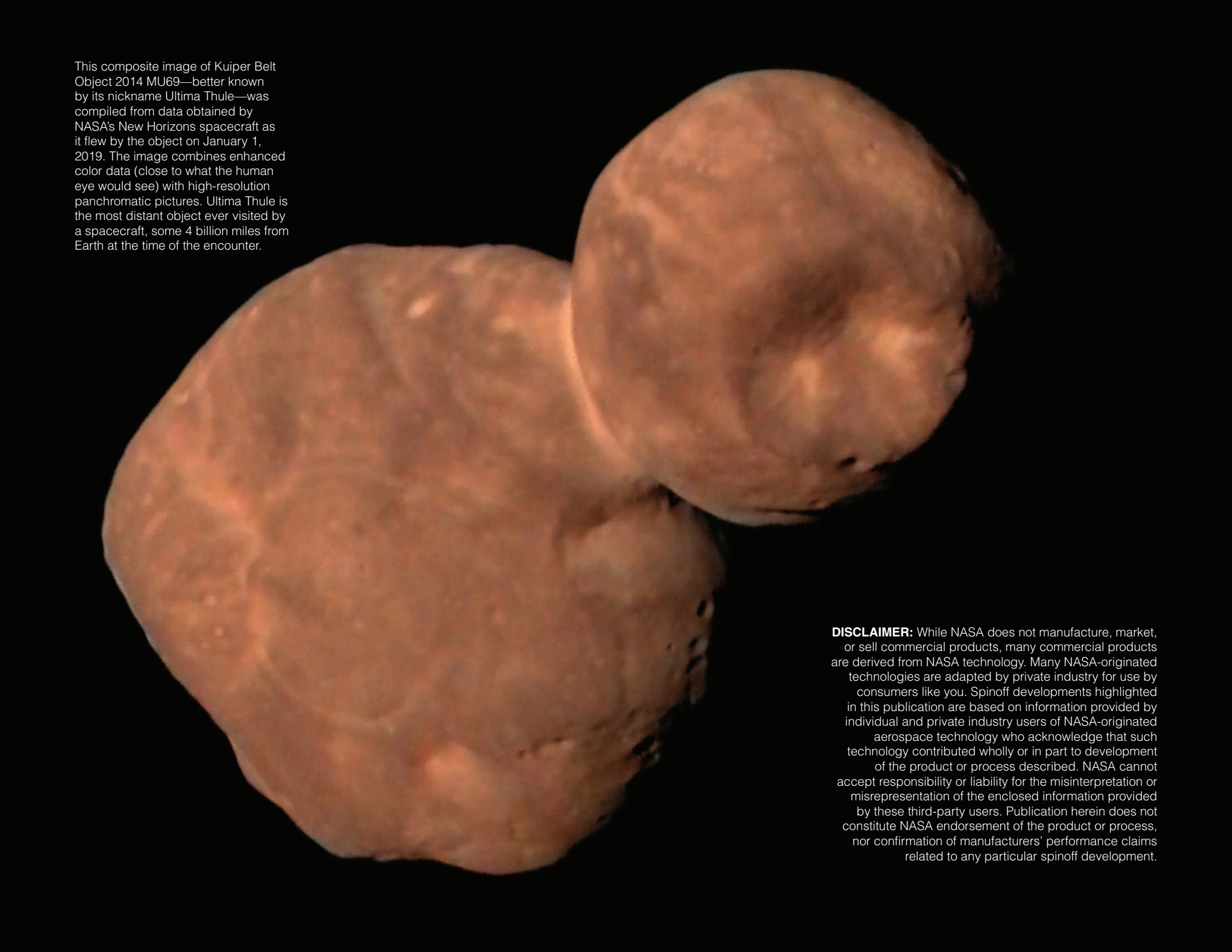


This composite image of Kuiper Belt Object 2014 MU69—better known by its nickname Ultima Thule—was compiled from data obtained by NASA's New Horizons spacecraft as it flew by the object on January 1, 2019. The image combines enhanced color data (close to what the human eye would see) with high-resolution panchromatic pictures. Ultima Thule is the most distant object ever visited by a spacecraft, some 4 billion miles from Earth at the time of the encounter.

Foreword

Even as NASA continues to unpack data from the most distant world ever visited—Ultima Thule, which the New Horizons probe zoomed past 4 billion miles from Earth at the start of last year—the Space Agency never takes its eyes off our home planet. In fact, the Agency's longest continually operated program is the Technology Transfer Program, which works to put the countless innovations that drive space exploration into the hands of U.S. companies and entrepreneurs.

Now, as we gear up to send astronauts back to the Moon for the first time in more than half a century, those inven tions and advances will only multiply. As always, NASA will rely on many commercial industry partners to help carry out this ambitious mission, which will see the first woman and next man set foot on the Moon and establish sustainable lunar exploration with our commercial and international partners by 2028. Just as the Apollo Program yielded some of NASA's most important commercial spinoffs and advanced the state of the Nation's technology, these new partnerships under the Artemis Program are sure to produce innovations that will benefit all Americans.

Already, the Space Agency is partnering with com panies to deliver payloads to the Moon through its new Commercial Lunar Payload Services program. Other companies are responding to calls to provide some of those payloads in the form of scientific instruments and technology investigations. We also selected 11 companies to study options and build prototype elements for landers as part of the Next Space Technologies for Exploration Partnerships program. These landers will carry astronauts from the lunar space station—named Gateway—to the Moon's surface. One day, companies will operate these landers commercially.

NASA itself is also developing cutting edge technology demonstration payloads designed to prepare for our lunar future, including systems to prospect for resources, gather data on the environment, assist precision landing, and try out advanced solar arrays, among others.

In the future, whether companies license technology NASA develops under Artemis, commercialize their own solutions to new lunar challenges, or use NASA scientific data or software in other applications, there are many avenues for these technologies to take on their own lives as commercial spinoffs benefiting the public.

The Space Launch System, NASA's next-generation rocket that could make its first test run to the Moon as soon as this year, and the Orion capsule that's planned to carry astronauts to lunar orbit in 2022 have already led to several products documented in earlier editions of *Spinoff*, with more to come.

As you learn about the contributions that the 50 technologies featured in *Spinoff* 2020 have made to our economy, our planet, and our quality of life, imagine what might be possible in the future, as we take on the grand challenges of establishing a permanent human outpost on the natural satellite where humanity once briefly stepped.

Jim Bridenstine
Administrator

National Aeronautics and Space Administration

In this image, taken on June 13, 2019, engineers at NASA's Jet Propulsion Laboratory install the starboard legs and wheels on the Mars 2020 rover. Mars 2020 is scheduled to launch from Cape Canaveral Air Force Station in Florida in July of 2020. It will land at Jezero Crater on Mars on February 18, 2021, where it will (among other tasks) look for signatures of past microbial life on Mars.

Spinoff (spin´ôf) -noun.

1. A commercialized product incorporating NASA technology or expertise that benefits the public. These include products or processes that:
    - were designed for NASA use, to NASA specifications, and then commercialized;
    - are developed as a result of a NASA-funded agreement or know-how gained during collaboration with NASA;
    - are developed through Small Business Innovation Research (SBIR) or Small Business Technology Transfer (STTR) contracts with NASA;
    - incorporate NASA technology in their manufacturing process;
    - receive significant contributions in design or testing from NASA laboratory personnel or facilities;
    - are successful entrepreneurial endeavors by ex-NASA employees whose technical expertise was developed while employed by the Agency;
    - are commercialized as a result of a NASA patent license or waiver;
    - are developed using data or software made available by NASA.
2. NASA's premier annual publication, featuring successfully commercialized NASA technologies.

Introduction

When NASA's newest Mars rover touches down on the Red Planet next year, it will carry more scientific instruments than any of its predecessors. As we worked to fit all that technology into a vehicle no larger than its predecessor, Curiosity, we and our partners innovated a great deal of new technology that is now finding uses here on the ground.

One partner invented a laser a fraction of the size of any comparable laser, which can now analyze Earth's atmosphere, improve glaucoma treatment in developing countries, and more. The 2020 rover will also carry the first aircraft—a helicopter, in fact—to fly in Mars' thin atmosphere. The company that built the craft's rotors and other components, which has worked with NASA on multiple previous aircraft, applied its Mars-honed expertise in the creation of a commercial drone that's now helping farmers monitor their crops.

You can find the full story on both of these NASA spinoffs, along with dozens of others, in the following pages.

Every day, our scientists and engineers, and the companies we partner with, advance the technology in our toolbox to help us progress in our understanding of the solar system and the universe beyond. The mission of NASA's Technology Transfer Program is to get those same innovations into the hands of American companies and entrepreneurs, who can use them in a variety of applications to feed the economy, cut costs, and improve life on Earth.

Technology that might find the first signs of past life buried below the Martian surface can almost certainly prove useful here at home. At NASA's Technology Transfer Program, it's our job to make that happen.

Since 1976, it has been the mission of NASA's *Spinoff* publication to document these success stories and share them with the American public. In this issue, we feature 50 stories of successful spinoffs in every sector of the economy, from health and medicine to industrial productivity. My favorites include:

- The computer cluster architecture that modernized supercomputing. In the early 1990s, heavy Government investments in supercomputing weren't paying off as expected. Two engineers at Goddard Space Flight Center set out to use a new open source operating system to turn a cluster of off-the-shelf desktop PCs into a supercomputer, an effort that many doubted would work—but they succeeded. The resulting Beowulf cluster is now the basis for most supercomputers, which are used to design everything from airliners to tooth paste tubes, bringing down costs and improving quality across the board. (Page 118)
- Telemetric systems monitoring vital signs in most modern hospitals. The company that built the technology to monitor astronauts' heart rate, breath cycles, and more during the Gemini missions and transmit that data to Earth soon adapted it for use in hospitals, sending data in real time to healthcare providers in other parts of the hospital. The company has continued to improve its sensors over the decades, and this spinoff can be found in innumerable hospitals around the world. The latest developments can send alerts to doctors when there are problems with outpatients. (Page 24)
- Modern conference calling. In the 1980s, at NASA and elsewhere, conference calling involved a room full of technicians manually unplugging and plugging in cables across huge panels of ports. Ready for a digital upgrade, the Agency hired a company to build new systems that allowed connections and conference loops to be reconfigured instantly and automatically. The company commercialized the technology and spun off into three companies that now handle conference calls and sell hardware like conference bridges around the globe. (Page 122)

In addition to commercial success stories, this issue of *Spinoff* also features 20 NASA technologies that the Technology Transfer Program has identified as promising future spinoffs, as well as information on how to license them or partner with us to further develop them for commercialization. (Page 162)

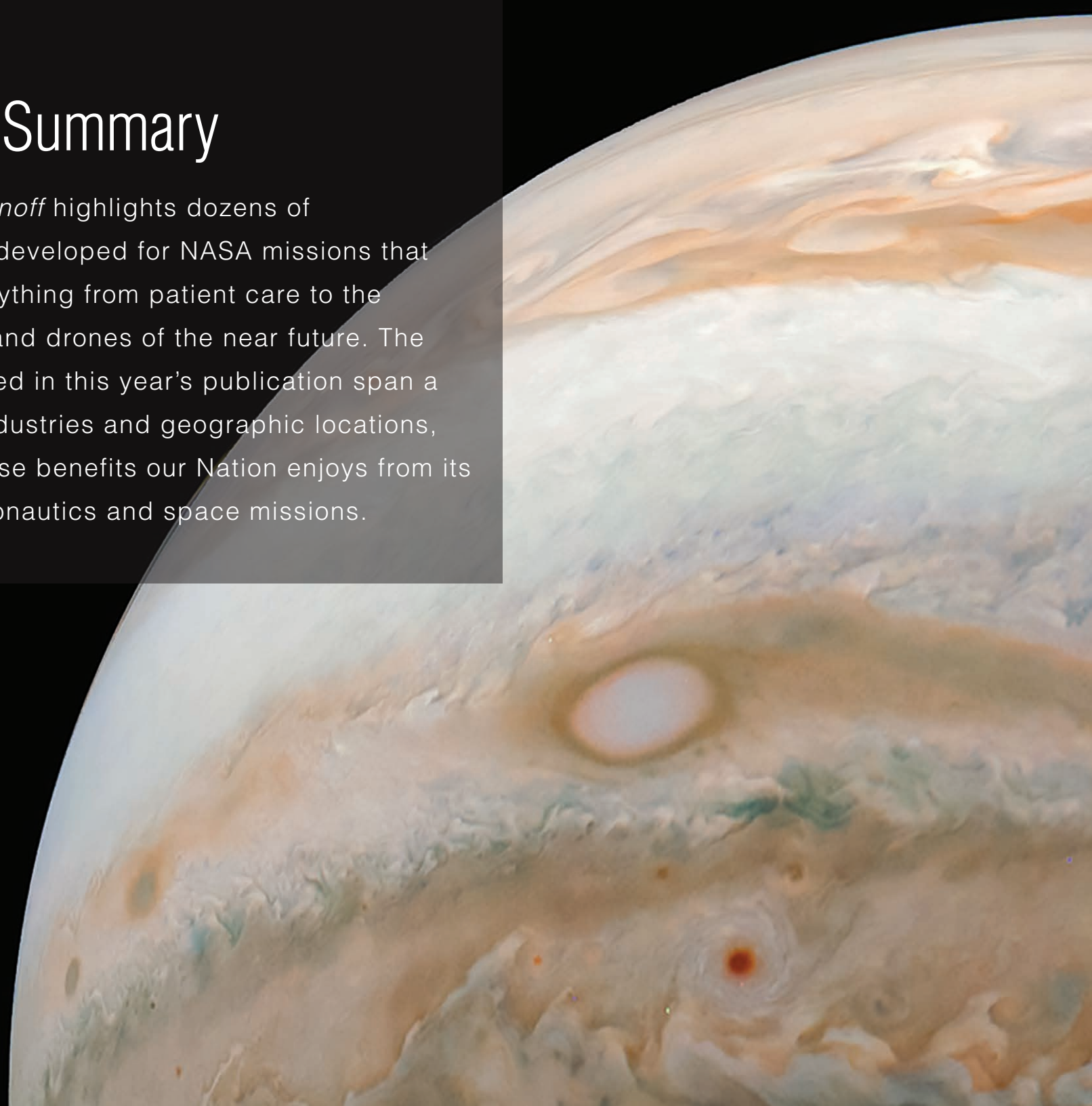
Transferring NASA technology beyond the Space Agency is part of our mandate and our longest-standing mission. At the same time that our engineers and scientists are working toward our next discovery, we're working to ensure their innovations find other uses and, ultimately, benefit you. *Spinoff* 2019 demonstrates the continued success of that mission. I hope you enjoy reading it and recognize a few ways space has made its way into your life.

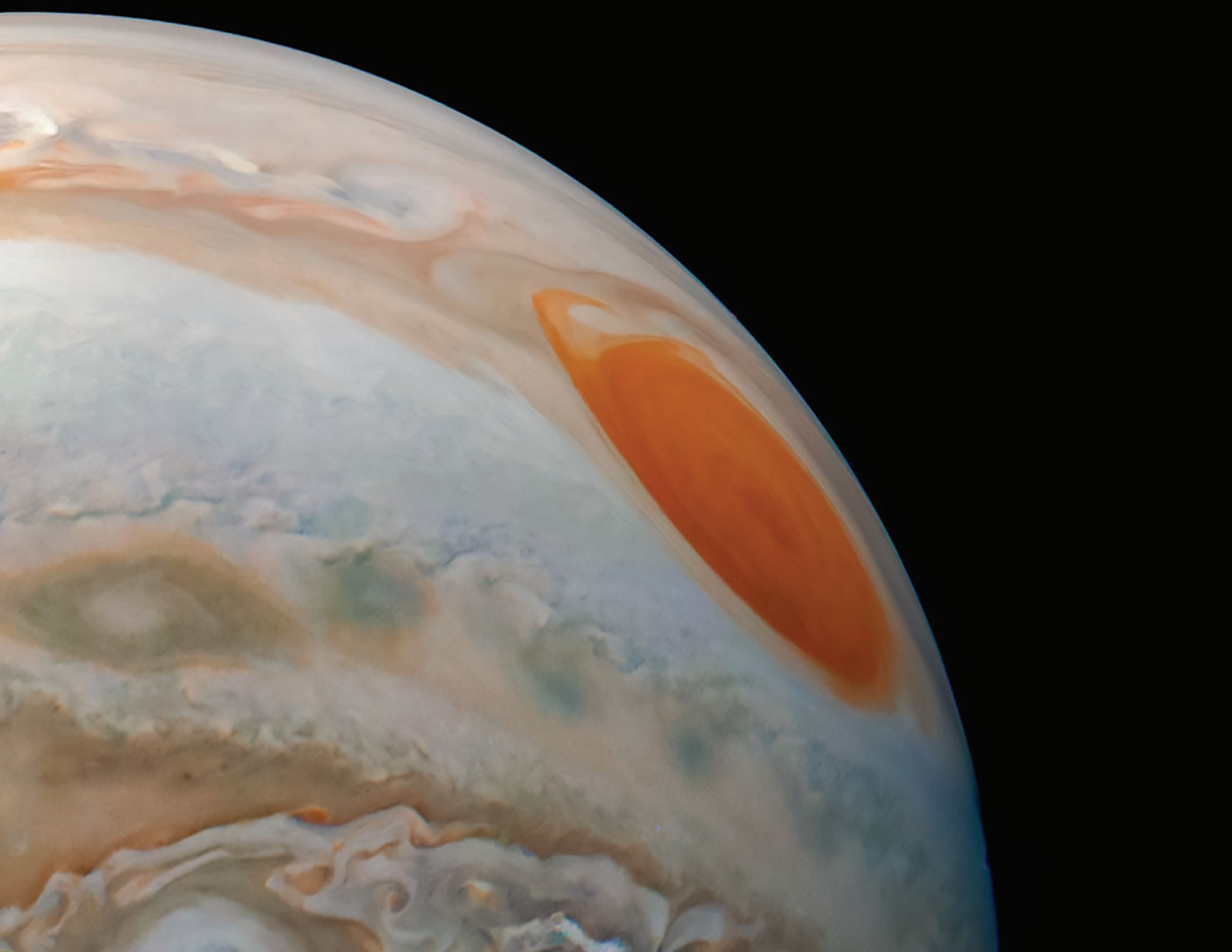
James L. Reuter
Associate Administrator

Space Technology
Mission Directorate

Executive Summary

Every year, *Spinoff* highlights dozens of technologies developed for NASA missions that now improve everything from patient care to the self-guided cars and drones of the near future. The companies featured in this year's publication span a broad range of industries and geographic locations, showing the diverse benefits our Nation enjoys from its investment in aeronautics and space missions.





Executive Summary

HEALTH AND MEDICINE

(24) Remote Monitoring Promotes Community Health beyond Hospitals

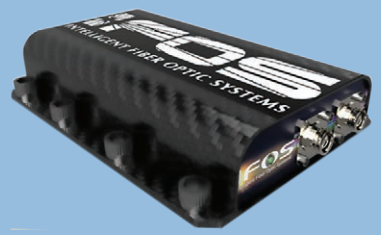
Starting with the Gemini Program, Spacelabs Healthcare worked with Johnson Space Center to develop a system to send data on astronauts' body temperature, heart rate, breathing cycles, and blood pressure to ground stations during flight. The Snoqualmie, Washington-based company quickly saw potential in healthcare on the ground, and today, Spacelabs Healthcare telemetric monitoring systems are in most hospitals around the world. The company is now expanding into community health monitoring—for example, sophisticated, diagnostic-level health monitors that can be worn home and alert doctors if the patient needs intervention.

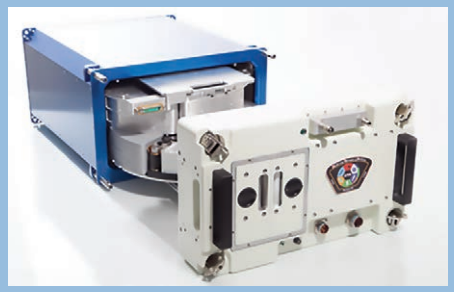
(27) Balance Scale Predicts, Helps Prevent Falls

Astronauts returning to Earth often experience balance problems. Two interns at Johnson Space Center helped develop a way to measure a person's balance control. They went on to found Houston-based Zibrio Inc., which released the home version of its balance scale in 2019. The device assigns users a score, and an app lets them explore possible causes and solutions for balance issues, which can change based on various factors. Testing showed the scale could even predict the likelihood of a subject falling.

(30) Low-Outgassing Space-Grade Coatings Cover Electronics, Sensors, Pacemakers

Over the last three decades, the Outgassing Lab at Goddard Space Flight Center has tested and validated 10 varieties of Parylene—ultrathin coatings that protect circuit boards and other equipment in space. Like all the lab's testing data, the Parylene results are listed in a publicly accessible database, where any researcher can learn that the materials, made by Indianapolis-based Specialty Coating Systems Inc., are stable and release virtually no volatile compounds. The coatings' terrestrial applications include automobile electronics systems, coronary stents, and surgical needles.





(32) Fiber-Optic "Nerves" Enable Sensitive Surgery Tools

Intelligent Fiber Optic Systems (IFOS) Corporation's first funding came from NASA SBIR contracts to develop optical fibers with strain and temperature sensors etched at intervals into their cores, a technology with many possible applications. SBIR funding from Johnson Space Center let the Santa Clara, California-based company adapt the technology to enable tactile sensing in a robot's fingers. IFOS has used that capability to create sensitive surgical tools, which it has sold to university research labs and is putting into clinical testing.

(36) Variable-Gravity Device Enables Medical, Pharmaceutical Research

NASA knows little about the long-term effects of partial gravity, such as what astronauts experience on the lunar surface. So Johnson Space Center awarded SBIR contracts to Techshot Inc. to build the Multi-Use Variable-Gravity Platform now on the space station. The device uses centrifugal force to simulate different levels of gravity and is available for use by any commercial, academic, or government researchers. Modules suiting any experiment's needs can be snapped in. In addition to space exploration, partial gravity can have implications for basic biological processes.

(38) Space Station Research Platform Paves the Way for Zero-G Manufacturing

The space station offers a unique platform for learning how to take advantage of zero gravity to benefit people on the ground. That's what motivates Lexington, Kentucky-based Space Tango, which sells lab space in orbit. In addition to being hosted on the space station (which supplies power and a data connection), the company designed its modular TangoLabs with help from safety and engineering groups at Johnson Space Center. Today, the company has launched over 100 experiments for clients ranging from researchers to Fortune 500 companies.

TRANSPORTATION

(42) Pressure Vessels Improve Transportation of Liquid Fuels

The "gas tank" of a rocket holds fuel in the form of liquid or gas, and those special tanks will now be used for moving similar substances on Earth. Huntsville, Alabama-based Cimarron Composites LLC is licensing several of the original patents and leveraging a Space Act Agreement to commercialize this space technology. The new composite overwrapped pressure vessel approved for highways by the U.S. Department of Transportation started with work done at Marshall Space Flight Center.

(44) Weight-Estimating Software Helps Design Urban Air Taxis

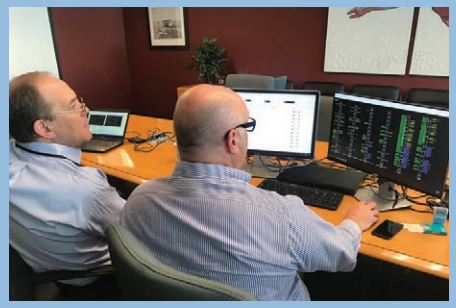
Designing new concepts for aircraft opens a universe of uncertainty. One important detail is weight, which can be difficult to estimate on a brand-new design. Software built by Long Beach, California company M4 Engineering Inc., with help from SBIR funding from Ames and Langley research centers, as well as NASA-developed and NASA-spinoff software, speeds up and simplifies the process. Today, many companies use the software, either through license or in consultation with M4, to help design new aircraft.

(47) Plane-Launched Rocket Opens Up Space for Small Satellites

Small satellites have had to piggyback on larger missions, restricting when they could launch and to what orbit. Virgin Orbit, located in Long Beach, California, is eliminating that constraint with its LauncherOne rocket, a small rocket that launches after a plane carries it up 35,000 feet. Under NASA's Flight Opportunities program, Ames Research Center helped model the aerodynamic performance of the plane/rocket configuration, and Marshall Space Flight Center and Glenn Research Center experimented with 3D-printed bimetallic combustion chambers that will bring down Virgin's manufacturing costs.

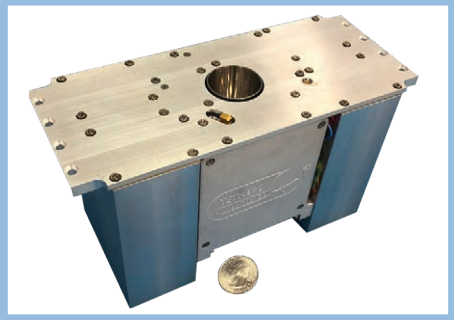
(49) Flash Lidar Enables Driverless Navigation

A special 3D imager, a global shutter flash lidar, is helping NASA sample an asteroid and could soon help cars safely navigate the road. With SBIR and other project funding from multiple centers including Langley Research Center, Santa Barbara, California-based Advanced Scientific Concepts Inc. improved and tested global shutter flash lidar, which instantly creates a 3D map of its surroundings on a focal plane array with thousands of pixels. Today Continental AG, which bought the company, markets the technology for driverless cars, and the original team, as ASC LLC, sells it for military, commercial aerospace, and marine applications.



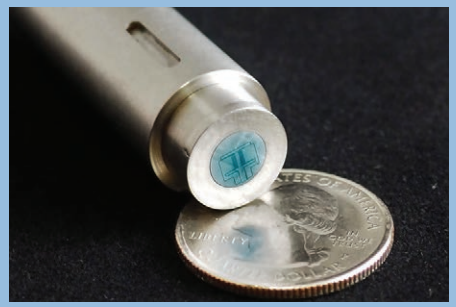
(52) Virtual Airspace Hosts a Training Program for Air Traffic Managers

Training air traffic controllers and managers to keep flights running smoothly in increasingly crowded skies is a key aspect of efforts to modernize the national airspace. That's why Leesburg, Virginia-based Mosaic ATM built the COMETTS training platform, which simulates conditions—including flights, communications, and weather—for air traffic manager trainees. Developed with SBIR funds from Ames Research Center, the platform works within the ATM-X Test Bed, an Ames project to help designers test their aviation concepts under realistic conditions.



(54) Water-Powered Engines Offer Satellite Mobility

Thrusters powered by electrolyzed water have been integral to NASA's plans for deep-space exploration since the 1960s. With funding from SBIR contracts with Ames Research Center and through NASA's Tipping Point solicitation, Tethers Unlimited Inc. of Bothell, Washington, has built the first practical water-electrolysis engines. Electrolysis separates water into oxygen and hydrogen, which NASA has long used for rocket fuel. It's safe and easy to store and can likely be foraged from asteroids and other bodies in space. An early application is CubeSat thrusters.



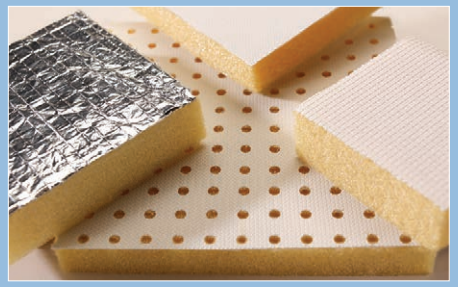
(56) Unique Sensors Will Improve Aerodynamic Design, Aircraft Performance

A series of NASA SBIR contracts, most of them with Langley Research Center, let Interdisciplinary Consulting Corporation (IC^2) of Gainesville, Florida, invent the first commercial devices to directly measure the localized force that passing air exerts on the surface of a vehicle model, known as wall shear stress. This force accounts for about half of a vehicle's overall drag, and the ability to observe it directly is improving wind tunnel testing and aerodynamic simulation software used to design aircraft and other vehicles.

(58) Doppler Lidar Makes Self-Driving Cars Safer

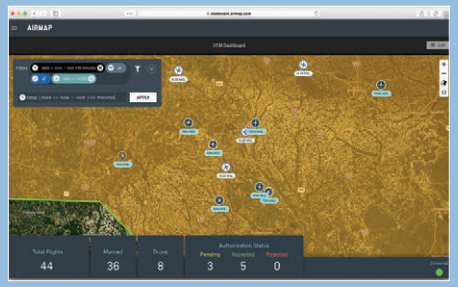
Navigational Doppler lidar, created to land spacecraft safely, can help self-driving cars successfully navigate rush-hour traffic. Lidar helps in the process of identifying objects such as cars, buildings, and people while providing their speed and direction, if any. Thanks to Hampton, Virginia-based Psionic LLC's technology license and Space Act Agreement with Langley Research Center, the company is enabling a cost-effective lidar for cars to "see" where they're going.

PUBLIC SAFETY



(64) Polyimide Foam Offers Safer, Lighter Insulation

Under the Fire Resistant Materials Engineering Project of the 1970s, Johnson Space Center and a contractor invented methods to turn a particular polyimide into durable, lightweight, fireproof foams for thermal and acoustic insulation, known as SOLIMIDE. Now owned by Boyd Corporation, the SOLIMIDE plant in Magnolia, Arkansas, produces millions of board feet of the material annually. It's used in nearly all U.S. airliners and Navy ships, as well as many other applications around the world.



(68) AirMap Guides Drones toward Widespread Use

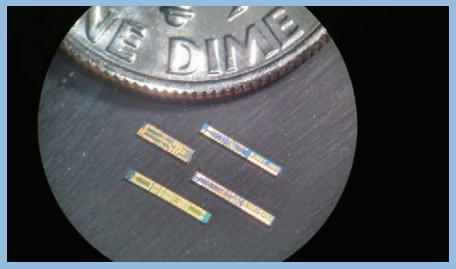
Autonomous flying vehicles have incredible potential to change how we use the skies. But first we need a system to safely track them. Engineers at Ames Research Center envision a future where drone operators share trajectories and flight plans with each other, and onboard algorithms and sensors ensure aircraft safely avoid each other. Santa Monica, California-based AirMap Inc. worked with NASA and other industry partners to develop its AirMap UTM platform, which already enables more than 100,000 drone flights per day.

(70) Rockets, Rovers Spur New Offshore Drilling Safety Technology

After Bastion Technologies Inc., a company with a long history at Marshall Space Flight Center and other NASA locations, helped investigate the *Deepwater Horizon* oil spill, the company sought a way to prevent such a disaster. Using the knowledge of propellants, mission assurance, and structural analysis its employees gained at NASA, the Houston-based company invented its SureShear product for subsea blowout preventers. Rather than using pressurized gas, SureShear burns a solid propellant to power rams that quickly and reliably shear and seal a well's drill pipe.

(73) Wool Mask to Fight Fires in Space Inspires Fire Equipment on Earth

Auckland, New Zealand-based Lanaco adapted one of its wool filters to prolong the life of the mask astronauts would wear in the event of a fire on the Orion spacecraft. Work on the project, through a Johnson Space Center contract with Jacobs Engineering Group, inspired Lanaco to develop filters for firefighting on Earth. The company expects the work will also inform its sheep breeding program, which aims to maximize the strengths of wool as a filter material.



(75) Autonomous Drone Navigation System Ends Reliance on GPS

When regulations are issued to allow self-piloted drones to fly beyond operators' line of sight, one requirement will be that they be able to navigate without GPS. SBIR contracts from Ames Research Center funded one company's development of a simultaneous localization and mapping system that can do just that. Pittsburgh-based Near Earth Autonomy has sold prototypes of the technology and is working with companies and agencies to adapt it for disaster site surveillance, building and infrastructure inspection, and military reconnaissance.

(77) Smaller, Cheaper Lasers Can Detect Gas, Monitor Structures, Take Tissue Images

SBIR and Tipping Point contracts from Goddard Space Flight Center helped Freedom Photonics of Santa Barbara, California, develop tunable lasers for sensing methane and other gases. The lasers are much smaller, cheaper, and more efficient than alternatives and have possible applications in environmental monitoring, the oil and gas industry, and other fields. Advances made under Armstrong Flight Research Center SBIR funding have helped the company develop capabilities that could be used for structural monitoring and medical imaging.

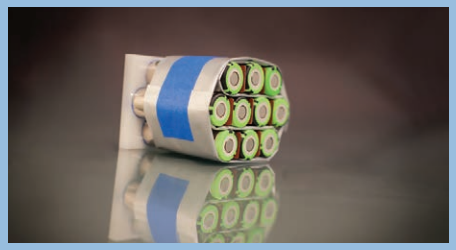
CONSUMER GOODS

(82) Astronaut Experience Inspires Single-Handed Drone Flight Controller

Scott Parazynski's astronaut experience helped him create a joystick that controls drone fight with a single hand and will one day, he hopes, revolutionize robotic surgery. Parazynski, who is also a physician, used the expertise he gained at Johnson Space Center and in space to build a more intuitive controller for robotic surgery. While working on FDA approval, he adapted the controller for the growing commercial drone market. His Houston-based company, Fluidity Technologies Inc., launched the FT Aviator in November 2018 and quickly garnered hundreds of pre-orders.

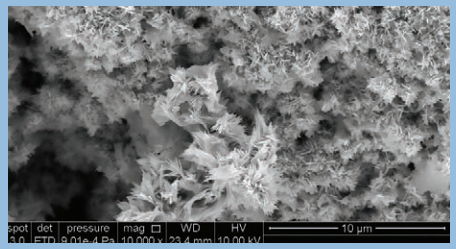
(84) Freeze-Dried Foods Nourish Adventurers and the Imagination

Freeze-dried food is commonplace today, thanks in part to NASA, which helped innovate many of the modern techniques during early research into food preservation for space exploration. In particular, NASA's advances made freeze-dried meals easier to rehydrate without boiling water. Capitalizing on the interest in astronauts in the early 1970s, the gift shop at Ames Research Center reached out to Boulder-based American Outdoor Products, already using NASA's improved techniques for its freeze-dried foods, and asked them to create "astronaut ice cream." The company now sells it around the world.



(86) Carbon-Fiber Heat Sink Makes Batteries Safer for Electric Cars, Bikes, and More

Keeping modern energy-dense batteries from overheating (and sometimes even exploding) is an important challenge. Campbell, California-based KULR Technology specializes in the field. In collaboration with with Johnson Space Center, the company recently created a thermal runaway shield for lithium-ion battery packs that promises to improve safety in battery-operated devices from cars to bikes and more. The company also licensed a patent co-owned by NASA for an internal short-circuit device that makes it much easier to test batteries, which KULR sells to its customers to help them improve their in-house safety testing.



(89) Nanotechnology Repairs Engine Damage in Cars

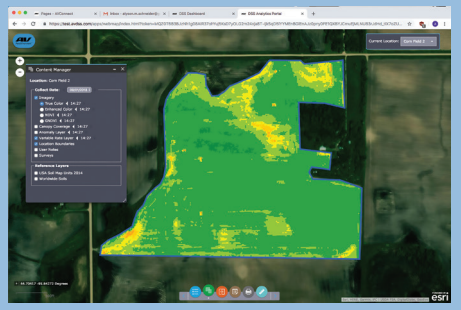
Repairing worn engine parts instead of replacing them could save consumers millions of dollars in parts and labor costs annually. Colfax, Washington-based TriboTEX LLC gives drivers a way to do just that with a nanoparticle lubricant called TriboTEX that fills in grooves and other wear patterns resulting from friction. A NASA fellowship from the Washington Space Grant Consortium helped fund the initial research. Now more than 30,000 cars and trucks are getting the benefits of increased oil pressure, improved gas mileage, and increased torque.

(92) Zero-Gravity Body Posture Influences Acupressure Massage Chair

How the human body acts in microgravity influences the equipment and procedures NASA develops, as well as consumer products on Earth. Johnson Space Center neutral body posture research revealed the positions an astronaut's body assumes in space, and that same data is used for a robotic medical massage chair. LURACO Health and Beauty LLC, based in Arlington, Texas, created a zero-gravity setting for the i7 PLUS to leverage a person's weight to enhance the acupressure massage to speed healing, alleviate pain, and reduce stress.

(94) Spacesuit Insulation Protects Personal Devices

Can a case that protects phones and tablets from the extremes of heat and cold, keeps out sand and dirt, floats, and has drop protection also look cool? Yes, and eXclaim IP LLC of Cornelius, North Carolina, has done it using the radiant barrier insulation used in spacesuits developed at Marshall Space Flight Center. The versatile NASA technology reflects more than 90 percent of solar radiation to prevent devices from overheating and retains heat to keep technology from freezing.



ENERGY AND ENVIRONMENT

(98) Rocket Expertise Assists Transition to Green Energy

Economic prosperity is tied to the consistent availability of cheap energy. Coal's abundance makes it a cheap resource to generate electricity and a major source of toxic pollution. An alternative to burning coal for power—gasification—is getting a boost from NASA rocket expertise developed by companies working with Marshall Space Flight Center. Des Plaines, Illinois-based Gas Technology Institute is leveraging this expertise to help developing countries use coal in a less environmentally damaging manner.

(102) Satellite Imagery Helps Farmers Cut Water Use in Half

Irrigation accounts for around 80 percent of fresh water use across the United States. Oakland, California's Tule Technologies Inc. aims to improve irrigation efficiency by calculating how much water plants are using and losing daily, in part thanks to data from multiple satellites built at Goddard Space Flight Center. Today, the company sells its systems to grape, almond, and other growers across California, who use the data to cut their water use in half or get higher yield with the same amount of water.

(105) Gas Processors Turn Oil Drilling Emissions into Fuel for Sale

Robert Zubrin founded Pioneer Astronautics in the 1990s, and the company devised a multitude of technologies for space exploration. Several developed under SBIR contracts with Johnson Space Center would take apart molecules abundant on Mars and reassemble them into useful resources. Realizing that some of this technology could be adapted to the oil and gas industry, Zubrin spun off Lakewood, Colorado-based Pioneer Energy. The company now markets Flarecatcher and Vaporcatcher systems that turn what used to be waste products and greenhouse gas emissions into fuel.

(108) Field-Scanning Drone Gives Farmers Better Data

Flight enables access and perspective impossible from the ground. A field-scanning drone—designed by Los Angeles-based AeroVironment using expertise in autonomous flight engineering gained on NASA's high-altitude, solar-powered, unmanned airplanes—now makes that perspective more accessible for farmers. Sold as Quantix, the drone is giving farmers better data about their sprawling fields, helping increase yield or farm more efficiently. The company also used the same expertise to help the Jet Propulsion Laboratory build a helicopter for Mars, set to become the first vehicle ever to fly there.

(112) Versatile Fuel Cells Stop Natural Gas Emissions at Oil Wells

A Jet Propulsion Laboratory engineer taught two California Institute of Technology students how they might make a fuel cell based on their professor's invention of a crystal that conducts protons at record speeds. The students and professor started a company offering fuel cells now used at oil drilling sites to run pneumatic equipment traditionally powered with high-pressure methane, a greenhouse gas that drillers then vent. Based in Pasadena, California, SAFCell also works with another company to make wearable fuel cells for the military.

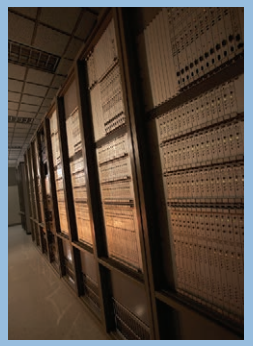
(114) Laser Enables Precise Measurements for Weather Forecasting, Industry

Although Hurricane Irma devastated many areas, accurate forecasts helped countless residents prepare. Helping inform those forecasts? Temperature and humidity information from the Cross-Track Infrared Spectrometer, built out of Langley Research Center, which scans the atmosphere from a polar-orbiting satellite. A crucial laser that measures the alignment and proximity of mirrors within the instrument to sub-micrometer levels was built by ABB Inc., whose U.S. headquarters is in Cary, North Carolina. Today, ABB sells hundreds of industrial spectrometers per year with that laser, which is smaller and requires less power than previous options.

INFORMATION TECHNOLOGY

(118) Beowulf Clusters Make Supercomputing Accessible

In the 1990s, efforts to develop supercomputers were stalling well short of Government goals until a pair of computer engineers at Goddard Space Flight Center successfully used a new, open source operating system to turn a cluster of standard computers into a single supercomputer. Known as the Beowulf cluster, the technology dramatically reduced the cost of supercomputing, and most of the world's top supercomputers today are based on it. Minneapolis-based Nor-Tech custom-builds Beowulf clusters for customers that use them primarily to design products through modeling and simulation.



(122) Mission Control Conference System Enables Global Collaboration

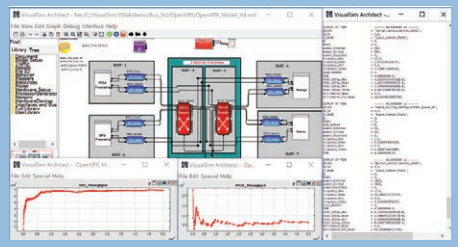
Conference calling is easy and common, but it requires complicated technology that didn't exist before the 1980s, when NASA wanted to improve its own communications system. Originally, NASA's global and space networks required constant manual reconfiguration. To upgrade to a digital system, Goddard Space Flight Center called on Pittsburgh-based Compunetics. The company created a conference bridge that allowed connections and conferences to be reconfigured instantly and automatically. The company has since sold millions of similar systems worldwide based on what it created for NASA.

(124) Swarming Technology Lets Drones Work as a Team

As U.S. skies become more crowded, NASA wants to help aircraft coordinate with each other autonomously. Langley Research Center granted SBIR funding to help Heron Systems Inc., based in California, Maryland, advance its Multi-Agent Cooperative Engagement (MACE) technology—software and hardware that allows drones to cooperatively allocate tasks and resources and plan flight paths without the help of an operator. MACE has immediate applications in military training and could soon help monitor crops and infrastructure before eventually helping to manage U.S. airspace.

(126) AURA Software Tackles Uncertainty in Complex Systems

Langley Research Center awarded SBIR contracts to Charlottesville, Virginia-based Barron Associates Inc. to build on earlier work the company did with Langley to predict the performance of aircraft diagnostic and control systems. The result, Algorithms for Uncertainty Representation and Analysis (AURA), can determine uncertainties and probabilities of various outcomes in a single calculation. AURA has been used to validate autonomous systems for planes and drones and to predict how drug molecules might behave in the body, but it can be applied to any complex system.

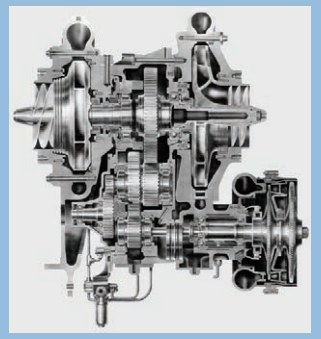


(128) Simulation Software Optimizes High-Speed, Efficient Data Networks

In 2010, the Jet Propulsion Laboratory (JPL) sought a new computer communications protocol for spacecraft. This set of standards defines the physical and functional qualities of communication systems within or between computers. JPL settled on the Serial RapidIO protocol and wanted to use VisualSim—electronics simulation software by Sunnyvale, California-based Mirabilis Design Inc.—to model its behavior. The Center partnered with Mirabilis to build a RapidIO simulation capability, which is now available to other industries that use the protocol, such as data centers, supercomputing, communications, and automation.

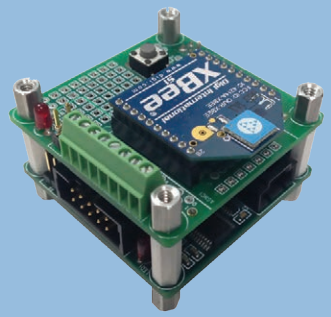
(130) Data Visualization Platform Helps Missions Fly

Software designed at Ames Research Center helps mission controllers see at a glance what's happening and when there's a problem. The web-based platform, Open MCT, can display streaming and historical data, imagery, timelines, procedures, and other data visualizations and can be quickly configured and reconfigured. Now that it is open source and freely available, it has many users, including the Planetary Society, based in Pasedena, California, which adopted Open MCT to visualize the data coming in from LightSail 2, a spacecraft that is propelled solely by sunlight.



(132) Turbopump Modeling Software Propels Fluid-Flow Simulations

As the commercial space economy grows, both established and start-up aerospace companies are doing work that was previously performed by NASA and other Government entities. To make sure they have the same powerful tools to design and improve spacecraft, Marshall Space Flight Center is making Generalized Fluid System Simulation Program (GFSSP) licenses available through Denver-based Mode Technologies Group. This testing and analysis program is available to businesses and educational institutions, with three new licenses sold in 2019.



(134) Smart Sensor Networks Monitor System Health—and Themselves

Stennis Space Center awarded Simi Valley, California-based American GNC Corporation several SBIR and STTR contracts to develop smart sensor networks that monitor systems to detect and predict faults. The technology can also detect faults in its own sensors. The work led to the company's Reconfigurable Embedded Smart Sensor Node and its Smart Transducer Integrator, which can gather information from many sensors, package it, and deliver it wirelessly.

INDUSTRIAL PRODUCTIVITY

(138) Metallic Glass Coatings Improve Power Plant, Oil Rig Productivity

A tough, durable, versatile coating with the atomic structure of glass helps keep power plants running. NASA has been working on the material, called liquid metal or metallic glass, at least since the 1980s. That work continues today at the Jet Propulsion Laboratory's Metallurgy Facility. Spring, Texas-based Liquidmetal Coatings LLC, which licenses the original NASA-funded technology, created a range of coatings that protect vital components at power plants, petrochemical refineries, and oil and gas drilling sites around the world.

(141) Aerogel Insulations Save Millions in Industrial Applications

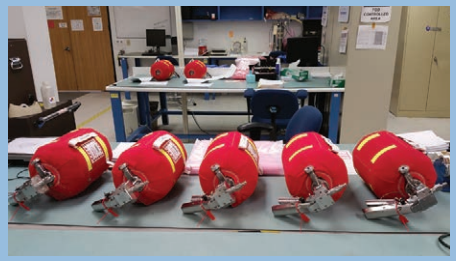
Beginning with two SBIR contracts from Kennedy Space Center, Aspen Systems worked with NASA to develop the first sturdy, practical aerogel insulations. The effort spun off into Northborough, Massachusetts-based Aspen Aerogels, a 300-person company with over $100 million in annual revenue. While the ultra-lightweight, super-insulating materials appear in many consumer products, their primary applications are in power plants, steam distribution systems, buildings, pipelines, and other industrial applications all over the world, where they conserve energy and reduce costs and downtime.

(145) Revolutionary Battery Replacement Leads to a New Humidity Sensor

Developing a new power source material to replace batteries resulted in an unexpected outcome–a solid-state humidity sensor. Technologists at Marshall Space Flight Center partnered with Roscid Technologies Inc. of Woburn, Massachusetts, to test the new energy storage material that uses nanotechnology and non-toxic ingredients. It performed so well that Roscid licensed the technology to create a new class of industrial humidity sensors.

(148) Printed Polymer Makes Integrated Airplane Parts

Additive manufacturing, or 3D printing, makes it possible to manufacture entirely new structures or integrate existing ones into single components. But for applications like aerospace, high-grade structural materials and extensive testing are required. As part of the America Makes initiative, a public-private partnership to advance research in and applications for additive manufacturing, Goddard Space Flight Center teamed up with private companies on a project to investigate the properties of PEKK, a high-grade polymer, and now Stamford, Connecticut-based Hexcel Corporation is selling the material and 3D printing parts for spacecraft and aircraft.

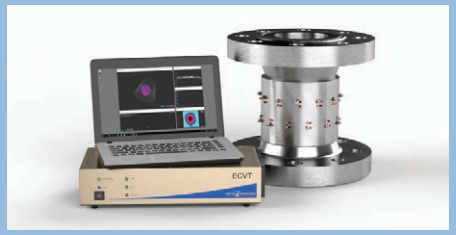


(150) Zero-Leak Valve Holds Tight in Demanding Environments

Liquid leaks in the space station can cause serious problems. So when NASA needed a new fine-mist water fire extinguisher to use in zero gravity, the contents had to stay contained. A zero-leak valve manufactured by Doering Company LLC in Clear Lake, Minnesota, proved to be a perfect fit. After Glenn Research Center funded several SBIR grants for ADA Technologies to develop the hand-held fire suppression system, the same class of zero-leak valve is now stopping leaks in several industries on Earth.

(152) Pulsed Laser Innovations Power Nobel-Winners' Research

Astronauts regularly post tweets from orbit, and images stream across the solar system, but the amount of data coming from space is growing rapidly. We need more bandwidth, and the best solution is laser communications. San Jose, California-based PolarOnyx Inc. specializes in very fast-pulsed lasers, which are ideal for space-to-ground transmissions. The Jet Propulsion Laboratory funded multiple SBIR contracts over the years that have helped the company develop and perfect its lasers, and it has sold more than 400 since 2005, including to multiple Nobel Prize winners.



(154) New Imaging Technique Measures Unseen Flows

In the interest of studying interactions of liquids and gases in zero gravity, Johnson Space Center awarded SBIR contracts to Tech4Imaging LLC of Columbus, Ohio. The company had invented a technique that used electrical signals to create a 3D image of solids and gases inside a pipe or vessel. With the SBIR funding, the company developed the ability to distinguish water and oil and also improved resolution. The technology has clear applications in the oil industry, as well as manufacturing, testing infrastructure, and medical imaging.

(156) Separation Device Launches New Science Payloads

Rockets typically come in stages, optimized for different parts of the launch. Ensuring each stage separates correctly is complicated and crucially important. The Interstellar Boundary Explorer spacecraft (IBEX) needed three separation devices. Silver Spring, Maryland-based Planetary Systems Corporation had a proven track record with their Lightband devices, so the Goddard Space Flight Center team called on them to build a lighter model that would work for IBEX. The resulting product completely replaced its predecessor and paved the way for the company to double in size.

(158) Tiny Pulsed Lasers Have Medical, Industrial, Military, Environmental Applications

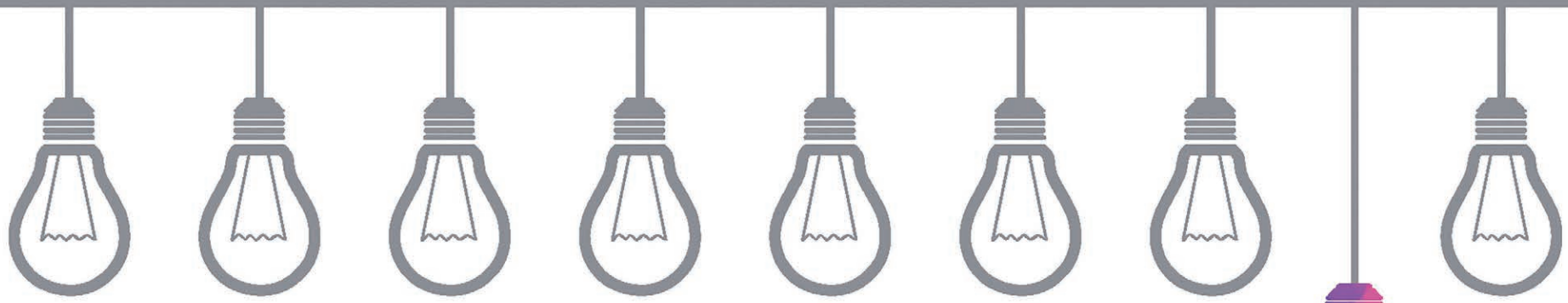
To pack more instruments into the Mars 2020 rover than its predecessors, NASA had to shrink components. SBIR contracts overseen by Goddard Space Flight Center paid Q-Peak Inc. of Bedford, Massachusetts, to develop a high-powered, pulsed-energy laser of unprecedented tininess for one of the rover's spectrometers. Based on that work, the company's Moonbow lasers pack technology that would normally fill a shoebox into a housing the size of a matchbox. These lasers could be used to treat glaucoma in developing countries, as well as in spectroscopy, lidar, and military applications.

(160) Electrostatic Discharge Training Improves Manufacturing Practices

The shock you might get when touching a doorknob is electrostatic discharge, and when you're building sensitive electronics, it can wreak havoc. Goddard Space Flight Center's Alvin Boutte and others across NASA devise and implement protocols to minimize electrostatic discharge. One tool that helps is a training seminar conducted by Moffett Field, California-based RMV Technology Group. Boutte and others have provided feedback that has helped shape and improve the course, and now that same training is helping the company's other training clients, including the U.S. military and universities.

National Aeronautics and Space Administration

NASA Patent Portfolio



Aeronautics | Communications | Electrical/ Electronics | Environment | Health, Medicine, and Biotechnology

IT and Software | Instrumentation | Manufacturing | Materials and Coatings | Mechanical and Fluid Systems

Optics | Power Generation and Storage | Propulsion | Robotics, Automation and Control | Sensors

NASA maintains a portfolio of patents with commercial potential and makes them available to the public through our patent licensing program. Whether you're looking to start a new company using NASA technology, enhance an existing product, or create a new product line, you can gain a competitive edge in the marketplace by putting NASA technology to work for you. Search the Patent Portfolio at technology.nasa.gov

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NASA Spinoff Technology across the Nation

Health and Medicine

1. Remote Monitoring Promotes Community Health beyond Hospitals (WA)
2. Balance Scale Predicts, Helps Prevent Falls (TX)
3. Low-Outgassing, Space-Grade Coatings Cover Electronics, Sensors, Pacemakers (IN)
4. Fiber-Optic "Nerves" Enable Sensitive Surgery Tools (CA)
5. Variable-Gravity Device Enables Medical, Pharmaceutical Research (IN)
6. Space Station Research Platform Paves the Way for Zero-G Manufacturing (KY)

Transportation

7. Pressure Vessels Improve Transportation of Liquid Fuels (AL)
8. Weight-Estimating Software Helps Design Urban Air Taxis (CA)
9. Plane-Launched Rocket Opens Up Space for Small Satellites (CA)
10. Flash Lidar Enables Driverless Navigation (CA)
11. Virtual Airspace Hosts a Training Program for Air Traffic Managers (VA)
12. Water-Powered Engines Offer Satellite Mobility (WA)
13. Unique Sensors Will Improve Aerodynamic Design, Aircraft Performance (FL)
14. Doppler Lidar Makes Self-Driving Cars Safer (VA)

Public Safety

15. Polyimide Foam Offers Safer, Lighter Insulation (AR)
16. AirMap Guides Drones toward Widespread Use (CA)
17. Rockets, Rovers Spur New Offshore Drilling Safety Technology (TX)
18. Wool Mask to Fight Fires in Space Inspires Fire Equipment on Earth (New Zealand)
19. Autonomous Drone Navigation System Ends Reliance on GPS (PA)
20. Smaller, Cheaper Lasers Can Detect Gas, Monitor Structures, Take Tissue Images (CA)

Consumer Goods

21. Astronaut Experience Inspires Single-Handed Drone Flight Controller (TX)
22. Freeze-Dried Foods Nourish Adventurers and the Imagination (CO)
23. Carbon-Fiber Heat Sink Makes Batteries Safer for Electric Cars, Bikes, and More (CA)
24. Nanotechnology Repairs Engine Damage in Cars (WA)
25. Zero-Gravity Body Posture Influences Acupressure Massage Chair (TX)
26. Spacesuit Insulation Protects Personal Devices (NC)

Energy and Environment

27. Rocket Expertise Assists Transition to Green Energy (IL)
28. Satellite Imagery Helps Farmers Cut Water Use in Half (CA)
29. Gas Processors Turn Oil Drilling Emissions into Fuel for Sale (CO)
30. Field-Scanning Drone Gives Farmers Better Data (CA)
31. Versatile Fuel Cells Stop Natural Gas Emissions at Oil Wells (CA)
32. Laser Enables Precise Measurements for Weather Forecasting, Industry (NC)

Information Technology

33. Beowulf Clusters Make Supercomputing Accessible (MN)
34. Mission Control Conference System Enables Global Collaboration (PA)
35. Swarming Technology Lets Drones Work as a Team (MD)
36. AURA Software Tackles Uncertainty in Complex Systems (VA)
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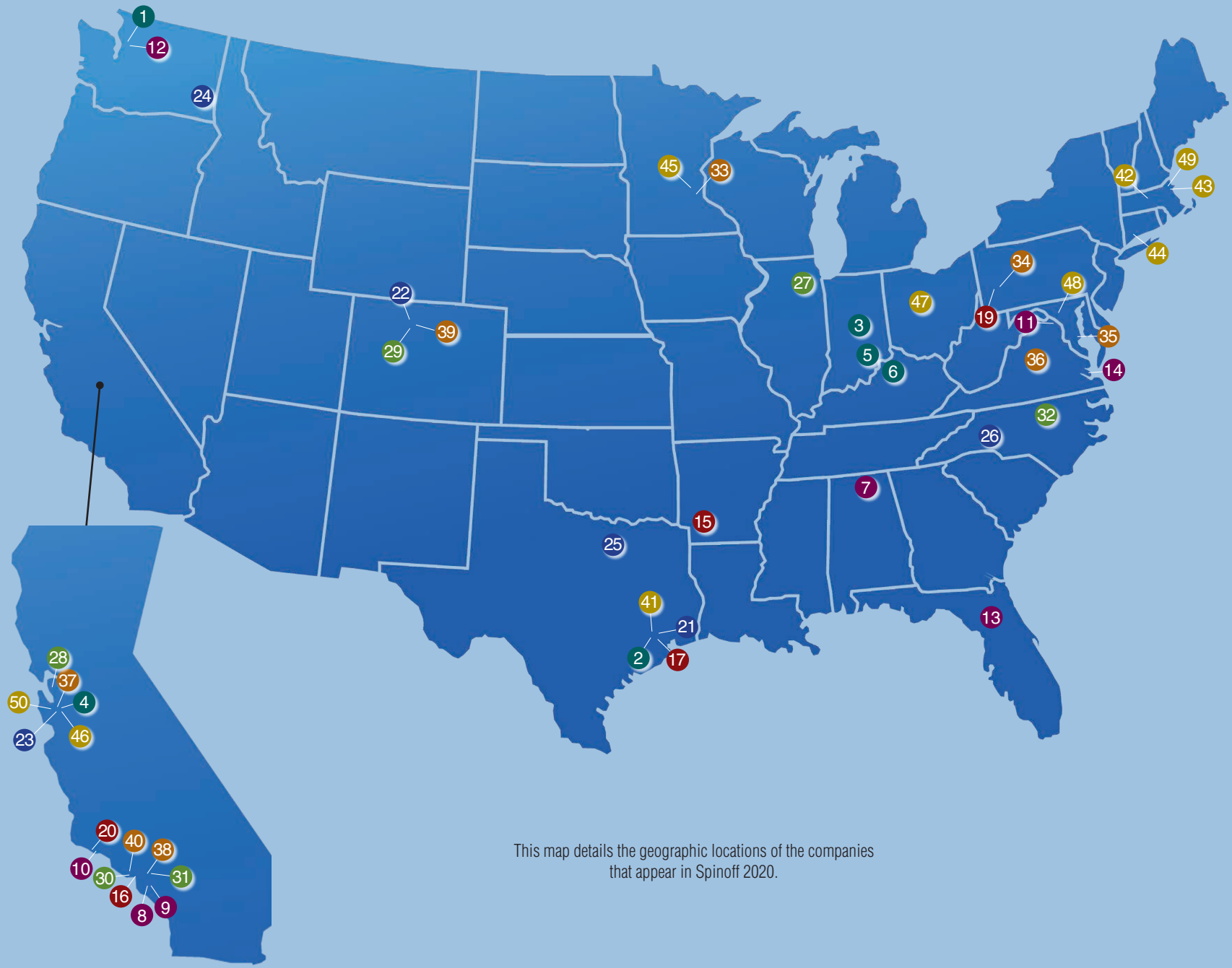


This map details the geographic locations of the companies that appear in Spinoff 2020.

NASA Technologies Benefiting Society

Innovations developed to support space exploration and other NASA missions have been pouring into the private sector since the Space Agency's inception more than 60 years ago. Technology that helps keep astronauts healthy, improves spacecraft design, or protects against the extreme conditions of space almost invariably prove useful for many applications on the ground. NASA also has missions on Earth that more directly benefit the public, such as improving aeronautics, helping to manage the airspace, and monitoring the environment. The following is just a handful of examples of the Agency's work improving lives across the country and around the world.

Health and Medicine

Some of NASA's most important spinoffs have stemmed from the need to keep astronauts healthy in some of the most remote, unusual environments possible. So it's no surprise that technology invented to monitor astronauts' health in space or assess their balance after they return from months of weightlessness is now improving healthcare for the general population. But the ability to conduct research and manufacture products in zero or partial gravity is also leading to medical advances.

Remote Monitoring Promotes Community Health beyond Hospitals

NASA Technology

Hospital rooms are full of sensors, screens, and beeps. Those sensors send signals not just to screens in that room but down the hall to the nurse's station and sometimes even across the hospital or beyond, which means when an alarm goes off, the right people come running to help.

It's technology that helps save lives daily. But before it reached the ICU, the technology was invented for something even more extraordinary: sending health data from space down to the ground.

These days astronauts are continuously monitored while in space: heart rate, body temperature, sleep cycles, even the composition of the air they exhale is measured to better understand how human bodies react to being in space. All that information streams down to the ground, where it is logged and analyzed in the moment and over time.

But it didn't start out that way. Like much of what was needed to get humans safely into space, the technology to remotely monitor vital signs didn't exist until NASA came along. While physiological measurements of the Mercury astronauts were taken during flight, little was known about what was happening in their bodies in real time during orbit.

The Gemini Program aimed to develop techniques for longer-duration space travel—and that included ensuring astronauts were safe and well along the journey. It was the first time Americans would spend days in space instead of just hours. In 1958, two engineers, James Reeves (then in the Navy) and Ben Ettelson, approached NASA with a plan for what is now called telemetric health monitoring. "They said, we can do this. We can bring it down so you can monitor the health during these missions," recounts Jim Green, now president of Spacelabs Healthcare Inc., the company Ettelson and Reeves founded.

The challenge was formidable. Among other difficulties, according to an article published in the journal *Electronics* in 1965, "equipment must be extremely small, lightweight, and highly reliable in the face of severe environmental loads

The first telemetric health monitoring—in which biometric data was captured and sent to the ground for real-time monitoring—was built for the Gemini Program. Here, astronaut Virgil "Gus" Grissom is fitted with electrodes that would gather data on heart rate, breath cycles, and more during his spaceflight.

Spacelabs Healthcare Inc. got the contract to design the telemetric health monitoring system for the Gemini Program and improved it further for the Apollo Program. But they also soon adapted it for hospitals on the ground, enabling doctors and nurses to use small sensors and monitor patients from anywhere in the hospital.

Today Spacelabs Healthcare is moving to a new frontier—home-based health monitoring. This device can send blood pressure reports from home to the medical provider.

and variations. Good contact with the astronaut must be made and maintained far longer than in normal practice despite the restrictions imposed by his spacesuit."

In the end, the astronauts wore a belt carrying four different signal conditioners that each captured data from sensors and electrodes attached across the body: an oral probe for temperature, electrodes for ECG (electrocardiogram) heart data and breath cycles, and an inflatable cuff with a sound transducer over an artery for blood pressure.

Then the data was fed directly into the onboard telemetry system, explains the article. For the first time ever, "ground monitoring stations receive the telemetered signals during flight. These signals are used to assess the physiological condition of the astronaut."

According to authors Herbert Seal, then-chief project engineer at Spacelabs, and then-researcher Gershon Weltman, the goal was to monitor the wellbeing of the astronaut during the flight as well as to gather data for the planning of subsequent missions.

Technology Transfer

Spacelabs designed and built three of the four signal conditioners (all except the one for blood pressure) as well as the onboard telemetry system that sent the data back to the ground via radio frequencies. The system was first worn by astronauts James McDivitt and Ed White during the historic 1965 Gemini IV mission—when White completed the first-ever spacewalk by a U.S. astronaut. It later flew with astronauts on additional Gemini missions, and an expanded system flew during Apollo flights.

Recognizing the huge impact Spacelab's technology had in successfully and safely landing astronauts on the Moon and bringing them home, in July 1969—just days after Neil Armstrong's first steps on the Moon—NASA's Manned Spacecraft Center (now Johnson Space Center) honored the company with a certificate of appreciation for its "outstanding" contributions to the Apollo Program.

For the new company, it was a foundational success. "The NASA contract was a fundamental enabler of this technology. It allowed people to think about how to invent this and make it happen," says Green. Once the technology existed, the company moved to transition it for the broader potential market here on the ground.

> "It's a pretty good chance, if you walk into any hospital, somewhere along your stay, you'll run into Spacelabs Healthcare technology."
>
> — Jim Green, Spacelabs Healthcare

That required some additional product development, including adapting the radio signal to work with shorter frequencies than the long-range ones used to send signals from space. And the company has continued to advance and improve the technology in the decades since. However, says Green, "the fundamentals haven't changed much at all. Being able to monitor someone far away, without having them hardwired up all the time—that fundamental innovation is what this is all about."

Benefits

Soon after the first flights during the Gemini project, the Snoqualmie, Washington-based company began working with hospitals in the Los Angeles area, starting with intensive and critical care monitoring. The goal was "to bring in this concept of monitoring and telemetering that information—so you could watch them not just in the room, but from room to room and down the hall."

Green explains that one of the important new features the Spacelabs system offered was its portability, thanks to the miniaturization developed to fit into spacesuits and the fact that the signals could be sent to stationary monitors elsewhere via radio frequency. Now, instead of unhooking patients to move them "blind" from one room to the next, say from the emergency room to radiology, you could still keep track of the patient while they were moving around.

As the technology advanced, Green says, the resolution increased, enabling more and better data to be collected. Then the company moved a step further, to make the technology "smarter" by incorporating algorithms that interpret the health data and suggest a diagnosis. "The algorithms are used to determine if something is alarming," Green explains. In other words, "is this something that somebody needs to do something about?"

In the decades since, the company's business has expanded exponentially around the world. "It's a pretty good chance, if you walk into any hospital, somewhere along your stay, you'll run into Spacelabs Healthcare technology," Green says.

But the company is looking to expand its reach even further, so at-risk patients and their doctors can keep track of their health even outside the hospital. Eventually, Green says, "we expect that home-based monitoring will start to be bigger than hospital-based—the market is pushing that way."

This can already be seen in the explosive growth in fitness trackers and smart watches over the past few years, but Spacelabs offers diagnostic-level monitoring with fidelity and resolution beyond the current reach of consumer wearable technology.

Starting with cardiology, they have developed a line of at-home ECG and blood pressure machines. The devices are easy to use and non-invasive, and they send alerts to the medical provider if a problem develops.

"When a patient leaves the hospital, it's very costly if they have to be readmitted," Green explains. But not all post-hospitalization complications are the same. Through remote monitoring, health providers "might see that you are not taking your meds properly. Maybe you don't need to come back. Or maybe you do need to come back, and this device will alert you and your doctor before things get worse."

And while most of the devices today are prescribed for specific at-risk patients, as the cost of the high-fidelity sensors goes down, Green expects usage to expand.

"What we're working on is how to really provide a full continuum of care," Green adds. "This kind of monitoring can really help healthcare providers keep eyes on their entire population's health." ❖

Balance Scale Predicts, Helps Prevent Falls

NASA Technology

The inside of the International Space Station is designed to give astronauts the illusion of verticality in the weightlessness of orbit. The "floors" are relatively uncluttered, and lighting runs along the opposite "ceilings," with most of the monitors, cables, and frequently used equipment packed onto the "walls." Signage and labeling provide further visual cues. It's said that astronauts learn to use their eyes rather than their inner ears to establish their orientation. It's an illusion that's easily broken, often resulting in confusion, nausea, and vertigo, but this happens less with time.

The return to Earth results in a similar adjustment period. Bill Paloski, who studied balance issues as a senior scientist in Johnson Space Center's Neurosciences Laboratory, recalls an astronaut who seemed to have regained his land legs a couple of days after returning from a space shuttle mission. Nonetheless, Paloski advised him to avoid sports and other activities that would test his balance, counsel that the crewmember disregarded in favor of playing basketball with his son. "He said, 'You were right. I went for a jump shot and didn't know how I was going to get back down, and I ended up in a pile on the driveway,'" Paloski recalls, noting that the astronaut became disoriented as soon as he lacked information from the bottom of his feet.

Shuttle crewmembers typically made a full recovery in anywhere between 12 hours and two or three days, but it's not unusual for astronauts who spend months on the space station to take more than a week to fully readjust to gravity.

To observe space-induced balance disorders, NASA uses a technique called computerized dynamic posturography (CDP). Prototyped in the 1970s by a Massachusetts Institute

NASA astronaut Anne McClain is carried from the landing site after returning from more than 200 days on the space station in 2019. It can take astronauts more than a week to fully regain their balance after extended stays in space.

For decades, NASA flight doctors have used a technique called computerized dynamic posturography to assess astronauts' balance after stays in space. Moving visual cues and a shifting platform challenge the subject's equilibrium. But a system of this size wouldn't be practical for a mission to the Moon or Mars.

of Technology (MIT) graduate student, based on earlier NASA-funded MIT studies, CDP tests a subject's balance in a controlled environment, moving a platform and visual cues to challenge the subject's equilibrium. It's a standard diagnostic technique today, and flight doctors at Johnson still use it to determine when returned astronauts are ready to go back to their normal duties.

About the size of a phone booth, the system would not be practical for a lunar or Martian surface mission, though, so in the mid-2000s, Paloski and colleagues started looking for other methods. Another MIT graduate student, Erez Lieberman Aiden, happened to be an intern at the Neurosciences Laboratory at the time, as was Katey Forth, then a post-doctoral researcher.

As the team worked to gain a better understanding of how the brain controls balance, Paloski says, "we discovered a lot of patterns of the brain searching for information from the bottom of the feet." They thought they might use that same information to measure balance. Using multiple pressure sensors under a subject's feet to passively monitor pressure distribution was simple enough. Then Lieberman Aiden, whose expertise was in mathematics, figured out how to apply known algorithms to those pressure distributions over time to quantify postural stability, with no need to challenge the vestibular system, Paloski says.

It was an entirely new technique, based on a new model of postural control. In 2008, the three filed for a patent, which was granted in 2011. By the time the patent was filed, Forth and Lieberman Aiden had founded a company and were working to turn the technique into a commercial product.

Technology Transfer

Forth recalls talking with Lieberman Aiden over lunch at Johnson and realizing that the ability to detect patterns of balance instability could have wide applications. Both of them had grandmothers whose health and quality of life had permanently declined after a serious fall. "We knew first-hand that if we could prevent falls, we could really impact people's lives," she says. "That was the beginning."

> "With our technology, we're really trying to empower people with insights far beyond what they know about themselves and what others know about them."
>
> — Katey Forth, Zibrio Inc.

At first, they worked to develop shoe insoles. Formed at the start of the global recession, though, the company foundered. It resurrected in 2015 under the name Zibrio Inc. "By 2015, Fitbit had turned up," Forth says. "People were more receptive to the idea of gathering data about themselves." And with older baby boomers about to turn 70, she adds, the timing couldn't have been better.

While NASA and MIT have a joint invention agreement around the technology, MIT manages the patent, which Zibrio, based in Houston, has licensed exclusively.

Instead of insoles, the company designed a product that looks like a bathroom scale. "A scale was a much more familiar form factor, and we didn't think 70- or 80-year-olds were ready to plug in their shoes," Forth says. There would be a home version and a clinical version for medical facilities, and the devices would assign users a fall-risk score between 1 and 10, with 7 and up indicating low risk and 1 to 3 meaning high risk.

In 2018, the company took its technology on the road, testing more than 500 seniors at home, in senior living facilities, and in hospitals, a representative cross section of the older population, Forth says. The company found that its algorithms could actually predict the likelihood of a fall.

Zibrio released its home version at the National Senior Games in June of 2019, with the clinical version due for release around six months later.

Based on a new technique pioneered in Johnson Space Center's Neurosciences Laboratory, the Zibrio balance scale assesses balance by applying algorithms to changes in pressure distribution over the course of a minute. The company found it could even predict a subject's likelihood of experiencing a fall.

Benefits

A person's balance is by no means fixed and can be influenced by anything from balance exercises to changes in medication, sleep, diet, mood, and activity level, Forth says. An app for the consumer version of the balance scale lets users explore possible causes and solutions for balance issues. "The SmartScale gives you a score and then, through the Zibrio app or with a physician, you can deep-dive into what's helping and hurting your balance." The app generates a personalized plan for improvement.

Just knowing one's risk level can be a major advantage. As the company was conducting tests, Forth says, a balance scale got left at a senior living facility, and falls there subsequently dropped by 50 percent. Without a control group, she notes, it's hard to make strong claims based on the experience, but it seems clear that residents were taking action based on their scores, whether that meant taking the balance class that was available at the facility or making other changes.

Meanwhile, in the more rigorous studies, users who weren't told their score were found to experience falls at the expected rate, given their scores. That predictive power is unprecedented, Forth says. "Currently, the best indicator of whether you'll experience a fall is whether you've already fallen. I think we can do better in this day and age."

The balance scale isn't just for the elderly, either. It could be useful to anyone trying to improve their physical performance, Forth says, noting that balance indicates the functioning of not just the vestibular system but also the overall nervous and musculoskeletal systems. "Your balance doesn't just go when you're 80, and we can detect changes in 20-year-olds and 30-year-olds," she says. "With our technology, we're really trying to empower people with insights far beyond what they know about themselves and what others know about them."

The clinical version provides an even larger package of information to guide physicians' recommendations.

"We want to be the gold standard of balance measurement," Forth says, noting that no widely preferred method has even existed. "We want to be in every doctor's office."

The simplicity that lets it test balance without provoking a fall has also helped make it affordable, with the consumer version running $249 and the clinical scale priced at $499. NASA's CDP booth, meanwhile, runs about $70,000.

Forth credits NASA with creating the opportunity to take a new approach to an old problem. "The Johnson Space Center work is the core of everything we're doing. Now we're bridging the gap between the science and how to help people." ❖

Low-Outgassing, Space-Grade Coatings Cover Electronics, Sensors, Pacemakers

NASA Technology

You might open a window after painting a room, or let a foam mattress air out before sleeping on it so the materials can off-gas and odors will blow away and disperse. Getting rid of compounds that outgas in space isn't so simple.

If coatings or other materials outgas, as the phenomenon is commonly called, in the vacuum and extreme temperatures of space, weights can change, throwing off flight calculations, and the gases can resettle, coating nearby surfaces with a film, potentially obstructing sensors, cameras, and other optical equipment.

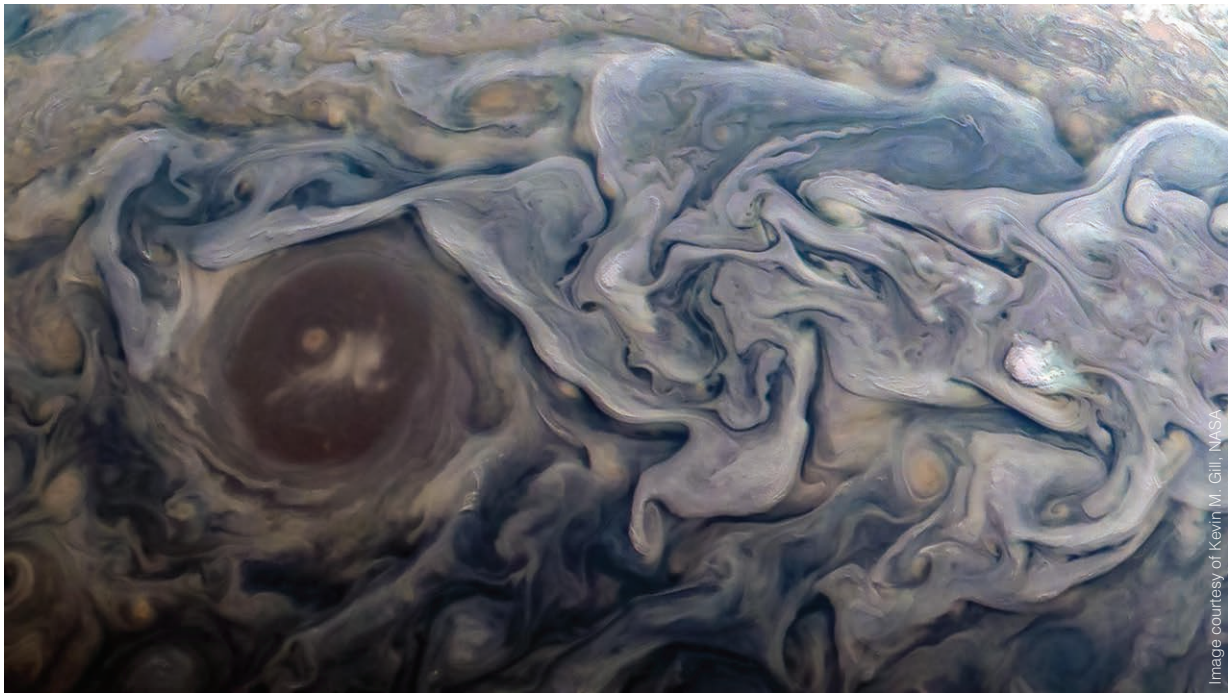
This is why NASA has been testing substances for outgassing since 1967, compiling a publicly available database with tens of thousands of entries for low-outgassing materials suitable for space. (Some materials have been tested multiple times to ensure accurate data and to allow for changes in formulations of the materials over time.)

The Outgassing Lab in the Materials Engineering Branch at Goddard Space Flight Center tests any material under consideration for a NASA project, upon request, and adds the test results to a database maintained by the branch, where anyone looking can find them. And people do look.

"Although we don't track usage of the database, whenever the database or the website is down for maintenance or updating, we do hear from people wanting to know what's going on and when will it be up and running again," says Alejandro Montoya, who heads the Materials Engineering Branch.

Tim Seifert, aerospace and defense market manager at Indianapolis-based Specialty Coating Systems Inc. (SCS), says the database lends credibility and specificity to the materials it lists, including SCS' Parylene coatings.

"NASA has tested and verified several Parylene variants and published the findings, and they are, indeed, low-outgassing coatings," Seifert says, noting that anyone looking for a coating with these properties can view the results for Parylenes in the database.



Dramatic atmospheric features in Jupiter's northern hemisphere are captured in this image created using data from the JunoCam imager aboard the Juno spacecraft. A Parylene coating on the camera's circuit boards helps JunoCam withstand intense magnetic fields and radiation to capture high-resolution images of Jupiter's cloud bands, polar regions, and auroras.

Technology Transfer

The database lists 10 varieties of Parylene that NASA has tested since the mid-1980s, including, most recently, in 2015, a version with an SCS-proprietary adhesion promotion technology.

Parylene coatings are ultrathin and pinhole-free and fully conform to components through molecular-level polymerization—they essentially "grow" onto a surface, one molecule at a time, according to SCS. They have excellent moisture, chemical, and dielectric barrier properties and remain stable in a variety of extreme conditions, making them useful in the electronics, aerospace, defense, transportation, and medical device industries.

They have been used in numerous NASA applications, including on the Juno spacecraft, which launched in 2011 and has been orbiting Jupiter since 2016.

Specifically, a Parylene coating on the circuit boards of the JunoCam, a camera mounted to the body of the spacecraft, protects them from damage, helping the camera perform up to specifications.

JunoCam's goal is to engage the public in the Juno mission to investigate the origin and evolution of the fifth planet from the Sun. The camera captures high-resolution images of Jupiter's cloud bands, polar regions, and auroras—withstanding massive magnetic fields and a powerful radiation belt to do so.

The camera and the coating have held up.

To measure the outgassing of materials such as Parylene coatings, NASA uses a standardized method developed by the American Society for Testing and Materials (ASTM).

Jeremy Knipple, who has been conducting the tests at Goddard since 2014, places samples in a chamber, draws a vacuum, and then keeps the chamber under high heat for 24 hours, as required by the ASTM method.

Before and after the tests, he places the samples in a humidity chamber at 50 percent humidity to see how much of the lost mass is regained just from surrounding humidity—a way of gauging how much mass loss is simply water vapor.

Knipple then reports a series of data points, including total mass loss and the amount of volatile condensable materials he collects.

In the case of Parylenes, the NASA tests provided new information for those using the materials, as well as potential users. "We didn't have any outgassing data prior to this, but Parylene coatings have long been known in the industry as a space-grade material," says Seifert.

"The ability to be part of the outgassing database certainly was helpful to us, and, more importantly, it's helpful for people who are looking for materials to use when they're considering reliability while designing applications."

Applied in a vacuum with equipment like this device from Specialty Coating Systems Inc., Parylene coatings conform completely to the surfaces they cover.

Benefits

Parylenes' ability to conform completely to the surfaces they cover make them ideal coatings for circuit boards and other electronics to prevent corrosion—particularly, but not only, in the harsh environment of space, where they have been used for decades.

A Parylene coating protects 20 printed circuit boards on the Japanese spacecraft Hyabusa2, which, in February 2019, touched down briefly on an asteroid to collect the first of multiple planned samples before its return to Earth, scheduled for 2020.

Parylenes are also used in emission sensors, fuel cells, and electronics systems in hybrid cars.

The coatings protect numerous medical applications and devices, including pacemakers, cochlear implants, coronary and cerebral stents, catheters, and gastric balloons. They're used in hypodermic and acupuncture needles, as well as surgical tools.

"One of the reasons Parylenes meet ultra-low-outgassing criteria is due to their purity, which, consequently, is a very attractive characteristic for medical applications, contributing to outstanding biocompatibility," says Dick Molin, medical market manager at SCS.

SCS currently has five commercially available types of Parylene, each with differing properties and specifications. Parylene C, the first to be tested by NASA, is the most widely used because it's the best barrier to moisture and gases.

Parylene HT, the most recent type to be tested by NASA, is for the highest-temperature applications—for instance, offshore and down-hole exploration sensors and feedback devices, where outgassing characteristics are usually less of a consideration.

Still, the outgassing tests at NASA have given Parylenes a boost. "It's a way to legitimize, if you will, at the highest level, the value of the coatings," says Molin. ❖

Fiber-Optic "Nerves" Enable Sensitive Surgery Tools

NASA Technology

Can you make a robot feel? That was the question posed to Johnson Space Center engineer Toby Martin.

It wasn't a heart that NASA wanted to give its Robonaut, though—it was tactile sensing for the robot's hands.

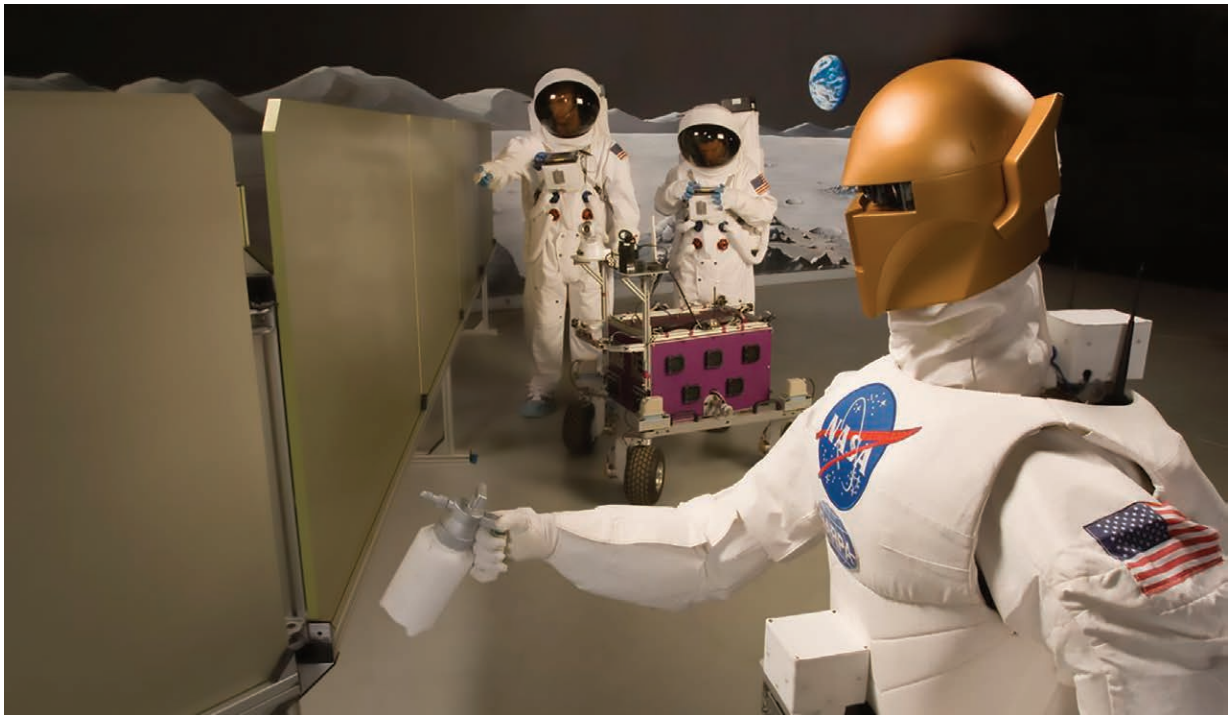
"It didn't have an autonomous grasping capability," Martin says of the first version of NASA's robot astronaut. A control systems specialist, he was tasked in 2004 with looking for a way to give it that ability. "First we had to figure out how to sense when it's grasping something," he says. "We wanted the hand to be able to grab an object and adjust finger forces and positions and tensions to pick up irregular objects."

At least one company that responded to Martin's request for proposals, Intelligent Fiber Optic Systems (IFOS) Corporation, was no stranger to NASA. Much of the Silicon Valley, California-based company's funding to develop its initial technology had come from two Small Business Innovation Research (SBIR) contracts with Langley Research Center a decade earlier.

NASA's SBIR and Small Business Technology Transfer (STTR) programs make relatively small investments in promising technologies that could prove useful to the Space Agency's missions and also show commercial potential.

For the Langley project, the company had proposed developing "smart surfaces" for aerospace materials and other applications by creating what IFOS calls "optical nerves." These are optical fibers with reflective micro-structures called fiber Bragg gratings imprinted within their cores at intervals. A device known as an optical interrogator sends light along the fiber, and each grating reflects back a particular wavelength signature, which changes slightly if there are changes to strain or temperature.

"If you stretch a grating, the wavelength that comes back becomes longer, proportional to the strain," a phenomenon known as red shift, explains Richard Black, chief scientist at IFOS. "If the grating is compressed, there's a proportional blue shift." Similarly, a rise in temperature causes red shift, while a drop leads to blue shift. The IFOS interrogator can detect changes in wavelength on the order of picometers to femtometers, the infinitesimal unit used to measure atoms, which it uses to determine strain or temperature change.



Under contract to Johnson Space Center, Intelligent Fiber Optic Systems (IFOS) developed a system that aimed to give tactile sensing to the hands of NASA's first Robonaut robot. The work improved the capabilities of the optical interrogator that's at the heart of most of the company's systems and improved technology that IFOS has since used to let surgical equipment sense pressure and extrapolate its position in space.

With a series of fibers attached to or embedded in a surface, each with several fiber Bragg grating sensors along its length, the interrogator can monitor strain and temperature across the entire surface, a capability that has a multitude of possible applications across many fields (*Spinoff* 2002).

For Robonaut's hand, the company proposed that its technology could determine the position of each finger in real time by measuring the strain that comes with bending, and if it took readings fast enough, it could even detect vibrations and textures.

Technology Transfer

"I was kind of dubious that it would work for our application, but I was intrigued," says Martin. "It provided many of the benefits of strain gauges without some of the negatives, like external electrical noise and interference. With several gratings per fiber, the density of sensors that could fit into a small space was also a plus." Johnson granted the company an SBIR contract to explore the concept's feasibility. To

avoid rebuilding the hands, NASA asked for a glove that fit over the existing hands.

At the time, IFOS was still using much the same interrogator it had developed for Langley, supporting no more than 10 sensors. To outfit an entire hand requiring many more sensors, though, the company made a fundamental change by developing a scalable architecture that produced an enduring improvement in its sensing capabilities, says Black.

With Johnson funding, the company took an optical chip concept made for telecommunications applications, modified it for its massively parallel sensing architecture, and worked with a foundry to customize a photonic spectral processor—a single chip with many waveguides stamped into it. The processor acts like a prism, sending different parts of the spectrum to different photodetectors in an array. The interrogator monitors changes in the ratios of various spectral components simultaneously to allow precise determination of the sensor wavelengths.

The ability to monitor multiple sensors simultaneously allows for much faster readings, which is important for detecting, for example, the tiny, rapid vibrations caused by friction with a textured surface.

The glove didn't work well due to misfires caused by wrinkles and other issues, says Martin. Under a Phase II SBIR contract, however, IFOS and the Mechanical Engineering Department at Stanford University developed their own finger prototype. "We tested it and verified the experiments the company had run showing it worked," Martin says. At the time, both the finger prototype and the interrogator were too large to incorporate into a human-sized hand.

That was as far as the project went, but someone from the Johnson team pushed Behzad Moslehi, the company's chief executive and chief technology officer, to pursue funding for possible medical applications through the National Institutes of Health (NIH), he says. "I looked into it, and I found it was the right home."

Benefits

IFOS has since found a multitude of possible medical applications for its fiber-sensing technology.

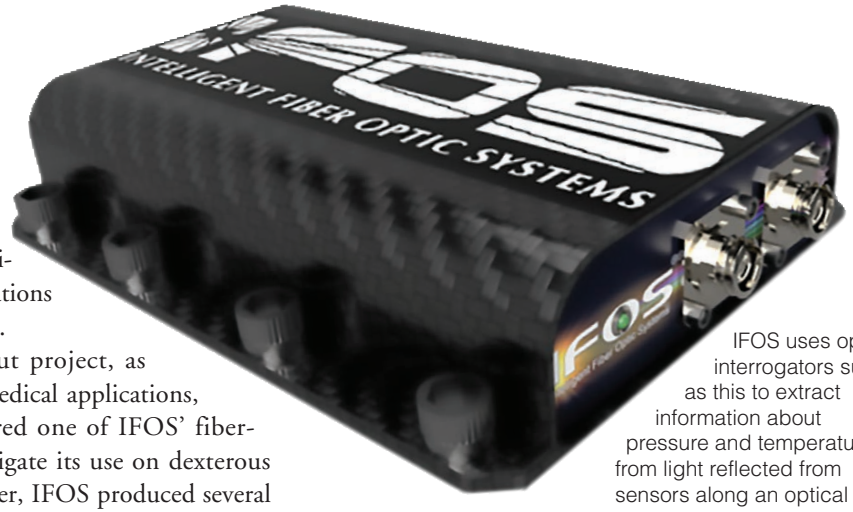
Shortly after the Robonaut project, as the company was exploring medical applications, Intuitive Surgical Inc. acquired one of IFOS' fiber-optic sensor systems to investigate its use on dexterous surgical robots. A few years later, IFOS produced several instrumented grasper assemblies with haptic sensing for a medical application Samsung was evaluating. Moslehi says he sees the medical robot market as an opportunity for the company's future, through strategic partnerships with other companies.

Closer to commercialization are instrumented biopsy needles that surgeons can use in conjunction with both MRI and ultrasound machines. Stanford has been collaborating with IFOS through its engineering and medical schools to evaluate and test the technology on animals in the MRI environment.

Tools used in real-time MRI-guided surgery—where the surgeon is either reaching into the MRI machine or working remotely from a control room—must not react to magnets or use electricity, Black says. "Optical-fiber sensors are ideal for the sort of sensing we're doing." But such a needle is almost invisible in the MRI image.

"We came up with a way to measure the shape of a biopsy needle in real time, down to the tip of the needle, and superimpose the precise shape over the blurry artifacts from an MRI," he says. This lets surgeons see what they're doing.

The tool can also measure forces on the tip, which relate to tissue hardness. This provides another clue for surgeons, as tumors are typically harder than the surrounding tissue. The team is working on providing haptic feedback, such as a joystick for remote surgery that vibrates according to strain on the needle.



IFOS uses optical interrogators such as this to extract information about pressure and temperature from light reflected from sensors along an optical fiber.

A catheter for sucking up fluids during surgery would work much the same way.

The company has successfully tested the technology on pigs but has yet to go through clinical trials and FDA approval, so the operating room is still a ways off. IFOS is also working with Civco Medical Solutions to develop needles with optical fiber sensing.

Meanwhile, at the University of Calgary, another team is working on a similar device for MRI-guided neurosurgery, known as NeuroArm. IFOS sold the team an interrogator and outfitted a pair of surgical forceps with its fiber-optic sensors.

Sleep centers at Stanford and at the University of California, Los Angeles, are collaborating with IFOS on a device to monitor sleep apnea with a real-time pressure profile of the airway, and the company has a proposal pending with NIH for similar technology to monitor male incontinence.

In all these applications, fiber-optic sensing allows for a thinner probe or surgical tool and uniquely high-resolution, multi-dimensional mapping.

In another project, the company is building on its robotic-hand experience to work with the NIH and George Mason University to develop a robotic prosthetic hand that combines IFOS' fiber-optic sensors with ultrasonic imaging technology that senses the activation of finger-specific muscles in the forearm. This lets the user control the fingers with high precision.

This prototype hand IFOS developed for Johnson can sense when it's grasping something and adjust finger pressures and position to grasp irregular objects.

More-recent NASA work will also likely lead to commercial applications in medicine and beyond. Under recent Small Business Technology Transfer (STTR) funding from Goddard Space Flight Center and Johnson, IFOS and Stanford are collaboratively developing specialized photonic integrated circuits (PICs), in this case for a "lab-on-a-chip" device to monitor concentrations of biochemicals such as protein and creatinine in animals and humans, including astronauts. The technology is similar to electronic integrated circuits, with a light source and various optical tools densely interconnected within a chip smaller than a fingernail.

"It's like a miniaturized, specialized photonic computing device or signal processor," says Moslehi. "And it works at the speed of light."

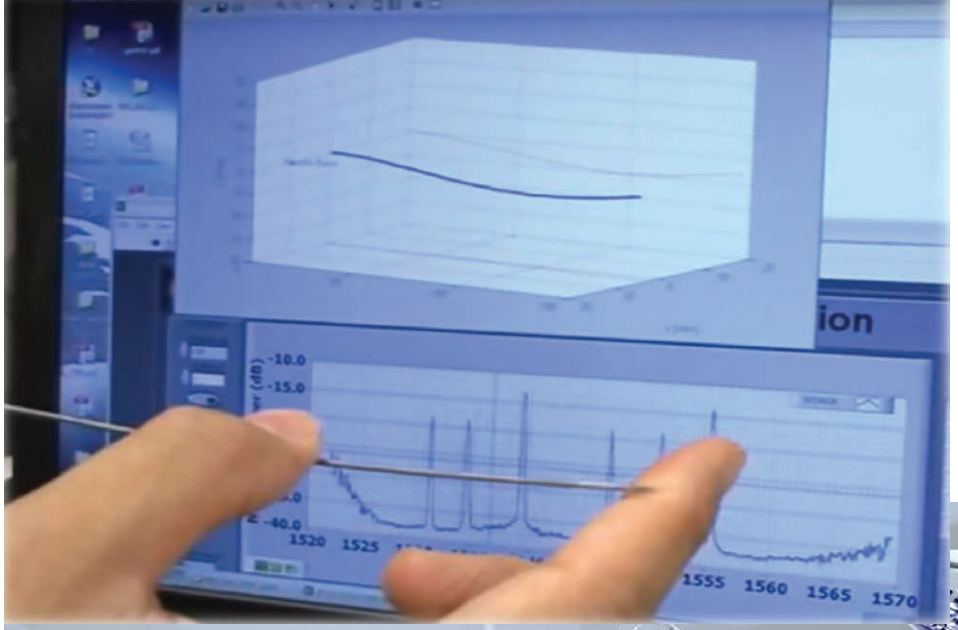
IFOS is already working with several PIC foundries to fabricate the optical chips, which could find a multitude of uses.

Black notes that, while the interrogator used in the Robonaut work was desktop-sized, the one now being used for surgical devices is half the size of a shoebox. The company is working to reduce that to the size of a smartphone.

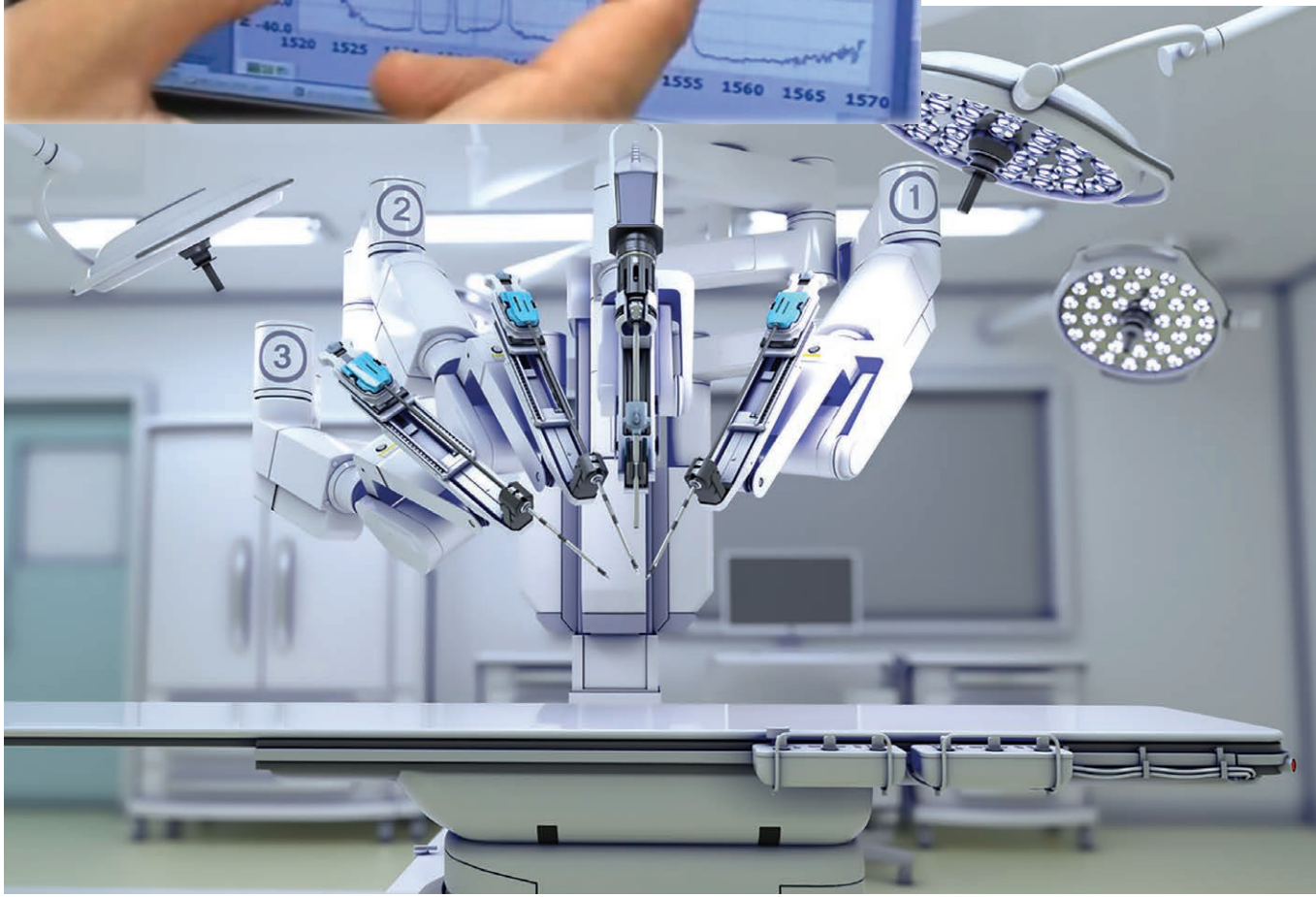
In the early days, says William Price, IFOS' strategic programs manager, "the cost to build a high-performance interrogator was a significant limiting factor, but IFOS is continually working to reduce costs." IFOS recently completed beta testing and will soon launch a family of interrogators priced under $10,000, a fraction of the price of its first interrogators, he says, noting that he expects these new products to open up new applications for fiber-optic sensing beyond the medical industries. They will complement IFOS' other high-performance interrogators for acoustic and vibration measurements.

Moslehi says NASA in particular, as well as other Federal agencies, has been instrumental in providing the funding needed to develop the company's technology innovations into products since the beginning. "Certainly, in the early days when IFOS was still run out of a garage in Silicon Valley, NASA funding was what helped us take off and develop this technology," he says.

Many of the projects since then, intended for use in spaceflight, rocket testing, atmospheric reentry, and other extreme environments, have kept that technology robust, reliable, and cutting-edge. ❖



This surgical needle prototype IFOS made can sense its position along its length and also detect changes in hardness. A surgeon working on a patient in an MRI machine, for example, can hardly see the needle in the MRI image. IFOS' technology can superimpose an image of the needle in the body.



IFOS and researchers at a handful of universities are working to apply the company's technology to medical devices, including tools for robotic surgery.

Variable-Gravity Device Enables Medical, Pharmaceutical Research

NASA Technology

Through decades of sending astronauts into space, scientists have learned much about the biological effects of weightlessness. In the absence of gravity, for example, astronauts' muscles and bones lose mass. Their eyes change shape too, worsening their vision. And even their genes express differently.

Still largely unknown, however, are the long-term effects of partial gravity, such as that which astronauts experience on the lunar surface. Such conditions are impossible to create on Earth for any extended time, but government, academic, and industry researchers can simulate precise levels of gravity in a device aboard the International Space Station.

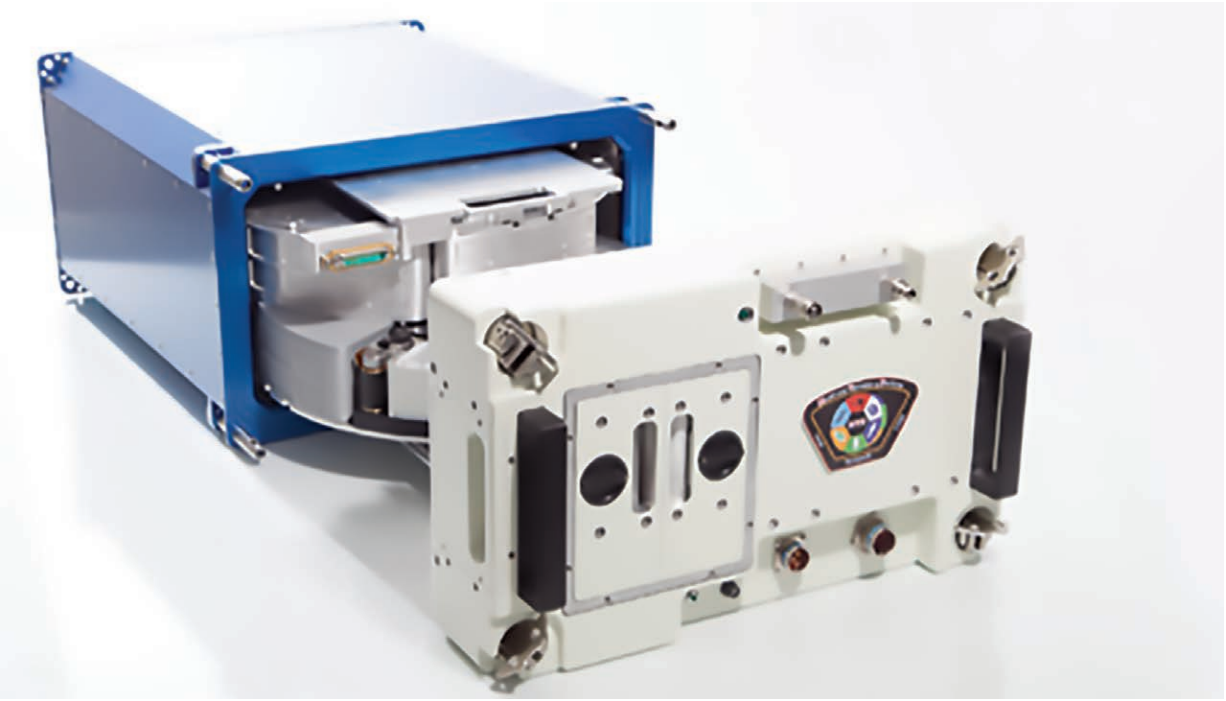
The Multi-Use Variable-Gravity Platform (MVP) that Greenville, Indiana-based Techshot Inc. built for NASA, which arrived at the space station in spring of 2018, uses centrifugal force in two spinning carousels to simulate gravity. It's not the first artificial-gravity machine in space, but it is the most advanced and versatile yet.

Using funding from Small Business Innovation Research (SBIR) contracts, Techshot built a similar device in the late 1990s to observe the effects of gravity on the development of Japanese quail embryos. Under the same project, other companies worked on similar devices tailored to different types of specimens, such as mice, fish, and cell cultures.

Techshot built its new multi-gravity platform with the goal of housing any of these types of experiments in a single device. "This updates the capabilities of the heritage item we flew back in 2001, which could only accommodate one type of sample," says Rich Boling, Techshot's vice president. Rather than building custom machines, the company now uses custom modules that snap in and out of the system's two carousels. The modules can be specially designed to hold cell cultures, plants, microorganisms, fish, and other life forms.

In a 2018 demonstration, the MVP successfully housed a fruit fly population on the space station. "We got lots and lots of fruit flies," says Marybeth Edeen, manager of the ISS Research Integration Office at Johnson Space Center. "Everybody lived, through multiple generations."

Fifty flies went up in each of the device's 12 chambers. Thousands made the flight back to Earth.



Techshot's Multi-User Variable-Gravity device, about the size of a microwave oven, contains two carousels that spin at varying speeds to simulate different forces of gravity. Modules designed for specific experiments can be snapped in and out.

Technology Transfer

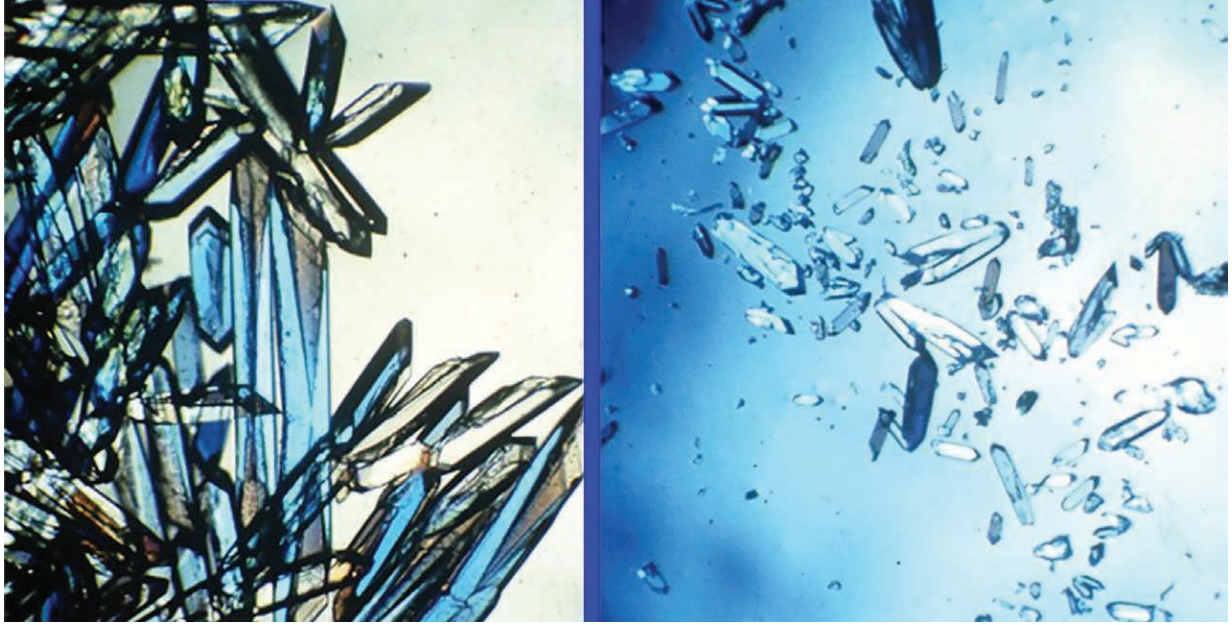
Edeen helped Techshot design the MVP to meet various researchers' needs, based on NASA's experience. For instance, plant specimens will require an ethylene scrubber to stay healthy in zero gravity. And infrared cameras allowed scientists to observe the fruit flies in the dark while they slept.

The MVP is one of a suite of devices the company is creating for space station research under a Space Act Agreement with Johnson. It was funded in part by SBIR contracts with Johnson , matched by funds from the Center for the Advancement of Science in Space (CASIS).

"They recognized the MVP as a tremendous capability for commercial researchers," Boling says of CASIS.

The device can simulate any level of gravity between weightlessness and 2 G, or twice Earth's gravity. Its modules are outfitted with lighting, video cameras, microscopes, and oxygen and carbon dioxide sensors. Pumps, valves, and bags in the little chambers allow for sample collection. Hardware can be added or removed according to the needs of individual experiments.

Temperature and humidity are kept steady throughout the entire system, although Boling says future modules may be able to regulate these individually. The entire MVP



Gravity can have surprising effects on basic biological products and processes. For example, protein crystals grow much larger in the absence of gravity, making it easier to analyze a protein's structure. The bovine insulin crystals on the left were grown in space, while those on the right formed on Earth.

is about the size of a microwave oven and fits in a single locker on the space station.

Any customer, including NASA, pays Techshot for use of the facility. The company expects the Space Agency to account for about half of that business, with the rest coming from industry and academic researchers.

Benefits

Boling notes that the MVP serves a function that was always intended for the space station. A planned Centrifuge Accommodations Module was canceled in 2005, and the European Modular Cultivation System, which also used rotors to simulate gravity between 0 and 2 G, was used almost entirely for plant research until it was decommissioned in 2018. "That leaves the Techshot MVP as the go-to artificial gravity device," Boling says.

NASA's biggest interest in simulating partial gravity is in understanding how gravity on the Moon or Mars, being far weaker than Earth's gravity, would affect astronauts or crops, Edeen says. For human research, scientists use stand-in life forms of the lowest possible order. For example, a fruit fly has a cardiac system that responds to altered stimuli roughly as a human's would.

In particular, scientists want to understand whether all responses are directly proportional to any gravity level, Edeen says. "Is it a straight line between the two points? An S-shaped curve or an exponential curve? Does it level out at 1 or 1.5 G?" she wonders. "No one knows how organisms respond to other levels of gravity." For example, she says, if partial gravity is enough to prevent bone and muscle loss, adding just a slight spin to a spacecraft could provide enough artificial gravity to counter those effects.

Other researchers, however, want to understand how gravity masks certain biological processes, Boling says. "They really are working to make life better on Earth by looking for a better understanding of biological processes," he says, noting that such insights could help manipulate processes like metabolism and cell and tissue repair on the ground.

The improved structures of protein crystals formed in zero gravity is another phenomenon pharmaceutical companies want to explore and indeed has already led to a better treatment for hepatitis C. Experiments on protein crystallization that Schering-Plough Research Institute carried out in the space shuttle produced a structure of protein that was better at fighting the disease and caused fewer side effects.

> "No one knows how organisms respond to other levels of gravity."
>
> — Marybeth Edeen, Johnson Space Center

Boling says the MVP was already booked for months after the fruit fly demonstration. Medimmune, a subsidiary of the biopharmaceutical company AstraZeneca, was slated to fly an experiment. The Massachusetts Institute of Technology and the National Institutes of Health were preparing research using "tissue chips," plastic and fluidic chips that imitate various human tissues. NASA was readying an experiment on the solidification of cement mixtures in Martian and lunar gravity.

The artificial gravity device is "a great capability that allows us to do different kinds of research and will keep us using the space station for technology development, exploration research, and fundamental science," Edeen says.

"I feel like the American people are really getting their money's worth if we can develop an on-orbit capability that helps AstraZeneca develop a new drug treatment," Boling says. "I think everybody wins."

Techshot, which has opened an office at Kennedy Space Center, where many of the space station resupply missions launch, handles all the logistics for its MVP customers, from paperwork to executing the experiments to sending results and returning samples.

The company is also in various stages of putting several other devices onto the space station, all of which will be available to researchers outside NASA. These include a similar centrifuge for rodents, a 3D bioprinter capable of printing organs from stem cells, and another device capable of 3D printing metals and electronics.

"The space station is just so remarkable," Boling says. "It's a magical place that lets people think differently about human health and even pharmacology." ❖

Space Station Research Platform Paves the Way for Zero-G Manufacturing

NASA Technology

Much of the research NASA does on the International Space Station is designed to better understand how to work and live in zero gravity to help plan for longer crewed missions deeper into our solar system. But the space station also offers a platform for research with a very different goal: learning how to take advantage of a zero-gravity environment to benefit people on the ground.

It's the latter concept that motivates a small start-up called Space Tango, and the company is well on its path, already selling lab space in orbit and making plans for an orbiting factory.

The company's TangoLabs are located in the U.S.-operated National Laboratory on the space station, explains Mike Read, who manages NASA's Commercial Space Utilization program for the space station from Johnson Space Center. "They have developed a plug-and-play modular system for doing research on the station," he says. The units are self-contained but connect to power and data networks on the space station through the EXPRESS racks (which stands for Expedite the Processing of Experiments to Space Station) in which they are installed.

U.S. astronaut Drew Feustal, left, displays TangoLab hardware on the space station alongside German astronaut Alexander Gerst. There are currently multiple TangoLabs installed in the U.S.-operated National Laboratory on the space station. Each house experimental modules called CubeLabs, which enable zero-gravity research in plant biology, microbiology, medical device manufacturing, and more.

They're hardly the only player selling lab space on the space station (see, for example, *Spinoff* 2012, as well as page 36 of this book). NASA is actively supporting and partnering with such companies to expand commercial access to and interest in microgravity. In fact, in 2010 Congress mandated that half of the National Laboratory's resources be made available to entities outside NASA, including commercial, academic, and governmental organizations.

Read says NASA stands to benefit in the long term from all this commercial activity. "NASA is always going to need to do research and technology development in microgravity. We won't send a crew to deep space without them having been in space. We won't fly environmental control systems without testing in microgravity. Not going to happen," he emphasizes. "Having said that, if there are no other users of microgravity, of the next platform, then we are left holding the bag to pay all of the cost. And that's not tenable."

Technology Transfer

Space Tango was founded in Lexington, Kentucky, by then-graduate student Twyman Clements in 2014, in partnership with then-Kentucky Science and Technology Corporation chief executive Kris Kimel. The company sent its first TangoLab to the space station just two years later, and by 2017, had a second one installed as well.

In 2017, the company also signed a Space Act Agreement with NASA to work with safety and engineering groups at Johnson to vet their designs and improve safety, particularly in regard to electrical systems. The space station is "very sensitive with electronics, in how you draw power but also how much electromagnetic interference you radiate," Clements explains. He says the company's designers worked closely with NASA engineers and planners to better learn

how to work within safe parameters. "We couldn't be here without some of those people's patience and help."

Read notes that Space Tango is already one of the more commercially diverse companies in the National Laboratory. Where many of the other lab platforms are contracting mainly with NASA and government agencies, he says, "Space Tango is actively doing business development, and they are bringing in people who maybe haven't done spaceflight before. It's pretty unique and pretty fun to watch them evolve and grow."

Space Tango launches CubeLabs, which hold experiments and slot into the suitcase-sized TangoLabs on station. The company designed the CubeLabs as an open source platform so any researcher could develop an experiment using their platform, but Clements says most customers have preferred to work with Space Tango to do the required engineering and scalable design.

Since the experiments must be essentially autonomous once in orbit—an astronaut transfers the CubeLab from the launch vehicle to the TangoLab, but after that, any monitoring is done through the internet connection from the ground—everything must be carefully planned in advance. For example, Clements says, some biological experiments need power to move fluids and condition growth media. "Typically we build everything in-house. We write the code, machine the parts, design the circuit boards. Everything."

Space Tango's Gentry Barnet (back) and Paul Kuehl (front) prepare a CubeLab to host a tissue chip investigation that launched in 2019. The company has delivered more than 100 experiments to the space station for clients ranging from high schools to nonprofits to research groups to Fortune 500 companies.

Image courtesy of Slicked Media for Space Tango

Benefits

As of mid-2019, the company had launched over 100 experiments for clients from all kinds of backgrounds, Clements says. "Everything from high schools to nonprofits to research groups to Fortune 500 companies."

Among the more notable names on the Space Tango client list is Budweiser—yes, the beer company. "It's marketing, but it's also science," Clements says. The company launched a research project to look at how microgravity affects the growth of barley, one of the core ingredients of beer, all in the service of eventually becoming the first beer in space.

Other customers have done research into materials manufacturing, biomedical devices, flow chemistry, and more. But research isn't Space Tango's big-picture goal, Clements says—manufacturing is. "What we're trying to do is create use cases for scalable manufacturing," where the microgravity environment adds value.

For example, one customer, Lambda Vision, is building retinal implants. Fabricating the implants requires very even, very thin layers, or the patient getting the implant won't be able to see clearly. However, the layers take time to bond, and on Earth, Clements explains, gravity creates a settling effect that makes the coating uneven. So even though launching to orbit adds significant cost, the benefits of microgravity for manufacturing small but very high-value items like these could outweigh that.

"The goal for the TangoLab contract is to test out the new automated process we helped them develop. And then later they might use the process to produce the implants on a commercial scale," he explains.

For that, they might use a new system Space Tango has in the works. The company is building an orbiting platform called ST-42, which would be independent of the space station and allow for larger-scale manufacturing.

To keep costs down, it wouldn't stay in orbit. Instead, it's a capsule that would "go up, run its operations and return," Clements says. With the expansion of the commercial launch industry and reusable rockets, the cost of getting to space is going down. The company is planning the first launch in the mid-2020s, and says the financial forecasts they have done look good.

"Space is really a means to an end," emphasizes Clements. "And so we use space to create these things—retinal implants, fiber-optic cables—for the benefit of Earth." ❖

Transportation

Space travel is the most daunting travel humans have undertaken. The need to minimize weight and to create and optimize new vehicle designs, for example, has led to innovations in software and materials that are useful in many fields. NASA also develops technology that helps the private sector follow it into space, where companies are putting satellites into orbit and preparing to venture deeper into the solar system.

Pressure Vessels Improve Transportation of Liquid Fuels

NASA Technology

Few people will ever pass a rocket on the freeway, but anyone could soon see the "gas tank" of a liquid propulsion engine outside the passenger window. That's because a modified design of this unique fuel tank, called a composite overwrapped pressure vessel (COPV), was approved by the U.S. Department of Transportation for use on American roads.

Pressure vessels, used in everything from spacecraft to gas grills, hold and dispense liquid or gas under pressure. Most, like the propane tank underneath your grill, are made entirely of metal and are heavy, but COPV technology promises to improve on that standard. A COPV uses only a thin metal lining to contain its contents, over which a composite fiber is wrapped. The composite provides most of the tank's strength, and because composites are much lighter and stronger than the metals they replace, COPVs can hold contents at higher pressures than their all-metal counterparts. This means that a lighter and smaller tank can hold the same amount of gas as a larger, heavier metal one—or that a similar-sized COPV can hold more.

NASA pioneered COPVs in the 1960s and '70s (*Spinoff* 2019), but advances in composite materials and improved manufacturing in the '80s and '90s inspired Tom DeLay to investigate ways to make a better COPV. Working in the Materials Lab at Marshall Space Flight Center, DeLay was the composite manufacturing team leader supporting multiple projects, including experimental airplanes, or X-planes.

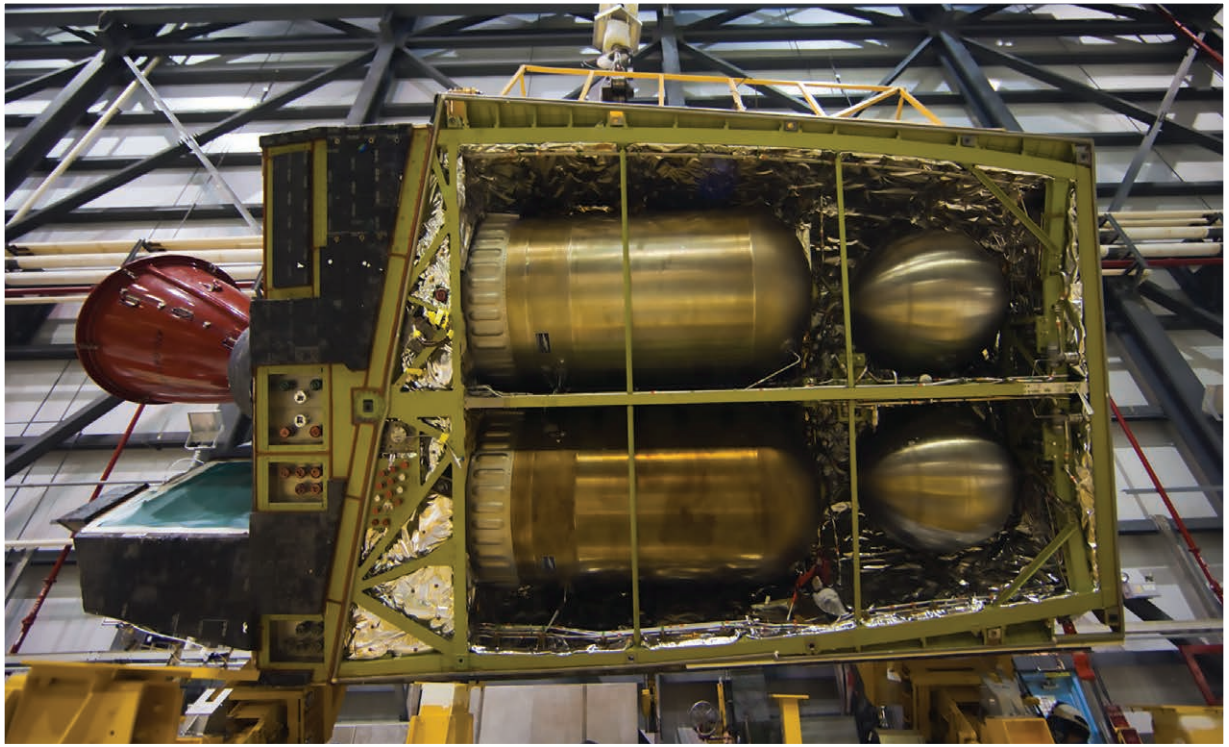
The X-planes testing new technologies at that time included X-33, X-37, and X-43A, and they all needed the same thing—a lightweight tank for high-pressure gases. The higher the pressure, the more fuel a tank can hold. The more fuel a plane can carry, the more it can accomplish in a single flight. DeLay also saw that a better COPV could benefit liquid propulsion rocket engines such as those used in the space shuttle.

Early designs used a metal cylinder, usually made of steel, aluminum, or titanium. The overwrap was a fiber soaked in a resin or epoxy. The fibers provided tensile strength for structural integrity, while the resin carried shear loads in the composite and secured the position of the fiber over the vessel exterior.

The first resin-soaked material was fiberglass, but that soon gave way to lighter options such as Kevlar and carbon fiber. The resin or epoxy used to soak the fibers has also changed over time. Different "recipes" were developed to meet different requirements.

NASA patented the original COPV designs and funded a business to perform additional testing and create prototypes, resulting in commercial hybrid tanks leveraging the durability and strength of carbon fiber to overwrap an aluminum liner (*Spinoff* 2004). This new pressure vessel proved useful in a number of industries, including storage systems for buses using natural gas, chemical processing, pharmaceutical manufacturing, and offshore drilling, oil production, and petroleum refineries.

Meanwhile, DeLay's continued research and testing at NASA improved the technology, which includes an



NASA stores fuel in composite overwrapped pressure vessels (COPVs)—an early NASA invention—like those in the space shuttle Endeavour's orbiter maneuvering system. A Cimarron Composites version of this technology, called the Jupiter, passed the rigorous testing mandated by the U.S. Department of Transportation for certification to travel on U.S. roads. These COPVs will also carry liquids and gases under pressure. The higher the pressure, the more a tank can hold.

> “There’s a miniature space race going on. The knowledge NASA developed over decades is now filtering into the new aerospace companies.”
>
> — Tom DeLay, Cimarron Composites LLC

all-composite COPV that replaced the metal liner with plastic. In various forms, these updated pressure vessels are a part of many NASA missions, used as storage tanks in the space station and the Orion crew and service modules. Today nearly all NASA missions include COPVs—rockets, launch vehicles, satellites, and landers.

In addition to making him an expert on COPVs, DeLay’s extensive experience inspired him to find new applications for the technology and pursue its commercialization through entrepreneurial efforts.

Technology Transfer

In 2008, DeLay founded Cimarron Composites LLC to take COPV development to the next level. In addition to licensing several of the original patents DeLay worked on while at NASA, the Huntsville, Alabama, company entered into a Space Act Agreement with Marshall in 2018.

“I’ve got some really nice resources at Cimarron related to manufacturing and testing with high-pressure liquid nitrogen,” he says. “But hydrogen testing is very difficult. That’s where the Space Act Agreement is nice—NASA test facilities are unique. They can handle things nobody else can deal with.”

That includes cryogenic proof tests, cycle tests, and all of the testing required for Department of Transportation qualifications of pressure vessels.

Through company work, DeLay created multiple proprietary resin and carbon overwrap systems and invented a new plastic pressure vessel, eliminating the need for the conventional metal lining. The all-composite COPV is slightly different in that the plastic lining is non-load sharing, making the system dramatically lighter. This all-composite COPV was the structure that went to Marshall for liquid hydrogen testing.

This empty, 10-pound Cimarron Composites COPV can hold up to 25 pounds of pressurized liquid hydrogen.

The partnership is paying off for both NASA and Cimarron, according to DeLay. “Government funds paid me to learn all of this, and I created the patents. The licensing and Space Act Agreement fees mean that initial investment is paid back, and then some.”

Benefits

Numerous private-sector space companies are among those taking advantage of the improvements Cimarron is making on NASA technology. The company produces COPVs that routinely fly in a commercial launch vehicle and is developing ultra-light COPVs and composite fuel tanks for several start-up companies building smaller launch vehicles.

“There’s a miniature space race going on right now,” explains DeLay. “The knowledge NASA developed over decades for space applications is now filtering into the new aerospace companies that are popping up.”

Transportation companies in the business of moving highly volatile liquids and gases on Earth can also take advantage of these NASA-derived COPVs. Safely shipping gases such as methane and hydrogen on U.S. highways requires a vessel that has passed the rigorous certification process of the Department of Transportation. The tanks must be able to survive everything from a crash to a gunshot without fragmenting. That makes some of the testing for space seem simple, according to DeLay. Most of NASA’s COPVs are protected—encased in a rocket, inside a vehicle, or in the space station. “On Earth it has to handle all kinds of environments,” he says. “For certification, you have to set it on fire, drop it, and pressure cycle it 30,000 times. It has to last for years, not just a single use as in space applications.”

The Cimarron Jupiter COPV is the only large type-4 composite tube certified by the Department of Transportation. The 30-inch-diameter, 18.5-foot-long plastic tube has a carbon overwrap and can be used for stand-alone transportation. Or it can be stacked with multiple tubes on a trailer, making it possible for a company to haul more fuel in a single load.

Cimarron is currently developing a 7,500-pound-per-square-inch hydrogen tube called Neptune, which will be instrumental in the development of hydrogen fuel cell systems for transportation.

The same need to carry more fuel and save weight is also a priority for the water-borne shipping industry. Cimarron is currently working on a customer request to make COPVs for ships.

“We’re making liquid and gas transportation on Earth safer, thanks to NASA,” says DeLay. ❖

Weight-Estimating Software Helps Design Urban Air Taxis

NASA Technology

Picture an airplane. What you imagine is probably what most commercial airliners look like, a design that has been improved and tweaked—but not really overhauled—for decades.

Modern airliners work well at carrying dozens or even hundreds of passengers from airport to airport. But what if you're designing an aircraft for a different purpose and want something smaller, that doesn't need a runway? Something that could carry a few people from their office to a restaurant across town?

These aircraft may not look like what you're used to. But open the universe of design concepts, and you also open a universe of uncertainty: How will it fly? Is it strong enough? Are the batteries big enough? How much fuel will it need?

Getting quick answers to these questions is relatively easy when designing a new variation of a tried and true aircraft. If it's like a 737 but 15 percent bigger, then you can use mathematical formulas to determine what that will likely mean for other characteristics.

"For aircraft within our scope of knowledge and experience, we can probably estimate within 5 percent what the empty weight of that aircraft would be at conceptual design," says Chris Silva, a research engineer in the aeromechanics branch at Ames Research Center.

But with an entirely new concept, that's much harder. For those, "there have historically been pretty big error bars on how well we can lock down the numbers we come up with in conceptual design," Silva says.

It may seem like a small detail, but weight has ramifications for many aspects of how an aircraft will look and ultimately fly. For one thing, heavier aircraft require more fuel, which in turn adds to the weight. Weight puts more stress on structures, which then might require thicker or stronger materials. And in the worst case, these factors all circle around endlessly until the aircraft is too heavy to get off the ground.

This urban air mobility concept vehicle was designed to carry up to six passengers for up to 75 nautical miles. However, estimating the weight of a novel design like this can be a challenge, in part because a wing with so many rotors faces very different loading conditions than a traditional wing. Thanks in part to NASA funding, M4 Engineering Inc. has designed software that quickly and accurately predicts the weight of structures like this one, helping speed up and improve the design process.

There are ways to make decent weight estimates on conceptual designs, but these methods tend to take a long time and a lot of work, Silva explains. "We wanted to come up with something that's both credible and pretty fast, because we like to be able to look at several things in succession," since the results can help inform decisions about how best to refine the design.

Technology Transfer

That's where M4 Engineering Inc., based in Long Beach, California, came in. The company had already been working on M4 Structures Studio, software that estimates weight for conceptual aircraft designs, when Silva came across them—and NASA was already heavily involved.

Not only had the company received two NASA Small Business Innovation Research (SBIR) contracts to fund early stages of the development, but the program integrates open source NASA code, Open Vehicle Sketchpad (Open VSP), to generate the initial computer model of the design, and another NASA spinoff code, NASTRAN, to analyze the optimization-ready structural analysis model created in M4 Structures Studio.

Although both those tools were already good, M4 Engineering added extra features to make them work even better for their purposes. For example, says Tyler Winter, the company's research and development manager for technology and projects, they added a plug-in to OpenVSP to lay out what they call structural hard points—places on the structure where you might attach something heavy, like an engine or landing gear.

With help from NASA funding, M4 Engineering also built its Sketch Editor, which combines the initial model developed in Open VSP with the structural hard points created in the plug-in and other inputs, and creates a visualization of the internal structural layout. It also allows the engineer to provide all of the necessary structural detail to rapidly generate an optimization-ready structural analysis model.

This model feeds into NASTRAN, he says, which in turn generates the inputs needed to run the weight statement generator. The weight statement gives the total estimated weight of the vehicle and breakdowns for the weight of structural and non-structural components, as well as more fine-tuned weights for different parts of the vehicle. The user can also customize the report, Winter says, for example, if they want to know the weight of a specific subset of components.

The early NASA funding focused on developing M4 Structures Studio for fixed-wing aircraft, but the NASA Revolutionary Vertical Lift Technology project funded a Phase III SBIR contract to extend the software to vertical takeoff vehicles.

Benefits

One of the biggest benefits with M4 Structures Studio is speed, explains Myles Baker, M4 Engineering's president. "When we were doing it manually, it was something on the order of six months to go through the physics calculations to get the weight of the airplane," he recalls.

But with M4 Structures Studio, the process shrinks to just weeks or even hours. "Especially in the early phases of a program, where you're updating things constantly—stretching the wing, stretching the fuselage—to figure out a combination that works, turning those iterations is enormously faster."

He says this can change the entire workflow for design engineers. In the past, they might make their best attempt at a first design, do the analysis, and make improvements, and then repeat that process two or three times over the next year or so, "and hopefully you get something that's good enough, or it gets cancelled."

But with M4 Structures Studio, the feedback comes right away, especially once the initial models are completed. That means "the number of designs you can explore is much larger, and the chances of finding a design that really works are much higher," Baker emphasizes.

Today, M4 Engineering offers the software package as a stand-alone product, but the company also uses it in-house for its consulting business. They are also looking

"The number of designs you can explore is much larger, and the chances of finding a design that really works are much higher."

— Myles Baker, M4 Engineering Inc.

M4 Engineering licenses its weight estimating software, M4 Structures Studio, and also uses it in its consulting for clients. Its customers are working on a variety of novel aircraft designs, including high-altitude gliders similar to this one.

Another customer is Uber, which is using custom-designed M4 Engineering software—developed with expertise created for Structures Studio and including many of the same components—in its Uber Elevate program, which aims to create a system of urban air taxis.

Image courtesy of Uber Technologies Inc.

to put out an academic version for engineering programs at universities and even high schools.

Uber is also a client. The ride-sharing company is using custom M4 Engineering software—developed with expertise created for Structures Studio and including many of the same components—in its Uber Elevate program, which aims to create a system of urban air taxis based largely on electric vertical takeoff and landing (eVTOL) vehicles. "We're working with Uber to analyze Uber's common reference models, such as Tilt Rotor or Tilt Wing eVTOL vehicles, and develop weight prediction methods that apply to some of the most unique features of this new class of eVTOL vehicles that Uber's Partners and network will support," explains Dan Abir, M4 Engineering's director of sales and marketing.

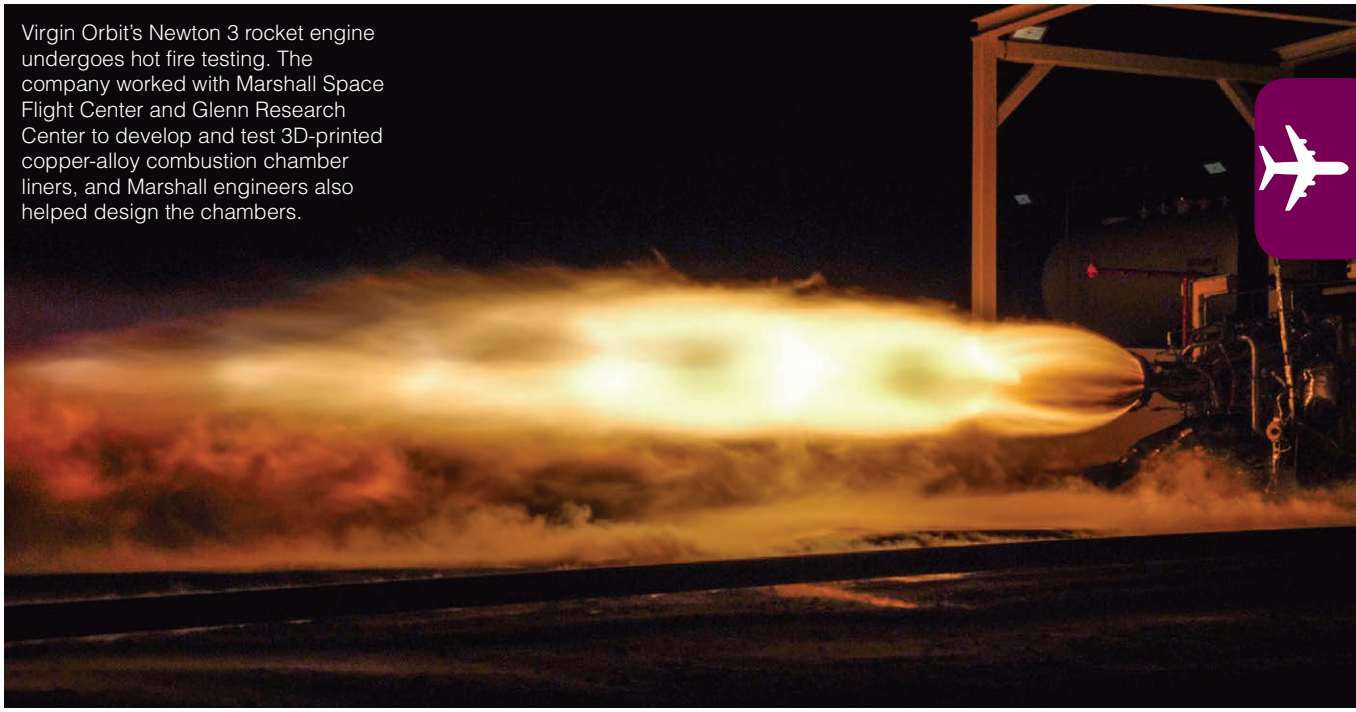
Other customers are working on new designs for supersonic jets, the fast-changing drone industry, and high-altitude platform station aircraft, which are essentially high-altitude gliders, Abir says, most often powered with solar or hybrid energy. These fly lower than satellites but can serve similar functions, for example in relaying communications signals.

Outside of the aeronautics sector, Abir says they have done some work in designing new submarines and even wind turbines. And they are even exploring work with companies interested in designing flying cars—which, unlike Uber's air taxis, would be hybrid vehicles, able to drive on the ground as well as take off vertically and fly.

Abir says it's exciting to see the diverse ways this software is helping create a new air mobility landscape. "We're living in the age of the Jetsons," he says, and with NASA's help, companies like M4 Engineering are helping lead the way into the future. ❖

Plane-Launched Rocket Opens Up Space for Small Satellites

NASA Technology



Virgin Orbit's Newton 3 rocket engine undergoes hot fire testing. The company worked with Marshall Space Flight Center and Glenn Research Center to develop and test 3D-printed copper-alloy combustion chamber liners, and Marshall engineers also helped design the chambers.

More than ever, day-to-day life on Earth depends on the growing number of satellites in orbit used for communications, navigation, tracking, science, defense, and a host of Earth-observation purposes. In 2018, Morgan Stanley estimated the space industry's annual revenue could grow from $350 billion to $1.1 trillion or more by 2040, an expansion driven especially by the demand for satellite-based internet service. SpaceX alone has announced plans to launch a mega-constellation approaching 12,000 satellites, about six times the number of active satellites now in orbit. The advent of CubeSats—tiny, standardized, low-cost satellites built with off-the-shelf parts—has opened up orbit to students, start-up companies, and others.

The cost of launching satellites has fallen dramatically as more companies get into the space business, but even a small rocket launch remains too expensive for small satellites, forcing them to piggyback on larger missions. This inconvenience has been a major restraint on small satellites, the fastest-growing class.

In the interest of making launches more flexible, and getting in on a chunk of the growing satellite business, Virgin Galactic started working on a new approach to satellite launch in 2007, with NASA coming on board as a partner in 2015. The effort has since spun off into Long Beach, California-based Virgin Orbit, which made its first flights to space in 2019. Rather than lift off from a launch pad, its LauncherOne rocket takes off from midair after hitching a ride on a sort of "flying launch pad"—a specially outfitted Boeing 747 airliner.

The partnership between NASA and Virgin began with an Announcement of Collaboration Opportunity (ACO) under the Space Agency's Flight Opportunities program. Under that agreement, work at Ames Research Center included computer simulation and modeling to analyze the aerothermodynamic performance of the airplane carrying the rocket under its wing, as well as the rocket's heat shield. Ames engineers also helped optimize the rocket to carry satellites.

A second ACO, started in 2017, experimented with 3D-printed bimetallic combustion chambers at Marshall Space Flight Center and Glenn Research Center. "Traditionally, propulsion systems have been the most expensive and highest-risk components on a launch vehicle," says Paul Gradl, who was the lead propulsion engineer at Marshall for the project, noting that 3D printing, also known as additive manufacturing, stands to bring those costs down substantially.

Technology Transfer

The effort at Marshall and Glenn built on work Marshall had pioneered in recent years under the Low Cost Upper Stage-Class Propulsion project, developing the tools and processes to 3D print a combustion chamber liner from GRCop-84, a copper alloy invented at Glenn by materials research engineer David Ellis.

The alloy, always intended for rocket combustion chambers, had shown promise in its strength, high conductivity, and resistance to oxidation and fatigue. Producing and processing it, however, had been extremely difficult, costly, and time-consuming, Ellis says, noting that it took six to nine months just to get a block of the material. But making the alloy as a powder and 3D printing it into a component turned out to be only a matter of weeks, he says. "It's almost like it was made for 3D printing, now that we've demonstrated the process."

Marshall and Virgin also experimented with additively manufacturing chamber liners out of two other alloys. Each printed liner was sent for inspection to Glenn, which has a

number of tools and environments for material characterization. "It was an iterative process between Marshall, Glenn, and Virgin Orbit," Gradl says. Marshall engineers, having extensive experience in propulsion systems, helped design the overall chambers.

Under the agreement, Virgin was responsible for hot-fire testing the engine, which run on liquid oxygen and kerosene rocket fuel, but because the company's facilities were booked, Virgin paid Marshall to test the GRCop-84 chambers. Gradl says the testing validated them for even higher temperatures and pressures than they were originally designed for.

The combustion chamber work was still ongoing when the 747, known as Cosmic Girl, made its first test flight with a LauncherOne rocket secured under its right wing near the fuselage by a specialized pylon in November of 2018.

Benefits

By then, Virgin Orbit had received orders for dozens of flights on the rockets and planned to manufacture about two dozen of them per year.

The LauncherOne design is a two-stage, all-carbon-composite, expendable rocket, about 70 feet long and weighing about 57,000 pounds at takeoff, including its payload. It drops from Cosmic Girl at about 35,000 feet and then fires off into space. It can carry single or multiple satellites totaling between about 660 and 1,100 pounds, depending how high it's taking them. This makes it a small satellite launcher by definition in an industry where anything weighing 1,100 pounds or less is considered "small." (For comparison, a GPS satellite at launch weighs about four times that much.)

> "We're really looking to be able to provide flexibility to customers in terms of being able to launch when they want, where they want."
>
> — Sirisha Bandla, Virgin Orbit

For now, LauncherOne can insert satellites anywhere in low-Earth orbit up to about 310 miles, where they can achieve Sun-synchronous orbit. The company is looking for ways to expand to geosynchronous orbit, which is far higher at more than 22,200 miles.

Each launch of the rocket costs less than $12 million. That's not exactly cheap, in terms of cost per pound of payload, but LauncherOne promises something no one else can: a dedicated service that can take off from virtually anywhere, anytime.

"We're really looking to be able to provide flexibility to customers in terms of being able to launch when they want, where they want," says Sirisha Bandla, business development and government affairs manager at Virgin Orbit.

She notes that small satellites have become an established industry in recent years but lacked a convenient path to space. "They've been really restricted in where they can go because they've got to follow a primary payload's orbit and schedule."

Previously, anyone who wanted to launch a small satellite had to find space on a mission that had already been planned and would launch from one of a handful of launch pads, most of them on the coasts. If that mission was delayed, so was the satellite. The orbiter's starting altitude and latitude were also determined by the primary mission, and many small satellites lack the ability to alter their orbit.

LauncherOne ends those limitations. Though it will start out taking off from the Mojave Desert, Cosmic Girl is capable of taking off from any runway—and under any conditions—that any other 747 can, and LauncherOne can place satellites in just about any orbit within its altitude range.

The Department of Defense and commercial launch company Spaceflight Industries are among the customers who have already purchased rides.

Another is NASA: by early 2019, the Agency's Venture Class Launch Services had already purchased a ride for small satellites and CubeSats on LauncherOne. ❖

Cosmic Girl, Virgin Orbit's specially outfitted Boeing 747, carries the LauncherOne rocket to about 35,000 feet before the rocket drops and launches from midair.

Flash Lidar Enables Driverless Navigation

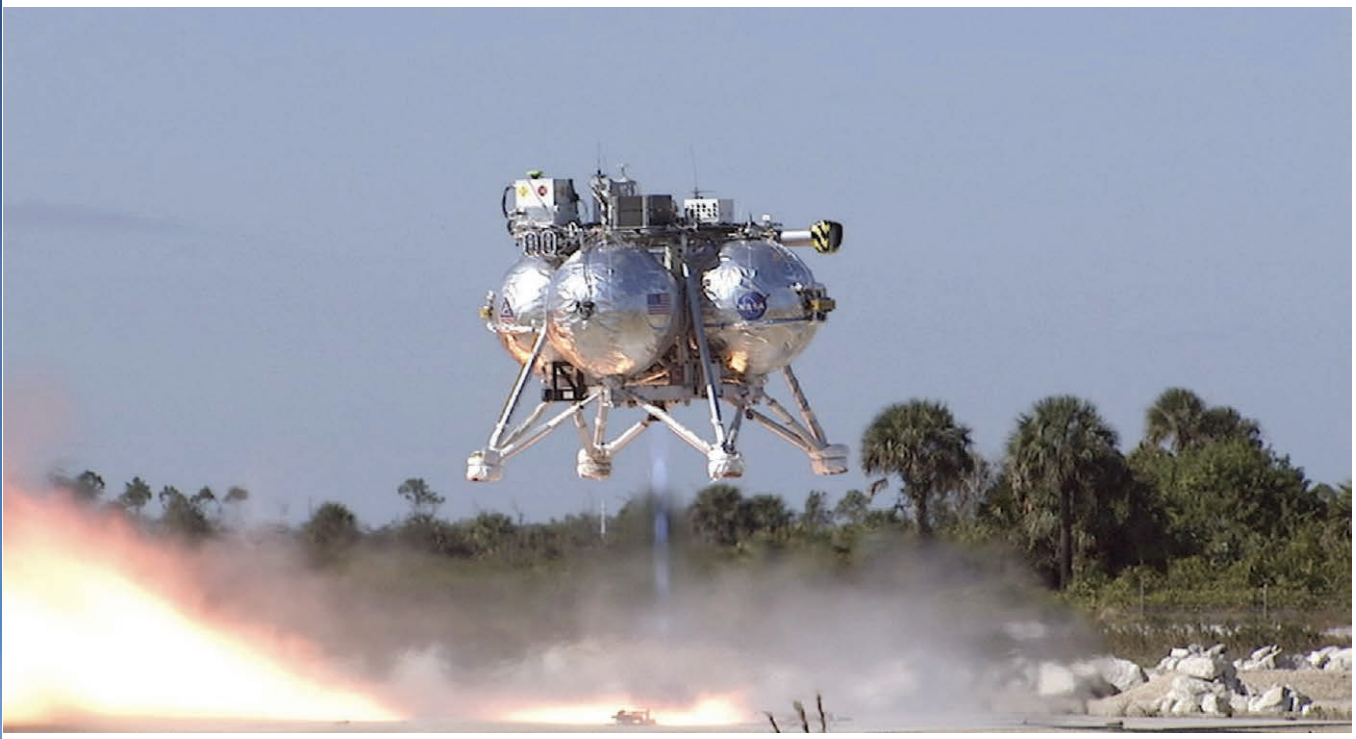
NASA Technology

A spacecraft hovers over the gray, cratered moonscape, scanning for its landing spot, and then, in a blaze of rocket fire that kicks up a massive cloud of dust, the lander, Morpheus, lowers down, safely and steadily, to a clear spot amid the rocky, debris-covered surface.

In reality, this 2014 flight was not a new Moon landing—the carefully crafted moonscape was actually just off to the side of the runway at Kennedy Space Center. But it did demonstrate something very new: an autonomous landing enabled, in part, by a special kind of 3D imager, called a global shutter flash lidar, which is being employed to help NASA approach and sample an asteroid and could soon be helping your car safely navigate the roads.

Traditional lidar works by sending out laser pulses. As the laser mechanically scans across a scene, the device calculates how long it takes for pulses to bounce back from various surfaces. It is then able to stitch together a 3D topographical map of the scene, pixel by pixel.

Global shutter flash lidar, as the name suggests, acquires the data all at once, using a single laser pulse to generate the entire map, explains Langley Research Center engineer Farzin Amzajerdian. The pulse is received by a focal plane array with thousands of pixels, which offers many advantages—most importantly, speed. "You can have tens of thousands of pixels in one single shot of the laser," he explains.



Morpheus, seen here during a test flight, is a prototype of an autonomous lunar descent vehicle. It is equipped with technology from the Autonomous Landing and Hazard Avoidance Technology project, one of the key components of which was a global flash lidar that can instantly create a 3D topographical map of the surface to help guide the vehicle to a smooth landing site.

But it also significantly reduces the computational load, because all the data is received at the same moment and in the same physical location. In contrast, with traditional lidar, the craft carrying the device is often in motion as it sends out a series of laser pulses. "You have to keep track of that movement very precisely in order to correctly calculate how to put all these pixels together," says Amzajerdian.

Amzarjerdian's team at NASA began exploring the use of flash lidar as early as 2006, while working on the Autonomous Landing and Hazard Avoidance Technology (ALHAT) project, an effort that eventually led to Morpheus' successful simulated Moon landing in 2014. "The idea there was to use a lidar like a 3D camera, so when we go to the Moon or Mars, the lander can look below and see the rocks and craters and then figure out where would be the best place to sit," he says.

In previous missions, NASA would analyze images ahead of time to find a smooth and safe landing spot. "Going forward, now the scientists want to go to places that are more interesting. In order to do that, they can't just pick the safest and most benign areas to go to," he says. "If we want to go to these interesting places, we have to have an onboard hazard avoidance sensor."

Technology Transfer

By the time the ALHAT project came around, flash lidar technology was already in development. Crucially, Santa Barbara, California-based Advanced Scientific Concepts Inc. (ASC) had already developed the focal plane array at the heart of the device, says the company's president and CEO, Brad Short.

But it still needed work, especially for space applications, so over the next several years the Jet Propulsion Laboratory, Langley, and other NASA field centers provided additional funding through the Small Business Innovation Research (SBIR) program and other project funds. "We funded them

“The ability of our **camera** to produce **distortion-free data,** point cloud data, **is enabling real-time** autonomous **navigation,** in all kinds **of applications.”**

—Michael Dahlin, Advanced Scientific Concepts LLC

Advanced Scientific Concept's (ASC) global flash lidar provides crucial safety benefits when navigating amid cars and other obstacles at high speeds, because it reduces software processing requirements to identify road hazards more quickly. That's because it gathers 15,000 pixels with every pulse, and because the image is gathered all at once, there is no distortion from motion.

to build cameras that we took and put in a system, and we tested it on helicopters, airplanes, and even a rocket-powered vehicle," Amzajerdian says. "And through all this process we were working with them. When we saw problems, we tried to understand them and communicate to the company what we saw, and sometimes we'd also suggest solutions to them."

Short credits the funding with helping the company mature the technology significantly. "The NASA funding was very instrumental," he says. "They funded the right things for us to do." While they may have ended up with a functional camera eventually, he says, the NASA SBIR and other funding accelerated the process by years and also helped them develop a space-ready camera that may not have been possible otherwise.

Benefits

Today, ASC's flash lidar is more than space-ready—it is a space pioneer. NASA's Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-REx) asteroid sample return mission has one of the cameras to help guide the final approach to Bennu, its target asteroid. "Our sensor provides the range to the asteroid and a 3D map of the region they were approaching, so they could position themselves within those last few meters." In July 2020, OSIRIS-REx is scheduled to navigate in close proximity to target asteroid Bennu, to perform the sample return mission, thanks in part to the flash lidar guidance.

But the imager has plenty of earthbound applications as well, including for driverless cars, and in 2012, ASC began working on optimizing its technology for the road, sparking interest from a German automotive manufacturer, Continental AG.

Continental is best known for its tires, but it also makes a number of other car components for major car makers worldwide. It is also working hard on technology for autonomous driving, Short explains, and is already one of the largest makers of radar devices for cars.

In 2016, Continental bought out ASC, aiming to further develop flash lidar for the autonomous car market. "They looked at the scanning technology that is being used," Short says, referring to traditional lidar, "and they didn't think it would be robust enough. They wanted a solid-state, no-moving-parts system."

ASC's automotive flash lidar had been adapted from the space-ready devices like the one that flew to Bennu, but "the basic technology is the same," notes Short. Among other differences, the car version is significantly smaller, four inches by four inches by two inches, about an eighth of the size needed for the space-qualified version.

But the essential benefits are the same. Most importantly, "traditional lidar would have one pixel per pulse. We have 15,000 pixels. And because we take that whole frame of data in one capture, there's no distortion from motion," says Short. By reducing the software processing requirements, flash lidar can identify road hazards more quickly—a crucial safety benefit when navigating roads with other drivers, pedestrians, cyclists, and more.

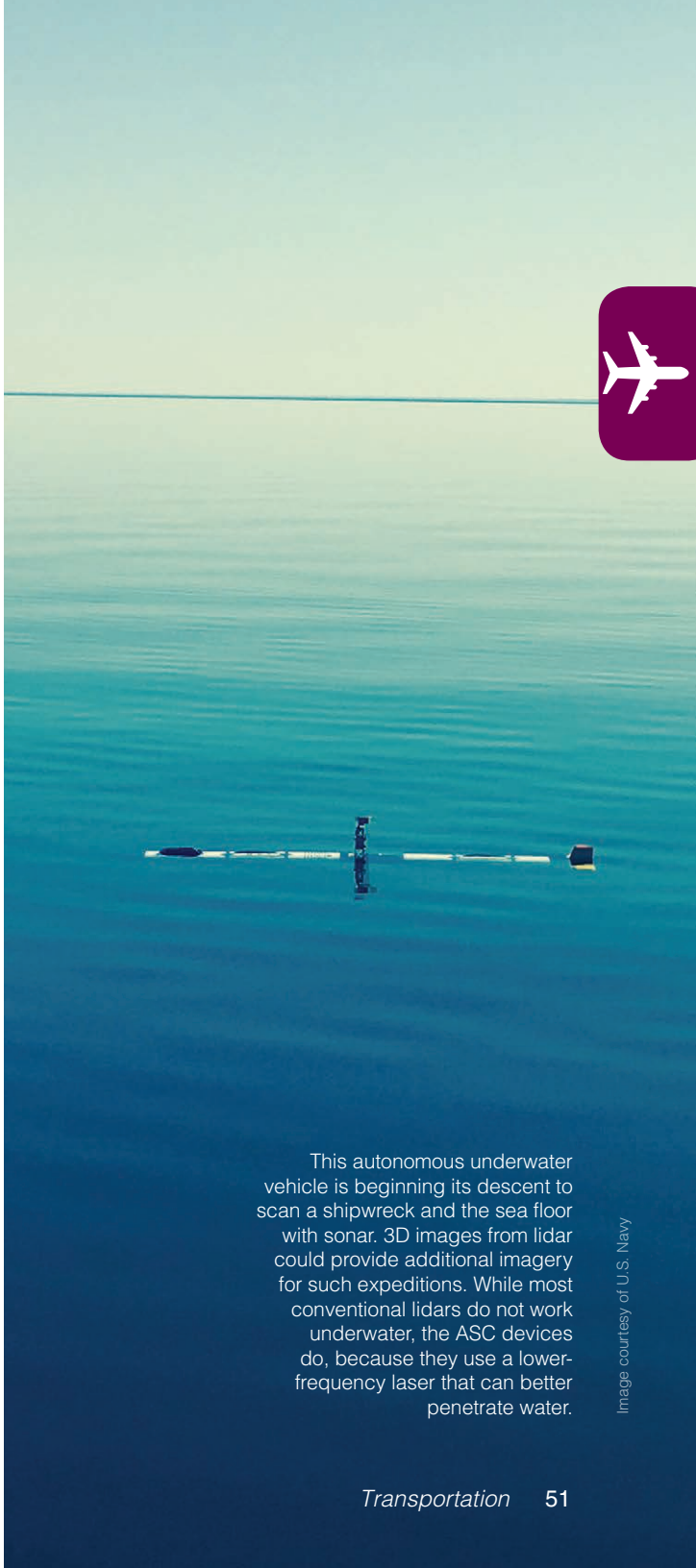
That reduced processing load also has other benefits, including reducing the required power from around 150 watts for a traditional lidar to just 40 for the ASC space-ready system.

Meanwhile, the original team at ASC, interested in smaller but lucrative applications like military and aerospace, founded a new company, ASC LLC, after negotiating an exclusive, royalty-free license agreement from Continental for the original technology.

ASC LLC currently sells three systems, including the Peregrine system, its original prototype for driverless cars, as well as the TigerCub, a long-range, full-feature, general purpose flash lidar, with range capabilities of just over half a mile, and the GoldenEye, a space lidar system with a range of just over three miles.

And all the ASC devices are compatible with 532-nanometer lasers, which is higher than the laser frequency used with conventional lidar systems, explains Michael Dahlin, the company's director for business development. That enables an additional application, marine-based navigation, because the higher frequency laser is better able to penetrate water.

"The ability of our camera to produce distortion-free data, point cloud data, is enabling real-time autonomous navigation, in all kinds of applications: space platforms, airborne, terrestrial platforms, and marine platforms," Dahlin says. ❖



This autonomous underwater vehicle is beginning its descent to scan a shipwreck and the sea floor with sonar. 3D images from lidar could provide additional imagery for such expeditions. While most conventional lidars do not work underwater, the ASC devices do, because they use a lower-frequency laser that can better penetrate water.

Image courtesy of U.S. Navy

Virtual Airspace Hosts a Training Program for Air Traffic Managers

NASA Technology

The skies are on the brink of major change. The number of U.S. aircraft flying through the national airspace is likely to multiply many times over in coming years, with the expected introduction of delivery drones, other unmanned vehicles, and, perhaps eventually, air taxis.

"Humans can't deal with monitoring and managing so many vehicles at a time," says NASA's Kee Palopo. "It's beyond what a brain can handle. Automation is necessary in areas that could support decision making—for example, in conflict detection."

Researchers and developers working on new aviation technologies need to understand how thousands of new aircraft will interact with each other and the thousands of flights already in the skies. To help them, a team at NASA's Silicon Valley-based Ames Research Center, including Palopo, is building the Air Traffic Management-eXploration (ATM-X) Test Bed, an environment that hosts simulations of air traffic based on real Federal Aviation Administration (FAA) and other data, sometimes in real time.

The idea is for other technology developers to conduct their own simulations using the test bed's air traffic management simulation environment and framework.

The skies of the future are likely to be full of all sorts of high- and low-flying aircraft, both with and without pilots, as shown in this artist's depiction. To help speed the development of technology for these future skies, NASA is building a simulation of the national airspace that researchers can use to test their concepts.

With the goal of accelerating technology development, ATM-X will enable the aviation community—including government, private-sector, university, and international researchers—to test their technologies without having to create a complete test platform that simulates the country's complicated air traffic control system. NASA is currently working with the FAA, Boeing, Uber, and others on ATM-X projects, and the Space Agency expects to begin transitioning the platform to general users after September 2020.

"As the airspace management system modernizes," Palopo says, "it is expected to accommodate new operations, like supersonic flights—which are coming back—air taxis, and drones. The test bed is also able to evaluate this range of technologies."

In developing the ATM-X Test Bed, Palopo and his Ames colleagues realized that airspace simulations used in technology development were often slowed down by a lack of both quick access to operational data and the tools to build, archive, and recall flight scenarios. Without better simulation tools, simulations were labor intensive to create, less realistic, and less repeatable.

"Using realistic data and air-traffic-management systems make the simulation more convincing," Palopo says. "The datasets and systems in the test bed let technology developers confirm whether their concept makes sense or not—whether it can work in reality." Also, ATM-X simulates flight scenarios under various weather and traffic conditions before additional investments are made to mature the technology.

Technology Transfer

One aspect of national airspace system modernization efforts is training, which is "a really big deal," according to Chris Brinton, CEO of Mosaic ATM Inc., a Leesburg, Virginia-based company that works on airspace technologies. "Training is really important, especially as aviation technology becomes more and more complicated and as managers become overseers of the whole system rather than making every single individual decision down to the flight level."

Mosaic won Phase I and Phase II NASA Small Business Innovation Research (SBIR) contracts to develop a simulation platform to work within the ATM-X Test Bed to train air traffic managers, who oversee air traffic controllers.

Based at air traffic control facilities around the country, managers keep their eyes on flow control, making sure the controllers don't get overloaded and that there aren't too many airplanes in the same place at the same time. The job involves a good deal of human interaction with other managers at air traffic control facilities across the country and with the Air Traffic Control System Command Center, which oversees the national airspace from Warrenton, Virginia.

Mosaic's training platform, called COMETTS for Comprehensive Environment for Traffic Management Training by Simulation, aims to train the managers in all aspects of the job. "We've emulated many of the systems that traffic managers have to use," Brinton says. "But then we also created a simulation not just of the flights and the flight routes that they follow but also of the people in the air traffic control system, like other traffic managers in different facilities."

One problem Brinton says FAA experts flagged is that, for staffing and scheduling reasons, air traffic managers are often trained in winter months and get no exposure to summer weather flight scenarios, when traffic can be at its peak level. COMETTS can simulate conditions under any weather or traffic conditions, giving managers experience with the types of situations they'll actually face on the job, no matter the season.

With its Phase II SBIR funding, Mosaic developed specific training scenarios and tested them with recently retired FAA air traffic managers.

Benefits

Brinton has given COMETTS demonstrations to a number of FAA organizations and high-ranking officials, with the expectation the FAA will invest in it to train U.S. air traffic managers. Indeed, the platform was designed with the FAA in mind.

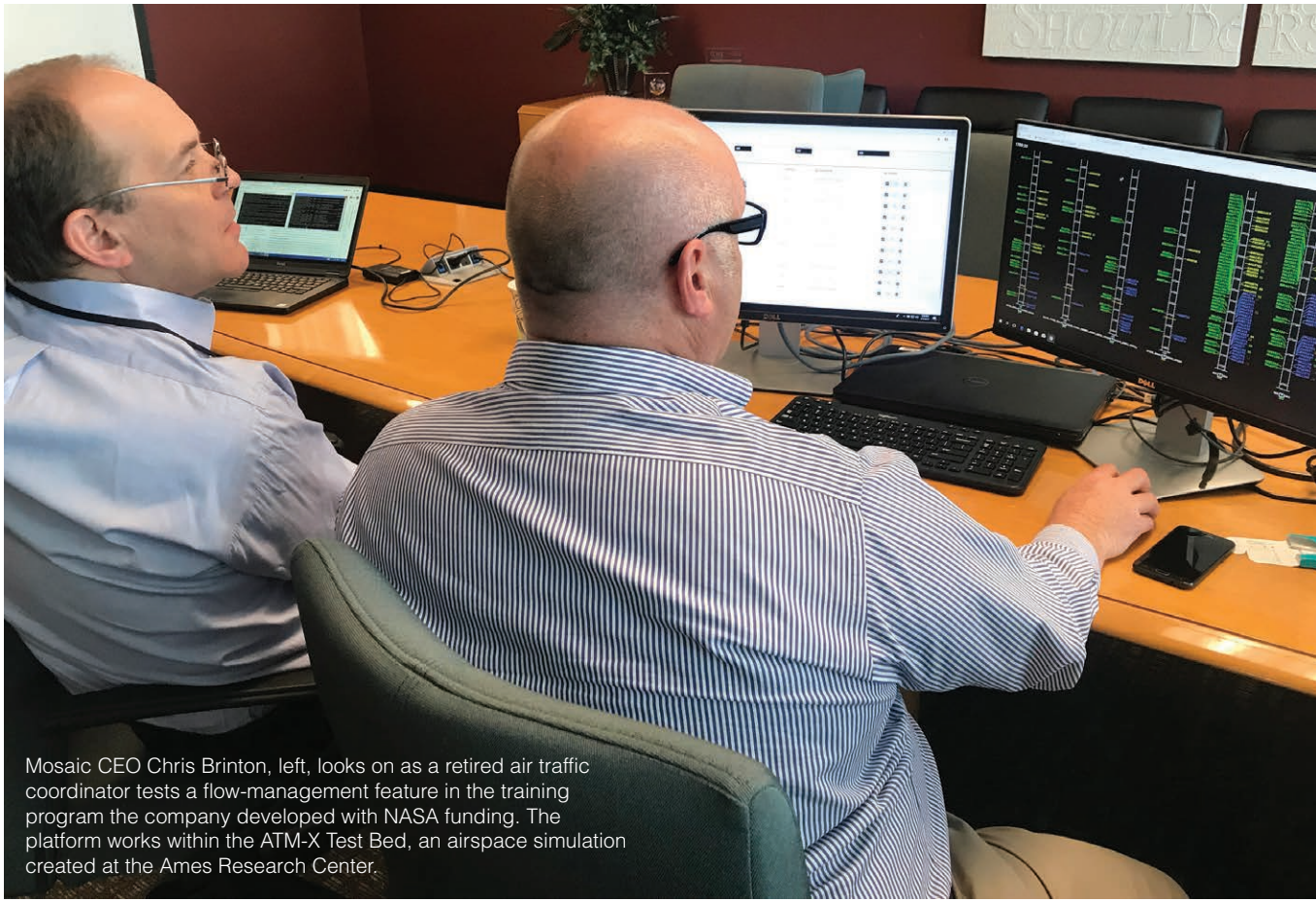
Looking forward, Brinton says future markets for the platform could include international air traffic control organizations, and COMETTS could be adapted for other fields that involve complex operations requiring communication among many different people. These situations might include nuclear power plant management, military operations, hospital operations, law enforcement, first response, national emergencies, and firefighting.

NASA's Palopo, who worked with Brinton and the Mosaic team on the SBIR project, notes that some of the technology they developed will also help other users of the ATM-X Test Bed.

"When they put this system together, there were many components that needed to be synchronized to work correctly," Palopo says of COMETTS. "That capability is reusable. It's part of why NASA and the ATM-X Test Bed team in particular is interested in this project."

Another technology that Mosaic calls Check Point enables users to go back to a particular moment in a simulation to repeat or work with a variation in the scenario. It creates what Palopo describes as a snapshot of any given point in the simulation, with all inputs saved.

"This capability is useful for users to create training programs of their own technologies and other non-training applications as well," Palopo says, adding that the technology helps ATM-X Test Bed projects move beyond mere simulation into more rigorous, live-testing conditions. ❖



Mosaic CEO Chris Brinton, left, looks on as a retired air traffic coordinator tests a flow-management feature in the training program the company developed with NASA funding. The platform works within the ATM-X Test Bed, an airspace simulation created at the Ames Research Center.

Water-Powered Engines Offer Satellite Mobility

NASA Technology

NASA has been planning for a water-powered rocket engine since the Agency's early years. After all, water is made of hydrogen and oxygen, which have been powering the Space Agency's rockets since the 1960s. Hydrogen produces the highest exhaust velocity of any rocket fuel, and the oxygen helps it burn. All it takes to separate water's two elements is an applied electrical charge.

"Theoretically, the water-electrolysis rocket offers many advantages over more conventional control systems," reads a 1969 paper out of NASA's Lewis Research Center (now Glenn Research Center), including high performance, safe materials, simple storage, long lifetime, and low power requirements. The paper details the performance of an early prototype thruster.

But the technology at the time was considered complex and had disadvantages, too, such as its size and weight and the limited power available for electrolysis, notes a 1997 Glenn paper detailing the performance of another, more advanced water-electrolysis engine prototype. Yet even today, the concept remains integral to NASA's deep-space exploration plans, which rest partly on the ability to find water on other worlds or asteroids and turn it into rocket fuel.

During decades of experimentation, though, no one actually produced a practical water-electrolysis engine. Until now.

"Managing hydrogen and oxygen and superheated steam, there are a lot of materials issues, like corrosion," says Robert Hoyt, cofounder and CEO of Tethers Unlimited Inc. (TUI). "You have to be very careful with materials throughout the device to avoid corrosion and make sure the electrolysis components are not contaminated by any other materials."

With this in mind, and with NASA's help, the Bothell, Washington-based company has built the first viable water-electrolysis engines. Currently, NASA's interest in the technology stems from its effort to advance the state of technology for CubeSats—tiny, low-cost satellites built with off-the-shelf parts.

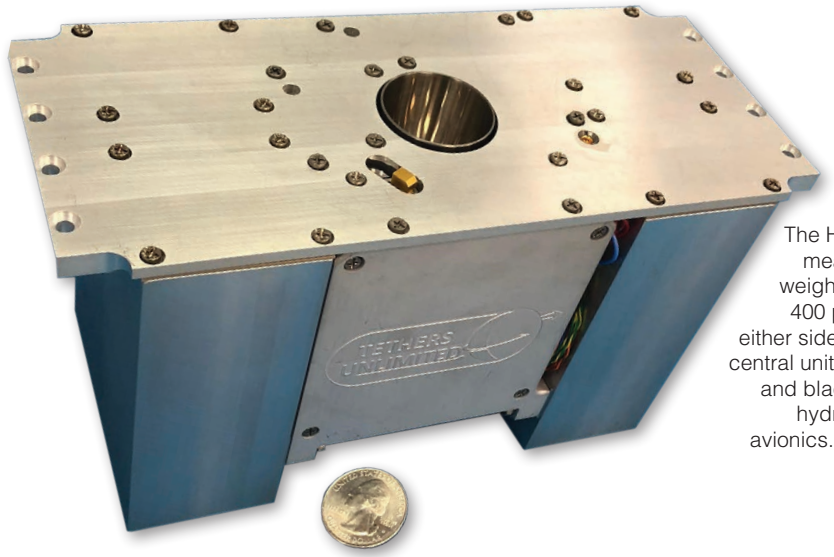
"Until the early 2000s, the smallest spacecraft up there was still over 500 pounds," says Ames Research Center's Elwood Agasid, who has been involved with various stages of TUI's work on the electrolysis thrusters. Before, only major corporations built satellites, which required large investments of time, money, and R&D. But as manufacturing costs came down, and especially as CubeSat kits became available, access to space launch opened up to more players, Agasid says.

NASA now regularly carries little satellites built by universities, start-ups, and others into orbit as secondary payloads through programs like its CubeSat Launch Initiative. But the Agency is also enhancing small satellites' capabilities to use them more in future exploration and science missions.

As part of the Space Agency's overall effort to foster CubeSat innovation, in 2010, NASA's Small Business Innovation Research (SBIR) program released a solicitation for propulsion systems for the mini-satellites, and TUI was one of the respondents selected to receive funding through Ames. Agasid was the contracting officer representative for the two SBIR contracts. "Their approach seemed sound and addressed the issues of water containment and generating sufficient power to enable electrolysis," he says.

At the time, CubeSats didn't have propulsion systems. Building small enough thrusters has been a challenge. And Agasid says there are concerns about allowing pressurized propulsion systems aboard launches. As a result, CubeSats

Tethers Unlimited's HYDROS-C thruster is intended to introduce propulsion capabilities to relatively tiny CubeSats, letting them maintain or change their orbits. It was slated to fly on NASA's Pathfinder Technology Demonstrator 1 in 2019.



The HYDROS-M thruster is meant for small satellites weighing between 110 and 400 pounds. The tanks on either side hold water, while the central unit holds an electrolyzer and bladders for oxygen and hydrogen gas, along with avionics. The hole in the top is the thruster nozzle.

have largely been stuck with the orbit of the primary payload they hitched a ride with, unable to change their altitude or maintain their orbit long-term.

Technology Transfer

With the SBIR funding, TUI built two prototypes and started testing them, Hoyt says. "Control avionics, software integration, and performance and lifetime improvements were still necessary."

Under NASA's Tipping Point solicitation, the Space Agency found a corporate partner—Millennium Space Systems—to share the cost of maturing what TUI now calls its HYDROS thrusters, in exchange for three of the resulting propulsion systems for use on its Altair small satellites. Millenium wanted larger versions of the technology, known as the HYDROS-M, designed for satellites weighing between 110 and 400 pounds, which have already been delivered.

Meanwhile, NASA selected the CubeSat version, the HYDROS-C, to fly on the first of five Pathfinder Technology Demonstrator (PTD) project, which will try out new CubeSat technology. It's expected to launch in mid-2020. Agasid manages PTD at Ames, in collaboration with Glenn.

Both HYDROS versions launch with tanks carrying enough water to power them for about three years. Once in orbit, an electrolyzer powered by solar panels splits the water into oxygen and hydrogen gases, stored in separate bladders to be transferred to the combustion chamber as needed. Hoyt describes the system as a hybrid of electric and chemical propulsion—one that's powered by solar panels but can unleash the powerful thrust of a chemical engine.

Benefits

The HYDROS approach avoids the risks of sending up a pressurized system, as it's unpressurized until it starts filling its gas bladders in orbit, says Agasid. The system is also relatively inexpensive and easy to manufacture, scalable for different satellite sizes, and fuel-efficient, he notes.

And it runs on fuel that's harmless, both in terms of emissions and handling. "You can let undergrads play with it, and they're not going to poison themselves," Hoyt says.

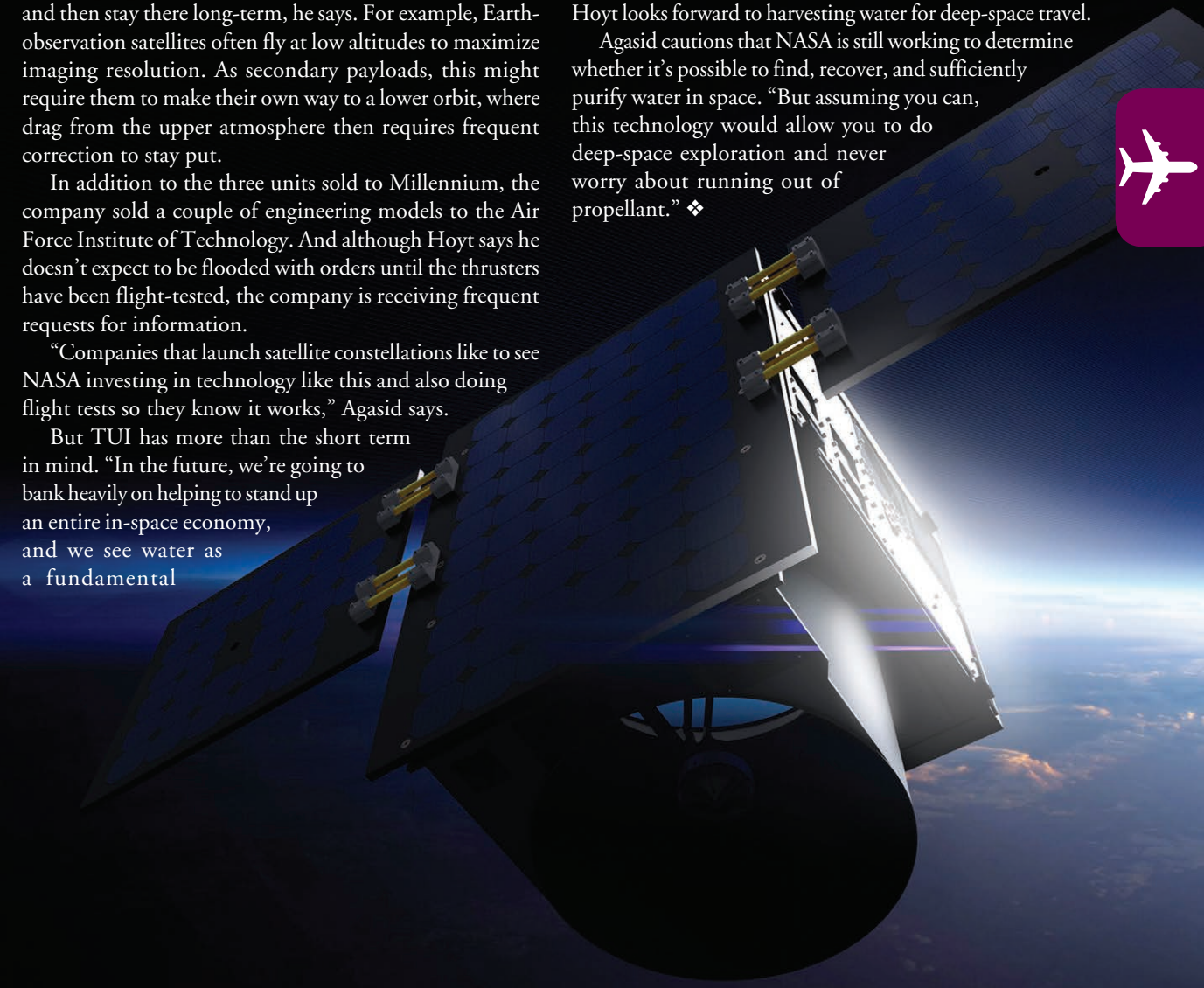
HYDROS' ability to deliver powerful bursts of energy and its long operating life make it ideal for any satellite that needs to move from one orbital altitude to another and then stay there long-term, he says. For example, Earth-observation satellites often fly at low altitudes to maximize imaging resolution. As secondary payloads, this might require them to make their own way to a lower orbit, where drag from the upper atmosphere then requires frequent correction to stay put.

In addition to the three units sold to Millennium, the company sold a couple of engineering models to the Air Force Institute of Technology. And although Hoyt says he doesn't expect to be flooded with orders until the thrusters have been flight-tested, the company is receiving frequent requests for information.

"Companies that launch satellite constellations like to see NASA investing in technology like this and also doing flight tests so they know it works," Agasid says.

But TUI has more than the short term in mind. "In the future, we're going to bank heavily on helping to stand up an entire in-space economy, and we see water as a fundamental resource that's key to that economy," Hoyt says. The next generation of HYDROS thrusters will include refueling ports, extending their operational lifetimes indefinitely. And Hoyt looks forward to harvesting water for deep-space travel.

Agasid cautions that NASA is still working to determine whether it's possible to find, recover, and sufficiently purify water in space. "But assuming you can, this technology would allow you to do deep-space exploration and never worry about running out of propellant." ❖



Millennium Space Systems bought Tethers Unlimited's first three water-electrolysis engines by helping to fund the technology's final stage of development through NASA's Tipping Point solicitation. The thrusters were to fly on Millennium's Altair small satellites.

Image courtesy of Millennium Space Systems

Unique Sensors Will Improve Aerodynamic Design, Aircraft Performance

NASA Technology

Even after almost 150 years of wind tunnel testing, no commercial product had ever been able to directly measure the localized force that passing air exerts on the surface of a vehicle model—until now. Known in the industry as wall shear stress, or skin friction, the force is a major factor in a vehicle's drag, affecting its fuel efficiency and aerodynamic performance.

Thanks to two decades of research and engineering, Interdisciplinary Consulting Corporation (IC^2) now has sensors that introduce the unprecedented capability to sense these forces directly.

Without this ability, engineers doing aerodynamic testing have come up with ingenious techniques like observing the change in voltage required to maintain the temperature of a heated film on a model's surface or tracking the localized thickness of an oil film and then backing out the data to arrive at an estimate of shear stress.

"All of these methods have limitations which lead to large uncertainties, and direct measurement is the only way we're going to get what we need," says Cathy McGinley, head of the Flow Physics and Control Branch at NASA's Langley Research Center.

In the mid-2000s, three University of Florida professors set out to address the problem with funding from a three-year NASA Research Announcement and an idea for a microelectromechanical systems (MEMS) sensor that could directly measure shear stress. One of those professors, Mark Sheplak, had co-founded Gainesville, Florida-based IC^2 in 2001 to commercialize technology developed in his lab at the university, known as the Interdisciplinary Microsystems Group.

It took more than another decade—and considerably more NASA funding—to arrive at a product.

"For the first 10 years, the company focused on small consulting jobs and the occasional SBIR," says company President Steve Horowitz, referring to a few Small Business Innovation Research (SBIR) contracts with the military, only one of which was directly related to the shear stress sensor. Then, in 2010, IC^2 landed Phase I and II SBIR contracts with Langley Research Center to work on a MEMS skin friction sensor. This led to several more NASA SBIR contracts, most of them with Langley.

"That was our first steady revenue to lead to full-time employees and eventually a commercial product," says Horowitz, noting that the company has seen 20 to 30 percent annual growth ever since. "For us, it was a pivotal time."

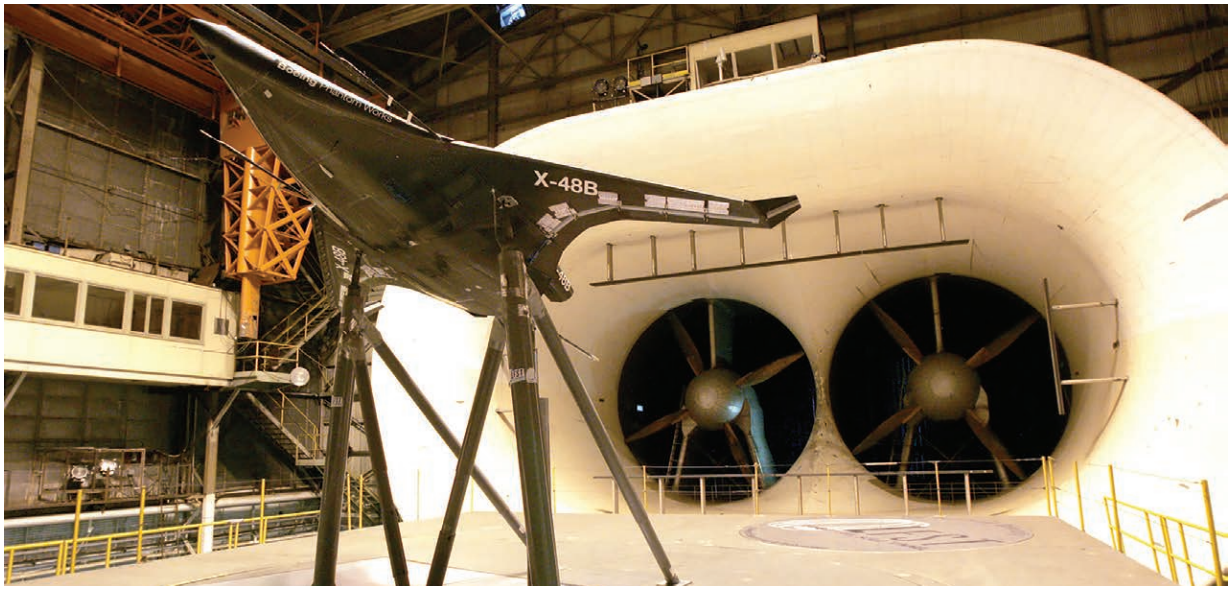
Technology Transfer

The sensor IC^2 built under the 2010 contracts used the same concept as the company's current commercial product, known as DirectShear: a micromachined silicon sensor that moves back and forth as air passes over it. A voltage is applied across two tiny pairs of parallel plate capacitors in the sensor's surface, and their electrical capacitance varies slightly as they move, creating a change in the output voltage that is directly related to wall shear stress.

"The first ones were large, bulky, and short on performance," says David Mills, the company's vice president of engineering. He notes that NASA ended up investing almost $2 million in the technology over nearly 10 years, including three Phase III SBIR contracts.

McGinley, who oversaw IC^2's original NASA SBIR work, says building a sensor that works is only the first challenge. The final product also has to be resistant to swings in temperature, pressure, and humidity, as well as electronic noise. "Getting those things solved, that's the hard problem," she says.

The company announced the DirectShear sensor line, its first commercial product, in early 2017. The product line includes six sensor heads varying in sensitivity, resolution,



The Boeing X-48 blended wing body was the last test subject in Langley Research Center's Full Scale Wind Tunnel, which was demolished in 2011 after 80 years of service. Langley has several wind tunnels onsite and a long, rich history of testing models and full-scale air- and spacecraft. In recent years, researchers there have been working with a brand-new wind tunnel testing capability—direct sensing of shear stress with Interdisciplinary Consulting Corporation's (IC^2) DirectShear sensors.

and bandwidth depending on the force of the shear stress they're designed to measure. Made for use at subsonic wind speeds—that is, slower than the speed of sound—the six versions together can sense, with high fidelity, shear stress levels from about 5,000 pascals down to 20 micropascals, the latter being about equivalent to the force of the slightest sound audible to the human ear. Shear stress forces are typically orders of magnitude lower than atmospheric and acoustic pressure levels, which is part of what makes measuring them so difficult, Horowitz says. The sensors need to measure these slight forces while remaining insensitive to pressure.

DirectShear sensors are not only the first commercial product to directly measure shear stress but also the first that can easily observe and quantify the effects of both mean flow—the overall stress air puts on the vehicle—and fluctuating turbulent air structures. The latter requires the devices to have a high bandwidth, up to 20,000 cycles per second. "Our DirectShear sensors can replace two families of technology," Mills says.

Benefits

Shear stress accounts for about half of a vehicle's overall drag. Understanding that drag tells a designer how a planned vehicle will perform and how far it could go on a given amount of fuel, McGinley says.

She's been working with other NASA scientists, as well as industry and academic representatives, on a project known as the Juncture Flow Experiment, aimed at better understanding and predicting complex airflows where an aircraft's wing meets its body. The team has been using DirectShear sensors in wind tunnel experiments with success.

In addition to improving subsonic wind tunnel testing, DirectShear sensors can also significantly improve computational fluid dynamics (CFD) software, which designers use to digitally predict a vehicle's performance. McGinley says improving CFD technology was the main motivation behind both the Juncture Flow Experiment and Langley's interest in IC²'s sensors. The software represents a huge cost savings over physical wind tunnel testing, but only to the extent that it's accurate.

CFD's predictive powers break down when confronted with novel vehicle designs or complex airflow separations.

In IC²'s DirectShear sensors, a tiny, micromachined silicon sensor moves back and forth as air passes over it, changing the output voltage to indicate shear stress.

For example, McGinley says, at the outset of the Juncture Flow Experiment, each participant used its own CFD software to try to predict the nature of the airflow separation bubble that would form at a particular wing-body juncture. No two programs produced the same results.

NASA has long been both a leading pioneer and a heavy user of CFD software, although many others, from commercial airplane manufacturers to automakers, have adopted the technology.

IC² is now in talks with government agencies, academic researchers, and space and aeronautics companies interested in buying DirectShear sensors for improved wind tunnel testing, Horowitz says. "More accurate measurement is essential to making a better-performing design and trusting that it's going to work in the field."

Better performance means less fuel burned, lowering both costs and emissions, as well as less noise. "Given the amount of fuel an airliner burns and how many airliners are in the air," says Horowitz, "you can make a big difference even if you reduce drag by just a small percentage."

He credits the SBIR program with making the DirectShear line possible. While the market for improved CFD software will be relatively large, the wind tunnel testing community is not, meaning the product's decades of development won't yield the sort of big, immediate payoff that venture-capital investment would have demanded. That said, he adds, "As we drive down complexity, we hope to develop a larger market outside the core science community."

The company is preparing to bring a number of other wind tunnel testing instruments to market in the coming years, from new DirectShear products to high-frequency dynamic pressure sensors and aeroacoustic microphones, all based on the same MEMS techniques and know-how it developed to create its first product, Horowitz says. "And we used the same SBIR model of development across all of them." ❖

Doppler Lidar Makes Self-Driving Cars Safer

NASA Technology

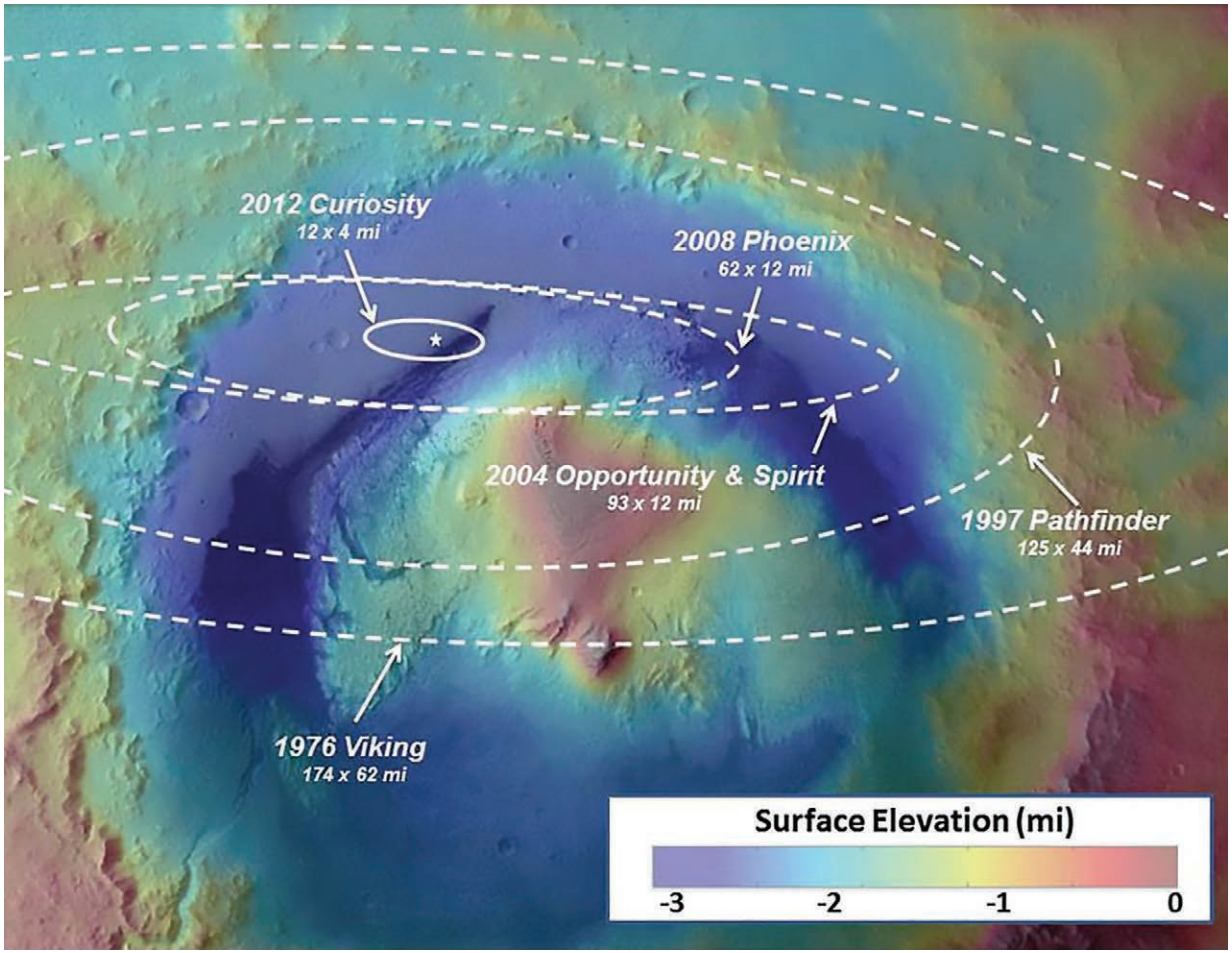
Lasers designed to help a lunar spacecraft land on a proverbial dime might help self-driving cars navigate rush hour traffic on this planet. The path from the Moon to Main Street was mapped out as NASA engineers designed a new approach to safely manage multiple trips to the Moon and Mars, in addition to exploring other planetary bodies for the first time.

That includes delivering tons of scientific and life-support equipment to specific locations in advance of crewed missions—payloads heavier than anything ever flown by NASA.

It helps to compare the proposed challenge to previous landings: NASA's InSight Mars Lander had a target landing area 81 miles long and 17 miles wide. It used a less sophisticated (and less expensive) descent and landing system than the Curiosity rover, NASA's most precise Mars landing to date, which had a target landing area 12 miles long and 4 miles wide. Future missions will require supplies and people to land within an area the size of a football field.

Only a precision landing and hazard avoidance system can make that possible. Future landing vehicles will be equipped with a full suite of technology including next-generation sensors, cameras, specialized algorithms, and a high-performance spaceflight computer that all work in concert. In 2018, NASA organized the development of these capabilities under the Safe and Precise Landing—Integrated Capabilities Evolution project, or SPLICE. And even before SPLICE has its hardware fly in space, one of its technologies is spinning off into the commercial sector—navigational Doppler lidar.

Lidar is a detection system similar to radar that uses light waves instead of radio waves to detect objects, characterize their shape, and calculate their distance. Navigational Doppler lidar goes even further: it detects the movement and velocity of distant objects, as well as the spacecraft's own motion relative to the ground (such as speed, pitch, and roll).



As landing technology has improved, Mars landers and rovers have aimed for ever-smaller landing zones, from Viking's 174-mile-wide target to Curiosity's 12-by-4-mile landing zone. Navigational Doppler lidar will help narrow landing areas even further, to about the size of a football field. During the approach, lasers and sensors will scan the surface, feeding data to an onboard computer that will identify potential hazards.

Navigational Doppler lidar inventor Farzin Amzajerdian, who is the technology's principal investigator at Langley Research Center, explains that the frequency of the system's laser is at least three orders of magnitude higher than radars. "Higher frequency translates to higher-precision data and potentially more efficient and compact sensors," he says. Future spacecraft will send three continuous laser beams, one to two inches in diameter, down to a planet's surface. As these bounce back from the ground, a corresponding sensor, programmed to watch only for incoming light

“Everything from **autonomous** air **vehicles** and **self-driving cars** to **smart appliances** need to be able **understand** and **interact** with the **world around them.”**

— Steve Sandford, Psionic LLC

Image courtesy of Erik Drost, CC BY 2.0

For an autonomous vehicle to travel urban streets safely, it must be able to “see.” Navigational Doppler lidar supplies data to an onboard computer that, when combined with information from cameras, makes it possible to identify buildings, people, and other vehicles. It can also detect motion, along with the direction and speed of an object.

from its laser beam, will measure how long it took the light to return.

"This travel time is directly related to distance to the ground," explains Amzajerdian. "The velocity or speed is obtained by using the Doppler effect." That is, the frequency of the returned laser light will shift when bouncing off the ground. With three laser beams, the velocity vector can be presented in three-dimensional space. In other words, a spacecraft will have precision data to verify exactly how quickly it's moving toward the ground and at what angle.

All of this takes place 20 times per second.

According to Amzajerdian, this ability to generate highly accurate range and velocity data relative to the nearby environment uniquely positions navigational Doppler lidar to improve Earth-based transportation.

Technology Transfer

Steve Sandford, former engineering director at NASA's Langley Research Center, also believes the technology has valuable terrestrial applications. He supported the development of Doppler lidar during his tenure with the Agency, seeing initial results first-hand. After retiring, he formed Psionic LLC, based in Hampton, Virginia. In 2016, the company licensed the Doppler lidar technology from Langley and also entered into a Space Act Agreement with the Center to leverage the facilities and expertise of NASA while developing its commercial version of the technology.

Psionic is reengineering the hardware to meet needs on Earth, an effort led by Diego Pierrottet, a lidar co-inventor when he worked at NASA and now chief engineer at Psionic. These applications use some of the same techniques, such as a continuous beam (as opposed to intermittent pulses of light) that measures the return signal frequency to determine the range and velocity of the object in its path. However, the process of developing a functional, cost-effective system is challenging, so the company's engineers maintain a close working relationship with technologists at Langley, including Amzajerdian.

Sandford says the work invested by NASA for decades makes it possible for Psionic to reengineer the technology for a viable manufacturing process to enter the market. To that end, the three products in development—Psionic Navigational Doppler Lidar, Navigator Class, and Scout Class—use telecom industry hardware for efficient production.

The Psionic Navigational Doppler Lidar systems are being customized for use in cars, on planes, and in commercial space vehicles. They are already smaller and more powerful than the system developed for planetary landings in space.

"Everything from autonomous air vehicles and self-driving cars to smart appliances need to be able understand and interact with the world around them," he says. "Cameras can only get you so far, because it's difficult to differentiate foreground from background using a two-dimensional image. Sensor fusion—taking a number of different sensors and blending that data together—is where Doppler lidar fits in. It's an enabling technology."

Benefits

As the commercial products continue to be refined, each system is smaller and cheaper and performs better (velocity and range resolution are higher and faster) than the one before. One reason is that the Psionic lidars scan 50 times

per second, more than doubling the rate achieved during the original NASA work.

Sandford says the company has customers in the automotive industry who are developing self-driving systems for cars, where the technology aids in both navigation and collision avoidance. Defense customers are using the adapted technology to reduce the impact on landing aircraft, improve the safety of in-air refueling, and detect drones. In addition, space companies are exploring applications of the technology in rendezvous and proximity operations and precision landing on the Moon and Mars.

Just as a lunar lander needs to be able to deal with the varied topographies of foreign terrain in the dark or light, an autonomous car must drive safely, day or night.

"Doppler lidar's high resolution can distinguish between objects that are only several inches apart and even at a distance of several hundred feet," explains Sandford.

This matters when a pedestrian is crossing a road or a truck is passing in front of a building. Algorithms need accurate data to determine what the object is—person, building, or truck—and if it's in the path of the car, avoiding the potentially fatal mistake of not slowing down or stopping in time.

Psionic Doppler lidar provides a continuous stream of data compatible with any make of onboard computer using any proprietary algorithms. Moreover, the lidars from another self-driving vehicle can't disrupt or alter the Doppler lidar performance.

A game-changing characteristic of this lidar is that it only sees the laser light it generates, ignoring the laser light transmitted from other cars. This means there's dramatically less of the signal interference that causes existing lidars to generate what Sandford calls "messy data." It also makes the system virtually impossible to hack or jam, according to Amzajerdian.

The Psionic lidar can collect sufficient data when dust, heavy rain, snow, or light fog is a factor. No lidar will penetrate solid objects such as walls or a dense fog, just as human vision can't. But Sandford says the lidar will see better than a person in bad weather.

This high level of performance also makes Doppler lidar appealing to the aeronautics industry. When a GPS signal is unavailable, a Doppler lidar installed on a plane or helicopter will continuously provide onboard systems with accurate data to calculate velocity, altitude, and direction. Because the system is tamper-resistant, it's dependable for in-flight operations.

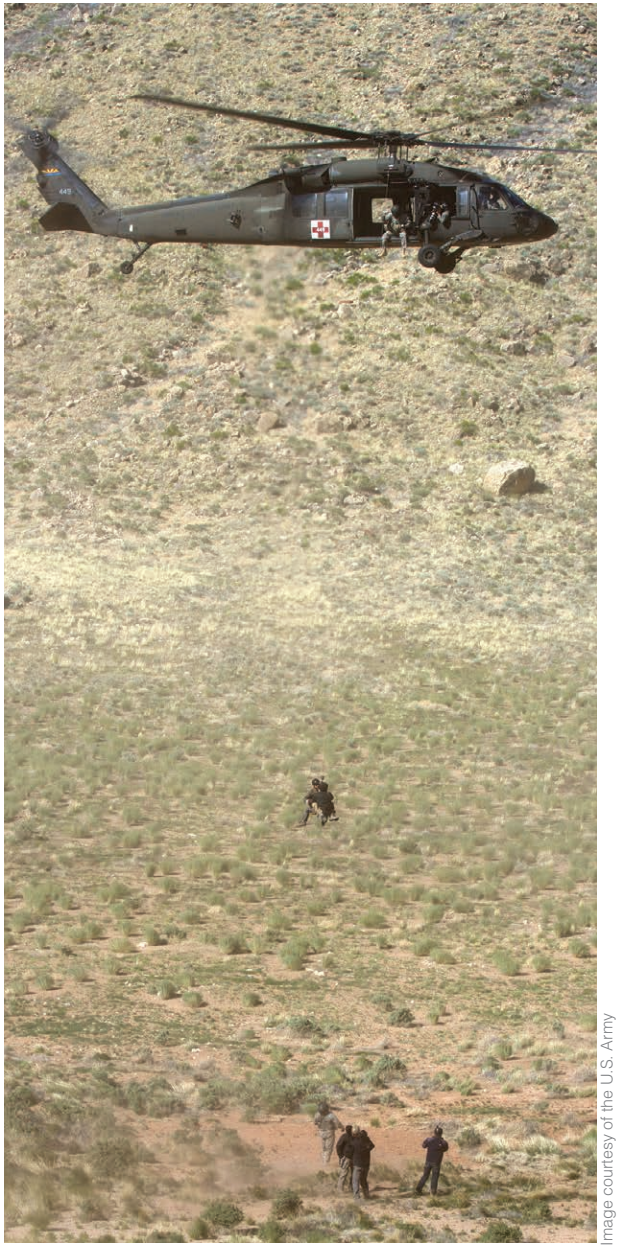


Image courtesy of the U.S. Army

Navigational Doppler lidar will help search and rescue operations respond more quickly to people in distress. Installed on search planes or remotely piloted vehicles, the technology will be able to provide pinpoint location data to ground rescuers.

"The navigational doppler lidar has some advantages over GPS for aircraft navigation," says Amzajerdian. "It provides position and velocity relative the ground. GPS gives position relative to a universal reference. So, the lidar can be much more useful in some situations."

Sandford sees other practical applications for terrestrial lidar. Autonomous and remotely piloted vehicles could follow a preprogrammed flight path and avoid colliding with other craft or stationary objects. In recovery and rescue operations, crewed or autonomous vehicles could navigate successfully and provide precise coordinates to searchers on the ground.

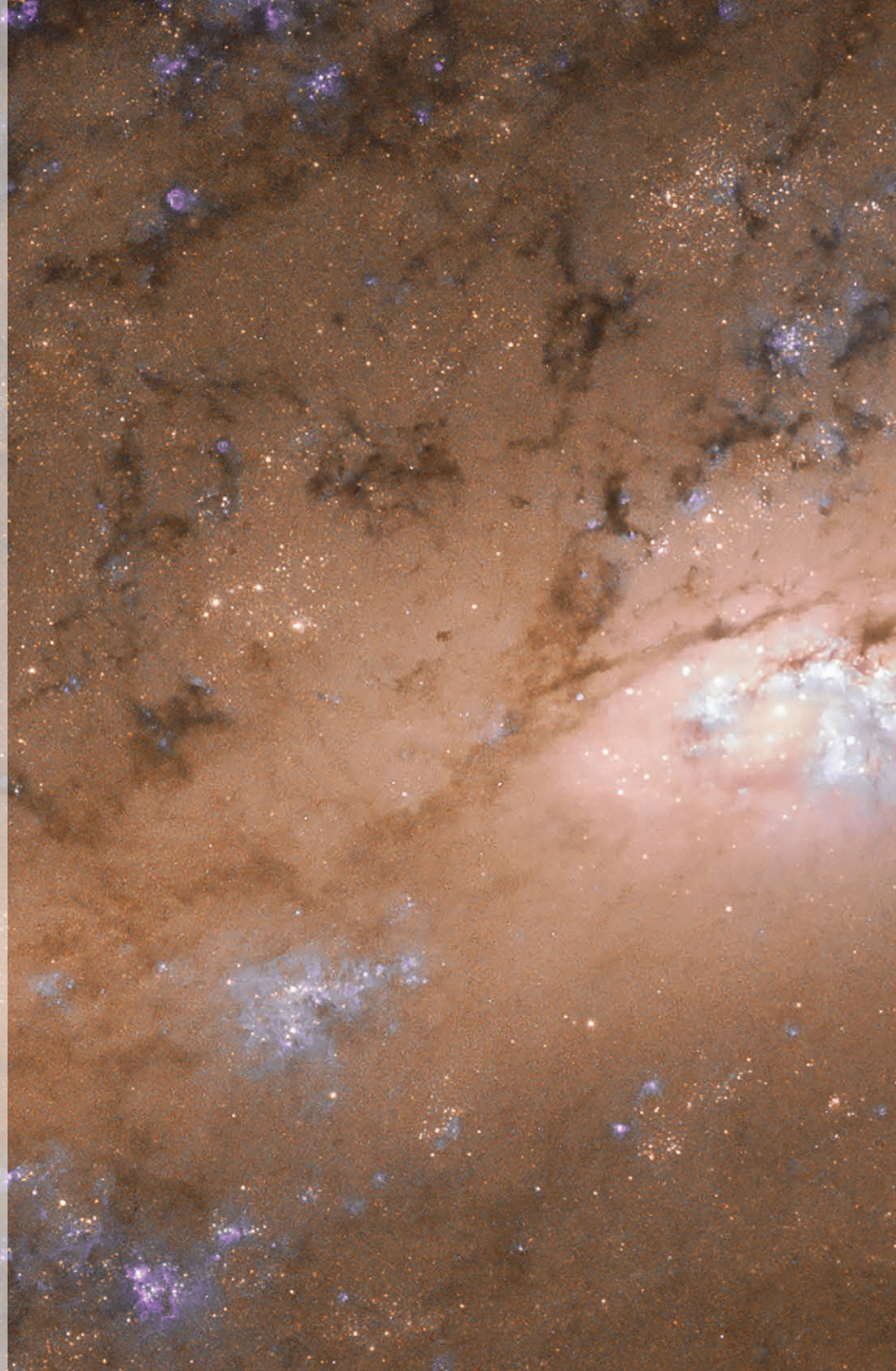
He credits NASA with making these opportunities possible on Earth. "They take our agreement very seriously and are a great partner to do business with," says Sandford.

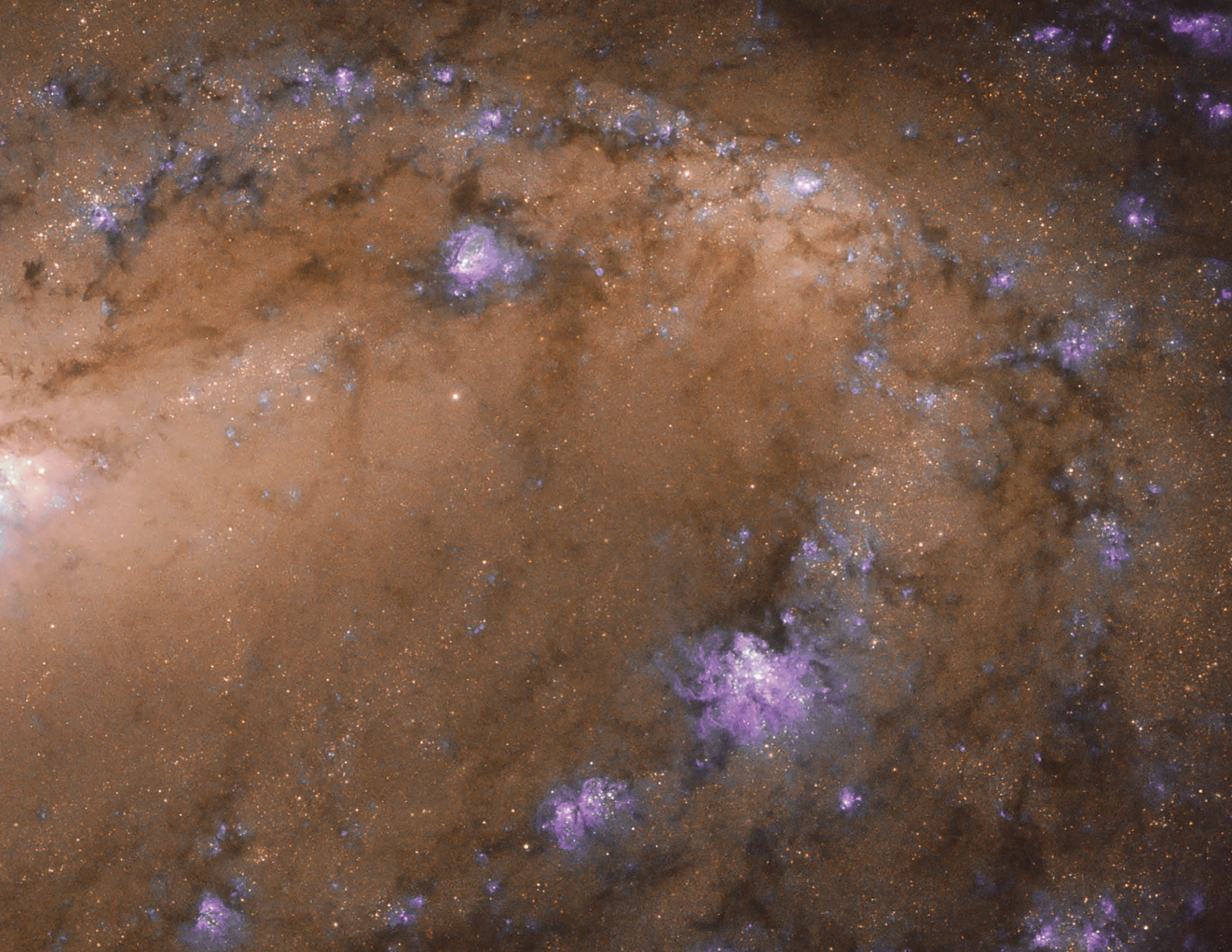
The company is looking forward to the day when it provides NASA with better, cheaper sensors. But for now, Psionic has the immediate goal of making it much safer to drive an autonomous vehicle, ensuring all drivers, pedestrians, and cyclists will arrive safely at their destinations.

The Space Agency is also working on better, safer transportation with Doppler lidar. Amzajerdian and his team are using the test result data shared by Psionic to support the development of NASA's next-generation navigational Doppler lidar. This version will be even more efficient and compact and may add new capabilities like wind velocity measurements—a potential boon for aeronautics, shipping, and other industries. ❖

Public Safety

Safety is an obvious challenge for space travel, and meeting it has led to countless spinoffs over the years. But other projects aimed at airline safety, drone guidance, and measuring greenhouse gases in the atmosphere have also led to products that improve safety on Earth. In one case, expertise with launch systems, rovers, and other NASA technology led to a system that could prevent the next offshore drilling disaster.





Polyimide Foam Offers Safer, Lighter Insulation

NASA Technology

Oxygen, which comprises just over a fifth of Earth's atmosphere, is highly reactive and able to form compounds with nearly all other elements. Heat facilitates these reactions. Once a material is sufficiently heated to combine with oxygen, that reaction releases more heat, often setting off a chain reaction that can become difficult to stop or even contain—a conflagration.

To avoid fires, the trick is often to start with materials that resist oxidation, even at high temperatures. But in the 1970s, the airline industry found there was no adequately fire-resistant material fit for use in airplane cabins. NASA came up with a solution that never quite made it into the cabin but can still be found in other parts of most planes flying today and now has many other applications.

Congressional testimony in 1979 suggested that between 1969 and 1978, 419 deaths resulted from post-crash fires. The fatalities almost certainly could have been avoided, given more time to evacuate. And it was often not the fire but the smoke and toxic gases it released that killed passengers.

By then, industry had found ways to incorporate fire-retardant additives into materials such as the foams used in airplane seating, but it was then discovered that, once these additives were hot enough to ignite, they produced large quantities of smoke and incapacitating toxic gases.

NASA had come up with some fire-resistant materials for the Apollo Program and Skylab by the late 1960s and recommended them for public use, but industry deemed them too fragile and much too expensive to manufacture.

So in the mid-1970s, the Federal Aviation Administration and NASA, along with industry players, launched a cooperative effort to improve fire safety in aviation. At NASA, the effort was known as the Fire Resistant Materials Engineering (FIREMEN) Project, and it involved a number of the Agency's field centers between 1976 and 1981.

Materials research under the program culminated with a contract between Johnson Space Center and a company called Solar Turbines International, a division of International Harvester, building on previous work by Solar Turbines, Boeing, and others, mainly at Johnson and Ames Research Center. The goals were ambitious: take a type of polyimide foam identified in earlier work and optimize it for seat cushioning, low-density wall panels, high-strength floor panels, and thermal/acoustic insulation; figure out the best way to manufacture all four products; and make it economically viable—something industry would actually use.

Solar Turbines had been working on foam insulations for solar energy systems since the late 1960s, and its recent work with Johnson had determined this particular type of polyimide foam not only withstood high temperatures but also produced virtually no smoke or flames when it finally

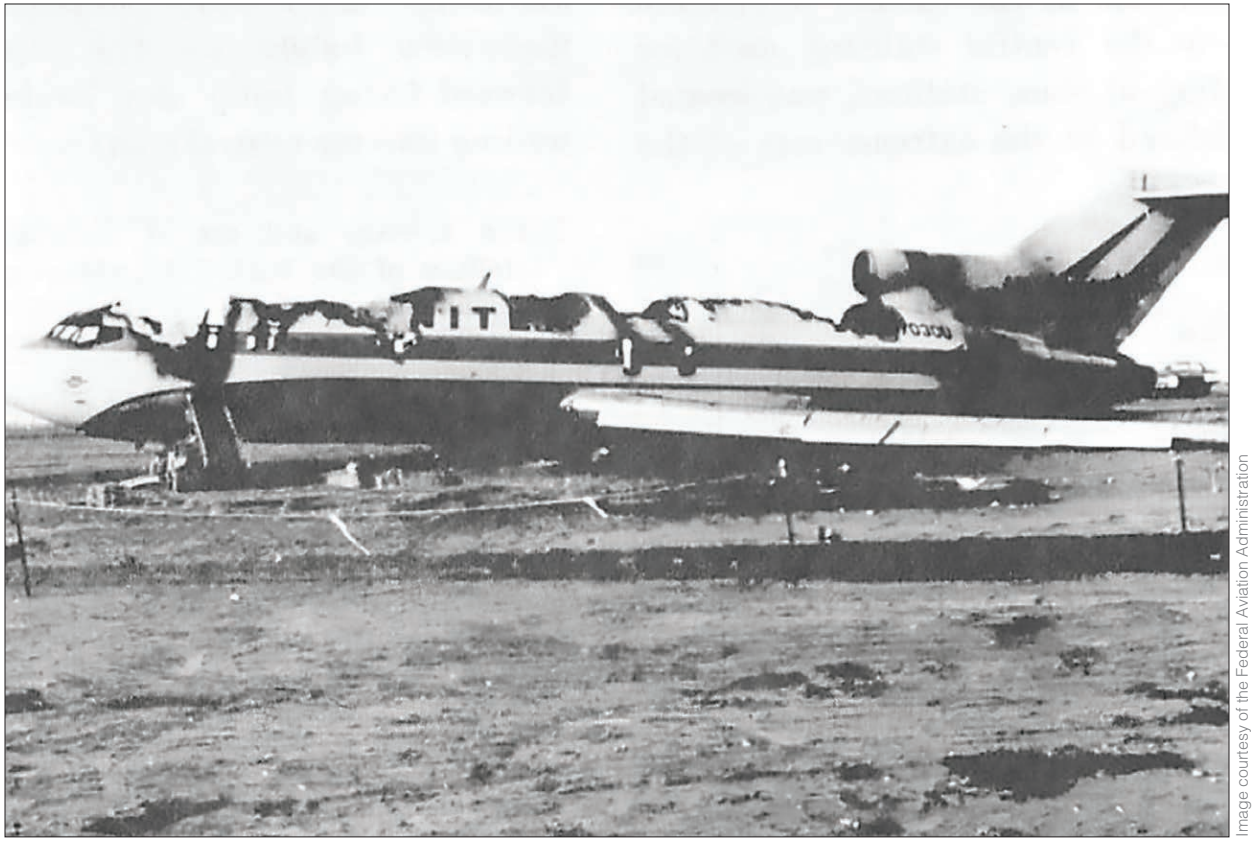


Image courtesy of the Federal Aviation Administration

In 1965, United Airlines Flight 227 crashed during landing at Salt Lake City International Airport. According to reports, landing gear broke free and ruptured a fuel line in the fuselage. At the same time, sparks from the fuselage's friction with the runway and/or severed generator leads immediately ignited the fuel, and the plane burst into flames. Forty-three of the 91 occupants were killed, many, if not most, due to the fire and smoke inhalation. Incidents like this prompted the Federal Aviation Administration and NASA to launch the joint Fire Resistant Materials Engineering Project in 1976, seeking to develop materials for airplane interiors that were fireproof and didn't give off smoke.

began to char. NASA's ultimate goal was to extend escape time from a burning fuselage from about two and a half minutes to five minutes.

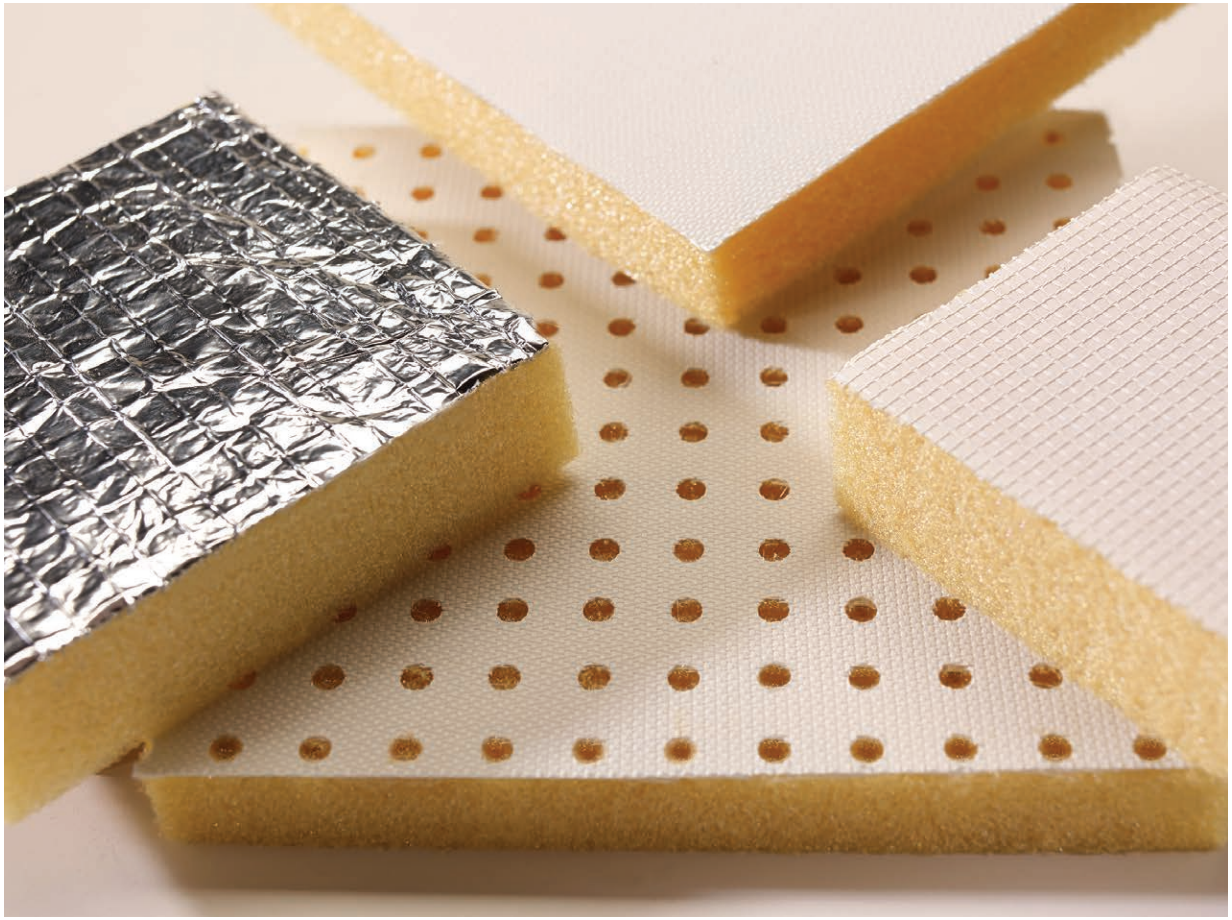
Lasting more than two years and meticulously documented, work under the final contract was exhaustive. Researchers tried various ingredients, ratios, fillers, and additives in the recipe for the starting powder, as well as different processes for turning the powders into foams and for mass-producing the foams into the four end products. Throughout, different timing, temperatures, and countless other variables were tested.

The end products were assessed for resistance to extensive wear and tear, dry heat, humidity, and flames, as well as thermal and acoustical insulation properties.

Technology Transfer

The results were not quite final products, but the material formulations and processing and fabrication techniques were refined enough for industry to take over. Researchers had identified, for example, the molecular ratios in the basic resins that yielded the best mechanical properties, that spray drying worked best for producing the precursor powders, and how to adjust that process to achieve different properties. They learned that conductive fillers coupled with a powerful microwave oven allowed for foaming and curing in a single step, and pulsing the microwave on and off produced a more homogeneous foam. They found that adding ceramic fibers to the powder precursors significantly improved fire-resistance. All these formulas and processes were optimized for each end product.

NASA waived its patents on the materials to allow Harvester International to produce it commercially, and in January of 1982, the company announced full-scale production of fire-resistant SOLIMIDE foams at a 25,000-square-foot facility in Illinois. Within two years, a company called Imi-Tech had acquired the operation, and several aircraft manufacturers were using SOLIMIDE products, mainly as a lightweight, fireproof thermal and acoustic insulator in fuselages (*Spinoff* 1984). The Navy was funding development of a slightly different version of the foam for use in ships.



The use of different laminates can alter the thermal and acoustic insulation properties of SOLIMIDE foams.

In 1988, Imi-Tech moved to Magnolia, Arkansas, doubling the size of its SOLIMIDE production facility—the plant where SOLIMIDE is still produced today.

A decade later, the material had replaced fiberglass insulation in the fuselages of many commercial airliners and was also used in spacecraft, satellites, industrial cryogenic applications, and the Navy's ships and submarines (*Spinoff* 1998).

Benefits

SOLIMIDE hasn't made it into airline seats or cabin panels, but it can now be found somewhere in 90 percent of commercial airliners in the western world. Almost every ship in the U.S. Navy uses it for thermal and acoustic insulation.

In 2014, Boyd Corporation, a global company that specializes in sealing, thermal, and protection solutions,

Almost every **ship** in the **U.S. Navy uses [SOLIMIDE]** for **thermal** and **acoustic insulation.**

The U.S. Navy was an early adopter of SOLIMIDE and helped fund some of its early development.

Image courtesy of the U.S. Navy

purchased the SOLIMIDE plant in Magnolia. Boyd had been a major consumer of the material for the commercial aerospace industry for years, says Richard Montgomery, field application engineer at Boyd, noting that the plant is the only one in the world that produces large quantities of polyimide foam. "It's a unique foam, in that it's lightweight, nonflammable, and a great insulator," he says.

All these qualities, in addition to its durability, acoustic insulation, and ease of handling, have made it a popular alternative to fiberglass for insulating commercial, private, and military airplane fuselages, where it saves hundreds of pounds on each plane, translating to fuel efficiency and safety improvements. Airframe manufacturers also commonly use SOLIMIDE to insulate ducts and electronics in planes. The Navy has specified the material as a thermal and acoustic insulation in applications where weight is a critical factor.

"The material aligns with industrial and design initiatives of today, and sales have continued to increase as new applications are found," says Mitch Weirenga, marketing manager at Boyd..

It is non-toxic and environmentally friendly, with some versions receiving a Greenguard Certification from Underwriters Laboratories—signifying low chemical emission—and it supports industry initiatives for minimizing the manufacturing carbon footprint and the treatment of goods at their end of life, Wierenga says. It also does not support microbial growth, making it ideal for medical applications in environments where condensation is a risk.

SOLIMIDE now comes in seven varieties, depending on the temperatures and other environmental needs of end users.

For spacecraft manufacturers, including NASA, two more of SOLIMIDE's qualities become important: It doesn't release any chemicals, which, in the absence of convection, can build up in and around spacecraft. And it has an enormous temperature range, staying flexible and resilient at temperatures from -300 °F to 575 °F, and barely expanding or contracting with temperature swings. "Most things, if you dip them in liquid nitrogen and drop them on the floor, they'll explode," says Montgomery. "Not SOLIMIDE."

James Williams, left, manager of Boyd Corporation's SOLIMIDE plant in Magnolia, Arkansas, shows SOLIMIDE panels to local Congressman Bruce Westerman during Westerman's 2016 visit to the plant.

Other applications include missile guidance systems, railcars, medical devices, solar energy systems, indoor climate control, electronics, and cryogenic pipelines and storage.

The fact that SOLIMIDE has no fibers or toxins has also made it attractive, for example as Europe is making an effort to get fiber insulation out of appliances and heating and ventilation systems, says James Williams, manager of the plant in Magnolia. The tiny fibers can be inhaled or get under the skin, which is dangerous to consumers. That's what led a manufacturer of heating appliances for hospitals to start using SOLIMIDE. And those who work directly with it appreciate SOLIMIDE's ease of handling. "Installers who work with the material absolutely love it for a number of reasons, the biggest being that they don't have to suit up with safety gear," says Williams. "That helps from a marketing standpoint."

Williams estimates that SOLIMIDE supports about 100 jobs at Boyd—40 at the plant he manages and 60 more who work with it at Boyd's Portland plant.

In 2016, Boyd commercialized a "densified" version of the material, which provides the same insulating qualities at about half the volume, making it work for small spaces. One application for this denser, harder material is in the cryogenic nitrogen generation systems in all large aircraft. As fuel is used up, these systems replace that fuel in the tanks with nonflammable nitrogen gas, preventing fire. Other applications include temperature control under the hoods of automobiles and in mobile electronics.

"We've found some niche markets for densified SOLIMIDE, and we're finding new ones every month," says Montgomery. ❖

AirMap Guides Drones toward Widespread Use

NASA Technology

The drones are coming for us all—and that's a good thing. While unmanned, remote-controlled, or programmed flight is not new, it is becoming increasingly sophisticated. New autonomous flying vehicles have incredible potential to change how we travel, how we ship our stuff, and how we keep track of our infrastructure. But first, we need a system to safely track all the new flying vehicles, and NASA is playing a big role in developing it.

"We have been doing air traffic management research for more than 35 years," says Parimal Kopardekar, principal investigator for NASA's Unmanned Aircraft Systems Traffic Management (UTM) project. "How do we enable new entrants, increase scalability, increase efficiency of current operations?"

But drone traffic is a game-changer, he says. Today, there are nearly 50,000 aircraft operations in a day across the United States. Daily drone flights, he predicts, will number in the millions.

"The current system will not be able to keep up with that," emphasizes Kopardekar, who runs UTM out of Ames Research Center. "We need a new way of enabling this: how to manage drones in a different way without overloading the air traffic system."

Today, most air traffic management is a human operation. While flights are tracked with radar, and increasingly GPS, around airports, human air traffic controllers must actively monitor and direct planes to avoid collisions.

But increase the number of aircraft by a couple orders of magnitude, and those human operators will quickly get overwhelmed. Kordpardekar had a vision of a highly automated system that would work hand-in-hand with the existing air traffic system, to keep the airspace safe for everyone.

NASA began working with the Federal Aviation Administration (FAA) on the UTM system in 2014. Under this model, which Kopardekar describes as a "share and care" environment rather than a "clearance" approach, operators share their trajectories and flight plans with each other, and onboard algorithms and sensors help to ensure all the aircraft safely avoid each other.

A small drone flies near Reno, Nevada, in a test done through NASA's Unmanned Aircraft Systems Traffic Management (UTM) project that aims to develop technology and systems to ensure safe integration of drones into the airspace. In the test, five drones simultaneously crossed paths at different altitudes, while some of the drones were flying beyond the line of site of their operators.

Technology Transfer

Kopardekar didn't want to develop this system in-house at NASA, however.

"We opened a whole new ecosystem," he says. "We opened it for anybody who wants to do that work. That's true competition, and as a result, you get even more innovation."

The NASA and FAA project partnered with dozens of private companies. The project also established a set of standards and requirements for third-party developers, which meant the innovative new tools being developed would work together and with the existing FAA air traffic management system.

One partner is Santa Monica, California-based AirMap Inc., which today sells what the company's cofounder and chairman, Ben Marcus, calls "the leading airspace management platform for drones in the world."

Working with NASA as well as with other industry partners, the company developed the AirMap UTM platform, which he says enables more than 100,000 drone flights per day, both commercial and hobbyist.

Although the company was founded independently of NASA's project, Marcus says NASA's influence permeates much of what the company does. "In a lot of ways, we're executing NASA's vision for UTM in a commercial sphere," he says.

Besides creating standards that allow different groups to work together and integrate their systems, Marcus notes that NASA coordinated operational flight testing and data collection, and served as an interface with the FAA, to help the regulating agency understand the potential of drone flights and how to manage them.

Benefits

The initial product, says Marcus, was a simple map to show drone operators where they were and were not

allowed to fly. Today that simple map has been enhanced in a number of ways. Now, with the free AirMap app for mobile devices, users can see a live view of the airspace around them and get alerts when other aircraft are flying nearby, as well as draft a flight plan and submit it to the FAA (and get notified if their actual flight deviates from the plan).

The latter makes logistics simpler for the drone operators and significantly easier for air traffic control managers. Before, Marcus explains, hobbyist flyers would call airports to notify them if they were nearby, which is required by the FAA whenever flying within five miles of an airport. "But managers didn't get useful info out of the phone calls because they'd say, 'Hey I'm flying by the 7-Eleven over here,' and the airport didn't really know what that meant."

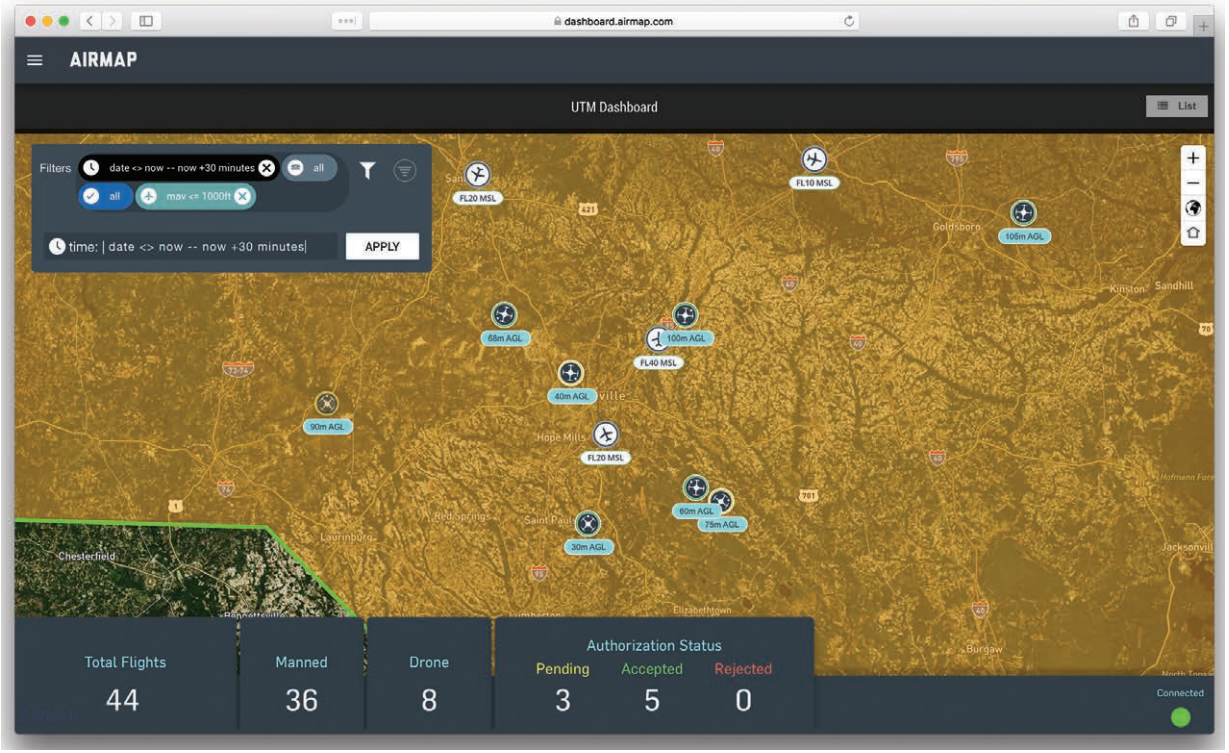
The AirMap UTM system provides airport authorities with software to visualize and monitor where the drone operators are flying, in real time. The system also includes a communication tool, so air traffic control managers can send messages directly to drone operators for safety assurance.

Today, AirMap UTM supports more than 500 airports in the United States and is authorized by the FAA as a Low-Altitude Authorization and Notification Capability service supplier so drone operators can get authorized access to fly in controlled airspace.

AirMap software has also been integrated into the vehicles themselves by some of the biggest drone manufacturers. That allows AirMap to provide geofencing, which automatically blocks the drone from flying in prohibited airspace, as well as to directly steer the drone, if the operator opts in. In addition, says Marcus, anyone building a drone can integrate the AirMap flight controller, which is available for free through the Dronecode open source platform.

AirMap's customers fall generally into two categories, he says. First are the airspace managers, by which he means national air navigation service providers around the world, including skyguide in Switzerland and the Air Navigation Services of the Czech Republic. They use AirMap to monitor low-altitude flight traffic and approve flight plans near airports.

The second category comprises drone makers and operators, as well as people making apps for them. For example, one company in Switzerland, Matternet, is using AirMap to enable a service that flies blood samples from the hospital to labs for testing. Matternet is now testing that same capability in North Carolina, as part of a Department of Transportation-approved pilot program to explore advanced use cases for unmanned aerial vehicles.



One partner in the UTM project is AirMap Inc, which, with NASA's support, has developed an airspace management platform used by drone operators and airport authorities to submit and approve flight plans, monitor the airspace in real time, and get alerts about restricted zones.

Current U.S. laws require special permission to fly beyond the line of sight of operators, but this pilot program is testing regulations and technology that would allow such flights routinely. AirMap is the unmanned traffic management platform for 6 of the 10 pilot groups around the country. These teams are working on disaster recovery, search and rescue, agriculture, inspection, package delivery, and more.

Likewise, AirMap's air traffic management dashboard helped incident managers coordinate manned and unmanned flights in Florida and Texas after hurricanes Harvey and Irma to help assess damage, inspect bridges, and monitor flooding.

Kopardekar says these kinds of flights, as well as drone deliveries and air taxis, are going to become more and more common. "We see a future where that is likely. How soon is yet to be determined, but our research will set the foundation to enable those operations."

Marcus says NASA's leadership has helped speed up that future. "We're very excited for what's coming with urban air mobility," he adds, "and eager to continue our collaboration with NASA in the years to come." ❖

Rockets, Rovers Spur New Offshore Drilling Safety Technology

Explosions that destroyed the *Deepwater Horizon* drilling vessel in 2010 were just the start of a disaster that resulted in millions of barrels of oil gushing into the Gulf of Mexico over the following months. Bastion Technologies helped well owner Transocean look for the cause of the debacle and ultimately came up with a way to prevent such disasters in the future, based on the company's experience working with NASA.

Image courtesy of the U.S. Coast Guard

NASA Technology

On the night of April 20, 2010, a flow of oil, gas, and mud erupted onto the floor of the *Deepwater Horizon* drilling vessel from the oil well below. As workers realized they were losing control of the well, they tried to activate its subsea blowout preventer, a massive device that's supposed to sever the drill pipe and seal it shut. But the outpouring continued. A plume of gas filled the rig floor and ignited, triggering two explosions and a fast-moving fire. The crew evacuated.

Eleven people were killed and 17 more seriously injured in the disaster. During repeated efforts to seal the well over the following months, somewhere between 3 and 5 million barrels of oil gushed into the Gulf of Mexico in the worst maritime oil spill in history.

Later investigations concluded that one set of rams that should have sheared the drill pipe was never properly triggered. The other set closed on the pipe but, because the pipe had bent or buckled, failed to shear it completely. The blowout was not contained, and the rig was subsequently lost.

One company involved in those investigations, Bastion Technologies Inc., gets most of its business from NASA. Now the Houston-based company is using knowledge gained from its years of experience with the Space Agency to prevent such disasters in the future.

Since its first contract with Johnson Space Center in 2002, Bastion has picked up work at most of NASA's field centers, primarily working in safety, mission assurance, and structural analysis. Not long after, the company started working in oil and gas, often applying expertise and lessons learned from planning for the rigors of space travel. Bastion's

first work with offshore-drilling giant Transocean was to develop a method of connecting and disconnecting a well's blowout preventer and its lower marine riser package, for example in the event of a storm. For that project, Bastion came up with a design based on experience it had with technology for docking spacecraft to the International Space Station.

With this experience, Bastion approached Transocean, which owned and operated *Deepwater Horizon*, to help analyze possible causes of the disaster and identify technology to prevent another one.

To solve the oil well problem, the company again used its experience with both NASA technology and the Agency's rigorous systems engineering methodology.

Virtually every subsea blowout preventer relies on a series of compressed-gas tanks to power its critical systems. These tanks when triggered, push pistons that force hydraulic fluid against the rams that shear and seal the well. This was where Bastion identified a weakness. "We said, they've got to get away from compressed gas," says Bastion President and CEO Jorge Hernandez.

Increased water pressure at ocean depths offsets the gas pressure in the tanks, he explains. "The deeper and deeper you get, efficiency just goes down the drain." Another problem is that, as the gas is released, it generates steadily less pressure, and in the end, very little of the hydraulic fluid is actually ejected from the accumulator. The tanks, of which there may be dozens in a single system, are also heavy, producing increased stress on the well, and the systems simply aren't sufficiently reliable, Hernandez adds.

"One of our NASA guys said, how about we use a propellant?"

Technology Transfer

Marshall Space Flight Center, where Bastion has worked for the last 12 years and where it serves as the prime contractor for safety and mission assurance, is where rockets are built and tested, including propulsion systems. The company also has employees at Stennis Space Center, which is primarily a rocket testing facility. "So we have quite a bit of propulsion-systems background," Hernandez says. Many of the people Bastion has hired for a contract at the Jet Propulsion Laboratory (JPL) previously worked on the Curiosity Mars rover, Mars Pathfinder, and other systems that used solid propellant to inflate airbags or shear parachute cords.

Bastion's idea was to replace pressurized gas with a solid propellant that would expand into gas when burned, generating a high-energy force.

"It was really just our NASA guys who worked on it," Hernandez says, noting that these were primarily the Bastion employees who work at Johnson, Marshall, and JPL.

The team settled on a hybrid solid propellant, something between the explosive propellants used to inflate airbags and the slow-burning, lower-pressure fuels used in solid rocket boosters. But it's not a simple system, and it was the team's NASA experience working with fuses, igniters, electronics, batteries, and software that made the idea a reality, Hernandez says. The company also brought to bear its primary NASA work of safety and mission assurance.

The first SureShear system was built in 2014, and the company was awarded a patent for it the following year. In early 2016, Bastion demonstrated the system for officials from the Bureau of Safety and Environmental Enforcement, which regulates offshore drilling, resulting in SureShear's official recognition as a drilling safety technology. The next year, the company tested a full-scale, subsea-ready version at the Transocean test facility.

Today, Bastion continues working with drillers and operators on subsea testing and seeking other commercial partners for collaborative development and deployment.

Benefits

SureShear is more than 99.9 percent reliable, Hernandez says. "The key to our system is that we're using all the

Many Bastion employees who work under contract to NASA have experience working with solid propellants like the one used in the company's SureShear system. For example, some who had worked with the Jet Propulsion Laboratory were familiar with solid propellants that detonated to inflate airbags on probes like the Spirit and Opportunity Mars rovers.

At demonstrations in late 2018 and early 2019, Bastion showed major players in the oil industry how five of its SureShear chambers (left) could power the very blowout preventer that failed to completely sever and seal the drill pipe in the *Deepwater Horizon* disaster (above). This 15,000-pound SureShear system replaces 170,000 pounds of compressed-gas tanks in a traditional system and severs the pipe about three times as fast.

hydraulic fluid." Because the burning propellant continues to expand into gas until the piston travels the full length of the pressure chamber, pressure never flags and all the fluid is expelled behind the rams that shear the drill pipe.

The system also generates significantly more power than conventional alternatives. Compressed-gas-based accumulators can only store gas at pressures up to around 6,000 pounds per square inch (psi), making that the most force they can ultimately exert on a drill pipe. Higher pressures would require thicker, heavier tanks, and the systems are already ungainly. Bastion's system, on the other hand, isn't pressurized until the propellant is ignited on the ocean floor, where the surrounding water pressure counteracts the internal pressure, ensuring the tank's integrity. The company expects SureShear to be able to achieve pressures of at least 10,000 psi—more than enough power to sever so-called "unshearables" like drill collars, should they end up between the rams.

The system's cutting power also allows it to be far smaller than traditional compressed-gas accumulators. A rig that might have required 10 compressed-gas-based accumulators totaling 70,000 pounds and taking up 314 cubic feet can instead use an 8,000-pound, 38-cubic-foot SureShear system. This reduces costs and increases capability for the driller, who can now drill in locations that are extremely sensitive to the weights and stresses exerted on the subsea conductor pipe. "What's killing them is the weight of the material," Hernandez says. "They want to keep the size down as much as possible."

The solid propellant has a guaranteed lifetime of at least 10 years in subsea conditions. And the arming and ignition subsystems use technology proven to NASA and military reliability standards.

Jeff Cardenas, who has worked in the oil and gas industry and is now operations manager on Bastion's JPL contract, notes that industry tends to view major investments in training, planning for an entire project's life cycle, and taking every safety precaution—NASA's approach—as inefficient. However, says Hernandez, "If we hadn't had that NASA experience, we wouldn't have been able to design and build SureShear." ❖

Wool Mask to Fight Fires in Space Inspires Fire Equipment on Earth

NASA Technology

A New Zealand-based company's work to help astronauts fight fires in case of an anomaly on the Orion spacecraft is already informing its line of wool filters for firefighters on Earth. The work is poised to guide the company's sheep-breeding program as well.

Astronauts on Orion, NASA's first crew-carrying space vehicle since the space shuttle, will be equipped with emergency breathing devices that were designed to protect astronauts during a fire on the International Space Station. But fire procedures on the two vessels will differ, so the Space Agency is looking to improve the respirator for Orion—for instance, by making it last longer.

Image courtesy of the European Space Agency

For the Orion spacecraft, NASA is improving the life of the emergency breathing device currently aboard the space station and pictured here during fire training at NASA's Johnson Space Center.

During a fire in space, astronauts are trained to wear respirators while they extinguish the blaze. But any fire would almost certainly release gases and particulates, so it could take hours of cleanup before the air is breathable without a mask.

The emergency breathing device NASA designed for the space station and other spacecraft includes a one-size-fits-all-astronauts (the general population may have a wider range of sizes), fire-resistant mask that can be fitted with a filter cartridge developed specifically for fire. The fire cartridge has 10 layers of filtering materials, including black carbon, co-catalysts, and rayon.

Unlike on station, where, in the event of a fire, astronauts would likely be able to move for a time to another of the numerous habitable modules, astronauts on Orion, a much smaller vehicle, could have to spend more time in a fire-contaminated space.

"Orion is a unique environment," says Justine Wiles, who is working on the respirator at Jacobs Engineering Group, a contractor at Johnson Space Center in Houston. "We have to adapt what we already have for this new environment."

Technology Transfer

Jacobs searched around the world for organizations that might have the technical expertise to extend the life of NASA's current respirator.

In May 2018, a call went out to Lanaco, a New Zealand company that develops and produces wool filter material, with a focus at that point on personal protective equipment in the workspace and air pollution filtration.

The Jacobs team was especially interested in particle filtration, which intrigued Lanaco founder Nick Davenport because, though his company hadn't been working on emergency breathing devices, he knew wool was well suited to such an application.

Davenport, a materials applications engineer, and his colleagues had noticed the interesting properties of wool while working with polymers about a decade earlier.

"The deeper we dug into the science of wool and how it could perform in an industrial application, using new science, the more we saw there was an opportunity," he says. Wool is naturally resistant to fire and bacteria, and it manages water well.

Davenport and his colleagues wondered why this extraordinary material wasn't being used for filtration around the world. They realized air filter technology was focused on synthetic materials, overlooking this natural alternative.

He founded Lanaco and developed his proprietary wool filter technology. The company has built up a specialized commercial flock of sheep by working with a top breeder to maximize the qualities that make good filters and to reduce the material's variability.

"We analyzed the wool fiber from hundreds of different types of sheep and then established a breeding program to specifically focus on the attributes that we needed to make the world's best all-natural fiber air filter for respiratory applications," Davenport says.

Wiles and her team at Jacobs were looking specifically for a prefilter that could fit over NASA's existing fire cartridge to increase the life of the system for Orion. Lanaco then began to tailor its Helix filter for the application.

The particles that would fly around in the event of a spacecraft fire—including droplets of water used to extinguish a blaze—are potentially small and hot, and the existing technology is typically made of polymers with a relatively low melting point, Davenport says. A product

New Zealand-based Lanaco is breeding sheep, pictured here, for its wool filters, which have also benefited from the company's research on fighting fires in space. The company expects its research on wool filter technology for NASA will eventually inform its sheep-breeding program.

like wool, which doesn't promote a fire or degrade rapidly under hot particles, has clear advantages.

"As a prefilter, our technology enables the main filter to function in the presence of those hot particles and dangerous gases," Davenport says.

Lanaco Chief Technology Officer Shaun Tan adds that it "does this by removing the bigger, nastier stuff, like water and toxic components that could stop the main filter from working."

Benefits

Prior to the NASA contract, Lanaco had not been working directly in the area of critical breathing applications. Now the company has some expertise, with wool performing particularly well in fire resistance and moisture management.

"We have commenced developing some of the features in the NASA application of our filters for use in critical respiratory applications," says Davenport. He's creating filters for Fire and Emergency New Zealand applications by testing and prototyping the product with local fire personnel. He expects to have a filter to offer them by 2020.

He says the firefighting services appreciate the ability of Lanaco's Helix filters to capture coarse, hot particles, filter well in high-moisture environments, and offer the lowest possible resistance to breathing.

"Working on the Orion project and understanding this very unique situation has allowed us to think more closely about how to design filters, specifically as it relates to fires, particles, and hot gases," Davenport says.

He notes that firefighters fleeing from an encroaching forest fire, for instance, may fear their respiratory gear could actually hinder their breathing while they're running. They will be more likely to wear a more effective system.

"If we can widen the envelope of performance that is offered to a first responder in a fire, we can certainly help," he says. "The rigor of our work with the NASA program is directly applicable to the fire service. It informs our formulations and complementary materials."

Davenport says the work will eventually guide Lanaco's science and breeding programs as well. He believes it will also continue to inspire consumer confidence in the company's existing markets, such as personal protective equipment, urban air pollution masks, and air purifiers.

"If it's good enough for an astronaut to use it, that's a big builder of confidence," he says. "It's a door opener." ❖

Autonomous Drone Navigation System Ends Reliance on GPS

NASA Technology

Self-piloted drone traffic may be just over the horizon, metaphorically speaking, but for now, vehicles cannot legally fly beyond the operator's line of sight, at least not without special permission. While the Federal Aviation Administration (FAA) works to craft drone regulations and engineers work to build the features that would meet those rules, however, some of this new technology is opening up applications that don't involve flying across town.

Using unmanned aerial systems (UAS) to inspect buildings, bridges, and other infrastructure, for example, or survey disaster sites doesn't necessarily require FAA compliance. An impediment to this sort of application, though, has been reliance on the GPS signals that such structures can obstruct. Without GPS, drone navigation drifts, making it difficult to register data from onboard sensors and, eventually, causing instability. With NASA's help, Pittsburgh-based Near Earth Autonomy is breaking drones' dependency on GPS.

NASA has taken a leading role in pioneering and fostering the advances necessary for safe autonomous flight, establishing its UAS Traffic Management (UTM) project, centered at Ames Research Center, in 2015. That year, Ames granted Phase I and II Small Business Innovation Research (SBIR) contracts to Near Earth Autonomy to build the technology for safe, self-piloted takeoff and landing without the use of GPS or maps.

As the UTM project brings on commercial partners, it directs them to focus efforts on the areas of need it has identified for future autonomous air traffic, says Parimal Kopardekar, the project's principal investigator. "One of the challenges we need to solve for drone traffic management is the ability to operate without GPS," he says.

That's partly because one of the FAA's requirements will be the ability to navigate in the event of a GPS outage and because GPS signals can often be degraded at low altitudes in urban areas—exactly where the highest precision is needed.

The problem is that most automated navigation systems start by determining their location with GPS, Kopardekar says. Devising a good alternative is challenging, not least because a small drone has limited power and can't carry much weight. "Whatever sensors we put on a drone have to have very low size, weight, and power."

Technology Transfer

Near Earth Autonomy's SBIR work focused on safely navigating the most difficult parts of a flight—the first and last 50 feet, says Sanjiv Singh, the company's CEO and cofounder. In practice, this meant flying entire, short missions with no GPS whatsoever. "If we didn't use any GPS, we can certainly deal with a GPS outage."

The company managed GPS-free navigation with a tricky technique known as simultaneous localization and mapping. As it flies, the drone has to build a map of its surroundings while tracking its own movement through that environment. An onboard lidar scanner senses physical surroundings and their distances by measuring how long laser pulses sent in all directions take to bounce back to a sensor. Meanwhile, inertial sensors record the craft's move-

Outfitted with Near Earth Autonomy's technology, a drone can navigate without GPS, letting it find its way through tunnels and other areas where satellite signals are blocked.

ments, assisted by a camera for visual tracking. Singh and his team had to create their own algorithms to continually process all of that data and "successively stitch together a map and use it to navigate," he says.

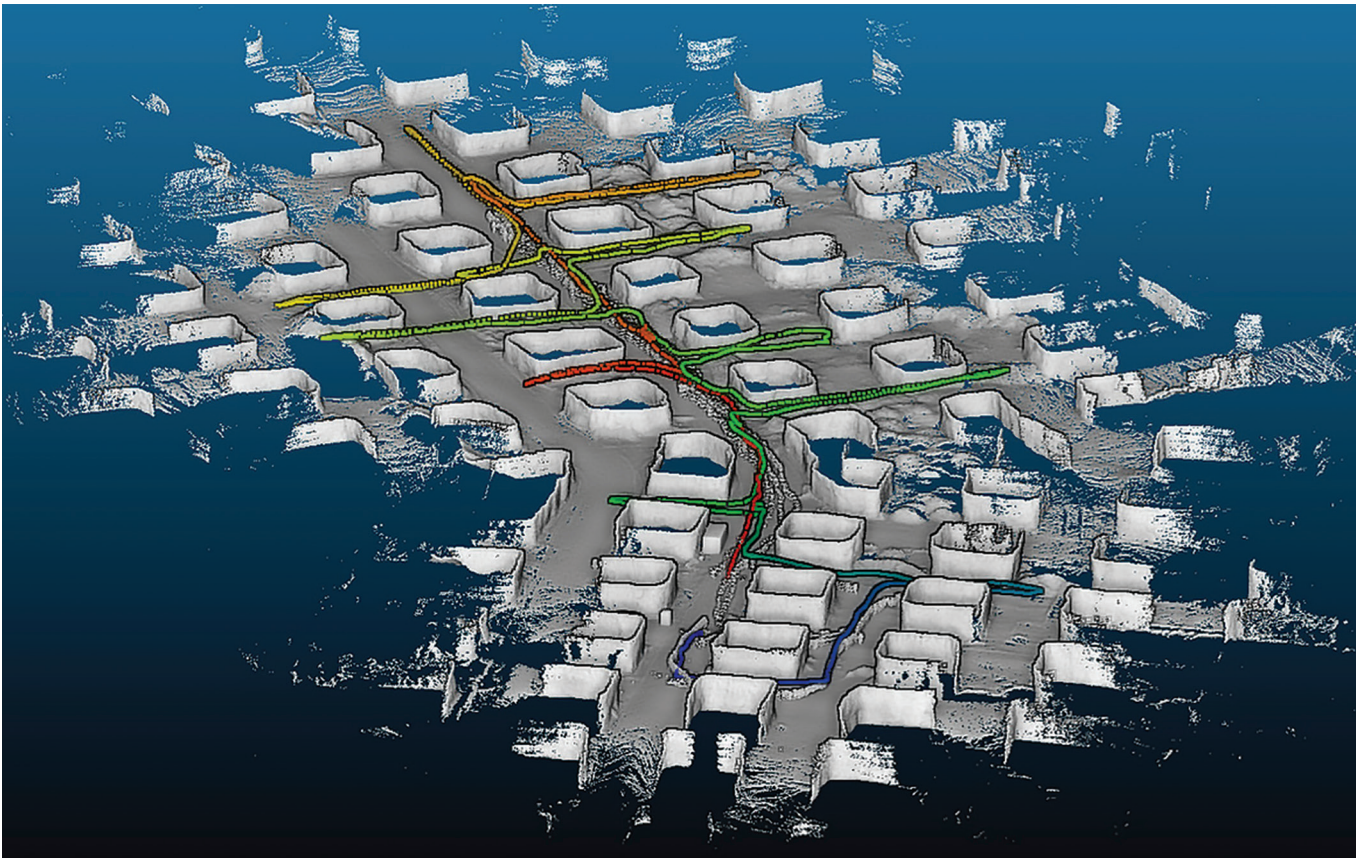
And the company was able to do it using small, state-of-the-art commercial components, minimizing the weight and cost of the payload.

"We've sort of shot ahead from a technical standpoint to show you could do this," Singh says. "This is the capability we demonstrate that gets more attention than almost anything we do."

Benefits

Kopardekar says NASA will have an interest in the technology not just for drone traffic management but also, for example, for missions over the poles, where GPS signals don't reach.

In the long term, Singh hopes the capability to navigate without GPS will help make FAA drone regulations a reality. "We can take our results and say, 'This is what such a system looks like, this is the complexity of such a device, what elements are involved, what conditions it works under.'"



> "This is the capability we demonstrate that gets more attention than almost anything we do."
>
> — Sanjiv Singh, Near Earth Autonomy

And it could one day enable capabilities such as autonomous urban transport and delivery.

For now, though, Near Earth Autonomy has—somewhat unexpectedly—received the most interest from entities that want drones to be able to navigate near or inside large, potentially GPS-disrupting structures. A group from Japan, interested in disaster site surveillance, is working with the company. Others are interested in inspecting buildings, tunnels, bridges, tanks, and towers. The military wants to map buildings, as well as carry out drone reconnaissance that isn't vulnerable to GPS denial.

The company has sold a few prototypes and is working with commercial and government entities to adapt the technology to specific applications and bring costs down. For different types of inspections, for example, drones will need different sets of tools and sensors. As Singh puts it, "Yes, it can fly in a building, but what's it doing in the building? How are people using it?" These are the questions the company is working with potential customers to answer.

But Singh says he might not be asking them if not for the UTM project. "The NASA SBIRs were extremely productive, relevant, and timely. They allowed us to take some chances and develop and demonstrate this technology and get a lot of interest." ❖

Near Earth Autonomy's simultaneous mapping and localization system builds a map of a drone's surroundings, such as this network of tunnels, while it tracks the craft's movement through that environment.

Smaller, Cheaper Lasers Can Detect Gas, Monitor Structures, Take Tissue Images

NASA Technology

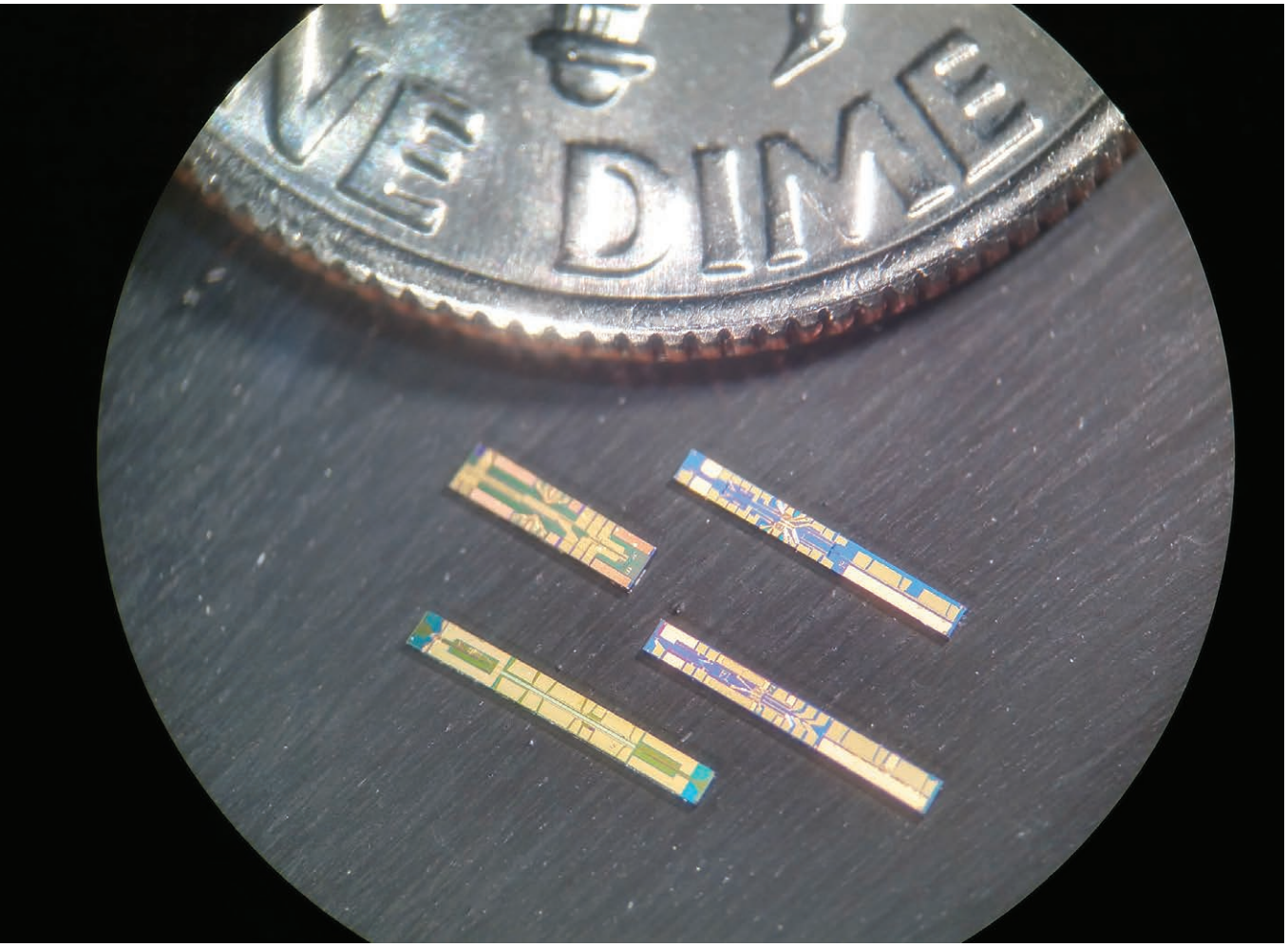
Since the invention of lasers in 1960, engineers have found countless ways to create these coherent, monochromatic beams of light and have harnessed them for just as many purposes. Light can behave in different ways, depending on its wavelength and intensity. Now, cutting-edge advances that one company made for NASA have resulted in better lasers for gas sensing, and they're likely to improve laser-based structural monitoring and medical imaging.

To understand climate change, it's important to monitor greenhouse gases in the atmosphere. While we have been measuring carbon dioxide from satellites, though, the technology for satellite detection of methane, a more powerful greenhouse gas, didn't exist until recently.

By 2016, NASA engineers were working to eliminate that blind spot. Haris Riris, an optical physicist in the Atmospheric Chemistry and Dynamics Branch at Goddard Space Flight Center, had been leading a team working to develop a lidar called the Methane Sounder to measure methane. It would send a pulsed laser beam into the atmosphere and analyze the reflected light to detect the presence of methane in the air. It would be able to detect methane through most cloud cover and at night, unlike passive spectrometers that use reflected sunlight to detect the gas.

There are a few different wavelengths of light that can be used to detect methane, but the one that runs into the least atmospheric interference and delivers the best results is the near-infrared wavelength of about 1,650 nanometers, which has been difficult to generate with lasers. And the team wanted the laser to rapidly scan from a slightly shorter to a slightly longer wavelength. There was no commercially available laser that met these requirements.

Haris Riris, left, principal investigator for the Methane Sounder at Goddard Space Flight Center, and Stewart Wu prepare a prototype of the device before test flying it in 2011. Freedom Photonics later developed a laser for the sounder, leading to advances the company is turning into commercial products for gas sensing.



Freedom Photonics' tiny laser chips are dwarfed by a dime.

Technology Transfer

A company called Freedom Photonics LLC, based in Santa Barbara, California, was working at the time under a pair of Small Business Innovation Research (SBIR) contracts with Armstrong Flight Research Center to develop a wavelength-swept laser. That means it can tune linearly across a range of wavelengths at speeds of hundreds or thousands of times per second.

The company specializes in chip-scale semiconductor lasers, which are much smaller, cheaper, simpler, and more energy-efficient than other types of tunable lasers. Riris notes that the company's lasers are enabled by the use of specialized reflectors in the laser cavities, known as distributed Bragg reflectors, which let them rapidly tune across wavelengths without creating any adverse effects.

In 2016, NASA selected Freedom Photonics to receive funding through the Tipping Point solicitation to build a high-power, narrowly tunable laser to support Riris' Methane Sounder. That same year, the company won two SBIR contracts with Goddard to develop a separate, lower-powered, widely tunable laser around the same wavelength that could sense other gases in addition to methane.

For the widely tunable version, "we had to start from scratch, with a different semiconductor material, and design a device that works with its properties," says Milan Mashanovitch, Freedom Photonics' cofounder and CEO. "But the methods used to package the laser into a module and align the optical fiber and plug it into the system are shared."

He says creating the narrowly tunable laser for the Methane Sounder, which is an order of magnitude more powerful than any tunable laser the company had built before, was even more of a technical challenge.

Riris says attaining that higher power meant changing the entire architecture of the laser. "There were doubts about whether it could be done," he recalls. "But it's all semiconductor physics, and they've got a good handle on it."

He says the high power would make the methane sensor more accurate, while the semiconductor laser design makes for a simpler, smaller, cheaper lidar.

Benefits

The simplicity, high reliability, and attendant low cost, size, weight, and energy consumption are the main advantages of a semiconductor laser, says Mashanovitch.

"Semiconductor lasers are made on a semiconductor wafer, and you can make thousands of those laser chips on a single wafer," he says, noting that the result is "a 10-times reduction in cost" when compared to solid-state

lasers, which typically involve multiple laser sources and other additional components.

The widely tunable 1,650-nanometer-wavelength laser built under Goddard SBIR funding is commercially available, with most customers using it in gas-sensing applications. Freedom Photonics sells its lasers to customers who incorporate them into end products. In addition to environmental monitoring, gas-sensing applications can include looking for emissions from oil and gas wells, locating leaks in gas lines, running safety checks at chemical plants, or even measuring methane output from cattle feedlots. Mashanovitch would like to see them deployed on drones, which wouldn't be possible with larger, less-efficient traditional lasers.

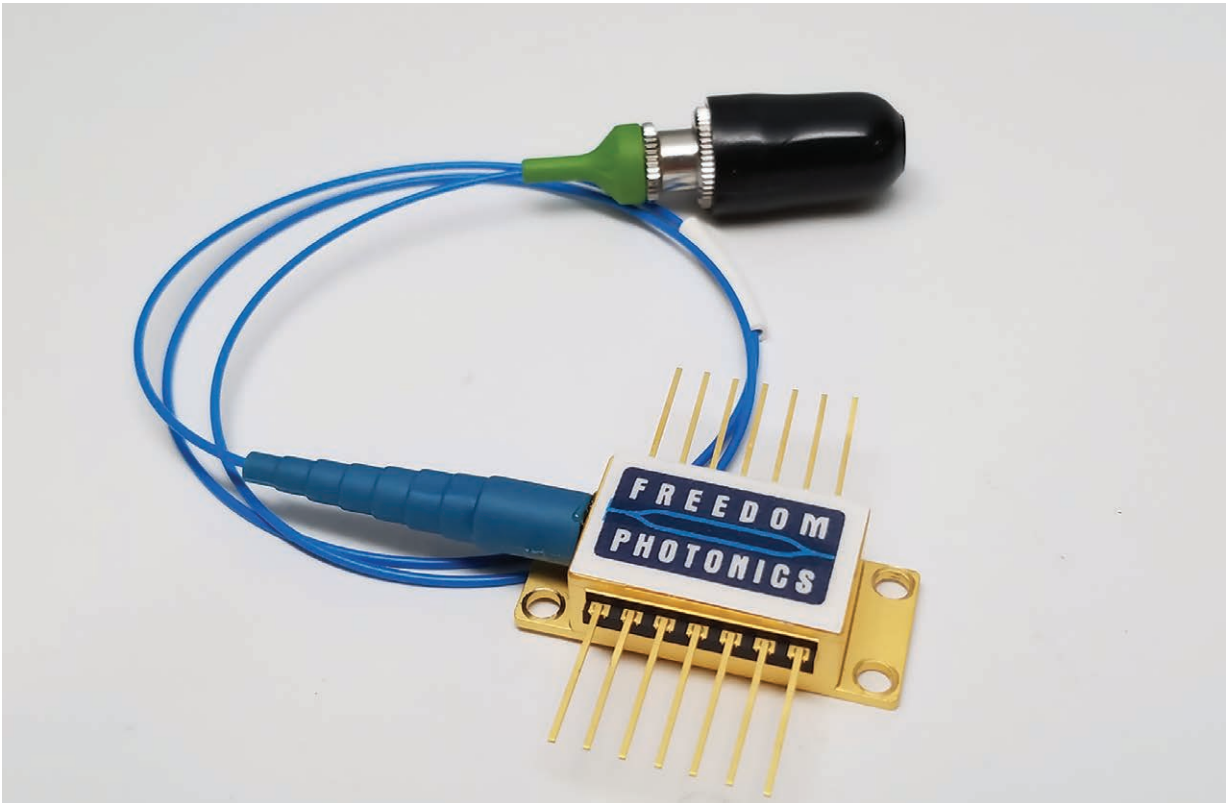
He also sees a future for the laser in what's known as fiber sensing. Fiber-optic cables on or embedded in the surface of a structure, such as an aircraft wing or a pressure vessel, are inscribed with periodic distributed Bragg reflectors—the same structures used in Freedom Photonics' laser cavities. As a laser is shone down the length of the fiber, the Bragg reflectors bounce back only a select few wavelengths of light, transmitting the rest. By observing changes in the frequencies that are reflected or transmitted, a computer can detect changes in temperature, strain, and other characteristics of the surface, which is useful for structural health monitoring.

This was the application for which Armstrong first contracted the company. Freedom Photonics' solution replaced a mechanically tunable laser Armstrong was using for fiber sensing with a unit that is 5 to 10 times cheaper.

Mashanovitch says customers interested in fiber sensing would benefit from the ability to extend its lasers' ranges into the 1,650-nanometer region of the spectrum, but the company first needs a tunable laser that can bridge the gap between about 1,570 and 1,620 nanometers. "It will happen," he says.

The wavelength-swept laser capability developed for Armstrong, which required changes to both the laser chip structure and the control electronics, will also find commercial applications. For example, fast sweeping across frequencies is necessary for optical coherence tomography, a high-resolution imaging technique used in ophthalmology, cardiology, dermatology, and other disciplines. It's a field the company is getting into, having found several customers for lasers incorporating the chips it developed for Armstrong, and Mashanovitch says Freedom Photonics has combined the chip and control electronics for sweeping into a single module that's available for customers to try out.

"At all wavelengths, this is going to be the highest-performance swept laser available," he says.



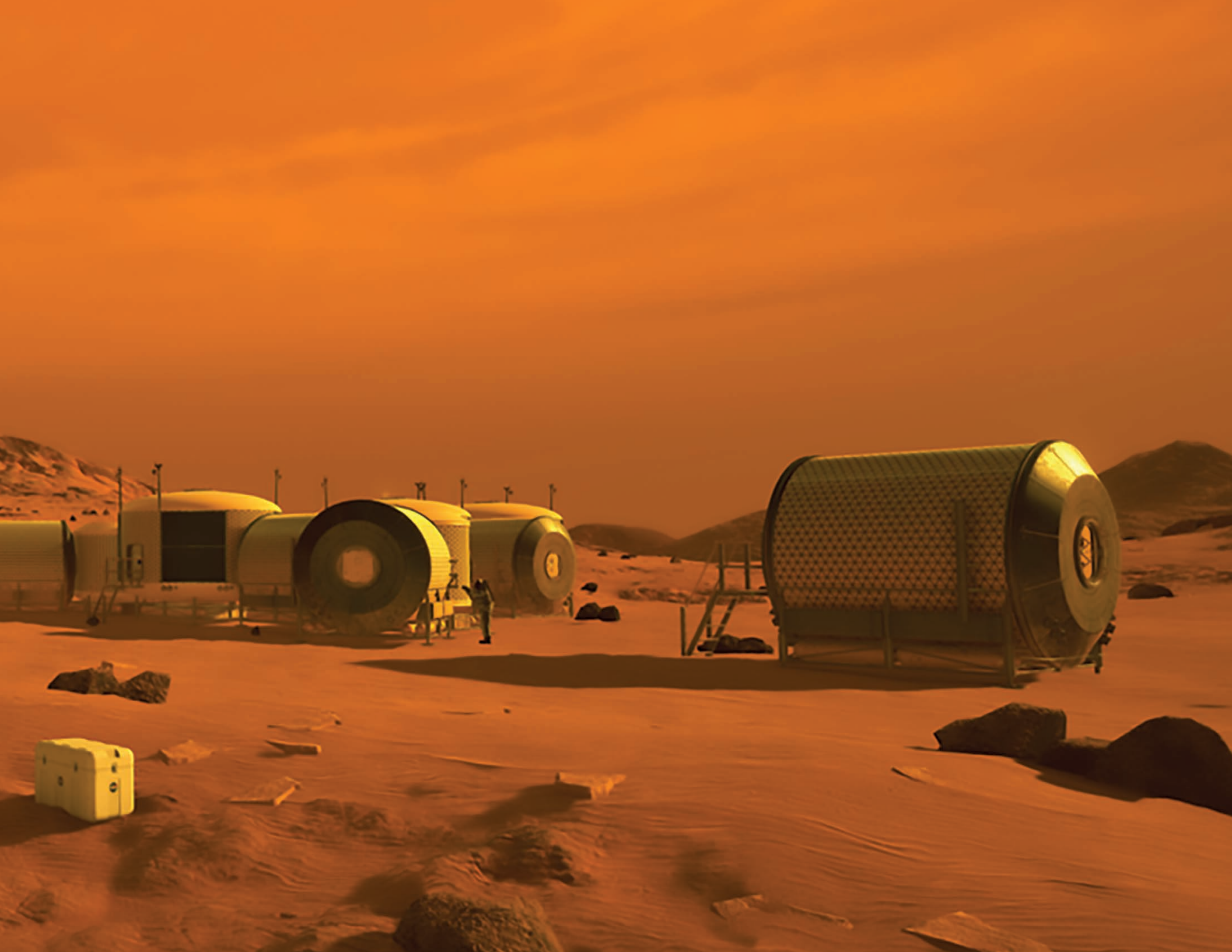
The company originally developed its 1,650-nanometer-wavelength tunable laser with SBIR funding from Goddard, and it's now available for gas-sensing applications such as monitoring the atmosphere and looking for emissions at oil wells, gas lines, and chemical plants.

And the high-powered narrowly tunable laser the company developed for Riris' Methane Sounder just became commercially available. It enables high-resolution, highly sensitive methane detection from an aircraft or spacecraft.

"This has helped us on many fronts," Mashanovitch says of the NASA work. "It's an opportunity to work with expert users, helping us to become better at what we do and helping us move into these new markets more successfully." ❖

Consumer Goods

When you look around your home, do you see NASA spinoffs? The astronaut experience has inspired many consumer goods since the early days of the space program. Some, such as freeze-dried foods and radiant barrier insulation, are classics. Others are brand new, such as a joystick that allows drones to be controlled with a single hand and a massage chair incorporating research on astronauts' posture. Research on power systems and nanoparticles has also ended up in consumers' hands.



Astronaut Experience Inspires Single-Handed Drone Flight Controller

Astronaut Scott Parazynski peers into a window of the International Space Station during a spacewalk in 2001. After he retired from NASA, Parazynski launched a company using his experience training and in space to design a new controller for drones.

NASA Technology

Astronaut Scott Parazynski has flown airplanes, climbed Mount Everest, and scuba-dived deep in a volcanic lake—but he says floating in space was like nothing else he's ever experienced. He loved "the freedom floating in space gives you, the ability to move perfectly in 3D space"—and the experience helped inspire and inform his latest invention: a joystick that puts all the primary drone fight controls into a single hand and will one day, he hopes, revolutionize robotic surgery.

Parazynski spent 17 years as an astronaut and conducted seven spacewalks, including four in a single space shuttle mission, becoming the second astronaut ever to accomplish that feat. In the final, unplanned spacewalk of the 2007 mission, he went farther from the airlock than any previous astronaut to repair a damaged solar array.

Moving through zero gravity allowed maneuvering that just isn't possible when gravity is a factor, he recalls, describing how you can manipulate your direction not just moving back and forth, sideways, and up and down (the x, y, and z axes), but through rotations (pitch, yaw, and roll). "There's a precision of flight you get when you're moving in space. It's really missing in all the ways we move here on Earth."

In total, Parazynski spent more than 47 hours spacewalking in his more than eight weeks in orbit, and he spent many, many more hours and weeks training for the experience. "I flew the robotic arm aboard the space shuttle, I helped assemble the space station arm," he says, "and I spent a lot of time training in a virtual trainer getting ready for flight, using the translational hand controller and rotational hand controller for the robotic arm and simulator."

This is standard operating procedure, explains Eddie Paddock, who manages the virtual reality laboratory where astronauts train at Johnson Space Center. For example, there are both ground simulators and onboard simulators for all the different robotics on the space station.

Many of those are two-handed, as Parazynski noted, with one hand controlling translational movement (forward, sideways, and vertical) and the other controlling rotational movement. Astronauts spend around six months training on the ground for operations like vehicle capture, Paddock says, and then will brush up again on board before the actual attempt.

Likewise, before any EVA (extravehicular activity, the technical term for a spacewalk), every astronaut is also required to complete four to eight two-hour training sessions, as well as an on-orbit refresher, on the SAFER system, the spacesuit jetpack that activates in an emergency if the astronaut's tether to the station were to snap.

In the SAFER system (SAFER stands for Simplified Aid for EVA Rescue), a single, small hand controller pops out of the suit, Paddock says. The controller "controls four degrees of freedom in each mode: x, y, z, and one axis of rotation (pitch) in one mode, and then with a push of a button, can switch to rotation mode, to control pitch, yaw, and roll, as well as x."

Technology Transfer

Parazynski took all the experience he had with astronaut robotics controllers as well as aircraft joysticks into his next venture as an entrepreneur. But it was his experience as a physician that first gave him the idea.

Unlike most standard drone controllers that use two-thumb joystick models, the FT Aviator puts all the primary drone flight controls in one hand, freeing up the other hand to complete other tasks, such as controlling an onboard camera. The controller also has a mount for a smartphone, allowing the operator to easily see the "drone's-eye view."

After he retired from NASA, Parazynski, who also holds a medical degree and trained in emergency medicine and trauma, took a position as the chief technology officer at a hospital in Houston. When he started to look at robotic surgical tools, he was not impressed.

"Of course a master surgeon can have great outcomes," he emphasizes, and indeed robotic surgery has led to many safer, less-invasive surgical procedures. But the tools are clunky, he noticed, and require a lot of hands-on training on fundamental maneuvers. "If a surgeon only does a robotic case every other week, outcomes are not nearly as good," he says.

He saw an opportunity to use his space and piloting experience with hand controllers to build something better. He teamed up with George Guerrero and founded a company, Houston-based Fluidity Technologies Inc., to create a better controller for robotic surgery.

"What's really interesting, the core tech goes back to the Mercury Program," Parazynski says, referring to joysticks for rotational control. In the earliest designs for the Mercury spacecraft, yaw (rotation around a vertical axis) was controlled with foot pedals. However, because of high g-loads, the way spacesuits restricted leg movement, and general weight and space limitations, engineers needed instead to create a three-axis rotational hand controller for yaw, pitch, and roll.

"Fast-forward several decades and additional innovation, and we have the FT Aviator, our first product, which allows us to move in up to six degrees of motion with a single hand."

Benefits

Fluidity Tech launched the FT Aviator with a Kickstarter campaign in November 2018, raising over $100,000 and generating hundreds of pre-orders. But as the name suggests, it's a controller for aviation, specifically for flying drones, rather than robotic surgery.

Surgery is still the ultimate goal, Parazynski says, but the process of getting FDA approval is long and arduous, so in the meantime, to launch the business and start turning a profit, the company decided to apply its controller to the drone market. "It's one of the most rapidly growing industries and has a much lower bar for regulatory hurdles," he says.

The FT Aviator is currently compatible with a number of models from drone-maker DJI, which offers a software developer kit designed to enable third-party accessories. But after a high-profile appearance at popular electronics trade show CES in Las Vegas in January 2019, where it was named a CES Innovation Awards 2019 Honoree, Parazynski said he was fielding meetings with other companies interested in partnering with Fluidity Tech to integrate the new controller—including helicopter manufacturers and surgical and medical manufacturing companies.

The biggest advantage of the new controller, Parazynski says, is that it is far more intuitive than the industry-standard, two-thumb joystick models. With FT Aviator, the pilot grips the controller with the whole hand, resting the thumb at the top. That means the thumb tip movement correlates to the movement of the aircraft: "You lift up your thumb, you're going to climb. If you push forward, you'll move forward. And so on. Within a matter of moments, your surrogate drone is your thumb tip and you're weaving through the sky like Luke Skywalker," he says.

In other words, "You can fly like an astronaut."

The other main benefit is that the single joystick frees up the other hand to do non-flight-related tasks. The FT Aviator makes that very easy by building in camera controls to the base of the unit, as well as a mount for a smartphone or tablet to view the camera feed or manipulate any other relevant app.

That means a single person can accomplish tasks that previously required two sets of hands, which could provide significant cost savings in businesses where drone imagery is becoming increasingly important, from cinematography to real estate, roofing, and utilities inspections.

The same benefits apply beyond drones, Parazynski emphasizes, and he sees his one-handed controller taking on new industries in the near future. "We can use our technology in a wide range of applications, but we wouldn't necessarily want or need to create a new controller for every application. We can be a provider of a smart human-machine interface—the underpinnings of the controller that other providers could then build around." ❖

Freeze-Dried Foods Nourish Adventurers and the Imagination

NASA Technology

Freeze-dried food, today, is commonplace. It's in the baby food aisle and next to the dried apricots. Hikers carry it on backwoods treks and doomsday preppers stock it in their basements. But first, astronauts brought it on trips into orbit—and NASA helped create a novelty ice cream treat to connect young museum visitors to the wonder of space exploration.

In the early days of the space program, one of the many problems to solve was feeding the astronauts during their time away from Earth. Food needed to be shelf-stable and long lasting, and it needed to pack small and light and be easy to prepare.

NASA funded research on an array of possible food preservation techniques. "Of these, the most prominent are: dehydration, freeze-drying, intermediate moisture, pasteurization by irradiation, and nitrogen packing. None of these methods of preserving is new, but NASA has contributed to and stimulated advances in this area," explains a 1971 report prepared for the Agency's Technology Utilization Office.

In the earliest human missions, the Mercury flights, astronauts ate bite-sized cubes, freeze-dried powders, and semi-liquids squeezed out of aluminum tubes like toothpaste. Not only were the foods unappetizing, but they were hard to rehydrate and prone to sending crumbs floating into the spacecraft's instruments.

The astronauts complained, and for the Gemini missions, NASA went back to work. Among other requirements, the team was looking for "food that could be reconstituted in cold (approximately 80 °F) water," according to the 1971 report, in just 10 minutes or less. Previously, reconstituting dried food required boiling (or near-boiling) water, and most foods needed a good 20 minutes to prepare.

NASA funded research at the Army Natick Laboratories, which was able to develop special gravies that, when freeze-dried, could be reconstituted with 80-degree water in just five minutes. The new gravies were encased in a special plastic container that made it easier to mix in the water.

In the decades since, NASA has continued to improve the cuisine it sends for its astronauts—among other advances, astronauts on the International Space Station have access to a refrigerator for fresh fruits, as well as an oven to better heat up their meals—but freeze-drying continues to play a role. Not only does it help preserve nutritional value and extend shelf life, but removing the water also reduces the weight significantly, which is always an important consideration in space travel.

Technology Transfer

With millions of people around the world riveted to TV footage of astronauts landing on the Moon, interest in the space program grew enormously in the late 1960s and early '70s. Looking to capture—and expand—that interest, museums developed exhibits on space exploration, and their gift shops offered new ways for visitors to take the experience home. In 1973, the visitor center at Ames Research Center in California had a new idea: what if visitors could taste astronaut food?

Freeze-dried food was key in the astronaut diet at the time but still only just starting to hit the wider market. Ames got in touch with Boulder, Colorado-based American Outdoor Products, one of the few companies making freeze-dried food for the consumer market.

The company was started in 1951 by a Girl Scouts leader interested in lighter foods to take camping. Until then, the best option was heavy canned food. She decided to make dried and dehydrated foods.

When NASA improved methods for freeze-drying food, the dried food industry began adopting it too, says current President Rodney Smith, whose father bought the company with a friend in 1971.

"Freeze-drying offered the opportunity to have longer shelf life, quicker rehydration, and better nutrition than dehydrated food could," he explains. "So that's why they started using freeze-dried as much as they could."

By 1973, when Ames got in touch, American Outdoor Products was becoming a known source for freeze-dried meals like stews and even pasta dishes for serious campers and backpackers. But Ames wanted something different. "They called us, asked us if we did a freeze-dried ice cream," Smith says. "We said, 'No, but we can.'"

Of course, it required some additional innovation, even beyond the basic techniques NASA had already improved and popularized. No one had ever made freeze-dried ice cream.

"Freeze-drying is a basic principle, but a difficult process," explains Smith. "It takes anywhere from 8 to 24 hours. Ice cream takes 24 hours." The first step is to freeze the food to an extremely low temperature, he says, around 40 degrees below zero. The item is then placed in a vacuum

In the earliest days of human spaceflight, food needed to be compact, have a long shelf-life, and able to be reconstituted with relatively cold water. It also had to be packaged so crumbs would not fly loose. This photo shows water being injected into a packet of dehydrated roast beef, alongside sides, prepared for the Gemini III flight.

> “They called us, asked us if we did a freeze-dried ice cream. We said, ‘No, but we can.’”
>
> — Rodney Smith, American Outdoor Products

chamber, which lowers the pressure around the food. When heat is added at that low pressure, the water content within the food sublimates, or transforms directly to a gas.

That water vapor is sucked out of the chamber, and the process repeats, Smiths says, anywhere from 20 to 100 times. At the end, more than 99 percent of the water has been removed.

Benefits

At the beginning, Smith says, the company would freeze-dry gallon buckets of ice cream, and then chip out portions to wrap individually and sell. Later, they found a supplier of sliced Neapolitan ice cream.

Today, they sell ice cream sandwiches, still in the classic Neapolitan flavor combination. In whatever shape, however, Astronaut Ice Cream has proven a big seller: it is now available at more than 1,000 retailers around the world and is the top seller in the Smithsonian Air and Space Museum gift shop, according to Astronaut Foods’ executive sales director, Kelly Cavill.

“Today we’re on third-generation brand loyalty: grandparents buying it for their grandkids,” she says. “It stimulates conversation. Do astronauts really eat this? How do you make it?”

Astronaut Foods now also sells additional freeze-dried treats, including fruits and yogurt, and in 2019, the company planned to add to its line Astrodog, a freeze-dried treat for pets.

But the company also continues to sell an even wider range of freeze-dried foods through its other divisions to its core market of backpackers and campers, using the techniques popularized and improved by NASA, says Smith. One of their best-selling items? Freeze-dried fettucine Alfredo. “The beauty of a freeze-dried noodle is that it keeps its shape. It doesn’t disintegrate like a standard dehydrated noodle would,” Smith says.

Of course, noodle integrity is only one of the benefits of freeze-drying, Smith emphasizes. Compared to traditional dehydration techniques, which can extract as much as 92 or 96 percent of water content, freeze-drying gets out more than 99 percent of the water, which leaves a lighter product. It’s also, as NASA found for its astronauts, easier to rehydrate.

Just as important is what it leaves behind. “Freeze-drying offers the best shelf life and preserves the most minerals, enzymes, and other nutrients,” Smith says. “All it takes out is just the water.” ❖

Here U.S. astronaut Sunita Williams enjoys a cup of ice cream. Unlike during early missions, the International Space Station is equipped with a freezer, an oven, a microwave, and other tools to store and prepare fresh food.

Although freeze-dried ice cream sandwiches were not actually part of the astronaut diet, the treats took advantage of advances in freeze-drying techniques NASA pioneered for its missions and were first created at the request of Ames Research Center’s Visitor Center.

Carbon-Fiber Heat Sink Makes Batteries Safer for Electric Cars, Bikes, and More

NASA Technology

Batteries have come a long way in recent years. Lithium-ion batteries in particular are more powerful, longer-lasting, and smaller—and they are powering ever more devices, from smart watches and phones to electric cars, and even electric-powered aircraft.

However, one of the biggest challenges of these highly energy-dense batteries is heat management, and in particular avoiding a short that explodes.

As batteries generate power, they also generate heat, which can be damaging to sensitive electronics nearby. Larger batteries are typically made up of packs of dozens or hundreds of cells working together, which means even more heat.

A bigger problem in lithium-ion batteries is a phenomenon called thermal runaway, when a cell overheats—which can be caused by a latent defect that appears in about one in every 5 million lithium-ion cells. That can cause a catastrophic response in the ones next door, setting off a chain reaction. Not only is this disastrous for the electronics, but it could result in a life-threatening explosion.

To deal with heat, batteries often include a heat sink: a conductive material (most often copper or aluminum) that carries heat away from the cell. In some cases, heat sinks employ a phase-change material that "soaks up" the heat as it melts or vaporizes, explains Eric Darcy of Johnson Space Center, who has worked on batteries for NASA over three decades.

That was the case with a massive 350 amp-hour battery for the later-cancelled X-38 crew return vehicle. The initial battery design overheated during performance tests in part because it was fastened to non-conductive composite materials in the vehicle, instead of metal, which kept it from effectively carrying away heat.

Working with a company called Energy Science Labs, founded by Tim Knowles, they converted the base of the battery into a heat sink with 30 pounds of wax laced with carbon fiber to make it more conductive.

U.S. astronaut Christina Koch enters an airlock on the space station after a successful spacewalk to upgrade batteries and adapter plates for the power storage system. In space, NASA relies on batteries to power everything from spacesuit systems to vehicles to life support on the space station, and so it devotes considerable research to improving power and safety.

However, the new heat sink also added 120 pounds to the vehicle's mass—hardly ideal when it came to meeting launch requirements.

Technology Transfer

In 2014, Energy Science Labs merged with Campbell, California-based KULR Technology, which also focuses on thermal management, and together they have continued to collaborate with NASA.

Since the X-38 battery project, KULR phase-change heat sinks have been used and improved in a variety of NASA projects all the way through the Neutron Star Interior Composition Explorer instrument installed aboard the International Space Station in June 2017.

"We're a direct beneficiary of the technology push that NASA requires and also the funding that NASA gives to

In a series of Small Business Innovation Research (SBIR) contracts, Darcy says, "KULR proved NASA could have saved half the mass or more in the base of the X-38 battery if we had gone to a vaporizing heat sink," using water instead of wax. That's because evaporating water transfers 10 times as much heat from the battery as melting wax.

KULR has also taken advantage of a battery advance Darcy created during a sabbatical at National Renewable Energy Labs (NREL) in Colorado: an internal short circuit (ISC) device that makes testing for thermal runaway much easier.

To ensure a battery pack is built with enough safeguards to keep a single cell's failure from propagating, engineers need to see what happens when a cell fails. That means overheating or puncturing a cell as it operates, which is hard to do in the middle of a battery pack, where some of the most dangerous shorts occur.

Darcy's ISC device allows engineers to trigger a short circuit on demand within a battery pack. The resulting failure acts more like the occasional faulty cells that turn up in real life, which means tests are more accurate. KULR has signed an exclusive license for the technology, which was co-patented by NREL and NASA, and will be producing it on a large scale for its customers to improve their own safety testing.

In 2015, KULR signed on for yet another NASA project with Darcy, to develop a thermal runaway shield (TRS) for spacesuit lithium-ion battery packs. The company, building on concepts it had been working on with NASA, the Department of Defense, and others over the decades, decided on a water-vaporizing heat sink encased in carbon fiber. As they had proven on the X-38 project, vaporizing heat sinks can save on weight and size. Likewise, carbon fiber is very lightweight—and it can withstand extremely high temperatures, a necessity when lithium-ion cells can reach 1,800 °F in thermal runaway.

Because heat exchangers need a large surface area to transfer heat, the company built its TRS using carbon-fiber processed into velvet, a material pioneered by Knowles. "Velvet has an order of magnitude higher surface area than flat materials," Mo notes.

KULR built several prototypes, and Darcy put them through their paces, including testing with an ISC device trigger cell. "One of his studies showed that our TRS was the lightest and kept the temperature the coolest of all the things he tested," Mo says.

KULR Technology specializes in safe management of battery heat. Working with NASA, as well as receiving project and SBIR funding more than once over the years, helped the company develop new products, including this thermal runaway shield that protects lithium-ion battery cells from each other. If one overheats, the shield will contain the heat so it doesn't set off a chain reaction.

Benefits

That was encouraging, so the company kept working. "By 2017, the TRS was ready for commercial prime time," he says. "It takes a lot of customization to fine-tune the carbon fiber: how much liquid is in the system, as well as what the enclosure needs to be, to fit into a customer's end product. A lot more research went into how to build that tech into a system."

By early 2019, the company was already seeing the TRS in some of its customers' products: one car company was in final testing before rolling it out commercially, and several others were expected to be doing the same by the end of the year. "It will be in every category," Mo says, from satellites and spacecraft to electric bikes and scooters and eventually electric cars, drones, and planes.

The TRS plays a part, he says, in making any batteries safer and more powerful. Batteries work better—recharge and discharge faster—at optimal temperatures, so good thermal management has always been important. But the threat of thermal runaway explosions in lithium-ion batteries "presents a new class of risk for these products," Mo says; now thermal management is a critical safety issue.

Saving weight by using carbon fiber is also important, especially in vehicles: "Every ounce of weight is sucking juice out of the battery, reducing the range," Mo notes.

The company has also become a founding member of the Global Alliance for Battery Safety alongside NASA, the Department of Energy, the National Renewable Energy Laboratory, the Chinese National Energy Storage Alliance, and several battery manufacturers and logistics companies. The group will work to create and promote best practices for battery safety, Mo says, using Darcy's ISC device and KULR's TRS as the starting point.

He credits the NASA funding with helping build such a highly advanced product. "NASA forced us to build something quite exotic to start out with," he says, with a high safety margin and a budget to match. "And then in the years after, it becomes really about how to save significant cost in the material and manufacturing for the end customer, where literally every penny counts." ❖

“We’re a direct **beneficiary** of the **technology push** that **NASA requires** and also **the funding** that **NASA gives** to the **team to enable** us to **push** the **envelope.”**

— Michael Mo, KULR Technology

Battery-powered devices, from scooters to cell phones to cars, are gaining in popularity around the world. KULR’s heat management and battery safety testing products, developed with and by NASA, help make safer and more powerful batteries for these applications.

Nanotechnology Repairs Engine Damage in Cars

NASA Technology

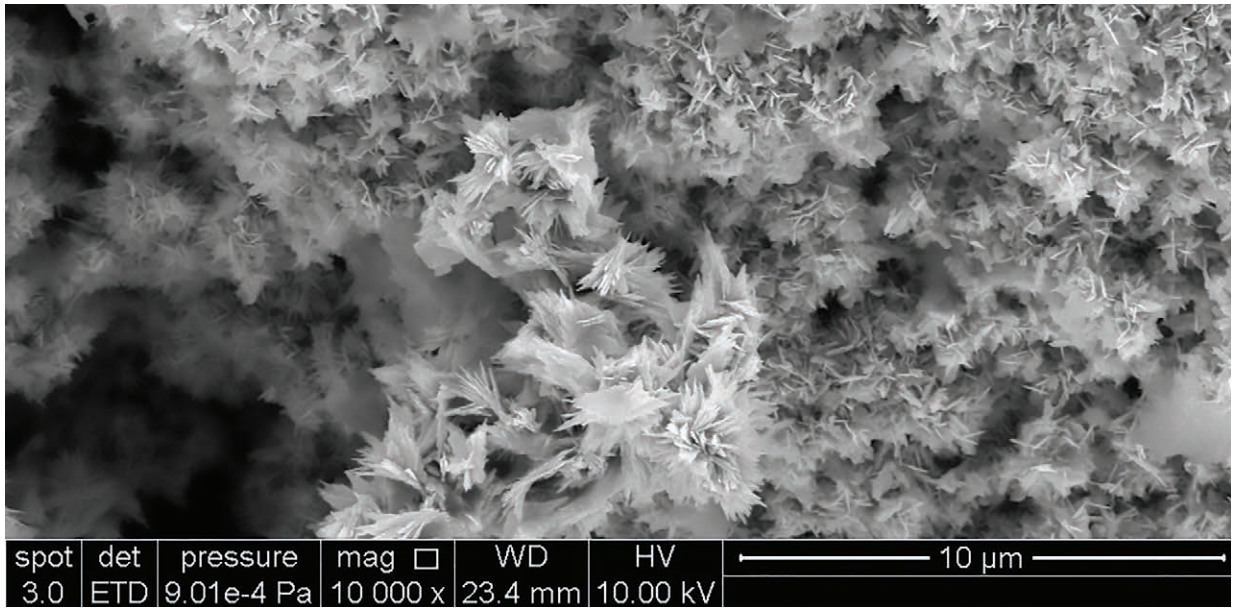
That spot of oil on the garage floor dripping from your engine indicates a problem. It's so small that you put off going to the mechanic, until you hear a new noise and the oil pressure warning light goes off. The bad news is that one of the bearings in the crankshaft is the source of the issue. Due to wear, the normally round part is now more elliptical in shape. Some of the metal has worn away, landing you with a costly repair.

This kind of wear on engine components is common because of friction, and it happens in all machinery with moving parts. Lubricants that reduce friction can only delay and minimize this inevitable damage. The idea of reversing that wear by fixing a worn part was the dream of Washington State University PhD candidate Pavlo "Pasha" Rudenko, who decided to research using smart nanoparticles to replace eroded material.

Restoring damaged parts to a like-new condition was also intriguing to NASA, which in 2011 awarded Rudenko a fellowship through the Washington Space Grant Consortium to pursue this new application of nanotechnology.

In 1989, NASA started the National Space Grant College and Fellowship program, also known as Space Grant, to "contribute to the nation's science enterprise" in disciplines that help advance missions. The competitive awards represent the cutting edge of new research or taking established disciplines in new directions. Rudenko's nanotechnology coating fell into a field of study known as tribology—the science and engineering behind friction, lubrication, and wear.

Parts that move in relative motion, either working together or against each other, will always experience friction and, sooner or later, wear. In situations where the friction between parts inhibits machine performance, lubricants are used. Many common lubricants are oil-based—mineral or plant—and contain numerous fortifying additives, without which the oil would quickly degrade. Additionally, these chemicals, which are dissolved or suspended in the oil, perform a variety of functions: they maximize viscosity at different temperatures, remove debris, and improve chemical stability.



Seen under an electron microscope, the nanoparticles in the TriboTEX are "sticky" on one side and "slippery" on the other. The sticky side is attracted to areas of friction and attaches itself to those pits and grooves, building up layers until the friction is eliminated. The heat and pressure of the engine environment fuse the nanoparticles in place, creating a new, slick surface that's usually smoother than the original material.

Rudenko's research into a nanotechnology additive to fix the wear on engine parts began in 2009, starting with efforts to improve existing lubricants. A grant from the Hydropower Research Foundation with money from the U.S. Department of Energy developed the initial data. His successful NASA fellowship application proposed creating a nanoparticle lubricant that would work at any temperature, including in the extremes of space.

The goal was to use an existing liquid lubricant to carry nanoparticles directly to the point of friction. Rudenko believed this solution would be ideal for satellites and space vehicles. In addition to keeping parts in good repair, such a nanofluid lubricant could extend the functional life of the systems using it. His initial university research identified the best material—a type of ceramic—which was effective, durable, and nontoxic. But the synthetic material was also expensive to create.

NASA's feedback was positive yet tempered by the reality of how long it takes to qualify such a new technology for space. Qualification wasn't practical at such an early stage in the life of the technology, so Rudenko turned to the private sector to continue his research and development.

Technology Transfer

Before starting TriboTEX LLC in 2013 and becoming its chief technology officer, Rudenko pursued additional funding opportunities for nanoparticle manufacturing.

“NASA support was critical in **getting** to **this point.”**

— Pasha Rudenko, TriboTEX

All metal engine parts experience wear when lubricants fail to prevent the damage caused by friction, but TriboTEX claims its product can reverse that damage by replacing the material worn away by friction. The company offers products formulated for a range of engine types, from large, high-performance engines in sports cars and semi-tractor trailers to the smaller engines in compact cars, lawn mowers, and generators.

A Global Impact Award from Singularity University, an organization supported by a Space Act Agreement with Ames Research Center and housed in NASA Research Park at Ames, helped the fledgling company get started. Two Small Business Innovation Research (SBIR) contracts from the National Science Foundation enabled Rudenko to scale the production of his nanoparticles.

The material, also called nano-flakes, is sticky on one side and smooth on the other. The sticky side is attracted to points of friction and attaches itself to those spots, leaving the smooth side facing out. This happens over and over, building up layers of nanoparticles until a given rough spot is smoothed over, much like filling in a pothole in a street. The heat and pressure that naturally occur with friction bond the nano-flakes together, forming a new, durable carbon-lattice surface that Rudenko calls "diamond-like."

Even when the surface of a metal part appears smooth to the eye and touch, an atomic force microscope can reveal imperfections at the nanoparticle level that can and do create friction. With an aim toward fixing these tiny imperfections in engines, the first TriboTEX formula was created to work in automobiles.

Benefits

With his product formula refined, the ability to manufacture it at scale, and a company to market and distribute the product, Rudenko launched a crowdfunding campaign. In 2017, he secured the funding needed to launch TriboTEX, raising over a half a million dollars and earning the Indiegogo Innovative Product of 2018 award.

Throughout the 10 years of product development, the company made numerous appearances at conferences and trade shows. Some of the many awards the technology earned include a Defense Innovation Award, American Society for Engineering Education Fellowship, Licensing Executives Society Members Choice Award, and the University of Washington Best Technology.

Today more than 30,000 cars and trucks are using TriboTEX. That usage data is expanding the body of evidence that synthetic nanoparticles yield the intended results. The most common benefits drivers report are improved gas mileage, increased torque, and increased oil pressure.

TriboTEX's product can be added by the consumer directly to a warmed-up engine. From there, it begins to repair damage over time.

In cars with 130,000 miles or more, the company claims that fuel economy can be improved up to 6 percent along with increased in-cylinder compression. The particles also decrease engine noise by filling in gaps and grooves as small as 40 microns, about the width of a human hair—although they also stop building up once the gap is filled. Cars can also increase their engine power up to 3 percent, says Rudenko, noting that this is remarkable for a treatment that circumvents the cost of dismantling any part of the engine. Adding TriboTEX to a vehicle every 40,000 miles will ensure that there are enough nanoparticles available to fix new instances of wear in parts of the engine that experience significant friction, he adds.

As consumers have used TriboTEX, they've suggested other potential applications, and the company is responding. It now offers a small-engine product for use in motorcycles, lawn mowers, generators, and compact cars. A high-performance version is formulated to work in diesel trucks and large-engine sports cars. The "big rig" formula treats semi-tractor trailer engines. A national, commercial trucking company is testing TriboTEX in a number of trucks in its fleet. But cars and trucks are just the beginning.

"We're working on using nanomaterials in aviation gearboxes," says Rudenko. AFWERX, a program of the U.S. Air Force designed to foster engagement across industry, academia, and non-traditional contributors to develop a culture of innovation, awarded TriboTEX a Phase I SBIR contract. This is making it possible for TriboTEX to create the new formula and develop the required mechanic's procedures. If Phase II funding is approved, the nanoparticle additive will run in the Air Force test stand.

Rudenko sees this opportunity in aviation as coming full circle to NASA and helping him realize his dream of being in flying machines.

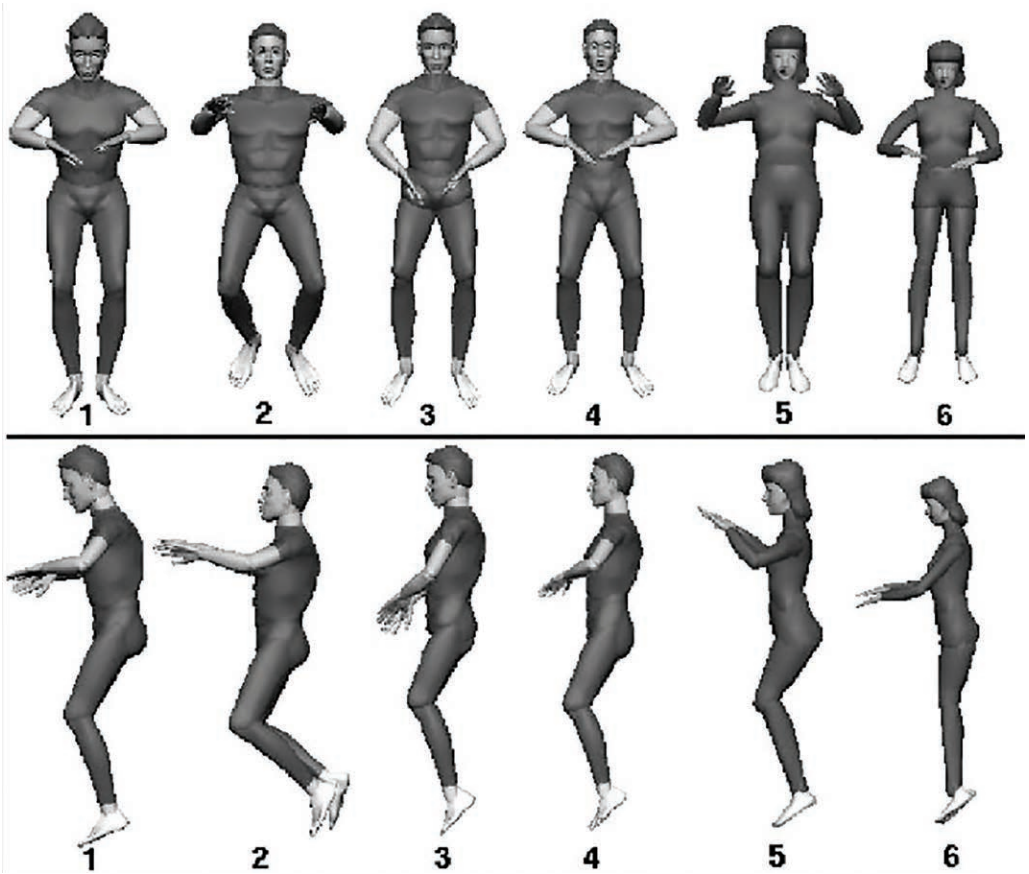
"NASA support was critical in getting to this point," he says. ❖

Zero-Gravity Body Posture Influences Acupressure Massage Chair

NASA Technology

Most people don't think about how easy it is to sit behind a desk or go through a door—for them, it's automatic. But sitting horizontally at a command console or trying to exit a spaceship while wearing a bulky pressurized spacesuit aren't commonplace, much less automatic. Less than 400 Americans have worked or lived in space, so the standards that govern everything from hardware to procedures are constantly evolving to make working and living in space not just possible but safe and comfortable, too.

At Johnson Space Center, human health and performance teams conduct research into the operational, habitability, and environmental factors that impact astronaut health and productivity—including the analysis of body posture. Employing the discipline known as anthropometry, they make an ongoing study of human body proportions and ergonomics in space. The data is used to develop and test space hardware and procedures, from spacesuits to living quarters and mission equipment.



Neutral body posture is the term used to refer to the relaxed position a human body naturally assumes in zero gravity. On Earth, seating that mimics the posture can facilitate circulation and relieve stress on joints. Pictured here are the range of such postures found in astronauts aboard a 1993 space shuttle mission that studied the phenomenon.

Investigations into body posture in space began with Skylab, the first American space station, which launched in the years after the Apollo Program. The Skylab measurements formed the basis of what is today known as neutral body posture, a specified range of angles and positions of human joints and limbs that represent what our bodies do when relaxed in a weightless environment.

NASA's first set of posture standards, based on photographs from Skylab, were included in a document known as NASA Standard 3000 created during the late 1980s. These specifications were revisited during the 1993 space shuttle mission STS-57. Johnson researchers not only wanted a larger sample size of astronauts (including measurements of women as well as men) but also wanted to improve the precision of observations. They did this by making use of video cameras in addition to photographs and by having astronauts wear tank tops and shorts to expose limbs, among other improvements.

What this and other NASA studies revealed is that there is no universal posture the human body takes on in zero gravity. Rather, the neutral body posture in fact represents a range of postures, with certain commonalities in the angles of joints and the positions assumed by the limbs and neck. The updated NASA Standard 3001 takes these commonalities into account in its design requirements for human spaceflight.

Technology Transfer

For decades, neutral body posture data has been informing designs for earthbound humans, such as office chairs (*Spinoff* 1997) and specially designed car seats that make driving more comfortable (*Spinoff* 2013). Now the Arlington, Texas-based company LURACO Health and Beauty LLC is combining the ancient health benefits of acupressure therapy with neutral body position research in the first medical massage chair.

The i7 PLUS massage chair offers a Zero Gravity setting that is based on NASA's neutral body posture specifications. The reclining position reduces stress on the body, while the user's weight provides the resistance needed to get the most out of the acupressure massage. Acupressure has been shown to speed healing, alleviate pain, and reduce stress.

Acupressure is well documented as an effective therapy to speed healing, alleviate pain, reduce stress, and impart a host of other wellness benefits. Kevin Le, an inventor and chief technology officer with LURACO, realized that the neutral body posture observed in zero gravity could enhance a robotic medical massage. He used the NASA data to mimic the body positioning and joint angles exhibited in low-Earth orbit in the Zero Gravity setting of the company's iRobotic 7 PLUS massage chair.

The reclining position, which supports a neutral posture, relieves the strain on joints and muscles caused by gravity. At the same time, the user's body weight provides the amount of resistance needed to get the most out of the massage.

Advanced robotics powered by 12 motors deliver a unique massage tailored to the acupressure points of anyone seated in the chair. A touchscreen similar to that of a smartphone controls the initial body scan and acts as a remote control for numerous settings. Acupressure point techniques applied to the neck, shoulders, and back in addition to arms, legs, and feet provide a whole-body massage.

Benefits

According to LURACO, its i7 PLUS model, made in the United States, accommodates any body shape including individuals over six feet tall and weighing up to 300 pounds.

The chair adjusts to each person by way of a patented operating system that conducts a two-minute scan to identify shape, size, and acupressure point locations. The system can generate and store up to five body scans along with individualized massage preferences. Integrated health-monitoring features measure blood pressure and heart rate.

One benefit of massaging muscles is that it removes lactic acid from the body's tissues. This helps improve the lymph fluid circulation that takes away metabolic waste and promotes blood circulation. If a muscle is injured, that increased circulation improves the flow of healing nutrients and oxygen. Massaging injured tissue can also reduce stiffness and swelling while increasing flexibility, aiding the healing process and improving pain management.

"Our chairs are built around the health benefits for the user," says Robyn Readicker, international sales and marketing manager. "The i7 PLUS was recognized by the Consumer Electronics Association with the Mark of Excellence Award at the Consumer Electronics Show in Las Vegas because of its benefits."

In addition to rest and relaxation, she explains that recovery from health issues, such as joint pain, muscle strain, mental strain from anxiety, and depression, defines the medical nature of the massage. The chair replicates a hands-on massage and eliminates the discomfort many people experience with the physical contact of a masseuse.

"As the population ages, an awareness of massage chair therapy is becoming more common," says Readicker. "When a person uses a zero-gravity body posture, it allows their body to have the full benefit of massage therapy. NASA has made that possible." ❖

Spacesuit Insulation Protects Personal Devices

NASA Technology

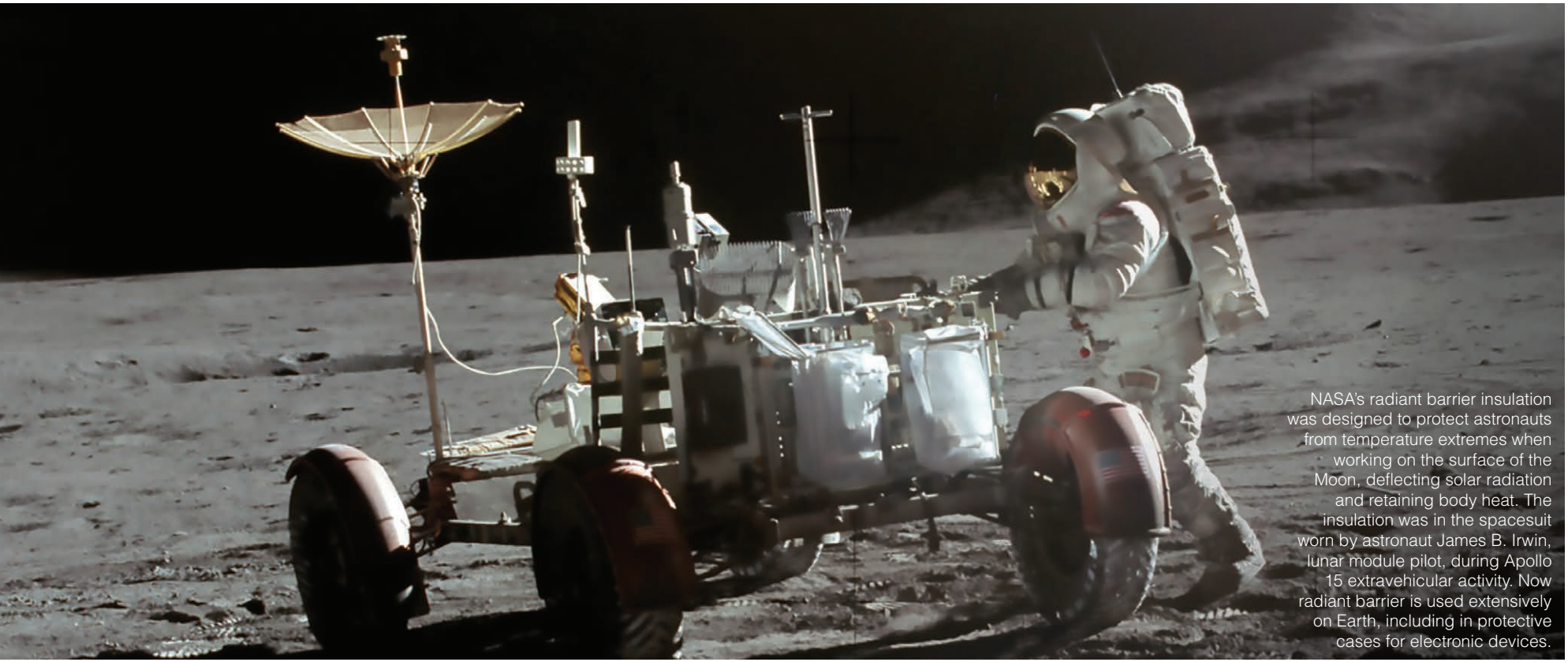
Protecting astronauts from the extreme temperatures of space while they explore the Moon or repair the exterior of the International Space Station requires a suit that performs well in temperatures ranging from 249 °F to -245 °F. Now the same insulation used in spacesuits keeps mobile phones and other electronics on Earth at optimal temperatures, regardless of the thermometer reading.

The extravehicular activity spacesuit has evolved from those designed for the first moonwalk in 1965. For that first model, it took six years for NASA technologists and clothing manufacturers to create, test, and refine the construction of a suitable material. A lightweight insulation, now called radiant barrier, was part of the multi-layered fabric that was ultimately used to create the spacesuits. It performed the essential functions of maintaining body heat and reflecting heat from the Sun's rays.

Reflective insulation was already in use in industry when NASA started exploring its possible uses in space applications in the mid-1960s. However, the Space Agency improved this technology when Marshall Space Flight Center contracted the metallized products division of the National Research Corporation to create an insulation made from multiple thin sheets of crinkled, aluminized Mylar. Ultimately, the NASA-pioneered material became the model for various types of lightweight, durable insulation that have found their way into dozens of uses on Earth such as protecting buildings (*Spinoff* 2013), emergency blankets for people and animals (*Spinoff* 2010), and improving light fixtures (*Spinoff* 1988).

Technology Transfer

Relaxing on a boat enjoying the sun and sea was great until Kevin Conway realized he missed an important call



NASA's radiant barrier insulation was designed to protect astronauts from temperature extremes when working on the surface of the Moon, deflecting solar radiation and retaining body heat. The insulation was in the spacesuit worn by astronaut James B. Irwin, lunar module pilot, during Apollo 15 extravehicular activity. Now radiant barrier is used extensively on Earth, including in protective cases for electronic devices.

> “You can’t beat Mother Nature—the heat and the cold will eventually get through. But thanks to radiant barrier, we can delay that process for quite a while.”
>
> — Kevin Conway, eXclaim IP LLC

By reflecting 90 percent of solar radiation with NASA’s radiant barrier, PHOOZY smartphone and tablet cases help prevent sensitive electronics from overheating at the beach, on a boat, or in the backyard on a hot summer day.

because his mobile phone overheated. Subsequent trips to every phone store he could find, where he was unable to locate a case with high-performance thermal protection, only added to his frustration. If he wanted a case to insulate his device from the heat while enjoying outdoor sports, he was going to have to make it himself.

Conway, a professional racecar driver, recalled that the fireproof suit he wears when driving uses a lightweight material called Nomex that can also be found in spacesuits. (The fabric was invented by DuPont in the 1950s and ’60s, finding its way into NASA’s spacesuits for its fire-resistance, durability, and comfort.) This led him to study NASA’s spacesuits and how they have been engineered to overcome the extreme temperatures in space. When he discovered that the metallized thin films used in radiant barrier are not only paper thin but also able to insulate against both heat and cold, he knew he had hit on a potential solution.

“If we could design a phone cover that could withstand the heat of the beach, why not protect against the cold of the ski slopes as well?” says Conway.

In 2017, Conway and his friend Josh Inglis cofounded Charlotte, North Carolina-based eXclaim IP LLC to develop and launch multiple lines of smartphone protectors under the brand name PHOOZY. In addition to a layer of radiant barrier insulation, Conway says the Apollo Series and subsequent XP3 Series are space-inspired in that they incorporate ripstop nylon and Velcro, two other materials made popular during the space age, though neither was invented by NASA.

Benefits

“You can’t beat Mother Nature—the heat and the cold will eventually get through,” says Conway. “But thanks to radiant barrier, we can delay that process for quite a while.”

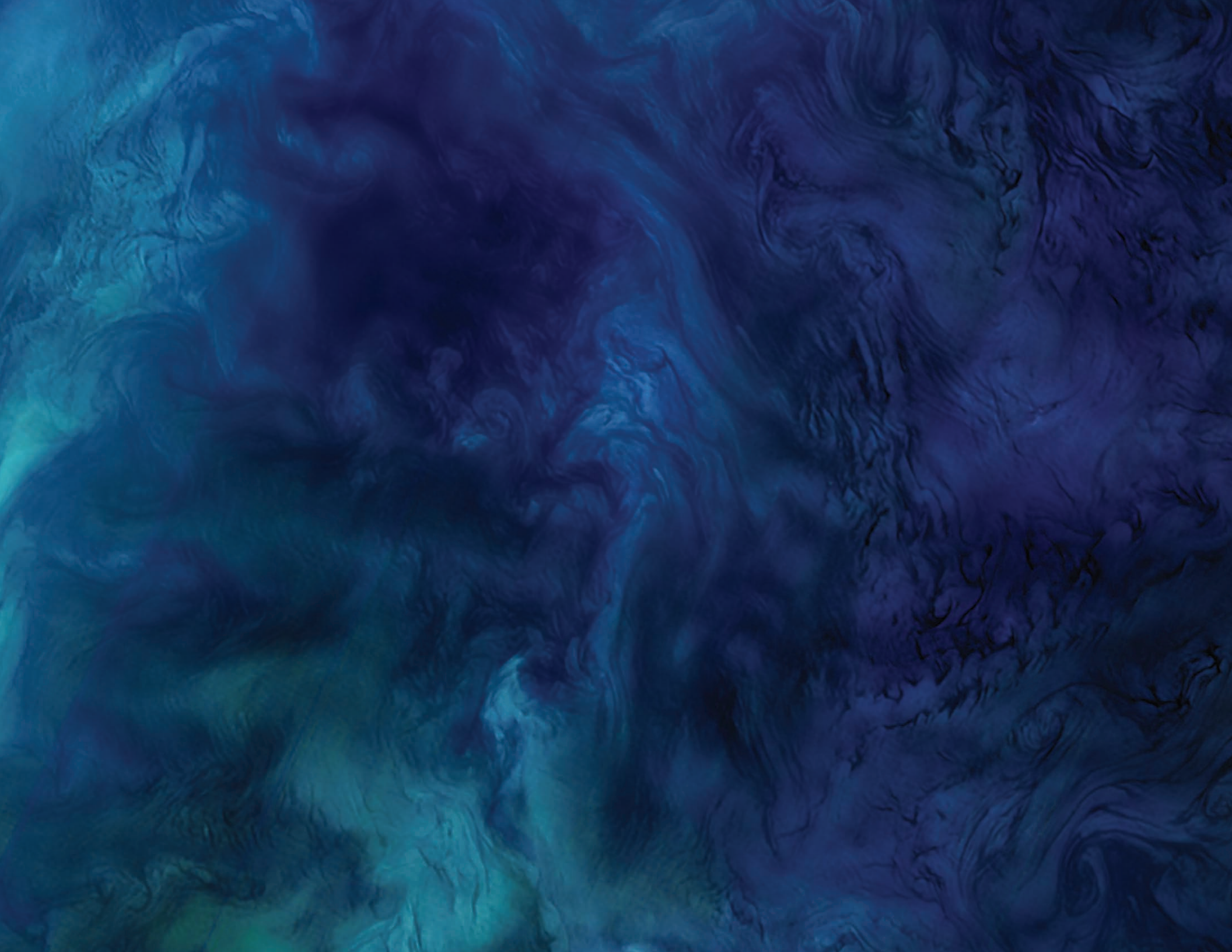
The company’s patented layering of materials include their Chromium Thermal Barrier that reflects more than 90 percent of solar radiation. Several layers of additional materials protect devices from liquids, sand, and snow while adding buoyancy to prevent sinking. And the company’s proprietary Impactor Core technology provides military-grade impact resistance, which it claims can protect a phone from drops up to nine feet.

Moreover, the case does all of this without negatively affecting Bluetooth connectivity and cellular signals.

Conway notes the PHOOZY has proven popular enough in online sales that it’s now also sold in several national retail outlets, including Best Buy, Home Depot, and REI. Tablet and laptop protectors made available in 2019 are just the start of the company’s expansion into other product lines. An upcoming pocket-sized PHOOZY hot/cold storage case for emergency epinephrine (better known as EpiPen), insulin, and other heat-sensitive medications will help maintain an optimum temperature while hiking or just sitting by a campfire. ❖

Energy and Environment

Making the best use of, and protecting, the environment around us—whether on a spacecraft, another planet, or here at home—is crucial to our health and survival. In this section, read about how our Earth-observing satellites are helping farmers produce more with less water and how expertise in rocket engineering led to a technique that lessens the environmental impact of burning coal. Other innovations include a fuel cell that runs equipment at oil wells, reducing the need to vent greenhouse gases, and a laser that is a key part of weather-forecasting satellite tools.



Rocket Expertise Assists Transition to Green Energy

NASA Technology

Around the world, economic growth and prosperity is tied to the availability of cheap energy. Coal is abundant and cheap, but in developed countries the regulations and expensive technology required to control by-products offset its cost savings. It's a different story in many developing countries, however, where the fundamental need for power overwhelms environmental considerations. There, regulations frequently forgo strict pollution mitigation requirements to keep energy costs low.

Surprisingly, NASA's rocket expertise is making energy production, a significant contributor to climate change, less damaging and more cost-effective.

When deriving energy from coal, one alternative to combustion is gasification. This technology employs the same heat and pressure used in rockets to reduce some of the pollution, making gasification a safer way to use coal until sustainable sources of power are more affordable.

Rocket engines have always been efficient at transforming the chemical energy of fuel into mechanical energy, or motion. Yet improvements in rocket technology over the past 50 years mean modern-day rockets generate more motion very efficiently, says R.H. Coates, propulsion engineer at Marshall Space Flight Center.

He explains that a liquid propulsion rocket engine uses fuel and an oxidizer, which reacts with the fuel. Pumped from separate storage tanks into a chamber, they're ignited and chemically burn. This breakdown and formation of new molecular bonds yields a high-pressure, hot gas, which is directed out of the open end of the combustion chamber and exits though the back of the rocket. The mass of hot gas moving in one direction causes an equal and opposite reaction: thrust pushing the rocket forward.

"A rocket engine's capability comes from efficiently converting chemical energy into the energy of motion, thus producing a very large amount of thrust for a relatively small sized engine," Coates says.

To accomplish this, NASA and industry partners relied on computer-aided design tools to create new propulsion systems and precision hardware, as well as sophisticated instrumentation. This was particularly helpful when building a new engine for the space shuttle vehicles. They required engines that could generate more power for their size than any thrusters previously built.

Such requirements began testing the limits of design. "If you need a very precise temperature to get the most efficient output of a system, it may also be very close to some limits

The Mars Curiosity rover launched aboard this Atlas V rocket in 2012, which was powered by liquid-fuel engines. These included the upper-stage RL-10 engines, manufactured by Aerojet Rocketdyne. The company has spent decades refining rocket engine technology. In 2015, engineers from the company left to join the Gas Technology Institute (GTI), which had purchased Aerojet Rocketdyne's energy technology portfolio, where they began work on a gasifier for energy production from coal.

of the materials," explains Coates. "Say the material melts at 1,100 °F, and the temperature that you want to run at is 1,000 °F. It's close. If that temperature varies plus or minus 200 °F that could damage the hardware."

That potential for damage forced NASA to "get really good at thermal management on rocket engines." Even though the engines run at temperatures that are well above the melting point of some of their component materials, Coates says that isn't a problem. "We take a lot of the cold propellants and cool the rocket engine with it before we turn around and burn it."

"The better you control pressures and temperature, the more useful output you will get from any process," he adds.

This required constant monitoring to maintain optimum operating temperatures. Employing high-tech sensors and other instrumentation throughout the rocket made it possible to collect measurements and make minute system adjustments on demand.

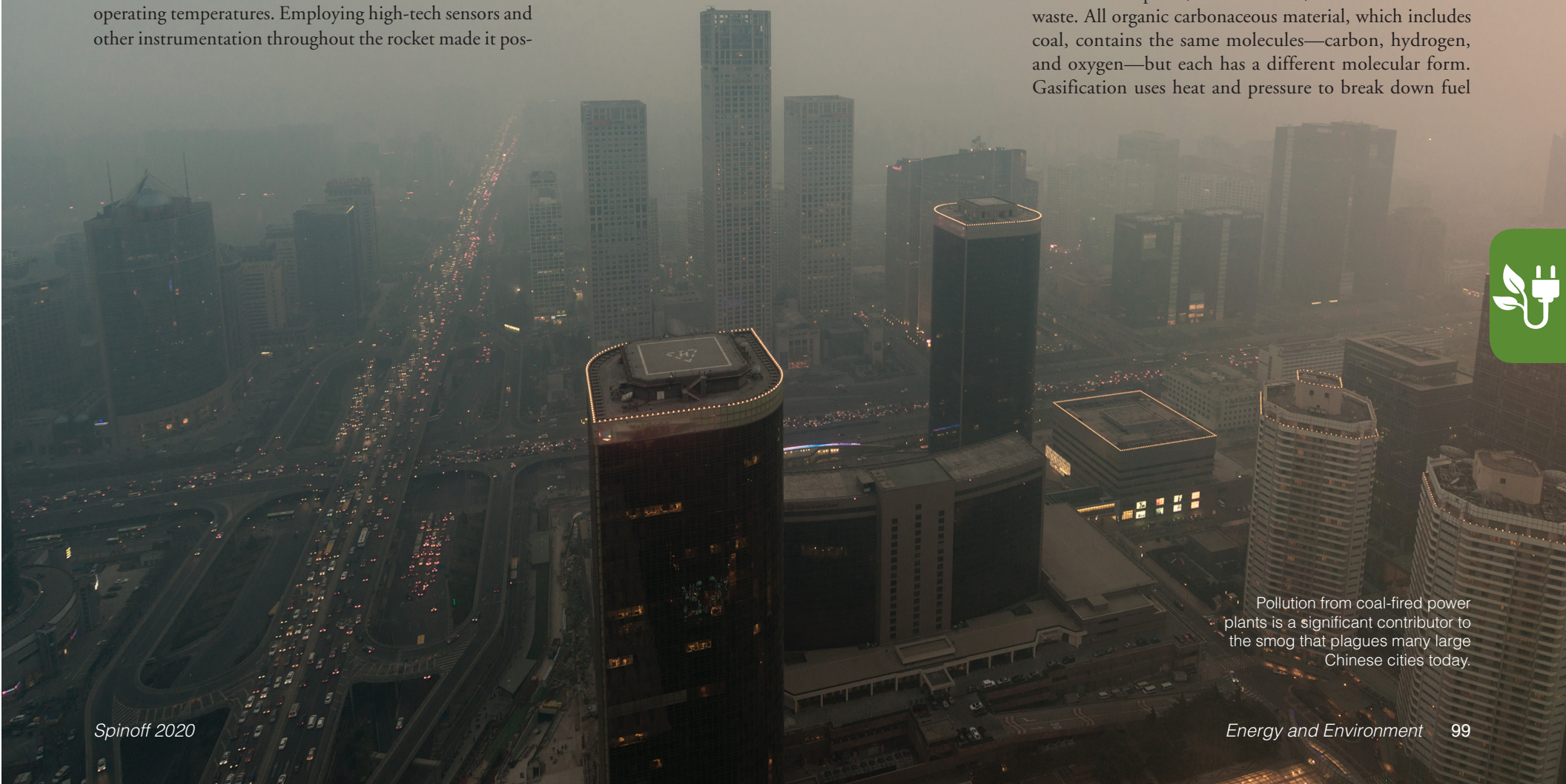
Technology Transfer

Numerous commercial partners supported NASA's efforts to mature, build, and perfect rockets over the years. El Segundo, California-based Aerojet Rocketdyne Holdings and its predecessor companies accumulated a wealth of knowledge applicable to technology used on Earth as it built rocket engines for NASA and others.

The company's in-house research and development team went on to use that expertise in the private sector. In 2015, as priorities shifted away from entering new commercial markets, Gas Technology Institute (GTI) of Des Plaines, Illinois, bought Aerojet Rocketdyne's energy portfolio, including intellectual property, facilities, and technology. Many of the researchers followed to work for the nonprofit research, development, and training organization, whose mission is to address global energy and environmental challenges.

One outcome of that effort is a 21st century update for gasification. Tony Eastland, formerly chief engineer for the Clean Fossil Energy Technologies program at Aerojet Rocketdyne and now senior director of energy supply and conversion engineering at GTI, is using his rocket know-how to improve this 200-year-old process.

Converting the energy stored in coal is less damaging with a gasifier, because it doesn't pump harmful gases into the atmosphere, uses less water, and creates less toxic waste. All organic carbonaceous material, which includes coal, contains the same molecules—carbon, hydrogen, and oxygen—but each has a different molecular form. Gasification uses heat and pressure to break down fuel



Pollution from coal-fired power plants is a significant contributor to the smog that plagues many large Chinese cities today.

into its constituents by controlling the chemical activity leading up to combustion.

The primary product of gasification is synthetic gas, or syngas, which comprises primarily carbon monoxide and hydrogen. By using what's called the Fischer-Tropsch process, it's possible to convert syngas into end products: methane, ammonia, and other chemicals.

The first recorded use of a gasifier was in the late 1700s to generate fuel for residential lighting. As less expensive methods of energy production such as coal-fired power plants became more prevalent, gasification dropped in popularity.

A coal-fired power plant generates electricity by burning coal to boil water into steam, which runs through turbines to generate electricity. However, the combustion process also creates highly destructive by-products such as carbon dioxide, sulfur dioxide, nitrogen oxides, particulate matter, and heavy metals.

Concerns about climate change and the need to transition to more environmentally responsible energy sources revived interest in gasification. Surprisingly, the expertise GTI's engineers gained while downsizing rocket engines was a boon for building a compact gasifier. Whereas older systems are building-sized, GTI offers a model, marketed as the R-Gas gasifier, that's about the size of a semi-tractor trailer. R-Gas can be constructed onsite and operates at a low cost. The system to cool R-Gas during operation, as well as its fuel injectors, were derived directly from previous aerospace projects.

By controlling the temperature and pressure and limiting oxygen, the coal is brought just short of a temperature where it would combust. At that point, molecular bonds break down and the gasifier can separate and manipulate the different molecules to create specific products. The team's expertise in tightly managing these same types of processes in rocket engines allowed them to design a unit capable of higher operating temperatures and pressures than previous systems. These parameters can be adjusted to create numerous "recipes" for producing different liquids and gases, says Eastland.

One alternative to burning coal is gasification, where coal is processed under high temperatures and pressures to extract synthetic gas and other products, which can then be used to generate electricity. GTI's R-Gas gasifier, shown here, helps relieve some of the environmental impact from the use of coal while also creating products for industry.

"Either through the way the gasifier operates or through downstream processing, you can alter the ratio of the hydrogen to the carbon monoxide in order to better prepare syngas for producing the ammonia or methanol needed to make other chemicals or transportation fuels," he explains.

Benefits

While no process can transform a fossil fuel like coal into a nonpolluting form of clean energy, GTI's rocket-inspired technology can eliminate some of the harmful effects of burning coal. Environmental benefits of gasification include reducing ozone-depleting gases, toxic slag, and contaminated wastewater that result from coal combustion.

The gasifier also produces slag, commonly called ash, but it won't contaminate soil or groundwater. "Because we end up converting a lot more of the carbon to syngas than other gasifiers, we create a slag that is non-leachable," explains Eastland. "That means when it ends up in contact with the earth, water does not leach out damaging chemicals or heavy metals."

Burning syngas will still release all that carbon into the atmosphere. However, when syngas becomes the basis for creating other chemicals, gasification makes it easier to capture and sequester the carbon.

In this image taken in China, a coal mine can be seen in the foreground with an industrial port behind it. China is the world's largest producer and consumer of coal. Although coal's prominence among energy sources in the country is falling, its low cost still makes it essential to powering much of the economy. Gasification can offer a way to get energy from coal that's less harmful than burning it.

This form of processing carries significant capital savings. A gasifier limits the need for costly environmental controls designed to mitigate pollution, which developing countries struggle to afford. Additionally, this relatively compact technology costs less money to build than a coal power plant.

The precision control of temperatures throughout the system means R-Gas achieves the hotter temperatures required to use the cheapest, hardest-to-process coal. This high level of operating efficiency reduces the amount of electricity and other resources required to operate the gasifier. Expensive, noxious chemical additives required by other gasifiers to help control temperatures aren't necessary. Nor does the system use a large quantity of water for cooling, thus reducing the expenses of wastewater processing, storage, and environmental cleanup.

GTI substantiated the performance expectations for R-Gas with a pilot unit operated at the company's headquarters, processing about 18 tons of coal a day. A demonstration plant built for a nylon factory in China in late 2019 anticipated processing 800 tons of coal a day as designed.

Now a business or public utility can do more than just burn coal exclusively for power. For example, the nylon factory added R-Gas to the existing facility to produce ammonia. It's an important chemical for creating Caprolactam, a monomer for a type of nylon. The plant looked forward to reducing its power requirements, and the sale of various end products generated a new income stream.

"Overall, we want to try to move away from fossil fuels, but developing nations are going to use coal because it's cheap. It's the easiest way for them to improve their standard of living," says Eastland. "So helping them to use it in a more environmentally friendly fashion is what we're trying to do." ❖

Satellite Imagery Helps Farmers Cut Water Use in Half

NASA Technology

Irrigation—supplying water to growing crops—is one of the most important ways humans use water. Across the United States, for example, a full 80 percent of fresh water gets used for irrigation, and in western states, that figure can rise as high as 90 percent. Improving irrigation efficiency, to ensure only enough water is being used when and where it is needed, can increase profitability for farms while also conserving water for other uses.

An Oakland, California start-up is helping farmers do just that—and the company says it couldn't do it without data provided by NASA imagery from the Geostationary Operational Environmental Satellites (GOES) and Landsat satellites.

Tom Shapland, who founded Tule Technologies Inc., studied agriculture as a college student at the University of California-Davis, where he was surprised to learn that most farmers didn't know how much water their plants actually needed. "Water use is so critical to how plants grow and how much money a farmer can make," Shapland emphasizes. "That context just astounded me, that farmers didn't know how much water their plants were using."

But he quickly realized it wasn't so simple to find out. One method to estimate evapotranspiration, or the total amount of water evaporating from the ground and transpiring from plants, relied on satellite imagery, but it had large error margins. Other methods, like using a lysimeter to measure water loss from plants by weight, were more accurate but prohibitively expensive and impossible to do on a large scale.

But Shapland had an idea to adapt the evapotranspiration method in a way that would reduce the error rates significantly. In short, Tule uses a surface energy balance approach. This measures the energy coming into the field, that is, the energy coming in from the Sun, and the energy going out. The outgoing energy goes into the ground, warms the air, and vaporizes water, and a negligible amount goes to other miscellaneous but important processes including photosynthesis.

Image courtesy of National Oceanic and Atmospheric Administration

The Geostationary Operational Environment Satellites (this illustration shows one of the GOES-R series satellites), built by NASA, take high-resolution images of Earth from orbit. The images are made available to the public, which allows companies like Tule Technologies Inc. to use them to improve their data products.

By measuring the first two of these heat sinks, Shapland explains, they are able to calculate the third—the amount of energy that goes into vaporizing water, through which they can then extrapolate just how much water has been vaporized.

So far, this method is not hugely different from the error-prone models he wanted to replace. But he says the key difference is in how his company measures the second energy sink, the heat warming the air. "The reason there's so much error," he explained, is because "wind is a significant driver of the evapotranspiration rate." Specifically the turbulent motion of wind plays an important role in how quickly water vapor transfers away from the plant.

Wind speed, the basic measurement that might show up in a weather report, reflects the "mean flow" of wind, or about how fast the air is moving on average across a wide area. But it doesn't capture the turbulent transfer in the field, Shapland says. "Turbulence is individual eddies of wind carried in the mean flow. These eddies, or packets, come in contact with the surface, heat and water vapor transfers into them, and then a new eddy comes from above and pushes the old one away," he explains. That new eddy is then poised to absorb a new round of moisture and heat before being pushed off by a fresh one yet again.

The difference between Tule's model and the ones based entirely on satellite imagery is this measurement. "We're measuring the turbulence within the field and measuring the rate at which the wind is taking water vapor away from

> They never imagined they could do that, but using our technology to see how their plants are responding to irrigation, they were able to see where and when to cut the water."
>
> —Tom Shapland, Tule Technologies Inc.

the field," he explains, using very sensitive temperature sensors. That gives them an input to the energy balance equation, resulting in a more accurate number for heat going to water vaporization.

However, even though Tule doesn't rely exclusively on satellite imagery, it does rely heavily on it. "We use NASA technology for the energy-in part of the equation," Shapland explains, to accurately measure how much heat is going into the field from the Sun.

This actually requires two measurements. The first is the "downward component," he explains, "the sunshine you feel." Tule measures it using infrared imagery from the GOES system. (These satellites are built by NASA and operated by the National Oceanic and Atmospheric Administration).

Because geostationary orbit keeps a satellite over the same geographical region, Tule is able to get short-wave radiation measurements up to every five minutes.

In addition to this downward radiation measurement, Tule calculates the radiation that reflects back up from the ground. For this, the company looks to the Landsat satellites, which supply new images every eight days. (Landsat satellites have been imaging the Earth's surface from low-Earth orbit since the 1970s. They are built by NASA and jointly managed by the Space Agency and the U.S. Geological Survey.)

Irrigation accounts for 80 percent of fresh water use across the United States. By giving farmers better data on how their plants are using the water and how much they need, Tule helps farmers reduce their total consumption or get better yields for the same input.

This difference in sampling frequency aligns well with the speed at which these variables change, Shapland explains. "For shortwave downward radiation, you need to sample at least once an hour, because the main thing affecting crop surface is cloud cover, and cloud cover changes constantly," he says. In contrast, "shortwave upward, how much that surface reflects, changes very slowly, as a function of plant height and type. It changes on about a month-long scale."

Technology Transfer

NASA satellite imagery is available to the public for free, which has enabled many products—more than a half dozen such products have been featured in *Spinoff* in the last five years alone. Shapland says the free imagery was crucial to its business model as well. For one thing, while commercial Earth-observing satellites are proliferating, there just aren't geostationary ones like GOES in the commercial imaging sector yet, and the commercial satellites in low-Earth orbit don't measure in the wavelength spectrum Tule needs.

But equally important, he says, is the cost factor of paying for images versus getting them free from NASA. "We would have to charge a lot more to our customers if these satellite data sources weren't available," Shapland says. "I suspect our business wouldn't be as large and thriving if we had to charge a lot more money."

Benefits

Currently, Tule's customers are all in California, Shapland says, with 80 percent growing wine grapes, 15 percent in almonds, and the remaining 5 percent in other specialty crops. Tule installs its wind turbulence sensors in a farmer's field—these communicate wirelessly to send their readings to the server, which then uses that information along with other data sources, including the energy in from

satellite imagery, to calculate what it calls “Actual ET,” or actual evapotranspiration.

With that, the company is able to provide information on how much water the plants are currently using and how thirsty the plants are, as well as a recommendation for how much water the farmer should irrigate with at that time. Depending on the crop and the particular point of the growing season, a farmer might want the plants to be stressed to a certain degree, so an irrigation recommendation is more complicated than simply replacing all the water lost through evapotranspiration.

Customers have seen huge results. One large almond grower was able to save around six acre-inches of water (essentially the amount of water it would take to fill an acre six inches deep, equivalent to about 25,000 gallons) in the early part of the growing season, Shapland says. The farm was able to redirect that water to other parts of the operation that needed it more, so with the exact same water consumption, it was able to significantly boost yield.

Another success story comes from a grape grower in Southern California. A typical grape season will use about two acre-feet of water, or around 100,000 gallons per acre, Shapland says. This vineyard, thanks to the data provided by Tule, was able to cut its water usage by half, a number that is even more impressive, Shapland notes, because it cultivates across 100 acres.

“They never imagined they could do that,” Shapland says, “but using our technology to see how their plants are responding to irrigation, they were able to see where and when to cut the water.”

So better information about water can mean saving water or it can mean getting a bigger yield for the same input. Either way, it’s a win for the farmer, Shapland says. “A farmer doesn’t have a whole lot of control over how much money they make from their crop. How to irrigate can really influence how much they can make: it’s the most important lever, the most substantial thing they can do to change how much money they can make.” ❖

Tule says it is able to calculate evapotranspiration more accurately than its competitors because of the sensors it places in the field to measure turbulent airflow, which plays an important role in how quickly water vapor moves away from the plant.

Gas Processors Turn Oil Drilling Emissions into Fuel for Sale

NASA Technology

Pioneer Energy brings an unusual perspective to the oil and gas industry: many of its employees, including founder Robert Zubrin, have a background devising ways to extract energy not from the earth but from environments like Mars.

Zubrin began his wide-ranging career at Martin Marietta (now Lockheed Martin), as an aerospace engineer in the late 1980s. There, he gained his first fame as coauthor of the 1990 Mars Direct plan to reduce the cost of human exploration of Mars to a fraction of previous estimates, largely by making use of resources already on the Red Planet. After founding Pioneer Astronautics in 1996, he led the development of a slew of new technologies, mostly under NASA Small Business Innovation Research (SBIR) contracts. Several of the earliest of these projects were Johnson Space Center-funded technologies for turning materials abundant on Mars, such as carbon dioxide, into resources like propellants.

For example, a pair of Johnson SBIR contracts from 1996 developed a system to combine a small amount of imported hydrogen with carbon dioxide from the Martian atmosphere to produce methanol and water. With an electric charge, the water could then be split to produce oxygen and hydrogen. The methanol could fuel a rocket engine, with the oxygen helping it burn, and the hydrogen could be fed back into the system, to be recombined with carbon dioxide. Alternatively, methanol could power a fuel cell, and oxygen could be used for life support.

Among the subsequent innovations developed with Johnson SBIR funding were ways to produce hydrocarbons with lower hydrogen-to-carbon ratios, thus reducing the amount of hydrogen that needed to be imported, and an efficient, low-cost freezer to store carbon dioxide at temperatures below -200 °F.

Technology Transfer

After realizing that some of that technology could be adjusted to benefit the oil and gas industry, Zubrin spun off Pioneer Energy, based in Lakewood, Colorado, in 2008 and started work on what the company came to call its Portable Enhanced Recovery Technology (PERT) and Mobile Alkane Gas Separator (MAGS) systems (*Spinoff* 2015).

PERT, the first invention, essentially reversed technology for creating fuels from carbon dioxide, instead producing carbon dioxide that could be used to extract additional oil from defunct wells. It then dawned on Zubrin that many of the PERT subsystems could be used in a system to separate and process the gases that escape from oil wells. Turning these gases into fuel would give oil producers another product to sell while helping them meet pollution and greenhouse gas regulations. He started work on MAGS.

The methane and other natural gases that pour out of oil wells, especially in their early days of operation, are a major problem for oil companies and the environment. Currently, most of that gas is burned off in flares, releasing carbon dioxide and other pollutants into the atmosphere, a practice that governments are cracking down on. The World Bank estimates flaring releases about 350 million tons of carbon dioxide, a greenhouse gas and major driver of climate change, into the atmosphere each year.

A 2015 Stanford University study detailed the local health effects of flaring, which releases pollutants that cause various irritations and inflammation, as well as respiratory problems, blood abnormalities, and other symptoms. And a 2016 NASA study showed black soot from flaring in at least two major North American oil extraction sites, the Bakken Formation and the Athabasca Oil Sands, was ending up in the Arctic, where it absorbs sunlight and accelerates warming.

Flaring also represents a massive waste of resources. In 2018, the World Bank reported that 141 billion cubic meters of the gases were flared globally at oil production sites in the previous year, equivalent to about one-fourth the total annual gas consumption of the United States.

As the shale oil boom made oil relatively cheap and abundant, there was less interest in using the PERT system to revive older wells, says Joseph Palaia, vice president of business development at Pioneer Energy, noting that the system was eventually shelved. But with new wells springing up across the country, the market for processing well gases expanded, so the company continued developing the MAGS system, which has now evolved into its mobile Flarecatcher

Long stays on Mars would require the technology to rearrange molecules from the surface and atmosphere to make resources like fuel and oxygen. First with Martin Marietta and later with his own company, Pioneer Astronautics, Robert Zubrin worked for NASA on a number of such projects for in-situ resource utilization. He later realized he could adjust some of those systems to benefit the oil and gas industry and founded Pioneer Energy.

These Flarecatcher units can capture and process the natural gases that escape from oil wells, using the kinds of advanced refrigeration and gas separation techniques that Pioneer Astronautics developed to convert materials on Mars. This allows drillers to sell the gases as fuel, instead of burning them off in a practice called flaring, which releases the greenhouse gas carbon dioxide as well as various pollutants.

and Vaporcatcher systems, with more than two dozen units now in the field.

While Flarecatcher units, which come in three versions with varying capacity, continue capturing and processing gases that escape from wells, the Vaporcatcher does the same for the gases that build up in oil tanks at well sites.

This new product line still relies on the kinds of advanced refrigeration and gas separation techniques that would be necessary for converting materials on the surface of Mars, but it also benefits from the years the company has now spent in oil fields. "In the beginning, we didn't have anyone who had worked in oil and gas before," says Palaia. "Now we've been in the field long enough that we've learned not only how to operate our equipment better, to better meet customers' needs, but we also understand better what the customers' needs are."

Benefits

One thing the company came to understand was that simplicity, efficiency, and reliability are often more important to its customers than total refinement of gas products. While the MAGS system chilled gases to nearly -100 °F and used a molecular sieve for complete purification, a standard Flarecatcher unit can achieve satisfactory purification at around -20 °F, reducing cost, complexity, and maintenance. "At first, we were always building Cadillacs, and now we've got some economy models," Palaia says.

Along with improvements to the design and the purification process, advances have cut back the time that units have to be shut down for maintenance, halting well operations, he says. "We're at 90 to 95 percent up time, which is just great. Producers really like that."

Capacity is also way up, with the units boasting almost twice the recovery rate of competitors. While an original MAGS system could process about 200,000 cubic feet of raw field gas per day, a new 20-foot unit can process a million cubic feet per day. A 50-foot unit can bring that up to 5 million.

For customers who want total purification, supplemental distillation units are available at four levels of capacity.

"We're now more tailored to your particular application," says Palaia.

The Vaporcatcher works in much the same way but at warmer temperatures, because vapors that accumulate in oil tanks are heavier, which makes them more potent greenhouse gases if they're vented but easier to capture and distill.

"In many cases, the value of the fuel product stream is equal to or exceeds the cost of having our systems out there," Palaia says, meaning the cost of complying with regulations is free or better. "And then it's kind of a no-brainer. Why wouldn't you do it?"

The fact that the units can be trucked to a site and operated remotely adds to their convenience.

And if oil producers aren't interested in bringing small streams of fuel to market, Pioneer Energy even has its own network of buyers. "We've got a market set up, we have trucks lined up, and we take care of all that," Palaia says. "They just get a report and a check."

In early 2019, the company was serving a dozen well sites across the Denver-Julesburg Basin, to the east of the Rockies, and in the Bakken formation, which straddles the borders of North Dakota, Minnesota, and Canada. Many sites have more than one unit in operation. By then, the company had recently expanded to another 40,000-square-foot manufacturing facility and planned that year to build enough units to process 100 million cubic square feet of gas.

And talks were underway to enter markets in the Middle East, sub-Saharan Africa, and Indonesia. "That will drive another big expansion phase," says Palaia. He notes that the ability to fully refine and separate fuel products, whether through additional distillation units or with a version of the Flarecatcher that can chill to nearly -100 °F, is of special interest to operators in the developing world, where energy is scarce and cooking with fuels like butane is common.

Palaia attributes the company's success in part to a mentality that never settles on a final version but constantly looks for ways to boost efficiency, reduce down time, and otherwise improve its product. And he says its employees' background in space exploration technology "has really paid dividends, in that we haven't looked at these problems in the way traditional oil field companies have." In an industry that's resistant to change, he says, a major challenge has been to convince customers that Pioneer Energy's approach isn't risky just because it's different.

"One of the biggest ways NASA and the aerospace industry have contributed to the economy is the mindset of the people who work there and their impact on society," Palaia says. "If we can land a nuclear-powered rover on Mars, we can process gas in an oil field." ❖

Flaring at drilling sites releases about 350 million tons of carbon dioxide per year and is associated with health problems among nearby populations. It's also a major waste, as the gases being burned, if properly processed and separated, can be valuable fuels.

A 2016 NASA study showed **black soot** from **flaring** in at **least** two major **North American** oil **extraction sites … was** ending up **in the Arctic,** where it **absorbs sunlight** and **accelerates warming.**

Field-Scanning Drone Gives Farmers Better Data

NASA Technology

There's a reason people talk about a "bird's-eye view" and "as the crow flies": flying allows access and a perspective you just can't get with feet planted firmly on the surface. Now, thanks to advances in autonomous flight and the shrinking of all kinds of sophisticated electronics from computer chips to batteries, the bird's-eye view is becoming more widely accessible for farmers—and, for the first time ever, on Mars.

The first Mars spacecraft reached the Red Planet in 1965, and the first landers touched down just over a decade later. NASA has been exploring our nearest planetary neighbor from the surface and from orbit ever since.

But in those 50-plus years, there has never been an aircraft on Mars—for good reason. "First of all," explains MiMi Aung, project manager for Mars Helicopter at the Jet Propulsion Laboratory (JPL), "the atmosphere at Mars, is very, very thin. Compared to Earth, it's less than 1 percent."

That means there's almost no air to lift up an aircraft's wings or rotors. And although a JPL principal engineer, J. Bob Balaram, proved in the 1990s it was theoretically possible to fly on Mars, the technology simply didn't exist at the time to accomplish it, Aung says.

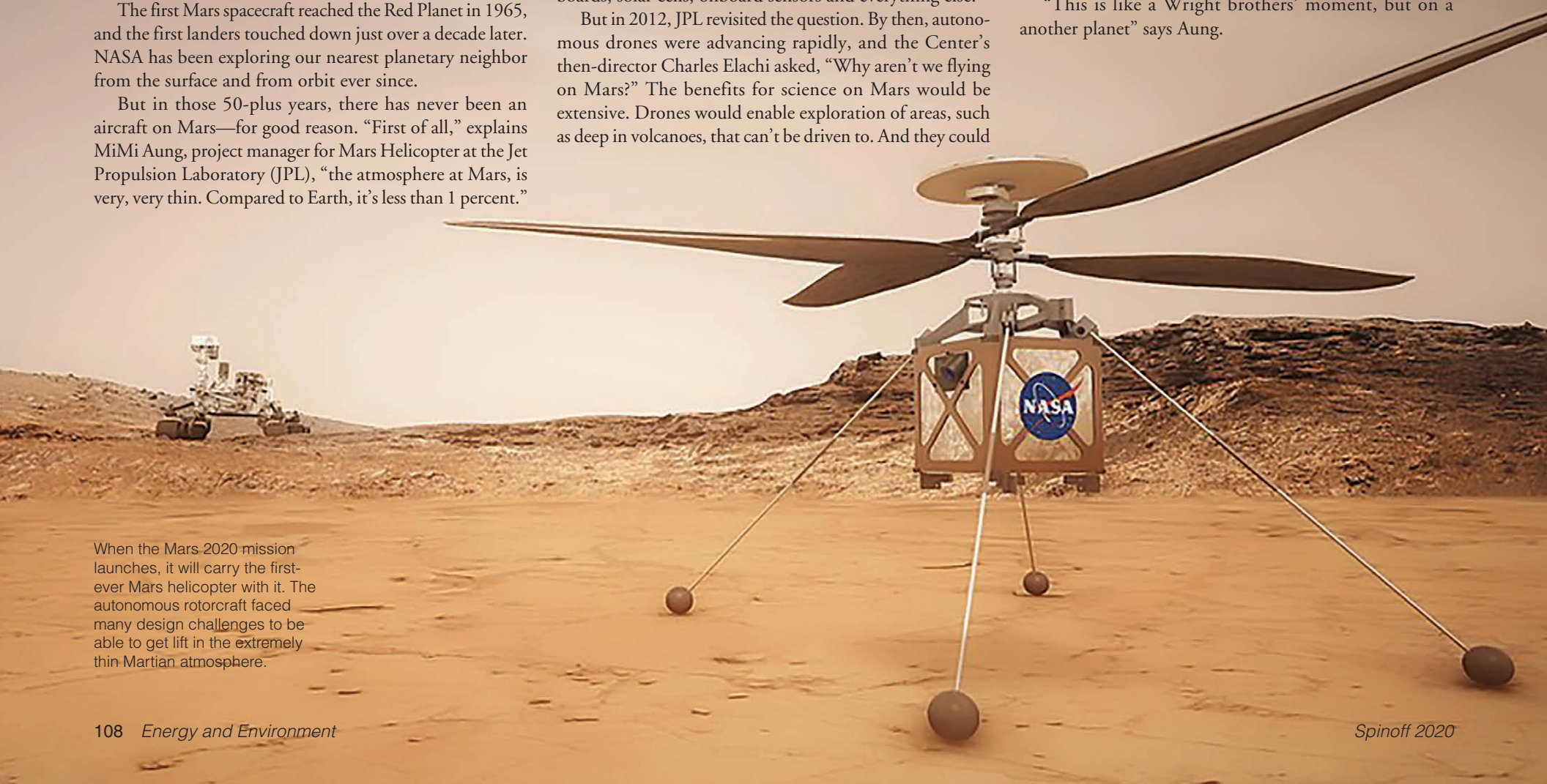
"The thing about flying somewhere with so little atmosphere," she explains, "is that rotors have to spin very fast." At the same time, however, the aircraft has to be incredibly, extremely lightweight. There simply weren't light enough batteries able to power such fast rotors, let alone computer boards, solar cells, onboard sensors and everything else.

But in 2012, JPL revisited the question. By then, autonomous drones were advancing rapidly, and the Center's then-director Charles Elachi asked, "Why aren't we flying on Mars?" The benefits for science on Mars would be extensive. Drones would enable exploration of areas, such as deep in volcanoes, that can't be driven to. And they could provide wide-area imaging at much higher definition than can be done from orbit.

A team was formed to study the question, and by 2014, they had built and demonstrated a small-scale prototype that was able to lift off in a near-vacuum chamber simulating the Martian atmosphere.

Fast-forward six years and a great deal of additional development and engineering, and the first Mars helicopter is now ready to catch a ride on the Mars 2020 mission and demonstrate the first flights on another planet.

"This is like a Wright brothers' moment, but on a another planet" says Aung.



When the Mars 2020 mission launches, it will carry the first-ever Mars helicopter with it. The autonomous rotorcraft faced many design challenges to be able to get lift in the extremely thin Martian atmosphere.

To build the Mars helicopter's rotors, landing gear, and solar panels, the Jet Propulsion Laboratory team turned to a company called AeroVironment, which had built up expertise in thin-atmosphere flight while working with NASA on several high-altitude, solar-powered unmanned vehicles. One, the Pathfinder Plus, is seen here during a 1998 test flight over Hawaii.

Technology Transfer

The launch-ready helicopter was built by 2017 and successfully flight tested in 2018, says Aung, who led the project. It features nearly four-foot-long rotors that must spin between 2,300 and 2,900 revolutions per minute, solar panels to recharge the battery, and a thermal management system to keep it from freezing in the frigid Martian nighttime. The vehicle also sports a camera, a communications system to send back images and vehicle health data, sensors and control systems, and landing gear.

And all together, the entire vehicle weighs just under four pounds.

Aung says building so many systems into such a small package was a monumental challenge—the whole team cheered when they put the completed vehicle on a scale.

To build several of the critical systems, JPL turned to AeroVironment, which had worked with NASA previously and, explains Aung, "were known experts on high-altitude aerial vehicles."

The Los Angeles-area company designed and delivered a complete rotor system meeting the size, weight, and stiffness requirements imposed by NASA, ensuring it would also be compatible with the control system JPL was building in-house. The company also delivered the landing gear, as well as the solar panels. "And again, all design considerations had to be designed jointly. We worked very closely," Aung says.

In fact, AeroVironment had previously worked with NASA on several (Earth-based) high-altitude, solar-powered unmanned vehicles, starting in the 1990s, including Pathfinder, Centurion, Helios, and Pathfinder Plus. "Each one of these was successively larger and capable of flying at a higher altitude for longer," explains Steve Gitlin, AeroVironment's chief marketing officer. In 2001, Helios smashed records for highest-altitude flights, beating both the previous records for a propeller-driven craft and a jet-powered craft, and reaching over 96,000 feet.

That altitude is significant, because just a few thousand feet higher and the atmosphere thins all the way to the 1 percent of sea-level Earth atmosphere found at ground level on Mars. "Developing technology that enables flight and propulsion at 100,000 feet made us uniquely capable of applying it towards generating lifts in Mars' atmosphere," Gitlin says.

But the expertise built during these high-altitude projects applies to other situations as well, he emphasizes. "Everything we've done, including our work developing solar-powered unmanned airplanes, all contributes to a body of knowledge, of expertise and intellectual property that enables us to solve these really hard problems."

Among other things, the company has worked to ensure its products work reliably in extremely tough conditions, whether flying in the stratosphere, on Mars, or over a field. NASA's requirements for ruggedness "certainly taught us much about reliability in harsh environments, which serves our customers in the military and on the farm," Gitlin says.

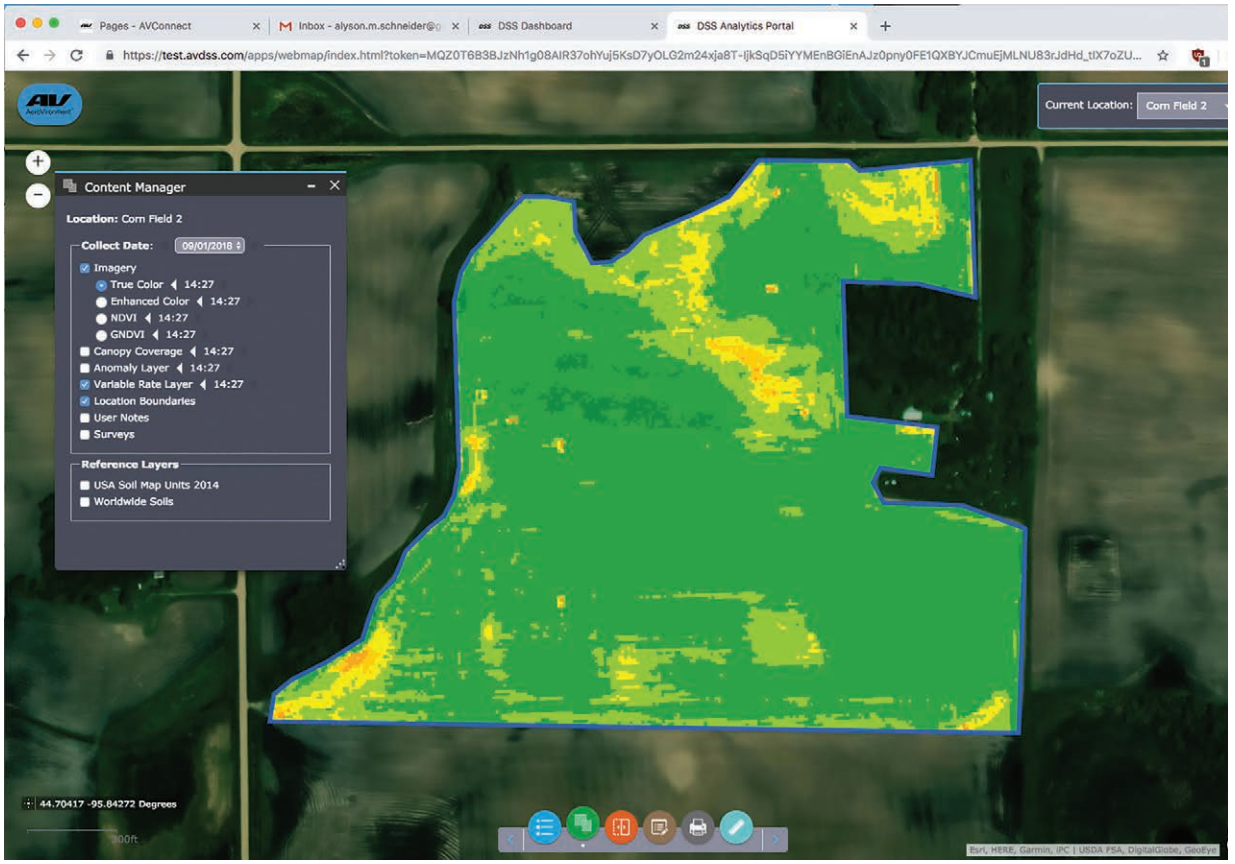
Benefits

After a few clicks on a tablet, four rotors start spinning on what looks like a little model airplane, pointed nose-up on the ground. The drone lifts straight up, and when it's about 100 feet above the ground, it turns onto its side, and the wings take over. The drone circles even higher until it's just a distant speck in the sky and then begins making sweeping passes, row by row, until it's covered the whole area that was outlined on the tablet. It comes back to where it started, first circling lower and lower and eventually flipping vertical again to land softly.

The drone is called Quantix, says Gitlin, and its job is to scan the crops with two high-resolution cameras, one in color and the other using different spectra to identify different plant health issues. "At the end of the mission, all these images are arranged in geo-referenced fashion, so they form a high-quality composite image of the field. When you see an anomaly, you can determine the exact GPS location," he explains.

The goal is to give farmers more detailed information about their crops to help them make better decisions. "Over the last 150 years, as farms have gotten bigger and bigger, the level of intimacy between farmer and field has diminished. A farmer can't walk every foot of a 1,000-acre farm," says Gitlin. That's where a bird's-eye view can come in handy.

The company started delivering Quantix to farmers in mid-2018, and the success stories are already coming in. One walnut farmer in central California, who grows some 2,500 trees across 40 acres, scanned his orchard and saw that the trees on the northern end were not thriving as well as the ones on the southern part of the orchard. He knew the soil there was sandier, but the images and data showed him the sandy soil was more extensive than he had thought. "Based on the data, the farmer made some changes to how that area was irrigated, how nutrients were delivered, and even how the fruits were protected from the sun."



AeroVironment drew on the expertise it built on projects with NASA when designing its latest drone for agriculture, Quantix. The drone scans crops with two high-resolution cameras, one in color and the other capturing non-visible spectra, and then an app stitches the data together to form a high-quality composite image of the field, giving farmers a birds-eye view of how their crops are doing.

The impact was clear, Gitlin says. "The next growing season, he was able to increase yield by over $50,000—in one season."

Quantix may not be flying on Mars or even in Earth's stratosphere, but Gitlin says the legacy of the NASA work AeroVironment has done benefited the drone's development significantly, from ensuring it was rugged enough to work in the dusty, moist, sunny conditions on a farm, to automating it so it would fly without a skilled pilot-operator, and perfecting the vertical takeoff.

"Our people, and our company, love working on these very difficult projects," says Gitlin. "Working with NASA challenges us even further to develop solutions that have never existed before." ❖

“Working with **NASA challenges** us even **further** to **develop solutions** that have **never existed before.”**

— Steve Gitlin, AeroVironment

Quantix launches vertically, but then turns on its side to let the wings take over. It makes sweeping passes over a field or orchard, autonomously following boundaries the farmer draws using the app.

Versatile Fuel Cells Stop Natural Gas Emissions at Oil Wells

NASA Technology

In 1999, a NASA engineer and a professor from the California Institute of Technology (Caltech) ran into each other at a conference and hatched an idea. It would take two decades to bring to fruition, but the result is now stopping natural gas emissions at a handful of oil wells and is poised to spread throughout the industry.

Sekharipuram "Sri" Narayan had designed and patented a fuel cell that ran on methanol at NASA's Jet Propulsion Laboratory (JPL), taking advantage of funds from the Department of Defense to come up with a power source that might also be useful for space missions. At the time, though, he was struggling with an issue with the cells: water in the electrolyte transports some of the methanol across the cell membrane that separates the electrodes, reducing efficiency.

Meanwhile, Sossina Haile, then a professor at Caltech in the Materials Science Department, had invented a solid acid crystal with a super power: at high temperatures it became, as she put it, "superprotonic," meaning protons could pass through it at record speeds. Transferring protons happens to be an electrolyte's job in a fuel cell, and this acid crystal not only could do that exceedingly well, but it also didn't rely on the water that tends to misplace methanol in methanol fuel cells.

During a chance meeting at a conference in San Francisco, the two scientists realized their inventions might make a good combination. But this was the first Narayan had heard of solid acid crystals, and Haile's team had no experience making or testing fuel cells. They agreed she would send two of her students to work with him. Calum Chisholm and Dane Boysen soon showed up at Narayan's JPL laboratory with a quantity of the solid acid—cesium hydrogen sulfate was what they were working with at the time.

"I thought of a way to mix it with a polymer, hot press it, and create some free-standing membranes," Narayan says. "It wasn't very good, but it was functional." Over the course of a few visits, he showed the pair of students how to apply electrodes at each end and create a structure to supply fuel. They were able to test it and show that it worked, even if the electrolyte was inclined to decompose under some conditions.

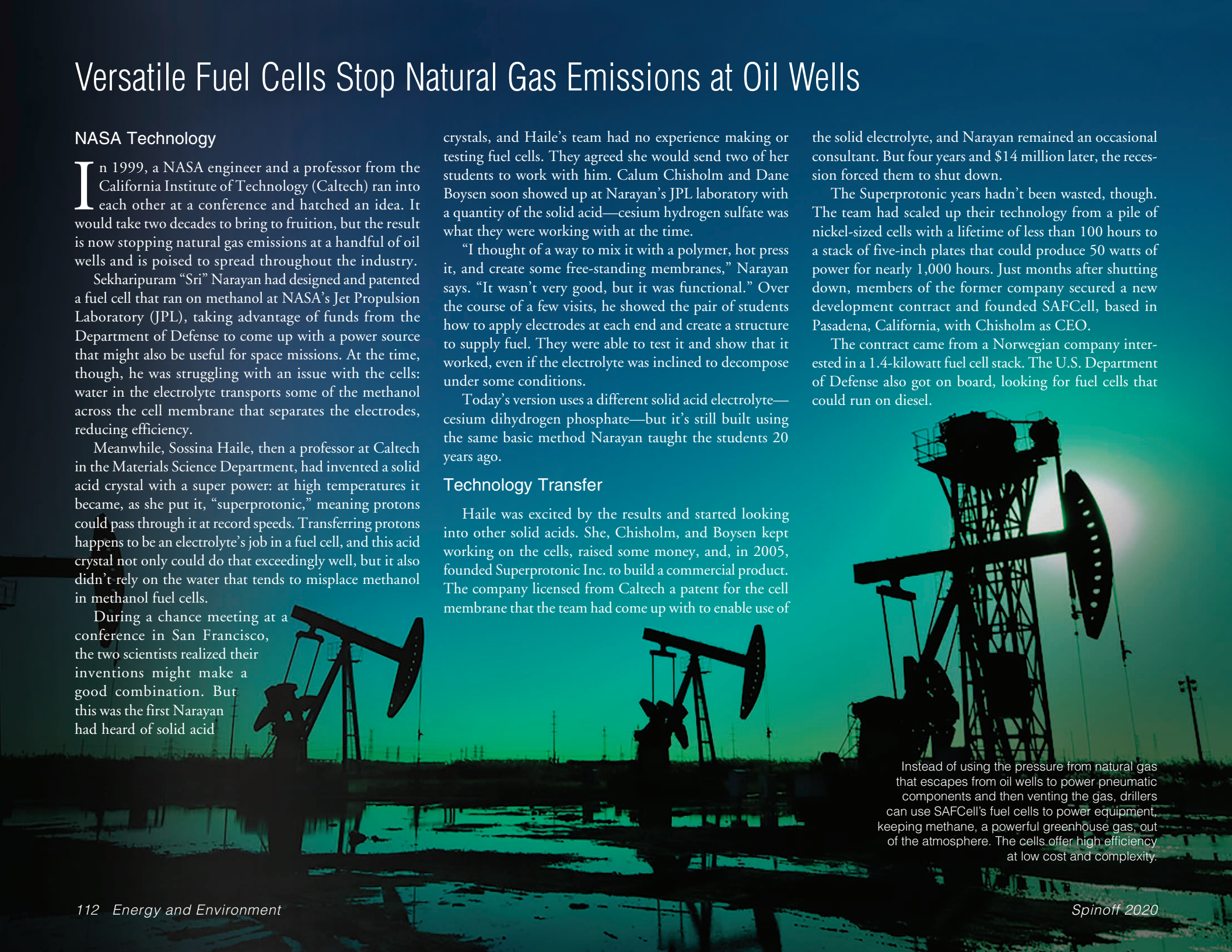
Today's version uses a different solid acid electrolyte—cesium dihydrogen phosphate—but it's still built using the same basic method Narayan taught the students 20 years ago.

Technology Transfer

Haile was excited by the results and started looking into other solid acids. She, Chisholm, and Boysen kept working on the cells, raised some money, and, in 2005, founded Superprotonic Inc. to build a commercial product. The company licensed from Caltech a patent for the cell membrane that the team had come up with to enable use of the solid electrolyte, and Narayan remained an occasional consultant. But four years and $14 million later, the recession forced them to shut down.

The Superprotonic years hadn't been wasted, though. The team had scaled up their technology from a pile of nickel-sized cells with a lifetime of less than 100 hours to a stack of five-inch plates that could produce 50 watts of power for nearly 1,000 hours. Just months after shutting down, members of the former company secured a new development contract and founded SAFCell, based in Pasadena, California, with Chisholm as CEO.

The contract came from a Norwegian company interested in a 1.4-kilowatt fuel cell stack. The U.S. Department of Defense also got on board, looking for fuel cells that could run on diesel.



Instead of using the pressure from natural gas that escapes from oil wells to power pneumatic components and then venting the gas, drillers can use SAFCell's fuel cells to power equipment, keeping methane, a powerful greenhouse gas, out of the atmosphere. The cells offer high efficiency at low cost and complexity.

By 2014, SAFCell had delivered to both customers, and the Norwegian company had built an auxiliary power unit around the technology. It was expensive, though, and impatient investors shuttered the operation.

On the military side, SAFCell partnered with another fuel cell company, UltraCell, to successfully develop wearable propane-fueled units for the Army, as a lightweight power source for troops' electronic devices. Chisholm's company built the fuel cell stacks and UltraCell integrated them into the final system. It's a partnership that continues to develop portable power systems for the military today.

As SAFCell looked for new markets, the oil and gas industry emerged as a clear possibility. Drilling sites typically use the pressure of natural gas escaping from the well to power pneumatic components such as the methanol injection pump that keeps a well from freezing. Then the gases—mostly methane, one of the most powerful greenhouse gas—are vented into the atmosphere. SAFCell saw an alternative: a fuel cell could run on the methanol that's already on site for freeze protection and power non-emitting electrical components, eliminating natural gas emissions.

Benefits

"Methane mitigation is a huge focus in the oil and gas industry," says Chisholm, noting that drillers often search their gas lines to stop gas leaks while at the same time intentionally venting the same greenhouse gases to drive equipment at the well site. "It's outrageous, and they recognize that very soon that's not going to be doable, whether regulation or public-image concerns bring it to an end."

In Canada, where methane from oil and gas production accounts for 6 percent of the country's greenhouse gas emissions, new regulations give producers four years to cut these emissions in half. These rules have created an estimated $3.1 billion market for retrofitting wells, of which Chisholm guesses about 10 percent will go to systems to power electric equipment. "That's a big, juicy market to go after," he says. "We like that combination of making money and going green while we're doing it."

Solar panels don't generate nearly enough energy to do the job, and the only other standard alternative, thermoelectric generators, are only about 3–6 percent efficient.

Image courtesy of the U.S. Army

SAFCell partnered with another company to develop lightweight, wearable propane fuel cells for the military, to power troops' electronic equipment in the field. The Defense Department is now funding the development of similar cells that run on JP-8 jet fuel.

A SAFCell fuel cell generator, meanwhile, is about 30 percent efficient.

SAFCell's "superprotonic" solid acid electrolyte increases efficiency not just by rapidly transferring protons from anode to cathode but also by operating at a high temperature. Heat accelerates chemical reactions, explains Narayan. His methanol cells are constrained by the boiling point of their water-based electrolyte, above which membranes dry out. The solid acid cells, on the other hand, can operate around 480 °F. "Under those conditions, oxidation of methanol occurs rapidly," Narayan says, referring to the chemical reaction that results in usable electricity. The heat also lets the cells break down more complex fuels like diesel, natural gas, and propane.

Other, hotter fuel cells operate between 900 and 1,800 °F, increasing efficiency even further, but they're complex and expensive. These are typically large, high-power stationary units.

"We're kind of the intermediate solution to existing fuel cell technologies," Chisholm says. "We look good for lower-power units in portable, mobile, or remote stationary applications. We have a nice combination of ruggedness, portability, and low cost."

The company deployed its first five units to well sites in Canada in 2018 and was slated to deliver at least 13 more in 2019. The military remains a customer and is now funding the development of cells that can run on JP-8 jet fuel to power portable equipment. "Once we have a JP-8 system, it's off to the races with them," Chisholm says.

No matter how large the military and oil and gas markets turn out to be, SAFCell doesn't intend to stop there. "We want to get the volume up and the price down so we can enter bigger markets, like range extenders on vehicles and residential heat and power units," says Chisholm. "If we can get the price point down and extend the lifetime, we can compete in a lot of markets." ❖

Laser Enables Precise Measurements for Weather Forecasting, Industry

NASA Technology

News of Hurricane Irma dominated forecasts for days before it made landfall in the Caribbean and then the southeastern United States in September 2017, with predictions of where it would hit, when, and just how powerful it was going to be. And although the massive storm devastated many areas, those forecasts helped countless residents prepare to weather it more safely.

But how did forecasters get such a clear picture of what was coming? One important tool in their arsenal was a sophisticated device called the Cross-Track Infrared Spectrometer (CrIS), which scans the atmosphere, from the ground all the way up, from a polar-orbiting satellite.

After the fact, recalls David Johnson, a scientist at Langley Research Center, analysis showed that prediction models without readings from satellite instruments such as CrIS showed the storm sputtering out in the Atlantic Ocean soon after forming. "But when they include the data from these sounders," he says, referring to CrIS, "the models showed the hurricane intensifying and becoming a major storm"—which is what actually happened. (In fact, it was one of the strongest storms ever measured in the Atlantic basin, and even after it weakened to a tropical storm over land, its slow-moving path and large wind field left a huge swath of destruction.)

Hurricane Irma was massive on September 10, 2017 as it approached Florida—seen here in a NASA satellite image. (Hurricane Jose can be seen in the lower right corner.) The Cross-Track Infrared Spectrometer (CrIS) on a different satellite helped predict the hurricane's path and intensity, enabling communities to better prepare for the storm.

"The improved temperature and humidity information from CrIS improves the ability to predict tropical cyclone intensification as well as improve your storm tracks," giving more accurate information three to five days beforehand, Johnson says—crucial for emergency planning.

Building CrIS was no easy task—and one of the lasers needed to make it work has since gone on to help in everything from oil refineries to milk production.

CrIS is what's called a Fourier Transform spectrometer. Put simply, spectrometers observe a solid, liquid, or gas, and then measure which spectra of the light are emitted or absorbed. From that, they are able to determine information about the composition of that substance. In this case, CrIS measures temperature and humidity by observing thermal emissions—that is infrared light—from the Earth's surface that are absorbed and reemitted by the atmosphere.

To get the spectral measurements, the infrared emissions are first split and bounced between two mirrors—one of which moves at specific intervals to control which wavelengths of light are reflected—before being sent to a detector. This process is repeated many times as the second mirror moves, alternately blocking and allowing different wavelengths to pass through. After all that, the data must be analyzed using complex mathematical models (specifically, the Fourier Transform) to get the targeted answer.

But if the mirrors aren't aligned absolutely perfectly, and the distance the mirror moves isn't calibrated precisely, to submicrometer levels, the entire process breaks down.

This is achieved with a metrology laser—in other words, a laser measurement—that constantly checks the alignment and distance of the mirrors, telling the spectrometer exactly when the distance is correct to take a reading and ensuring that reading isn't filled with noise.

"CrIS wouldn't work without a laser metrology system," Johnson emphasizes.

One essential component of CrIS is a metrology laser designed by ABB. The company has since incorporated the smaller and longer-lasting laser into many of its commercial spectrometers, used for quality control in the pharmaceutical industry and to measure octane in oil and gas refineries, among many other applications.

Technology Transfer

The metrology laser for CrIS was built by a multinational company called ABB, based in Switzerland but with its U.S headquarters in Cary, North Carolina, as a subcontractor to L3Harris Technologies. ABB had been building metrology lasers for spectrometers at least since the 1990s, explains Marc-Andre Soucy, ABB's director for space and defense systems. But CrIS needed something different.

"On industrial systems, we used to use a helium-neon laser. Essentially, that's a tube with gas inside, and by applying a high voltage, it creates a laser signal," Soucy says. But that wouldn't work in space for a variety of reasons. For one, in the vacuum of space, it is difficult to contain the helium. For another, the lifespan of these lasers is only about three to four years—far too short for a satellite expected to last 10 to 15 years.

So ABB needed to find a laser that would be reliable and long-lasting and would work in space. They needed it not just for CrIS but for a concurrent project with the same problem with the Canadian Space Agency.

The solution was a semiconductor laser. These weren't new—among other applications, they had previously been used for telecommunications—and they offered a number of advantages over helium-neon lasers. They are smaller, both in physical size and power requirements, they have a much longer lifespan, often up to 25 years, and they are very reliable.

However, there were a number of challenges that had to be overcome to make them work for space-based spectrometers. The most important was that, unlike helium-neon lasers, which have a constant wavelength based on the atomic properties of the helium-neon gas, semiconductor lasers have a variable wavelength that depends on the temperature and the current flowing through them. But for the sub-micrometer accuracy needed in a spectrometer, the wavelength needed to be held absolutely constant.

"It took us some time to find ways to get similar levels of performance to the helium-neon lasers," says Soucy, "but today the results are very good. Probably not as good as helium-neon lasers, but it is sufficiently good so that it does not limit the performance of our spectrometers."

It was good enough for CrIS, which launched in 2011 and has been improving weather forecasts ever since, as well as for the Fourier Transform spectrometer on the Canadian satellite. In fact, ABB has a half-dozen of these metrology lasers flying on satellites currently, and, notes Eric Beaubien, CrIS program manager at L3Harris Technologies, his company is already working on the next-generation model with ABB components.

"Before the L3Harris-built CrIS became operational, sounders provided 19 'slices' of the atmospheric column from the ground up through the clouds. The next-generation CrIS captures more than 2,000 slices, vastly improving weather forecast models with more detailed information about moisture, temperature, and pressure."

And plenty of ABB's Earth-based clients have also jumped on board.

Benefits

ABB had already sold thousands of industrial spectrometers with helium-neon lasers before developing the semiconductor-based version. Some of those customers have chosen to stick with what they know, Soucy says.

Most, however, have not. "I would say now about 90 percent of our industrial spectrometers are using the semiconductor laser like the space ones," he says. "We deliver more than 1,000 systems every year now."

Moreover, he notes, since adding the semiconductor laser to their catalog, "we have more than doubled our business volume. It's not only due to that, but we can say for sure this has resulted in higher sales."

The benefits for industrial customers are largely the same as for space: the lasers deliver extreme accuracy in a smaller, less power-hungry, longer-lasting package. For example, ABB spectrometers are used in oil refineries to measure octane and other chemical parameters in real time. Every time the metrology laser needs to be switched out, oil production must come to a halt, costing the refinery money.

"For those customers, having less maintenance or as few interruptions as possible is very important. Because for them it means higher yield or higher production," Soucy says.

ABB's spectrometers are also used in the dairy industry, to measure fat content of the milk so it can be accurately labeled as skim, 1 percent, 2 percent, or whole milk. Other customers are in the pharmaceutical industry, environmental sector, and even in semiconductor production.

So whether you're checking your five-day forecast, buying whole milk, or filling up with high-octane gas, there is a small but powerful laser playing a crucial role. ❖

Information Technology

We interact with software constantly, on our phones, in our cars, on our televisions. Even home appliances are getting “smart.” But we may not realize other ways computer power affects our daily lives—for example, many of the products we use, from shoes to aircraft and more, were designed with the help of supercomputers. Other software is readying our infrastructure for a new wave of drone flight that may soon deliver products or ferry riders across town. And simulation software helps optimize the systems by which computers communicate with each other. Before they were improving our lives, the advances making these new applications possible started at NASA.

Beowulf Clusters Make Supercomputing Accessible

NASA Technology

In the Old English epic *Beowulf*, the warrior Unferth, jealous of the eponymous hero's bravery, openly doubts Beowulf's odds of slaying the monster Grendel that has tormented the Danes for 12 years, promising a "grim grappling" if he dares confront the dreaded march-stepper.

A thousand years later, many in the supercomputing world were similarly skeptical of a team of NASA engineers trying achieve supercomputer-class processing on a cluster of standard desktop computers running a relatively untested open source operating system.

"Not only did nobody care, but there were even a number of people hostile to this project," says Thomas Sterling, who led the small team at NASA's Goddard Space Flight Center in the early 1990s. "Because it was different. Because it was completely outside the scope of the supercomputing community at that time."

The technology, now known as the Beowulf cluster, would ultimately succeed beyond its inventors' imaginations.

In 1993, however, its odds may indeed have seemed long. The U.S. Government, nervous about Japan's high-performance computing effort, had already been pouring money into computer architecture research at NASA and other Federal agencies for more than a decade, and results were frustrating.

Under one Federal program, the High-Performance Computing and Communications Initiative, started in 1992, Goddard had set a goal of achieving teraflops-level supercomputing performance by 1997—a teraflops representing a speed of one trillion floating-point operations per second. And it needed to work on systems cheap enough to be assigned to a single employee. But by 1993, the best codes were achieving just a few tens of gigaflops on the biggest machine, more than an order of magnitude slower and at many times the desired cost per operation. There was no clear path to achieve performance goals within the required cost range.

Thomas Sterling, who co-invented the Beowulf supercomputing cluster at Goddard Space Flight Center, poses with the Naegling cluster at California Technical Institute in 1997. Consisting of 120 Pentium Pro processors, Naegling was the first cluster to hit 10 gigaflops of sustained performance.

Parallel processing—using a cluster of processors to achieve a single task—was understood, but each vendor was developing its own proprietary software to run on costly proprietary hardware, and none was compatible with another. A single workstation might cost $50,000 per user. The existing systems also crashed regularly, forcing reboots that restarted all running jobs and could take half an hour.

All this is documented in a 2014 paper by James Fischer, who managed the Earth and Space Science (ESS) Project at Goddard at the time. ESS housed Goddard's arm of the high-performance computing initiative, as the Center required high-speed data analysis to work with the massive amounts of data generated by its Earth-imaging satellites.

"It is only 20 years ago, but the impediments facing those who needed high-end computing are somewhat incomprehensible today if you were not there and may be best forgotten if you were," Fischer writes.

In late 1992, Fischer asked Sterling if he would be interested in transitioning from NASA Headquarters to conduct supercomputing research efforts at Goddard. Around this time, Donald Becker, a longtime colleague of Sterling's, arrived in town to start a new job at another Government institution. Sterling let him stay at his place for a couple of weeks while he looked for an apartment.

"Don was very much his own thinker," Sterling says. For one thing, Becker had taken to writing code using the new, free, open source Linux operating system, which, to

Sterling's thinking, was a fun toy but of little other value and sorely deficient for real work.

One evening Becker came home depressed and worried that he would lose his job due to a certain inattention to formalities, Sterling says. "He wasn't someone who would do the right paperwork."

This prompted Sterling's eureka moment. It occurred to him that Linux, and Becker's skill with the software, might be applied to the supercomputing problem he was grappling with at Goddard, letting him bypass supercomputer vendors entirely. "I needed a piece of software where we could get ahold of the source code, create the necessary cluster ecosystem, and provide a robust system area network at low cost," he says.

He wrote an appeal to Fischer, proposing that Goddard hire Becker to help tackle the supercomputing problem by using Linux to marshal an army of off-the-shelf personal computers to carry out massive operations. It was the first Fischer had heard of Linux, but he let himself be convinced. "He took a lot of heat, but he saw the opportunity and he didn't give in," Sterling says.

Thus NASA became the first major adopter of Linux, which is now used everywhere, from the majority of servers powering the internet to the Android operating system, to the animation software used in most major studios.

"People said Linux wouldn't last two years," Sterling recalls. "I said, I don't need more than two years. I'm just running an experiment."

By the summer of 1994, Sterling, Becker, and their team had built the first supercomputer made up of a cluster of standard PCs using Linux and new NASA network driver software. It didn't meet all the requirements of Goddard's supercomputing initiative, but subsequent generations eventually would.

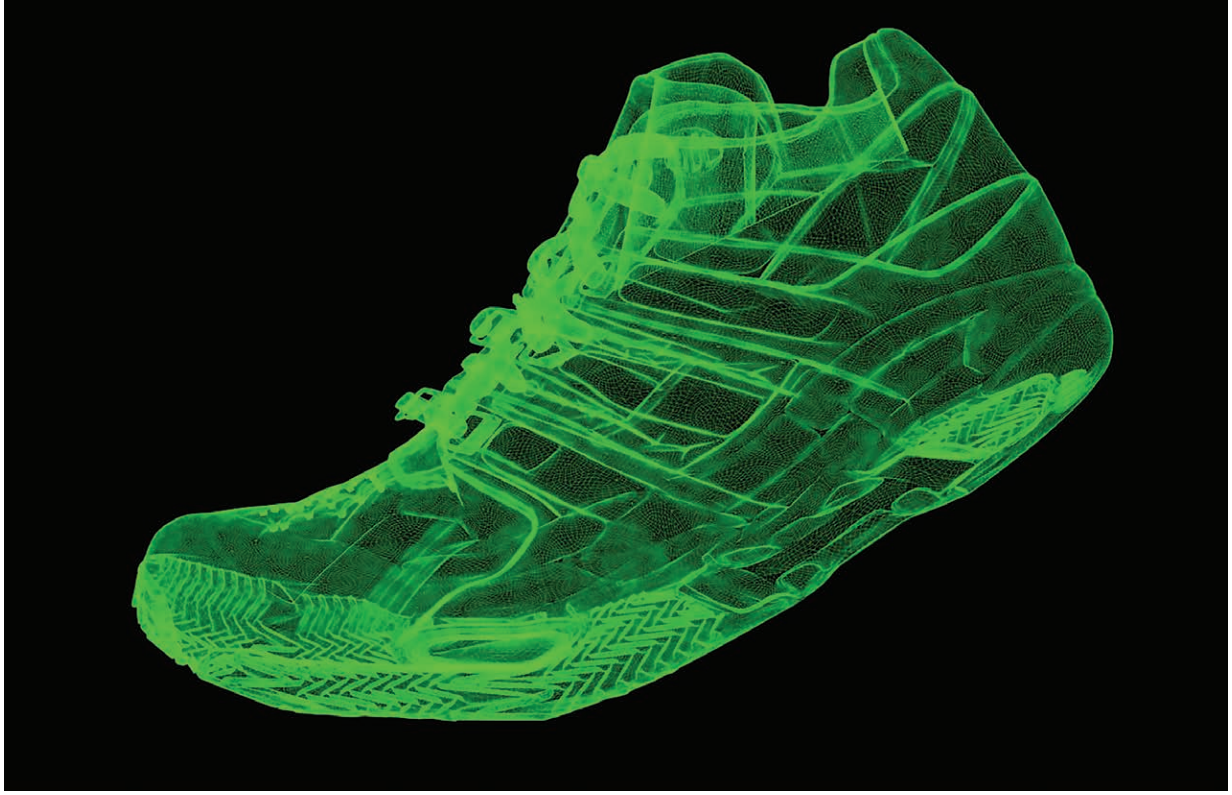
Those first years were not easy, Sterling says. "It can't be done," he recalls one member of the ESS external advisory committee telling him, in remarks that were not unusual. "And if it could be done, no one would use it. And if people used it, no one would care. And if people cared, it would destroy the world of supercomputing."

That world was dominated by "people wearing suits and ties and sitting at large tables," Sterling says. "You were expected to have a large machine room and be using Fortran." The prospect of a coup by a handful of informal young people using personal computers didn't sit well. Open source freeware also was new and violated industry expectations.

"We broke all the rules, and there was tremendous resentment, and of course the vendors hated it," Sterling says.

For the next 10 years, Sterling and Becker told anyone who asked that they'd named their invention for an under-

In this illustration, two black holes orbit each other, preparing to merge. Such a merger caused the first gravity waves ever detected, which the Laser Interferometer Gravitational-Wave Observatory registered in September of 2015. The Pulitzer Prize-winning project used a massive Beowulf cluster of 2,064 central processing unit cores and 86,000 graphics processing unit cores—custom-built by Nor-Tech—to crunch its data.



Thanks to the low-cost supercomputing made possible in part by the invention of Beowulf supercomputing clusters, manufacturers now use modeling and simulation software to design all kinds of consumer goods.

dog challenging a formidable opponent. But Sterling now admits this tale was invented in hindsight. In fact, he chose the name when a Goddard program administrator called and asked for a name on the spot. "I was helplessly looking around for any inspiration," he says. His mother had majored in Old English, and so he happened to have a copy of the early Anglo epic sitting in his office.

"I said, 'Oh hell, just call it Beowulf. Nobody will ever hear of it anyway.'"

Technology Transfer

"If you're in the business, certainly most people have heard of it," says Dom Daninger, vice president of engineering at Minneapolis-based high-performance computing company Nor-Tech, one of a number of companies that optimize Beowulf-style clusters to meet clients' needs. The annual SC supercomputing conference even includes a Beowulf Bash every year, he says.

Despite the initial pushback, as word of the Beowulf cluster got out, interest also began to build. Sterling says even the strange name seemed to grab people's attention. In 1995, he started giving tutorials on how to build a Beowulf cluster, and two years later, he, Becker, and their colleagues received SC's Gordon Bell prize for their work. In 1999, the team co-authored the MIT Press book How to Build a Beowulf.

The Ethernet driver software Becker had created to overcome Linux's inherent weaknesses and tailor it to supercomputing was made open source and easily downloadable, paving the way for it to become the top operating system for supercomputing and many other applications. The creators also started the website Beowulf.org, where an international community of users post questions and discuss the technology.

The difference between Beowulf and other parallel processing systems is that it has no custom hardware or software but consists of standard, off-the-shelf computers, usually with one server node controlling a set of "client nodes" connected by Ethernet and functioning as a single machine on the Linux operating system. Other open source operating systems can be used. A cluster can easily be scaled up or down by adding or subtracting units.

Benefits

"I hadn't anticipated the freedom Beowulf clusters gave a lot of people, who were no longer tied down by cost and proprietary software," Sterling says.

The technology costs anywhere from a third to a tenth of the price of a traditional supercomputer, according to Beowulf.org.

"People were free to configure their own systems, determine their software stack without interference, and contribute to the entire community," Sterling says. "Beowulf was the people's computer."

Nonetheless, it took many years to come to dominate the market.

Recently, Daninger says, many industries have come to rely on software for computer-aided engineering and modeling and simulation. But programs for such complex applications as finite element analysis and computational fluid dynamics (many of which, he notes, are based on NASA software) require huge amounts of processing and storage capacity. This used to limit their use to major corporations, such as a plane manufacturer running simulations on an airliner design before building it, saving huge amounts of money in the process.

Now the hardware for a Beowulf cluster is cheap enough that the cost of licensing simulation software ends up being about three-fourths of the total cost of the cluster over its lifetime, Daninger says, making it affordable to smaller companies designing smaller products.

"We constantly hear from pharmaceutical and manufacturing companies that they're running out of bandwidth,"

he says, adding that a simulation might tie up a workstation for 72 hours before generating its first answer.

Instead, a company can use a workstation to preprocess a simulation and then offload it to a Beowulf supercomputing cluster, he says. "They can go about their work on their workstations, and then the answer will come back to them."

Nor-Tech custom-builds each cluster, integrating the servers, computers, and Linux-based operating system. Another NASA-enabled technology, the portable batch system (*Spinoff* 2001) is usually incorporated to schedule and prioritize jobs and manage resources.

"By the time we deliver a cluster to the customer, they've already had a chance to remote in and test their simulation and modeling jobs, and we've trained them on how to use it," Daninger says. He says customers typically start with a small cluster of four to eight units but scale up within the first year. "A lot of our customers are on their third or fourth scale-up."

Where a motorcycle manufacturer used to build 5 or 10 prototype engines and test them—an expensive and time-consuming process—now it can generate and test simulated models. "It saves them a lot of physical modeling, and there's a quicker time to market with more reliable products," Daninger says.

One customer, a recreational vehicle manufacturer, came to Nor-Tech after spending more than $1 million designing, tooling, and producing a vehicle hood that it had to scrap due to heat and stress issues. A pharmaceutical company using simulation software for molecular modeling went from a three-day turnaround time to nine hours when it switched to a small cluster. "They could have gotten it down a lot more if they had scaled up," Daninger says.

Other customers include aircraft builders running aerodynamics simulations and lawnmower manufacturers who want to predict where the machines will propel grass, among other behaviors. Companies now run modeling software on Beowulf clusters to design such everyday objects as toothpaste tubes, soap dispensers, and diapers. Others use the technology for such disparate applications as predicting beam behavior in proton-beam therapy for cancer treatment and modeling radiation emissions from a hypothetical nuclear catastrophe.

In the last few years, two of the company's customers have won the Nobel Prize in Physics. Both the Laser Interferometer Gravitational-Wave Observatory that first detected gravitational waves and the IceCube observatory that first sensed neutrinos from beyond the solar system used Nor-Tech Beowulf clusters to crunch their data.

Nor-Tech started out as a computer parts distributor, but after almost 20 years of building clusters, these now account for about half of the 30-person company's business.

Thanks to the Beowulf cluster, virtually every one of the world's top 500 supercomputers runs on Linux. Four out of five of those are based on Beowulf.

"There was never a plan to revolutionize computing," Sterling says, adding that Beowulf only triumphed because many others contributed to it over the years. "If we had tried to do something world-changing, we wouldn't have succeeded."

Now a professor of engineering at Indiana University and president of the new start-up Simultac LLC, Sterling says, "I'm working on other things that people think are stupid—a sign that I must be doing something right." ❖

Another Pulitzer Prize-winning project, the IceCube Neutrino Observatory at the South Pole, used a Nor-Tech Beowulf cluster to process data that led to the first detection of neutrinos from beyond Earth's solar system in 2013.

Mission Control Conference System Enables Global Collaboration

NASA Technology

Today conference calling is so easy and common it is essentially unremarkable. Share a toll-free phone number and instantly dozens, hundreds, or even thousands of people from anywhere on the globe can call in and talk to each other. Share a meeting link and, with a click, everyone can see video of other participants' faces or a live view of their computer screen.

But behind the scenes, all of these simple operations take quite a bit of complicated technology—technology that didn't exist before the 1980s, when NASA mission control decided to improve the system by which its engineers, technicians, and astronauts communicate. The spinoff benefits have rippled widely.

During any mission, information flows constantly, as technicians and engineers monitor a spacecraft's fuel levels, the weather at the landing site, biometric readings from the astronauts, and more. As early as the Mercury missions in the late 1950s, the Agency built a complex system that managed to connect all the people on the ground and in space through a network of 18 ground stations and three ships in different oceans, with the central hub at Goddard Space Flight Center in Maryland.

But by the 1980s, NASA was ready for an upgrade. In particular, the Agency wanted a digital 4,000-port system that would instantly connect people within multiple, interchangeable groups across distant physical locations. The existing system allowed such networking, but it was cumbersome, explains Curt Suprock, now the chief of the NASA Communications (NASCOM) Division, based at Goddard.

"There would be these huge patch panels with all the cables pulling in, and that's how you connected people," by manually plugging and unplugging the cables to link different ports together, he explains. And if you wanted to connect a group of people on a single call, that required a different manual "conference ring" that was difficult to reconfigure once it was set up—it might even require ending the call and starting from scratch.

"We had an operation staff that knew intimately all the patches. With that team, you could do things very quickly. But you required that kind of expertise," Suprock says. With improving computer technology, NASA saw the potential to automate the system to make it easier on the front and back end.

NASA hired a company called Compunetics to build two new digital systems for voice switching and voice distribution (VSS and VDS), which allowed voice connections and conference loops to be reconfigured instantly and automatically. Where before dozens of highly skilled technicians were racing to move cables between ports, now it could be done instantly with the push of a button.

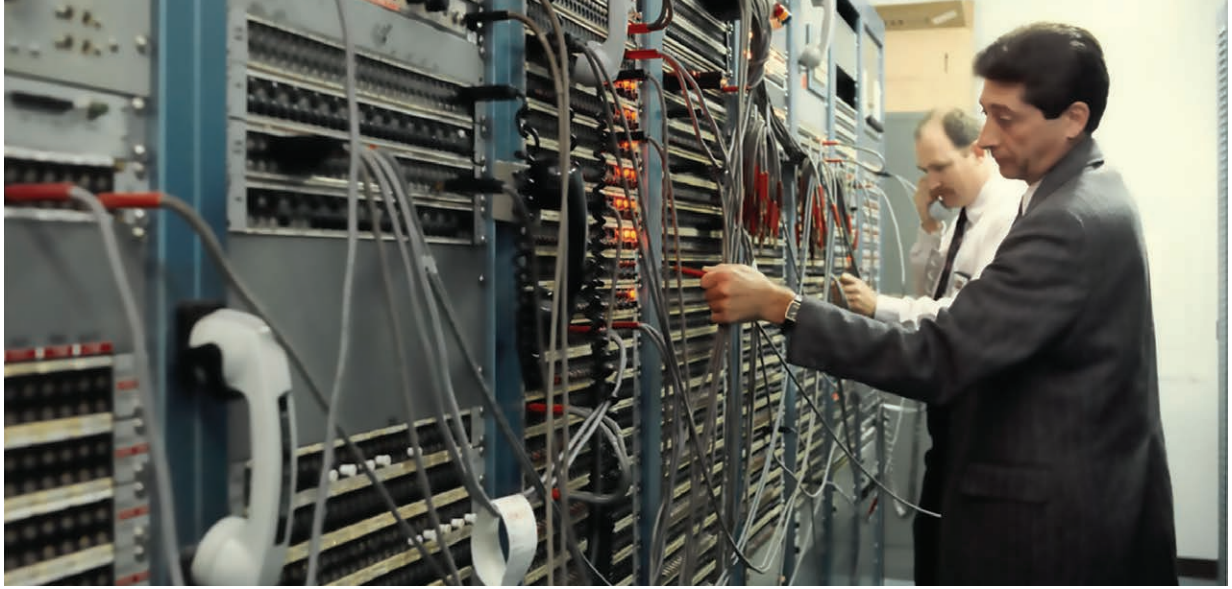
The Compunetics systems were installed in 1992, and after extensive testing, NASCOM ultimately switched over entirely. The network has been updated since, and another update is in the works, Suprock says. But overall the change from analog to digital improved speed and flexibility, all while requiring far fewer people behind the scenes. Today NASCOM is still staffed around the clock, but instead of 40 or 50 technicians, it needs just 8.

Technology Transfer

Outside of NASA, phone companies would typically arrange the hardware to make a conference call happen. "You had to fax over a list of numbers to the AT&T operator, and they'd build up a conference," explains Michael Hockenberry. First hired in the late 1980s as the NASA project was getting underway, he's now a senior vice president of the Federal division of Compunetix, one of two companies that spun off from the original business.

With the new system it built for NASA, Compunetics knew it had something far better. Among other advances, the company had integrated its newly patented invention,

All crewed space missions are monitored at the Mission Control Center at Johnson Space Center. Behind the scenes, a vast communications network, based out of Goddard Space Flight Center, makes it all possible.



NASA's original communications network was a complicated analog system that required manually plugging and unplugging wires to link different ports (left). By the 1980s, the Agency was ready for a digital upgrade, and it turned to Compunetix to design and build a digital system that allowed voice connections and conference loops to be reconfigured instantly and automatically (right).

a non-blocking switch, which meant that once a set of ports were hooked up, calls could be connected in any configuration within the network, even without contiguous connections. Although Compunetics founder Giorgio Coraluppi had actually invented this non-blocking algorithm prior to the NASA contract, Hockenberry explains, it took the NASA contract and funding for the company to figure out the market and develop the invention into a fully functional system.

That system "became the foundation for our communications systems division," Hockenberry says, and the basis for the products and services the company offers to this day. The company based their commercial offering on the VSS system it had built for NASA and called it a conference bridge.

Next, Compunetics added a user-friendly operator interface that allowed an operator to add and drop parties from the conference by computer. Essentially, it changed conference calls from a manual task of connecting phone wires to contiguous ports, to a software function of linking different pieces of an interconnected network, which is the backbone of how conference calls still work today.

The Goddard contract "was really instrumental for us," explains Robert Haley, communications director at Compunetics. "We took the technology from that large 4,000-port NASA system, and we really reconfigured it and commercialized it and took it directly to the commercial telecom market. We've never slowed down since then."

Benefits

Today Compunetics actually comprises three companies, all based in Pittsburgh, and all of which trace back in different ways to the original innovations created for NASA. The original company, Compunetics, was founded in 1968 and today specializes in building small runs of complex printed circuit boards, including for the conference bridges but also for NASA's Jet Propulsion Laboratory, the military, Intel, IBM, and other companies that need specialized circuit boards for specific projects.

The second company, Compunetix, spun off in 1990 as a separate entity to manufacture and sell the conference bridges first developed for NASA. Thanks to numerous updates along the way, Haley says, "we're still the leading conference bridge manufacturer. We have millions of ports deployed worldwide."

The third company, commercial conferencing agency Chorus Call, was created around the same time to help build the case for the Compunetix conference bridges, Haley explains. "If we were going to MCI and wanted them to buy our conference bridge, we wanted to prove to them we could build a business on that," he says. "That small company created as a proof of concept is now a worldwide collaboration provider. We're in 12 different countries right now."

Among other modernizing updates along the way, an operator is no longer needed to add and drop callers from a particular conference. Compunetix built an automated system where the caller enters a passcode prompting the software to automatically drop him or her into the conference. The company has also added video conferencing capabilities in recent years.

Although there are many conference calling services available, to this day, when someone in an office dials into a conference call line, they are in many cases dialing into a Compunetix conference bridge. "Pretty much every large conference bureau around the globe uses us to some extent," Haley says.

Even web-based video conference calling relies in part on Compunetix, Haley says. For example, the video connection may be through WebEx conferencing software, he explains, but for the audio, "you can connect with your phone or PC audio, or they can dial you back. That can be our switch doing that." ❖

Swarming Technology Lets Drones Work as a Team

NASA Technology

Even before much-anticipated autonomous drones finally take to the sky, the U.S. airspace is saturated, says now-retired Langley Research Center scientist Kennie Jones. A delay at one airport sends ripple effects through the system, causing more delays and missed connections. Flight infrastructure can't support more than the 7,000 or so aircraft that are flying over the United States at any given time. Yet, once regulations and safety precautions are put in place to allow unmanned drones, that number is expected to skyrocket to around 2 million.

"We're going to go from thousands to millions overnight," Jones says. "It's a huge problem."

Drones won't use airport runways, obviously, but they will complicate flight paths, especially for smaller, lower-flying aircraft.

One solution he thinks could help alleviate the problem would be the ability for aircraft to communicate with each other and autonomously coordinate their actions. This idea drew his interest to a proposal by California, Maryland-based Heron Systems Inc., which wanted to develop software and hardware to allow drones to cooperatively allocate tasks and resources and plan flight paths, working together toward a common goal without the help of an operator.

Planes, especially airlines, have been moving toward autonomy for decades, as autopilot systems have taken over more and more of a pilot's job. "The goal at first wasn't autonomy but to have machines help pilots make better decisions," Jones points out. "Now they can auto-land."

Both in the drone community and in the Federal Aviation Administration's effort to create what it calls the Next-Generation Air Transportation System, there has been debate about whether autonomous cooperation should be orchestrated by a central controller or worked out between the aircraft themselves. Jones figures any automated solution will lie somewhere in between, but he leans toward letting the craft make the decisions.

He appreciated that Heron Systems seemed to be thinking along the same lines, even if the company wasn't thinking about airline flight control specifically. "Heron was toward the end of the spectrum where you're putting local intelligence on the aircraft to make local decisions," he says.

Technology Transfer

"Kennie was a bit of an iconoclast," says Brett Darcey, vice president of Heron Systems, noting that Jones also influenced the company's approach. It was Jones who oversaw the two Small Business Innovation Research (SBIR) contracts NASA awarded the company in 2015, one each funded by Langley and Armstrong Flight Research Center.

Since its founding in 1997, Heron Systems had worked as a defense contractor, providing testing and simulation products and services primarily to the Navy. But the company wanted to branch out, Darcey says. What is now known as Multi-Agent Cooperative Engagement (MACE) started out around 2013, when Ken Kroeger, a software engineer with the company, began working on a pet project for command and control of multiple drones. He had a background in multi-robot coordination and had recently started doing some drone work with farmers and energy companies.

"The first SBIR launched it into something more realizable than just a pet project in my backyard," Kroeger says.

He started with tools and software modules from the popular, open source Robot Operating System (ROS). This not only provided a ready set of building blocks but now makes MACE compatible with other robotic systems based on ROS. (Kroeger describes the result as a software Lego play set.) Heron Systems adapted these tools and added its own software modules and hardware to let multiple aircraft

Heron Systems and the University of Maryland test the company's Multi-Agent Cooperative Engagement (MACE) system for autonomous drone teamwork in June 2019 at the university's Fearless Flight Facility. A Heron Systems employee and a graduate student conduct a flight of five drones of two different types, with MACE being used to create the swarm, negotiate tasking between agents, coordinate path planning, and establish ground control.

communicate, keep track of each other, and interactively plan flight paths and avoid collisions.

Because a small, commercial drone can't carry a lot of extra weight or sacrifice a lot of power, the hardware to run MACE is small and simple—"nothing an engineer with a soldering iron couldn't accomplish," Kroeger says.

The basic software is available for free under an open source license, in part to establish a community of users and a market for future swarm technology, and to get feedback, for example on what sorts of applications end users want to adapt it to.

Benefits

By late 2018, only about five months after Heron Systems completed the SBIR work, the company had won about $750,000 in follow-on contracts from NASA, the Defense Advanced Research Projects Agency (DARPA), and the Department of Homeland Security. The University of Maryland is using MACE to help with the DARPA work, and Virginia Tech was looking into obtaining it.

"That's not bad for one summer," Darcey says.

He sees immediate applications in military training, where virtual environments provide a cheaper alternative to live training. One difficulty virtual combat training has run up against is programming simulated enemy fighters, whether troops, aircraft, or boats, to behave realistically. MACE software would let virtual fighters function more like an actual team. "When I go to defense firms and related programs and brief them on MACE, I get a lot of raised eyebrows and attention," he says.

Once autonomous drone regulations are in place, swarms for monitoring crops and infrastructure will be an obvious application, Darcey says. The little aircraft still have a fairly short battery life, so deploying a group to survey a field would make more sense than changing the batteries on a single drone every 20 minutes or so. "As the market matures and we can legally operate a swarm, we'll be well positioned to address applications where scale matters," he says.

In 2018, Langley awarded the company another SBIR contract to create algorithms that would plug into MACE and act as a virtual "auctioneer" to distribute tasks. Each "agent" in the swarm will calculate the resources it would expend on a given task, and the job will go to whichever can do it cheapest. The bidding continues on new tasks until all the drones are busy. "This starts to break from an operator telling everyone what to do," Darcey says. "The agents decide who does what. That's the bleeding edge of robotics research right now and something that we are keen to explore from an end-user perspective."

This capability, he says, "is the real secret sauce that's going to make MACE commercially viable." Meanwhile, he says, the company continues to look for more applications within NASA.

Jones says he could see uses well beyond air traffic control. For example, years ago NASA scientists discovered a significant presence of methane in the Martian atmosphere. They would like to determine its origins on the surface, but this can't be done remotely, and a rover can only cover a tiny portion of the planet. But what if a vast swarm of simple sensor drones were deployed on the surface?

"When you use a swarm, you could have 80 percent failure of individuals and still have 100 percent success," he says. "A swarm has built-in redundancy. But you have to overcome coordination problems."

Darcey says he expects to find interest in places the company hasn't even looked yet. "The SBIRs let us prototype something that was both ambitious and possible," he says. "It was enough money to create something new and mature it to the point of viability." ❖

Existing flight infrastructure can barely manage the 7,000 or so flights a day in U.S. airspace, and an estimated 2 million self-piloted drones will join airplanes in that space once regulations for autonomous flight are in place. NASA hopes technology like Heron Systems' MACE software and hardware will help planes and drones work together to avoid accidents and work out flight paths with minimal guidance.

AURA Software Tackles Uncertainty in Complex Systems

NASA Technology

The software started as a way to evaluate the reliability of systems that look for anomalies in aircraft components and respond to them in flight. Today it is predicting how autonomous drones will behave and how drugs will move through the body, and its creators see no reason why it couldn't be applied to any complex system: the stock market, the spread of an illness through a population, or the actuarial science of insurance pricing.

It's software that predicts the future, or at least the probabilities of various outcomes. And it started at NASA's Langley Research Center.

Called the Algorithms for Uncertainty Representation and Analysis (AURA) program, the software is based on polynomial chaos theory, a branch of mathematics so complex that it wasn't much used until computing capabilities caught up to it in the 1990s.

By the mid-2000s, there was a lot of interest in developing advanced, intelligent, automated diagnostic and control systems that could detect and respond to aircraft damage and failures and thereby increase aircraft safety and autonomy. But no transition to new flight-safety algorithms is taken lightly.

"If you're going to put a system on a plane that detects failure and responds, it is critical to understand that system's performance so we can be certain it solves more problems than it creates," says Alec Bateman, a principal research scientist at Barron Associates Inc., the Charlottesville, Virginia-based company that built the AURA software.

Such a system could miss a failure, give a false positive, or misidentify the component that failed, he explains. And even if the problem is identified correctly, the system could still take a corrective action that fails to solve the problem or even exacerbates it. Engineers want to know the probability and impact of any such glitch.

"Safety-critical resilient systems are developed to act when things go wrong, and a lot of things can go wrong in a lot of ways," says Christine Belcastro, who, along with her identical twin Celeste Belcastro, worked in Langley's Aviation Safety Program, where most of NASA's work in this field was being done at the time. "It makes the problem very complex very quickly."

After developing its Algorithms for Uncertainty Representation and Analysis (AURA) software with Langley Research Center's help, Barron Associates tested and validated it on a fault-detection and control system for Langley's Generic Transport Model, part of the Center's Airborne Sub-Scale Transport Aircraft Research (AirSTAR) test bed.

Technology Transfer

Due to this complexity, at the same time that NASA was developing these autonomous systems, the Agency was also working on the means to validate them through analysis, simulation, and experimental testing, Belcastro says. This required new methods and tools, which is where AURA came in.

In 2007, Langley awarded Phase I and II Small Business Innovation Research (SBIR) contracts to Barron Associates to develop a software package that could measure the performance of integrated diagnostic and control systems—systems that the company had also been helping Langley develop. Belcastro oversaw the SBIR work. It built on a previous project that she and her sister had worked on with the company to adapt and improve a predictive technique known as Monte Carlo simulation, which relies on running millions or even billions of simulations with randomly altered variables.

This approach can take months to obtain meaningful results, is extremely expensive, and can miss worst-case combinations of uncertainties.

The 2007 SBIR contracts funded an effort to build on the earlier project and extend the uncertainty assessment capability to include probabilistic considerations. The idea was to come up with algorithms that could mathematically represent uncertainties and probabilities in a single calculation, using polynomial chaos methods. While this single calculation is very complex, it is much faster than running the huge number of simulations that would otherwise be needed. Polynomial chaos has been used in other areas where there are uncertainties in a system's parameters, but it's never been developed into a general-purpose tool, Bateman says.

With the SBIR funding, Barron Associates developed the software and successfully demonstrated it, testing it on

a fault-detection and control system for Langley's Generic Transport Model, a small-scale replica of a commercial aircraft.

The company built the program using the MATLAB computing environment, as well as the Simulink modeling and simulation package that integrates with MATLAB, both commonly used by engineers. Initially, though, AURA was difficult to use. "Until recently, it was hard to apply. Even a trained engineer would have a pretty steep learning curve," says Michael DeVore, a senior research scientist at Barron Associates who helped develop the program.

As a result, few licenses had been sold by the end of 2018, and most commercial activity around AURA had come from the company using it to solve problems for Government agencies, primarily NASA and the military.

In 2019, however, the company rolled out a new, user-friendly version for sale. "We did a lot of work to integrate these tools with MATLAB in a way that would make them much more accessible to people familiar with that software," Bateman says. The company also introduced a basic, free version of the program that's available for download.

Benefits

For NASA and the military, the company has used AURA to continue verifying and validating advanced aviation safety systems. Work for the Navy has focused on autonomous vehicles like drones.

The Army hired the company to calculate probabilities of how a drug will be absorbed, metabolized, and excreted—a field known as pharmacokinetics. "There are a lot of uncertainties with the human body and how it's going to react to a drug, and these are tied to different physiological parameters from person to person," DeVore says.

The company has heard considerable interest from makers of autonomous vehicles like drones and self-driving cars. The technology for autonomy already largely exists or will in the near future, but it can't be fully used until the risk of significant failure is proven to be acceptably low. "The benefit will be helping to move these systems toward reality," Bateman says. "This technology is a key enabler for verification, validation, and regulatory approval."

Belcastro retired from NASA in 2019 but is continuing her work as a distinguished research associate at Langley.

The Langley researcher who oversaw Barron Associates' work on the AURA software now plans to use it to develop resilience and safety assurance for autonomous multirotor drones.

She expects to incorporate AURA into work on resilience and safety assurance for multirotor drones, she says. This effort stems from research her twin started before dying of cancer in 2008, and Belcastro says she's pleased to see it come to fruition and widespread application.

"This kind of validation tool opens the door to safety-critical resilient systems that will allow autonomous vehicles and autonomous aircraft," Belcastro says. "Until you really solve the resilience problem and can evaluate the effectiveness of complex resilient systems when something goes wrong, you might as well not talk about having autonomous systems."

Likewise, Bateman is excited at the healthcare possibilities that could arise from the ability to model the implications of physiological differences between patients.

"These are what I think of first, because that's my background," he says, noting that Barron Associates is at home in the aerospace, aeronautics, and biomedical fields. The company has also discussed financial modeling with AURA, as well as validating the safety of automated systems at material handling facilities, Bateman says.

While there are other probabilistic analysis tools out there, he says, he doesn't know of any that's as easy to use and can be applied to virtually any complex system. "Hopefully, when we get the tool out in the world, people with other applications will use it for things we're not familiar with." ❖

Simulation Software Optimizes High-Speed, Efficient Data Networks

NASA Technology

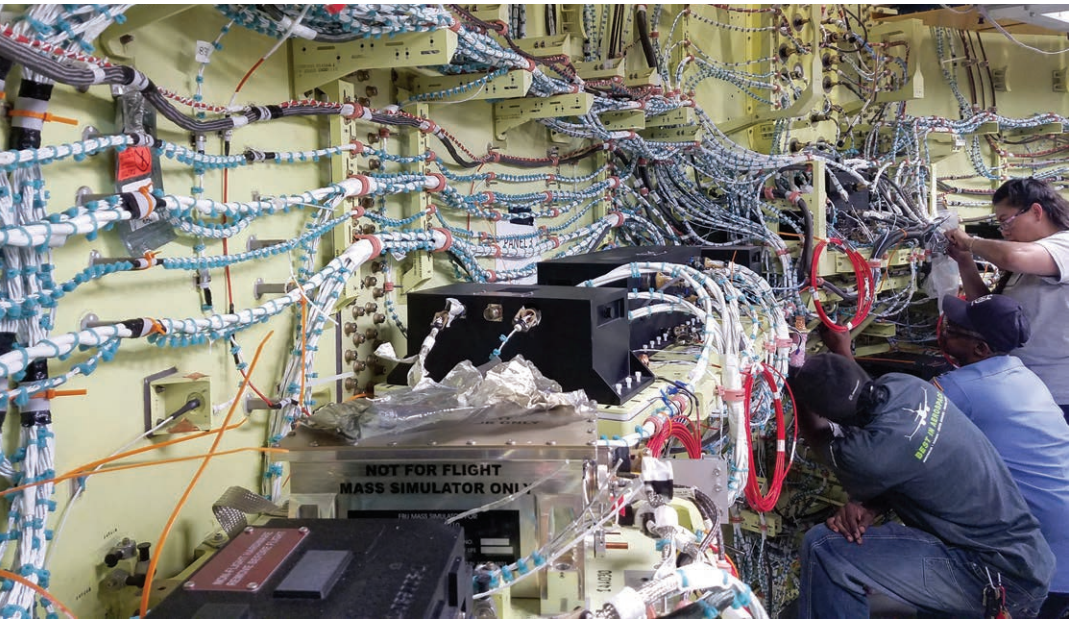
NASA famously uses simulation software to design spacecraft, predict satellite orbits, and train astronauts. But modeling and simulation are powerful tools that can generate valuable information anywhere they can be applied. In the early 2010s, a group at the Jet Propulsion Laboratory (JPL) successfully used simulation software to model the data transmissions, storage, and processing within and among all the sub-systems on a hypothetical spacecraft. The team wanted to predict the performance of a possible replacement for outdated, inefficient spacecraft data networks.

But they couldn't do it on their own. Instead, they helped enable existing commercial software to simulate what is fast becoming a popular communication protocol in the space community and beyond, known as RapidIO.

A computer communication protocol is a set of standards defining the physical and functional qualities of communication systems within or between computers, known as data networks. Spacecraft data buses were traditionally designed according to a protocol the military established for avionics in the mid-1970s, known as the 1553 protocol, which results in networks that can handle about one megabit of data per second. SpaceWire, a network standard developed in the early 1990s, offers higher speeds—up to 250 megabits per second—but lacks the fault tolerance and predictability the 1553 standard offers. By the 2000s, though, future space exploration demanded interconnect technology with bandwidths up to 10 gigabits per second or even higher for onboard applications.

So around 2010, JPL's internal research and development program funded a three-year project to explore alternatives.

"We were tasked with looking at all the available commercial standards out there, the notion being that to start from scratch would be hard and wouldn't be well accepted," says Raphael Some, chief technologist of the Autonomous Systems Division at JPL, who led that effort at the Center and later across multiple Government agencies and commercial industries. The group assessed 14 different network standards, narrowed those down to four, and finally settled on Serial RapidIO, an open source protocol.



Cables line the core stage of NASA's Space Launch System, connecting flight-guidance avionics to the Orion capsule, ground control, and other systems. NASA's need for higher-speed onboard electronic and communication networks drove the adoption of the Serial RapidIO communication protocol, but only after the Space Agency funded the development of a computer simulation of the Serial RapidIO standard by Mirabilis Design.

Compared with other candidates, Serial RapidIO offered a scalable bandwidth starting from a few gigabits per second to 100 gigabits per second or beyond. It had the lowest complexity for the capabilities it offered, including flexibility of implementation, multiple data transmission types, high levels of fault tolerance, easy encapsulation of Ethernet and other message packets, and excellent power efficiency. Being an open standard, it was also royalty-free.

But the standard needed augmentation to meet the needs of spaceflight, so JPL wanted a way to simulate its performance and try out modifications, which would be far cheaper than building and rearranging actual avionics systems in a lab.

JPL researcher Yutao He, principal investigator of the trade study for protocol evaluation, searched for software-based modeling and simulation that might provide a solution and ultimately selected a software called VisualSim. Made by Sunnyvale, California-based Mirabilis Design Inc., VisualSim simulates electronics and networking systems.

"It included an off-the-shelf library of compoments commonly used in avionics systems, which could be tailored to meet our technical needs at a low cost," says He. And the software was able to provide a high-level analysis to simulate a system's overall behavior and look for bottlenecks, for example, or it could drill down and model the workload on individual components. And it could calculate detailed, complete power consumption values that are especially important to NASA space missions.

Technology Transfer

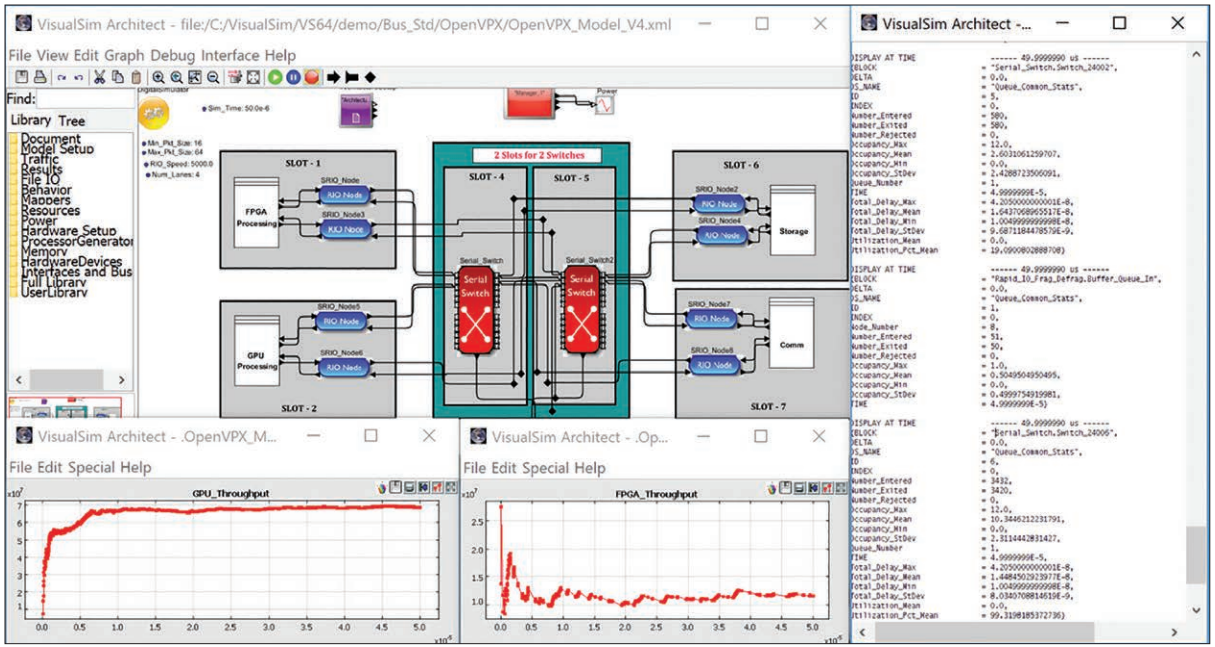
JPL partnered with Mirabilis to build a VisualSim library simulating Serial RapidIO-based spacecraft avionics for the study.

"We gave them our requirements, the features we wanted, and they were very supportive in the technical and business aspects," says He. As JPL started using the software, the company provided technical support and a discount licensing fee for his project.

Mirabilis founder Deepak Shankar describes VisualSim as a graphical environment with a library of standard hardware components, each with its own set of attributes, as well as generic blocks that the user can customize with attributes and parameters. Simulated software, schedulers, interfaces, and other components can also be plugged in. Once a system is built, he says, "the discrete event simulator simulates what would happen in real time, and when."

In the example of a satellite, he says, systems might operate in one mode during launch, another in the initial orbit, and then two more day and night modes. "We map these behaviors against the satellite hardware platform and make a recommendation for the best configuration for this set of use cases."

The ability to do all this according to the RapidIO protocol is now a standard feature of VisualSim.



This screenshot of VisualSim's RapidIO simulation shows multiple computers of different configurations connected by the Serial RapidIO communications protocol. Graphs on the bottom display the amount of data being processed on individual computers.

Benefits

Designed and controlled by a nonprofit corporation, the RapidIO communication protocol has come to be used in the data center, supercomputing, communications, and automation industries, among others.

"The name of the game for spaceflight is high speed at low power and low complexity, and RapidIO did that best," says Some, adding that the design is also highly reliable and compatible with different types of networks, from copper wire to fiber optics.

After JPL successfully modeled an entire hypothetical spacecraft network using the Visualsim Rapid IO model that Mirabilis developed, Some and a representative from the Air Force Research Laboratory convened a joint Government-industry working group to discuss spacecraft interconnect protocols. The workshop resulted in the formation of the Next Generation Spacecraft Interconnect Standard (NGSIS), which subsequently joined the RapidIO Trade Association and developed the space and harsh environment Serial RapidIO standards. The NGSIS also joined another trade association that was working to develop physical standards for space system electronics.

"Combining physical electronics packaging standards with Serial RapidIO provided an interoperable set of standards for next-generation spacecraft avionics that is being adopted across the industry," says Some.

NASA's involvement has led to improvements to the Serial RapidIO standard itself, such as adapting it to the longer wires in spacecraft and increasing speed, reliability, and accuracy, Shankar says. The project also brought more commercial attention to RapidIO in the space and high-reliability markets, in part through the experiments JPL ran, demonstrating the protocol's high throughput, low latency, and other efficiencies. "After we started this, a lot of people came onboard with RapidIO," he says.

"We're moving to use RapidIO as the fundamental interconnect that will be incorporated into spacecraft," Some says.

It's just one of many standards VisualSim can simulate, but adding it helped expand the software's customer base, Shankar notes. "The more libraries we have, the more customers we can access." And as aspects of RapidIO get incorporated into other standards, "people are asking us to model them because we were there from the beginning."

NASA, the Department of Defense, and other Federal agencies and their contractors are among the primary users of VisualSim's RapidIO capability, he says.

Other VisualSim RapidIO users include designers of lithography equipment for semiconductor manufacturing, which runs massive systems with many interconnected processor boards. Companies building mobile phone infrastructure have come on board, as have computer chip manufacturers who want to incorporate the RapidIO fabric into data signal processors on their chips.

Meanwhile, NASA and the Air Force are working on another joint project, to define the requirements for high-performance space computing. The processor will operate with the latest version of Serial RapidIO. ❖

Data Visualization Platform Helps Missions Fly

NASA Technology

There are so many pieces to a successful mission in space, and keeping track of it all is no easy task. Software designed to simplify the interface between mission controllers and spacecraft data is making it easier than ever to see at a glance what's happening and where, and when there's a problem. And now, thanks to a NASA open source software platform, researchers, students, and others are all taking advantage.

The project started at Ames Research Center in the early 2000s, recalls Jay Trimble. The Ames computer scientist was collaborating with colleagues at the Jet Propulsion Laboratory (JPL) on software to support JPL's Mars rover operations team, and he found it challenging that the software separated displays between disciplines. It was an echo of issues he'd seen in earlier software as a flight controller for the space shuttle.

"In the early shuttle days, all of our displays were designed by discipline. If we had a display looking at payload data, and we also wanted communications data, we had to go to the display in the communications discipline or build our own display with their data," he explains. Same for electrical systems, data processing systems, and every other kind of data needed to know the status and health of the vehicle: there was no operational way to get it all in one place, or at the level of granularity at which we needed it across disciplines. Yet even team members working on a specific aspect of the mission often needed a more holistic view.

Today, Trimble is part of a NASA team designing rover missions to explore the lunar poles, and the same issues apply. For example, "if I'm looking at a payload on a rover, I need to know where that rover is, what the environment looks like, where we are on our mission operations timeline, and more, to understand the context in which my payload is operating," Trimble explains. "I need to be able to look at that data and not just ask somebody every time I need it."

In the early shuttle days, building and specifying displays was done months ahead of a mission he says. In the run-up to a mission, the different teams would anticipate what they'd need to see and test out displays during simulation and training. If needs changed later, it was extremely onerous to change the display. "We'd submit display requests, and it would take months to get those built."

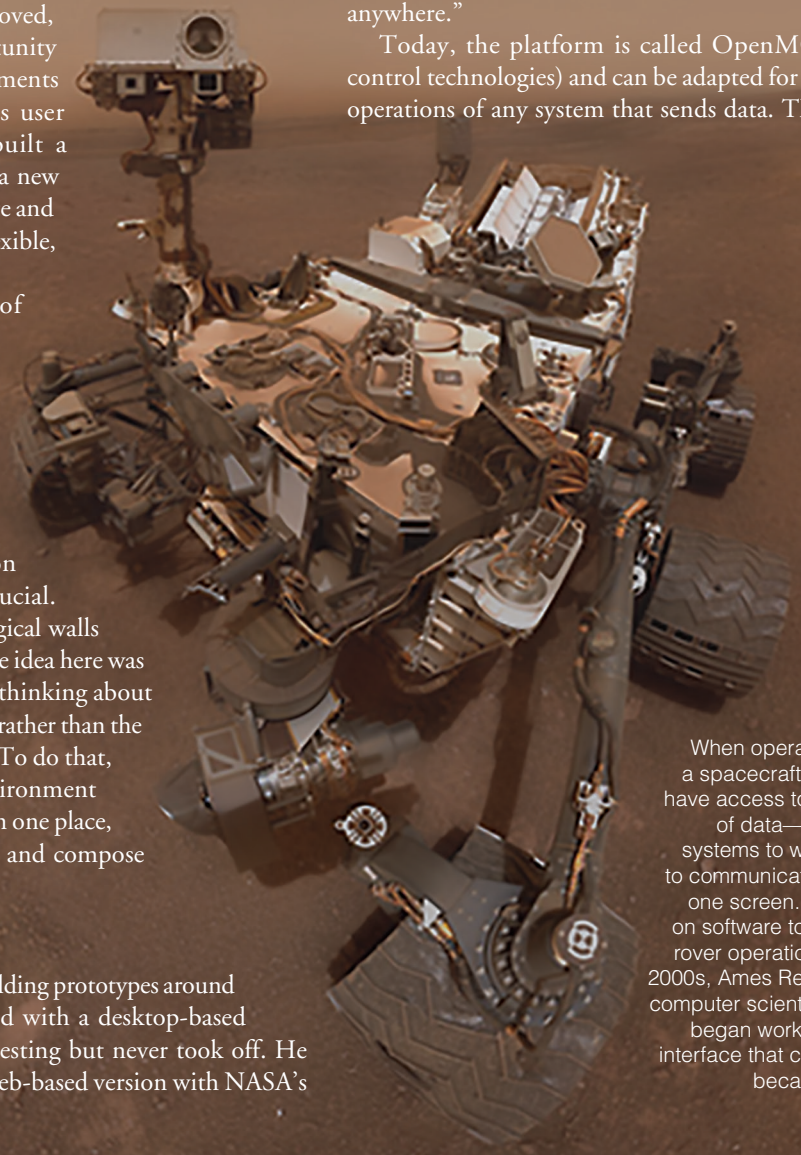
But computers had improved, and Trimble saw an opportunity to integrate those improvements into the flight controller's user experience as well. He built a team that began designing a new program that would integrate and display the data feeds in a flexible, dynamic interface.

That required a lot of work on the back end, to convert data feeds into compatible formats and display historical data to help visualize trends. But Trimble says he was most focused on the user experience, and on that end, flexibility was crucial. "There have been technological walls around those disciplines. The idea here was to knock those walls down: thinking about the data and how you view it rather than the applications," he explains. "To do that, we wanted to create an environment where you have all the data in one place, and you can view that data and compose it however you want."

Technology Transfer

Trimble's team began building prototypes around 2005, he recalls, and started with a desktop-based platform that was used in testing but never took off. He then started working on a web-based version with NASA's Advanced Multimission Operations System (AMMOS) and with JPL, which offers significant advantages for collaboration and portability across centers and partner organizations. The web-based version even works on smartphones, Trimble notes, which "extends control-center decision support to anywhere."

Today, the platform is called OpenMCT (mission control technologies) and can be adapted for planning and operations of any system that sends data. The web-based



When operating a rover or a spacecraft, it is helpful to have access to the full range of data—from electrical systems to weather reports to communications data—on one screen. While working on software to support Mars rover operations in the early 2000s, Ames Research Center computer scientist Jay Trimble began working to build an interface that could do that. It became OpenMCT.

> “The idea here was to knock those walls down: thinking about the data and how you view it rather than the applications.”
>
> — Jay Trimble, Ames Research Center

platform can display streaming and historical data, imagery, timelines, procedures, and other data visualizations, all in one place, and can be quickly configured and reconfigured.

It was designed for space missions, but Trimble is quick to note that it can be adapted to many other kinds of projects. To facilitate its wider adoption, in 2015 Ames released the software to the public as a free, open source code with an Apache 2.0 license through the software-sharing platform GitHub.

“We are excited to use open source as a model for collaboration,” Trimble says, adding that he is working with other potential partners to continue to disseminate the software as widely as possible.

The reception has been positive, he notes, including at NASA, where the platform has already been used on several NASA missions, from the Jason 3 Earth Orbiter to the MarCO CubeSats that launched with NASA’s InSight Mars lander.

Benefits

With any open source platform, it’s somewhat difficult to keep track of how it’s being used, since there is no way to know if or when someone is implementing it unless they report back. However, a quick glance at the program’s GitHub homepage shows thousands of “stars” and over 700 “forks,” the latter indicating a user has made a personal copy of the project for their own use, either to experiment with modifications or to use it as a jumping-off point for something new.

Trimble’s team at Ames is also trying to keep track of and publish user stories. One recent addition was the Planetary Society, which adopted OpenMCT to visualize the data coming in from LightSail 2, a spacecraft in Earth orbit propelled only by sunlight.

Image courtesy of ESA CC by-SA 3.0 IGO

Among other ways OpenMCT software is being applied outside of NASA is a Norwegian project to study algal blooms, seen in turquoise in this image from a European Space Agency satellite, which can be harmful to marine habitats. OpenMCT will help the team manage operations for a nano-satellite that will take images of coastlines from orbit.

LightSail 2 launched in mid-2019, but the team had already used OpenMCT for their July 2018 operational readiness test, after hearing about the software from colleagues at JPL. Previously, mission data was stored in a database with a very limited front end, says John Bellardo, the director of California Polytechnic State University’s CubeSat Laboratory, who overhauled the spacecraft’s software system for the Planetary Society. “It was cumbersome: we ended up with only a few composite graphs that everyone could see, and it limited the ability of our students and other team members to do analyses without involving someone who knew how to manipulate the database.”

OpenMCT was much more flexible and user-friendly, he says. “The majority of our students were able to figure out how to use it within three or four minutes, at least enough to play their role in the test.”

Bellardo says his group at Cal Poly has since used OpenMCT on several additional projects, including a satellite launch. He expects his group to continue relying on the platform, in part because he is training students for jobs at places like NASA, where knowing the software will give them a leg up. And of course, no cost is always an attractive feature.

The lack of price tag was also a key enticement for Mariusz Eivind Grøtte, a researcher at the Norwegian University of Science and Technology (NTNU), who was looking into using the software on an upcoming joint NTNU-NASA CubeSat mission.

The nano-satellite will house a hyperspectral imager to map coastlines and monitor ocean color in an effort to learn more about harmful algal blooms and their damaging impacts on marine habitats, which may be increasing, possibly as a result of climate change.

Grøtte said his team had initially considered another program to do the data visualization, “which has similar functionalities, but it costs money.” In contrast, he says, OpenMCT is “available for everyone—and understandable for everyone involved in mission management.” ❖

Turbopump Modeling Software Propels Fluid-Flow Simulations

NASA Technology

Only 12 people have walked on the Moon. That may soon change—within the next few decades, when it simply becomes a matter of buying a ticket. It will take the many innovations pioneered by NASA, leveraged by commercial space companies to make such moonwalks possible. That includes an important contribution from modeling software created by NASA to analyze fluid flow in rocket engines. Today, it has landed in private space companies as well as manufacturing businesses and research institutions.

In the mid-1990s, NASA was developing a new propulsion-system turbopump, dubbed Fastrac, for smaller space vehicles. Larger turbopumps, such as those used in the space shuttle main engines, were incredibly sophisticated and much too complicated for smaller-budget spacecraft. Fastrac was designed to be smaller, simpler, and less expensive to operate. But simplification required complex analytical capabilities in the design process that NASA couldn't perform on-demand.

Computer modeling and analysis programs are essential for the design of complex hardware for rocket engines. Available computational fluid dynamics (CFD) programs—software that models fluid mechanics and, often, thermodynamics and heat transfer—are good for analyzing a single component such as flow in a rotating impeller. However, it's not possible to use CFD software to analyze the entire internal flow in a turbopump, which includes multiple components such as bearings, seals, diffusers, and rotating parts with different fluids mixing in a complex flow network. It's necessary to have a robust flow network code to analyze such a complex fluid system.

Computer modeling and analysis programs make it possible to design and test hardware before it's ever built. What CFD didn't include at the time was a general-purpose solver to combine all of the individual test results for the entire propulsion system of a rocket. Private companies were willing to perform the task using their proprietary software and return results to NASA. The Agency's engineers, however, wanted to be involved in the entire development process.

That inspired the technologists at Marshall Space Flight Center—who are experts in analyzing rocket engines—to create their own tool, which became the Generalized Fluid System Simulation Program (GFSSP). The program predicts how fluids flow through a system, even if that fluid changes speed, temperature, and phase (for example, from liquid to vapor, and back to liquid).

The program was groundbreaking for its time and became the co-winner of NASA's Software of the Year Award in 2001, but the work didn't stop there. New capabilities have been continuously added for almost 20 years, making GFSSP an indispensable analytical workhorse (*Spinoff* 2003, 2016). More than 300 users across the country benefit from this easy-to-use, reliable, robust tool to analyze turbomachinery, propellant feed systems, nuclear propulsion, flight experiments, cryogenic propellant storage and transfer, and test facility design and operation.

Technology Transfer

Any company with a Government contract can obtain and use the latest version of GFSSP cost-free through NASA's Technology Transfer Program. Many have done so, becoming familiar with and relying on the user-friendly program. But Marshall specialists and technology transfer personnel wanted to make GFSSP licenses more readily available for use in the private sector.

To that end, the Agency granted a co-exclusive license to Denver-based Mode Technology Group LLC, which now offers commercial licenses for the complete program and education licenses for a limited version.

As the commercial space economy grows, both established and start-up aerospace companies are doing work that was previously performed only by Government entities, for which they require the same powerful tools. Meanwhile, NASA contractors are finding new applications for GFSSP to meet needs in the private space sector, and research institutions are interested in using the code for both public and private initiatives.

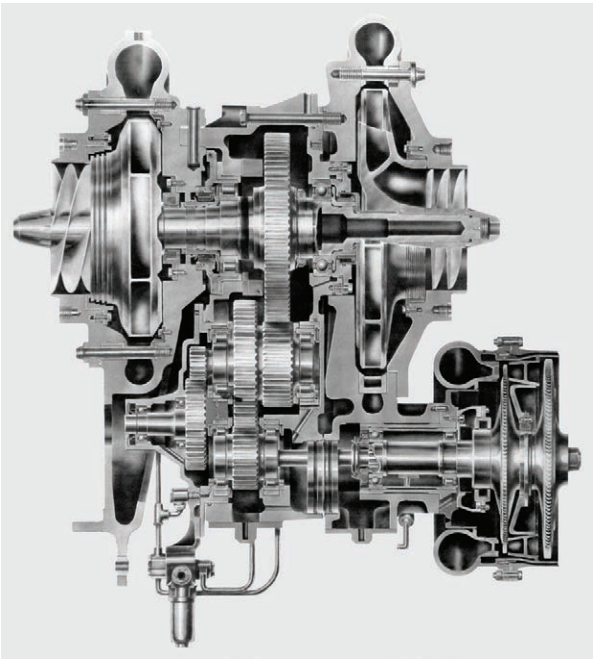


Image courtesy of Mike Jetzer/heroicrelics.org, Dave Christensen

NASA's propulsion-system turbopumps, such as the Rocketdyne Mark-3 turbopump shown here, are sophisticated, complex, and expensive. As part of an effort to develop smaller, simpler, more affordable turbopumps for smaller spacecraft, Marshall Space Flight Center engineers created the Generalized Fluid System Simulation Program (GFSSP) to simultaneously analyze all the interacting flows in these intricate machines.

Benefits

Before GFSSP, most programs could run a single analysis for a specific engine or perform a single portion of a test. Then designers would need to cobble together the results for each part and process to compile a complete set of results. One miscalculation in any of the inputs and the final results would be useless. GFSSP makes it possible

to test and evaluate every aspect of a complex system in a single program, producing accurate, comprehensive results.

One of the earliest commercial adopters was Concepts NREC Inc., which supports the design and manufacture of turbomachinery such as pumps and air compressors.

Concepts NREC incorporated GFSSP into its proprietary software package, which uses a custom graphical user interface to construct a mechanical system that moves fluids. In the case of turbomachinery, these systems use fluid to transfer energy, much like a windmill turbine uses the fluid of air to generate electricity.

Private-sector projects make different demands on GFSSP, according to Oren Kornberg, president and principal engineer of Mode. Having used the program extensively, he can customize the code to meet almost any requirements users have. For General Atomics Corp., a Government contractor that purchased a commercial license to use on a for-profit project, that meant rewriting part of the code.

"The NASA version is pretty static," explains Kornberg. "The normal NASA release can go up to 100 solid nodes. That means 100 things that make up a structure can be a point in the model. But General Atomics needed 300 nodes."

Other customers can get big benefits without making changes to the software. For example, Agility Fuel Solutions LLC lost access to the original NASA program after merging with another company that doesn't have a Government contract. Through a license with Mode, the company now continues to leverage the analytical capabilities of GFSSP for new commercial clients.

Mode is also working with other industries where the flow of fluids is critical, such as in HVAC manufacturing, chemical processing, and power plants.

Alok Majumdar, aerospace technologist at Marshall, explains that analyses already performed by NASA further enable private-sector applications. The program includes an extensive library of fluid properties and can model pumps, compressors, multi-layer insulation, and the pressurization, filling, and draining of cryogenic tanks.

How fluids flow through a system ultimately affects performance. The computer testing performed by GFSSP software makes it possible to identify areas that are performing according to specifications and those that aren't. It also helps to pinpoint the source of problems.

Educational institutions can also take advantage of the program to improve on existing analytical tools. The opportunity to learn and train using this code develops the kinds of computing skills student scientists and technologists need in future careers. The same individuals using the program can also continue to develop it. While only U.S. schools can obtain an education license at no cost, others can purchase an education license. The Indian Institute of Technology in Kharagpur, India, which purchased the first such license, will be using GFSSP to support its ongoing research projects.

"The majority of the users are currently from the aerospace industry," says Majumdar. "But the code is quite general and can be used for many different industries." ❖

Smart Sensor Networks Monitor System Health—and Themselves

Stennis Space Center has awarded American GNC Corporation several SBIR and STTR contracts over the years to develop smart sensor networks that could monitor rocket engines and systems in and around its rocket engine test stands.

NASA Technology

When it comes to monitoring and managing the health of any system, sensors are the front-line technology. They gauge a system's vital signs, such as temperature, pressure, fluid flows, and voltages—measurements that can be used to detect and even predict faults and failures. But what if the fault is in the sensor?

A company that develops advanced sensor network technology now has an answer, as a result of its work with NASA.

A potentially faulty sensor is a familiar problem to Fernando Figueroa, the lead for autonomous systems and operations at Stennis Space Center. System health management is essential for autonomy, he says. "If you want to make a system autonomous, it has to be able to detect anomalies, make a diagnosis, mitigate any fault, and continue operating."

NASA has a clear interest in this sort of technology. The Space Agency operates countless large, complex systems wherein small failures can trigger catastrophic ones. For example, Figueroa has been overseeing an effort to implement autonomous operations at Stennis' high-pressure gas facility, which provides air, helium, nitrogen, and hydrogen to the Center's rocket test stands. These gases are stored at cryogenic temperatures, making any failure dangerous and costly.

Autonomous operations at the facility are part of the NASA Platform for Autonomous Systems (NPAS) project, which ultimately aims to achieve autonomy of systems on spacecraft such as the planned Gateway lunar outpost. Stennis is the lead center for the project, with Figueroa as the principal investigator.

"Work in autonomous systems is portable to space as well," he says. "And it can potentially help not just NASA but also industry to develop autonomous systems."

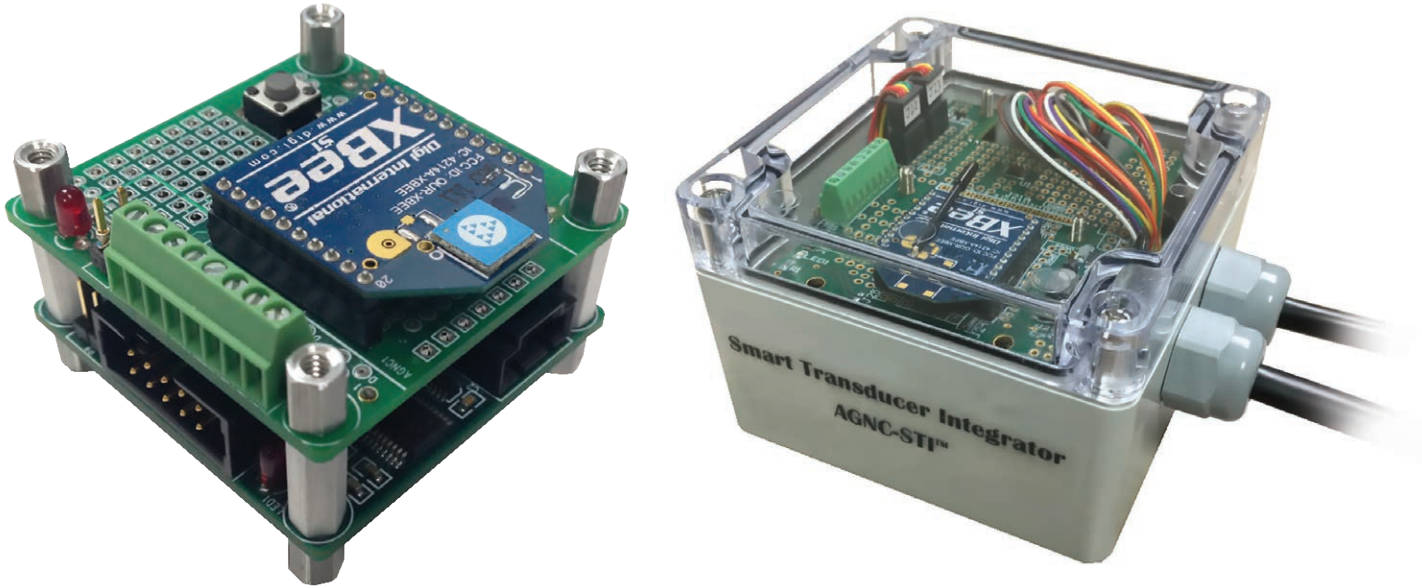
Technology Transfer

Over the course of more than 10 years, Stennis has awarded Simi Valley, California-based American GNC Corporation several Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) contracts to develop software and hardware that monitors systems, detecting and predicting faults. Some of the work has focused on health maintenance and predictive fault diagnosis for rocket engines and outfitting engine test stands with a network of sensors. Two 2015 STTR contracts funded a system of standardized "smart" sensors with diagnostic software at the sensor and network levels, as well as secure wireless communications.

All of this led to what's known as a Smart Transducer Integrator (STI). A transducer is a device that receives energy in one form and converts it to another useful form—typically some kind of signal. One example is the device in speakers that converts an electrical signal into sound. The transducers in this case are the sensors, and the integrator is a device that gathers and synthesizes information from the various sensors to deliver findings on a system's health.

Part of what made the sensors and integrators smart was their ability to detect faults not just in the system they were monitoring but also in themselves. This was largely thanks to Figueroa's early involvement in the work, when he suggested American GNC embed a transducer electronic data sheet (TEDS) for each sensor. A TEDS includes specifications and calibration data for a given sensor and can be used to detect the sensor's deviation from normal behavior. The Institute of Electrical and Electronics Engineers (IEEE) now includes TEDS in its standards for transducers.

"The idea is that sensors should contain information about themselves," Figueroa says. "TEDS is part of that." He notes that incorporating IEEE standards lets components be used interchangeably. Likewise, he suggested the company make its algorithms for detecting anomalies in a system standardized and modular so anyone could incorporate them into their system, enabling wider use. Figueroa and American GNC have since developed health electronic data sheets (HEDS), which are a new type of TEDS that enable the use of different fault-diagnostic algorithms in smart transducers using a common, standard format.



American GNC's work on smart sensor networks for Stennis led to the company's coremicro Reconfigurable Embedded Smart Sensor Node (left) and the Smart Transducer Integrator that can gather and package information from a sensor network (right).

The company is now working under a pair of Stennis contracts to hone a unique communication and charging capability for its STI design, which it pioneered with Rensselaer Polytechnic Institute. Rensselaer invented a way to use ultrasound to charge and communicate with a device wirelessly through a metal barrier that would block a radio signal. Charging relies on a piezoelectric element—a substance that generates an electrical charge when deformed. Two transducers are placed on opposite sides of a barrier. One generates ultrasonic vibrations that pass through the barrier and strike the piezoelectric material on the other, which might be a temperature or pressure sensor. The vibrations generate a charge to power the sensor, which then modulates the vibrations reflected back through the barrier to send temperature or pressure data without wires or radio signals.

"Rensselaer invented this, and we came along and made it more practical, smaller, embedded, and better for use in the field," says Stephen Oonk, chief scientist at American GNC, noting that Rensselaer's original device covered an entire tabletop. The ultrasonic device can now be mounted on the company's three-and-a-half-inch STI. "It expands the reach of measurement capabilities and sensing networks to previously inaccessible places," he adds.

Benefits

The company's STI and its coremicro Reconfigurable Embedded Smart Sensor Node (CRE-SSN), both of which benefited from the company's work with Stennis, are now among American GNC's commercially available products. Currently, the company is working with NASA and the Navy to further develop the STI for different applications and to expand its capabilities.

The STI translates different types of signals from various sensors and makes sense of them all taken together. Some sensors are digital while others are analog, Oonk notes, and they all have different data rates and require different signal conditioning. Both the STI and the CRE-SSN act as a bridge "between the end user and these sensors of all different types—a device in the middle handling calibration, conversion, signal conditioning, and communication."

They've been used in advanced system health monitoring applications. For example, the company demonstrated a trained neural network on the devices that could detect and classify leaks in a pipeline.

Both products send alerts to clients via smart devices, letting them know where and when a failure is detected. All failures and other data regarding the sensors and the system that's being monitored are automatically logged in a database.

The technology can be applied anywhere large sets of sensors are in use, and the company expects it to catch on in a number of industries as the ultrasonic through-wall communication capability expands. Francisco Maldonado, American GNC's director of product development, notes that it could monitor corrosion inside pressure vessels or send signals from sensors on the outside of an aircraft to the inside. In both cases, puncturing the pressurized structure to run a wire through it would compromise its integrity.

"The oil and gas industry would be an important customer," says Oonk. "They already have sensor networks related to pipelines, but a lot of that is using legacy technology."

The Navy wants it to communicate through ship hulls, and NASA is interested in getting sensor data from inside pressurized tanks and its vacuum-jacketed pipelines.

"We're extending the range of sensor networks by incorporating the ability to transmit data and power though barriers," Oonk says.

"We feel this product has a lot of potential in the market," adds Maldonado. ❖

Industrial Productivity

In space, a broken or worn part can be catastrophic—and, especially with uncrewed spacecraft millions of miles from home, repairs are often impossible. With that in mind, we have pioneered many technologies using or improving groundbreaking materials, such as metallic glass and aerogels, that help protect our machinery and are now doing the same for industrial and manufacturing plants on the ground, saving huge costs and improving productivity. Other innovations track flows within pipelines, improve training for the manufacturing of sensitive electronics, and create an entirely new class of solid-state humidity sensors.

Metallic Glass Coatings Improve Power Plant, Oil Rig Productivity

NASA Technology

A rover can be equipped with the most state-of-the-art scientific instruments NASA engineers can devise, but if the wheel breaks, that's going to seriously limit the science that can be done. The same is true in a power plant—it may not seem as exciting as planetary exploration, but tens of thousands of people rely on the energy being produced, which stops or slows if parts break or the plant has to be shut down for maintenance.

A coating could help prevent such problems. The coating is made from a remarkable material that has the atomic structure of glass, more toughness than metal, and the versatility of plastic. It's a material NASA has been working on at least since the 1980s, explains materials scientist Douglas Hofmann, and goes by a few names, including liquid metal and metallic glass.

Hofmann helped found and is one of the lead researchers at the Jet Propulsion Laboratory's (JPL) Metallurgy Facility. He's most focused on how to use metallic glass on spacecraft—such as coating the wheels of a rover to reduce wear and tear.

On Curiosity, the wheels are made of aluminum, he explains, which was chosen because it's very lightweight, always an important consideration for any spacecraft, where every additional ounce comes with a price tag. But aluminum is also relatively soft, which makes it prone to damage from the terrain. This has been a real problem with Curiosity, whose wheels are already pitted with holes and cracks from driving over the rough Martian terrain.

A coating could help protect aluminum on future spacecraft, and in 2017, Hofmann and his team began exploring the idea of using metallic glass to protect the wheels of the Mars 2020 rover.

Metallic glass is a broad category: it can be made from many different metals and using a wide assortment of manufacturing technologies. The key difference between metallic glass and heritage metals is at the atomic level.

This image, taken by one of Curiosity's cameras in 2015, shows damage to the aluminum wheel from the rocky surface on Mars. In the future, Mars and lunar rovers may use a metallic glass coating over aluminum wheels—adding much-needed toughness without significantly increasing the overall weight.

Where the atoms in traditional metallic solids form regular, repeated patterns in a crystalline formation, metallic glass is amorphous, meaning the atoms are distributed randomly throughout the material, like those in glass.

The crystalline structure of metals is one of their key weaknesses—the boundaries between grains are typically where a metal will be the weakest. But amorphous metal—metallic glass—doesn't have those boundaries, so it's much stronger and more wear-resistant. The challenge is how to produce the material.

Traditional glasses are made through rapid cooling, so the atoms don't have time to organize themselves into crystals. In 1959, a professor at the California Institute of Technology (Caltech), Pol Duwez, successfully created

an amorphous gold-silicon alloy in very thin layers. But producing the material in bulk was still challenging. One of Duwez's students, Bill Johnson, continued the work at Caltech—getting much of his funding from NASA and JPL. In the 1990s, Johnson's lab discovered that by combining different elements, in particular by mixing together elements made up of large atoms and those with small atoms, they could slow the crystallization process, which significantly opened up the possibilities for manufacturing.

Hofmann was one of Johnson's PhD students, from 2004 to 2008. In 2010, after years of collaborating with Caltech, JPL decided to build the Metallurgy Facility and brought Hofmann on board. "The facility we built is a world's leading lab for the development and manufacturing of bulk metallic glasses for applications in NASA spacecraft," he notes, but in the years since Johnson's lab first discovered a way to make bulk metallic glasses, industry has also moved the material forward.

Technology Transfer

One of the major players, Liquidmetal Technologies, licensed the patent for Johnson's metallic glass from Caltech in the 1990s. Over the next decade, the company went on to further develop the technology for manufacturing, earning dozens of patents of its own on different alloys, manufacturing processes, and usages of the material (for some early examples, see *Spinoff* 2001, 2004). In 2012, the company spun off its coatings division into a separate company, Spring, Texas-based Liquidmetal Coatings LLC, and it was this company Hofmann's metallurgy group turned to when it was looking for a metallic glass coating for potential use on Mars and lunar rover wheels.

NASA put the coating, a steel-alloy metallic glass powder that was thermally sprayed—melted into tiny droplets and sprayed at high velocity—on the wheels, through a battery of testing, Hofmann says, and the results were extremely promising. Although the Mars 2020 team ultimately chose a different solution for the rover wheels, he expects to see metallic glass coatings on future spacecraft.

"We do plan to land many more rovers on as many planetary bodies as we can, particularly icy asteroids and comets, as well as future Mars and lunar rovers, so this technology is beneficial because it allows us to make aluminum parts more resistant to abrasion," Hofmann says. "The coating is basically steel, it weighs what steel does, but it's thin so it doesn't provide a lot of additional weight."

NASA and the Jet Propulsion Laboratory (JPL) have been investing in metallic glass research for decades, and JPL now has a Metallurgy Facility to explore and advance the material further. Among other benefits, metallic glass does not get brittle in extreme cold, perfect for robotics operating in space or on icy planets.

Hofmann's lab continues to work with Liquidmetal Coatings on additional projects, including funding research on using their powder alloys in 3D printing. "NASA has invested a lot of time and money into amorphous metal technology since the 1980s," he emphasizes. "NASA funded Bill Johnson to do a lot of the work that resulted in this entire industry."

Today, that funding continues to foster innovation among the companies, like Liquidmetal Coatings, that have taken the original breakthrough and developed it into an industry, he says. "NASA still has a strong interest in developing and fostering activities in amorphous metals. When there's a company that has innovative technology that can be applied to NASA, there are a lot of potential benefits in adopting that technology."

Benefits

Meanwhile, Mars rover or no, Liquidmetal Coatings has already found plenty of use for their metallic glass coatings on the ground, especially throughout the oil, gas, and power industries. "Everywhere corrosion, wear, and erosion are an issue," explains Evelina Vogli, the company's vice president of research and development.

For example, power plant boilers are extremely harsh environments. In one study Liquidmetal Coatings did at a biomass-fired power plant in California, which generates power by burning scrap lumber, certain crops, and other

organic materials, boiler tubes without a protective coating wore out within three months. Tubes coated with nickel and other materials lasted six months to a year in testing.

The tubes coated with metallic glass lasted four years and more, with minimal need for repairs.

Testing was done by measuring the thickness of the coating with the boiler shut down at three-month intervals. Each time, the coating remained as thick as when it was applied, Vogli says, which meant the power plant could fire back up without requiring extra time for renewing the coating or replacing any parts. That translates to huge savings for the power company. "For the power plant we tested, it saved them almost $10 million over five years. It pays off," Vogli says.

The durable coating also meant the boiler tubes didn't fail unexpectedly between checks. "We are saving them from emergency shutdowns—which we've never had when our material was used," she adds.

For power plants, the coating is typically spray-applied onsite. In other cases, Vogli says, for example, certain high-value parts used in oil and gas drilling, the spraying is done in-shop, and then mirror-polished to provide additional protection. And for other parts, the coating is applied through a different process altogether, called hardbanding. This is typically used for joints in the long pipes used for drilling, Vogli says; a layer of metallic glass is deposited on the joint through welding. "This part of the pipe is more in contact with the rocks during drilling, and this part needs to be protected against wear," she explains.

Today, Liquidmetal Coatings are protecting key infrastructure at power plants across the United States, in Europe and in Asia, as well as petrochemical refineries and oil and gas drilling sites around the world. The coating is also used widely in the paper and pulp industries.

Although different alloys are used in different applications—for power plants, for example, the coatings are made with nickel and iron-based alloys, which are relatively inexpensive—the benefits of the coating all trace back to the amorphous atomic structure developed in Johnson's lab.

"In crystalline material, the grain is the weakest point. It starts to corrode on grain boundaries. Since we don't have that, we offer better protection," Vogli says. ❖

"We are saving them from emergency shutdowns—which we've never had when our material was used."

— Evelina Vogli, Liquidmetal Coatings

Liquidmetal Technologies licensed the patent for the original NASA-funded metallic glass, and has continued to develop the material in house and in collaboration with JPL. It spun off a separate coatings division, Liquidmetal Coatings, in 2012. The durable coating is used on power plant boilers around the world, lessening the need for costly and time-consuming maintenance.

Aerogel Insulations Save Millions in Industrial Applications

NASA Technology

It's no surprise that some of NASA's biggest breakthroughs and most popular spinoffs have been in the field of temperature management. The Space Agency not only has to deal with the temperature extremes of space and atmospheric reentry but also must manage large amounts of cryogenic liquids on the ground.

It was for this latter application that a Kennedy Space Center engineer sought a new material in the early 1990s. Aerogels, which are gels with all the water removed (and gel is almost entirely water), were already known to be the world's most insulating materials, along with several other superlatives, but these ultra-lightweight, nanoporous materials were also brittle to the point of uselessness, as well as costly to make. James Fesmire, who was in charge of the systems that provide liquid hydrogen and oxygen fuel to rockets on Kennedy's launch pads, put out a call for a flexible composite aerogel that could be used to better manage the transfer and handling of cryogenic rocket fuels.

Much has been made of the resulting insulation's use in consumer goods (*Spinoff* 2001, 2008, 2010, 2018), as well as a spinoff into building insulation (*Spinoff* 2009), but its most widespread use is in industrial applications, where it's saved users thousands—in many cases millions—of dollars by conserving energy and reducing labor, replacement and repair costs, and downtime.

Technology Transfer

In 1992, a company called Aspen Systems proposed a silica aerogel reinforced with ceramic fibers and won two Small Business Innovation Research (SBIR) contracts from Kennedy. The cookie-sized lab prototypes the company produced under that funding literally tested off the charts for insulation performance. Fesmire's team had to invent a new device, dubbed Cryostat-1, to adequately assess the thermal performance of the next version Aspen created under follow-on SBIR contracts from Kennedy.

In the spring of 2019, Aspen Aerogels won a $40 million contract to insulate pipelines at this liquid natural gas receiving terminal in Thailand with its Cryogel Z insulation.

Less than half as conductive as even the best foam insulations, these blanket aerogels—the first flexible, practical aerogel insulation—were used in several critical applications. One, in 1996, was in the cryogenic liquid hydrogen and liquid oxygen umbilical connections for the X-33, an experimental single-stage-to-orbit space launch vehicle.

Further gains were made under contract to Johnson Space Center in 1999 for use in spacesuits. For this job, the company substituted polyester fibers for the ceramic fibers, resulting in significant improvement, says George Gould, now the chief technology officer at Aspen Aerogels Inc., the company that spun off from Aspen Systems in 2001 to market this new type of insulation. The company continued working with NASA, undertaking almost three dozen SBIR contracts across most of NASA's field centers over the next decade or so.

These days, Gould says, most of the Northborough, Massachusetts-based company's work with NASA consists of supplying the Space Agency with the existing Aspen Aerogels products that NASA helped develop.

“We’ve certainly redefined **high-temperature** insulation, **and we’ve** redefined **the** expectations **of users** across **the world.”**

— Brian Cahill, Aspen Aerogels Inc.

All of Aspen Aerogels’ insulations are water-repellant, one way they prevent corrosion of the underlying pipes and vessels. Corrosion due to wet insulation in steam distribution systems, for example, is such a problem that many municipalities have given up on insulating their steam lines.

Insulation made with Aspen Aerogels' Spaceloft product is used to renovate a historic building in Belfast, Northern Ireland.

The company's three basic product lines, high-temperature Pyrogels and mid- to low-temperature Spacelofts and Cryogels—all in the form of flexible blankets—were established in the company's early years and are now installed in industrial plants, steam distribution systems, buildings, pipelines, and much more all over the world.

Benefits

One advantage of the company's insulation is that it's sturdy and easy to use, says Brian Cahill, director of marketing at Aspen Aerogels. "It's flexible, insensitive to workmanship, it installs faster, and it's low-maintenance."

One Gulf Coast refinery replaced six-inch-thick calcium silicate insulation, a traditional high-temperature option, on a single yield line with less than three inches of Pyrogel—and estimated it saved $25,000 in labor alone. It was also able to restart sooner than expected, leading to additional savings.

Being thinner than other insulations due to its high thermal performance, the material allows for effective insulation in tight spaces and even saves money on shipping, handling, and storage. Pyrogel XTE, billed as the most effective high-temperature insulation on the market, is two to five times thinner than non-Pyrogel alternatives.

In the past, customers with high-temperature insulation needs were stuck with low-performance insulation, Cahill says. The best insulators used binders that oxidize at 400 or 500 °F, while those based on ceramic or silica fibers survive higher temperatures but are much less effective. But Pyrogel, with its silica aerogel reinforced with glass fibers and laced with infrared-scattering particles, offers high performance at temperatures up to 1,200 °F. "We've certainly redefined high-temperature insulation, and we've redefined the expectations of users across the world," Cahill says.

The applications where Aspen Aerogels' insulations might hold the biggest advantage are steam distribution and other systems that are often exposed to water. Many municipalities, universities, and hospitals still use high-pressure steam for heating, cleaning, sterilization, humidification, and powering turbines and other systems. But the pipes that deliver steam are exposed to water in heavy rain and flooding.

Traditional insulation begins to disintegrate with repeated soaking, and the moisture causes the underlying pipes to corrode. It also cools the steam pipes, robbing them of their energy, and the insulation eventually has to be discarded and replaced at considerable expense. The corrosion causes safety issues and can even lead to explosions. It's such a problem that many municipalities have given up on insulating steam pipes, Cahill says. "We think of insulation as a force for good, but badly designed insulation can be a force for crisis and havoc when it misbehaves."

Gould notes that all of Aspen Aerogels' insulation is both water-repellant and breathable, meaning whatever moisture does get under it can quickly evaporate. "It has the fastest water-release response of any thermal insulation," he says. It also maintains a pH level that inhibits corrosion.

Cahill notes that one medical institution, worried that it wouldn't have enough steam to operate in a storm, had considered spending about $5 million to replace its steam equipment. Instead, it spent a few hundred thousand dollars replacing the pipe insulation with Pyrogel.

A South American petrochemical complex that replaced its steam line insulation with Pyrogel estimates it saves about $1.3 million worth of energy per year by avoiding insulation degradation.

"One customer described it as a pretty boring material, because it just stays where you put it," says Cahill, noting that the company takes this as the highest compliment.

Cities with Pyrogel-insulated municipal steam distribution systems include New York, Philadelphia, Boston, Seattle, and Baltimore. Rainy Seattle had given up on insulating its steam pipes for 30 years before discovering this aerogel option.

Twenty-four of the world's top 25 refineries use Aspen Aerogels insulation, as do most of the largest chemical companies.

Meanwhile, the company's lower-temperature insulations, based on polyester fiber-reinforced aerogels, have also caught on. Its Spaceloft line is most commonly used to insulate buildings and subsea oil pipelines. Spaceloft lines more than 550 miles of subsea pipelines in more than 40 locations around the world. German chemical giant BASF has an exclusive deal with Aspen Aerogels making BASF the sole customer for the Spaceloft A2 product, which it uses in its Slentex wall system for the building materials market, as well as a complementary fireproof insulation.

And Cryogel, which is similarly durable and easy to apply and stays flexible at cryogenic temperatures, is also becoming popular, Cahill says, noting that in spring of 2019 the company won a $40 million contract to insulate a liquid natural gas receiving facility in Thailand with Cryogel. It's an application that's also catching on domestically, he says. "Liquid natural gas is quite a boom commodity at the moment, with the U.S. becoming an exporter."

Other popular Cryogel applications include refrigeration, ethylene gas processing, and alkylation to upgrade petroleum or produce commodity chemicals.

Cahill notes that it's rare for a company to specialize in both high-heat and cryogenic insulation. "I don't think anyone else participates in both extremes of the spectrum."

In addition to countless industrial and consumer goods applications, Aspen Aerogels' insulations are also popular in cars and other vehicles. Cahill notes that many German auto manufacturers buy large quantities of aerogel but don't publicize their proprietary use of the materials. "We know we're installed in pretty much every Formula 1 car," he adds.

The company also has worked extensively with the military and supplies insulation to the Navy, Air Force, and Missile Defense Agency, although these agencies don't report back what they use it for.

And the extensive work with NASA promises new future products. Working across several NASA field centers, the company has developed, for example, polyimide-based aerogels, hybrid aerogel/multilayer reflective insulations, and ablative aerogels for heat shields for atmospheric reentry.

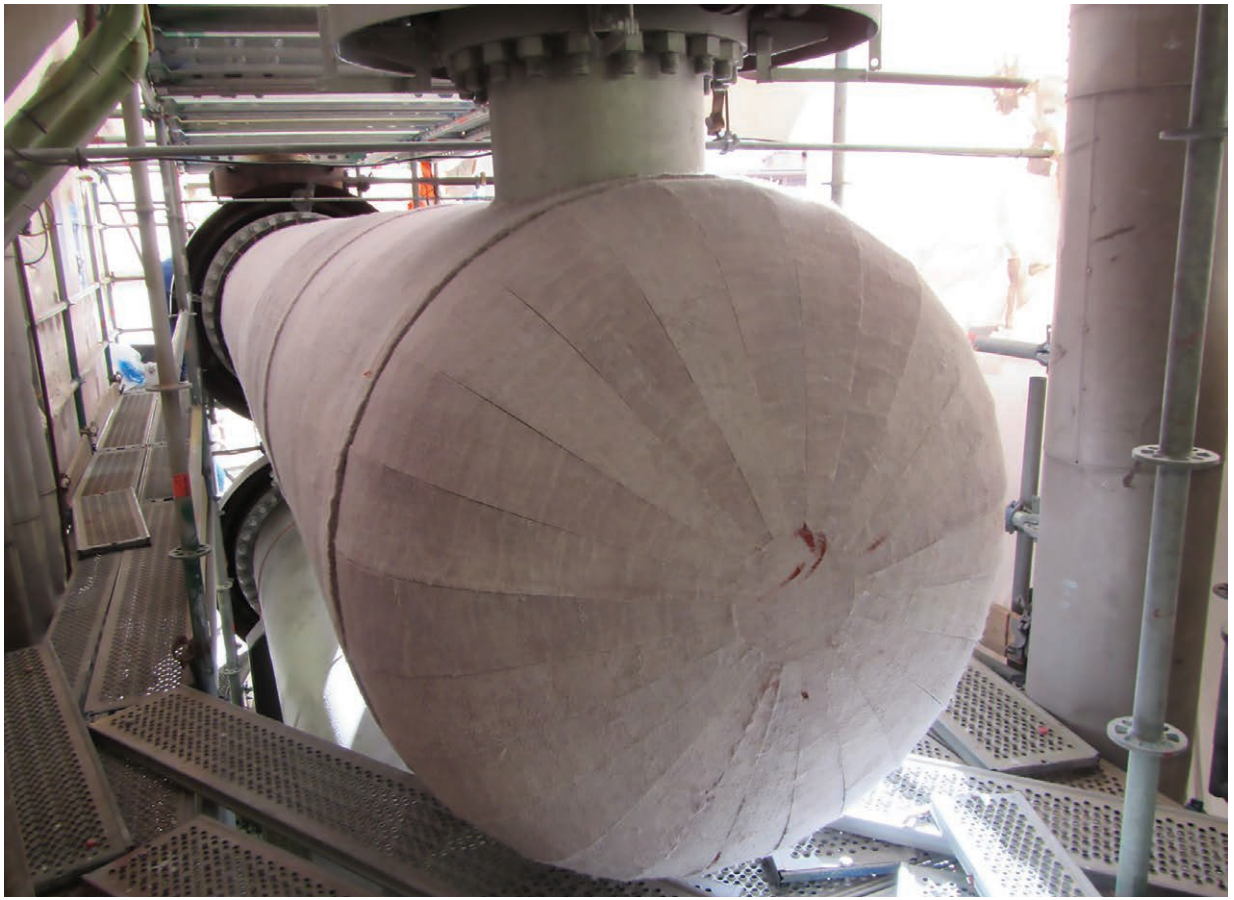
Gould says the work on polyimide aerogels has been key to a carbon aerogel that's now in late-stage development. "We have a treasure trove of technologies creeping their way to commercialization," he says.

As transportation moves toward electrical power, the company is also working on an insulation optimized for batteries, capacitors, and other components of electrical systems. "We're pretty excited about the future of nanoporous materials for energy generation, conservation, and storage," Gould says. "Insulation never goes out of fashion. No matter what you're generating energy from, you're still going to need to preserve temperature gradients."

He also notes that the company is open to partnerships with other entities that might have new applications for its insulations. "The number of things aerogel can do is astonishing. We don't know all the needs out there."

Aspen Aerogels now employs about 300 people to manufacture almost 40 million square feet of insulation per year, about twice what it was producing in 2010. The company's 2018 revenue totaled more than $104 million.

"We're growing, and we think there's a lot of good stuff to come," Gould says. He says the company's first years of product development with NASA were instrumental to its success. "That early work set the bar for what we could aspire to. I always say, if it's good enough for NASA, it's good enough for anyone on the planet." ❖



Pyrogel insulates a heat-exchange vessel in a petrochemical facility.

Revolutionary Battery Replacement Leads to a New Humidity Sensor

NASA Technology

A lot can and does go wrong with technology, as Dr. Terry Rolin, an electronic systems failure analyst at Marshall Space Flight Center, knows well. His job is all about finding solutions to problems—and, if he can't find any, inventing new ones. When Rolin and his team were tasked with figuring out what caused a particularly large battery system to fail in 2011, it led them to consider a fundamental question—can we engineer a better power source?

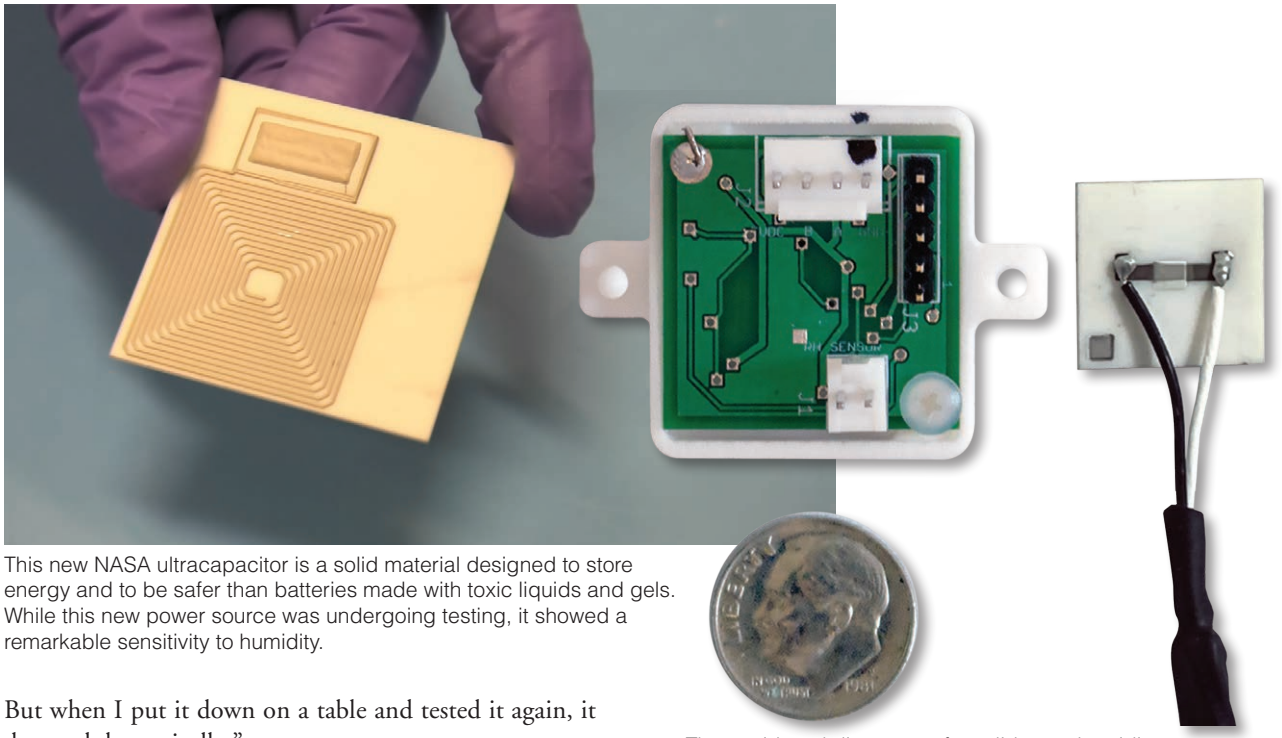
Drawing on the team's background in materials engineering, Rolin and his team got to work. They took a blank-canvas approach to the problem by considering the ideal characteristics of a power source and trying to find materials to meet those criteria better than traditional systems.

"We started working with solid materials to get away from liquids and gels and to avoid toxic material," explains Rolin. And following some cutting-edge engineering with nanomaterials, he says, "we were able to invent a novel device that we call an ultracapacitor."

This ultracapacitor, according to Rolin, is a new class of power source, representing something like a hybrid between supercapacitors and batteries. Specifically, it combines high capacitance (or the ability to store a charge) with "battery-like discharge characteristics"—that is, delivering sustained power over time. As a solid-state material, it's also more resistant to adverse conditions such as the temperature extremes of space, and it's safer to manufacture and operate than traditional battery systems.

While Rolin and his team hope this revolutionary material has a big future in space and commercial power systems, in the meantime, a quirk in the properties of their innovative material has opened up an unexpected application.

In early testing, Rolin noticed a peculiarity he couldn't explain: "For a good energy storage system, we need a lot of capacitance," he says. "When I held the ultracapacitor in my hand and tested it, the capacitance was really high.



This new NASA ultracapacitor is a solid material designed to store energy and to be safer than batteries made with toxic liquids and gels. While this new power source was undergoing testing, it showed a remarkable sensitivity to humidity.

But when I put it down on a table and tested it again, it dropped dramatically."

The technologists initially thought Rolin's body heat was affecting the capacitance, so they ran tests in a thermal chamber. The capacitance never changed.

"We soon realized it was the moisture in a breath that was causing this big change," explains Rolin. "We ran it in a humidity chamber, and sure enough, we saw this huge response of capacitance over a range of humidity."

Rolin's new ultracapacitor was also a solid-state humidity-sensing element.

Technology Transfer

Humidity sensors measure the amount of moisture in the air by detecting changes that alter electrical currents or temperature. The NASA ultracapacitor was extremely sensitive to changing conditions, detecting miniscule shifts.

The accidental discovery of a solid-state humidity sensor surprised the NASA engineers who were working on a new power technology. The effort to find a substitute for batteries made with toxic materials led to this new humidity sensor that can provide moisture-level readings for the inside of a refrigerator or spacecraft.

It also recovered quickly because it easily shed any surface moisture that collected.

To measure the speed of response time, the team tested its performance against commercially available humidity sensors and found that it was faster. After performing all the humidity testing they could in-house, Rolin says, they needed an industry partner for more extensive testing.

He approached the Technology Transfer Office at Marshall for help. The office advertised the technology, and a NASA supplier, Roscid Technologies Inc., based in

Moisture is a problem for manufacturing in numerous industries, including pharmaceuticals, making it critical to sense and control humidity. If a sensor fails or the calibration drifts, it can result in significant losses. NASA's new solid-state humidity sensor could revolutionize the industry with more reliable hardware.

in Woburn, Massachusetts, contacted NASA. The company supplies NASA with high-end analyzing equipment for testing high-purity gas measurements. Roscid offered to evaluate the new technology because the staff was intrigued. Collaborating on the humidity sensor was an opportunity to explore a new technology that, on first review, looked promising.

"We asked Terry if he could send some samples," explains Ken Murray, vice president of new business development. "We initially approached it with the idea of seeing if the material was robust and how well it would perform in numerous environments."

The tests run "in some pretty nasty environments," including "horrible chemicals, big temperature changes, and lots of cycling." The company confirmed the newly created NASA material has a valuable secondary property.

The size of the sensing surface needed to pick up humidity changes and give off a signal depends on a number of factors: the type of sensing material, the environment, and the application. Most sensors use some kind of polymer or ceramic, materials that can have low sensitivity, so they must be rather large.

A problem all existing sensors can experience is damage from the moisture they test. Over time, the sensors will absorb liquid, which erodes the sensing material. This causes the reading to drift, or it may cause the sensor to stop working altogether. Therefore, continuous monitoring is necessary to ensure accuracy of data and replace damaged units. This means most sensors are short-lived and add costs to system maintenance.

Murray found that a very small amount of the NASA material, about a hundredth of an inch, is all that's required to get consistent, accurate readings. To translate that signal into meaningful data, Roscid custom-built and perfected electronic components that are compatible with the new material.

"As we got further into the study of the sensor, we wanted to take it to the next level," says Murray. "Every time we made a comment on something we learned, Terry would tweak the recipe a little bit. The sensor would be a little bit more robust for the applications we were testing."

Roscid signed two back-to-back evaluation licenses with Marshall to move beyond NASA testing requirements. When Murray approached potential new customers with samples, he says, "the response was overwhelmingly positive." So the company signed a non-exclusive license and began marketing its model CBNS215 humidity sensor in 2019.

Benefits

Humidity sensors are necessary in moisture-controlled environments, whether that's to maintain specific conditions or prevent moisture from entering a product. In addition to regular maintenance and sensor replacement, humidity systems experience downtime requiring expensive calibration procedures. Roscid believes the NASA sensor will dramatically reduce this burden. Murray uses the pharmaceutical industry as an example.

"After processing every batch of drugs, pharmaceutical companies have to check sensors against calibration standards to make sure they haven't drifted," he says. "If any unit failed, they could have to go back and redo or quarantine the last batch."

Stable sensors will make it possible for a company to widen calibration cycles, resulting in a significant impact on the bottom line.

Sensors can drift or fail after a single "moisture event." That could be as little as condensation accumulating on the sensor or as great as dousing a sensor in some kind of liquid. Because this new material sheds moisture, these problems could become a thing of the past.

"The NASA sensing material is a solid-state construction, so there is nothing to wash away," explains Murray.

This reliability is an essential characteristic for high-humidity, low-temperature applications such as refrigeration. Because a refrigerator door is constantly opening and closing, humidity and temperature are always changing. Maintaining ideal conditions is extremely difficult without continuous monitoring.

A manufacturer of high-end residential refrigerators is evaluating the CBNS215 sensor for a vegetable crisper tray. The goal is to maintain 95 percent humidity at 37 °F. Until now, the company has never found a sensor that will do that consistently over time.

"There's a test that those guys run that's pretty challenging," says Rolin. "Roscid ran a similar test in-house and according to Roscid, ours was the only one that ever passed. That's pretty exciting."

A significant problem Rolin would like to solve is one that would save consumers and gas companies millions of dollars annually—water leeching into gasoline.

Murray believes the new sensor can help. "Monitoring moisture levels inside underground gas storage tanks can cut down on the transferability of the water into your automobile," he explains. Sensors could also be added to vehicle gas tanks warning drivers before moisture enters the fuel supply.

Companies that produce oil and gas have also expressed interest the CBNS215 sensor. They need a technology to function at low dew points and down to -94 °F. The aluminum oxide sensors currently in use have serious limitations—a slow response time and the duration of dry-down. It can take days or weeks before a system is operational after a moisture event. Murray is working with the industry to verify that the NASA sensor will be a viable replacement.

Cold sterilization, refrigerated shipping containers and trucks, and airlines are just a few more industries interested in this sensor technology and in discussion with Roscid.

"Especially for military airplanes, it's good to have a moisture sensor that accurately reads the dew-point levels in the atmosphere the plane is flying through," explains Murray. "That's being investigated right now."

These varied applications are introducing new industries to NASA technology, and Murray gives a lot of credit to the Space Agency for that.

"If NASA says it works, then it works," he says. "NASA is such a great partner because they're really committed not only to their work, but also to the commercialization process."

Rolin and his team are looking for space applications to benefit from this unexpected discovery.

"Now that we know it's sensitive over a range of humidity and that it seems to survive temperature excursions, we have the confidence to put this in one of our test beds," he explains. "Then if it performs well, NASA has a sensor that was made possible because of the partnership with Roscid."

The sensor is scheduled to go into space on the Materials International Space Station Experiment flight. A successful flight will prove the new material can be used in future missions.

Noting that NASA uses humidity sensors on the space station for environmental control and life-support systems, Rolin envisions a tiny sensor that will help monitor everything from sleep apnea in astronauts to early detection of dangerous system leaks.

As for the ultracapacitor application, preliminary results are promising, with more tests to come.

"You could have a combination system that stores energy and also serves as a humidity sensor in rockets and other spacecraft," says Rolin. ❖

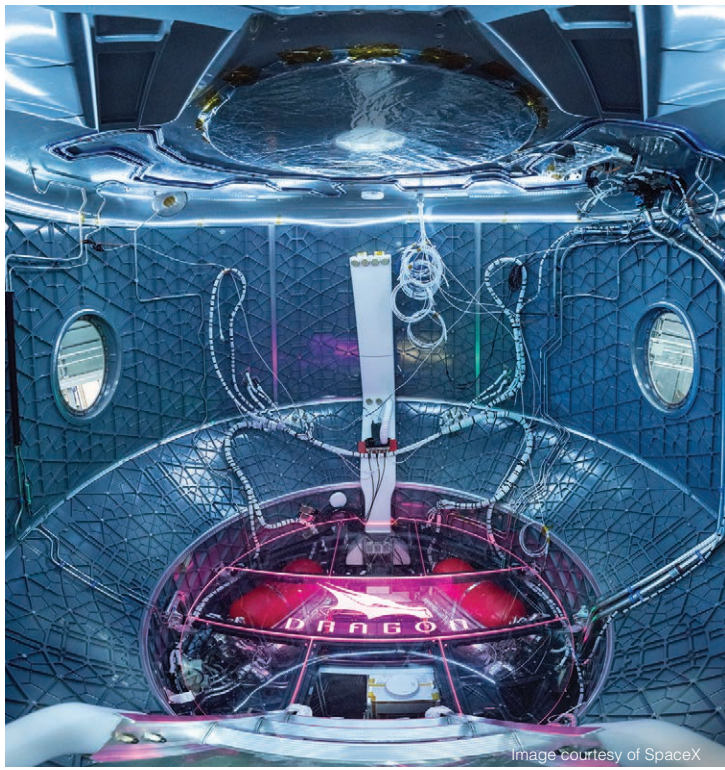


Image courtesy of SpaceX

This replica of the SpaceX Crew Dragon spacecraft is testing the Environmental Control and Life Support System for crewed spacecraft. Life-support systems in space are complicated and delicate. The NASA-invented solid-state humidity-sensing material could help detect small leaks in these systems because it's sensitive to minute changes in the air, making it possible for astronauts to make necessary repairs and prevent any serious problems.

Printed Polymer Makes Integrated Airplane Parts

NASA Technology

Spacecraft fuel tanks have always been round, because they need to hold as much fuel as possible under as much pressure as possible with a minimum of material, and the best shape to balance those factors in pressure vessels is a cylinder.

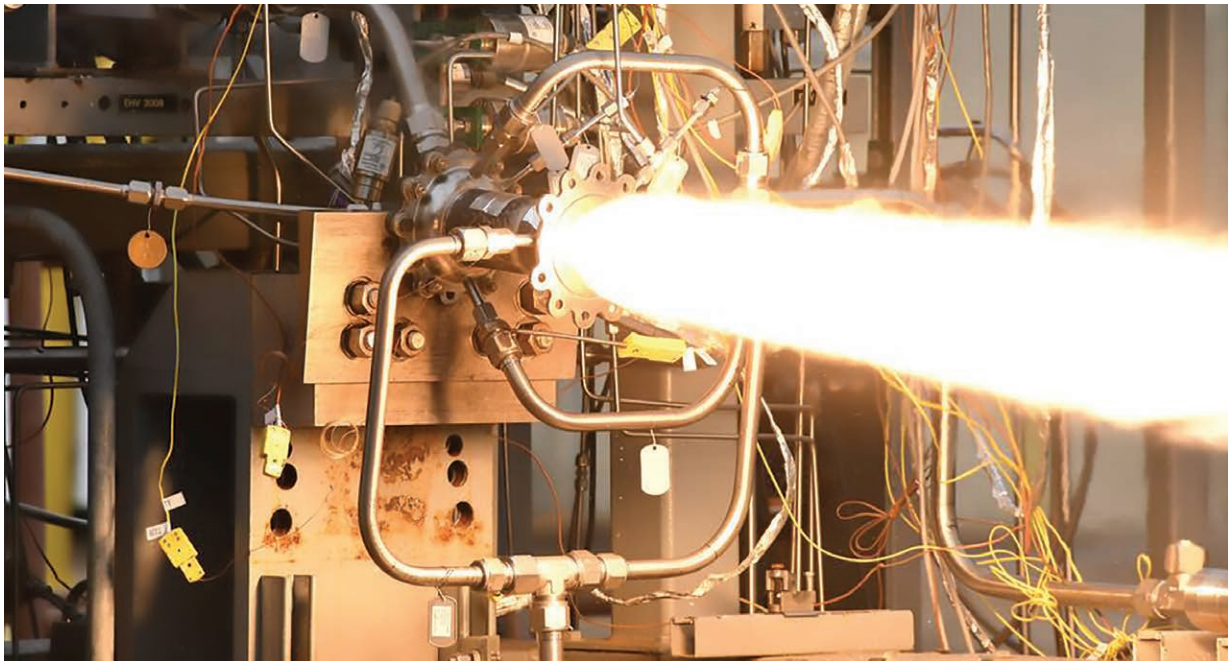
But even though round containers are stronger than square ones, which have weaknesses at their corners and edges, they're still a less efficient use of space. So what if you could build a cube that could maintain the same pressure as the cylinder, without adding much mass?

That's never been realistic under traditional methods of manufacturing, explains Ted Swanson, who recently retired as Goddard Space Flight Center's senior technologist for strategic integration. But there is a way to do it, he says, at least potentially, with 3D printing. "You can maintain the pressure by building internal struts, and it's all built at once so there's no welds or anything like that."

That's not the only type of structure that could be vastly improved or made possible for the first time through 3D printing (also called additive manufacturing, because structures are typically built up layer by layer). "We're also looking at it for things like sensors: getting parts small and making a 3D structure such that you don't have to worry about adding in these tiny wire bonds, which are a failure point on electronics. You can just print it all together, and fewer parts means higher reliability and lower costs," Swanson says.

And of course there is another massive benefit to 3D printing: portability. "When we're up in space, we don't want to carry a storehouse of stuff. We'd like to be able to make anything we want."

In short, says Swanson, 3D printing "is the way of the future," or at least a big part of it. But getting to that future will still take a fair amount of work, because compared to traditional manufacturing, much less is known about the materials, the vendors, the equipment, and ultimately, the potential pitfalls of the process.



In 2019, engineers test-fired a 3D-printed rocket engine combustion chamber at Marshall Space Flight Center. NASA has been exploring the use of 3D printing for a variety of spacecraft applications, because it speeds up the development and production timeline for prototypes and new parts and allows for replacement parts to be easily manufactured away from Earth.

"We currently don't have the perception of reliability, and therefore there's a much higher perception of risk," Swanson says. "There are a lot of variables that just leave you wondering, 'Well if I get this part out of this thing, can I use it? Do I know that it's going to perform the way I expect it to perform?'"

The only way to combat that perception of risk is with plenty of research and testing, which is something NASA does very well.

Technology Transfer

NASA isn't the only Federal agency looking at 3D printing. The Air Force, for example, is interested in having a reliable source of spare parts in remote locations without waiting for them to be flown in.

Recognizing that widespread interest, as well as the broader commercial potential within the U.S. economy, in 2012 the Obama administration established a public-private partnership called America Makes to advance research in and applications for additive manufacturing. NASA was among the original partners and provided some of the funding.

Swanson, who was already advocating for more 3D printing research at NASA, went to the kickoff event for America Makes and there met Larry Varholak, then head of Oxford Performance Materials (OPM) Aerospace and Industrial, who was interested in a thermoplastic called Polyetherketoneketone (or PEKK) for 3D printing.

Swanson immediately thought the material could be great for space, he says, "because it's a very high-grade polymer. It can be used for selective applications—if we

> "You can build anything in any shape with any level of complexity. Now you're building things that historically only nature could conceive."
>
> — Larry Varholak, Hexcel Corporation

know its printed properties and we can be assured that it's manufactured in a reproducible and predictable fashion."

Varholak teamed up with Northrop Grumman, which was already working on adding PEKK to the materials it uses for printing airplane parts, explains Eric Barnes, a Northrop Grumman Fellow. "This eventually led to our current formulation of PEKK mixed with discontinuous carbon fibers," which help dissipate electrostatic charge.

Northrop Grumman proposed research and testing of printed PEKK, with the material supplied by OPM and another company, to America Makes. The proposal included testing for some 3,000 data points on strength and durability and other qualities important to knowing how a part would perform over time in real life.

Of the 3,000 data points, nearly 1,000 were suggested by NASA to qualify the material for space, Swanson says. "We go much colder than aircraft ever go, so I wanted some cryogenic tests done. I also wanted to know if it will outgas volatiles, which might condense on our sensors or optics and mess things up," he says, adding, "We weren't involved in the proposal, but we were involved in the analysis."

Benefits

The testing was a success, says Varholak, whose division at OPM has since been sold to Stamford, Connecticut-based Hexcel Corporation. First and foremost, the printed material performed extremely well: among other results, it showed almost no outgassing and it was resistant to deterioration from radiation, which made it a good material for space. It's also a 600-degree melt plastic, which means it is able to withstand temperatures from 300 °F below zero to 300 °F above, and in a fire, it is flame retardant with very low smoke generation and toxicity.

Another benefit of additive manufacturing is that, because the process builds components layer by layer, it allows engineers to combine parts together into a single component rather than joining multiple pieces. Hexcel Corporation printed this piece using the NASA-tested Polyetherketoneketone (PEKK) material and was to be used for ducting.

Although the printed parts are not quite as strong or durable as ones machined from a solid using traditional manufacturing, the results are very close, and the benefits of 3D printing outweigh the difference for many applications, Varholak says.

"The unique thing about 3D printing is there are no tools and no upfront costs," says Varholak, which makes it much faster and less expensive to build a prototype or a new part. In addition, "you can build anything in any shape with any level of complexity. Now you're building things that historically only nature could conceive."

The comprehensive test results enabled the company to demonstrate to customers they could have confidence in the reliability and properties of the final product. That quickly paid off, Varholak says: "We won a major contract from Boeing to build parts for the Starliner," a new commercial crew spacecraft. He says they built 600 parts for that spacecraft, including important structural elements such as brackets to hold fuel lines, as well as components of the life support systems inside the crew capsule.

Since the America Makes project ended in 2015, Northrop Grumman, with Hexcel as a key supplier, has also been using the PEKK-carbon fiber composite, says Barnes. They started with parts for ground systems and in 2017 expanded to parts for military aircraft. The company is also developing it for space applications, he adds.

Varholak says commercial aircraft will be next, with Hexcel already currently qualifying its proprietary HexPEKK powder or alloy and the associated proprietary HexAM part fabrication process for commercial airliners.

The process will replace existing parts, he says, or combine multiple processes into a single part, and because the material is safe in a fire, it could be used inside the cabin to provide a very high level of safety for passengers in an emergency.

The basis for getting these new applications approved is the database the company created with NASA's input during the America Makes testing, he emphasizes. "It's an excellent story of how America Makes funded the development of this next-generation technology that has been wildly successful. ❖

Zero-Leak Valve Holds Tight in Demanding Environments

NASA Technology

There's no safe way to set anything substantial on fire on the space station to observe how spreading flames act in zero gravity, to test a fire extinguisher, or to see if protective gear will perform as designed. So NASA must use everything already learned in and about space to prepare for a worst-case scenario, including constantly evaluating fire protection tools and technology. One such review revealed an opportunity for improvement.

Some fire extinguishers in NASA space vehicles and the U.S. modules of the space station contain carbon dioxide (CO_2) and halon, chemicals that can pose risks for humans and an enclosed environment, respectively. On the space station in particular, this raised a serious concern because emergency breathing equipment doesn't filter CO_2.

This prompted the Agency to develop a safer option. The new hand-held fire suppression system needed to be lightweight, discharge rapidly, and work on a variety of fires (electrical, composite materials, chemicals, and others). It also had to contain liquids or gases readily available on missions to enable a refill after a discharge. A fine-water-mist portable fire extinguisher made the most sense: it wouldn't cause damage to structures or require special cleanup procedures and would meet the other criteria.

The Colorado School of Mines performed early NASA-funded research on the rudiments of water mist technology, culminating in a spaceflight experiment flown aboard space shuttle Columbia. Building on those initial results, Glenn Research Center and ADA Technologies developed a novel design that would work in microgravity. The extinguisher would discharge from any orientation because it didn't rely on gravity to produce the unique thermal properties of micro-atomized water droplets.

The metal tank accommodated 6 pounds of water and 1.2 pounds of nitrogen gas. Held under pressure in separate bladders, the contents wouldn't release until the extinguisher handle was squeezed, triggering the flow. That opened two cartridge valves and allowed the nitrogen and water to mix before discharging through the nozzle. The effervescent water would put out flames in an open cabin, and a special wand extension attached to the nozzle would reach fires behind an instrument rack or wall.

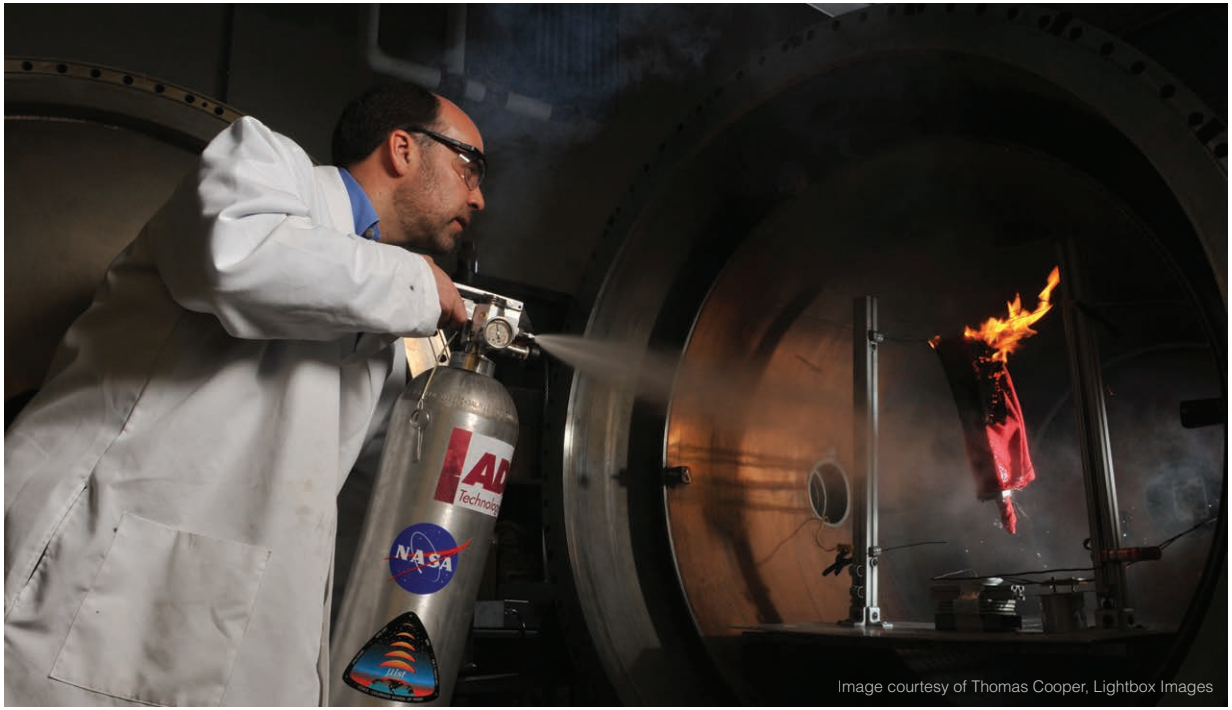


Image courtesy of Thomas Cooper, Lightbox Images

ADA Technologies received several NASA SBIR and STTR contracts that enabled the development of a fine-water-mist portable fire extinguisher intended for use aboard the space station. The device required a no-leak valve, which Doering Company LLC built and now sells for industrial, military, and other applications.

Technology Transfer

The success of the new extinguisher hinged on one part—a zero-leak valve. Doering Company LLC, then a small, family-owned company based in Clear Lake, Minnesota, provided that critical part. The company specializes in the precision design and quality construction of valves to meet the most demanding performance requirements. Zero-leak valves were already part of Doering's catalog, but Marty Dombroske, vice president, says that level of performance is not the industry standard.

"Almost every valve has a leak rate associated with it, and that leak rate is going to decrease your level of pressure," he explains.

Doering was able to modify an existing zero-leak valve to meet the exacting requirements for space.

A number of Small Business Innovation Research (SBIR) contracts from Glenn funded ADA's development of the fine-water-mist extinguisher over the course of 10 years. During that time, specialists like Doering were contracted to create specialized components such as the zero-leak valve. The project team established fire test standards for

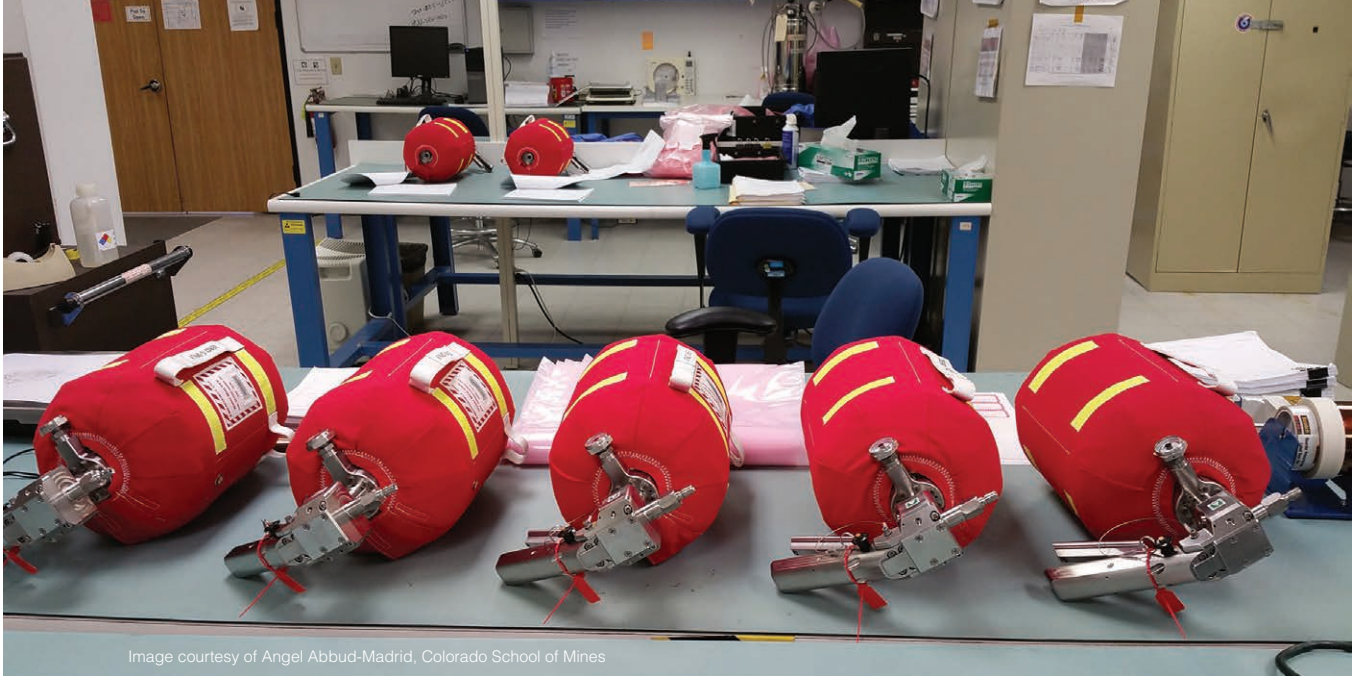


Image courtesy of Angel Abbud-Madrid, Colorado School of Mines

A set of nine fine-water-mist fire extinguishers were built to replace the carbon dioxide extinguishers that were incompatible with astronaut emergency breathing equipment. They were designed to fit in the existing storage lockers, with the last one arriving on the space station in 2016.

microgravity environments and built a technology suitable for use in space and on Earth.

Russ Doering, retired president of Doering, says the process of customizing and testing the company's zero-leak, air-piloted poppet valve challenged everyone in the company to take their already high standards to a new level.

"Each valve was serialized and had its own documentation," explains Doering. "All that was new ground, so it gave us that capability going forward. We later had other projects where we were able to do trace-gas testing and document it."

A point of pride for Doering is the fact that the final product exceeded the project's requirements.

Benefits

All nine new water fire extinguishers built to replace the original CO_2 fire suppression devices arrived on the space station by 2016. And the class of zero-leak valve orbiting Earth is now improving the performance of systems in numerous industries with equally demanding requirements.

From industrial to military applications, the primary advantages of this precision hardware over standard valves are performance and safety. When leaks can result in unacceptable risks or negatively affect outcomes, zero-leak is essential.

One client uses the pneumatic-piloted poppet cartridge valve in a grease dispenser built for industrial applications such as automotive assembly. During vehicle production, numerous locations require an application of grease. The ability to squirt the liquid where it's needed might seem simple enough, but oil viscosity changes with the temperature. Whether the grease is cold and thick or warm and runny, the valve in the dispenser that controls the flow must close completely. Otherwise, that slippery substance could end up on the assembly line floor, posing a serious risk to workers.

Hydraulic equipment depends on effective valve operation to maintain the right level of liquid and pressure in a system. This is one of the applications where valve leakage is common, even expected, because of how hydraulics function, according to Dombroske. A very high pressure or force combined with a small amount of fluid in a contained space (such as a piston) enables a machine to move extremely heavy objects. For example, a bulldozer employs hydraulics to shift tons of soil or rocks. Such a powerful force can easily cause leaks. However, such a leak can endanger human life.

"A manufacturing company had a problem with the equipment that holds large rolls of papers for printing presses," says Dombroske. "They had a valve that was leaking. The hydraulics weren't able to keep that paper that weighs multiple tons in position overnight. A worker could be crushed if it failed completely."

The company installed Doering's hydraulic-piloted poppet cartridge valve to address the immediate safety need. At the same time, they sent more of the valves to their facility in Italy for extensive testing. Now these valves are the only approved hardware for the equipment.

Another high-risk application is the Growler A/M32K-10 munitions trailer. This military vehicle transports up to 15,000 pounds of munitions and carries a safety requirement for the trailer's brakes to hold for 24 hours before deploying an emergency parking brake. The first valve failed, allowing the trailer to move. The Doering valve never failed and is installed in more than 450 Growler trailers.

Russ Doering credits the NASA project with making it possible to introduce the zero-leak valve to new markets. In addition to NASA "helping us in our weak areas," Doering says the staff "came out with a better knowledge of what our capabilities were."

"It was interesting to work with NASA," he says. "They were willing to spend the time to fully communicate and to look at the design objectively. That cooperation was really great."

While the company expands its reach into new markets such as mobile and industrial hydraulic, the zero-leak valve is getting ready for another trip into space. NASA is developing the next-generation fine-water-mist fire extinguisher using the same Doering valve. This new fire extinguisher is for the Orion spacecraft. ❖

Pulsed Laser Innovations Power Nobel-Winners' Research

NASA Technology

When Neil Armstrong took his first steps on the Moon, the video and his first words—transmitted across nearly 240,000 miles and broadcasted around the world—were instantly famous.

These days we take for granted that astronauts can post tweets from orbit and data can stream back from across the solar system. We see high-definition images of Pluto taken by a spacecraft over three billion miles away and monitor the progress of the Curiosity rover on the surface of Mars.

But all that information has to travel to Earth—and as the quantity and quality of the instruments being sent into space get better and the sheer number of spacecraft is growing, the amount of data is only getting bigger and bigger.

In short, we need more bandwidth. And right now, it looks like the answer is lasers.

That's where Malcolm Wright's group at the Jet Propulsion Laboratory (JPL) comes in. For the last 20 years, he's been working on developing the technology to build optical communications into spacecraft.

If that sounds a little familiar, you're not wrong. We already use optics—usually fiber optics—for high-definition cable television, telephone lines, and high-speed internet access. And in fact, Wright says his team's goal was to find existing laser-based telecommunications infrastructure that could be adapted for space communication.

Today, ground-to-space communications are typically transmitted through microwave-frequency radio waves. The amount of data you send in a given time is governed by the length of the wave, Wright explains, with shorter wavelengths able to pack in more information.

Lasers transmit light waves, which have a much higher frequency. They also focus the light a lot more precisely than radio transmitters do, Wright says. "Radio communications energy spreads out. But with a laser, all that light can be concentrated on a small spot. That means, for a small amount of transmitted power, we can get a stronger signal back on Earth."

That's a big part of the reason optics have been so successful in telecommunications on the ground too. But space-to-ground was going to require some pretty important modifications. For one thing, in fiber optics, the fiber acts as a guide for the laser, Wright explains, so no light is lost from transmitter to receiver. But you can't run a fiber from the International Space Station to the ground, let alone from Mars or the further reaches of the solar system.

Laser beams can still travel those long distances, he says, but the beam will diverge somewhat, diminishing how much signal reaches the receiver. That means the system needs to start off with more power.

The other difference is in how the information is transmitted over extremely long distances, say from the Moon or deep space to Earth. Transmitters use very short but very high-powered pulses, explains Wright, rather than transmitting continuous streams of ones and zeroes. "It's very data-efficient. You don't need a lot of signal to determine when a bit comes."

These pulses need to be extremely fast to avoid over-taxing the laser—and to avoid the need for a very power-hungry laser. "The average power requirement is not too demanding, around a few watts, but peak power might be up to a kilowatt," Wright says. "All that energy but only for a short amount of time."

For communications, Wright was looking for lasers capable of nanosecond pulses—pulses that last just a billionth of a second.

Technology Transfer

For that, he turned to a San Jose, California-based PolarOnyx. "Their expertise was in making these lasers support very high peak powers," Wright says.

PolarOnyx had built its expertise in telecommunications lasers and received Phase I and II Small Business Innovation Research (SBIR) contracts from JPL in 2002 to develop short-pulse fiber lasers for optical communications from

This high-resolution, color image of Pluto was taken by an imager on the New Horizons spacecraft as it flew by in July 2015. The image then streamed billions of miles across the solar system back to Earth. As the quantity and quality of data coming from space increases, NASA is working to increase bandwidth using laser communications.

> We had to keep innovating to stay ahead of the market. The NASA funding enabled us to do that—so we could move faster than every competitor."
>
> — Jian Liu, PolarOnyx

space. (Unlike with fiber-optic telecommunications, the fiber in this case refers to how the laser pulse is generated and amplified, rather than how it travels.)

Since those JPL contracts, PolarOnyx Inc. has received additional SBIR funding from Goddard Space Flight Center, Langley Research Center, and JPL to continue developing fast-pulsed lasers and amplifiers.

Company founder Jian Liu says the company has benefited tremendously from the SBIR funding. "Through those projects, we have developed several key technologies for the fiber laser project." Among other advances funded by the SBIR contracts, he says, was the ability to scale up a laser's power to 100 watts while managing thermal issues and others that could damage equipment at high power.

So far, the company has delivered several laser systems to NASA under the SBIR funding, including a few recent 20-watt lasers that can pulse at nanosecond rates with repetition rates up to 100 megabits per second. Wright says these projects have not been for specific space missions. "This is more like, show me the capability so when the project comes along we can say, hey, we can do this."

However, he says, looking forward he can see applications in the next generation of upcoming space communication projects. "What we use right now, you can get six megabits per second from Mars using radio frequencies. And we would be pitching from 30 to 100 megabits per second using laser communications."

But in the meantime, Liu says the laser systems designed thanks to SBIR funding are already finding plenty of customers on the ground.

Benefits

PolarOnyx spun off a subsidiary, called Laser-Femto, to commercialize the fiber laser systems like those developed with SBIR funding, and Liu says they have found a solid market among research institutions, including well-known universities such as Howard, Yale, Stanford, and more. The Army and Air Force research labs are also customers.

Thanks in part to multiple SBIR contracts from the Jet Propulsion Laboratory and other NASA field centers, PolarOnyx has developed and improved its ultra-fast pulsed fiber lasers. The company has sold more than 400 of the systems, including to three Nobel Prize winners.

Among other selling points, the company took the work it did for NASA and improved it by building it into femto-pulsed lasers. While nanosecond pulses last a billionth of a second, femtosecond pulses are orders of magnitude faster, lasting a quadrillionth of a second.

"We are the leading company in ultra-fast pulsed fiber laser in this field. We are able to offer the highest energy and the highest power and the shortest pulse in a fiber laser," Liu says, adding that the company has sold more than 400 lasers since around 2005.

The company has won multiple awards for its "first-to-market" femtosecond fiber laser products. And being first positioned them well for the most cutting-edge research, Liu notes, in fields such as physics, materials processing, and biomedical science. "Our lasers have supported three Nobel Prize winners," he boasts.

Most recently, Donna Strickland won in 2018 for "groundbreaking inventions in the field of laser physics." Although the Nobel-winning research was published in 1985, Strickland has used PolarOnyx lasers in her more recent work: the company notes that Strickland bought her first system from Laser-Femto back in 2006 and has been a loyal customer ever since.

Liu says the NASA funding has been instrumental in the company's success, particularly in staying ahead of low-cost competitors. "We had to keep innovating to stay ahead of the market," he explains. "The NASA funding enabled us to do that—so we could move faster than every competitor." ❖

New Imaging Technique Measures Unseen Flows

NASA Technology

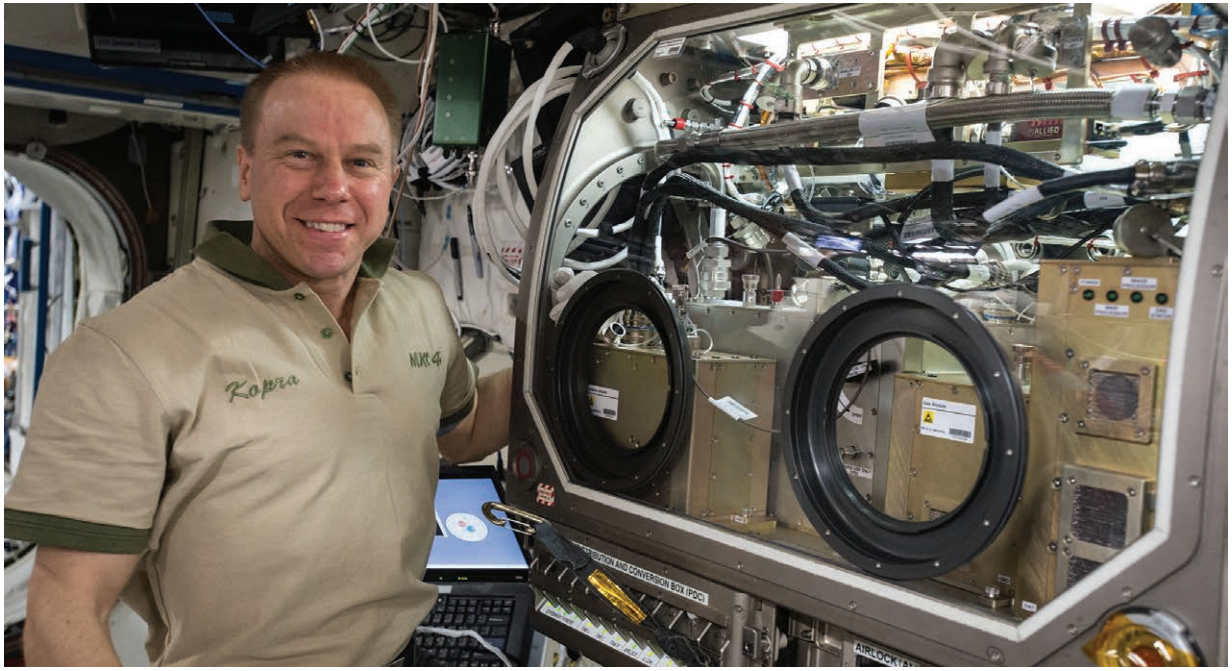
Gravity draws water from a faucet into a cup. Air bubbles rise because they're lighter than the water around them—gas and liquid effortlessly self-separating. In countless ways, we take advantage of such predictable behavior, every time a boat floats or water circles a drain. But in space, none of these rules apply. Without gravity to put them in order, gases and liquids must be managed in other ways.

So NASA scientists have long sought better ways to observe the behavior of these fluids in zero gravity and to monitor the systems that handle them, such as those that purify air and water in spacecraft.

"There's always been a desire to measure how phases are distributed in a tank or in a flowing tube and how that impacts function," says Brian Motil, chief of the Thermal Systems and Transport Processes Branch at Glenn Research Center.

This was especially important for projects like the Two-Phase Flow Separator Experiment and the Packed Bed Reactor Experiment, both of which Motil oversaw. The former aimed to separate air and water through inertia by spinning them. The latter observed how air and water moved together through a packed bed reactor, a type of device that directs substances into a vessel packed with a catalyst to create desired reactions. Packed bed reactors are used on the International Space Station in air and water purification systems, fuel cells, and other devices, as well as in many applications on Earth. Currently, none of the packed bed reactors on the space station handle both liquid and gas, because scientists don't know how a two-phase system would perform in microgravity, but such a device would promise more efficient thermal-management and life-support systems.

In the interest of both projects, Glenn started talks with a few teams that were using electricity for three-dimensional imaging in the mid-2000s. One, at Ohio State University, was working to bring new advances to the technique of electrical capacitance tomography (ECT) and would soon found Tech4Imaging LLC of Columbus, Ohio.



NASA astronaut Tim Kopra shows off the Packed Bed Reactor Experiment on the space station. The experiment, which observed how gas and liquid move together through a packed bed reactor in microgravity, was one reason NASA invested in Tech4Imaging's electronic capacitance volume tomography (ECVT). It would have helped to get clearer images of substances moving through the packed bed, although the technology wasn't ready in time to fly with the experiment.

The technique isn't entirely different from other forms of tomography—ways of seeing the insides of pipes, structures, or bodies. "A ray passes through the material, and the intensity of the ray changes," explains Qussai Marashdeh, the company's CEO and cofounder. "How it's attenuated by the material inside will tell you what the material is."

ECT uses low-frequency electrical signals instead of the sort of high-frequency, dangerous radiation used in CT scans and X-rays. And it doesn't require any of the bulky, high-powered equipment used in MRI techniques. Instead, a series of metal capacitance plates surrounding an object send and receive the signals. But ECT had serious limitations. Its three-dimensional scans were built from layers of two-dimensional scans, leading to low resolution.

Marashdeh and his Ohio State colleagues solved the problem by inventing what they call Electrical Capacitance Volume Tomography (ECVT), in which improved circuitry allows the plates to send signals to each other in all directions, vastly multiplying the number of signals. These are combined with sophisticated mapping software to create a true three-dimensional image.

When Motil started talking with Marashdeh's team, they were able to image solids and gases reasonably well with this method. "He did it better than anyone else, showing an ability to measure these things, but only in a really pristine lab setting," says Motil, adding that there were still

> “The end result is going to have more impact on industry than on NASA. I think there’s tremendous spinoff potential with this.”
>
> — Brian Motil, Glenn Research Center

issues with resolution and calibration. After Tech4Imaging formed, Motil encouraged the company to apply for NASA Small Business Innovation Research (SBIR) funding.

Technology Transfer

In 2015, under a Phase I SBIR contract from Johnson Space Center and a larger Phase II contract with Glenn, the company set out to measure multi-phase flows with ECVT technology.

“Through the NASA work, we were able to overcome a major hurdle, which is how to measure liquid water,” says Marashdeh.

Motil says another major development under the Phase I work was the ability to measure the rate and amount of liquid, gas, and solid flowing through a conduit by detecting shifting gradients in capacitance. Motil says Marashdeh’s team is the first he knows of to develop algorithms to translate that gradient into a velocity profile. It can distinguish oil from gas and water, suggesting one likely lucrative market.

With Phase II funding, the company developed new algorithms and refined its electronics to detect not just changes in the amplitude of electric signals but also shifts in their phase, Motil says, noting that this resulted in higher resolution and eliminated a need to frequently recalibrate the system.

The resulting ECVT technology still hasn’t flown in space, as it wasn’t ready when the Packed Bed Reactor Experiment launched in 2015, and funding was cut for the Two-Phase Flow Separator Experiment.

However, the company had already been selling earlier versions of the technology to scientists and researchers, and Marashdeh says he’s been in talks with major companies in a number of industries about a commercial version of the technology he developed for NASA.

Benefits

“The oil industry now can’t tell you how much oil is flowing through a pipeline,” Marashdeh says. “They have to wait on separation, drain it, and then measure it.” Tech4Imaging has been working with industry leaders to develop a standard product for gas and oil pipelines, which he expected to be available around late 2019.

The company is also working with Marashdeh’s colleagues at Ohio State University to validate a product to measure powder and airflows in pharmaceutical manufacturing. But he notes that the technology could help optimize and monitor manufacturing processes in any industry, from plastics to potato chips.

He and colleagues have also been working on applying the technology to nondestructive testing of infrastructure. For example, it can detect holes, cracks, and water in concrete piping, and an added magnetic signal can look for corrosion on steel rebar.

Another potential application, he says, is in improving computational fluid dynamics software that engineers use to simulate air and liquid flows when designing vehicles and a slew of other products.

Marashdeh is especially excited, though, at the possibility of using ECVT for medical imaging. “It’s safer, smaller, and cheaper, and you could wear an image sensor and link it to a device,” he says. Although an MRI scan still offers higher resolution, he adds, the company is working to close that gap.

For now, though, he says the company is in talks with major players in the oil and gas, mining, and chemical industries, who see immediate opportunities for savings.

While the SBIR funding seemed like a high-risk investment at first, Motil says, it was always apparent that if the technique could be improved to meet the Space Agency’s needs, it would also open many other possibilities. “The end result is going to have more impact on industry than on NASA,” he says. “I think there’s tremendous spinoff potential with this.” ❖

Tech4Imaging’s ECVT technology uses a series of capacitance plates surrounding a pipe to sense flows of up to three phases. A processor uses sophisticated mapping software to make sense of the data, calculating the flows and displaying three-dimensional images.

Separation Device Launches New Science Payloads

NASA Technology

Rockets typically come in stages, each optimized for different parts of the launch. When each stage has finished its part, it drops away, allowing the smaller remainder to continue on its journey.

Have you ever considered how that process happens? Just like everything else with rocket science, it's complicated yet crucially important to get right.

"Not only do you need enough spring force" at the moment of separation to avoid a collision, explains Susan Pope, director of the Space Instrumentation Department at the Southwest Research Institute, "but you need stable force in the direction you want to go, distributed around the whole diameter, so you're pushing out straight."

There are other complicating factors. Among the most important, true of any spacecraft component, are weight and power: too much of either and the separator will be stealing resources from all the other important systems on the spacecraft.

And about a decade ago, this complex engineering problem got even more difficult on a small spacecraft that needed to travel two-thirds of the way to the Moon to observe the very edges of our solar system.

IBEX, for Interstellar Boundary Explorer, only had a $100 million budget and a Pegasus XL launch rocket, explains Dave McComas, principal investigator for the mission and today a professor at Princeton University. The rocket wasn't powerful enough to get the spacecraft all the way to its final orbit, so the team came up with a way to piggyback a second rocket engine on the first, which would fire after the Pegasus got the spacecraft into low-Earth orbit.

That math worked, but just barely, McComas recalls. "We were so mass-constrained, we had to launch off the Marshall Islands, because that's closer to the equator, and you get more energy out of the rotation of the Earth. It made tens of pounds of difference" in terms of how much could be loaded onto the spacecraft.

IBEX required three stage separations: the first to push away the Pegasus rocket, another to push away the adapter that connected the two rockets, and finally one to push away the second rocket engine, explains Pope, who was the lead mission systems engineer on IBEX. And, it turned out, the separation devices were pretty heavy, especially times three.

So the IBEX team turned to Silver Spring, Maryland-based Planetary Systems Corporation and asked them to make their devices, called Lightbands, smaller and more energy-efficient. And since each stage of separation required a different diameter, they requested three custom-built Lightbands, all meeting IBEX's stringent requirements.

"It was truly mission-enabling for us," says McComas. "These devices were not the only thing, but one of the things that saved us enough mass to fly to the orbit we needed."

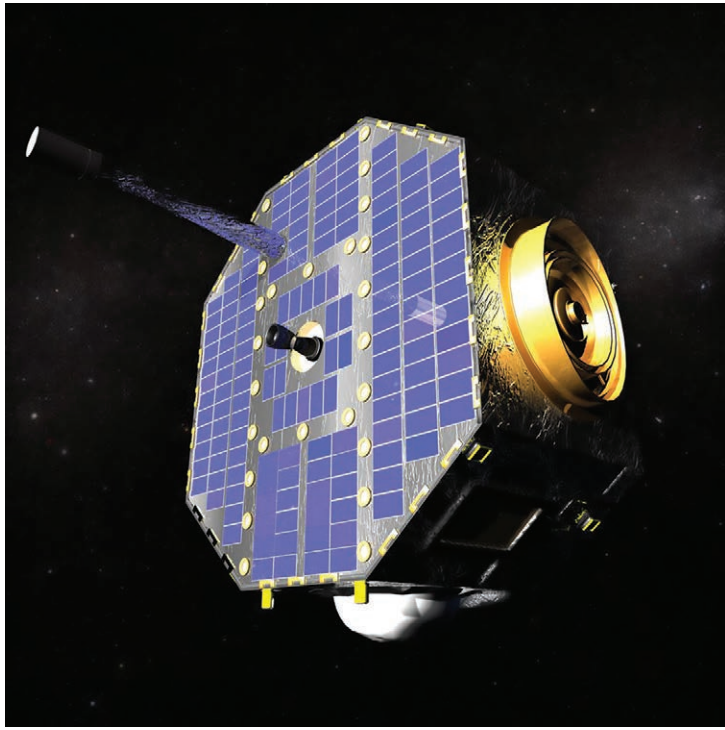
Technology Transfer

Planetary Systems had developed their Lightbands years before with funding from the Air Force Research Lab, and they had already flown many times.

But the needs of the IBEX mission pushed them much harder. "IBEX was every requirement on top of every requirement," says company founder and chief engineer Walter Holemans. Not only did the company have to design Lightbands to meet all the requirements, but naturally, extensive testing was required to prove they would work without a hitch in space.

The devices consist of twin metal rings clamped to each other by an inner ring. An electric motor mounted on the rings contracts the clamping ring, releasing its hold, which frees up a series of springs to push the two spacecraft components apart.

"One big concern was we would self-collide, and that would cause the spacecraft to tumble," he recalls. It's difficult to prove that won't happen with computer analysis, because you typically input a broad range of possible scenarios, and "if you keep doing that enough, pretty much anything will happen," Holemans says. So instead, they had to build the parts and do physical testing to show what would happen in real conditions.



The Interstellar Boundary Explorer (IBEX) spacecraft helped draw the first map of the boundary between our solar system and interstellar space.

"There's more," he adds. "In development, we had some challenges with our motors, so we got some help from Goddard Space Flight Center debugging the failure modes."

Overall, Holemans says, the company spent around two years, as much time as the IBEX team gave them, developing new Lightbands for the mission. And although it was reasonably profitable as a project, the real payoff was all the data the company collected as a result of the NASA requirements.

"They asked a lot of terrific questions, and we always tried to answer with tests as exhaustive as we could make

them, because we knew this would be breakthrough," he emphasizes.

Benefits

Today, every Lightband Planetary Systems makes uses the improvements pioneered for IBEX. For one, their Lightbands are, across the board, around 17 percent lighter than before, thanks to all the changes they made, from sourcing smaller and lighter screws to redesigning the motors.

"Everything improved after IBEX," Holemans says. "Everything about the Lightband got more sophisticated."

The company also used its extensive test results to write a definitive user manual for the Lightbands, which they still use today. "We did so much testing, we could fill up a 90-page user manual with all kinds of answers to all kinds of questions. That allowed other users to an get unheard-of level of insight into how this works."

Holemans says the IBEX mission paved the way for the company to double in size, and today the company sells around 40 Lightbands a year to government, military, and commercial clients. Among other achievements, Lightbands have enabled commercial Earth-observing satellite constellations and science missions for space agencies including NASA and the European Space Agency.

As the commercial space industry expands, and especially as CubeSats become increasingly common, Holemans sees the need for lightweight Lightbands only increasing.

He credits the IBEX experience with playing a huge role in the growth of their business. "That success opened doors for us," he says. "Once we had the heritage on such a mission, it was easier for us to make sales, because we had the confidence to say this worked on a very challenging mission."

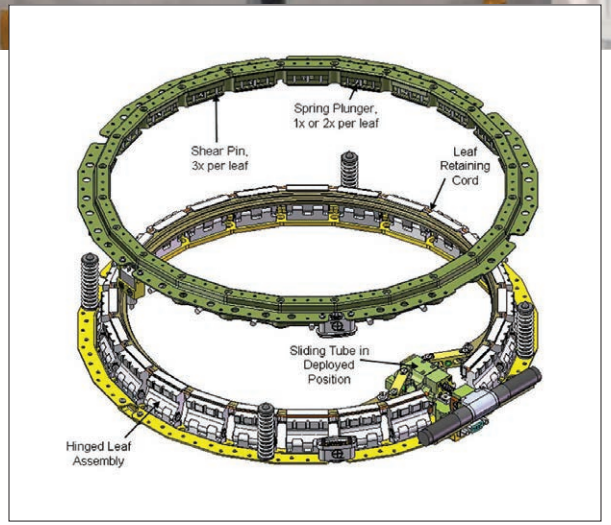
McComas says the success of the IBEX mission has opened exciting new doors for exploring the universe. The data it gathered has helped scientists better understand the region at the edge of our heliosphere, where charged particles from the Sun block out dangerous interstellar radiation.

In 2018, based on the successful results from IBEX, NASA began working on a much larger mission, the Interstellar Mapping and Acceleration Probe, to learn even more details about the interstellar boundary region. McComas says that might never have happened without Planetary Systems' Lightbands.

"Without solving our mass problems, of which the motorized Lightbands were an important part, we wouldn't have been able to fly IBEX, which means we wouldn't have had these fabulous global results, and now we wouldn't have a new mission." ❖

> "That success opened doors for us."
>
> — Walter Holemans, Planetary Systems Corporation

To reach its destination, IBEX needed two rocket engines, which had to be carefully separated from the spacecraft during flight. Here an engineer is about to attach the spacecraft to one of the separation devices, called Lightbands, built by Planetary Systems Corporation for the mission.



This diagram shows the Ligthband right after separation. Beforehand, the green and yellow rings are clamped together by an inner ring. When the externally mounted motor activates, the inner ring contracts, shearing the two outer rings and freeing up springs to push them apart.

Tiny Pulsed Lasers Have Medical, Industrial, Military, Environmental Applications

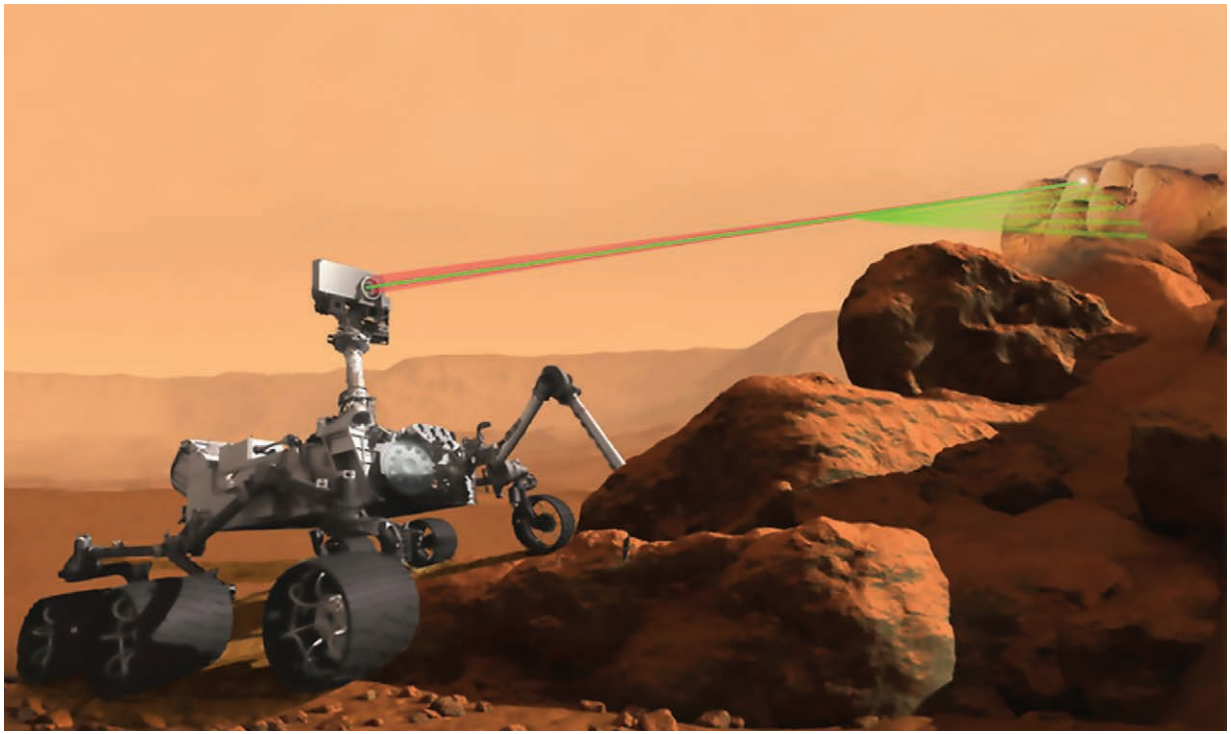
NASA Technology

On the outside, NASA's Mars 2020 rover will look nearly identical to the 2011-launched Curiosity rover. But inside, engineers are packing more-advanced instrumentation—and more instruments—into the same frame. Together, these will, for the first time, search directly for signs of past microbial life on the Red Planet and attempt to extract oxygen from the carbon dioxide in the atmosphere, among other objectives.

One of Curiosity's most-used instruments is its laser-induced breakdown spectroscopy (LIBS) system, which can analyze the composition of surfaces at distances of more than 20 feet. The instrument, the first of its kind ever flown in space, fires a high-powered laser pulse that momentarily rips surface molecules into plasma, producing a brilliant flash. By analyzing the spectrum of that flash, the system can determine the molecular composition of the surface. In its first two years on Mars, the LIBS instrument was used 160,000 times at 4,500 locations.

The only way to fit this handy tool into the 2020 rover with all the additional and enhanced instruments was to shrink it down, so in 2015, the Space Agency put out a call for a smaller, more efficient version. The Hawaii Institute of Geophysics and Planetology at the University of Hawaii responded with a plan to enhance a compact LIBS prototype it had built. To do this, the university partnered with longtime laser specialist Q-Peak Inc. of Bedford, Massachusetts.

Q-Peak, which has been doing cutting-edge laser work for NASA and other Government agencies since the 1980s, was awarded two NASA Small Business Innovation Research (SBIR) contracts to develop a pulsed laser source far smaller and more efficient than anything on the market, a feat the company pulled off in short order. The work has resulted in a new commercial product from Q-Peak, the first to make laser diode-sized packaging practical for a pulsed-energy laser.



The Mars 2020 rover will look almost identical to the Curiosity rover that landed on the Red Planet in 2012. But it will pack more—and more advanced—scientific instrumentation. In an effort to help make that happen, Q-Peak Inc. developed a pulsed laser source smaller than any laser of its kind for the rover's laser-induced breakdown spectroscopy (LIBS) instrument, which can determine the composition of a surface by zapping it and observing the resulting flash.

Technology Transfer

Q-Peak's Moonbow laser, based on the laser it developed for possible use on the Mars 2020 rover, is the smallest laser of its kind. "This is a new capability," says company Vice President Eric Park. "It's never been possible to get 1- to 10-millijoule laser pulses in this kind of package size." While comparable lasers have been around the size of a shoebox, he says, Moonbow is closer to in size to a matchbox.

It wasn't a single innovation or a new configuration that dramatically reduced the laser's size, weight, and energy efficiency, but rather a series of careful, clever, and meticulous engineering, packaging, and material choices, says Anthony Yu, of the Lasers and Electro-Optics Branch at Goddard Space Flight Center. Although funding for the laser came from the Jet Propulsion Laboratory (JPL), Yu oversaw the work. To rethink laser engineering, he says, "you have to involve a multidisciplinary team—an optical engineer and electrical, thermal, and mechanical engineers."

The smallest, simplest lasers, such as those used in DVD players, are typically diodes that produce low-energy, continuous output or micro-Joule-level pulses. To get the kind of power that will disintegrate molecules, energy has to be stored up and then fired in a short, high-powered burst.

> “It’s never been possible to get 1- to 10-millijoule laser pulses in this kind of package size.”
>
> — Eric Park, Q-Peak Inc.

A common method for achieving pulsed laser is known as Q-switching: A diode pumps energy into a crystal, with the Q-switch letting energy build up until the crystal is saturated. At that point, the Q-switch suddenly allows optical amplification to begin, and light intensity builds up rapidly, resulting in a brief, high-energy pulse.

Q-Peak relied on this well-known technology to design both its Mars rover laser and its commercial Moonbow device, but the company managed to pack all these elements into a device a fraction of the size of other commercial pulsed laser sources. “You have to use the right materials, have the right cavity design, control the temperature of all the elements in the cavity,” says Yu. “Then, how do you package it? That’s the optomechanical design.”

According to the University of Hawaii, using Q-Peak’s laser source brings down the size of its entire LIBS system by 20 percent and reduces its weight by 30 percent.

While the laser source on Curiosity’s LIBS system weighs about 500 grams, the one provided by Q-Peak weighs just 65 grams.

Benefits

There are a number of uses for a tiny, powerful laser, but one of the most exciting to emerge so far, according to Park, is to treat glaucoma in the developing world.

Glaucoma is most commonly treated with eye drops, but in remote locations, it can be hard to provide consistent, ongoing treatment. An increasingly popular glaucoma remedy is laser surgery, which is quick, painless, and effective for about three years. In early 2018, Q-Peak began working in conjunction with a medical equipment supplier on a variant of the Moonbow CB-G laser source, the one most closely based on the Mars 2020 work, as the laser source in a small, portable, rugged unit to perform laser surgery in the field.

Q-Peak Inc.’s Moonbow laser series produces higher-energy pulses than any other laser of its small size, in green and infrared wavelengths. The technology is useful not just for the LIBS instrument NASA needed but also for lidar range-finding, Ramen and fluorescence spectroscopy, and other applications.

“The intent is to build an instrument the size of a small coffeemaker that can be put in the back of a Land Rover and carried from village to village,” Park says. Clinical trials and regulatory approvals are underway, and the treatment is expected to become available within a couple of years.

Other customers to date include the Air Force Research Lab and Sandia National Laboratories, and Park sees potential markets in the oil and gas industry, the Department of Defense, and beyond. A laser like Moonbow can be used to determine molecular composition through not just LIBS but also Raman and fluorescence spectroscopy, making it useful for mining, drilling, industrial process control, and environmental monitoring, among other fields. It can also be used in lidar instruments that have a host of applications, from sensors for autonomous drones—where size, weight, and efficiency are especially crucial—to three-dimensional measurement of mechanical parts. Park notes that non-lethal dazzler weapons, which use intense light to temporarily blind opponents or sensors, are another potential application.

The company is continuing to advance the technology under SBIR contracts with JPL to develop an ultra-compact lidar range-finding capability that will help guide the landing of a probe planned for Jupiter’s moon Europa.

“Anytime you need a 1- to 10-millijoule pulsed laser, it’s possible to build a much smaller, more flexible system with this technology,” he says. “This is a new scale factor that hasn’t been available before.” ❖

Electrostatic Discharge Training Improves Manufacturing Practices

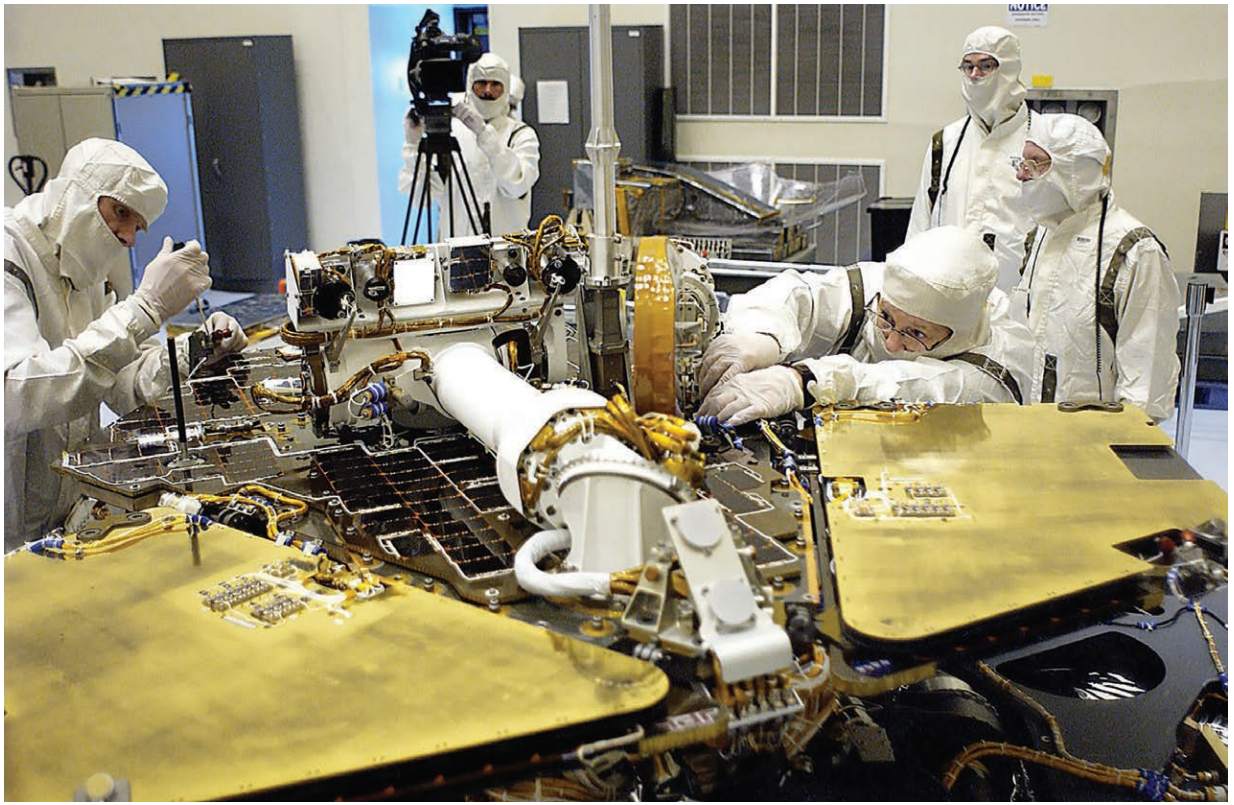
NASA Technology

Everybody has felt it from time to time: that sharp jolt of electric shock you get when you walk across a rug and touch a doorknob.

It's a result of static electricity—electrons rubbing off the rug and building up on your body and then jumping to the metal knob. What you might not realize is that this happens all the time, all day long. In fact, by the time you feel that electric shock, explains Goddard Space Flight Center's Alvin Boutte, it's only because the electric charge has built up to at least 3,000 volts or more.

Of course, besides making you jump, that electric shock isn't going to do much damage. But what if, instead of touching a door knob, you were building a delicate sensor for a Mars or lunar rover? "When you're building an instrument for a spacecraft, you start at a very low level: tiny parts being put on a board," says Boutte, "and that's probably when it's most susceptible.

"Once you put it on a board, then in a box, then in a spacecraft, it gets less and less sensitive," he explains, because each of those layers is built in part to protect the electronics. But in the early stages, that 3,000-volt charge from your finger is more than enough to fry the entire instrument, he says. "Many of your electronic parts are going to be sensitive at much lower ranges, 250 to 300 volts. You could build up that much charge without even knowing it and discharge without even realizing it happened."



Technicians remove a circuit board on the Mars Exploration Rover 2 to repair it. They must be especially careful to avoid electrostatic discharge, essentially an electric shock. These shocks happen all the time, usually at low enough levels that people don't even feel it. But sensitive electronics such as circuit boards on spacecraft can be damaged by even extremely low-level shocks.

Technology Transfer

That's where Boutte, his team at Goddard, and their counterparts across NASA come in, helping devise and implement protocols to minimize and avoid any electrostatic discharge events during instrument manufacturing.

One tool that has helped in recent years is a training seminar conducted by RMV Technology Group, based in Moffett Field, California. Although multiple companies offer trainings on electrostatic discharge, NASA initially went to RMV because it was one of the few that include hands-on exercises during the course, which the company holds in its own electrostatic discharge (ESD) laboratory environment.

The first training RMV provided was in 2014, Boutte recalls, and since then there have been several sessions—and the feedback Boutte and others have provided has helped shape and improve the course. For example, Boutte explains, NASA shares with the company the materials it typically uses, helping RMV tailor the training to the types of processes that would work best in those contexts.

The company said the back-and-forth has paid off in more than just improved NASA trainings. "We were very specific in our training that it applies to what the NASA requirements are," says RMV President Renee Mitchell. "And what's interesting is that what NASA requires, the Department of Defense requires. This collaboration with NASA also benefits the U.S. military."

Mitchell is quick to clarify that there was never an exchange of funds or specific contract between NASA and the company to develop the training. Nevertheless, "since

> "You could build up that much charge without even knowing it and discharge without even realizing it happened."
>
> — Alvin Boutte, Goddard Space Flight Center

we work closely with NASA program managers from most centers, they collaborated with us, and we incorporated their requirements into the training program."

Among other areas the company added to its training at NASA's request were modules on recognizing suspected counterfeiting—so engineers and technicians could ensure the materials they buy from outside suppliers maintain the required specifications.

Last year, RMV partnered up with a company called Exemplar Global, an affiliate of the American Society of Quality, to get formal certification. As a result, NASA's ESD program managers and NASA's Safety Center were the first to earn certification from the International Association for Radio, Telecommunications, and Electromagnetics (iNARTE) as ESD Aerospace and Defense Engineers, a credential that is now also available to the public.

"It's really a great case of a vendor listening to the feedback from their customer and actually implementing it in their product," says Boutte.

Benefits

Now RMV is finding clients outside NASA also appreciate the improvements that have been made in the training. The company has just launched a subsidiary devoted specifically to marketing the course, called ESD Aerospace Training. It has already conducted two seminars for the U.S. military and had interest from two universities.

"In the military, it's all about logistics," Mitchell says. The company's electrostatic discharge training teaches engineers and technicians how to handle and store electronics so they maintain their integrity over long periods of time, especially in places with extreme temperatures and very low humidity, such as the Middle East or Afghanistan. In addition, she says, like NASA, the military often manufactures its own sensitive or classified equipment, which requires careful handling.

Image courtesy of U.S. Army

RMV Technologies is one of the few companies that offers hands-on training for best practices in avoiding electrostatic discharge during manufacturing, handling, and storage of sensitive electronics. Their seminar benefited from input from NASA, and is now being offered widely. The U.S. military is one customer.

The commercial aerospace industry is also booming, she notes, and all these new entrants are also prime candidates for electrostatic discharge training.

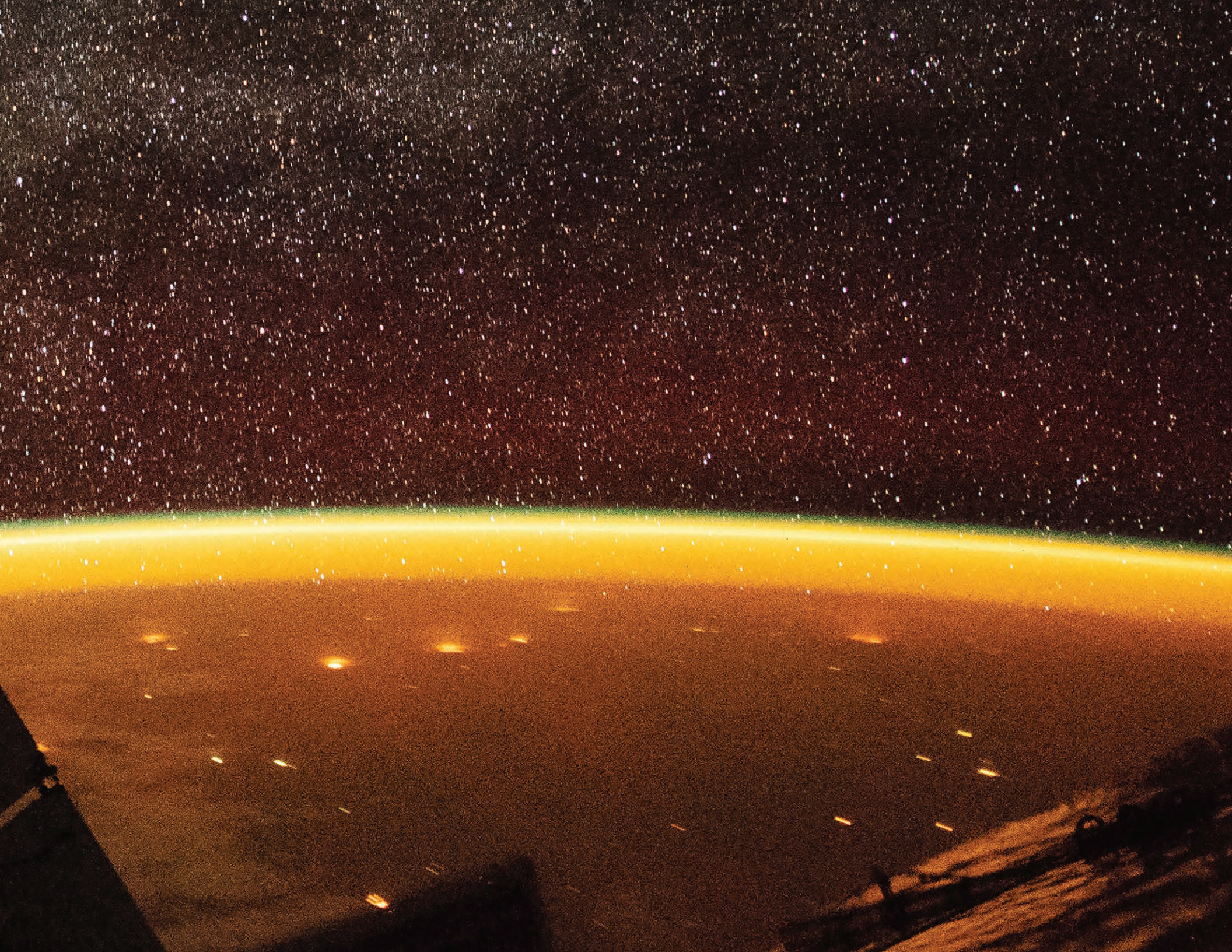
As with NASA, the big selling point for the company's training is what Mitchell calls the "deep dive"—a detailed, hands-on approach. Many competitors, she says, offer basic training on standard processes but don't teach how to troubleshoot and solve problems. "The engineer or technician isn't able to learn how to use instruments and audit a facility or to test materials before they're used," she says.

And Mitchell sees much broader market potential, for example in the medical industry, which "is also dealing with harsh environments—the human body is considered a harsh environment." Whether a company is building a pacemaker or a microdevice to track or adjust drug dosage in the body, she says, "you have to understand the relationship between conductive materials and biology." ❖

Spinoffs of Tomorrow

We've documented dozens of spinoffs in this issue, and thousands over the years—and we're just getting started. We've got hundreds of innovations in our technology portfolio ready for you to take the next step: licensing and developing a commercial product. This section features 20 technologies available for entrepreneurs, businesses, and researchers to license that we think show great promise for future commercial success.

To license these or any of the more than 1,000 technologies NASA has made available to the public, please visit http://technology.nasa.gov.



Ames

Nanosensor Array for Scenting, Diagnosing Illness

A low-power, compact nanosensor array chip

Analyzing a person's breath can reveal the presence of volatile compounds, called biomarkers, that give clues for a diagnosis and can help choose the right treatment. This requires an analytical tool with very high sensitivity, since these biomarkers often appear at low parts-per-billion levels.

Ames Research Center invented an array of chemical sensors combined with humidity, temperature, and pressure sensors for real-time breath measurement. This tool provides a non-invasive method for fast and accurate diagnosis, with sensor data transmitted by wire or wirelessly to a computer terminal at the doctor's desk or hospital monitoring center.

Benefits

- Detection range from parts per million to parts per billion
- Low power: milliwatt per sensor
- Low cost
- Fast and accurate, response time in seconds
- Multiple sensors for comprehensive measurement
- Wired or wireless data transmission over a long distance

Applications

- Medical diagnosis
- Nanotechnology
- Health monitoring
- Homeland security
- Biomedicine
- Aerospace

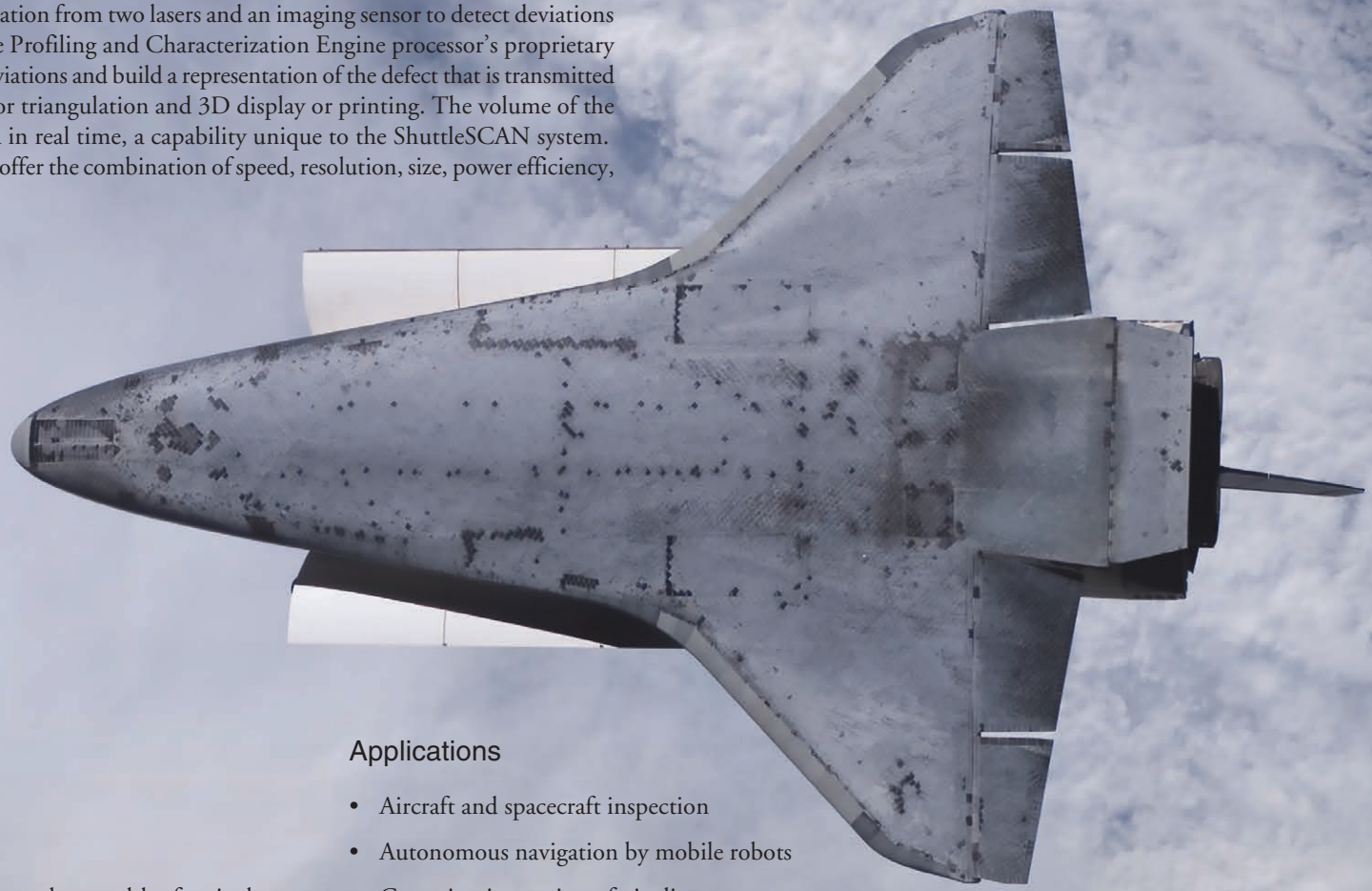
ShuttleSCAN 3D Laser Scanner

High-speed three-dimensional laser scanner with real-time processing

This high-speed 3D laser scanner was originally developed to inspect damage to the thermal protection tiles of the space shuttle. Now available for commercial license, this advanced system can be used for product quality control, autonomous navigation, and more.

The scanners use triangulation from two lasers and an imaging sensor to detect deviations in a flat surface. The Surface Profiling and Characterization Engine processor's proprietary algorithms interpret these deviations and build a representation of the defect that is transmitted in real time to a computer for triangulation and 3D display or printing. The volume of the defect can also be calculated in real time, a capability unique to the ShuttleSCAN system.

No other 3D scanner can offer the combination of speed, resolution, size, power efficiency, and versatility.



Benefits

- High speed
- Fast results
- Can detect details smaller than a thousandth of an inch
- Small and power-efficient
- Wireless

Applications

- Aircraft and spacecraft inspection
- Autonomous navigation by mobile robots
- Corrosion inspection of pipelines
- Optical 3D scanning of printed circuit boards for inspection and positioning
- Scanning industrial machined parts for dimensional accuracy
- Road surface profiling

Armstrong

Fuel-Saving Software to Optimize Aircraft Formations

A new method of estimating the optimal trailing aircraft position in a formation

Formation flying—when one aircraft flies behind another—reduces drag and, as a result, fuel consumption in the trailing vehicle. However, no sensor currently exists that directly measures drag, which makes it hard to determine when the trailing vehicle is maximizing the benefit from the formation.

Individually, the measurements used to estimate drag, fuel flow, and aircraft moments are imprecise. But combined, they provide a more accurate picture. Armstrong Flight Research Center researchers have developed software to combine these measurements and estimate the location for optimal fuel savings.

Operators can save 5 to 10 percent in fuel costs through optimal aircraft placement with this system.

Benefits

- Increases the accuracy in assessing optimal aircraft placement during formation flight
- Reduces fuel consumption and cost
- Reduces emissions

Applications

- Commercial air cargo
- Military transporty

Image courtesy of U.S. Air Force

Fiber-Optic Sensing Portfolio

A unique suite of sensing technologies for a range of applications

Innovators at Armstrong Flight Research Center have developed a fiber-optic sensing system that can give ultrafast, reliable measurements of shape, stress, temperature, pressure, strength, operational load, and liquid level.

Originally developed to measure strain on unmanned aerial vehicles and other aircraft—Armstrong's primary research areas—the technology has the potential to be used in a wide variety of fields in addition to aeronautics.

Applications include endoscopic surgery, to ensure precise placement of the tiniest catheters and to track their movement. In clean-energy markets, the system can improve the efficiency and increase the longevity of turbines by monitoring blade shape and force. For oil drilling operations, the sensors can provide data on drill direction as well as temperature and pressure. Armstrong-derived sensors could also provide liquid level sensing in industrial, pharmaceutical, and cryogenic applications.

Benefits

- Thousands of sensors on a single strand
- High-resolution visualization
- Powerful processing algorithms that allow refresh rates of 100 scans per second
- 3D shape determination and visualization

Applications

- Energy-market infrastructure and equipment
- Biomedical devices
- Industrial, pharmaceutical, and cryogenic monitoring
- Aeronautical and aerospace vehicles

Glenn

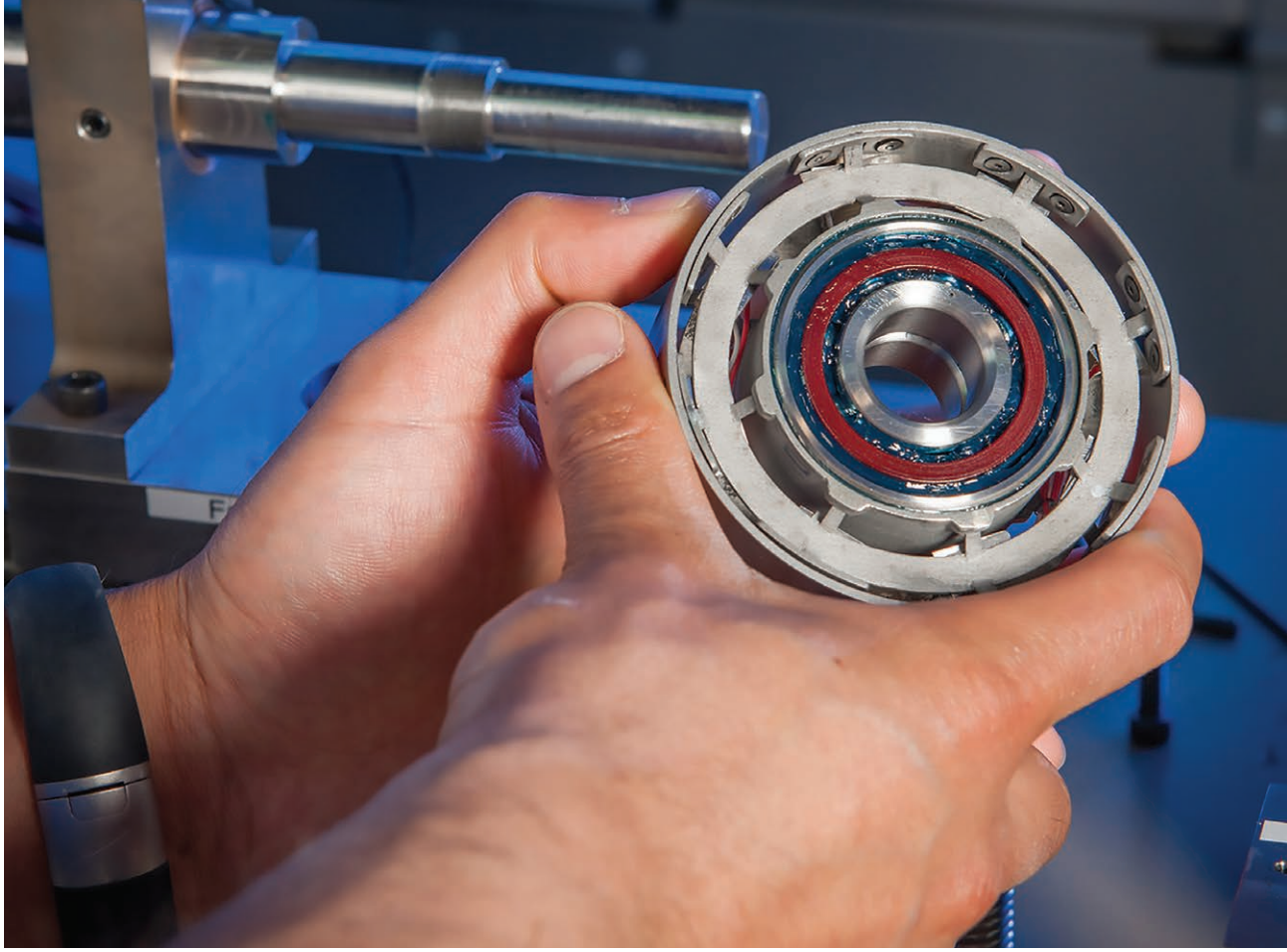
Noise-Reducing Ring

Reduces damaging and noisy vibrations within mechanical drivelines

When components, such as rotors, gears, and fans, rotate at high speed, this often creates vibrations that can be noisy and increase wear and tear. Innovators at Glenn Research Center have developed a unique device to solve this problem by converting applied vibratory energy into electricity.

The ring-shaped mechanism was originally designed to reduce helicopter cabin noise, which is so loud that occupants must wear headsets to communicate with one another, but could be used in a wide array of applications. These include ground and air vehicles, agricultural and construction equipment, cutting machines, and wind turbines.

The mechanism is self-contained, requires no external wiring, and does not disrupt the operation or position tolerance of the mechanical assembly. Besides significantly attenuating vibration-induced noise, the device also reduces overall wear and tear, and the electricity generated can power sensors on rotating machine parts.



Benefits

- Reduces noise by attenuating vibration at its source
- Converts vibration into electricity that can power system health monitors and sensors
- Reduces driveline wear and tear, and thus repairs
- Installs into the driveline as easily as a mechanical spacer

Applications

- Automotive
- Construction and agriculture
- Rotorcraft
- Wind turbines
- Generators
- Drilling and cutting machines

Polymer Electrolyte-Based Oxygen Microsensor

Allows fire, fuel-leak, and personal-protection monitoring in a variety of environments

A miniature sensor originally developed to monitor oxygen levels in spacesuits could also be used in any confined space where oxygen loss, fire, or fuel leaks are a risk. And because the technology detects oxygen levels from 7 to 21 percent in nitrogen, it could also be used for environmental and personal health monitoring.

Unlike ambient-temperature oxygen sensors that are optical-based—typically large, complicated, and expensive—this sensor is small, consumes little power, and operates in a wide humidity range. It is also simple to fabricate in large batches using state-of-the-art thin-film technologies.

Benefits

- Flexible: works even in dry environments
- Low cost
- Miniaturized
- Efficient: uses little power and has relatively high sensor yield

Applications

- Personal health monitoring
- Environmental monitoring
- Hyperbaric chambers
- Submarines
- Mines
- Aerospace
- Monitoring oxygen in spacesuits
- Any confined space where oxygen loss, fire, or fuel leaks are concerns

Goddard

Hacker Alert System

Independent monitoring system to identify suspicious behavior

Hackers and suspicious activity are a common challenge in complex computer systems. Goddard Space Flight Center has developed a process to detect unauthorized access by monitoring typical user behavior across multiple workstations, mobile devices, and facilities. After establishing this baseline, the system can effectively identify discrepancies that suggest unauthorized activity. And because the process combines various functional checks across devices and operating environments, it is more difficult for the unauthorized user to infiltrate the network without detection.

Benefits

- Rapid identification of unauthorized activity
- Minimal infrastructure and process changes

Applications

- Defense security

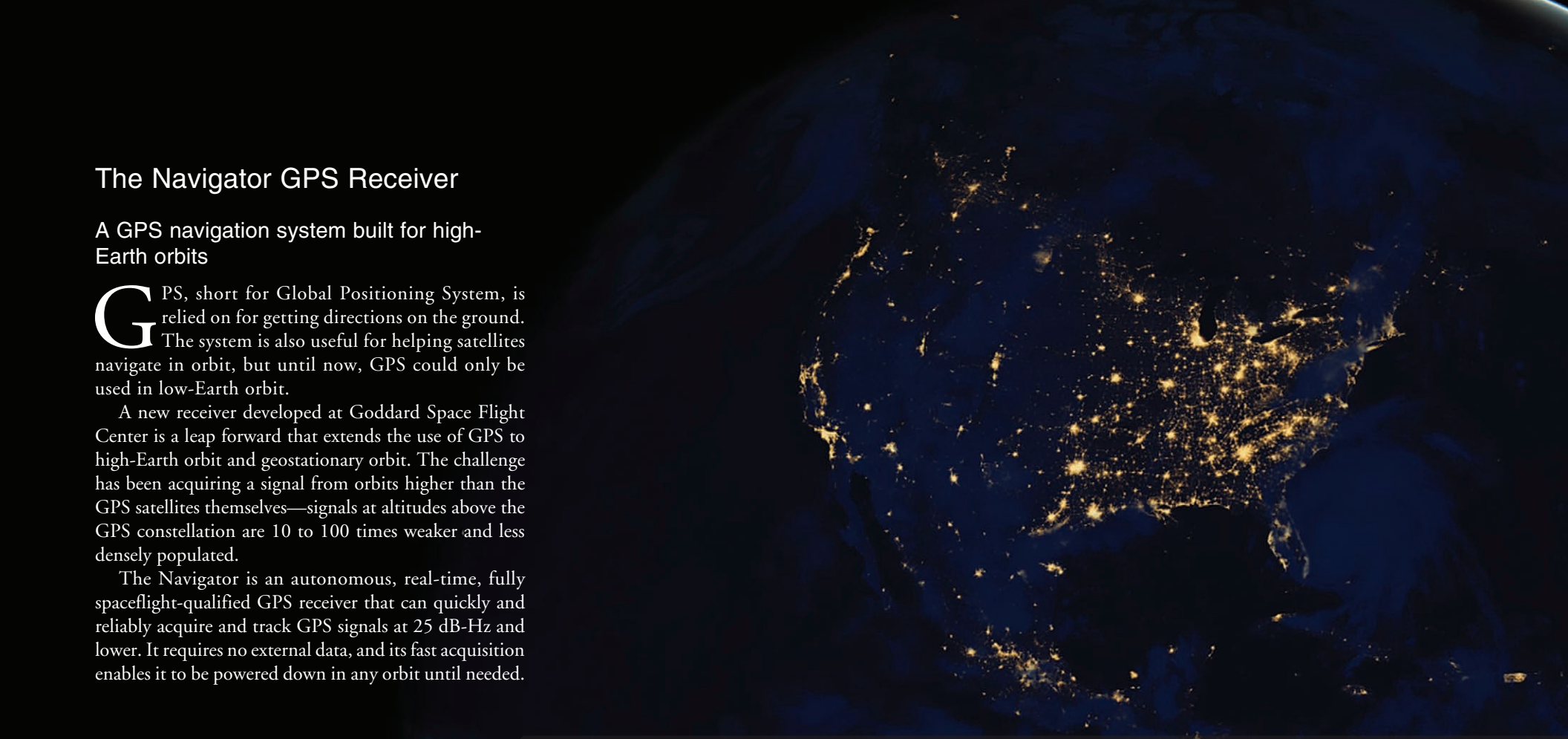
The Navigator GPS Receiver

A GPS navigation system built for high-Earth orbits

GPS, short for Global Positioning System, is relied on for getting directions on the ground. The system is also useful for helping satellites navigate in orbit, but until now, GPS could only be used in low-Earth orbit.

A new receiver developed at Goddard Space Flight Center is a leap forward that extends the use of GPS to high-Earth orbit and geostationary orbit. The challenge has been acquiring a signal from orbits higher than the GPS satellites themselves—signals at altitudes above the GPS constellation are 10 to 100 times weaker and less densely populated.

The Navigator is an autonomous, real-time, fully spaceflight-qualified GPS receiver that can quickly and reliably acquire and track GPS signals at 25 dB-Hz and lower. It requires no external data, and its fast acquisition enables it to be powered down in any orbit until needed.



Benefits

- Enables GPS in high-Earth orbit
- Acquires signals faster
- Operates autonomously
- Is robust and reliable
- Fast acquisition rate also improves use for low-Earth orbit

Applications

- High-altitude spacecraft
- Low-Earth-orbit spacecraft

JPL

Portable, Rapid, Quiet Drill

Handheld drilling device for quiet drilling operations

A handheld drilling device, suitable for a variety of operations and developed by the Jet Propulsion Laboratory, is portable, rapid, and quiet. Noise from drilling operations often becomes problematic because of the location or time of operations. Additionally, the use of hearing protection in high-noise areas may be difficult in some instances due to space restrictions or local hazards. This drill is capable of effectively and efficiently drilling hard surfaces quietly enough to permit drill operation without hearing protection.

The device includes a housing, a piezoelectric transducer, a rotating motor component, and a rigid cutting end-effector. As the motor component rotates the cutting end-effector, the piezoelectric transducer imparts axial movement to the end-effector. The end-effector includes a removable and replaceable drill bit. It can form a central borehole, and a compressor can be connected to this borehole to flush out dust, powder, or other bits during operation. The drill weighs less than five pounds and operates at a noise level of about 45 decibels.

Benefits

- Multicomponent drill bits allow for lower cost per unit with increased functionality of the drill bits
- Drills through concrete at a rate of two centimeters per minute or faster
- Operates at a noise level of about 45 decibels

Applications

- Planetary exploration
- Covert military operations
- Late-night maintenance operations

Regional Hydrological Extremes Assessment System

Drought assessment and prediction system provides early warnings

Drought is Africa's most devastating natural disaster, threatening the livelihoods and lives of millions of people. The Jet Propulsion Laboratory has developed a drought assessment and prediction system, called the Regional Hydrological Extremes Assessment System, coupling a proven hydrologic model with an existing agricultural productivity model. The system benefits from a suite of satellite-based products, including soil moisture, precipitation, and evapotranspiration measurements that help forecast drought onset and recovery probability, cumulative soil moisture deficit, vegetation greenness, and agricultural productivity and yield.

This kind of information can be used to identify the needs of the population so that mitigation measures can be taken.

Benefits

- Early warning for drought
- Assesses current moisture levels
- Uses proven hydrologic model
- Data from suite of satellite-based imagers

Applications

- International aid
- State and local water management
- Agricultural forecasting

Johnson

Microwave-Based Water Decontamination System

Chemical-free water purification method and device

Innovators at Johnson Space Center have developed a microwave-based system to eradicate bacteria from water. Originally developed to replace water purification methods on the International Space Station that rely on hazardous chemicals, the technology is now available for license.

Testing demonstrated that exposure to microwave energy at a specific frequency band can eradicate bacteria and biofilm from water in a circulating test bed within 30 seconds. This microwave decontamination system could be further developed into a portable, lightweight system for use in remote locations as well as commercial space applications. The technology is chemical-free and requires minimal to no consumables.

Benefits

- Small and lightweight
- Portable
- Chemical-free
- Uses minimal consumable products

Applications

- Potable water purification
- Heat exchangers and water cooling systems
- Remote locations
- Hospitals and research facilities
- Commercial spaceflight
- Decontamination systems

Spinoff 2020

Lithium-Ion Cell Calorimeter

Cell thermal runaway calorimeter

Lithium-ion batteries are an integral part of energy storage systems used in space, as well as in many modern terrestrial industries, but they can occasionally fall into thermal runaway condition, leading to explosive fires. Johnson Space Center researchers have developed a calorimeter that can measure the total heat generated when specific types of lithium-ion cells are driven into thermal runaway. By understanding thermal runaway, designers can improve cell cases to contain or reduce damage and danger.

The calorimeter has at least two chambers, one for the battery cell under testing and at least one other for receiving the exploded battery debris. Both are structurally strong and thermally insulated. Thermal sensors are strategically placed throughout the chambers to collect data during the test, and customized software analyzes that data and determines key calorimeter parameters with a high degree of accuracy.

Benefits

- Reusable: designed for multiple tests within minutes
- Scalable: adjusts to different-sized cells
- Inexpensive: uses materials that are readily available
- Portable: fits in a carrying case for testing and transporting
-

Applications

- Consumer electronics
- Energy storage
- Battery safety
- Electric vehicles
- Electric bikes
- Cordless tools
- Lawn equipment

Kennedy

Powder Particles for Corrosion Prevention in Rebar

Coating protects rebar embedded in concrete from corrosion

Corrosion of reinforced steel in concrete structures is a significant problem for Kennedy Space Center, due to salt spray from the nearby ocean. To minimize this damage, Kennedy scientists developed coatings that can be applied as liquids to concrete with metal embedded in it.

This technology combines metallic materials into uniform particles that can be sprayed together with a liquid binder onto a concrete surface, providing optimum cathodic protection of the underlying steel. After the coating is applied, an electrical current is established between the metallic powder particles and the surfaces of the embedded steel rebar, preventing corrosion.

Benefits

- Coating is applied to the outer surface of reinforced concrete, not to the rebar
- Corrosion prevention is achieved after construction is complete
- Quick and repeatable application by brush or spray
- Reduces maintenance costs over the lifetime of the structure

Applications

- Parking decks, ramps, and garages
- Highway and bridge infrastructure
- Concrete piers, offshore platforms, piles, pillars, pipes, and utility poles
- Cooling towers
- Pipelines
- Buildings and foundations
- Engineered structures (commercial and civil)

Conductive Carbon Nanotube Ink for Inkjet Printing

Technology combines carbon nanotube inks with other additives for use in standard inkjet printing

An inkjet printer can apply conductive materials to various substrates, including textiles, polymer films, and paper. These adherent conductive materials can be used in damage detection, dust particle removal, smart coating systems, and flexible electronic circuitry. Although the use of inkjet printing technology to print conductive inks has been in testing for several years, the technology has not consistently produced resistances in the kilohm range.

Kennedy's invention combines carbon nanotube inks with other additives, such as metallic nanoparticles, to achieve resistances in the kilohm range. In demonstrations of standard inkjet printing, these composite inks have created coatings that are two to three times as conductive as inks containing carbon nanotubes alone. These inks are water-based and can be readily applied to a number of surfaces, including paper and textiles.

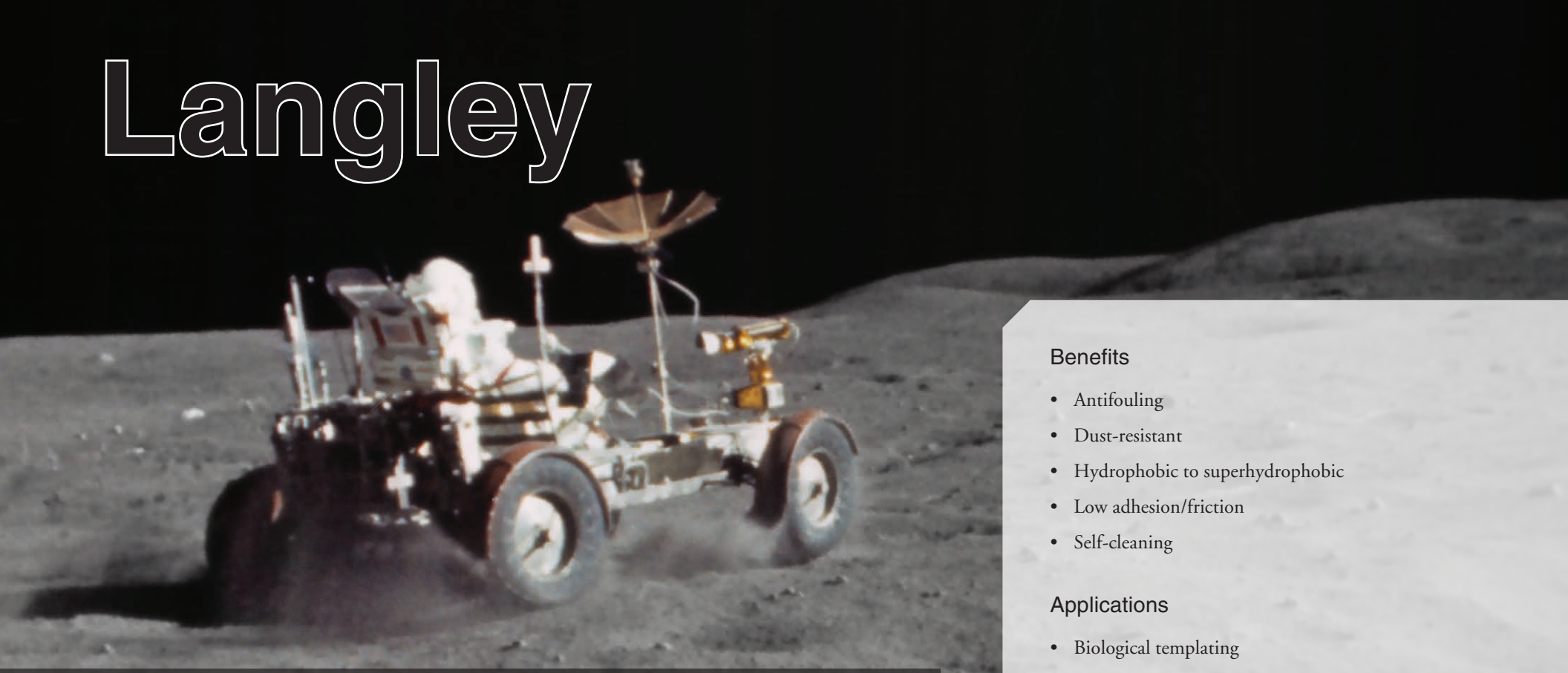
Benefits

- Ease of implementation: uses commercially available ingredients and off-the-shelf printing devices and ink cartridges
- Costs of ingredients and equipment compare to current conductive-ink systems
- More than twice as conductive as commercially available carbon nanotube inks
- Can be applied to various surfaces, including polymeric, glass, ceramic, paper, and textiles

Applications

- Wire damage detection
- Multidimensional damage detection for flat surfaces
- Radio frequency ID devices
- Smart labels
- Smart coatings
- Intelligent packaging
- Integrated circuit logic/memory
- Batteries
- Organic light-emitting diodes
- Dust particle removal

Langley



Particle Contamination Mitigation Methods

Unique surface properties such as increased hydrophobicity and self-cleaning

Langley researchers developed methods to avoid particle contamination to spacesuits and vehicles while exploring surfaces such as the Moon, Mars, and asteroids. One method for generating superhydrophobic surfaces is the synthesis of novel copolyimide oxetanes with unique surface properties. A small amount of an oxetane reactant containing fluorine is added to a polyimide coating, and the oxetane migrates to the surface, bringing fluorine with it. The copolymers mitigate particle adhesion and fouling from exposure to particulate and biological contaminants, and they exhibit reduced surface energy.

The other method modifies surface energy via laser ablative surface patterning. A laser is used to create nanoscale patterns in the surface of a material to increase the hydrophobicity. This is an advantageous method because it is fast and single-step, promises to be scalable, requires no chemicals, and could be applied to a variety of materials.

Benefits

- Antifouling
- Dust-resistant
- Hydrophobic to superhydrophobic
- Low adhesion/friction
- Self-cleaning

Applications

- Biological templating
- Biomedical devices
- Corrosion and stain resistance
- Drag reduction
- Reduced ice and water adhesion
- Reduced insect adhesion on aircraft and automobiles
- Marine antifouling coatings
- Microfluidics
- Particle and biological contaminant mitigation
- Self-cleaning of many kinds of surfaces
- Sensors
- Surface-specific chemical sensing

Carbon Nanotube-Based Sensors

Expertise in manipulating carbon nanotube-based sensors for structural health monitoring

To monitor the structural health of air and space vehicles, NASA required new strategies for the development of extremely small, lightweight sensors that are embeddable and scalable. Langley researchers are expert at producing carbon nanotube (CNT)-based sensors that can be embedded in structures of all geometries to monitor conditions both inside and at the surface to continuously sense changes.

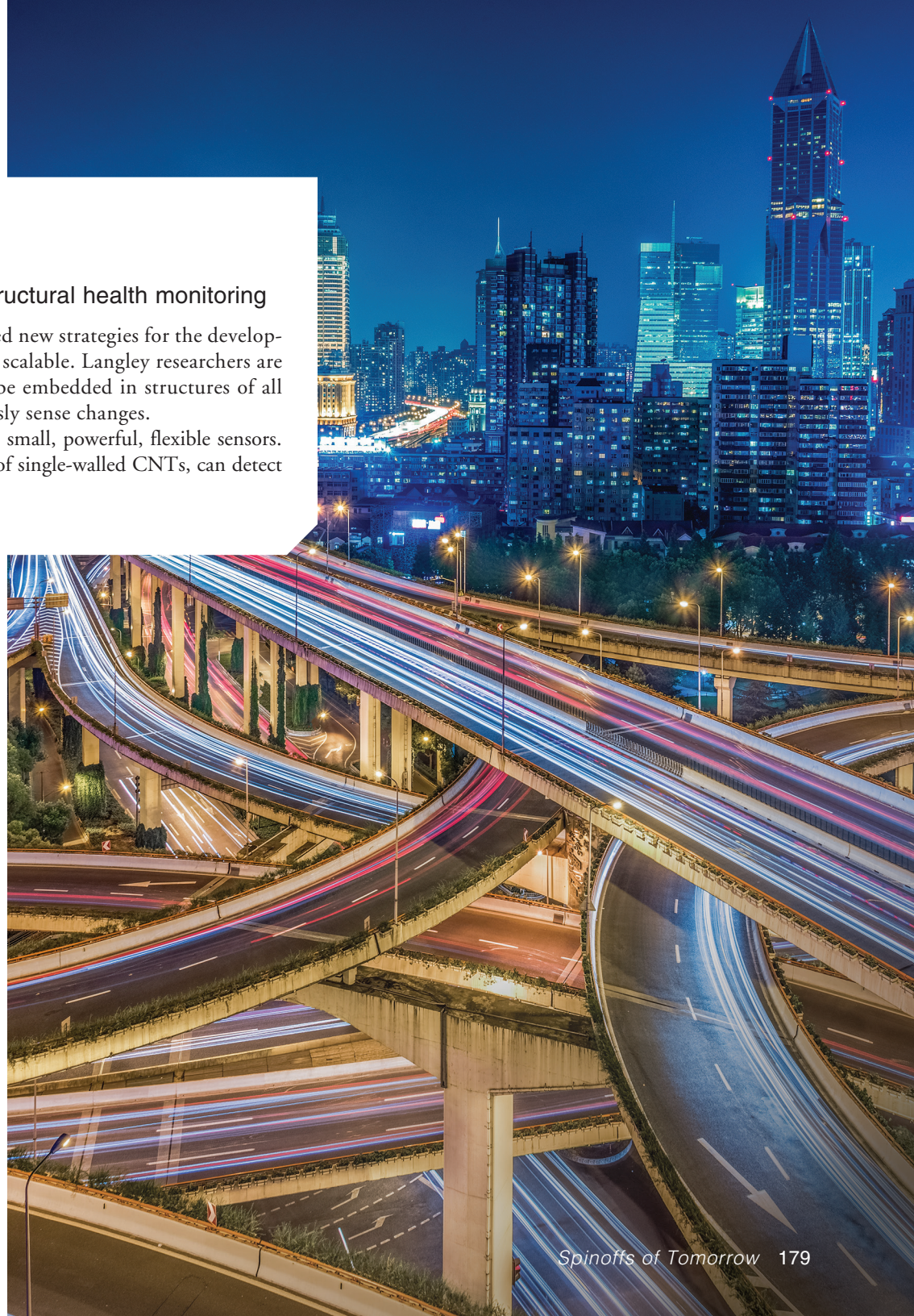
NASA is adept at manipulating the CNTs into specific orientations to create small, powerful, flexible sensors. One highly flexible sensor NASA created, a very dense and highly ordered array of single-walled CNTs, can detect crack growth and map strain fields.

Benefits

- Can be mass produced
- Inexpensive
- Can be packaged in small sizes
- Require less power than electronic or piezoelectric transducers
- Produce less waste heat than electronic or piezoelectric transducers

Applications

- Civil structures: CNT sensors embedded in bridges, roads, tunnels, and other structures to monitor strain, wear, and tear
- Turbines: monitoring crack growth
- Aerospace structures: smart skin to monitor strain, pressure, and temperature conditions; monitor fatigue and exposure both inside and at the surface of the aircraft skin



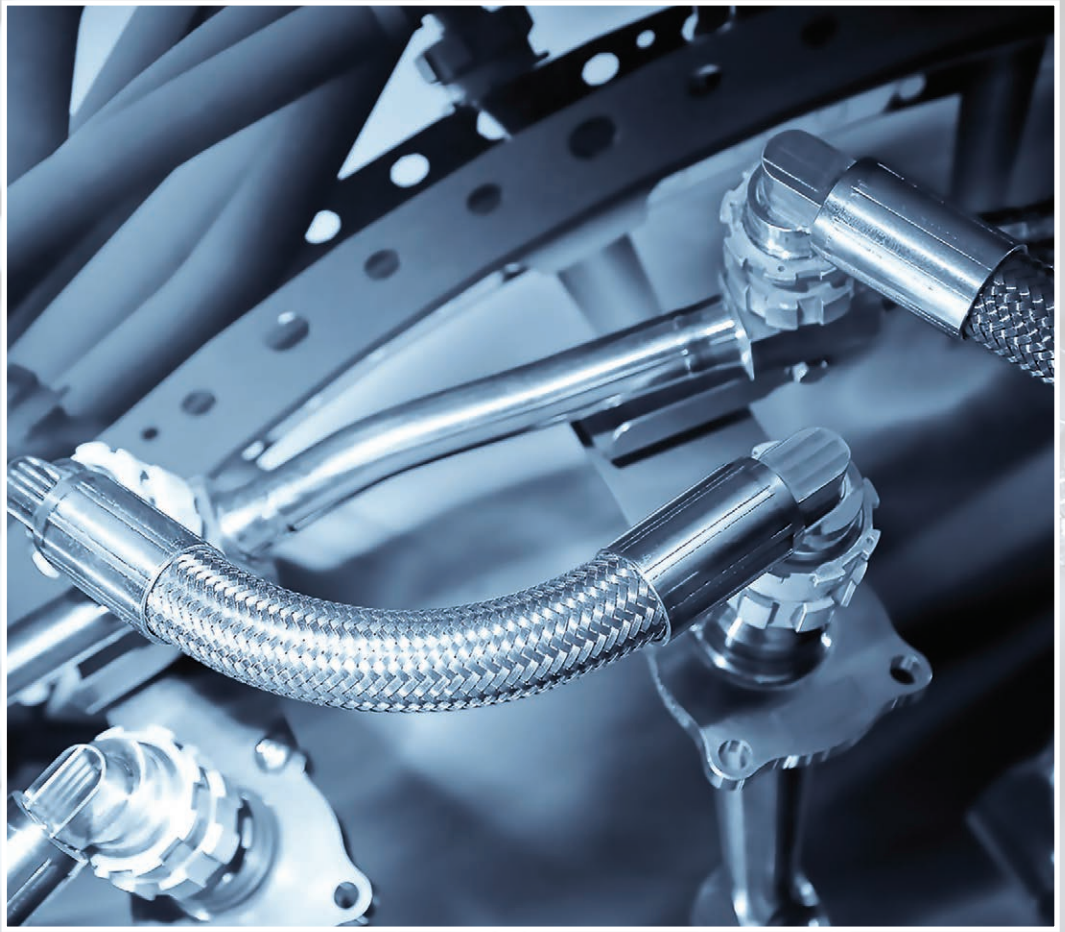
Marshall

Low-Cost, Long-Lasting Valve Seat

A simple new valve seat installation technique for leak prevention

Marshall Space Flight Center has developed a new, simplified method for installing valve seats, eliminating the need for a swaged assembly process and the additional hardware and equipment typically found in conventional, elastomeric valve seat installations. In addition to lowering the overall weight, the reduced number of hardware components decreases potential failure modes. This simplified technique saves time and installation costs and results in comparable leakage protection.

NASA has tested the long-term performance of a solenoid-actuated valve with a seat that was fitted using the new installation technique on an inductive pulsed plasma thruster. This solenoid-actuated valve test successfully reached a million cycles with desirable leakage performance, outperforming traditional solenoid valve requirements. The method is most applicable to instruments that have an orifice of half an inch or less.



Applications

- Solenoid valves
- Check valves
- Manual valves
- Disconnects
- Regulators
- Relief valves

Benefits

- Easy installation: simplifies the seat installation process
- Low manufacturing costs: eliminates traditional installation equipment and steps, such as the swaged manufacturing process, saving time and money
- Improved performance: reduces failure mode potential due to fewer material components while maintaining comparable or lower leakage rates
- Scalable: can be scaled up to install multiple seat seals simultaneously
- Lower mass: reduces payload weight

Modular Fixtures for Assembly and Welding Applications

Rigid, adjustable tooling that reduces configuration time and cost

Researchers at Marshall Space Flight Center have developed new, modular fixtures for holding metal in place during the assembly and welding of cylindrical and conical sections of rocket bodies. Previous methods required time-consuming design, fabrication, and assembly of expensive, project-specific fixtures, which often took up to six months and cost millions of dollars. NASA's modular fixtures are adjustable and easily form different configurations for rocket sections with various dimensions. This improved setup allows for a more rapid shift from one project to the next, allowing welding to begin in a matter of weeks rather than months.

Supporting braces that form the base of the modular structure slide into radial grooves. Other extending, clamping, and joining fixtures can be variously connected to the base structure to provide circumferential support for producing conical and cylindrical structures. NASA has used the tooling to produce structures with diameters of up to 27 feet.

Benefits

- Modular fixtures can be reused and repurposed for multiple projects of various sizes
- Tooling design and configuration time is reduced by half
- Project costs are reduced by as much as an order of magnitude
- Modular fixtures can enable the economical adoption of friction stir welding
- Modular fixtures enable large-scale rapid prototype development in a wide range of industries

Applications

- Shipbuilding
- Airframe assembly
- Pressure vessel assembly
- Commercial space launch vehicle assembly
-

Stennis

NASA Platform for Autonomous Systems

Innovative software platform for "thinking autonomy"

Autonomous operations are critical for the success, safety, and crew survival of NASA deep-space missions beyond low-Earth orbit, including the proposed lunar Gateway station. For the last 10 years, Stennis Space Center has been developing, and has demonstrated, an innovative software platform, along with expertise and processes for implementation of autonomous operations. The NASA Platform for Autonomous Systems (NPAS) was developed using the G2 platform, a commercial off-the-shelf product. It provides the foundational technology and processes to evolve from traditional "brute-force autonomy" toward innovative "thinking autonomy," creating live models for real-time autonomous operations that can be rapidly and affordably implemented, deployed, reused, and evolved.

Currently, NPAS includes autonomy strategies, integrated system health management strategies, and libraries of system elements for electrical, mechanical, computer, and communications applications that can be used for a wide range of implementations.

Benefits

- Leverageable and reusable: elements and modeling code apply to a wide range of system applications
- Sustainable: modular; knowledge base that enables systematic changes; inherent integration that is maintained throughout the life cycle of applications
- Scalable within each autonomous application and across networked distributed autonomous applications
- Affordable: long-term cost savings
- Reduced delivery time
- Evolvable

Applications

- Ground test and launch systems
- Space systems
- Satellite systems
- Deep Space Network
- Aeronautics

Remote-Sensing Toolkit

Online portal offers easy access to NASA Earth-observation data

NASA's policy making remote sensing data freely and publicly available has long benefited the scientific community, other government agencies, and nonprofit organizations—but there is significant untapped potential for commercialization. NASA's Technology Transfer Program has created an online resource to promote commercial use of this data and the software tools needed to work with it.

Through its constellation of Earth-observation satellites, NASA collects petabytes of data each year. With the Remote-Sensing Toolkit, users will now be able to find, analyze, and use the most relevant data for their research, business projects, or conservation efforts. The toolkit provides a simple system that quickly identifies relevant sources based on user input. The toolkit will help users search for data, as well as ready-to-use tools and code to build new tools.

Benefits

- Easy-to-use data
- No cost
- Centralized online repository with unified file formats
- Includes data from more than 20 satellites and missions
- Available to U.S. and foreign nationals

Applications

- Precision agriculture
- Crop forecasting
- Conservation
- Resource management
- Natural disaster planning and response

NASA's Technology Transfer Program

For nearly as long as NASA has existed, its Technology Transfer Program has worked hard behind the scenes to ensure the revolutionary technology developed here sees the widest possible use on the ground. We publish new discoveries, patent and license valuable inventions, and collect and distribute software codes—all with the goal of ensuring the public gets the full benefits of the innovations we create.

NASA's Technology Transfer Program

Bringing NASA Technology down to Earth

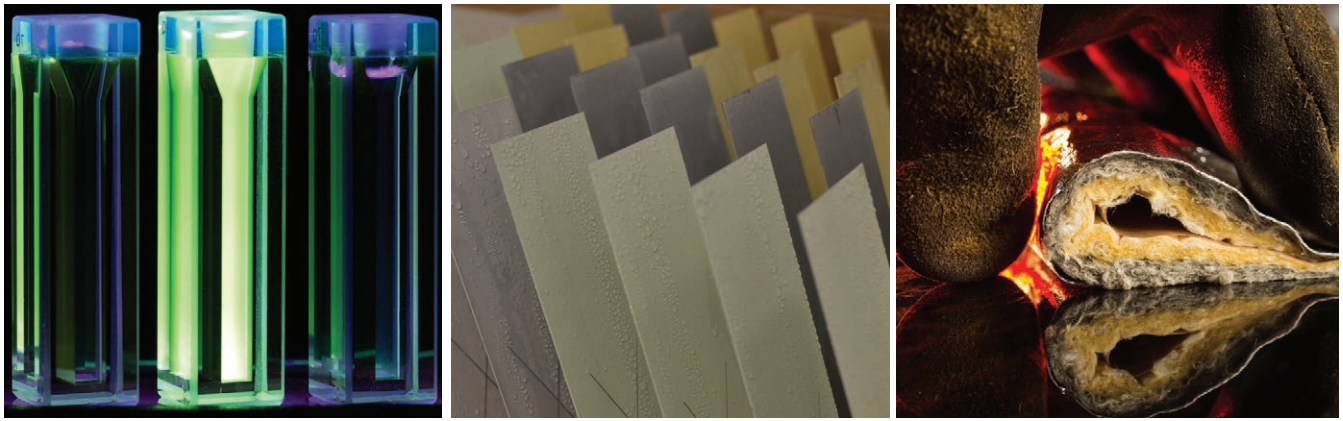
The pipeline of technology from NASA to the public—from Agency whiteboards and desktops to products on the shelf—often takes a complicated, twisting route. Guiding this journey is a relatively new software platform, created at NASA and now becoming available for any organization involved in technology development and transfer.

The word "technology" suggests a completed idea, but innovations are never born complete and whole. Technologies created by NASA employees and contractors are first reported in their infancy, and many inventions tracked and managed by NASA continue to evolve and mature for years. Not all of these inventions are ever commercially viable, and the Agency's policy is to only patent and offer for license those that are. Thus, each new invention must be assessed for its potential usefulness in other applications, with only the most promising technologies entering NASA's patent portfolio.

In addition, many of the products that develop from NASA patents come only after companies have partnered and worked extensively with NASA to research and further develop the technology, or after a period of time spent "test driving" it through an evaluation license. Meanwhile, the Agency also manages a robust software catalog, available to the public, filled with programs that change and improve as fast as anything else in the digital world.

By the time many NASA spinoffs hit the shelf as commercial products, they have spent years or even decades in various stages of incubation, tracked and accounted for by NASA the entire time.

Managing this whole process is NASA's Technology Transfer Program, which oversees the Agency's congressional mandate to spread the benefits of research in space and aeronautics as widely as possible. Each year, the program processes more than 1,500 new technology disclosures from NASA innovators, including commercial assessments for each one. It adds to and maintains the Agency's patent and software portfolios, each containing about a thousand technologies. And it handles the marketing, licensing, and granting of software usage agreements that put these innovations in the hands of the public.



Recent advances in technology at NASA include (from left) biomarker sensor arrays, a smart coating for corrosion detection and protection, and a multilayered fire protection system.

NASA continues to track its technologies even after handing them off to businesses: the *Spinoff* publication you are now reading has been published annually since 1976 and in that time has featured more than 2,000 stories of successful technology transfer.

A Technology Transfer Platform

All of this program activity runs on an "engine" known as NTTS, or the NASA Technology Transfer System, an enterprise-class software platform built in-house at NASA. NTTS is used to manage the program's entire workflow and generate metrics that allow NASA to evaluate its effectiveness in the mission to transfer technology to the public.

The system comprises a database of every reported NASA technology—at present some 60,000 in total—and a number of web-based and database-driven applications to make use of the core system. These custom-built modules make NTTS accessible to different types of users and support operations at every phase in the technology transfer pipeline, from the disclosure of new technologies right through commercialization. Among these modules is also a suite of tools used to manage day-to-day program operations and track metrics for internal analysis. The primary tools of the system include:

- **Website Content Management**. NTTS powers much of the content for the Technology Transfer Program's main website (https://technology.nasa.gov), populating the publicly accessible and searchable patent and software portfolios. The platform also powers the whole family of Technology Transfer Program websites, which includes homepages for each of the 10 NASA field center technology transfer offices, NASA's Inventions and Contributions Board (which manages Agency awards for technology), and NASA's *Spinoff* publication, among others.
- **Electronic New Technology Report (e-NTR)**. e-NTR is a web application designed to make new technology reporting as easy as possible for NASA employees and contractors. Reporting new technologies is a legal obligation, and e-NTR helps NASA personnel meet these obligations by significantly

reducing the number of questions researchers must answer (compared to previous paper-based forms) and guiding them through the process using an intuitive interface.

- **Innovator Dashboard**. Based on feedback from researchers, the Technology Transfer Program realized innovators are eager to know what happens to their technologies after they have been reported—and that providing this information encourages them to report their inventions. The Innovator Dashboard allows NASA researchers to see at a glance all of the technologies they have reported and where they are now.
- **Business and Marketing Communications Tools**. NASA has been able to leverage NTTS capabilities to automate and enrich the creation of marketing collateral and other tools that help program personnel connect with its potential customers: businesses and entrepreneurs who can take NASA technology and turn it into a successful commercial product.
- **Automated Licensing System**. ATLAS (Automated Technology Licensing Application System) is an application built on top of NTTS meant to streamline and automate the complicated process of licensing technologies. It provides a clean, intuitive, and easy-to-navigate interface for interested individuals and businesses, and it eliminates much of the back-and-forth communication that was required under the previous, largely paper-based system used to apply for a license.
- **Metrics Reports**. By pulling data from NTTS, a wealth of information can be extracted for internal analysis on nearly every facet of the Technology Transfer Program's operations. Tracking this data over time provides a solid basis for identifying strengths and weaknesses, setting goals for improvements, and strategizing future operations.

A Spinoff from Technology Transfer

While NTTS was initially developed to meet NASA's particular needs, it is also a powerful general-purpose tool that can benefit any agency, laboratory, or university in managing and transferring the intellectual property that results from research and development. As the platform has evolved, other government agencies, universities, and even commercial operations have approached the Agency to see whether they can acquire the software for their use.

Technology Transfer Program executive Daniel Lockney presents to entrepreneurs at the Los Alamos National Laboratory in New Mexico.

Such a transfer would represent a historic moment: the first time Technology Transfer Program infrastructure itself has become a NASA spinoff. It's a possibility that excites program executive Daniel Lockney. "With NTTS, we didn't set out to create a tool that could be used by others," he says. "As with any NASA mission, we were simply assessing the challenges our program faced and developing solutions for those problems, tools that would increase our efficiency and productivity."

As the software platform took its shape, however, Lockney began speaking with other technology transfer programs in agencies, laboratories, and universities, sharing best practices and comparing the tools each organization was using for program operations. It gradually became apparent that there was a ubiquitous need among these institutions for a robust tool along the lines of NTTS: a single platform that could handle the full technology transfer process, from reporting new inventions to tracking commercialization success stories.

As of 2020, the Technology Transfer Program is in the midst of multiple pilot programs to provide NTTS to other agencies, as well as readying the software for a wider release.

"NASA spinoffs, which are successful instances of technology transfer, have always been at the forefront of the Agency's public image," remarks Lockney. "In sharing NTTS with other agencies, we hope they will use it—as we have—to ensure taxpayer investments in research and development return benefits to the public." ❖

Technology Transfer Program Network Directory

Bringing NASA Technology Down to Earth

NASA's Technology Transfer Program pursues the widest possible applications of Agency technology to benefit U.S. citizens. Through partnerships and licensing agreements with industry, the program ensures that NASA's investments in pioneering research find secondary uses that strengthen the economy, create jobs, and improve quality of life.

To learn more about licensing NASA technology, visit http://technology.nasa.gov. General inquiries may be directed to the Spinoff Program Office at spinoff@nasa.gov. To suggest a story about a commercial product or service developed with NASA technology, assistance, or know-how, contact *Spinoff* at the email address above, or visit http://spinoff.nasa.gov.

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AFRC — Armstrong Flight Research Center
GRC — Glenn Research Center
GSFC — Goddard Space Flight Center
JPL — Jet Propulsion Laboratory
JSC — Johnson Space Center
KSC — Kennedy Space Center
LaRC — Langley Research Center
MSFC — Marshall Space Flight Center
SSC — Stennis Space Center

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