National Aeronautics and Space Administration

spinoff

2019

SPINOFF

2019

Technology Transfer Program

NASA Headquarters
Daniel Lockney, *Technology Transfer Program Executive*

Spinoff Program Office
Goddard Space Flight Center

Daniel Coleman, *Editor-in-Chief*
Mike DiCicco, *Senior Science Writer*
Naomi Seck, *Senior Science Writer*
John Jones, *Senior Graphics Designer*

Rebecca Carroll, Contributing Writer

This 2018 NASA photograph captured the International Space Station in silhouette as it transited the Moon.

INSIDE TABLE OF CONTENTS

37

66

DEPARTMENTS

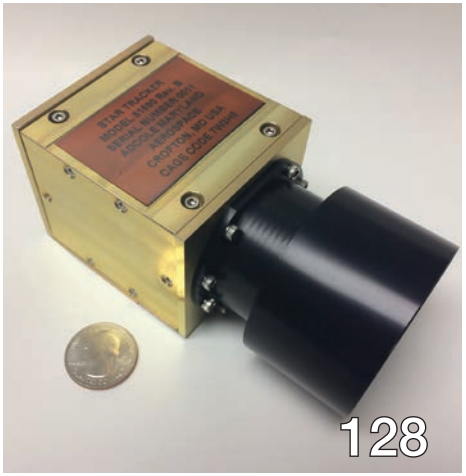
SPINOFFS

HEALTH AND MEDICINE

TRANSPORTATION

PUBLIC SAFETY

CONSUMER GOODS



ENERGY AND ENVIRONMENT

INFORMATION TECHNOLOGY

INDUSTRIAL PRODUCTIVITY

The worlds orbiting other stars are called exoplanets, and they come in a wide variety of sizes, from gas giants larger than Jupiter to rocky planets smaller than Earth or Mars. This rocky super-Earth is an illustration of the type of exoplanet NASA hopes to discover using TESS, or the Transiting Exoplanet Survey Satellite. TESS serves as the successor to the Kepler Space Telescope and will survey a large portion of the sky to catch exoplanets as they transit their host stars.

Foreword

NASA technology has been spinning off into private markets, other Government agencies, and academia across the country and around the world since the Space Agency was created in 1958. Many of these products and capabilities have since become part of our everyday lives, and this is no accident. Even while NASA hones the tools to explore the solar system and beyond, it never stops developing new ways to get these technologies into the hands of innovators here on Earth so that the public can benefit from its investment in aeronautics and space missions.

Some of NASA's most widespread spinoffs have come from its most memorable missions—such as the Apollo Program that first put astronauts on the Moon. These include cordless power tools, freeze-dried food, flame-resistant firefighter gear, the integrated circuit that gave rise to the microchip, and thin, lightweight insulations. Among the most surprising were perhaps improvements to kidney dialysis, a lightning detector, and automated credit card transactions.

Arguably more important than all the myriad inventions that spun off from Apollo, though, was the revolution in electronics and software that it helped to launch, ushering in an era of rapid miniaturization and quantum leaps in efficiency and capacity. Clunky technology like transistor tubes quickly vanished.

As we and our commercial partners now prepare to return to the Moon—this time to establish a long-term presence and carry out science and research—there's no telling what inventions and advances we'll make or how American industry will harness them. But if the past is any indicator, they'll span the various fields of science and technology, and they'll ultimately create jobs, boost the economy, improve efficiency, and even save lives.

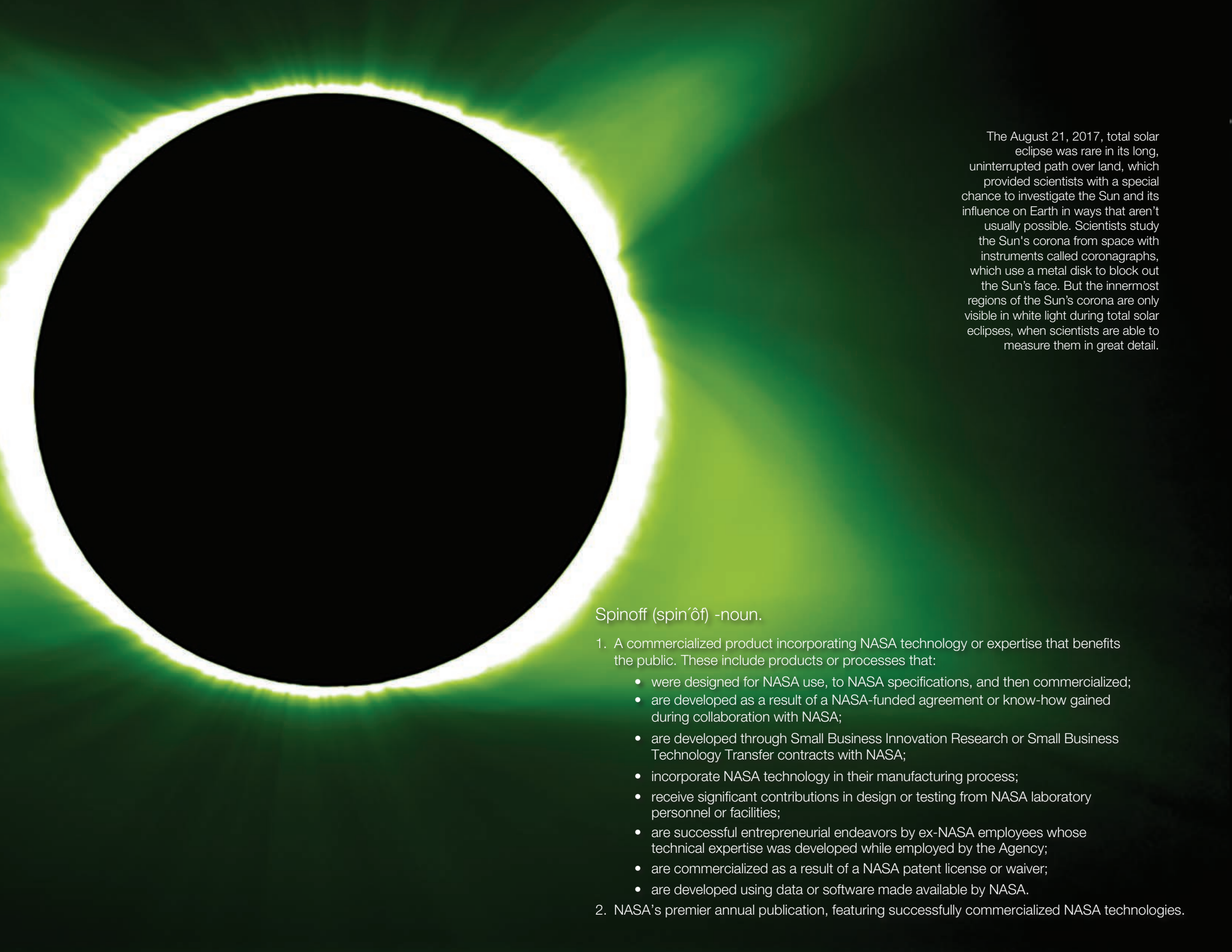
This is especially true at a time when the Space Agency has been putting new strategies into practice to accelerate the transfer of its technology to the private sector, with patent licenses and software usage agreements, for example, both significantly increasing in the last eight years. When it comes to putting new technology into the hands of businesses, NASA has cemented its status as a leader and model among Federal agencies.

Progress won't stop at the Moon, either. Much of our work there will prepare us for future missions to Mars and other destinations, with NASA and its partners in industry making breakthroughs and devising new solutions all along the way.

Several of the commercial technologies and products you'll learn about in *Spinoff* 2019 sprang from NASA's human exploration missions, from Project Mercury to the Orion crew capsule. The innovations from these missions to send humans into space never stop improving life here on Earth.

Jim Bridenstine
Administrator

National Aeronautics and Space Administration



The August 21, 2017, total solar eclipse was rare in its long, uninterrupted path over land, which provided scientists with a special chance to investigate the Sun and its influence on Earth in ways that aren't usually possible. Scientists study the Sun's corona from space with instruments called coronagraphs, which use a metal disk to block out the Sun's face. But the innermost regions of the Sun's corona are only visible in white light during total solar eclipses, when scientists are able to measure them in great detail.

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 or Small Business Technology Transfer 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

The images of Jupiter are arresting. The updates from Mars riveting. We are daily learning new details about our changing climate, watching hurricanes form, and getting ready to peer deeper into our universe than ever before. All this groundbreaking work requires NASA's scientists and engineers to continually innovate and create advances in technology, techniques, and capabilities.

But all that innovation doesn't stop here at NASA. Thanks to the efforts of the Agency's Technology Transfer Program and the many companies, small and large, that partner with us, the same technology created to understand our planet and explore the universe is applied to challenges right here on Earth.

For more than four decades, NASA's *Spinoff* publication has documented more than 2,000 of these "spinoff" stories, from the NASA missions they originated with to their successful launches as commercial products and the benefits they've brought the public. In the following pages, you can read our 49 latest. Some of my favorites include:

- Real-time precision GPS: Raw GPS data can be off by 30 feet or more, and the Jet Propulsion Laboratory (JPL) developed Real-Time GIPSY code to correct for these errors. Shortly after the U.S. Air Force's GPS satellites went live in 1994, JPL received funding from NASA to figure out how to use GPS data from a network of ground stations to make real-time corrections to signals from space craft. Further collaborations with industry and government improved the technology. Now emergency responders can trace a 911 caller's precise location—and get updates if the caller keeps moving—thanks to the JPL algorithms. (Page 58)
- Bowflex Revolution: With no gravity weighing on them, astronauts have to work to maintain muscle mass and bone density in space. Unfortunately, traditional weight-lifting techniques and machines don't work in microgravity. Inventor Paul Francis, with funding from Johnson Space Center, designed a "weightless weight trainer" that uses elastic resistance instead. It launched to the space station in 2000, and a commercial version of the technology launched in 2005 as the Bowflex Revolution, which quickly became a phenomenon in the home gym market. (Page 84)
- Internet ad auctions: What most Internet users may not know is that, every time they see an online ad, they are seeing the result of a near-instant auction that began when the web-page started loading. Millions of these auctions occur every second. One leading company in the ad-bidding market got its start planning NASA missions to the Moon and Mars—developing software that could instantly evaluate thousands of possibilities and choose the best one. (Page 128)

As you can see, some of these spinoff products are household names, and some you may not have heard of—but together they change our lives every day.

In addition to these success stories, this issue of *Spinoff* also features 20 NASA technologies identified by the Technology Transfer Program as promising future spinoffs, available to you or your business through licensing and partnership opportunities. (Page 156)

Ensuring every innovation made at NASA benefits the maximum number of people is an important part of NASA's mission, written into the original congressional mandate that created the Agency. *Spinoff* 2019 demonstrates the continued success of that mission, as well as highlighting the many varied ways technology gets transferred into the private sector and across other Federal agencies.

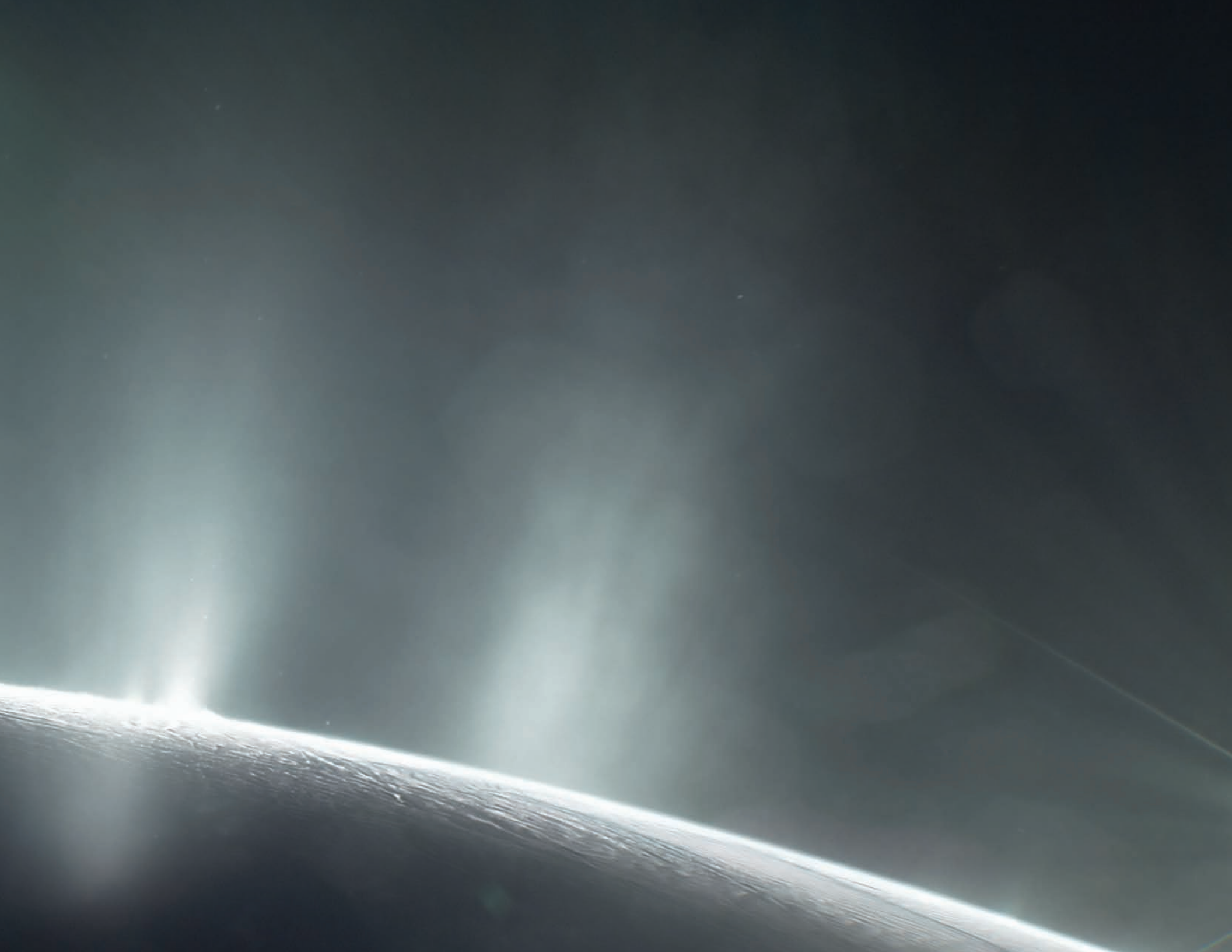
Over the decades, NASA spinoffs have saved tens of thousands of lives, generated tens of thousands of new jobs, created billions of dollars in revenue, and saved billions more in costs. We hope you enjoy reading this year's edition and learn more about the vast benefits America's investment in aeronautics and space brings to everyday life.

James L. Reuter
Acting Associate Administrator

Space Technology
Mission Directorate

Executive Summary

Every year, *Spinoff* highlights dozens of technologies with roots in NASA missions that now improve everything from surgical tools to aircraft to the clothes we wear. 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

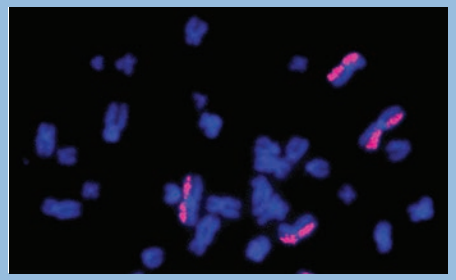
Health and Medicine

(24) Unique Polymer Finds Widespread Use in Heart Devices

A material that a Langley Research Center scientist stumbled on in the early 1990s has helped to keep hundreds of thousands of patients' hearts beating properly all over the world. Since 2009, medical technology giant Medtronic, based in Minneapolis, has been using the substance now known as LaRC-SI to get a relatively new type of pacemaker implanted into more patients more easily. As a result, many patients who might otherwise have continued to suffer symptoms of congestive heart failure were able to be treated.

(27) Material for Mars Makes Life-Saving Sutures

NASA aims to bring samples back from Mars, but challenges abound: for example, simulated Martian dirt interfered with a clean seal. Techno Planet Inc., building a canister with SBIR funding from the Jet Propulsion Laboratory, turned to Orangeburg, South Carolina-based Zeus Inc. to make a barrier to wipe dirt off the canister edge, which resulted in a new process to get the required properties. Since then, the company has found numerous uses for the extruded material, including as soft, flexible, strong sutures.



(30) Fluorescent Paints Spot DNA Damage from Radiation, Gene Editing

A cutting-edge technique for detecting chromosome damage developed for space medicine has major implications on the ground. In space, astronauts are exposed to radiation that causes damage to DNA. But some mutations are easier to see than others. KromaTiD Inc., based in Fort Collins, Colorado, developed a technique with SBIR funding from Johnson Space Center that uses chromatid paints to highlight previously undetectable abnormalities. Applications include helping doctors select cancer treatments based on identifying mutations, diagnosing genetic conditions, and, potentially, spotting unintended damage from gene editing.

(32) Image-Analysis Software Sees Cancer in 3D

NASA studies the physical effects of space travel, and that research benefits ground-based medical research as well. For a 2011 study on vascular changes in microgravity funded by Ames Research Center, lead researcher Ron Midura called on Image IQ, now owned by Philadelphia-based ERT, which developed software that helped count and identify the edges of stained blood vessels. The software has since been used for many clinical studies, and it may one day help doctors better diagnose—and remove—tumors.

(34) Miniature Positioner Focuses Lenses with Precision

An instrument designed to study dark matter and dark energy for the ground-based Subaru Telescope in Japan required thousands of miniature positioners powered with tiny piezoelectric motors. Engineers from the California Institute of Technology and the Jet Propulsion Laboratory worked with Victor, New York-based New Scale Technologies to perfect the rotary motors, and these low-voltage modules are now being used in a variety of contexts, including medical instruments.

(37) Biometric Sensor Tracks Vital Signs for Health

Technology developed to help monitor astronauts in orbit has pushed forward wearable technology here on Earth too, leading to devices that could provide clues to heart disease and more. Funded by SBIR contracts from Johnson Space Center, researcher Lino Velo developed a tiny sensor that tracks heart rate variability, a measure of the spaces between beats that can indicate stress level. Now Newark, California-based Salutron sells the sensor to wearable-makers and directly to consumers.

Transportation

(40) Battery Innovations Power All-Electric Aircraft

One major challenge to developing all-electric aircraft—safely delivering enough power to the motors—got a boost from industry, California-based Electric Power Systems. The company used funding from Armstrong Flight Research Center to develop a new technique to safely package thousands of off-the-shelf lithium-ion cells into one lightweight, powerful battery. The company is now supplying similar batteries to power an all-electric training airplane and has contracts with companies interested in designing electric vehicles for travel between small airports and within urban areas.

(43) Shuttle Tire Sensors Warn Drivers of Flat Tires

A flat tire can take drivers by surprise. This was something the Space Shuttle engineers at Kennedy Space Center worried about, too. In the 1990s, NASA commissioned a miniature pressure sensor on a silicon chip, powered by a small battery, that alerted pilots if the pressure was low. St. Marys, Pennsylvania-based Amphenol Advanced Sensors adapted the sensor for car tires and sold many millions, most of which ended up on U.S. passenger vehicles.

(46) Space-Age Insulator Evolves to Replace Plastic and Save Weight

When aerogels, the world's lightest solids, were first invented, they were incredibly brittle and nobody had much use for them. Nearly a century later, the material could become as ubiquitous as plastic, says the founder of Boston-based Aerogel Technologies. NASA has discovered ways to make different aerogels stronger, flexible, and able to withstand high heat, among a range of other properties. Now, after in-house R&D and licensing patents from Glenn Research Center, Aerogel Technologies is selling the material to a variety of industries, including airplane and car manufacturers.

(49) Software Helps Design Artery Stents, Lawn Mowers, Airplanes

Lockheed Martin developed the Structural Analysis of General Shells (STAGS) code under contract to Langley Research Center in the 1980s. It was a finite element analysis (FEA) program, meaning it broke down models of structures into tiny elements to model a structure's behavior as a whole. In 2005, French company Dassault Systèmes acquired Abaqus Inc. of Johnston, Rhode Island, which had developed the Abaqus FEA program. The company regularly consulted with users, including Langley's STAGS developers, and many of STAGS' capabilities were added to the program.

(51) Super-Accurate Atomic Clocks Could Aid in Navigation, Communication

Measuring time accurately is crucial for advanced scientific research, but it could also be key for what comes next after GPS, as well as for synchronizing communications satellites. Sunnyvale, California-based AOSense Inc. is working on a portable, world-class atomic clock. Thanks to several SBIR contracts, mostly from Goddard Space Flight Center, the company has built components, including a laser-cooled atomic source, that are already selling to researchers, helping fund other advances needed to complete the clocks.

(54) Probes Characterize Air and Water Flows over Aircraft, Yachts

A new approach to characterizing high-speed turbulence in wind and fluid flows is on track to become the new standard for wind tunnel measurements. Devices for measuring fluid speed are known as anemometers, and Hampton, Virginia-based Tao Systems Inc. first pioneered the constant voltage anemometer under two SBIR contracts with Langley Research Center in 1992, releasing it as a commercial product not long after. Today, the device is finally catching on in the aircraft-design industry and even among yacht builders.

Public Safety

(58) NASA Brings Accuracy to World's Global Positioning Systems

GPS is an Air Force program, but NASA algorithms are largely to thank for the system being useful for secure, precision applications like airplane guidance, self-driving farm equipment, and directing first responders. Raw GPS data can be off by 30 feet or more, so the Jet Propulsion Laboratory developed software to correct for these errors, enabling real-time precision GPS. An early adopter, Long Island-based Comtech Telecommunications Corporation, remains a major provider of location-based services, including for cell phone companies, helping 911 operators pinpoint the location of a caller.

(63) Gas Regulators Keep Pilots Breathing

Since John Glenn's first orbit in 1962, all U.S. astronauts have used a derivation of his oxygen regulator. For the original project, Cobham Mission Systems (then operating as Carleton Controls) needed to make a gas regulator smaller and lighter than ever before. Now the Orchard Park, New York-based business uses the innovative spring design it created for Johnson Space Center and its oxygen safety expertise in oxygen systems for pilots, as well as for applications like wastewater treatment and offshore drilling.

(66) RoboMantis Offers to Take Over Dangerous Missions

A rugged robot built at the Jet Propulsion Laboratory (JPL) has been adapted by Pasadena, California-based Motiv Space Systems into the five- or six-limbed RoboMantis, which could take over dangerous jobs in disaster zones or hazardous areas. JPL's version built on decades of robotics experience for Mars rovers and more to give the modular robot accurate vision and enable semi-autonomous navigation. Motiv has upgraded the software and tweaked the design and says the robot can carry out hazardous jobs like cleaning chemical containers or bomb disposal.

(70) Wrapped Tanks Cut Weight on Everything from Buses to Paintball Guns

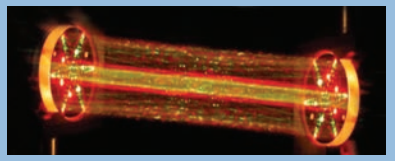
What do infant incubators, a Mars lander, and paintball guns have in common? All employ an invention developed at Glenn Research Center to cut weight from the Space Shuttles. Composite overwrapped pressure vessels, made of a liner tightly wrapped in high-strength filament, weigh half as much as all-metal pressure tanks by safely storing gases and liquids at higher pressures than was previously possible. Today, Worthington Industries, with production facilities in Pomona, California, sells them for, among many applications, fuel tanks for buses and breathing systems for firefighters.

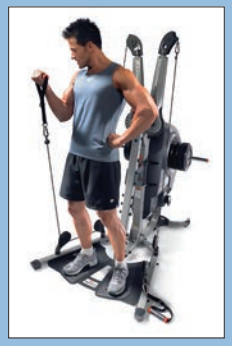
(73) Membranes Mimic Kidneys to Filter Water

Aquaporin A/S, based in Copenhagen, Denmark, approached Ames Research Center in 2007 with a proposal to create filters by infusing membranes with aquaporins, the proteins that let water in and out of living cells. With Ames funding and testing and eight years of development, the company released under-sink reverse-osmosis filters that clean water twice as fast as existing technology, with twice the recovery rate. Aquaporin sees a bigger future market for filtering industrial wastewater using highly efficient forward osmosis.

(76) Detailed Spectrometry Makes Dangerous-Materials Testing Safer

Mars rovers carry an instrument that can zap a sample with a laser and read its composition in the resulting flash. But this process can only identify molecules, not their isotopes, which would reveal more about a sample's age, formation, and radioactivity. An Ames Research Center scientist set out to build a laser spectrometer that uses the same technique to identify these subtle differences. After joining Fremont, California-based Applied Spectra, and with the help of Ames SBIR contracts, he accomplished what no one thought was possible.





(78) Methane Detector Sniffs Out Leaks

Methane is the main ingredient in the natural gas that powers heating, cooking, and electricity—and a potent greenhouse gas. Methane can also be a sign of bacterial life, which is why NASA installed a methane detector on the Curiosity rover, designing a brand-new tunable laser spectrometer for the task. A different team at the Jet Propulsion Laboratory made it even smaller and faster for methane sniffing on Earth, and Pasadena, California-based SeekOps licensed the technology to detect gas leaks at oil and natural gas wells and more.

(80) Biofeedback Loops Aim to Enhance Combat, Sports Training

Steadying a computer cursor with your brain might sound far-fetched, but NASA has had the technology for years. In the late 1990s, researchers at Langley Research Center observed different brainwave outputs to measure attention levels. The team found showing subjects their engagement level, as determined by brainwaves, enabled them to control it and stay more focused. They invented games cued to brainwaves, and now J&F Alliance Group of Hampton, Virginia has licensed the technology and is refining it for consumers and the military.

Consumer Goods

(84) Bowflex System Spurs Revolution in Home Fitness

The Bowflex Revolution home gym was a phenomenon of the 2000s and to this day sells well—but it might not exist without NASA. Inventor Paul Francis took his idea for a weightless weight-trainer, using elastic resistance, to Johnson Space Center, which was looking for ways to help astronauts retain muscle mass and bone density in microgravity. The end product launched to the space station in 2000, and Francis began approaching fitness companies. Nautilus Group, now based in Vancouver, Washington, licensed the technology and released the Bowflex Revolution in 2005.

(87) Spacesuit Air Filters Eliminate Household Pet Odors

NASA-backed research on spacesuit technology could improve air quality in the homes of pet owners, keep cars smelling fresh, and keep the air pure in microchip manufacturing facilities. Serionix Inc., based in Champaign, Illinois, developed an air-filtering technology involving polymers that carry a permanent electrical charge. Three SBIR contracts from Johnson Space Center funded the company's development of systems to filter out ammonia and formaldehyde in spacesuits and purify air in spacecraft, improving the Colorfil technology it now applies to air purifiers and filters for cars and HVAC systems.

(89) NASA Research Sends Video Game Players on a Journey to Mars

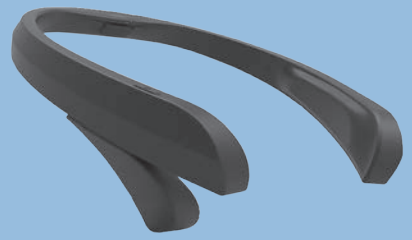
What would it be like to build a shelter on Mars? To plant a garden or explore its lava tubes? Now anyone can experience it like never before, in an immersive virtual reality "experience" developed by Miami-based Fusion Media Group Labs. Mars 2030, available for download and free for educators, is the result of years of consultations with researchers at Langley Research Center and across NASA. Its Editor tool is also free to the public, so others can build new simulations.

(92) Memory Foam Supports and Shapes in Women's Apparel

The famous, and famously cushy, memory foam was invented for a 1960s Ames Research Center project to improve airline seating safety. A new foam cushion, made out of "temper foam," did a remarkable job of absorbing impact. Today, the material, more commonly known as memory foam, is used in many commercial products, including San Franscisco-based start-up ThirdLove's high-end bras, which take advantage of the foam's ability to soften with body heat and conform to the body for a comfortable, supportive fit.

(94) Rocket Design Leads to Turbo-Charged Air Purifier

The founders of Wynd didn't particularly have space exploration on the brain when they built their personal air purifiers. But experience calibrating sensors for launch pads at Kennedy Space Center and designing turbines for rockets at Marshall Space Flight Center proved crucial when designing the smart, portable device. Now the Redwood City, California-based company sells a device that is extremely powerful and efficient, but lightweight and small, and which comes with an instant air quality sensor.



(96) Brainwaves Reveal Student Engagement, Operate Household Objects

In the mid-1990s, a team at Langley Research Center studying pilots' mental states created an "engagement index" to gauge subjects' attention levels based on their brainwaves. The team then demonstrated that subjects who were shown their engagement score could learn to control it. Decades later, the founders of BrainCo in Cambridge, Massachusetts, came across the work and incorporated it into a system for monitoring students' engagement and teaching kids with ADHD to control their attention by controlling video games or even objects around them.

(100) NASA Plant Research Offers a Breath of Fresh Air

In the 1980s, Stennis Space Center researcher W.C. Wolverton studied how to maximize the air-scrubbing potential of houseplants. He found that, perhaps counter-intuitively, plant roots and associated microorganisms in the soil did the bulk of the work, not plant leaves. AIRY GreenTech, a Hamburg, Germany-based company has designed plant pots based on this research, maximizing airflow through the soil and roots to increase air filtering and improve plant health. The products are available in some 50 countries around the world.

(102) Light Research Aids Slumber

When astronauts only spent a few hours or days in orbit, sleep was not the biggest concern. As stays stretched longer, however, Johnson Space Center and partner nonprofit National Space Biomedical Research Institute began studying rest and alertness in microgravity. The work showed different light wavelengths help govern sleep and wake cycles. Using these results, Headwaters Research and Development Inc., with U.S. headquarters in Marblehead, Massachusetts, has developed the Illumy sleep mask with light cues to help wearers fall asleep faster and improve alertness on waking.

Energy and Environment

(106) Electrified Bacteria Clean Wastewater, Generate Power

A group of graduate students used a NASA grant to study ideas for "bioelectric space exploration," including a fuel cell powered by wastewater and based on bacteria that "breathe" electricity. They later won NASA SBIR funding, including a Johnson Space Center contract for a cell that could turn waste into energy, hydrogen, or methane. Their company, Boston-based Cambrian Innovation, now offers the EcoVolt reactor, which uses exoelectrogenic microbes to clean wastewater while generating methane for energy at 10 breweries and wineries and counting.

(109) Building-Monitoring System Provides Insights for Sustainability

When Ames Research Center built Sustainability Base, the "greenest" building in the Federal Government, it counted on producing more energy than it consumed. To monitor energy consumption and production, it turned to Ramon, California-based Integrated Building Solutions Inc., which, with help from Ames, also added fault detection to its existing energy dashboard. Today, that's a standard component of its Intelligent Building Information System, which has been installed at corporate campuses across Silicon Valley and beyond.

(111) Space Station Garden Shines Light on Earth-Based Horticulture

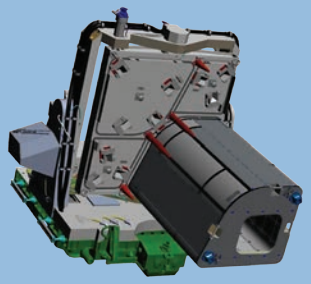
The new Advanced Plant Habitat on the space station has features its predecessors don't, including the ability to automate "light recipes"—variations in the color, intensity, and time intervals of lighting, which affect how plants grow. The German company OSRAM, whose U.S. headquarters is in Wilmington, Massachusetts, was developing a similar technology when its engineers were introduced to Kennedy Space Center scientists developing experiments for the Advanced Plant Habitat. Kennedy started using OSRAM's Phytofy platform, essentially beta testing, validating, and providing feedback on it ahead of its commercialization.

(113) Carbon Capture Process Makes Sustainable Oil

Palm oil, found in everything from soap to ice cream, is also a key driver of deforestation. Likewise, soybeans provide protein for fish and livestock but only at huge environmental cost. Now, San Francisco Bay Area-based Kiverdi offers a sustainable alternative: proteins and oils produced by bacteria—with a process based on early life-support studies for deep-space missions published by Ames Research Center. As the researchers discovered in the 1960s, the process is not only far more efficient than traditional agriculture but also captures, and transforms, excess carbon dioxide.

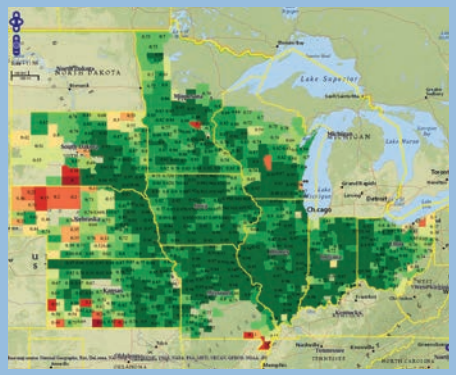
(115) Emissive Coatings Cut Industrial Costs, Emissions, Fuel Consumption

A high-heat coating first developed for a planned Reusable Launch Vehicle now helps industrial plants save money and cut way down on harmful emissions. The Protective Coating for Ceramic Materials, created at Ames Research Center in the 1990s, can withstand temperatures up to 3,000 °F. Blacksburg, Virginia-based Emisshield Inc. has licensed the patent and now sells a range of formulations in a variety of industries. The company has recently expanded its product line and made significant inroads into various industrial applications, reducing energy costs and emissions.



(118) Pointing Platform Enables Earth Imaging from Space Station

Although Earth-pointing satellites are increasingly common, the space station offers a more affordable option for orbiting science-grade imagers. ISS's National Laboratory, overseen at Johnson Space Center, partnered with Huntsville, Alabama-based Teledyne Brown Engineering to outfit the station with the Multi-User System for Earth Sensing, which can house multiple payloads and can point with extreme accuracy. The first customer, the German Aerospace Center, installed a hyperspectral imager that will help inform Germany on issues like climate protection and food security. The images are also available for purchase from Teledyne Brown.



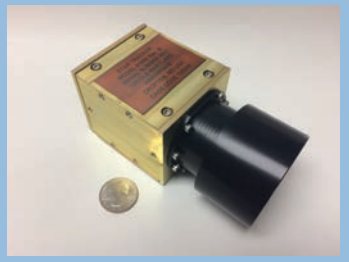
(122) Algorithms to Detect Clouds Forecast Global Crop Production

An algorithm originally created to detect clouds is now being used for everything from increasing food security in the developing world to guiding futures trading on Wall Street. Landsat satellites typically looked for clouds with a thermal imager, but when plans for Landsat 8 didn't include one, Stennis Space Center put out a call for software that could identify cloud cover. State College, Pennsylvania-based Geospatial Data Analysis Corporation won the SBIR contract and developed an algorithm that it later expanded with additional SBIR funding to detect other features, including crops.

Information Technology

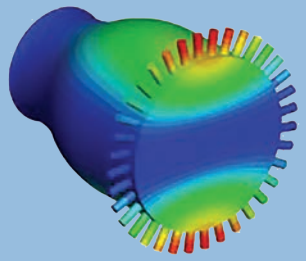
(126) Space Mission Planning System Targets Advertising with Precision

Most Internet users may not know that every online ad appears after a near-instant auction for that slot. A leading company driving that process got its start planning NASA missions to the Moon and Mars. A team from the Massachusetts Institute of Technology, one of several funded by NASA Headquarters, developed software to choose the best among some 1,162 possible mission architectures. In 2007, team members founded Boston-based dataxu to adapt the software for commercial purposes, ultimately finding a niche in online ad sales.



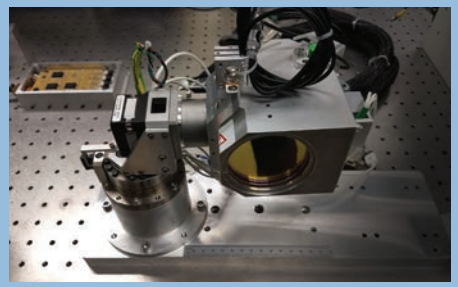
(128) Tiny Star Trackers Help Spacecraft Find Their Place

NASA tackles some of the universe's biggest questions, and the tools it needs are often big, in size and cost. But Crofton, Maryland-based Adcole Maryland Aerospace, with SBIR funding from Goddard Space Flight Center, has designed a modern take on an ancient navigation device that is tiny, cheap, and potentially revolutionary. The device, a "space sextant," fits inside a CubeSat but can match the accuracy of much larger instruments. The company now sells it in a variety of configurations, primarily for Earth-observation satellites.



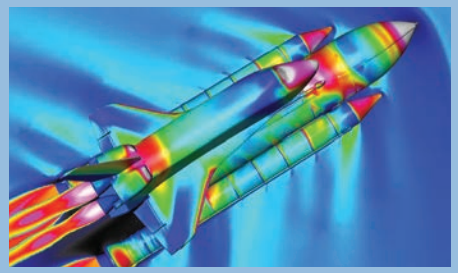
(130) Software Toolkit Steadies Rockets

Combustion instability, when oscillations from firing resonate into an explosion, is one of the biggest risks in designing a rocket engine. Tullahoma, Tennessee-based Gloyer-Taylor Laboratories, with several SBIR contracts from Marshall Space Flight Center and others, built its Universal Combustion Device Stability process and toolkit based on an insight that breaks the problem into different layers and can predict how an engine will behave and why, enabling engineers at NASA and beyond to change problematic factors during the early design phase.



(133) Low-Cost Transceiver Will Allow First Laser Mass Communication

Since the advent of the laser in the 1960s, engineers have struggled to use light beams in free space to send information the way we use radio waves. A transceiver created at the Jet Propulsion Laboratory, now licensed by Atlanta-based Xenesis, could be a breakthrough. Rather than burying fiber-optic cables, clients can beam secure laser signals above ground across a network of these transceivers. But the more widespread application will come when a satellite constellation and ground network now under construction begin to support mass communications.



(135) NASA Code Speeds Nation's Aircraft, Spacecraft Design

In the late 1980s, NASA engineers were working to improve airflow simulation software. The Space Shuttle, with an external fuel tank and solid rocket boosters each generating interacting airflows, posed a distinct challenge. To better model multiple-body problems, a NASA team created the overset-grid method and built OVERFLOW software to run the simulations. Now available through Langley Research Center, OVERFLOW has been widely adopted, including at Seattle-based Boeing Commercial Airplanes, which uses it throughout its operations for development of planes, rotorcraft, advanced concepts, and more.

(137) Tiny Springs Improve Electronic Reliability

A connection issue in printed circuit boards led to a tiny solution that could have an outsized impact. Printed circuit boards are layered with copper lines and pads that connect electronic components together. However, the joints can break when things heat up. Marshall Space Flight Center's Mark Strickland and Jim Hester engineered a micro-coil spring connector that is far stronger and longer-lasting. Milledgeville, Georgia-based Topline Corporation now sells the springs and attaches them to components for industry tests and verifications.

(138) Collaborative Platform Trains Students in Simulation and Modeling

NASA uses simulations every day to test new ideas and science, saving untold time and money and resulting in improved outcomes. To make it easier to share simulations across centers and teams, engineers at Kennedy Space Center built the Distributed Observer Network, a simulation viewer that works alongside a commercial game engine to make simulations portable. Now the platform is available to university students through the Simulation Exploration Experience, which aims to train the next generation of simulation builders.

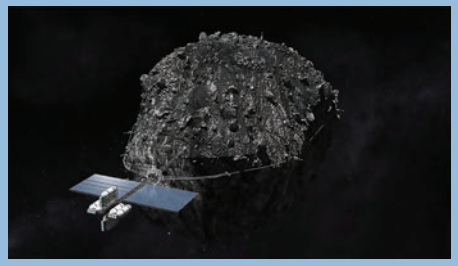
Industrial Productivity

(142) Spray Analyzer Turns Up in Cars, Planes, Medicine, Cutting-Edge TVs

A technology an engineer developed with SBIR funding from Glenn Research Center in 1985 continues to find new uses today. With further SBIR funding from NASA and others, Sunnyvale, California-based Artium Technologies Inc. has built on the Phase Doppler Particle Analyzer originally created to analyze fuel spray in rocket and jet engines. Today it's used to design and test products including automobile fuel injectors, aircraft parts, inkjet printers, and systems for printing organic LED displays, among others.

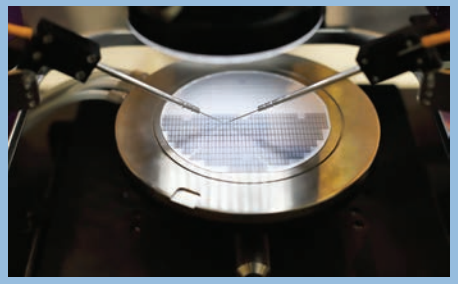
(144) Deep-Space Food Science Research Improves 3D-Printing Capabilities

Maintaining astronauts' nutrition becomes harder the farther they go from Earth. Contemplating sending astronauts as far away as Mars, Johnson Space Center took one company up on a proposal to explore 3D-printing foods, awarding SBIR funding. After the company built a prototype, one of its senior engineers adapted it to print pizzas to sell on the ground. He founded BeeHex, based in Columbus, Ohio, altered his Chef 3D device to decorate cookies for customers, and is now working on printing custom breakfast bars based on individuals' nutritional needs.



(146) Simulated Space Dirt Supports Future Asteroid Mining

Water is "space gold," and Deep Space Industries is working on technology to mine it from asteroids. The San Jose, California-based company answered a call from Kennedy Space Center to develop special mixes of dirt and rocks that mimic the surfaces of asteroids to help test equipment. Now the company sells the simulant to universities, space agencies, and other companies interested in space mining.



(148) Vibration Isolator Steadies Optics for Telescopes

For some very sensitive optics, even ordinary ground vibrations throw off the results. A vibration isolator, which creates a very stable platform, can help. Minus K Technology makes vibration isolators based on negative stiffness mechanisms, which, among other benefits, can work extremely well in a vacuum. The Los Angeles-area company improved its vacuum-capable system for the Jet Propulsion Laboratory and now sells it to companies that make semiconductors and optics, as well as the Department of Defense and the National Laboratories.

(150) IonCCD Enables Fast, Reliable, Inexpensive Mass Spectrometry

Jet Propulsion Laboratory engineers and a start-up company worked together to create a small, low-voltage mass spectrometer, which identifies isotopes in a material. A key innovation was replacing traditional camera film in the focal plane detector with a charge-coupled device array, a kind of digital imager. Today, College Station, Texas-based OI Analytical, a subsidiary of Xylem, incorporates that digital detector array into its IDS 2030 Charged Particle Detector, which analytical chemists, the pharmaceutical industry, the military, and others use for various mass spectrometry applications.

(152) Beryllium Blazes New Trail for Telescopes

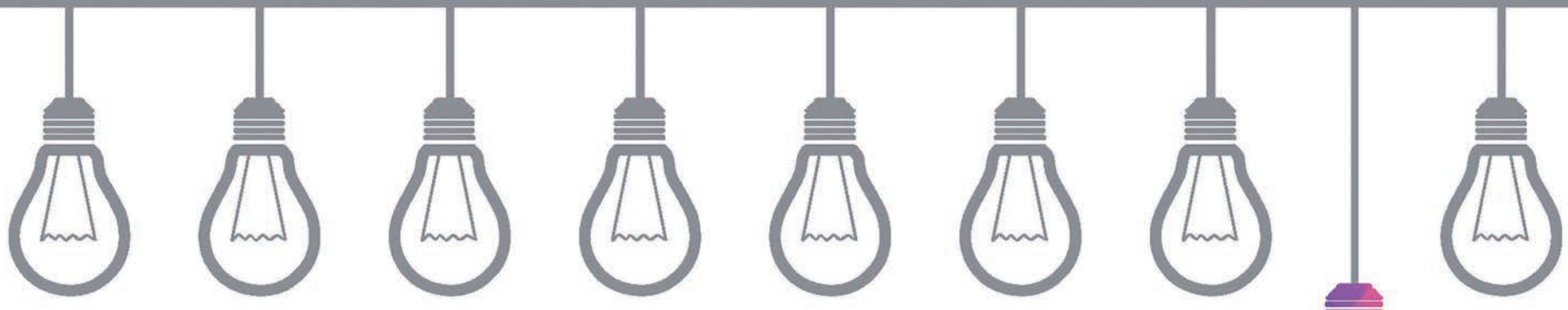
For the James Webb Space Telescope's mirrors, Goddard Space Flight Center needed a lightweight, durable material that would maintain a stable shape at frigid temperatures. The answer: beryllium, which is stiff and doesn't change size at temperatures below about -300 °F. Mayfield Heights, Ohio-based Materion Corporation, one of the top beryllium-producing companies in the world, created new tools and adapted its unique processes to make such large components. The work resulted in a new capability and a new industry standard for beryllium for space applications.

(154) Phase-Change Coating Absorbs Heat from Rockets, Pipes, Beer

Most people enjoy an icy drink without thinking about the physics of the phase-change reaction inside the glass. In the early 2000s, Marshall Space Flight Center materials scientist Raj Kaul encapsulated phase-change materials in a plastic that could be applied like paint, aiming to better protect the Space Shuttle's solid rocket boosters. A commercial license was quickly snapped up by entrepreneur Chris Bilec, whose Austin-based PrimeBilec company has plans to sell it for aviation, in hospitals, and even in an ice-free cooler.

National Aeronautics and Space Administration

NASA Patent Portfolio



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

NASA **TECHNOLOGY TRANSFER** PROGRAM

BRINGING NASA TECHNOLOGY DOWN TO EARTH

www.nasa.gov

NASA Spinoff Technology across the Nation

Health and Medicine

1. Unique Polymer Finds Widespread Use in Heart Devices (MN)
2 Material for Mars Makes Life-Saving Sutures (SC)
3 Fluorescent Paints Spot DNA Damage from Radiation, Gene Editing (CO)
4 Image-Analysis Software Sees Cancer in 3D (PA)
5 Miniature Positioner Focuses Lenses with Precision (NY)
6 Biometric Sensor Tracks Vital Signs for Health (CA)

Transportation

7. Battery Innovations Power All-Electric Aircraft (CA)
8. Shuttle Tire Sensors Warn Drivers of Flat Tires (PA)
9. Space-Age Insulator Evolves to Replace Plastic and Save Weight (MA)
10. Software Helps Design Artery Stents, Lawn Mowers, Airplanes (RI)
11. Super-Accurate Atomic Clocks Could Aid in Navigation, Communication (CA)
12. Probes Characterize Air and Water Flows over Aircraft, Yachts (VA)

Public Safety

13. NASA Brings Accuracy to World's Global Positioning Systems (NY)
14. Gas Regulators Keep Pilots Breathing (NY)
15. RoboMantis Offers to Take Over Dangerous Missions (CA)
16. Wrapped Tanks Cut Weight on Everything from Buses to Paintball Guns (CA)
17. Membranes Mimic Kidneys to Filter Water (Denmark)
18 Detailed Spectrometry Makes Dangerous-Materials Testing Safer (CA)
19 Methane Detector Sniffs Out Leaks (CA)
20 Biofeedback Loops Aim to Enhance Combat, Sports Training (VA)

Consumer Goods

21. Bowflex System Spurs Revolution in Home Fitness (WA)
22. Spacesuit Air Filters Eliminate Household Pet Odors (IL)
23. NASA Research Sends Video Game Players on a Journey to Mars (FL)
24. Memory Foam Supports and Shapes in Women's Apparel (CA)
25. Rocket Design Leads to Turbo-Charged Air Purifier (CA)
26. Brainwaves Reveal Student Engagement, Operate Household Objects (MA)
27. NASA Plant Research Offers a Breath of Fresh Air (Germany)
28. Light Research Aids Slumber (MA)

Energy and Environment

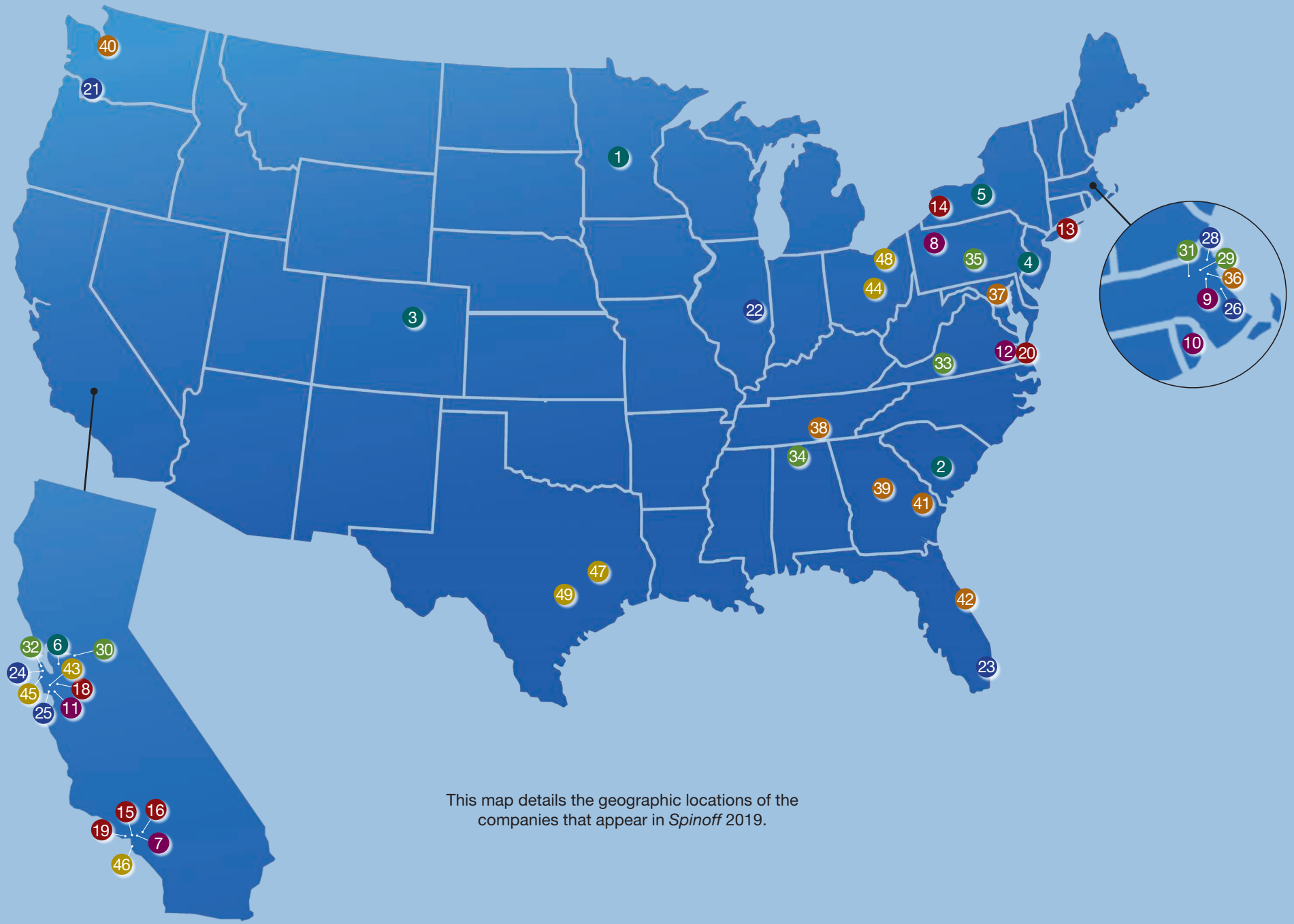
29. Electrified Bacteria Clean Wastewater, Generate Power (MA)
30. Building-Monitoring System Provides Insights for Sustainability (CA)
31. Space Station Garden Shines Light on Earth-Based Horticulture (MA)
32. Carbon Capture Process Makes Sustainable Oil (CA)
33. Emissive Coatings Cut Industrial Costs, Emissions, Fuel Consumption (VA)
34. Pointing Platform Enables Earth Imaging from Space Station (AL)
35. Algorithms to Detect Clouds Forecast Global Crop Production (PA)

Information Technology

36. Space Mission Planning System Targets Advertising with Precision (MA)
37. Tiny Star Trackers Help Spacecraft Find Their Place (MD)
38. Software Toolkit Steadies Rockets (TN)
39. Low-Cost Transceiver Will Allow First Laser Mass Communication (GA)
40. NASA Code Speeds Nation's Aircraft, Spacecraft Design (WA)
41. Tiny Springs Improve Electronic Reliability (GA)
42. Collaborative Platform Trains Students in Simulation and Modeling (FL)

Industrial Productivity

43. Spray Analyzer Turns Up in Cars, Planes, Medicine, Cutting-Edge TVs (CA)
44. Deep-Space Food Science Research Improves 3D-Printing Capabilities (OH)
45. Simulated Space Dirt Supports Future Asteroid Mining (CA)
46. Vibration Isolator Steadies Optics for Telescopes (CA)
47. IonCCD Enables Fast, Reliable, Inexpensive Mass Spectrometry (TX)
48. Beryllium Blazes New Trail for Telescopes (OH)
49. Phase-Change Coating Absorbs Heat from Rockets, Pipes, Beer (TX)



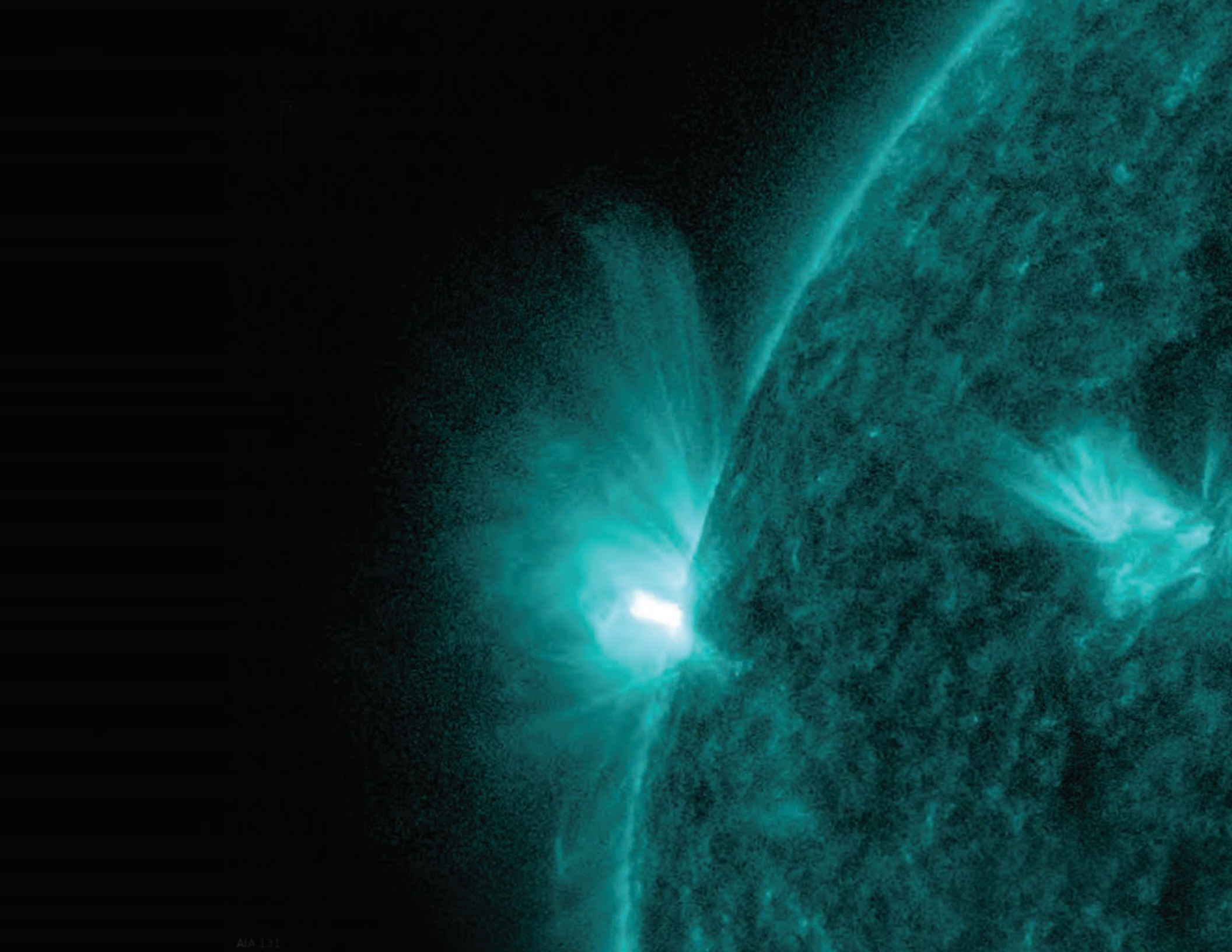
This map details the geographic locations of the companies that appear in *Spinoff* 2019.

NASA Technologies Benefiting Society

We all use “space technology” every day—innovations developed and research furthered in support of NASA’s missions, which have then proven useful in products here on the ground. These spinoffs, whether medical devices, advanced software, or household goods, create jobs, generate revenue, save costs for businesses, and decrease impact on the environment. They even save lives. It’s yet another way NASA technology works for the benefit of the Nation and the world.

Health and Medicine

Keeping astronauts healthy often requires innovations that advance medicine on Earth too—but that's not the only way NASA's work benefits human health. Whether collecting rocks from Mars or attempting to unravel the mysteries of deep space, NASA pioneers new materials and tools that end up in operating rooms and doctor's bags around the world. This section features sutures used in heart surgery, "paints" that highlight DNA damage, and a unique polymer that's been used on hundreds of thousands of pacemakers—all tracing their roots to a need or expertise stemming from NASA missions.


AIA 131

Unique Polymer Finds Widespread Use in Heart Devices

NASA's High-Speed Research Program of the 1990s, which yielded this model but no actual aircraft, was an unusual starting point for a unique polymer that's now used in a line of some of the safest cardiac resynchronization therapy devices on the market.

NASA Technology

A material that a NASA scientist stumbled on in the early 1990s has now helped to keep hundreds of thousands of patients' hearts beating properly all over the world.

Since 2009, medical technology giant Medtronic has been using the substance now known as LaRC-SI (Langley Research Center-Soluble Imide) to get a relatively new type of pacemaker implanted into more patients more easily (*Spinoff* 2008). Medtronic's entire line of left ventricular leads—some of the trickiest cardiac devices to implant—now relies on LaRC-SI. As a result, many patients who might otherwise have continued to suffer symptoms of congestive heart failure were able to be treated.

This success was anything but inevitable.

It began at an unlikely starting point: a program to develop an aircraft to carry 300 or more passengers on nonstop flights between Los Angeles and Tokyo at more than twice the speed of sound.

"To build this plane, we decided to do a lot of screening on polymers based on a lot of feedstocks, and we came on an unexpected formula," says Robert Bryant, the Langley researcher who would eventually shepherd LaRC-SI into the commercial realm. At the time, he was looking for materials for advanced composites and adhesives.

He hit on a combination of ingredients that produced a polyimide—a class of highly durable materials that make great electrical insulators, among other properties—that behaved unusually. It remained soluble when it shouldn't have and, unlike most polyimides, could be melted even after it was insoluble. It resulted in useful products with different properties at all of the three steps in the polymerization process. These could be applied to a substrate in any number of ways.

"I thought there were a lot of applications besides high-speed aeronautics," Bryant says, so he helped Langley patent the formula and process.

Technology Transfer

Sources for the raw materials in LaRC-SI and a number of other high-performance polymers were moving overseas at the time, which presented another challenge, as Federal labs can't buy directly from foreign companies. Bryant convinced a relatively small materials company called Imitec to obtain the ingredients and manufacture LaRC-SI with NASA as a customer, in hopes that more buyers would follow. He facilitated a series of Small Business Innovation Research (SBIR) contracts, through which the company built up the know-how and capability to manufacture the material.

This allowed Bryant to continue researching LaRC-SI at Langley, though he had to leave the High-Speed Research Group to do so. The SBIR contracts resulted in some demonstration resin, powder, and mechanical parts he could take on the road to show to companies. He also worked to publicize it through articles and papers. The R&D 100 award it won in 1995 helped.

"I had no idea what would be the first hit on this particular product. I just knew I had to get it out into the marketplace," Bryant recalls.

In the end, he helped create the first hit—the Thin Layer Unimorph Driver (THUNDER), a piezoelectric wafer that changes its shape when an electric charge is applied and releases an electrical charge when deformed (*Spinoff* 1999). The simple device can be used as a mechanical actuator, a sensor, or a power source and was soon produced by the thousands and incorporated into various commercial devices, including the Lightning Switch, a remote power switch that required no energy source (*Spinoff* 2005). LaRC-SI is the hot-melt adhesive that holds the wafer's layers together.

In 2004, Minneapolis-based Medtronic got a license from Langley to commercialize LaRC-SI, which it purchases from Imitec. Bryant was unaware of the transaction at the time, but Medtronic eventually brought him on as a consultant, a role he still fills. He and the company spent years developing a process to use the material as a coating and electric insulator for the thinnest left ventricular leads available, key components of Medtronic's cardiac resynchronization therapy systems.

In addition to adapting the material to standard manufacturing processes, the company undertook long and rigorous testing, Bryant says.

The technology began clinical trials in 2007 and received FDA approval in 2009.

Benefits

Traditional pacemakers address a slow heartbeat by delivering a tiny electrical charge to the heart's right atrium and right ventricle. It's estimated, however, that about 40 percent of patients with congestive heart failure or cardiomyopathy—enlarged, thick, or rigid heart tissue—lack coordination between the left and right ventricles, which are supposed to contract simultaneously. This significantly reduces pumping efficiency and isn't addressed by a regular pacemaker.

Cardiac resynchronization therapy addresses this problem by running a third electrical lead to the left ventricle. It's a challenging procedure, because the lead has to be threaded through a vein that's often convoluted in a small space.

Medtronic was an early pioneer of cardiac resynchronization therapy devices and left ventricular leads, and LaRC-SI was first used in its over-the-wire models, in which a guide wire is first inserted into the vein to help deliver the lead. The technique is standard today and has improved implant success rates, but it was cutting-edge at the time.

"Some patients have tortuous anatomies, making it difficult to get the lead into the right spot," says Dr. David Steinhaus, vice president and general manager of the Heart Failure business at Medtronic. "The LaRC-SI material allows the lead design to be very small and simple, yet highly flexible and reliable for navigating the left heart." He notes that the material allows the leads to use a flexible coil for multiple circuits, rather than a cable that can be susceptible to fractures or insulation breaches.

As a result, the company's left ventricular leads are some of the safest on the market.

Steinhaus also emphasizes the ease with which LaRC-SI is processed and applied, compared with other polyimides that can require multiple steps, harsh chemicals, and high temperatures. "This polymer can be applied and cured in one process step at temperatures amenable to multiple substrates," he says. "Once the material is cured, it is very durable, stable, and chemically resistant."


Image courtesy of the U.S. Navy

Left ventricular leads, used to coordinate the pumping of the heart's ventricles, are notoriously difficult to implant because they have to be threaded through a convoluted vein in a small space. The LaRC-SI polymer Medtronic licensed from Langley Research Center allows the company to make leads that are small and simple while highly flexible and reliable, making them easier to implant and improving patient safety.

Medtronic hasn't yet used LaRC-SI beyond its left ventricular leads, which now comprise several models that have been implanted in hundreds of thousands of patients, with the most recent line released in 2014, but that doesn't mean they won't. Steinhaus says the company's engineers

"continually evaluate different applications and processes for this polymer."

"I've always thought this was a good case study for the commercialization of an expensive but highly useful technology," Bryant says. "People are always under the impression that if you build a better mouse trap, people will run to your door. This is a fallacy that even people who should know better tend to believe." Instead, he says, the tale of LaRC-SI's long journey from a NASA aeronautics laboratory to the operating room is one of persistence, building relationships, and a little luck.

He concedes that NASA's brand recognition didn't hurt either: "If I had developed it in my garage, there's a distinct possibility that it wouldn't see the light of day. Working for the Space Agency certainly helped." ❖

"I had no idea what would be **the first hit** on this **particular product. I just knew** I had to **get it** out into **the marketplace."**

— Robert Bryant, Langley Research Center

Medtronic's left ventricular leads, the thinnest on the market thanks to a coating based on a NASA license, have helped to keep hundreds of thousands of people healthy and active.

Material for Mars Makes Life-Saving Sutures

This photo by NASA's Curiosity rover shows the Windjana rock site, where the rover's tools drilled down for a sample to analyze. NASA learns a lot from these rovers, but it could learn even more by bringing a rock sample home for deeper analysis in Earth-based labs.

NASA Technology

Although NASA has sent many missions to Mars, nothing, so far, has ever come back. That's something the Agency hopes to change—and it is working on the technology needed to make it happen. These innovations are already paying dividends on Earth, including a new twist on a well-known material that can now be used to stitch up hearts during surgery.

For NASA, "the mission to return samples from Mars has been at the top of the planetary science to-do list for some time," says Andy Spry, who worked at the Jet Propulsion Laboratory (JPL) during this project and is now a senior scientist at the SETI (Search for Extraterrestrial Intelligence) Institute and supports NASA's Office of Planetary Protection.

"Rather than being constrained by the limitations of how much hardware we can deliver to Mars, we can apply all of the hardware, all of the knowledge on Earth, to a Mars sample that's brought back," he says.

But any sample canister needs a strong seal, both to keep Earth's atmosphere from contaminating the sample, and to protect Earth from any potential contamination from Mars.

"The trouble is, when you're getting out a sample, it's typically very dirty," explains engineer Scott Stanley. "Drilling into a rock, you contaminate everything around you with debris." If Martian dust gets everywhere, the lid might not seal correctly.

Stanley, vice president of technology at a small company called Techno Planet Inc., was working on a seal, based on an award from NASA, that aimed at a leak rate "measured at the molecular level, in terms of what's getting in and out," he recalls. "No existing seal could meet that in a contaminated environment."

He wanted to use a "knife-edge seal," where the stainless steel edge of the canister-base cuts into a soft metal, in this case indium that fills a lip around the lid. However, if the "knife edge" is covered in dirt, that would get stuck in the soft metal, leaving gaps and preventing a seal.

Stanley had a plan: a barrier layer that covers the soft metal. When the edge pushes through that barrier, it would be wiped clean.

"The trouble was," Stanley says, "I was very limited on the materials choices by the science requirements." Among other requirements, he needed something qualified for space use, that doesn't emit gas that could contaminate a sample, and that could be completely sterilized before launch. "The only material I could use was some form of PTFE," or polytetrafluoroethylene, which is more commonly known as Teflon.

Technology Transfer

While most people are familiar with Teflon as a nonstick coating for pots and pans, the material has other uses and other forms. At first, Stanley thought he would make the barrier on his seal out of expanded PTFE (ePTFE) ribbon.

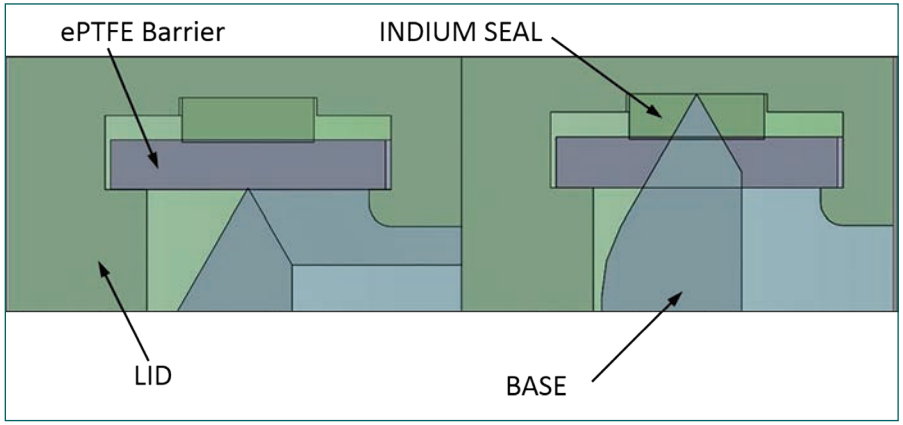
For that, Stanley turned to Orangeburg, South Carolina-based Zeus Inc., using funding from the Small Business Innovation Research contract he'd been awarded by JPL for the project. However, when the company sent samples, they didn't work as Stanley had hoped.

"The ePTFE, before the knife would be able to cut through it, the soft metal of the seal started squeezing out from underneath," even after multiple prototypes and tests, he says.

But Zeus wasn't ready to give up. ePTFE ribbon is made with a calendaring process—the PTFE is expanded and then flattened to make it thinner and stronger, but that also makes it stiffer, explains global market manager Jason Fant. "Basically, we needed to keep the favorable characteristics but to lose the side effect of making it stiffer."

They decided to ditch the calendaring approach and try to create an ePTFE ribbon in a different way: through a large-diameter extrusion, "kind of like a Play-Doh Fun Factory," Fant jokes.

PTFE starts as a powder, explains global business development manager Wayne Black, and the company creates unique extrusions with that powder. "PTFE powder is compressed at high pressures into a 'preform' at ambient temperature. That preform is then forced under high pressure through a finishing die in a customized extruder to create the finished part," Black says. By creating different heat processing zones, he adds, "we can stretch the material to give it unique properties."



This diagram shows a lid specially designed for a Mars sample return mission. To ensure no Mars dust interferes with the seal, the edge of the base first pushes through an extruded ePTFE barrier to wipe it clean, before it sets in a layer of soft indium metal, which ensures nothing gets in or out.

"This material is unique, because it's soft, flexible, and strong—and it's also biocompatible. It's a material that can safely interact in the body and can be safely implanted in the body," Black notes.

One product Zeus sells is extruded ePTFE sutures. "Let's say you had a heart condition that would be a ripe application for something like that, maybe mitral valve repair," Black says. "You don't have to go back in to take the stitches out. They can just stay there."

Likewise, the material is used to encapsulate stents that are also used in heart surgeries, he adds.

But it's also used in fiber optics and aerospace, he says, including at NASA: a space cable on the International Space Station uses the material.

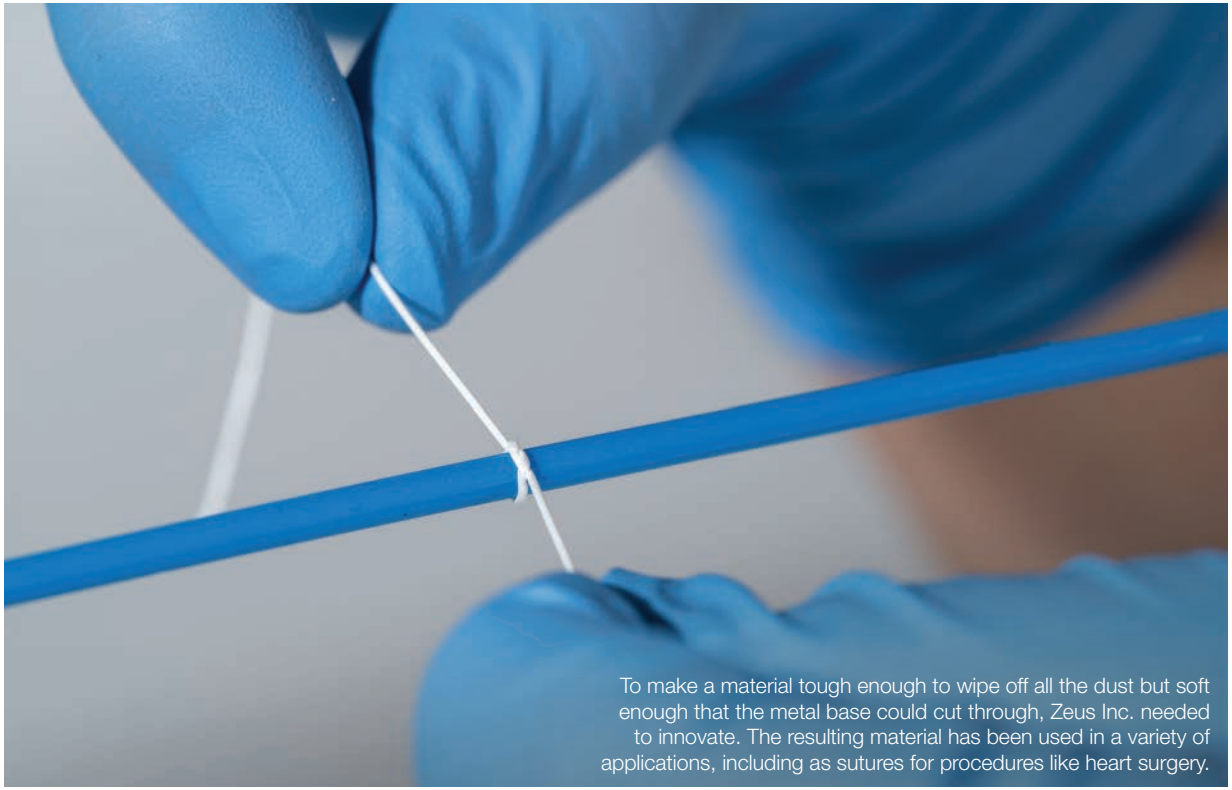
> "Once you have that base material, you can create different things in very different ways and explore new frontiers—literally."
>
> — Jason Fant, Zeus Inc.

The extruded ePTFE ribbon worked, and Stanley was thrilled. "Zeus was awesome—they're a huge company, and here they are running these small, custom runs for me," he recalls.

It was a significant investment of development time and dollars for what amounted to a very small sale to Stanley—but Zeus says it paid off. Altogether, it says, sales in PTFE ribbon, with both ePTFE and extruded PTFE combined, went up by double digits, with an increase of about 50 to 60 percent in the types of applications where the ribbon is used.

Benefits

So what are those applications? There are plenty, says Black, but one of the most surprising—and life-saving—is in the human body.



To make a material tough enough to wipe off all the dust but soft enough that the metal base could cut through, Zeus Inc. needed to innovate. The resulting material has been used in a variety of applications, including as sutures for procedures like heart surgery.

For many other applications, Black says, "the key to the material has always been that you're creating pores on the submicron level, which allows gas to move freely but not liquid." That makes it a great material for desiccant packaging aids—some of Zeus' customers use these when they ship sensitive electronics, for example.

In a similar way, oil and gas drilling companies use the material to help find places to drill. "They make a pouch and bury it in the ground. Their 'secret salt' that they put inside the pouch attracts and absorbs hydrocarbon vapor," explains Fant. "After they dig it up, they'll run it through a spectrometer, and it's like a map of where hydrocarbons are coming up and at what rate. And that helps them pinpoint where to point the drill."

Ultimately, says Fant, this is why the company didn't hesitate to do the work Stanley needed for his seal, because from a business perspective, "once you have that base material you can create different things in very different ways and explore new frontiers—literally."

Spry, back at SETI, calls these results "almost extraordinary, heartwarming.

"What was a small amount of money to NASA was a lever for Techno Planet to help them, it was a large contract for them at the time," he notes. "But alongside that, to know that a larger organization, Zeus, has actually gotten innovation out of the project—somebody was looking at what Scott was doing and saying, 'Oh, we have these problems in this other industry, we can use it to solve them.' That's how technology should work." ❖

Extruded ePTFE is soft, flexible, and strong, and because it is biocompatible, it does not need to be removed, making it ideal for use in the human body. Among other applications, Zeus has used the material to encapsulate arterial stents.

Fluorescent Paints Spot DNA Damage from Radiation, Gene Editing

NASA Technology

A cutting-edge technique for detecting damage to chromosomes showed enough promise for space medicine that its creators founded a company to market it in 2007. But they had no idea their technology would one day put them at the forefront of a coming revolution in genetics, with major implications for personalized medicine and cancer research, as well as agriculture, industrial safety, and more.

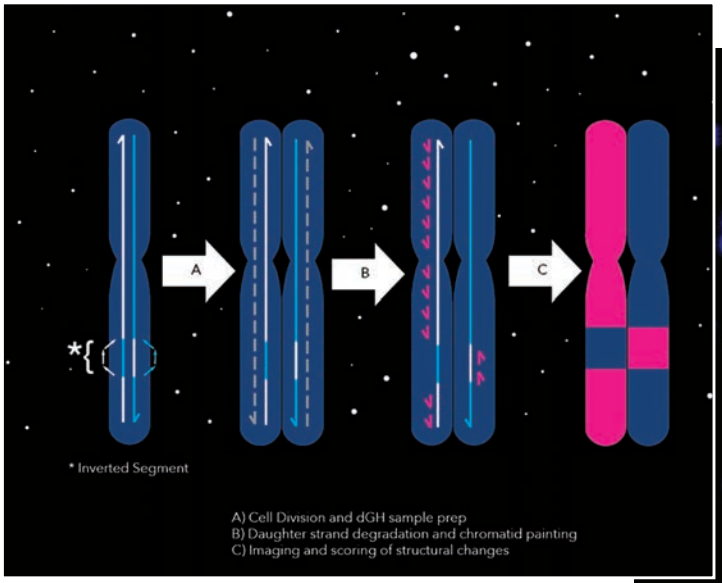
That same year, unbeknownst to the founders of KromaTiD Inc., a team in France was demonstrating that a feature of bacterial DNA known as CRISPR, for clustered regularly interspaced short palindromic repeats, serves as an adaptive immune system. In the years since, researchers have found that these snippets of DNA can be used to turn genes on and off and to add DNA coding to a genome: in short, to edit genes.

But the potential for gene editing can't be realized until its side effects, such as unintended genetic damage, can be understood.

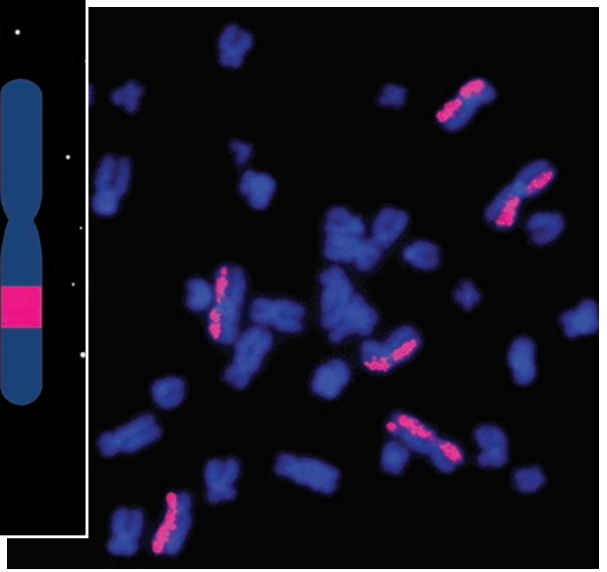
NASA has an interest in studying DNA damage because astronauts are exposed to high-energy charged particles from the sun and cosmic sources. These ions can rip through DNA, inflicting random harm, which could lead to cancers and other problems.

For years, flight doctors at Johnson Space Center took blood samples from every astronaut before and after a long-duration trip into space, examining the white blood cells for genetic damage, says Honglu Wu, of Johnson's Biomedical Research and Environmental Sciences Division. NASA used the findings in part for biodosimetry—to infer how much radiation they're exposed to in low-Earth orbit based on the amount of genetic damage they incurred.

However, although they could detect the translocation of DNA—when a bit of one chromosome ends up fused to another chromosome—other, subtler forms of damage were harder to see. KromaTiD's technique promised the ability to directly observe inversions within a chromosome, where a stretch of DNA gets flipped and reattaches backwards.



In a chromosomal inversion, one or more segments of a chromosome are reversed. As the chromosome divides, it produces corresponding mistakes in the new "daughter strands." At this point, KromaTiD's fluorescently tagged chromatid paints are introduced and highlight the damage to the daughter strands.



KromaTiD's fluorescent chromatid paints can visibly highlight areas of damage within chromosomes, seen here as bright pink spots, that don't match up to the human "reference genome." They can also be designed as probes to locate specific mutations or irregularities.

"Translocations can be stable or unstable, meaning the cell may not survive," Wu says. "An inversion is considered stable. This is more relevant to cancer risk because the cell survives." What's more, it repeats the error when it divides, perpetuating it down the cell line.

Technology Transfer

In 2008, Johnson awarded two Small Business Innovation Research (SBIR) contracts to Fort Collins, Colorado-based KromaTiD. It was the company's first funding, says Chris Tompkins, KromaTiD's president and general manager, and it went toward proof of concept and refining the technique.

The company calls its technology directional Genomic Hybridization (dGH)—directional, as in, "our ability is to see what direction a specific strand or region of DNA is running," Tompkins says. This is how it detects inversions and other structural variations.

Fluorescently tagged bits of synthetic DNA called chromatid paints are applied to prepared chromosomes, which have been arrested in the process of dividing and replicating, on microscope slides. Designed against the normal human "reference genome," the synthetic DNA couples with the divided parent strands everywhere they match the standard genome, so that any out-of-place signal is identified as a deviation. Or the probes might be designed to couple with and illuminate specific dangerous structural abnormalities in the DNA strands. In this way, inversions, translocations, and other variations that indicate genomic damage can be discovered, detected, and quantified.

"With dGH, we're directly observing structural changes to the genome, along with information about the cellular context of those changes," says David Sebesta, chief commercial officer at KromaTiD. He notes that this is different from techniques like gene sequencing, which pools the DNA from multiple cells and can indicate a probability of instances of damage but not directly observe them. "For diagnostic purposes, you need to know it's there and what it is," he says.

Tompkins notes that many inversions are harmless. KromaTiD's DNA probes can be used to detect disease-driving inversions, such as a gene that should be suppressed but ends up next to a promoter, which prompts gene transcription.

Benefits

The existing and potential applications for dGH chromatid paints are many.

In oncology, Sebesta says, examining patients' chromosomes before and after radiation therapy could allow the dosage to be tailored to the individual patient's sensitivity to radiation. "We don't all have an equal ability to repair damage," he says, noting that some patients develop secondary cancers as a result of radiation therapy.

The technology can also help doctors select treatments by identifying cancer-causing mutations. For example, says Tompkins, a patient with lung cancer can be tested for a particular inversion associated with the disease, letting doctors know whether the patient would respond to treatment for that specific genetic abnormality.

The ability to identify genetic drivers of disease can help researchers identify patients for clinical trials. "If your treatment is only for people with a certain mutation, you populate your trials with people who are likely to respond to it," Sebesta says.

Patients with undiagnosed conditions also stand to benefit. Sebesta notes that after thousands of dollars of testing had failed to diagnose a parent and child exhibiting similar symptoms, a simple KromaTiD dGH assay identified a structural alteration present in both patients' DNA.

The company also courts the Department of Homeland Security as a potential customer. In radiation-related disasters, KromaTiD's technology aligns with NASA's original interest in observing chromosomal damage to determine the extent and type of radiation exposure. One of the company's founders has used the technology in a study that examined the chromosomes of wild boars living around the site of the 2011 Fukushima nuclear disaster to determine remaining levels of radiation. Likewise, employers with radiation in the workplace could use it to determine which employees might have been exposed and who are the most sensitive.

NASA used KromaTiD's technology to compare DNA from astronaut Scott Kelly, left, and his identical twin Mark before and after Scott Kelly's record-breaking stay in space. As expected, the astronaut's DNA showed some damage after his return, while his twin's was unchanged. The damage, however, was minimal.

In 2016, NASA contracted KromaTiD's founder, Susan Bailey, for its Twins Study, which compared chromosomal damage in astronaut Scott Kelly and his identical twin before and after Kelly's record-breaking, yearlong stay in space. As predicted, Kelly had more DNA damage after his time in space, while his brother's DNA remained relatively unchanged. The amount of damage inflicted by space radiation, however, was so low it was hardly beyond statistical error, says Kerry George of Johnson's Human Research Program, who oversaw the study. NASA has since stopped testing astronaut DNA, although Wu predicts that travel to Mars, which would involve higher radiation exposure, will renew interest.

The company sees its biggest opportunities in the field of gene editing, where similar damage to that inflicted by radiation has been observed. Sebesta notes that numerous companies have been established and billions of dollars invested in CRISPR-enabled gene editing, which holds enormous possibilities for human health and other industries. But it's a field that requires refinement, studies into unintended consequences, and the establishment of standards and guidelines before it can begin to tap its potential.

KromaTiD sees itself as well positioned to provide a means of testing gene-editing techniques, quantifying results, and assessing risks, which will be central to standardization and regulation. "It's total serendipity, but without the jumpstart from NASA funding, we never would have been ready for this market," Sebesta says. "It put us in a position where we feel we're going to become a multi-hundred-million-dollar company."

"We're going to be right there on the front lines of standardizing gene editing and bringing these treatments to the medical community," says Tompkins, adding that this is "our top priority as a company." ❖

Image-Analysis Software Sees Cancer in 3D

NASA Technology

Even NASA can be surprised.

The Space Agency works hard to search out surprising discoveries, of course, but it works equally hard to avoid unpleasant ones related to the safety of its astronauts.

In the interest of the latter, NASA has identified approximately 30 risks to humans in space, from increased radiation to decompression sickness to interpersonal conflict between crew members. All of these risks are being studied carefully, explains Craig Kundrot, division director for Space Life and Physical Sciences Research and Applications, and any gaps in knowledge are being identified.

But even with this detailed roadmap of risks, he notes, there are still unknowns. "When we went from two-week Shuttle missions to six-month space station missions, that was a twelvefold increase in duration. All of a sudden we started seeing these vision problems," he recalls. "That caught us by surprise."

Although NASA is still working to fully understand the details of those vision changes and just how much of a risk they pose, researchers believe they are related to changes in blood flow in microgravity, which is something that has been studied for many years.

One of those studies dates back to the Shuttle days. Ron Midura, of the Cleveland Clinic's Lerner Research Institute, received funding through Ames Research Center's Fundamental Space Biology program to study the hypothesis that vascular remodeling precedes and impacts muscle and bone loss. Midura's project started with a ground-based model—studying the hind legs of rats kept elevated, to mimic the decreased blood flow seen in microgravity.

But after he began, he was presented with an opportunity to incorporate into his study tissue samples from mice that had flown on the final mission of the Space Shuttle Program, in 2011, which he could then compare with his ground-based samples. "The concept from our end was to look at gene expression changes in endothelial cells [which line blood vessels] to see if they are altered in spaceflight compared to ground control specimens," he says.

NASA astronaut Karen Nyberg tests the health of her eyes while in orbit in 2013. As space missions began stretching into months instead of weeks, NASA discovered that astronauts' vision was getting worse. The problems are believed to be related to blood flow changes from microgravity that have been studied for decades.

Another crucial part of getting useful data was being able to count the number of blood vessels in the tissue sample and make careful measurements of the thickness and shapes of the vessels. Typically, Midura explains, students would "take all the images, make outlines of the different regions, then count vessels and report the number of vessels, as well as a limited amount of data on thickness or shape of vessels."

The problem is, interpreting the images can be difficult, as is measuring the vessels. "Any manual accounting, even by highly trained technicians, would have been subjective and led to unnecessary variability," he notes. "The other part: it takes a long time, even for someone experienced, to do the full set of analysis of what we wanted for each tissue section."

Instead, Midura decided to turn to computer analysis to find the stained blood vessels and, knowing the spatial size of the pixels in the images, calculate their number, size, thickness, and other attributes.

Technology Transfer

To get the analysis Midura needed, he turned to a software program created by ImageIQ, which was originally spun out from the Cleveland Clinic where he is based but has since been acquired by Philadelphia-based ERT.

ImageIQ's software library was developed to analyze 2D and 3D images for research, but, as is typical for bleeding-edge research, the specific type of analysis Midura was looking for required some innovation. "We found trying to force-fit endpoints and metrics into previously existing software doesn't work," explains Amit Vasanji, cofounder of ImageIQ and now chief technology officer of imaging at ERT.

Instead, the company custom-developed an algorithm that segmented each image into five different regions and then used further analysis to detect two different stains within each region. It also created a filter that helped the computer better differentiate between the stained blood vessel and the surrounding tissue.

"The algorithm looks at every single pixel and then looks around it to see whether it's just noise or belongs to a larger structure that belongs to the analysis, Vasanji explains. In this way, the program is able to identify structures and edges in a way that might not even be visible to a human eye, and it can make extremely accurate measurements across the whole image.

Although the work was specific to its project, Vasanji says it has since proved useful for many other projects. "We talk about it like a spice rack. Every specific project requires a different mix of spices and ingredients," he says.

Once they create a new algorithm, however, it goes on the "shelf" and can be used later.

Benefits

Midura's study was successful—it showed that, indeed, there are genetic changes in the lower-leg vasculature system during spaceflight, and these precede the bone and muscle loss that have been observed—though he is quick to caution that the work is very much ongoing.

Over at ERT, Vasanji notes the advanced imaging software has also powered quite a few important scientific results unrelated to spaceflight, for example in clinical studies of pulmonary embolisms. "It used those filters that we had created in Dr. Midura's project and segmented 3D networks in vessels in the lungs, and it detected where there are disruptions in the vessel connectivity where you might have an embolism." Likewise, the tool is being used in clinical trials for stents and aneurysms, as well as for identifying lesions in the bladder.

Another potentially lifesaving application: to help study cancer—and one day potentially help treat it. Specifically, using the filters and algorithms created for Midura, researchers can identify the three-dimensional shape of the tumor within an image series.

"Right now, in clinical practice, the standard is to do a 2D view in a CT scan," Vasanji explains. But if the tumor is an irregular shape, that two-dimensional slice will miss a great deal of information, details that would be extremely useful, for example, to a surgeon looking to excise it.

Even more importantly, the tumor volume may be growing or shrinking in a way that a two-dimensional image slice does not capture. And knowing the full shape can also help with diagnosis. "Tumors that are benign usually are round with smooth edges. Tumors that are metastatic have spindles and are irregularly shaped," he says.

A key benefit of ERT's advanced imaging software, Vasanji notes, is part of what drew Midura initially: that when humans do the counting, the results are not consistent. "You get two readers looking at the same scan, we've seen in some cases, 70 percent variability," he says. That variability doesn't happen when a computer does the analysis, because the computer applies the same rules in the same way every time.

For Kundrot, back at NASA, these results are a very welcome side effect of the research the Space Agency funds and solicits. "For us, the principle driving question is what happens to humans as we go into space and especially deep space," he says.

NASA is still working to understand the vision changes that occur in space, and tools and studies like Midura's will help it find answers. ❖

Using filters and algorithms created for Ron Midura's NASA-funded vascular study, researchers today are able to identify the three-dimensional shape of a tumor within an image series. Among other features, the software is excellent at finding edges in a way that might not even be visible to the human eye.

Miniature Positioner Focuses Lenses with Precision

Dark matter can't be seen, but scientists observe its effects all around us. This composite image shows hot gas (pink) surrounding galaxy clusters, and the inferred position of dark matter (blue) through the effect of gravitational lensing.

NASA Technology

Nobody has ever directly seen dark matter or dark energy, yet physicists and astronomers observe their effects all around us. Dark matter is thought to hold together galaxies that should otherwise fly apart, and dark energy counteracts gravity to make the universe expand rather than collapse.

Researchers are working on new and exciting studies to learn more about these mysterious phenomena, and NASA is a big part of the effort, including by building the next generation of powerful instruments that will hopefully lead to big discoveries. Innovations developed for the task will also have repercussions in fields like robotic surgery and implantable medical devices.

One instrument, built with the help of engineers from the California Institute of Technology (Caltech) and the Jet Propulsion Laboratory (JPL), is set to be installed on Japan's Subaru telescope in Hawaii in 2020. It will investigate the rate at which hundreds of millions of objects in the universe are moving apart to help understand how dark matter and dark energy are distributed in the universe, explains David Braun, the Opto-Mechanical Engineering Group supervisor for JPL's Instruments Division.

"This tool will add a lot more granularity to our current understanding of the expansion of the universe," he says, which will give new insights into the nature of dark matter and dark energy.

This new instrument, called a fiber-fed spectrograph, measures expansion by looking at the red shift of distant galaxies. "If you think of telescopes as very big lenses, they form very big images," explains Dan Reiley, an instrument engineer at Caltech. In this case, the primary mirror reflects the light through a concentrator, which generates a smaller, brighter image that can more easily be studied. Instead of observing that image with our eyes, "we direct optical fibers to the spots of interest on that image. The fiber sends the astronomical light to a spectrograph," which breaks apart the light into its spectral components, like a rainbow, and measures them.

If that doesn't already sound complicated enough, now imagine what it takes to get all the individual fibers, some 2,398 of them, to line up exactly with the pinpricks of light on the image. Each fiber can move independently and needs to have enough range of motion that together, they can cover any point on the image without gaps, yet without tangling—all within the two minutes before the telescope points to a new part of the sky.

Technology Transfer

In 2008, says Braun, the JPL/Caltech team was working with a private group associated with Pennsylvania State University with expertise in the tiny piezoelectric motor technology that looked most promising for the positioners (piezoelectric ceramic elements change shape when voltage is applied). But finding the miniature motors for the positioners, which the team nicknamed "Cobra," was really only the start.

That's because they didn't just need one or even two positioners, they needed thousands—and each one had to be identical and perfectly precise. And that's where Victor, New York-based New Scale Technologies came in.

New Scale had invented and commercialized the Squiggle linear piezoelectric motor in 2003 and recognized that this product could be modified for the precise rotary movements needed by JPL/Caltech. The rotary Squiggle motor "only existed in our lab and needed to be commercialized and prepared for serial production," says New Scale CEO David Henderson.

Moreover, these motors had to be packaged into a complete Cobra positioner, an assembly that integrated the two rotary motors with multiple ball bearing guides

“This tool will add **a lot more granularity** to our **current understanding** of the **expansion** of the **universe.”**

— David Braun, Jet Propulsion Laboratory

Image courtesy of Hideaki Fujiwara - Subaru Telescope, NAOJ

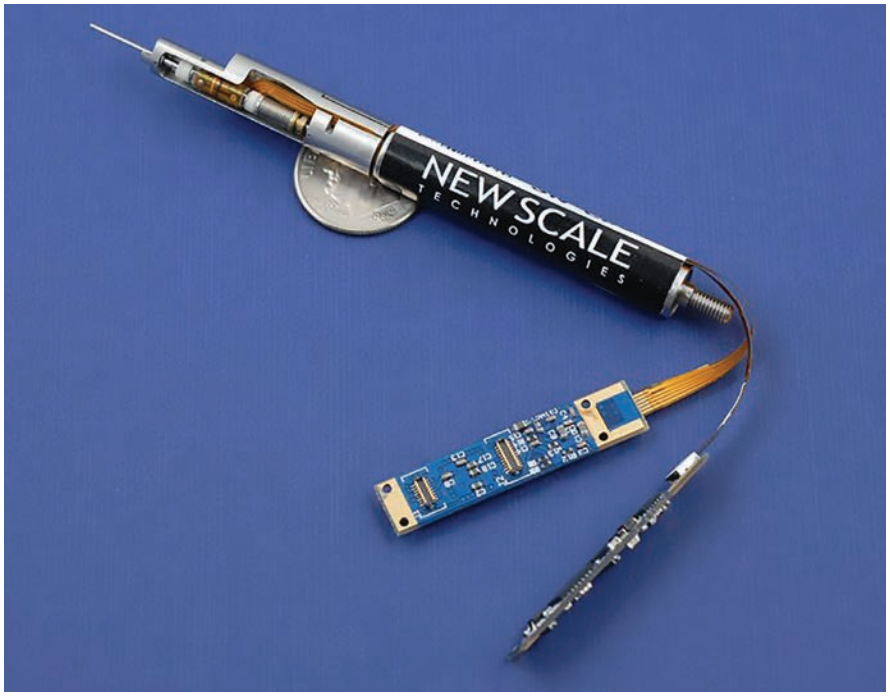
Scientists plan to add a new instrument to the ground-based Subaru Telescope in Hawaii that will help shed new light on the nature of dark matter and dark energy. The instrument, a fiber-fed spectrograph, measures the expansion of the universe by mapping the red shift of distant galaxies.

and a hollow shaft to allow the fiber to come through. And then the company had to figure out how to do it all with vastly smaller drive electronics, Henderson adds, because "the starting design operated at several hundred volts, with electronics so large they could never be integrated at the scale we needed."

Much of this was new territory for the company, notes Braun: "Doing the whole positioner, more than just the motors, that was new for them." In addition, "we pressed them for rigor on quality control, and really we were the highest-volume customer they've had."

Henderson says beyond the innovations required to make all the components work together and at very low voltage, the quality control requirements meant finding high-quality suppliers for all the parts and then developing in-depth inspection processes to ensure each part was exactly right before it moved to the assembly floor.

"These are things that are normal in precision manufacturing, and we already did it to a certain extent—but we improved those processes to a tremendous extent for the Cobra program," says Henderson.



Each of nearly 2,400 fibers on the fiber-fed spectrograph must move independently and needs a range of motion that can cover any point on the image. New Scale Technologies designed and manufactured an extremely tiny, low-voltage positioner that combines two rotary motors. The company now uses the technology on many of its products, including ones that turn up in medical instruments, like a portable blood analyzer that tests for HIV.

Benefits

The work New Scale did has implications well beyond space telescopes, Henderson says, especially thanks to the reduced-voltage, piezoelectric motors. "Everything we do now is at 10 volts or below. Getting down below 10 volts was a major improvement in the overall technology and its application across the board—the motion systems can be miniaturized and integrated to a much greater extent."

He says piezoelectric drives traditionally require much higher voltage, but they were able to reduce that by sourcing multi-layer co-fired piezoelectric components. "You layer it up like a cake," he explains. "You press together the piezo elements with screen-printed electrodes. The thinner the layers, the lower the voltage for the same amount of shape change."

New Scale now uses these reduced-voltage piezo elements across the board. "Even some of our more powerful products are now using reduced-voltage drives. It's essential for our mini-mechatronic solutions," he says.

The company has also expanded its product line, from its previous linear-only positioners to now including rotary modules, as well as offering multiple motors within a positioner. And "it's expanded our supply chain and our customer base. We're working with vendors and customers that we weren't working with before."

Overall, "being smaller and fully integrated makes it possible to move optics in very small spaces that were previously not possible," he says, but he acknowledges they are still in the phase of building a customer base, especially because "typically, people that have a little knowledge of piezoelectric motors, they think, oh, these need hundreds to thousands of volts coming from a separate box. Our reduced-voltage electronics are embedded with the motor."

Nevertheless, New Scale's products are showing up in a variety of contexts, including medical instruments. One, a portable blood analyzer, uses a positioner to provide focus for an embedded microscope. The analyzer fits in a backpack and can field-test someone for HIV.

Henderson reports the company is also getting interest for implantable devices, in robotic surgery, and in machines that sequence DNA, in all of which precise movements and precise camera focus are crucial, and lower power and miniaturization equally so.

Another area of potential interest, Henderson says, is for beam steering in things like lidar, which maps in 3D by sending out laser pulses and measuring how long it takes the beam to bounce off of an object and come back. "Our two-axis rotary positioners point the beam precisely and are about the size of your fingertip." ❖

Biometric Sensor Tracks Vital Signs for Health

NASA Technology

NASA monitors its astronauts in orbit 24/7, aiming both to learn new information about how human bodies adapt to microgravity as well as to keep track of their health day-to-day. Technology developed to aid in that monitoring has pushed forward wearable technology here on Earth too, helping create devices that could provide clues to heart disease and more.

Many people already keep track of heart rate, whether with a smart watch or an exercise monitor. But for a 2012-2014 project funded by NASA, researcher Lino Velo was interested in going deeper. "The purpose of the program was to be able to detect whether a subject, in this case an astronaut, is under stress," he explains, and the goal was to create a wearable device that detected this stress in real time, something that will be especially important for deep space missions.

Heart rate is one indicator of stress, he notes. "When you get scared, heart rate goes up." But there are other kinds of stress, and in this experiment, Velo was looking at cognitive load: "if you have to think fast and reason and be very alert, that kind of stress is what we focused on," he explains.

Velo and his team were interested in two possible ways to measure stress, one measuring brain activity with EEG (electroencephalography) and functional near-infrared spectroscopy, or FNIRS, and the other measuring heart rate variability using a miniaturized, wearable PPG (photoplethysmography) sensor, which measures light absorption through the skin to calculate blood flow.

Heart rate variability is a measure of how regular one's heartbeat is. Perhaps counterintuitively, the more irregular the rhythm, the less stressed the person is. That's because heart rate variability is a "measurement of the equilibrium of the body—whether it can rest and relax or whether it needs to be ready to run away or fight," says Velo.

Measuring heart rate variability is more difficult than simply counting beats per minute. Velo's goal was to test whether his mini PPG sensor could measure cognitive stress as accurately as EEG.

In the experiment, subjects completed difficult memory tasks under time pressure. By measuring the EEG waves as well as the PPG results, Velo says, researchers were able to see biological markers of stress and calm—and, importantly, the results from the two methods matched.

Technology Transfer

Velo's research was funded with Small Business Innovation Research (SBIR) contracts to his company at the time, Linea, through the Human Factors and Behavioral Performance Element of the NASA Human Research Program at Johnson Space Center, explains NASA's Kristine Kennedy Ohnesorge, who helped oversee the project.

However, when it came time to move on to the next step, NASA decided not to continue funding the work. Linea "obviously has a lot of technical experience and expertise when it comes to developing these types of wearable, sensor-based devices," Ohnesorge emphasizes, but "research budgets are smaller than they used to be."

Given the fast-moving market of commercial wearable sensors, she says, NASA has decided to focus on finding "off-the-shelf" technology to test in space. Meanwhile, Velo has taken results from the NASA work to develop internally at Newark, California-based Salutron, which acquired Linea.

Benefits

Today Salutron sells a number of different models of wearable health monitors directly to consumers, as well as individual sensors to companies for them to integrate into their own devices.

One model, available from Salutron's website, is the Zoom HRV, which measures heart rate variability using the PPG sensor developed during the NASA work. It also incorporates actigraphy—monitoring rest-activity cycles—and sleep sensors (the latter were developed under separate SBIR contracts with NASA). The company has also developed an app that presents the results in a user-friendly format.

Salutron sells a smart watch, the Zoom HRV, that measures heart rate variability using a blood flow sensor developed with funding from SBIR contracts from Johnson Space Center. The watch also monitors sleep, using additional sensors developed under separate SBIR contracts.

For now, Velo says, the core audience appears to be people interested in tracking fitness—and the heart rate variability data is helpful for monitoring how well the body is recovering during rest periods.

But he sees potential for these devices to help monitor health more broadly. By monitoring heart rate variability over weeks and months, for example, users can immediately be alerted to a change from the baseline, which suggests the body is becoming stressed.

"We're trying to address the state of an individual before he or she gets into any kind of ailment—trying to be ahead of the curve to help people," he says. ❖

Transportation

Not many humans ride in rocket ships, but all of us have benefited from the technology created to get the lucky few into orbit and beyond. We see space innovations in everything from sensors created for the Space Shuttle that alert drivers to flat tires to battery innovations that could power all-electric aircraft. Also in this section is software that helps design airplanes—and lawnmowers—and new developments in aerogel technology that could soon serve as a lighter-weight substitute for plastic in cars and planes.


NASA

Battery Innovations Power All-Electric Aircraft

As NASA develops its X-57 Maxwell aircraft, the Agency is tackling the challenges of building all-electric aircraft and passing the solutions on to private industry. One difficulty it overcame with help from industry was creating a battery pack that can power all of the plane's motors, weighs as little as possible, and meets stringent safety guidelines.

NASA Technology

The X-planes, experimental aircraft built by NASA and the military, started out by breaking the sound barrier in 1947 and have been pushing through invisible barriers ever since. The latest, known as the X-57 Maxwell, aims to make commercially viable, all-electric passenger aircraft a reality. To do that, it must overcome many technological hurdles—and some of that work is already paying off in industry with unprecedented battery reliability and power.

Sponsored by NASA's Flight Demonstrations and Capabilities Project, the X-57 is a joint effort between Armstrong Flight Research Center, Langley Research Center, and Glenn Research Center. These NASA facilities are also supported by a team of small business contractors led by Empirical Systems Aerospace (ESAero). The plane itself is a highly modified Italian Tecnam P2006T, a high-winged, lightweight, four-person, twin-engine craft popular among flight training organizations and private owners.

Its gas-powered engines will be replaced by two electric cruise motors on the very tips of the wings, reducing drag from wingtip vortices. Distributed along the leading edge of each wing will be six smaller motors to add to the flow over the wings, increasing lift during takeoff and landing.

A major challenge has been safely delivering enough power to the engines. During takeoff, all of these motors combined can use more than 200 kilowatts, for a total energy draw that would momentarily power more than 100 average American homes, says Brent Cobleigh, project manager for Flight Demonstrations and Capabilities at Armstrong. "It's a lot of power, and one battery system has to deliver it, and it's got to fit in the plane."

The group released demanding requirements for companies interested in building the battery, which some of the major government contractors found impractical, says Sean Clarke, principal investigator for the X-57 at Armstrong. The engineers selected Electric Power Systems (EP Systems), based in Industry, California, a company that Clarke says was "a little more aggressive" than the rest. "We're an aggressive project, and we're willing to accept a degree of risk going in, and it's paid off," he says.

The company specializes in reliable batteries and power systems for aerospace, as well as ground transportation, medical, and military applications. Under Small Business

> “If NASA didn’t have the foresight to see aviation going this way and the problems that need to be solved to get it there, this never would have happened.”
>
> — Nathan Millecam, Electric Power Systems

Innovation Research contracts, it built an 850-pound lithium-ion battery pack that could safely do the job. But not on the first try.

The first pack was based on a NASA design from years prior and incorporated some of EP Systems’ innovations, such as a method for pulling heat from a battery cell’s entire surface rather than just the side wall, as well as advanced welding techniques and lightweight packaging.

The battery pack actually holds thousands of off-the-shelf lithium-ion cells a little bigger than AA batteries. Lithium-ion batteries are the cells of choice for flight because they pack the most power into the lowest mass of any conventional battery, but they have one disadvantage: they can short-circuit and fall into what’s known as “thermal runaway,” ending in combustion. It’s rare, but it happens. The challenge for the X-57 battery pack was to ensure that if one cell burst into flames, it would be contained and wouldn’t set off a chain reaction.

When the first pack was built, a cell was intentionally short-circuited to see what would happen. “The whole battery caught fire,” Cobleigh says. “It cost us almost a year.”

The team called in experts, including specialists from the NASA Engineering and Safety Center and battery experts from Glenn and Johnson Space Center.

One contribution from Johnson engineers was a supply of “trigger cells” they had invented for testing lithium-ion battery packs. In these cells, the electrolyte between the anode and cathode is replaced with a wax disk that melts when heated, causing a short circuit. It’s an easier, safer way of inducing thermal runaway than overloading a battery, and it produces more realistic results.

With NASA’s help, Electric Power Systems (EP Systems) created this battery pack to power the Space Agency’s all-electric X-57 Maxwell airplane. The package houses thousands of off-the-shelf lithium-ion batteries and ensures that if one of them overheats, the problem won’t spread.

Clarke notes that NASA had recently developed a lithium-ion-battery casing technique that filled an aluminum block with holes to hold the batteries a millimeter or less apart, isolating them and dissipating heat from any runaway event throughout the block. It’s been used for batteries on the International Space Station, the Orion space capsule, and tools astronauts need on spacewalks.

“A lot of NASA design expertise and technology has gone into this,” Clarke says.

EP Systems adapted the technique and incorporated its own ideas on how to improve upon the NASA approach. The results were innovations in both cell welding and thermal management of the cell to improve safety without adding weight. The new design was able to stop thermal runaway at an individual cell level, where the previous design was intended to stop it at the pack level. The new approach also set a new standard for “packaging overhead,” or the ratio of the packaging weight to the weight of the cells. ESAero, meanwhile, provided its own insights into aircraft mounting of the batteries, as well as the connectivity of the packs’ ventilation system. The new design was tested successfully in late 2017.

“It’s really innovation all over,” says Clarke. “I think it’s a huge success story, but it relied on NASA and the contractors’ partnership.”

Technology Transfer

Another company, Bye Aerospace, was in a hurry to get its own all-electric Sun Flyer trainer certified under new Federal Aviation Administration (FAA) rules for electric aircraft.

“Bye Aerospace had heard of us and what we were doing on the X-57, and they approached us,” says Nathan Millecam, president and CEO of EP Systems. In March of 2018, Bye announced that EP Systems’ batteries would power the Sun Flyer, which made its first flight the following month.

There will be two- and four-person versions of the plane, which is intended for training and can fly for about an hour on a full charge.

Millecam says the Sun Flyer batteries are “very similar but not identical to” the batteries built for the X-57, leveraging advances made under the NASA work.

He notes that the aviation community has been divided over whether the FAA regulations for electric propulsion are too stringent, requiring batteries that end up too heavy and costly to be commercially feasible. “We proved we don’t have to loosen safety standards to be flight-feasible,” he says. “We can keep those standards and still have the energy density and even the cost target we want to have these technologies adopted. It’s a big deal for our industry.”

The X-57 team is also helping to shape safety and testing requirements for electric and hybrid aircraft by sharing its work with industry standards boards, Cobleigh says, noting that companies often would be reluctant to share such information. "NASA makes sure everyone learns the lessons taxpayer dollars paid for."

Benefits

Electric motors are far more efficient than internal combustion engines and require much less maintenance, replacing the high heat and friction of combustion chambers and pistons with wound wires and magnets, Cobleigh points out. They are 90 percent efficient or better, meaning almost all the power is turned into useful work, while gas-powered engines are less than 30 percent efficient.

Bye Aerospace calculates that the Sun Flyer will operate at a cost of $3 per hour.

Electric motors also generate lower noise and no emissions.

The low-hanging fruit for all-electric aircraft are short flights between small airports and vertical-takeoff and -landing vehicles for transportation within cities, Cobleigh says, both of which would be far easier to turn a profit on with the lower fuel and maintenance costs of electric aircraft.

Millecam says EP Systems has received considerable interest—and yet-unannounced contracts—in all those markets. Although the technology has a long way to go before there are three- or four-hour electric flights on large passenger airplanes, he says, "The technology is at the point now where it can be utilized on new vehicle concepts and new aviation business models."

Without the assist from Armstrong, though, electric propulsion batteries might not have gotten off the ground, he says. "If NASA didn't have the foresight to see aviation going this way and the problems that need to be solved to get it there, this never would have happened."

Clarke notes that the project didn't even set out to research batteries. It aimed to test efficient wing designs and power distribution systems. "And we ended up with this innovative component that's useful in industry now."

The X-57 is planned to make its first electric flight this year but will continue to evolve over the next few years. In its final form, it's expected to run on about a fifth of the energy it would as a gas-powered craft. ❖

Bye Aerospace's Sun Flyer, an all-electric training airplane that's already begun flight testing, is powered by a battery pack that EP Systems based on the one it built, with NASA funding and expertise, for the X-57 aircraft.

Shuttle Tire Sensors Warn Drivers of Flat Tires

NASA Technology

How many people can think of a time when they got to their destination only to realize one of their car tires was dangerously low on air? Or they heard an ominous pop on the highway, only to realize an undetected slow leak had turned into a blowout?

It's something that should be happening less these days, thanks to tiny sensors that light up a dashboard warning whenever the tire pressure is off. The fanciest models can even give a real-time pressure reading for each tire.

But the earliest versions of those sensors had a much bigger purpose: ensuring the tires on the Space Shuttles were fully inflated and safe for landing. The Shuttle had four rear tires, two under each wing, and if even one was low on air during landing, it would be a "very bad day," says Steve Sebesta, a Kennedy Space Center flight engineer.

"If one was flat, the other tire on that side would blow, then you would have two blown tires," he explains. "Then you'd roll on the rims until they were destroyed. You'd be yawing to the right or left, toward the side that had the tires no longer inflated, and eventually roll right off the runway. A very bad day."

Luckily, he says, "in the history of the program, we only ever had one tire go flat, and it happened when we were almost completely stopped." That was in the 1980s, Sebesta recalls, before there was really any way to monitor tire pressure during flight. There was an externally mounted strain gauge, he says, but it only gave a very rough estimate of pressure—enough to know if the tire had completely gone flat but not accurate enough to alert pilots if the pressure was simply low.

Proper tire pressure is crucial for a safe landing, but in the early days of the Space Shuttle Program, there was no good way to accurately gauge pressure in flight. Instead, engineers relied on extensive pre-flight ground tests to measure air loss over time.

Instead, the Shuttle engineers relied on extensive pre-flight ground testing to mimic flight conditions over long periods of time and learn the rate at which the tires lost air, so they could prepare the tires with enough margin to be safe during landing.

Sebesta was part of an effort in the late 1990s to redesign the Shuttle tires to make them significantly stronger and able to withstand greater speeds and crosswinds, and that project included designing an upgraded pressure sensor for the new tires. But even before that, NASA had built a much more accurate sensor for the Shuttle tires, thanks to a partnership with a then-start-up called NovaSensor, which aimed to give the astronauts and ground control an accurate picture of tire pressure before descent, to help ensure there were no ugly surprises.

Technology Transfer

In the 1990s, NovaSensor, now part of the much larger St. Marys, Pennsylvania-based Amphenol Advanced Sensors, was a few years old and building a name for itself in micro-electromechanical systems, or MEMS, sensors. That's just what it built for NASA: a pressure sensor based on MEMS piezoresistive technology, which converts pressure to electrical resistance, explains senior sales manager Mark Ready.

The sensor was built on a small silicon chip. "As pressure is applied to one side of the chip, that creates strain in the silicon," he says. When tire pressure got low, the strain would change, creating a proportional piezoresistive change that generated a tiny amount of electricity, measured in millivolts, signaling the problem.

"At the time, it was a very innovative way to measure pressure," Ready emphasizes. When NASA approached the company, "it was a technology that was pretty core to our capabilities," but it required a fair bit of work to make a fully operational sensor ready to work on tires. One of

Astronaut and pilot Michael Bloomfield feels the heat on the tires more than an hour after landing, following a 1997 flight. The friction from the runway used to wear the treads off the tires, leaving a narrow margin between safety and a potential blowout. Later redesigns aimed to improve the tire durability as well as add sensors to constantly monitor tire pressure.

> "In the history of the program, we only ever had one tire go flat."
>
> — Steve Sebesta, Kennedy Space Center

the biggest challenges, he says, was figuring out the best way to mount the chip within the tire without imposing any external strain. For example, if the adhesive is stiff and expands in heat at a different rate than the sensor itself, that could create a stress that interferes with the pressure reading.

The company also had to package the MEMS sensor into a complete device that was powered by a small battery and sent results via radio frequency. And although NASA only needed a handful of the finished sensors for its Shuttles, Ready says the company already envisioned a much wider market, especially for automotive tires.

Benefits

The Shuttle tires were originally based on aircraft tires and have significant differences from the all-weathers on a typical sedan. For one thing, Shuttle tires are massive: some four and a half feet in diameter, Sebesta says. For another, the air pressure required is an order of magnitude higher: while a typical car tire generally needs 35 to 45 pounds of pressure per square inch (psi), the original Shuttle tires needed 350 psi.

But when it comes down to the job of a tire pressure sensor, there wasn't much the company needed to change. They needed to scale up the manufacturing infrastructure to be ready to produce millions of parts instead of the dozens required by NASA and make some external design work to create a few choices for customers, Ready says. But otherwise, "we didn't have to do much beyond that to turn it into a commercial product. It's essentially the same as what we delivered to NASA."

The company has since sold many millions of the pressure sensors, and the vast majority of them went on U.S. passenger vehicles, as well as on "run-flat" tires for the U.S. market. "Run-flat" tires allow the driver to keep going for up to around 50 miles on a punctured tire without causing a blowout, Ready explains, and pressure sensors ensure the driver knows to head in for service.

Today, U.S. law mandates a pressure gauge on every car tire, and that's because of the increased safety that pressure sensors like these enable. Just like on the Shuttle, if one of four car tires starts to go flat, it could cause "a catastrophic situation where the tire could fail and cause a potential accident," says Ready.

And even when the pressure isn't low enough to cause a blowout, he notes, low tire pressure makes the car run less efficiently, which means it's using more fuel and wearing through the tires faster.

Amphenol continues to sell the NovaSensor P1602, which, though it has received some upgrades, is still essentially the same product it created 25 years ago. The tire pressure sensor is no longer a huge part of Amphenol's business, as the company has moved on to more cutting-edge work and competitors have crowded the scene, but "we were the leader with it," Ready emphasizes.

The tire pressure sensors, he says, "definitely played a critical role—it helped us turn the corner in terms of becoming a real company." ❖

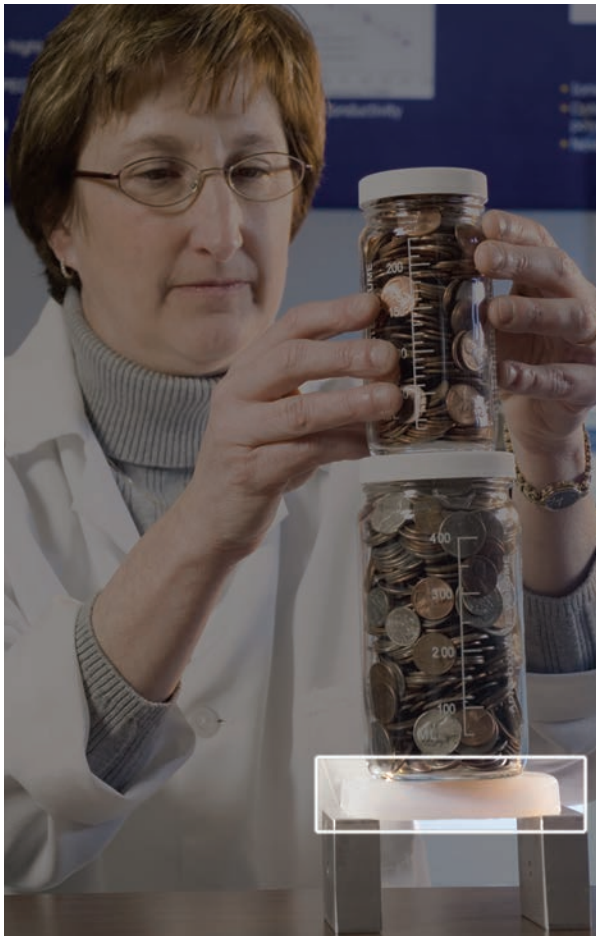
NovaSensors, (since acquired by Amphenol Advanced Sensors) was contracted to build a tire pressure sensor for the Shuttle. The company used MEMS piezoresistance technology, which converts pressure into electrical resistance, powered by a small battery, that sent readings via radio frequency. After it delivered to NASA, the company adapted the sensors for passenger vehicles, ultimately selling many millions of the device.

Space-Age Insulation Evolves to Replace Plastic and Save Weight

NASA Technology

When aerogels were first invented in the 1930s, nobody had much use for them. And yet, nearly a century later, these materials could become as ubiquitous as plastics, says one entrepreneur—and it never would have been possible without NASA.

Aerogels are a class of materials made by creating a gel and then carefully removing all the liquid. The result is the world's lightest solid—in some cases over 99 percent air, contained within nanopores distributed throughout a spongelike structure. While most aerogels have historically been made out of silica, over the last two decades scientists have developed aerogels out of a variety of other materials, each imparting its own special properties.



Aerogels are mostly air—they've been called the world's lightest solids. But early versions were extremely breakable. Here, Glenn Research Center scientist Mary Ann Meador shows off one of the new variations she has helped craft—one that is extremely strong.

But the commercial potential of aerogels only really got a jumpstart after a NASA-funded project figured out how to turn the famously brittle material into something useful. In the 1990s, a Small Business Innovation Research contract funded the development of aerogel-infused blankets, which were durable, flexible, and world-class insulators.

As the promise of aerogels started to be realized, NASA continued funding research into the materials for other applications. Most recently, says Glenn Research Center's Mary Ann Meador, "we've been working on using aerogels as a substrate for antennas."

Meador has been working on techniques to create aerogels out of polyimide and polyamide materials. Unlike silica aerogels, which can shatter at the slightest touch, polyimide and polyamide aerogels can be cast into tough, flexible, and extremely lightweight sheets and boards of various thicknesses. "If we have an antenna that we want to mount on the side of the aircraft, it can conform to the wing or fuselage or wherever," she explains.

And because aerogels are mostly air, they conduct electromagnetic waves extraordinarily well, "which means we can improve the gain of the antenna, the bandwidth, and also reduce the weight by 50 to 70 percent," Meador says.

Technology Transfer

Meador's antenna work for Glenn is part of a project called CLAS-ACT, which stands for Conformal Lightweight Antenna Structures for Aeronautical Communication Technologies. But she is among the first to say that the applications for these aerogels she has helped create have many other potential applications, including well outside NASA.

That's why Glenn has not only patented several of these aerogel inventions but made them available through the Technology Transfer Program. The compelling properties of these materials, plus the low cost of licensing patents from NASA, says Aerogel Technologies founder Stephen Steiner, made licensing Meador's aerogel portfolio "a no-brainer."

Steiner's company, based in Boston, was the first to license a Glenn technology through NASA's QuickLaunch program just after it went live in 2013 and was so pleased with the results that it went on to license more technology. "NASA is creating technology that can really transform the world," he says. "With a close relationship, companies like mine and researchers at NASA can really do the amazing things that neither of us can do alone and bring the technology to the next step."

Meador agrees the relationship has benefited both sides. "They seem to be pretty open with us, and the more open they are, the more we can help them," she notes. "And meanwhile, while we're working on our own NASA-funded projects, along the way there are opportunities where their interests and ours can converge." For example, Glenn is focused on the low electromagnetic resistance of aerogels, so there is little need for NASA to invest in measuring how well these new aerogel materials work as insulators. However, Aerogel Technologies does thermal conductivity testing itself as it works on developing other kinds of products and can share that information with Meador's team.

Benefits

Steiner traces his own interest in aerogels to a high school science fair project in 1999 in which he hoped to make a titania aerogel as part of a project to use sunlight to separate hydrogen from water for fuel. "I started by reading whatever I could about aerogels," he recalls.

Aerogel Technologies, thanks to internal research and development as well as several technologies it has licensed from Glenn, manufacturers a class of aerogels it has branded Airloys. They can be made with a variety of properties, including high temperature tolerance, transparency, and varying degrees of flexibility and stiffness, and can be cut and machined into any shape.

Ultimately, he won second place at Intel's International Science and Engineering Fair with his project, which by then included a homemade supercritical dryer, or autoclave, and a new process for rapidly gelling aerogel precursors.

More importantly, Steiner's interest was piqued—eventually leading him to see potential for aerogels to act as ultralight alternatives to plastics. "Our products are able to go into cars and airplanes to make them lighter—which can make them tremendously more fuel-efficient," he says. "That can reduce carbon emissions on a global scale more effectively than anything I would have done from making hydrogen with titania."

He spent more years studying aerogels and, even before the Glenn relationship, acquired aerogel patents for polymer crosslinked oxide aerogels originally invented at the Missouri University of Science and Technology, all with the goal of eventually supplying a lightweight plastic alternative to manufacturers. But he found production was limited by the size of his autoclaves—the pricey machines that extract liquid from the aerogel—because he could only make parts as big as would fit inside.

An accident in 2013 changed that: one of the autoclaves at Aerogel Technologies, loaded with drying aerogel tiles, rapidly depressurized, going from 100 atmospheres to zero in seconds instead of hours. "Normally if this happens, everything in your autoclave would be blown to smithereens. But the aerogels were intact. We took them out, put them on the counter, and found out the materials turned out just fine," he recalls.

Within a year, Steiner says, his team had reverse-engineered the accident to create a new technique for drying aerogels, without losing any of the materials' properties, in ambient conditions. "This new process, totally different and much faster, allows us to make aerogel parts of theoretically unlimited dimensions outside a vessel. That became the basis of the future of our company," he says. The new ambient drying process also lowers the cost of the materials, since, notes Meador, "probably the biggest cost in the aerogel is in the processing."

Aerogel Technologies has branded its mechanically strong aerogels "Airloys," and it makes them out of polyimides and polyamides based on the licenses from Glenn, as well as with other materials. "To the end user, they're different flavors of the same thing," Steiner says.

Airloys can be manufactured with a wide array of mechanical properties—including high temperature tolerance, transparency, and varying degrees of flexibility and stiffness—many of which are built on advances made at Glenn. "We're trying to reinvent the image of aerogels. These are a whole class of materials you can machine and glue—amazing new technology, not like what you've seen before," Steiner adds.

Aerogel Technologies is working with airline manufacturers and automakers from Airbus to Ford to potentially replace many plastic parts, in particular in airplane and car interiors, with Airloys. By reducing the overall weight of the vehicle, aerogels could significantly reduce costs and fuel consumption—for a passenger jet the size of a 737, Steiner says, that could add up to a savings of around $1,100 of fuel for an average U.S. domestic flight.

Other current customers include an apparel company, drone manufacturers, and companies that make coolers, he adds. There are also a number of sensors that have inte-

grated Airloys, he says, "where it's a tight heat-management problem and you also need a structural non-dusty material."

Another application: soundproofing, particularly in aerospace systems, Steiner says. "Our Airloy materials are the world's best soundproofing materials, by orders of magnitude," he claims. "Airloys offer up to 1,000 times more sound transmission loss compared to traditional acoustic foams."

Steiner thinks that within 10 years, Airloys will be a standard material for manufacturers in many industries, once Aerogel Technologies gets past the hurdle of testing and qualifying them for these new applications. "We're interested in the race to the top, to find the applications where a value-added material, even if you're paying more up front, is so compelling in terms of operating cost savings that it's definitely worth it," he says.

"We're working with multibillion-dollar companies that are foresighted enough to see opportunities in new materials to help reduce weight, reduce fuel consumption, and reduce costs for the world's most demanding applications." ❖

"NASA is creating **technology** that can **really transform** the **world."**

— Stephen Steiner, Aerogel Technologies

Aerogel Technologies sees its Airloys as a lightweight plastic replacement, which, if installed in cars and planes, could have a positive environmental impact by lowering fuel needs and emissions.

Software Helps Design Artery Stents, Lawn Mowers, Airplanes

NASA Technology

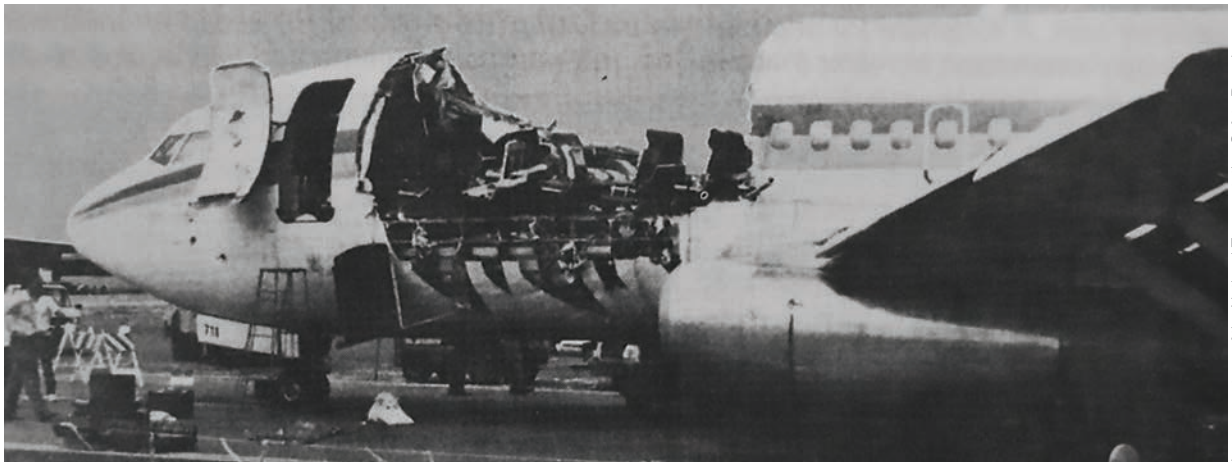


Image courtesy of the National Transportation Safety Board

A photograph taken of Aloha Airlines Flight 243 in April 1983 after it made an emergency landing. Unexpected fatigue cracking led to the structural failure of the top half of the fuselage, exposing crew and passengers to the elements. NASA aeronautics engineers used cutting-edge software known as Structural Analysis of General Shells to help determine the cause of the incident.

When Aloha Airlines Flight 243 made an emergency landing on Maui in April 1988, much of its upper fuselage was missing, leaving passengers entirely exposed to the elements. Remarkably, only one person, a flight attendant, died in the incident.

"The aircraft's roof had blown away in a way that everybody thought was not possible," says Carlos Davila, a senior research engineer at NASA's Langley Research Center. The Boeing 737, though nearly 20 years old, was designed to resist this type of cracking, and it was unclear how the damage occurred.

Researchers at Langley tasked with supporting the aerospace industry got to work running all the information they had on the Aloha accident through their various modeling software systems. They created models of the fuselage joints using the Structural Analysis of General Shells (STAGS) code that was being developed by Lockheed Martin under a contract from Langley. New failure criteria developed in the laboratory were applied to the computer models to understand how small cracks could link up and compromise the structural integrity of the aircraft.

At the time, a variety of software development teams were in the process of greatly improving finite element analysis, which enables analysis of complicated structures by subdividing them into smaller sections—called finite elements—like a mosaic. Once the simpler engineering problems are solved for each smaller section, the results are stitched back together to get a better picture of the whole.

NASA has contributed significantly to developing finite element method software systems since the 1960s. Advances in the 1980s with STAGS, for example, resulted in major improvements to the analysis of complex structures like an airplane wing or fuselage, parts of which might bend or buckle to create sudden reactions, sometimes in multiple locations simultaneously.

"At the time, there was a lot of effort at Langley on damage models and crack propagation," Davila recalls, noting that the researchers at NASA and elsewhere weren't just working with STAGS but also other finite element analysis software suites. "It was a time when the nonlinear tools were maturing," he says, referring to nonlinear finite element analysis, which models the strength and behavior of materials even as they undergo significant structural changes such as deformation, straining, and cracking.

"It was a good time to influence both the software vendors and the companies that needed these tools," he adds.

A little more than a year after the Aloha accident, the National Transportation Safety Board issued a 258-page report concluding that Flight 243's fuselage damage began in a lap joint on the left side of the aircraft as a result of multiple-site fatigue cracking that undermined the fail-safe characteristics in the aircraft's design.

The event was a warning to both the aviation industry and the public about the dangers of aging aircraft and the need to better understand how aircraft respond to stress over time. Finite element analysis was needed as much as ever to simulate how structures would respond to stress and eventually fail, and developers continued to improve their software suites significantly throughout the 1990s.

Technology Transfer

By the early 2000s, finite element analysis had come a long way, but so had the materials engineers were building with. The aerospace industry, in particular, was moving toward lightweight composite materials instead of metals such as aluminum and titanium alloys. The change had significant implications for failure analysis: because these newer materials are more brittle, they are susceptible to delamination, and they fracture in a combination of different failure mechanisms that are not experienced by traditional metallic structures.

Developers working on Abaqus Inc.'s finite element software suite, which had been around since 1978, began a major upgrade to incorporate the advances of the previous decades with a focus on fracture and failure, especially of composite structures.

At the time, manufacturing processes were getting more complex and expensive, as were the physics problems faced

Image courtesy of Ariens Company

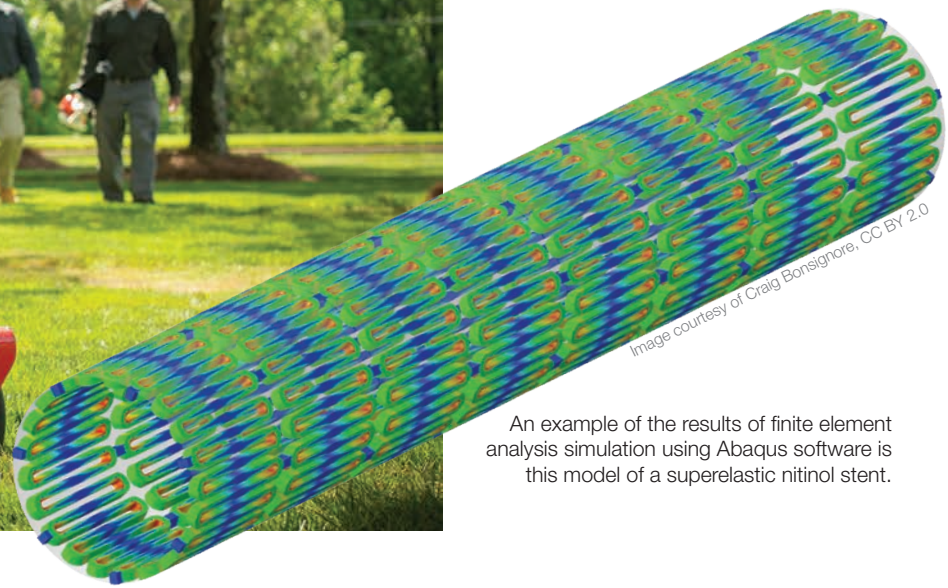


Image courtesy of Craig Bonsignore, CC BY 2.0

An example of the results of finite element analysis simulation using Abaqus software is this model of a superelastic nitinol stent.

Abaqus finite element analysis software is used not only for aeronautics but also in a wide range of industries, including by manufacturers of medical devices, windshield wiper blades, credit cards, and automobile tires. Engineers used the tool to help design the latest Gravely brand lawn mower.

by engineers working with the increasingly complicated materials. "So there was a tremendous interest in proving the ability to simulate some of these structures from beginning to end in a code like Abaqus," says Dale Berry, senior technical director at SIMULIA Marketing, which Abaqus now falls under.

French software company Dassault Systèmes bought Johnston, Rhode Island-based Abaqus Inc. in 2005 and continued to develop the software under its then-new SIMULIA brand, along with other simulation products. As part of the upgrade, SIMULIA developers formed and met regularly with a Fracture Customer Review Team, which consisted of Abaqus customers—including NASA—and others who were interested in seeing the product develop. Many of the capabilities of the STAGS code were added to Abaqus over time.

"We met as a team for many years as the effort matured," says Berry, noting that NASA and some of the STAGS development crew were active participants in these meetings, which continued through 2015.

"The spirit was to come talk about what's working, talk about what's next, how to prioritize, and really try to let us, on the Abaqus side, know what our next steps should be," Berry says. "Once the code was delivered, perhaps the next year, they would be very involved in helping test it and make sure the capabilities met their needs."

These NASA-Abaqus interactions continued with varying degrees of formality. In some cases, Abaqus developers might have merely read a paper by NASA researchers, and in other cases, NASA researchers developed benchmark problems to compare Abaqus' upgraded capabilities to analytical solutions or solutions from other codes.

The relationship continues to this day. Abaqus developers are now part of NASA's Advanced Composite Project, a consortium of industry and other partners who participate in weekly teleconferences to articulate their needs or discuss how software advances might be implemented.

"We have always been in communication with the Abaqus team," says NASA's Davila, who still uses the software every day.

Benefits

Today, Abaqus finite element analysis software is used in a host of industries in addition to aerospace. Engineers have used it to develop and optimize windshield wiper blades, tires, and composite airframes. It has helped model stents for human hearts. Engineers used it in the latest Gravely brand lawn mower, a streamlined machine with 50 percent fewer parts and less expensive production costs. And students at the Norwegian University of Science and Technology are designing award-winning Formula Student race cars with the software.

One company, TWI Ltd., formerly The Welding Institute, is even using the latest Abaqus product suite to model complicated 3D-printed parts that previously required many more time-consuming trials, fixes, and retrials.

Reducing the number of physical trials is a key goal for the software, according to SIMULIA's Juan Hurtado, who works on nonlinear mechanics functionality in the Abaqus code.

"Physical tests are very expensive," he says. "If you can minimize testing by doing the design in the computer and simulating the response of these materials to whatever loads, you can use those predictions to optimize your design." ❖

Super-Accurate Atomic Clocks Could Aid in Navigation, Communication

NASA Technology

Do you know what time it is?

Knowing the answer—being able to measure time accurately and consistently—is fundamental to advanced scientific research at NASA and elsewhere. But it could also be the key to what comes next after GPS.

The best clocks are atomic clocks, and the best atomic clocks currently made "won't lose a second in the entire life of the observable universe," says Gregory Heckler, the deputy telecommunications systems manager for NASA's Tracking and Data Relay Satellites (TDRS) at Goddard Space Flight Center.

Unfortunately, those clocks tend to be enormous—filling up an entire laboratory—and so impractical, to say the least, for a satellite. To make a clock small enough to fit on a satellite, scientists are currently able to achieve pretty decent accuracy, good to maybe a second of drift in 30,000 years, but there's still plenty of room to improve.

The differences can be traced to the type of atom at the heart of the atomic clock and how it's being measured. An atomic clock works because, when excited, atoms emit radiation at a certain measurable—and constant—frequency. That frequency provides the "tick" of the clock, the same way a gear turning works in a mechanical clock.

Traditionally, atomic clocks have used cesium, which emits radiation with a frequency in the microwave region, something you'd measure in gigahertz—billionths of a second—explains Heckler. These are the clocks that have been around long enough to be miniaturized and have already flown in space.

Increase the frequency, however—say into the optical region, measured in terahertz—and the clock's accuracy increases proportionally.

To give a sense of what that means, says Heckler, imagine you're drawing a ruler. With cesium atomic clocks, you can get hash marks accurate down to about a centimeter apart. "But what we can do with this tech coming out is making that ruler much more precise, down to tens of nanometers. That's an improvement of four or five orders of magnitude of measurement accuracy."

This kind of improvement could lead to significant scientific advances, Heckler says. For one thing, "with this sort of measurement accuracy, you can do experiments to further confirm general relativity."

Better clocks could also result in far better maps, he adds, because satellites orient themselves in space in part by synchronizing themselves to some known standard time. And improved synchronization could also expand the possibilities of smallsats, which, if synchronized well enough, could act as a single, dispersed instrument.

Heckler says these are just the start: "we're going to get four or five orders of magnitude increase in this capability, and that always historically has led to great things."

Technology Transfer

To get there, however, there need to be small, portable optical atomic clocks, and one company working on that problem is Sunnyvale, California-based AOSense Inc., with the help of several Small Business Innovation Research (SBIR) contracts from NASA, most of them with Goddard.

"The lab devices are awesome," says AOSense's former vice president of strategic planning Jamil Abo. "They're just not practical. We're doing the engineering necessary to make this thing a lot smaller, a lot more robust, and able to operate autonomously and at low power."

That's a big job, he notes, "because we have to reimagine all the components that go into a clock—take each piece and reengineer it in a professional way."

Although the full clock is still a work in progress, AOSense has completed some of the components, including the atom source, which is cooled by a laser. "We have to cool the atoms down to nearly absolute zero to make these measurements," Abo explains. "This is a source that allows you to do that, but we've engineered it down to a much smaller size."

Where the lab version probably consumes hundreds of watts of power, he estimates, the AOSense version consumes less than five, and the whole unit is "small enough to fit in a shoebox."

In fact, the AOSense atom source actually outperforms the large academic version, which means that "the academic labs aren't building their own anymore—they are buying ours."

Benefits

Among the customers, he says, is Jun Ye, a professor at the University of Colorado and a fellow at the National Institute for Standards and Technology, the Federal agency that provides the official time for the United States. "Our source provides 10 times as many atoms per second, which ultimately makes the clock roughly three times better," notes Abo.

There's not a big market for these atomic sources, he acknowledges, saying sales are in the tens per year, "but it helps sustain our engineering efforts" toward the finished atomic clock, and "it's great that these can flow back to academia already so they can improve on the measurements they're making."

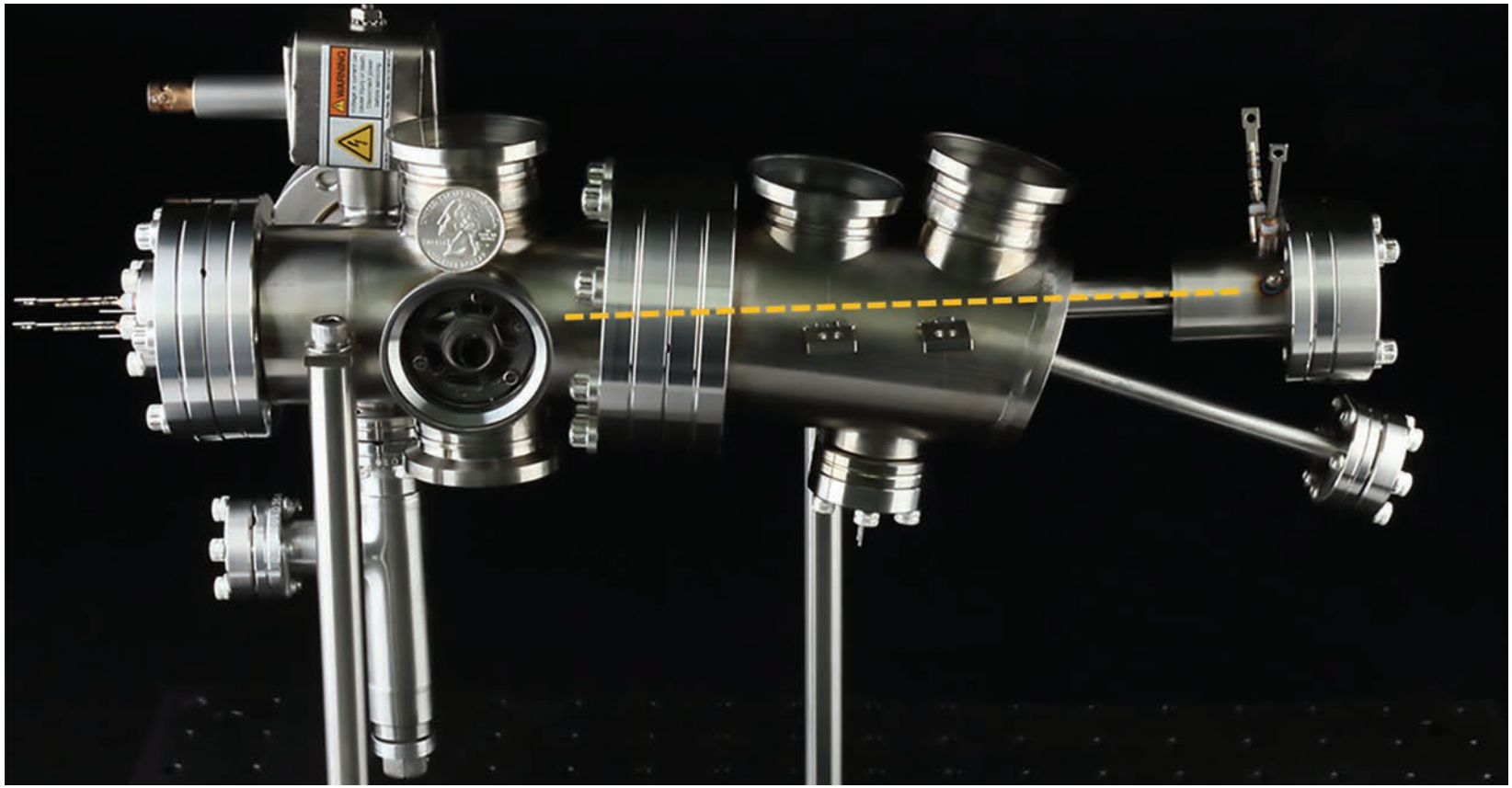
The company has also used NASA SBIR contracts to develop the clock laser (with sales on the order of 50 a year) and the frequency comb. "Each of these are components we can sell," Abo says. "It's a fairly specialized field, but researchers really like the stuff we're building because it is built very robustly and plugs well into their current systems."

This satellite uses GPS data to study independent rendezvous of spacecraft in orbit. GPS relies on synchronization with highly accurate atomic clocks on the ground, but NASA is interested in flying clocks of that caliber on spacecraft.

“Ultimately, if you want **to know** your **position to 10 meters,** you need **to know** your **time to** roughly **10 billionths** of a **second.”**

— Jamil Abo, formerly of AOSense

Many people may not realize that every cell phone call, ATM transaction, and GPS-enabled app relies on timing cues from satellites—which in turn are synchronized with atomic clocks on the ground. AOSense is working on making atomic clocks that could fly on a satellite orders of magnitude more accurate than anything that’s flown before.



This laser-cooled atomic source "powers" an optical atomic clock. Unlike lab-size versions, this source consumes less than five watts and fits in a shoebox, while actually outperforming its larger predecessors.

Eventually, AOSense plans to incorporate each of the components into a fully functional, compact, rugged atomic clock. For that, they anticipate a larger market, and a wider impact not just for science but also for everyday people, who may not realize they are already relying on satellite synchronization for every cell phone call, every ATM transaction, and every phone app that uses GPS.

"Ultimately, if you want to know your position to 10 meters, you need to know your time to roughly 10 billionths of a second," Abo explains. "In order to communicate, I'm sending some bits to you, and you need to synchronize to interpret those bits. All these things, all transfer of information is based on some level of synchronization between my system that's sending and yours that's receiving it."

Right now, the GPS satellites that provide this timing reference stay accurate by synchronizing with a bank of atomic clocks based at the Naval Observatory, but AOSense is looking to a future when each satellite could have its own timing reference, which, in addition to increasing accuracy, would also make it less vulnerable to cyberattacks.

"The satellites that broadcast GPS are about 20,000 miles away. It's amazing in that it's an incredibly low signal, and it works very robustly—but it's also very easy to interfere with," he notes. "For about $100 in parts, you can build a GPS jammer that can knock out GPS for several square kilometers."

That could threaten all the many systems we—the public, the financial sector, the military, and more—have come to rely on. And although the military and some others have built-in security measures to guard against these weaknesses, AOSense argues that a navigation system built into the vehicle itself, rather than relying on signals from satellites, would be safer.

Their system would look to inertial navigation: "like the Boy Scouts, carry a compass and count steps," Abo says, but with an atomic clock and incredibly precise accelerometers and gyroscopes.

"The better you can do that, the better you know where you are. And you carry it with you, so if something really goes haywire, and you don't have GPS or you seem to be getting a weird signal, you have something on board."

For a commercial jet, that could be a life-saving backup, and for a military jet flying a nuclear weapon, it might even be prudent as the first-line navigation system. ❖

Probes Characterize Air and Water Flows over Aircraft, Yachts

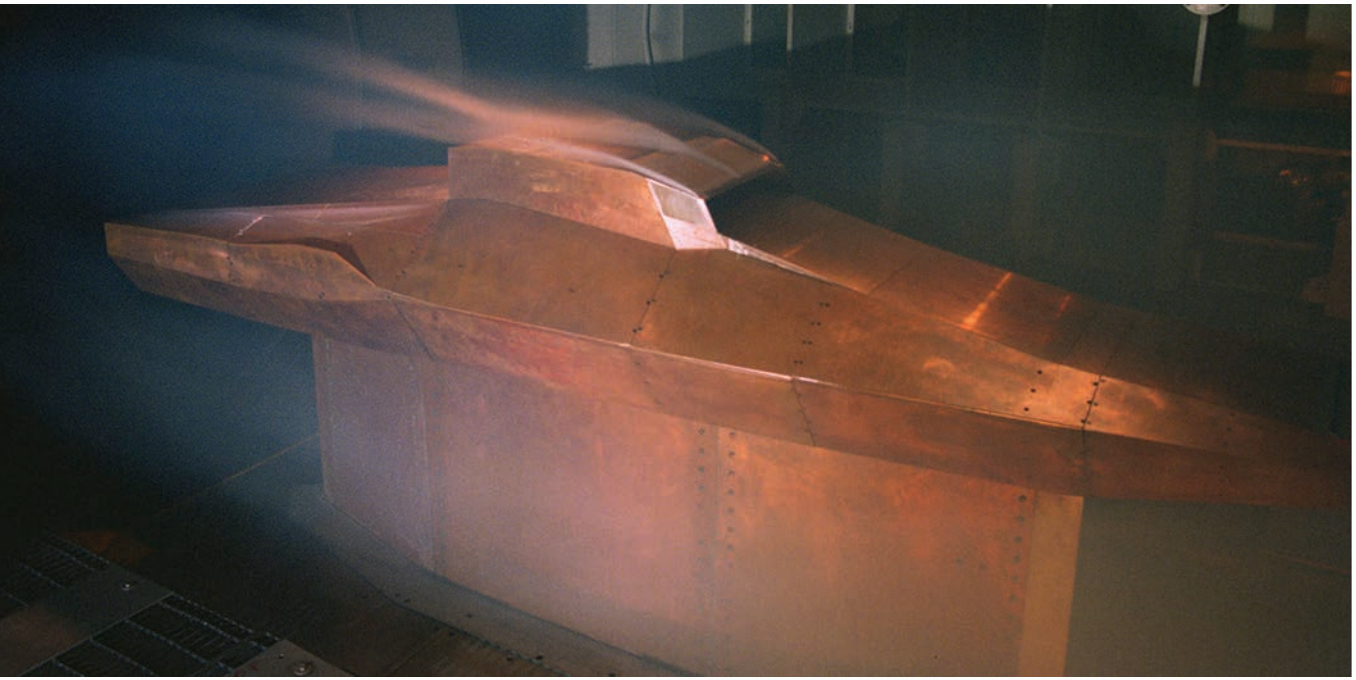
NASA Technology

A new approach to characterizing high-speed turbulence in wind and fluid flows is on track to become the standard for wind tunnel measurements—and is finally catching on in the aircraft-design industry and even among yacht builders.

Devices for measuring fluid speed are known as anemometers. NASA uses anemometers to characterize the behavior of unseen structures of airflowing around models of aircraft in wind tunnels or actual aircraft in flight. In wind tunnels, these flow fields, shock waves, and boundaries between relatively slow- and fast-moving air and any turbulence among them predict flight performance. Characterizing airflow behavior has also helped NASA learn about hypersonic flight.

All this testing also provides data for the creation and validation of aerodynamic modeling and simulation software known as computational fluid dynamics, which the Agency and industry use to evaluate aircraft designs well before wind tunnel testing. And anemometers are used to evaluate wind tunnels and establish baseline flow behavior before testing.

Tao Systems Inc. first pioneered the constant voltage anemometer (CVA) under two Small Business Innovation Research (SBIR) contracts with Langley Research Center in 1992, releasing it as a commercial product not long after. CVAs offer advantages over the long-established technology for monitoring airflows in wind tunnels and other applications, but they have yet to see widespread use.



Langley Research Center funded Tao Systems' efforts to make the first constant voltage anemometers (CVA) in the early 1990s, primarily for high-speed wind tunnel testing. Here, the experimental X-43 hypersonic aircraft undergoes testing in Langley's eight-foot, high-temperature wind tunnel. Tao Systems is still the only company producing CVAs, which provide highly accurate wind velocity and temperature readings.

"It takes a while for people to replace what they know with a new approach that is technically superior but requires retraining," says Arun Mangalam, president of the Hampton, Virginia-based company. "However, the CVA has been purchased by top researchers worldwide, including NASA." Indeed, Langley is preparing to pit Tao's CVA against similar technology in a wind tunnel.

Anemometers use a wide variety of probes. The CVA, as well as constant temperature anemometers (CTA) and constant current anemometers (CCA), usually use probes consisting of a tiny, extremely thin wire held in the wind with an electrical charge that heats it.

The faster air or other fluid passes over the wire, the faster it draws heat from the wire. Because the sensor resistance decreases the colder it gets, the anemometer can derive wind speed from the resistance in the wire.

A traditional CTA adjusts its voltage to hold the wire at a constant temperature. From the change in voltage, flow velocity is derived. A CVA, in contrast, holds input voltage constant, deriving flow velocity from output voltage.

Technology Transfer

NASA saw the CVA that Tao Systems proposed in the early 1990s especially as an advantage for testing in high-speed wind tunnels. This is because it's capable of taking readings at extremely high frequencies—up to 1 million per second. That high bandwidth is important when the airflow the sensor is attempting to characterize is passing at several times the speed of sound. The requirement for the rate of measurement is related to the size of aerodynamic structures in the flow and the speed of the flow, with the measurement of small structures at high speed requiring extremely high frequencies.

The CVA system can take such high-frequency readings because it naturally regains equilibrium more quickly than related systems. When voltage is held constant, an increase in resistance resulting from a rise in temperature naturally

causes a decrease in current, which brings the temperature back down, Mangalam explains, noting that related systems don't have the same stabilizing feedback loop.

With funding from the early Langley contracts, Tao Systems built prototypes, including software to run them, and tested and proved these advantages. Over the years, further SBIR work with Armstrong Flight Research Center and Johnson Space Center used the CVAs for in-flight measurement of turbulence and shockwaves and to monitor heat flux associated with shockwaves.

In addition to measuring flow velocity, the probes can also detect temperature fluctuations. They become sensitive to temperature variations at very low voltage levels too weak to heat the sensor. To detect wind velocity, the wire has to be heated.

Much of the company's work with NASA had the ultimate goal of a closed-loop flight control system that would use data from sensors on an aircraft in flight to allow it to automatically respond to flows and turbulence around it (*Spinoff* 2010), a project that is still in progress. Constant voltage anemometry is critical to this work.

Some of the NASA projects used hot-film sensors, rather than hot-wire sensors. These operate on the same principle but characterize surface friction rather than flow velocity because they take measurements right at the surface. Tao Systems offers both hot-film and hot-wire anemometer sensors, as well as entire arrays of surface hot-film sensors, which it calls Senflex. The films don't have quite the bandwidth the wire sensors do, Mangalam says, but he says he's working with NASA and the Air Force to mitigate the issue because the films are more robust.

Image courtesy of Dale Frost, CC BY 2.0

Tao Systems' CVAs measure liquid velocities just as well as they measure wind speeds, and they've been used to design America's Cup-winning yachts, among other applications. Meanwhile, the company's latest CVA, the high-bandwidth, multi-channel Model 4-600 (inset) is currently under testing at Langley to compare the CVA with other types of anemometers.

Benefits

"With this anemometer, I can do things in milliseconds that would take minutes with others," says Langley research engineer Greg Jones, who is overseeing the CVA testing at Langley's National Transonic Facility (NTF). He notes that the NTF, one of the most advanced wind tunnels in the world, operates at a high cost. "Using this technology I should save thousands of dollars because I can do everything much quicker."

Mangalam says this is mainly due to the probes' ability to rapidly shift back and forth between the low temperature ranges that detect temperature and the higher temperatures that sense velocity. Conventional systems would instead use multiple sensors at different dedicated temperatures and risk burning out if temperatures are changed too rapidly.

Jones says this also applies to ambient temperatures, which can alter a CTA's sensitivities and burn it up if it isn't adjusted just right. "With the CVA, you don't have that problem. It's got this huge temperature range. I'll have greater confidence in the results and cleaner, quieter signals." Again, this is particularly important in the NTF, where temperatures range from -250 to 140 °F.

He also says the company has wrapped software around the device designed to make it intuitive and user-friendly.

Tao Systems remains the only CVA manufacturer.

While the primary users for the technology have been and will likely continue to be NASA, the military, and aircraft manufacturers, Mangalam says there are other applications. Researchers working on managing heat in fuel cells have purchased it to monitor heat flows. The Air Force uses it not just for aircraft but to characterize flows and turbulence in the stratosphere. Others have used it to measure velocity fluctuations in a helicopter rotor and to measure flows through plane engines.

And the devices work just as well with liquids as with air. "America's Cup winners have used our technology for assessing turbulence characteristics, such as the extent of laminar flow and turbulent flow on lifting surfaces," Mangalam says, referring to the international yacht race.

"It's mostly used in research applications," he says. "But wherever you need anemometry with high bandwidth and spatial resolution, this is the best there is." ❖

Public Safety

Staying safe in space, which means dealing with a total lack of air and dangerous radiation among other things, is no easy feat. In this section, you will read about technology designed for astronauts, like the breathing regulator that provided safe oxygen to John Glenn, which has been adapted for pilots, oil workers, and everyday people. You'll also see how even seemingly unrelated scientific missions can end up saving lives on the ground—like corrected GPS that helps first responders find accident scenes and robots that can step in for humans in dangerous settings.

NASA Brings Accuracy to World's Global Positioning Systems

NASA Technology

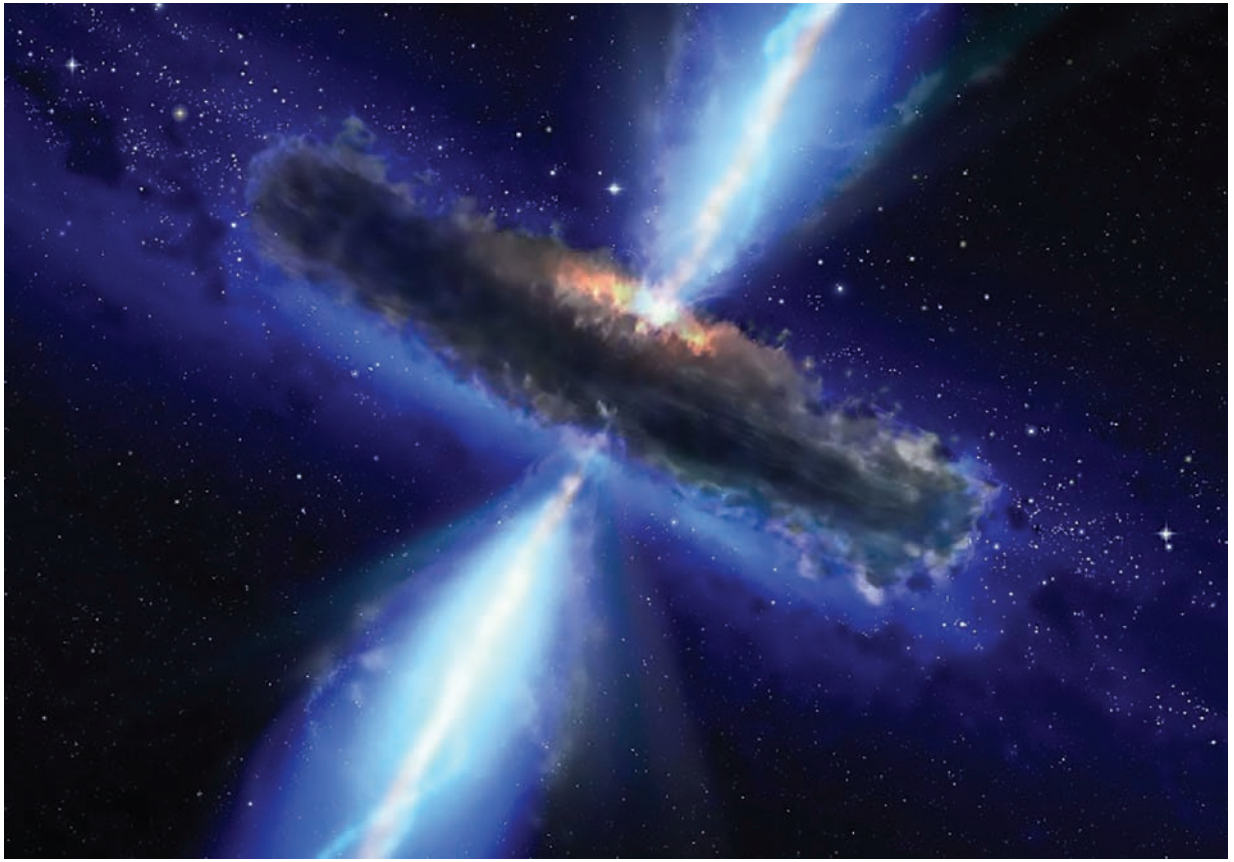
In the 1960s, NASA used a network of radio telescopes and a technique called very large baseline interferometry (VLBI) to capture images of quasars in distant galaxies. In the following decade, scientists reversed the process to determine the precise locations of the telescopes, painting a picture of Earth's shape and orientation in space. Today, an evolution of that technology supports another location-based system that has arguably become the world's most important communication infrastructure: the Global Positioning System (GPS).

When the first GPS satellite was launched in 1978, NASA's Jet Propulsion Laboratory (JPL) already had experience in tracking radio signals from faraway sources and extracting valuable information from them. Using VLBI, for example, JPL scientists measured the time difference between when the same radio signals from quasars—some of the brightest objects in the universe—hit different telescopes around the world to conduct geodesy, assessing Earth's size and shape.

These capabilities served as the springboard that let JPL recognize early on the potential that GPS held and compelled the center to invest in the technology and infrastructure to support it.

In the early 1980s, as the U.S. Air Force continued launching GPS satellites, JPL started building out a tracking network, collocating the first ground stations with VLBI tracking sites. These offered the necessary communications infrastructure and precise location information to tie the geodetic reference frame to that of GPS. Today the network includes more than 80 receivers, making it the world's largest geodetic-quality, centrally managed GPS tracking network.

Raw GPS data can produce positioning errors of 30 feet or more if not calibrated for signal delays caused by electrons and gases in Earth's atmosphere, errors in GPS satellite positions, and noise and drift in the satellites' atomic clocks. The software JPL developed to model delays, correct for errors, and perform GPS orbit determination and receiver positioning was called GIPSY-OASIS (GPS-Inferred Positioning System and Orbit Analysis Simulation Software). It quickly became one of NASA's most widely licensed software programs, with hundreds of licenses to academia and industry.



The Jet Propulsion Laboratory (JPL) got involved with the Global Positioning System (GPS) in the system's early days because JPL researchers had experience tracking radio signals from quasars, some of the brightest objects in the universe, to precisely locate radio telescopes on Earth's surface, giving an accurate picture of the planet's shape and orientation in space.

But no one was able to make these corrections in real time on a global scale until the Internet became widespread in the mid-1990s. Shortly after the GPS satellite fleet became fully operational in 1994, JPL received a small amount of funding from NASA's Deep Space Network program to figure out how to use GPS data in real time to enable faster turnaround time for deep-space navigation. That seeded the development of JPL's Real-Time GIPSY (RTG) software, which could make all these corrections and update them every second.

The corrections also were globally and uniformly valid, in contrast to the prevailing approaches at the time, which corrected signals based on local information, leading to

corrections that were only valid regionally and suffered from degradation when the satellites rose and set on the target region.

Once JPL had demonstrated precision global GPS in real time, a host of new possibilities opened up.

"We took an innovative approach to the opportunities and challenges the free Internet offered, and we also had the vision to recognize that real-time GPS processing on a global scale could be revolutionary," says Yoaz Bar-Sever, who was one of the developers of GIPSY and RTG and is now the manager of the Global Differential GPS (GDGPS) system at JPL. "But we were still surprised by the scope of the impact of the new capabilities we were building."

Technology Transfer

In the mid-1990s, both industry and government began forays into the use of GPS corrections to improve positioning, navigation, and timing. In 1995, Satloc, a small company vying for the U.S. market of industrial GPS corrections, licensed RTG and became the first provider of RTG-corrected GPS service across most of North America.

The following year, the Federal Aviation Administration (FAA) selected the software as the prototype for its Wide Area Augmentation System (WAAS), with the goal of providing accurate GPS navigation for pilots, and offered funding for JPL to further mature the technology.

"We had the track record, and we had the only proven software to do what they wanted," says Bar-Sever.

Another key investment in 2000 from the NASA Earth Science Technology Office helped JPL put in place the operational technology and infrastructure needed to launch a reliable, global, real-time service, and the GDGPS system was born. "As the Internet became more prevalent, we were able to get orbital determination in seconds globally," Bar-Sever says. "That led a lot of industry to us."

While NASA remained a key user of GDGPS, its ongoing development ever since has been funded almost entirely by other government users and commercial companies.

The Federal Aviation Administration invested in Global Differential GPS (GDGPS) early on for the development of its Wide Area Augmentation System, which now lets tens of thousands of smaller airplanes land at most North American airports in low visibility, using GPS guidance.

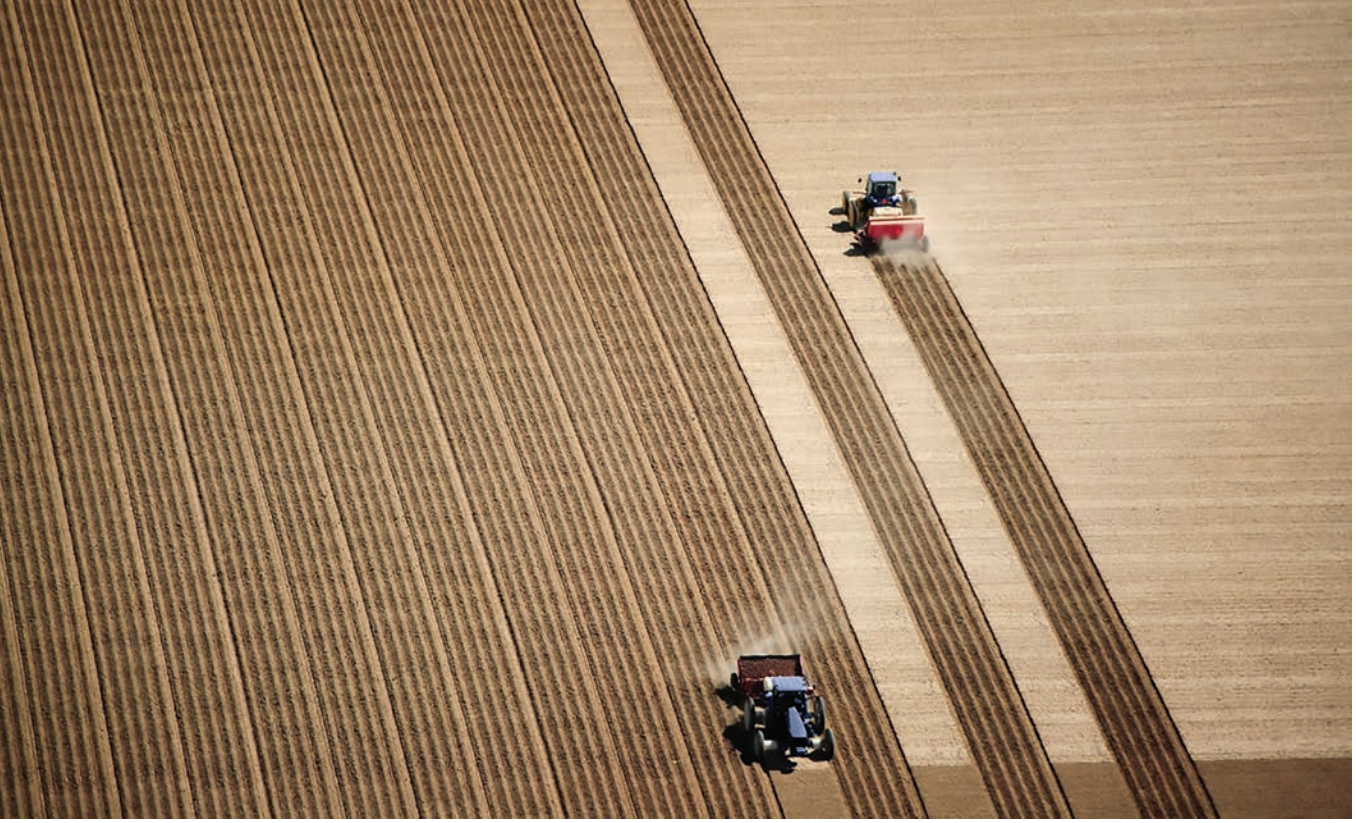
As word spread of the accuracy and global coverage of GDGPS, in 2002, the Air Force sponsored the development of a dedicated service to provide a wealth of information to its GPS operators, a service that has been enhanced over the years to adapt to the evolving GPS constellation and continues to this day. "In supporting operational GPS, the GDGPS system contributes to the reliability of the entire GPS enterprise," says Bar-Sever.

Also in the early 2000s, GDGPS found its first major commercial customer in the farm equipment company John Deere, which invested heavily to help JPL engineers make the system practical and reliable for guiding self-driving tractors (*Spinoff* 2017). The technology made precision farming commonplace around the world.

By this time, the system enabled positioning accuracy to within less than three inches.

Another early adopter was Comtech Telecommunications Corporation, which became a customer in 2002 and remains a major provider of location-based services, among other technologies. As cell phones became more prevalent, the Federal Communications Commission mandated that all providers include the ability to immediately locate 911 emergency callers. This capability was initially Comtech's main use of GDGPS, and it still provides the service for about half of U.S. cell phone owners, as well as millions of others around the world.

Comtech, headquartered on Long Island, sells its software and applications to mobile phone operators and original equipment manufacturers, explains Tsega Emmanuel, the company's product manager for advanced location services. On an emergency call, an initial, rough location can be determined from a network of mobile towers and GPS



The first major commercial customer for GDGPS was John Deere, which worked closely with JPL scientists to make the system practical for self-driving farm equipment, a technology that would eventually make efficient precision agriculture commonplace around the world.

satellites in the vicinity, and then company's positioning engine uses JPL data to refine the location based on satellites available to the mobile device. Since the caller might not stay in one place, the positioning engine provides responders with periodic updates.

"GDGPS connectivity has to be reliable. To assure device location accuracy, everything has to be reliable," Emmanuel says.

Benefits

Between the mid-1990s and the mid-2010s, GDGPS technology and data were at the heart of three technological revolutions with broad societal benefits, Bar-Sever says. "The first was the creation and deployment of WAAS, which revolutionized the safety and economy of commercial aviation." This was followed by the broad industrial application of corrected GPS, especially for precision agriculture. "And finally came its widespread usage to enhance the safety and utility of geolocation for mobile wireless users."

Comtech has long been at the forefront of that latest revolution. In addition to increasing safety and security with accurate emergency call locations, the assisted GPS capability provided by the company and others is the reason smartphone navigation applications have a short "time to first fix"—locating themselves almost immediately, unlike vehicle GPS units that can take time to acquire satellite connections.

With the help of GDGPS, Comtech has also become one of the top providers of location-based services for asset tracking, navigation, and social media. These use the same positioning engine, enabled by technology embedded in a high-value asset or even in a pet collar for tracking. Friend-finding and other location-based social media apps rely on the company's technology.

In all these instances, the equipment manufacturer or app writer creates and markets the product under its own name but relies on Comtech's data for positioning. The company computes more than 10 billion locations per month around the world.

JPL's GDGPS "is part of the value chain," Emmanuel says. "If we don't have it, we don't have accurate location. We don't have a product."

WAAS became operational in 2003, with Raytheon licensing the software to support it for the FAA (*Spinoff* 2015).

By 2014, about 73,000 planes across North America had been outfitted with the capability to use WAAS for navigation and, critically, to guide landing. While commercial airliners travel exclusively between major airports with instrument landing systems and have onboard navigation systems that combine GPS with inertial reference systems and radio beacon tracking, smaller planes were previously limited in where they could land, especially in low visibility. Now similar systems, based on software JPL and Raytheon developed to support WAAS, also guide planes in Japan and India.

John Deere eventually developed its own precision navigation technology for self-driving farm equipment, but only after relying on GDGPS as it established precision agriculture as a worldwide practice that saves farmers resources, increases yields, and cuts down on pollution.

A number of other industries rely heavily on GDGPS, but, says Bar-Sever, few require it more than offshore oil drilling operations. "They've got to do surveying, find a target reservoir, figure out where to drill and where to build a platform, and then navigate ships near them in rough seas," he says. And much of this has to be carried out without a landmark in sight. "They need high accuracy and super-high reliability. It's a high-risk, high-dollar operation."

GDGPS data is also commonly used in mapping, surveying, construction, and various Earth sciences. There are about a dozen companies around the world that provide corrected GPS data, and many of them are GDGPS customers.

NASA is using the system to enable an instrument on the Space Agency's Sentinel 6 mission—scheduled to be launched in 2020—that will improve weather forecasting in the United States and Europe. "Just like water refracts

light, the atmosphere refracts the GPS signal, and you can infer how much water is in the atmosphere, which is a key parameter in weather forecasting," Bar-Sever explains.

These days, GDGPS also monitors and processes data from the world's other navigation satellite systems—the Russian Global Navigation Satellite System, the Chinese BeiDou system, the Japanese Quasi-Zenith Satellite System, and the European Galileo system that's expected to go into full operation this year. It's an arrangement that benefits all users. "When you have more satellites, you can get more accurate and reliable positioning, especially in urban canyons," Bar-Sever says. "It also improves atmospheric observation. It enhances the overall capability."

The original RTG software couldn't have supported these other constellations. In 2010, though, the GDGPS team started a major overhaul of the software as part of a $1 billion contract with the Air Force to create the ground segment of a next-generation GPS system known as OCX, with Raytheon as the prime contractor. In 2014, the next-generation software, known as RTGx, replaced RTG as the operational engine of GDGPS.

"The years of GDGPS experience and refinements of RTGx are invaluable for a software that will be at the heart of operational GPS, with national security, the global economy, and the well-being of billions of people all at stake," says Bar-Sever, who also manages the JPL contribution to the OCX project.

OCX and its corresponding space segment have yet to go live, but he says the overall renovation of the system is bringing many advances, especially to cybersecurity and accuracy. "All users will benefit from better accuracy and timing."

The JPL team is working, for example, to achieve unprecedented accuracy to guide self-driving cars. "The accuracy that industry demands is very difficult to achieve," Bar-Sever says. "We're working on that with the support of the aggregate of our customers."

And none of this touches on the benefits enjoyed by the hundreds of entities that have licensed the GIPSY, RTG, and RTGx software. For example, DigitalGlobe, the satellite Earth-imaging company that provides the imagery Google and Bing use to build their maps, uses GIPSY to

Comtech, one of the earliest commercial customers for GDGPS, uses the data to provide first responders with locations for emergency cell phone calls for about half of U.S. cell phone users and millions of others around the world.

Smartphone navigation apps have a short "time to first fix," rarely having to search long for a satellite signal, thanks to data from JPL's GDGPS.

guarantee the precise coordinates where each image was taken (*Spinoff* 2010).

NASA itself has been, since the beginning, a prime beneficiary of GDGPS, especially considering that it has been funded primarily by outside customers. JPL's Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) craft, which studies changes in Earth's crust, glacier or vegetation cover, hydrology, and more, uses the system to enable its global operations. Precise navigation is critical when the craft needs to revisit areas and precisely repeat its earlier trajectories to observe any changes.

The Agency also promotes the application of precision GPS to detect and monitor earthquakes and predict tsunamis all over the world with its GPS Real-Time Earthquake and Tsunami Alert Project. "NASA has been supporting the demonstration of the technology's natural hazard-monitoring capabilities," Bar-Sever notes, adding that the goal is to ultimately transfer these capabilities to the National Oceanic and Atmospheric Administration.

With so many systems and industries coming to rely on precision GPS, as well as the millions of regular GPS users Bar-Sever says, "there is no more important communication infrastructure than GPS."

All the while, JPL has never stopped building ground stations and evolving the software, continuously reinvesting the funding it receives from its customers.

"It's provided NASA with significantly more than its seed investments in the system," says Bar-Sever. "It's a multi-beneficial system that continues to benefit NASA and the U.S. Government."

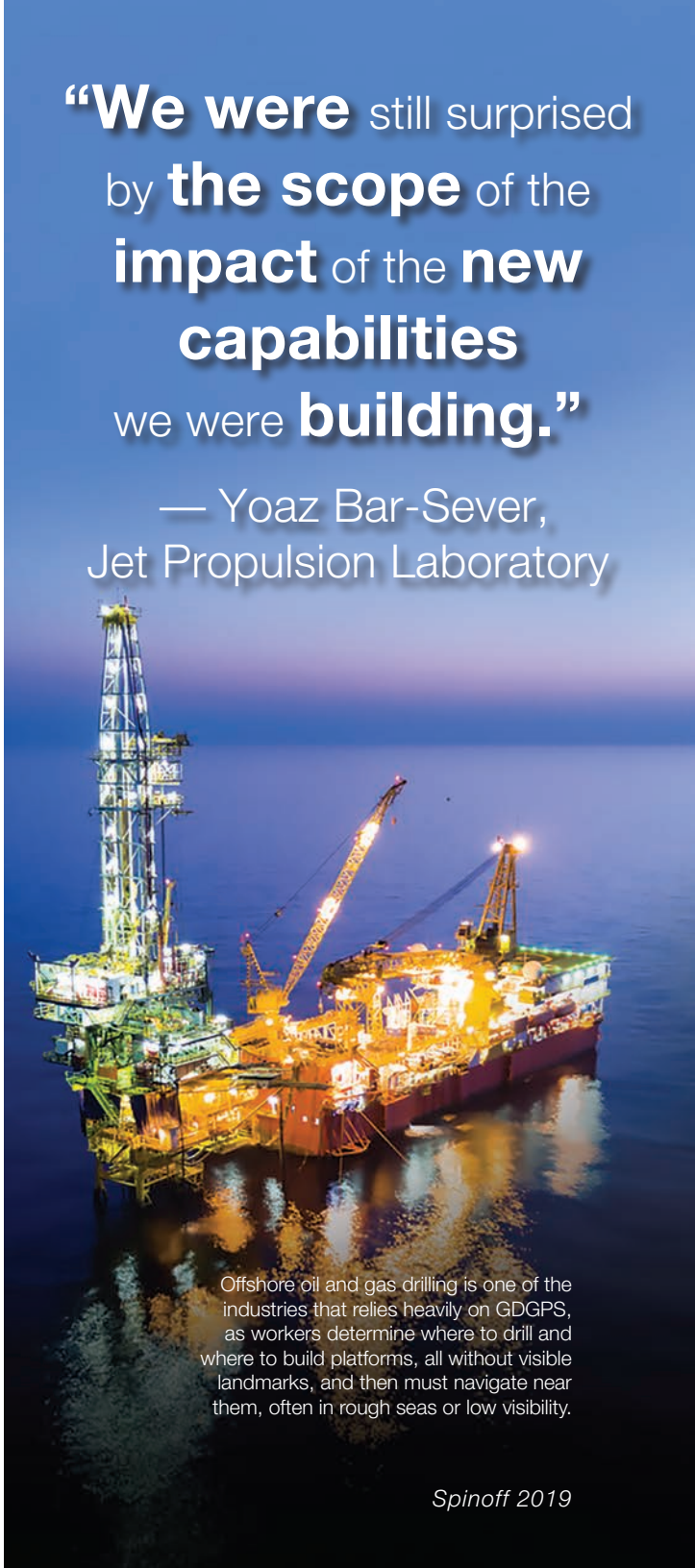
He notes that the many GDGPS customers share both the load and benefits of continually updating the system's capabilities, a necessity in the rapidly evolving domain of satellite navigation. "What's emerged is a self-supporting system, providing its customers and NASA many returns on their investment," he says. "This is the poster child for the tremendous value to NASA, the country, and society of the Agency's reimbursable programs." ❖

Through NASA's GPS Real-Time Earthquake and Tsunami Alert Project, GDGPS is used to predict and warn of impending tsunamis all over the world, and also to monitor earthquakes.

Image courtesy of Sadatsugu Tomizawa, CC BY-NC-ND 2.0

"We were still surprised by **the scope** of the **impact** of the **new capabilities** we were **building."**

— Yoaz Bar-Sever, Jet Propulsion Laboratory



Offshore oil and gas drilling is one of the industries that relies heavily on GDGPS, as workers determine where to drill and where to build platforms, all without visible landmarks, and then must navigate near them, often in rough seas or low visibility.

Gas Regulators Keep Pilots Breathing

NASA Technology

In 1962, John Glenn hurtled around Earth at speeds that exceeded 17,000 mph, managing three orbits before splashing down in the Atlantic Ocean. In all, his historic flight—the first time an American reached orbit—lasted four hours and 56 minutes.

And through it all, he was able to breathe, something we all take for granted day-by-day on the ground but which required important innovations for spaceflight.

Since that day, all U.S. astronauts, and many from other countries as well, have used a derivation of the same oxygen regulator that allowed Glenn to breathe in 1962. Current plans for the Orion capsule involve new innovations and technology, but there too, the breathing regulators trace back to that first one used on Project Mercury.

And around the world, commercial airline pilots rely on backup oxygen systems that also developed out of that first regulator.

But it all goes back to a problem with jet engines that no longer exists.

"Early jet engines had problems with flameouts," explains Jim Talty, vice president of engineering at Cobham Mission Systems, the Orchard Park, New York-based business unit of Cobham PLC. The solution required injecting oxygen to restart the engine, but it was important to regulate the flow and pressure of that oxygen: too much, too fast would cause another flameout, but not enough and the ignition wouldn't catch.

The company's solution to this problem was successful, and Cobham (then operating as Carleton Controls) became known for its devices to regulate gas pressure, so when NASA needed to build its life-support machinery for astronauts, the Space Agency turned to them. After all, explains Talty, "the basic technology of regulating oxygen is the same for a breathing regulator: you need to knock it down to a pressure where an astronaut can breathe it. The product was different, but the technology was the same."

Back in the early days of spaceflight, astronauts flew with pressurized canisters of pure oxygen. Today's astronauts, as well as the planned Orion crewmembers, breathe a mix of oxygen and nitrogen, closer to the ratio that exists in Earth's atmosphere. Either way, the gas or gases must be released slowly and carefully. Much like the jet engine, if too much air comes out too fast, it will hurt the astronaut, but too slow and the astronaut could asphyxiate.

For Orion, engineers have designed a system that will keep cabin pressure the same as Earth sea level, 14.7 pounds per square inch (psi), far higher than the 5-psi pure-oxygen environment of early spacecraft. But that pressure is too high for a spacesuit, which needs to be flexible enough for the astronaut to have mobility. To acclimate to a manageable 4.3-psi spacesuit, astronauts have to prepare their bodies for up to a couple days—and the spacecraft has to help by changing the pressure and gas mixture in predictable and safe ways, including hitting set pressure levels along the way that enable safety checks for leaks on the spacesuits.

"Cobham is going to do that with a smart electric motor that knows where it goes every time," explains Johnson Space Center's John Lewis, who is the Orion environmental control and life-support system manager. "In the past, we've used dual-setpoint regulators—they were basically done with leakages and levers. This is done with a full-on motor because we have to hit multiple points."

Behind the motor lies a small mechanical system: a spring-loaded valve that opens when the pressure lowers enough to relax the load on the spring. That was where Cobham needed to innovate for Mercury and the requirements of human spaceflight.

Technology Transfer

Cobham's oxygen regulators for fuel also relied on springs, but like many things for space, the version for Glenn needed to be smaller and lighter. "What they innovated back in the late '50s, early '60s was combining two different springs in a new way," explains Talty.

John Glenn, Gus Grissom, and Alan B. Shepard were the first three men in space. A breathing regulator created for Glenn's historic first orbit has continued to evolve and has since served every U.S. astronaut.

"They found that with this spring arrangement, they maintained their performance in a smaller size. Nobody had tried to combine those two types of springs in a single product, and that led to a lot of our other products."

It was also important to ensure that none of the materials were flammable, because as pressure increases in a pure-oxygen environment, the risk of a dangerous fire increases significantly. Even objects that normally would not ignite, like stainless steel, can begin to act like tinder, notes Lewis.

Cobham had worked on this problem with its fuel regulators too, but the danger is far more acute when building a breathing regulator for astronauts, so the team had to further enhance its expertise and testing protocols to ensure their safety.

“Every U.S. astronaut since **John Glenn** has **breathed off** our **equipment. That gives** other **customers** in the **military** and **commercial world** some **confidence** that **we know** what **we’re doing.”**

— Jim Talty, Cobham Mission Systems

Today, most commercial airlines equip their cockpits with emergency oxygen systems based on the technology Cobham Mission Systems developed for John Glenn’s orbit. For safety, at least one pilot is required to use the breathing system whenever the plane flies at altitudes above 40,000 feet.

Cobham's gas regulators, which needed to be small and lightweight to work in space, are now also used by high-altitude parachutists.

To do that, it learned from NASA, which was already building its own expertise on oxygen safety and lowering fire risk, and the company continues to grow from that base: "Everything we learned from NASA on how to choose materials for oxygen safety is used in these products," emphasizes Talty, referring to Cobham's line of commercial products.

Lewis adds that today, there are "two groups of people in the world that I have confidence in when I talk oxygen fire safety," and one of them is Cobham.

Benefits

Today's gas regulators have advanced in significant ways since the first version for Mercury, much like the Orion regulator that is automated with an electric motor to hit a half-dozen setpoints. However, Talty says, "the same techniques that were used back in the John Glenn days, we're using them in our latest products, too."

As a company, he adds, Cobham Mission Systems is known for its expertise in high pressure management: "that's the core that started and still drives us today. In terms of human environment, that traces back to John Glenn and NASA."

The company has now branched out well beyond aerospace and has grown significantly, notes Eric Stellrecht, product group director for space at Cobham Mission Systems. "We probably were a 5- or 7-person company when we worked on Mercury, now we're 500. Was it all due to this? No, but the NASA work certainly contributed to that growth."

Today, says Talty, "most major airlines use our technology." Specifically, the breathing regulators are used in emergency oxygen systems for pilots. These are required for at least one pilot when flying at altitudes above 40,000 feet, and also come into play whenever there is an emergency that depressurizes the cockpit.

Other applications for the breathing regulators include military planes and submarines, as well as elite military parachutists jumping from high altitude.

Cobham also used its expertise in oxygen safety to create a product that takes room air and produces high-purity oxygen—between 99.5 and 99.99 percent pure—for a variety of settings, including wastewater treatment and offshore drilling. The system, the company notes, is ideal for remote areas, where oxygen canisters would otherwise have to be delivered—and could potentially run out.

"We handle the highly critical, difficult applications where failure is not an option," Talty emphasizes, noting that in those situations, many customers find the NASA credentials reassuring.

"Every U.S. astronaut since John Glenn has breathed off our equipment. That gives other customers in the military and commercial world some confidence that we know what we're doing." ❖

RoboMantis Offers to Take Over Dangerous Missions

NASA Technology

Moving slowly and deliberately, the robot picked its way over a pile of cinder blocks, testing and often reconsidering every step of its four black, tubular limbs, each bending and twisting at an unnatural number of knees and elbows. Though it never raised more than one leg at a time, the four limbs steadily worked together to shift the weight of its white, headless, tub-like torso until it eventually mounted and descended the heap to move on to other challenges.

"Slow is smooth, and smooth is fast," says Brett Kennedy, head of the Jet Propulsion Laboratory (JPL) robotics team that built RoboSimian for the 2015 DARPA Robotics Challenge. The event called for automatons capable of carrying out disaster relief and rescue operations deemed too risky for human aid workers.

"The assumption is, you're in an environment where you don't get to make mistakes," Kennedy says. "By being careful and moving without mistakes, we can execute the overall operation faster."

Jet Propulsion Laboratory (JPL) engineers built RoboSimian to compete in the 2015 DARPA Robotics Challenge, where it had to perform tasks like clearing a path through rubble, traversing a heap of cinderblocks, and driving a vehicle. Even before the competition's final rounds, the entire robot was available for license as a package.

While some other entries, especially two-legged models, suffered falls and struggled to right themselves, RoboSimian remained as steady as the metaphorical tortoise, always with at least three limbs anchored when it wasn't sitting upright to roll on four wheels installed on its hindquarters and ankles. "We didn't make a recovery-from-fall capability because we couldn't figure out how to make it fall in the first place," Kennedy says.

At the finals in Pomona, California, working with equal deliberation, the robot drove a vehicle, dismounted while clinging to the vehicle frame, cleared a path through rubble, cut a hole in drywall, and opened and navigated doors, among other challenges.

RoboSimian operates with "supervised autonomy." For example, while it relies on a human operator to recognize a door and pick out the handle, it figures out for itself how to turn the handle and push or pull the door open. "The human's never going to tell the robot to move this or that joint," Kennedy says. "That's basically math that the robot's going to be better at than a human is."

There are also way too many joints for an operator to work them all at once. Each limb has seven, because, ball-and-socket joints being difficult to build and control, one hinge/pivot joint is necessary for each of the six degrees of freedom in three-dimensional space, plus an additional one to allow for different positions of the limb that keep the hand in the same place.

The actuators that power the joints include brakes that let the robot hold long, awkward poses, helping to make it "patient," meaning it can hold a position at low power if it needs to wait for an operator's decision. Each joint also has the torque of an F-150 truck. "This is a robot that can do pull-ups," Kennedy says, noting that it can hang from a single finger.

While it has no head, three sets of stereo cameras at one end of the torso can give the appearance of a face. Above them, a lidar device spins constantly, and two more sets of stereo cameras on its underside and one set on each side give it wraparound vision. While the lidar, which uses reflected

Much of the technology and expertise behind RoboSimian came from JPL's long history of building robots, such as the versatile, limbed and wheeled ATHLETE freight-carrying robots designed for planetary operations.

laser signals to map the space around it, is highly accurate, it creates an incomplete picture. The stereo cameras present the opposite—a complete but somewhat inexact 3D image.

Combining the two technologies to give the robot accurate vision and enable autonomous navigation is an old trick for JPL engineers, one that was developed for Mars rovers in the 1990s. In fact, much of RoboSimian's technology expands on and updates features of earlier JPL robots, such as the six-limbed LEMUR systems built in the late 1990s and early 2000s with space station construction and maintenance in mind, and the limbed and wheeled ATHLETE freight-carrying robots constructed soon after for planetary operations.

That's not to say building it was easy.

"There were definitely a lot of hardware bugs," Kennedy says, noting that trying to integrate, for example, an actuator with the encoder that plugs into it and the motor that spins beside it can produce unexpected results, which then require changes to the software. Commercial parts were often used in capacities they weren't designed for. "Putting these systems together was an enormous challenge in and of itself."

RoboSimian ranked fifth out of 23 robots in the competition.

Technology Transfer

Even before the finals, the California Institute of Technology, which manages JPL, made the entire robot available for license as a package.

The idea was not necessarily for a licensee to recreate RoboSimian but for it to enable new robot technology. For one thing, the robot was built with a modular design that would allow parts and systems to be rearranged. For example, JPL followed it up with the semi-humanoid SURROGATE robot that used one of the limbs as a spine to enable flexibility. The original robot was also packed with technology and solutions—actuators, sensors, simplified interfaces—that could be repurposed. "RoboSimian is a toolbox of technology," Kennedy says.

Robotics company Motiv Space Systems, located not far from JPL in Pasadena, California, licensed the technology and started up a subsidiary, Motiv Robotics. While the company did sell one exact replica of RoboSimian to Duke University, its engineers, including two who did some work on RoboSimian at JPL and another who worked on robots at both JPL and Johnson Space Center, used it as a starting point for a next-generation version. That robot, the alternately five- or six-limbed RoboMantis, was unveiled at CES in January of 2018, after years of research and development.

"RoboSimian was designed for disaster response and working in hazardous areas. This is basically version 2.0 of that concept," says Chris Thayer, president and CEO of Motiv Space Systems. The overall themes are still present, he says, such as stability, the modular design, and similar walking ability, stereo cameras, and lidar sensors, "but what's under the hood is quite different."

The most obvious difference is that, where RoboSimian gets around on all four of its identical limbs and then sits up to use its forelimbs to do jobs, RoboMantis takes the concept of stability even further, with four legs dedicated exclusively to mobility, each with a wheel on the foot. One or two additional arms, depending on the model, carry out the robot's actual work.

The newer model is also thoroughly upgraded. Motiv created entirely new software with increased computational ability on the open source Robot Operating System, making it publicly available. RoboMantis retains RoboSimian's

Motiv Robotics' RoboMantis is based on the company's license for JPL's RoboSimian but represents updates to most of the systems, components, and software. With four legs on wheels and either one or two arms capable of wielding various tools, the robot is intended to carry out jobs that are hazardous to humans.

modular design, but the team made the interfaces between modules quicker and easier to put together. The company designed its own actuators to power the robot's joints, with even higher torque, based partly on limbs Motiv has built for Mars rovers.

The power system also had to be entirely rebuilt, as RoboSimian experienced a dangerous explosion due to thermal runaway in its lithium-ion battery. RoboMantis still uses lithium-ion batteries, but they're off-the-shelf military models.

The newer robot uses a similar vision system of lidar and stereo cameras, although Thayer says it benefits from advances in stereo vision. Indeed, he says, RoboMantis takes advantage of upgrades that have been made across the board since its forebear's construction. "Having that refresh in technology is important. New advances are made every year."

Benefits

While RoboMantis is an upgrade, it leans heavily on JPL's work, says Brett Lindenfeld, vice president of operations at Motiv. "To do this from scratch without outside financing was unrealistic, so it made sense to leverage NASA's investment," he says. "They put millions of dollars into this over the years, and they demonstrated the utility of this configuration. That gets leveraged by us as we stand on its shoulders."

The new robot's first customer was Rutgers University, which received a five-limbed RoboMantis in early 2018.

But Motiv's target clientele for the robot is any company or organization that does work in hazardous environments—from disaster relief to the oil and gas industry—where it can stand in for a human. For example, to clean the inside of a large chemical container, workers currently enter the container in protective suits, Lindenfeld says. "Instead, you could send the robot in, and RoboMantis can work like a Roomba." Lindenfeld says the company's engineers are developing tools like a power-washing attachment for the robot arms, according to the needs they hear from potential users.

Military applications like bomb disposal represent another possibility. Thayer says he hopes to see RoboMantis in chemical plants, power plants, oil fields, subterranean operations, and other industrial settings. Since its debut, he says, "we discovered pretty quickly a broad interest in this type of robot and what people want to do with it."

He notes that the company might also end up selling pieces of the technology. For example, the military has expressed interest in the manipulators, while some others are primarily interested in the power system. "We show the total package to customers, and maybe they just need a subset of those capabilities," he says.

But the primary goal is an off-the-shelf robot for industrial purposes. "We're definitely hoping we can be the benchmark platform for mobile robots in a number of different fields," Thayer says. "We're hoping to supply these by the tens and even hundreds, and I think that's certainly a possibility, given the conversations we're having today."

Kennedy says his team at JPL is excited to see a new version of its robot make its way out into the world. "We've been building robots for a pretty long time, but something we haven't done much is push the technology for commercial and terrestrial use," he says. "Hopefully, this gives us another way of helping out the Nation by being able to feed technology to our companies." ❖

"**RoboSimian** was **designed** for **disaster response** and **working** in **hazardous** areas. **This is basically** version 2.0 **of that concept**."

— Chris Thayer, Motiv Space Systems

Image courtesy of the U.S. Air Force

Bomb disposal is just one dangerous job RoboMantis could take off of human workers' hands. The company hopes it can stand in for people in dangerous emergency rescue, oil and gas, chemical handling, mining, and other operations that pose significant risk to life and limb.

Wrapped Tanks Cut Weight on Everything from Buses to Paintball Guns

NASA Technology

What do naval anti-missile guns, infant incubators, the Phoenix Mars lander, and high-end paintball guns have in common? All these technologies—and many others—employ an invention developed at NASA in the 1960s and '70s to cut weight from the planned Space Shuttles.

The invention was a tank design that could safely store gases and liquids at higher pressures than previously possible. Known as composite overwrapped pressure vessels (COPVs), they comprise a liner—usually metal but sometimes plastic—tightly wrapped in high-strength filament embedded in resin, and they can weigh around 50 percent less than the all-metal pressure tanks that are still used where saving weight and space is less important than saving cost. The higher pressure allows the same amount of gas to be stored in a significantly smaller cylinder.

While the concept is simple, developing and testing the tanks was not. Scientists at Lewis Research Center, now known as Glenn Research Center, spent years exploring different combinations of liners, fibers, and resins, as well as various winding patterns and testing methods. But these were not just NASA researchers.

From 1963 to 1965, the Douglas Aircraft Company was contracted to investigate the structural properties of filament-wound pressure vessels. A follow-on contract with Aerojet General Corporation continued the investigation into the use of thin metallic liners in glass filament-reinforced pressure vessels. In 1971, four of the Aerojet engineers involved formed their own company, Structural Composites Industries (SCI), to continue the work under contract to Lewis. SCI would go on to become the first company to manufacture the composite pressure tanks for commercial use.

Due to the interaction of liners and fibers, failures in these tanks are harder to predict and address, and nondestructive testing methods traditionally used to evaluate pressure vessels, such as ultrasonic thickness measurement, were not sufficient. Extensive burst testing—filling the vessels to see when and how they failed under different conditions—was carried out on various designs at Lewis. SCI also created a computer program to design and analyze the vessels, calculating stresses and strains at various pressures over their lifetimes and establishing optimum physical characteristics based on capacity, temperature, and weight requirements.

Each Space Shuttle ended up incorporating 24 composite vessels supplied by General Dynamics, another early COPV manufacturer, to store pressurized helium and nitrogen, for propulsion and life support, respectively. They saved a total of 752 pounds per Shuttle, compared with all-metal tanks.

Technology Transfer

In 1970, Kennedy Space Center hosted a Technology Utilization Conference to determine how NASA might help meet the needs of municipalities. Improved firefighters' breathing systems were targeted as an area of need—the rate of respiratory injury among firefighters was on the rise—and NASA's expertise in life-support systems promised a solution. Based on input from fire departments, it appeared that firefighters too often chose not to use their breathing equipment because it was cumbersome and restricted movement.

Central to the problem were the size and weight of systems' steel pressure vessels. Several alternatives were considered, and engineers settled on an aluminum liner wrapped in fiberglass filament as the best replacement. Johnson Space Center managed the project, and SCI was one of two companies Johnson contracted in 1972 to supply the cylinders. A typical composite cylinder the company created under the program weighed 26 pounds and could hold as much air as a 41-pound steel cylinder. This was

Image courtesy of the U.S. Air Force

High-end paintball guns use composite overwrapped pressure vessels (COPVs) to pack more air pressure into the same-sized tank.

because it stored air at 4,000 to 4,500 pounds per square inch gauge (psig), about twice the 2,215 psig typical of firefighters' breathing systems.

Several major cities field-tested NASA's Firefighter Breathing System, finding that it reduced injury rates and was welcomed by users (*Spinoff* 1976). Composite cylinders are now commonly used among firefighters.

Boeing soon used SCI's composite cylinders to save 200 pounds on its 747 airliner, where they stored the gas that would fill inflatable escape chutes in the event of an emergency (*Spinoff* 1977), another use that is now commonplace. SCI led the commercial composite overwrapped pressure vessel industry for years after, finding an ever-growing array of applications for the lightweight, high-pressure tanks. The company was purchased by Worthington Industries in 2009, but its production facilities, still located in Pomona, California, remain among the leading manufacturers of this NASA-invented technology.

Image courtesy of the U.S. Air Force

One of the first applications for COPVs outside NASA was for the tanks in firefighters' breathing apparatuses, making them significantly smaller and lighter.

Image courtesy of the U.S. Navy

High-powered Phalanx guns, made to shoot down incoming missiles at close range, are powered by huge COPVs.

Benefits

What was SCI's main product is now a small part of Worthington's diverse business, but the company sells 60,000 to 80,000 composite pressure vessels per year, ranging in size from 2 by 8 inches to about 2 by 10 feet, says Daniel Orton, product manager at Worthington. "They're just everywvhere. It kind of boggles the mind sometimes."

Manufacturers still wrap the cylinders in fiberglass filaments, as well as Kevlar, and carbon fibers developed in the 1990s can reduce weight by an additional 20 percent.

Besides inflating the escape chutes on virtually every airliner in the sky, composite pressure vessels now hold the oxygen for the planes' emergency breathing systems and the gas that ejects their landing gear in case of emergency.

On helicopters, they hold air for pilots to breathe and, in emergency situations, to blow doors open and inflate emergency floats.

Among the most common applications—and the largest tanks—are the pressure vessels that hold compressed and liquid natural gas for fuel on buses and other vehicles. Worthington's composite tank customers include bus manufacturers Bluebird and Gillig, as well as UPS, Chevrolet, Honda, and other vehicle producers. In 2017, the company developed a 10,000-pound-per-square-inch tank for hydrogen-powered vehicles.

Breathing apparatuses also constitute a popular usage, not just for firefighters but for aviation, life support, deep sea diving, and high-altitude parachuting. Medevac vehicles use Worthington products in infant life support systems known as isolettes. Aqua Lung, one of the original scuba gear manufacturers, is a customer.

The lightweight tanks are also popular for military applications. The British Royal Navy saved 1,500 pounds per ship by replacing the steel cylinders on its minesweepers with Worthington's composite cylinders, and the air-powered Phalanx guns used by the U.S. Navy and others to shoot down missiles at close range are pressurized with the cylinders. Sounding rockets use them for inertial control

in their guidance systems. The Naval Research Center's first hydrogen fuel cell-powered drone, the Ion Tiger, uses Worthington composite tanks, and the AAI Shadow military drone uses them to power its takeoff slingshot.

"They got real popular about 10 years ago, even for paintballers," Orton adds. "They can go shoot each other all day long with that much pressure."

Composite pressure vessels are commonplace in the space industry where they originated, and where weight and volume are always primary concerns. Helium-filled composite tanks are often used to pressurize fuel tanks in space systems, as Worthington's do on the Antares rocket, the Phoenix Mars lander, and several others. They're also found in the Ariane 5 rocket's ignition system and the Falcon 9's landing legs. On the International Space Station, they're in the gas detection system and also inflate Bigelow Aerospace's Expandable Activity Module.

The Space Agency has never stopped pioneering this invention. Marshall Space Flight Center partnered with a company to address the tanks' vulnerability to impact damage, resulting in "hybrid" filament-wound and composite-overwrapped models resistant to high impact and fire (*Spinoff* 2004). More recent developments include high-strength carbon nanotube fiber overwraps and an automated system for monitoring the cylinders' structural integrity.

Countless companies and end users have benefited, Orton says, because "NASA asked, 'Is it possible to make a lighter-weight cylinder than we have now?' And they came up with this solution." ❖

"They're just **everywhere. It kind** of **boggles** the mind **sometimes."**

— Daniel Orton, Worthington Industries

Breathing apparatuses for aviation, life support, high-altitude parachuting, and deep sea diving are common applications for COPVs.

Image courtesy of Pirot4D, CC0

Membranes Mimic Kidneys to Filter Water

NASA Technology

When trying to solve a tough problem, it's not unusual for engineers to turn to nature for a solution.

"Nature is our biggest R&D lab. Whatever discoveries nature has made, they're quite efficient," says Peter Holme Jensen, CEO and cofounder of the company Aquaporin A/S.

One problem NASA has faced since its early days is the need to filter water efficiently. Given the great cost of ferrying water into space, as much moisture as possible has to be recycled into drinking water aboard spacecraft. On the International Space Station (ISS), every drop of moisture, from humidity to urine, is filtered, purified, and reused. But the current system relies on heavy filtration beds that weigh down resupply missions and have to be swapped out every 90 days. It also fails to filter out certain semivolatile contaminants.

A chance encounter at a seminar in 2007, where Jensen met Michael Flynn, lead for the Advanced Water Recycling group at NASA's Ames Research Center, introduced a possible solution. Jensen and colleagues had been working to develop a water filtration system based on aquaporins—the proteins that all living cells use to transfer water through their membranes.

Aquaporins enable plant roots to absorb water from soil and human kidneys to filter about 45 gallons of fluid per day, for example, and they come in hundreds of varieties.

"They've evolved over billions of years of life to carry out specific functions," Flynn says. "These proteins are great because you can pick them out and use them for what you want."

Moreover, he adds, they're highly selective, meaning only water passes through and not contaminates.

By the time Jensen and Flynn met, Aquaporin A/S had been founded in Copenhagen, Denmark, but the team was still struggling to incorporate the proteins into a viable film for filtration.

"They were basically a bunch of kids who wanted to come here and do some testing, and it sounded like a good idea," Flynn recalls, noting that NASA had plenty of data on existing water filtration systems for the Aquaporin team to run comparisons.

He ordered some prototypes with funding from the Agency's Next Generation Life Support project.

"At that time, we were 15 or 20 nerds with no commercial activity and no industrial production," Jensen says. "To say our first paying customer was NASA—that was something that really resonated with everyone at Aquaporin." Collaborating with the Space Agency also helped to attract investors, top employees, and attention in the company's early days, he adds. "You don't have to argue that you have something people need. You don't have to argue that you have quality. People know."

It took three more years, but in late 2010, Aquaporin arrived at Ames with test prototypes.

Technology Transfer

The company works with two basic types of filter—one for reverse osmosis, which uses pressure to push fluid through a filter, and one for forward osmosis, which operates without any energy or outside influence. In forward osmosis, with polluted water on one side of a membrane and saltwater on the other, the physics of entropy dictate that the salt spread evenly through all the water. But since the salt can't pass through the membrane, it draws all the

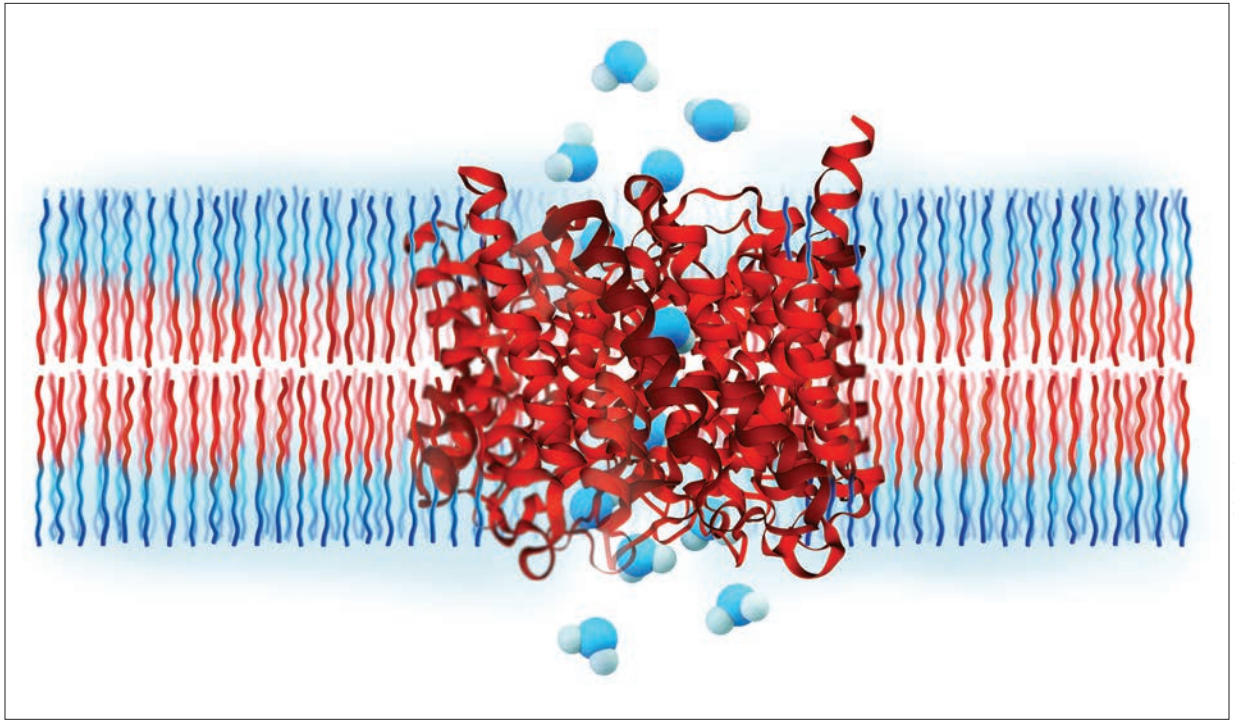


Image courtesy of Vossman, CC BY-SA 3.0

Aquaporins are proteins found in the membranes of living cells. Most allow water—and only water—to pass through the membrane, conducting water molecules from one side to the other rapidly but in single file. The first image of an aquaporin was taken in 1999.

Image courtesy of the European Space Agency

Astronauts on the ISS tested prototype water purification systems based on membranes infused with aquaporin proteins. The testing, which validated both forward and reverse osmosis-based systems, was sponsored by the European Space Agency and overseen by NASA.

water from the other side of the membrane, leaving only pollutants behind. To purify water for drinking, sugar has the same effect.

"When you apply pressure, eventually, the membrane clogs," Jensen says. "In forward osmosis, since you don't apply pressure, it's more like a sponge sucking up water. The membranes have a much lower tendency to clog." Flynn notes that this also means forward osmosis can handle very dirty water, eliminating the need for distillation.

This is what NASA is ultimately interested in, and it's what Aquaporin built for Ames and successfully tested over the course of three years, using sugar water to extract clean water from urine. With life-support systems as one of its primary missions for decades, Jensen notes that Ames even has its own urine collection center, although he adds, "It's not real astronaut urine—it's just NASA Ames employees."

The tests confirmed that the prototype Aquaporin membrane outperformed the system used on the ISS, including removing most semivolatile compounds.

Further tests on the space station, sponsored by the European Space Agency (ESA) but overseen by Flynn, have proven the technology works just as well in space and that the proteins are stable enough to last at least a year—the longest test so far, he says. "There's been no change in performance—it's been rock solid."

Testing on the ISS used the hollow-fiber membrane Aquaporin developed for forward osmosis, but it was tested using both forward osmosis and pressure-driven reverse osmosis. NASA is considering replacing the filtration beds on the existing water purification system, which operates in reverse osmosis, with an aquaporin membrane. In the future, though, the Agency would like an entirely new, forward osmosis-driven system.

Aquaporin A/S has a line of reverse osmosis-based under-sink water filters available through distributors primarily in India and China.

> “This is where we are really pioneering on a totally different level and can change the water purification landscape completely.”
>
> — Peter Holme Jensen, Aquaporin A/S

Danish company Aquaporin A/S is making a line of forward osmosis-based water filters available. The company hopes the technology will radically change industrial water purification, eliminating pre- and post-treatment steps, with membranes that rarely if ever need to be replaced.

In 2014, as the original Ames work was wrapping up, the company perfected its formula and started moving toward industrial production. The trick hadn’t been producing the proteins, says Jensen, but embedding them in a membrane. “That was what it took 20 people eight years to figure out.”

Aquaporin A/S also started Aquaporin Space Alliance, a joint venture with Danish Aerospace Company, to build the capability to produce water purification systems for NASA and ESA.

Benefits

The company now sells household under-sink modules made with its Tap Water Reverse Osmosis Membrane, to distributers abroad, especially in China and India, where Jensen says there is a huge market for home water purification. Globally, he says, home water filters represent a $27 billion market.

He says the reverse osmosis products filter water about twice as fast as other existing home purifiers, due to the proteins’ efficiency. They also nearly double the water recovery rate. In home systems, 70 percent or more of the water is used just to clean contaminants off the back of the membrane. “It’s not millions, it’s billions of liters of water that are wasted on a daily basis,” Jensen says, noting that many of the places that require water purification are also among those with the highest stresses on water supply.

The company is working on membranes that can use reverse osmosis to desalinate seawater at higher efficiency and lower cost than existing technology, and it’s also investigating the use of forward osmosis for desalination.

But Aquaporin mainly has industrial uses in mind for forward osmosis, such as treating wastewater in the oil and gas, food and beverage, dairy farming, and textile industries, among other businesses that generate large amounts of highly polluted wastewater.

The company is partnering with more than 50 wastewater treatment companies that have purchased and are pilot-testing forward osmosis membranes and considering new, industrial-scale systems built around them.

“This is where we are really pioneering on a totally different level and can change the water purification landscape completely,” Jensen says.

Systems built with Aquaporin Inside Forward Osmosis products can eliminate pre- and post-treatment steps. In animal farming, the membranes’ high selectivity lets them recapture urea from wastewater for fertilizer. In the pharmaceutical industry, they can trap active ingredients that other systems can’t, and they can even be used to collect virus particles for vaccines.

The new Aquaporin A/S production facility is equipped to produce 2.5 million square meters of membrane per year, for both forward and reverse osmosis. The company now has more than 100 employees.

Jensen says NASA’s patronage was especially important to developing forward osmosis membranes, which have a longer path to the mainstream market and therefore are less attractive to investors. “They’re not afraid to make the first move,” he says of the Space Agency.

“We do research in areas the private sector doesn’t want to for whatever reason,” Flynn says, noting that the established membrane industry has little incentive to develop products that need to be replaced only rarely, if ever.

His branch at NASA’s Ames Research Center hopes to eventually turn Aquaporin’s work into a product that will never need replacing, because it will heal itself. By genetically engineering bacteria to produce aquaporin proteins in a lipid membrane, NASA could create a forward osmosis filter with the resilience and regenerative power of the small intestine, he says. “You can really do horrible things to the intestine. You can swallow a paper clip, and it will fix itself.” The technology is still 10 to 30 years from feasibility, though.

He says Aquaporin, one of a handful of companies now manufacturing proteins for commercial use, is part of a movement that will pay off sooner than that. “Aquaporin is an example of a really interesting trend in technology right now—the ability to manufacture biological machines, or biomimetics.”

While companies have used proteins, for example, to make drugs or raw materials, Flynn says, “In the commercial sector over the next 10 years, you’re going to see a dramatic transformation, where they’re going to start making biomimetic consumer products”—like Aquaporin’s Tap Water Reverse Osmosis Membrane, which, he notes, is basically “a kidney to put under your sink.” ❖

Detailed Spectrometry Makes Dangerous-Materials Testing Safer

NASA Technology

In Chris McKay's search for signs of life on other worlds, some of the strongest clues can be found by identifying isotopes.

The Ames Research Center planetary scientist says his favorite isotopes are those of carbon, sulfur, and nitrogen, in that order, "because biology does interesting things with them and leaves an isotopic signature." For example, he says, the ratio of different isotopes in a carbon sample can reveal whether it's a product of biology. And his favorite compound is water, which carries isotopic evidence of its many phase changes between gas, liquid, and solid.

The Mars Curiosity rover, for which McKay is a co-investigator, has a mass spectrometer that can identify some of these isotopes, but it has its disadvantages. It has to physically collect a sample and then use turbopumps to create a vacuum in which to analyze it. The spectrometer's lifespan will likely be determined by how long the turbopumps last, McKay says, noting that researchers are forced to make tough choices about which samples are worth analyzing. In its first five years, Curiosity only tested about 15 samples with the instrument.

By contrast, another of the rover's tools has run more than 15,000 analyses. The laser spectrometer can zap any surface from a distance and determine its chemical content by observing the resulting flash. For a few brief nanoseconds, the surface molecules are ripped apart in a burst brighter than the surface of the sun, and as they reassemble, still blazing, they reveal their identities to an optical spectrometer. Every substance emits a different light signature as its molecules reconstitute. Curiosity's laser spectrometer can quickly and easily analyze hundreds of surfaces without the rover moving an inch, and with no moving parts, it's likely to far outlive the mass spectrometer, even while being used much more heavily. This technique, known as laser-induced breakdown spectroscopy (LIBS), has been used for decades.

But a laser ablation spectrometer can only identify chemical elements, not their isotopes. It is blind to much of the information encoded in its test subjects, missing many of the clues McKay relies on in his search for extraterrestrial life.

So in the early 2000s, Alexander Bolshakov, then a senior researcher at Ames, proposed fine-tuning LIBS technology to the point that it could recognize even the slight shifts in electrons that result from varying numbers of neutrons in an atom's core—to spot isotopes, in other words.

But he had trouble getting funding.

With SBIR funding from Ames Research Center, Applied Spectra was able to build the first device that uses laser ablation to detect different isotopes of an element. The technology will need further development, but the company has sold units to a university and a major corporation.

Technology Transfer

"Nobody actually believed that this was possible," Bolshakov recalls. He finally got a two-year National Research Council grant that let him start work at Ames. Then, in 2007, he left NASA to join Fremont, California-based Applied Spectra, which applied for and won a series of Small Business Innovation Research (SBIR) contracts with Ames to continue the work.

But even McKay, who lobbied for the SBIR funding and oversaw the contracts, had his doubts.

"No, I didn't believe it could be done," McKay says. "But I thought if it could be done, Rick and Alex could get it done, and I thought it was worth a try. I saw the importance of it." (Rick is Richard Russo, founder and executive chairman at Applied Spectra.)

The problem was that laser ablation spectroscopy is "a pretty blunt-force technique," McKay says, while the difference between isotopes is subtle. He compares it to firing two similar cannonballs at each other and trying to observe which is heavier.

For one thing, the moment when molecules in a laser-zapped sample reconstruct themselves while continuing to emit light is exceedingly brief. To have a chance at identifying isotopes, that time window had to be extended as much as possible, and the spectrometer watching it had to focus exclusively on that moment with the highest spectral resolution possible. The engineers had to shape and control the laser pulse, use the right detection sensors, and program them to observe just the right moment and the right wavelengths.

"Turns out, they did it," McKay says.

Applied Spectra calls the result Laser Ablation Molecular Isotopic Spectrometry (LAMIS).

Benefits

Just as isotopic signatures could reveal a trove of information in McKay's search for evidence of extraterrestrial life, they are already mined for all kinds of data here on Earth. This is the key to carbon dating, for example, which counts carbon-14 isotopes to determine the age of archaeological specimens and the dates of major events like ice ages. Forensic investigators measure isotopes to match samples of hair, fabric, and other evidence.

Image courtesy of Dean Calma, International Atomic Energy Agency

A technician packages radioactive pharmaceuticals into shielded containers. One possible application for Applied Spectra's Laser Ablation Molecular Isotopic Spectrometry technology is in nuclear medicine, where it could be used to remotely inspect radioactive materials.

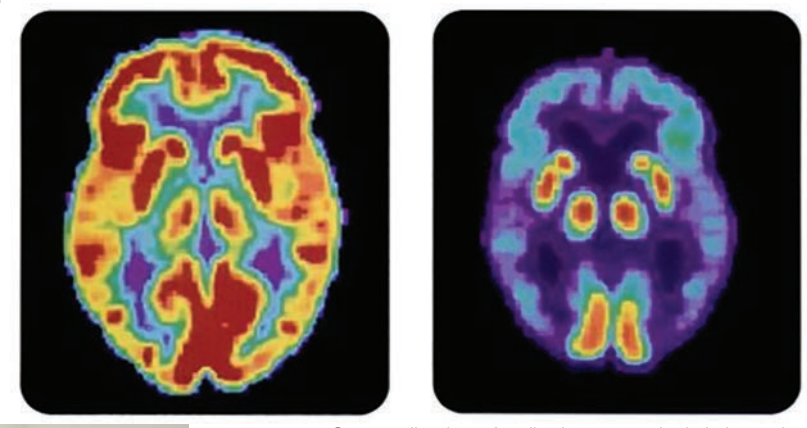


Image courtesy of the National Institute on Aging

One application of radiopharmaceuticals is in positron emission tomography (PET) scan imaging. Here PET scans show the difference between a normal brain (left) and the brain of a patient with Alzheimer's disease.

LAMIS should prove useful in these applications, but its big advantage over existing technology is that it can analyze samples without having to collect or even approach them. This is why Bolshakov thinks its most widespread application will be in characterizing radioactive material used in fields like nuclear energy and nuclear medicine—dangerous material that's better tested from afar.

"Some isotopes are not dangerous. Others can cause mass destruction," he points out, emphasizing the need to keep an eye on these materials, even while they can harm the observer.

The technology could also be useful where it's not practical to collect a sample of the material in question. For example, the shields used in nuclear cancer detection and therapy are regularly replaced because they degrade over time. To test whether the shield needs replacing, a conventional mass spectrometer would require an actual sample for analysis, which is impractical. A LAMIS spectrometer would allow them to be tested and replaced only when necessary.

Remote detection of isotopes could also be used to enforce nuclear nonproliferation agreements, as well as to trace other illegal substances, Bolshakov says.

McKay says detecting explosives is another application where remote sensing would come in handy, and he notes that the Department of Homeland Security has expressed interest in the technology. Applied Spectra also received funding from the Department of Energy, which is interested in LAMIS for contaminated soil analysis. Even where remote sensing isn't necessary, the technology would provide convenience and fast results, in part by eliminating the work of sample preparation.

The company has sold its first units to a university and one company: the University of Central Florida's National Center for Forensic Science purchased one, as did Honeywell, which is interested in developing a LAMIS/LIBS hybrid. Several other universities have expressed interest, and Applied Spectra expects to participate in at least some of the academic efforts to advance the technology. Other universities in the United States and Europe are working on their own versions, based on the company's published papers.

The technology won the company a 2011 Innovation Award from the Federation of Analytical Chemistry and Spectroscopy Societies and a 2012 R&D 100 award.

For NASA's part, McKay looks forward to the day when planetary rovers will be able to learn more about the worlds around them with all the ease and efficiency of Curiosity's laser spectrometer.

"To me, this is a good example of the SBIR program at its best," he says, noting that the Agency took a chance on a long shot that the private sector might not have been willing to invest in, and it's paying off. "There's a lot of talent and ingenuity at these companies, and NASA can benefit from that with relatively small grants." ❖

Methane Detector Sniffs Out Leaks

NASA Technology

Methane is everywhere on Earth, for better and for worse. Among other things, it's the main ingredient in the natural gas that powers heating, cooking, and electricity. It's also a potent greenhouse gas. So whether they're gas producers or scientists studying climate change, there's more than one group interested in knowing exactly how much methane is getting released into the atmosphere and where.

But the presence of methane is also interesting for a different reason: because the biggest source of the gas, on Earth at least, is bacterial life. That means when NASA planetary scientists caught a glimpse of it on Mars, it merited a closer look.

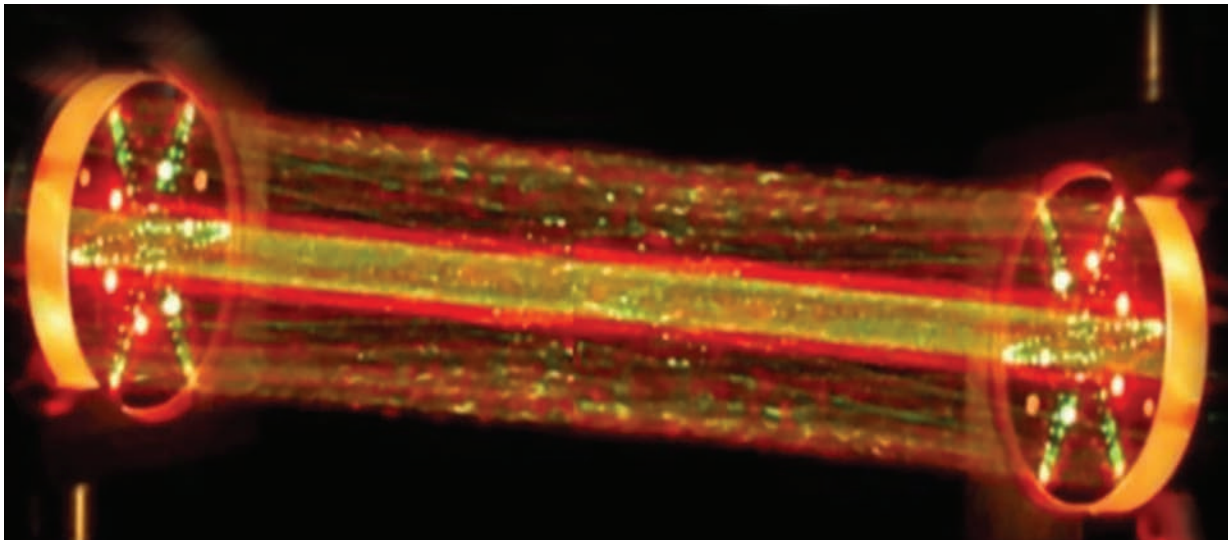
The first question, explains Jet Propulsion Laboratory (JPL) scientist Lance Christensen, was whether the methane was really there. "When you use a telescope on Earth, looking at Mars, you're looking through our atmosphere, which has methane in it. There's always a bit of uncertainty whether what you think is on Mars is really there," he says.

"So the next logical step: the next time you land a rover on Mars, why don't you sniff for it?" That's what NASA did. A team at JPL, led by Chris Webster, built a new instrument, a tunable laser spectrometer (TLS), that can detect even minute traces of methane, measured in parts per trillion, as well as carbon dioxide and water vapor, and installed it on the Curiosity rover.

Every month or so, the rover ingests some Martian air and analyzes it with the TLS. The results show tiny traces of methane all over and, in a few spots, some bigger plumes.

Technology Transfer

Building the TLS required plenty of innovation, because previous space-ready spectrometers weren't powerful enough, and none of the very sensitive Earth-based instruments were small enough in size, weight, or power consumption.



The Tunable Laser Spectrometer (TLS), installed on the Curiosity rover, was designed to measure traces of methane, carbon dioxide, and water vapor. It works by shooting lasers into a measurement chamber filled with Martian air and measuring absorption of light at specific wavelengths. This demonstration of the spectrometer used visible lasers, as opposed to the infrared lasers on the real device.

But technology and techniques had improved since the last Mars-bound spectrometer, and JPL was able to use these new and improved lasers, detectors, and electronics to build the tiny and powerful TLS. "That enabled us to shrink the entire system while maintaining the same level of accuracy and precision," explains Christensen.

In fact, NASA had a big hand in improving the lasers. For methane, a laser needs to be tuned to the mid-infrared range, and NASA had done quite a bit of design on the microstructure of mid-infrared lasers, he says, to make them more efficient.

After Webster's team built the TLS, Christensen's role was to validate the same technique for Earth applications and then to demonstrate it to industry, because JPL knew right from the start that the Mars sniffer would also be useful to the natural gas industry.

In the end, Christensen largely redesigned the TLS for Earth applications. He wanted something even more lightweight, so it could be mounted on drones, and something that could run its analysis 10 times a second. As a trade-off, however, he made his instrument somewhat less sensitive, to 10 parts per billion, since gas leaks typically appear in the range of 50 to 100 parts per billion.

In 2013, Christensen teamed up with the Pipeline Research Council International to test a handheld version of his methane sniffer (*Spinoff* 2016), but he knew the commercial possibilities were bigger and that the drone-based version could work even better.

Andrew Aubrey, who worked with Christensen on this project from JPL's National Space Technology Applications Program Office, also saw big commercial potential. He brought in funding from major oil and gas companies and coordinated and led field campaigns to demonstrate sensor performance. By 2016, Aubrey was hearing from industry contacts interested in a commercial version.

"That's when my JPL colleague and I decided to leave JPL and spin this off as an outside company to meet demand for emission-detection services as well as sensor manufacturing," Aubrey recalls.

“We’re able to do a more **comprehensive job** compared **to** traditional **leak-detection** operations in **about a third** of the **time.”**

— Andrew Aubrey, SeekOps

He and his cofounder licensed the sensor technology from JPL and created Pasadena, California-based SeekOps in 2017.

Benefits

“Companies hire us to go out and inspect their well pads where they’re producing oil and natural gas,” Aubrey explains. “We’re able to tell them exactly where the process emissions and leak locations are.” SeekOps also inspects distribution stations and metering stations downstream from the well, to see where any loss might be happening.

Because of the powerful JPL-developed sensor and the efficiency of monitoring by drone, Aubrey says, “we’re able to do a more comprehensive job compared to traditional leak-detection operations in about a third of the time.” In fact, he says, a full well-pad inspection can take as little as 15 minutes using the SeekOps system, which is 1,000 times more sensitive than competing technologies.

Aubrey says SeeksOps delivers value for the industry in three main areas. The first is improving safety for workers and the nearby community by ensuring better detection of dangerous leaks—after all, methane is combustible, and natural gas also contains other gases that can impact health. The second, related issue, is to inspect the infrastructure and highlight any unknown hot spots or emissions that could turn into danger zones down the road. And the third is minimizing product loss.

SeekOps also helps gas producers comply with regulations that require reporting on any leaks or emissions, which aim in part to minimize the industry’s impact on climate change. “Regulations in many states are very stringent in terms of requirements for leak-detection programs,” he notes, “so we come in, and we’re able to offer a more efficient and more effective method to find emission locations to grade and quantify these emissions.”

The company is fully operational as a methane emissions inspection service across five states including California, North Dakota, Ohio, Colorado, and Texas. And, now that the service side of the business is running smoothly, Aubrey says the plan is to ramp up sensor sales.

“We make the entire SeekOps sensor system in-house, from fabricating the optical cavity to combining it with electronics and then integrating it with unmanned aerial systems,” he says. The company plans to continue offering aerial inspection services, while also selling handheld and car-mounted sensors, all based on the same core technology.

The vehicle-mounted system, which also includes a wind sensor and transmits results in real-time to a tablet mounted near the driver’s seat, can continually inspect for leaks as company technicians drive around for their everyday duties. Although these ground-level systems don’t detect leak sources as comprehensively as aerial sweeps, Aubrey notes, “they are still useful to identify potential problem areas—all during day-to-day driving operations.”

Business is growing fast, Aubrey says: a year-and-a-half in, SeekOps already had 10 employees and were adding an office in Austin, Texas. And Christensen says he hopes the gas industry won’t be the only ones receptive to the technology.

“The game plan, hopefully, is we show how useful this is for industry to measure its fugitive emissions, then the science community sees how useful this is for monitoring emissions for climate change,” he says.

For example, as the tundra warms, more swamps form, and those swamps emit methane. “Having this inexpensive system, it doesn’t cost a whole lot, and it can be used 24/7 over large areas,” says Christensen, and it could provide a lot of useful data for scientists hoping to learn more about just what’s going on in those swamps and, by extension, our atmosphere. ❖

After designing the TLS for Mars, Jet Propulsion Laboratory engineers adapted it for use on Earth. SeekOps licensed the technology and now manufactures handheld and car-mounted sensor systems, as well as offering methane-detection services with drone-mounted sensors.

Biofeedback Loops Aim to Enhance Combat, Sports Training

NASA Technology

Steadying an undulating putting green or a wandering computer cursor with your mind alone might sound far-fetched, but NASA has had this technology for years. Now a company is applying these surreal capabilities to virtual reality military training and, soon, sports training and more.

The Space Agency has always monitored how its astronauts and pilots react to their environment, whether keeping track of vital signs during a spacewalk or watching for physical signs of stress during training. Observers often use software to try to make sense of that data, looking to make inferences about the subject's physiological and psychological state based on indicators like heart rate, skin temperature, and brain waves.

In the late 1990s, a team of researchers at Langley Research Center, concerned with pilots' distractibility during flight, came up with a new index for measuring engagement by observing different brainwave outputs. Then they put a new twist on physiological monitoring: they let subjects see their own attention index—and try to control it.

The team found that subjects who were shown their engagement level, as determined by brainwave output from moment to moment while performing a task, were, in fact, able to learn to control it, never becoming too stressed nor losing focus. They were responding to what's known as a biofeedback loop. What's more, the biofeedback-trained subjects outperformed peers on the same tasks weeks later, even in the absence of feedback.

"We realized we had some unique ideas that could be spun off into inventions based on biofeedback," says Alan Pope, the now-retired researcher who led the work at Langley. So he and his team started inventing.

First came a mechanical putting green that stayed still only when the putter's mind was still. Based on the premise that golfers putt best with a quiet, empty mind, the course physically undulated, with the hole dilating and closing and the sighting laser swinging back and forth, until electrodes on the golfer's forehead indicated strong alpha brainwave output, which is associated with an idling mind and meditation. The golfer had to mentally still the course, then putt.

Langley Research Center engineer Alan Pope, right, built and patented a mechanical putting green that works as a biofeedback training device, teaching subjects to control their state of mind. The green undulates, with its hole expanding and contracting and the sighting laser moving back and forth until the user's brainwave readings indicate a quiet, empty mind.

A video game the team produced was meant to induce a different state of mind. In a configuration developed for the Nintendo Wii, Pope and fellow Langley researcher Chad Stephens worked out a way to compromise the signal from the remote control until the player's brainwave output indicated alertness and engagement. A camera on the remote used lights from an LED array under the screen as points of reference to orient itself—and thus the cursor—in space. The lights would twinkle on and off in a pattern that caused the cursor to circle whatever target the control was pointed at until the player's neural output showed dominant levels of high-frequency beta waves and suppression of lower-frequency alpha and theta waves. Then the lights and the cursor would stay still, letting the user line up a shot.

In each case, Pope says, "there's an incentive to produce the goal brainwave pattern."

The group called the video game MindShift and the putting green Zeroing Out Negative Effects (ZONE). For several years, Langley has sought commercial partners to bring these innovations to market. NASA did license an earlier version of the technology to a company that applied it to video game and DVD platforms for attention, learning, behavior, and memory improvement (*Spinoff* 2003). And at least two other companies have been inspired by the team's publicly available research to develop their own similar products for educational and training purposes and to address symptoms of attention deficit hyperactivity disorder (*Spinoff* 2013 and page 94 of this book).

Technology Transfer

J&F Alliance Group Inc. of Hampton, Virginia, provides logistics and information technology consulting and services to the military, other government agencies, and private entities, and the company is breaking into the business of virtual and mixed reality technology for training and other

U.S. military organizations have been investing in virtual reality and augmented reality warfighter training in recent years. J&F Alliance aims to offer something new in the form of virtual reality weapons training that uses biofeedback to teach the user to maintain the optimal mental state and breathing pattern.

applications. When the company caught wind of Langley's biofeedback technology in late 2016, it seemed like a possible way to enrich its emerging digital reality products.

"One of our partners had a friend at NASA working with Alan Pope," says JarMarcus King, the company's chief operations officer. The company and Pope's team met a couple of times to check out each other's technology.

"The future of video games and sports training is connected to virtual reality and augmented reality," says Pope. "We wanted to bring the physiological into the virtual reality world."

J&F licensed the ZONE and MindShift technologies in the summer of 2017 with an intent to commercialize both. Pope, now a NASA distinguished research associate, is acting as a consultant to the company.

"This technology can truly make a difference in our work force and in people's lives," says Falana Dula-King, CEO of J&F Alliance.

The team quickly homed in on an application with a ready market: virtual reality for military weapons training, with likely spinoffs for law enforcement and security personnel.

> "Improving mental readiness overall can significantly reduce avoidable incidents in military situations, both in training and real combat scenarios."
>
> — JarMarcus King, J&F Alliance Group

Benefits

The Department of Defense Special Operations Command, for one, has put out a call for virtual reality training programs, calling this one of the joint military command's highest priorities, King says.

"We made the assessment that this application was the most marketable at this point," says Pope. "There are customers waiting for it."

In the summer of 2018, with the help of John Muñoz, a human-computer interaction PhD student funded by the National Institute of Aerospace, the company focused on developing a first-person-shooter-style virtual reality training based on Pope's biofeedback research. The system, which J&F planned to bring to market by winter, would incorporate several off-the-shelf components—a virtual reality headset, a brainwave-reading headband, a chest-strap heart rate monitor, and an Airsoft pistol that shoots with a realistic feel.

"In the past, we were playing catch-up with video game technology," Pope says. "This is the next logical step into virtual reality."

Like MindShift, the system would train the user to enter a state of heightened engagement and calmness by making targets easier to hit in response to higher outputs of beta waves and suppression of lower-frequency brainwaves. It would also favor proper breathing patterns, as established by Navy SEAL guidelines.

"Improving mental readiness overall can significantly reduce avoidable incidents in military situations, both in training and real combat scenarios," says King, adding, "The data collected during the training sessions produces a detailed report of the trainee's responses to the different stressors and events simulated, improving the training personalization."

The company also plans to repurpose the trainer, which it calls the Biocyber Physical System, or BioPhyS, for use by law enforcement and security firms.

And King says they still plan to commercialize the ZONE putting green and pursue other sports training applications. Further possibilities lay in healthcare and education, where, Pope says, "biofeedback loops have shown success in the past but now can potentially be enhanced with inexpensive virtual reality technologies."

In this way, the company also hopes to continue to capitalize on Pope's deep knowledge of biofeedback systems by bringing him on as chief scientist. "Part of our goal is to turn his passion into something real and bring it to market," King says.

"My investment in this is to see my ideas and inventions and patents get out there and contribute in some way," adds Pope. ❖

Consumer Goods

When you look around your home, do you see NASA spinoffs? This section highlights some well-known products, like the Bowflex Revolution, that you may not have known traced their origins to space. You'll also find familiar favorites, like memory foam, turning up in new places, and some more recent releases, like an air-filtering pot for houseplants that relies on decades-old research.

Bowflex System Spurs Revolution in Home Fitness

NASA Technology

The commercials were once ubiquitous, and the machines soon appeared in spare rooms and garages across the country. The Bowflex Revolution was a phenomenon of the 2000s—an exercise system that promised to bring the total gym experience into the home—and it continues to sell well today. But it might not exist if not for NASA.

In the 1990s, inventor Paul Francis had an idea for a weight-lifting system that didn't use weights.

"I was always interested in fitness, and I thought, 'What if I could build a portable home gym?'" he says.

Instead of relying on a series of dumbbells or stacks of cast-iron plates to provide the resistance the user works against, he had experimented with metal springs that would strain to retain their shape when pulled. But those failed faster than he wanted—after just around 10,000 cycles. Undeterred, he sought out an alternative material and came across an elastomer compound, which he enhanced and fashioned into spiral-shaped torsional springs of various dimensions.

In the fall of 1996, Francis was reading a newspaper at the coffee shop beside his office in Kansas City when he came across an item about the great lengths one astronaut had gone to in attempt to retain muscle and bone mass and density while in orbit in the Russian Mir space station. Upon return to Earth, she was able to walk but was still wobbly from muscle and bone atrophy.

By then, NASA was well aware that prolonged weightlessness causes muscle and bone loss. What wasn't clear was how to address the problem. Stationary bikes and treadmills, outfitted with bungee cord to strap the user down, weren't doing the trick. And weights, of course, are useless where there is no gravity. The problem was made more urgent by the construction of the International Space Station, which was expected to begin soon and house long-term crews.

Francis thought his springs, which he had dubbed SpiraFlex and had configured into round plates that could be stacked to increase resistance, might be the answer. He managed to find the direct phone number for the chief of the Medical Operations Branch at Johnson Space Center. Soon he was on his way to Houston with a series of prototypes.

Astronaut Sunita Williams poses while using the Interim Resistive Exercise Device on the ISS. The cylinders at the base of each side house the SpiraFlex FlexPacks that inventor Paul Francis honed under NASA contracts. They would go on to power the Bowflex Revolution and other commercial exercise equipment.

Liking what they saw, Johnson engineers asked him to contract through commercial partner Lockheed Martin and get to work on an astronaut exercise system.

Technology Transfer

"A lot of the intellectual property and innovation goes back to that project and NASA funding," Francis says, adding that the work, carried out over about 18 months, also included extensive testing for performance and durability. "It enabled us to take a prototype technology and turn it into a technology that met the specifications that would be required for not only NASA hardware, but also a commercial piece of equipment."

The end product for NASA was the Interim Resistive Exercise Device (IRED), which used stacks of the elastomer spring disks, now known as FlexPacks, arranged in two cylinders that produced up to 300 pounds of resistance. A 16-week ground test showed exercising with the IRED produced the same results as using free weights.

In 2000, the device was launched with the first long-duration crew to stay on the space station, where rotating teams of astronauts would use it for the next decade.

Astronaut Leroy Chiao, who spent more than six months aboard the space station in 2004 and '05, during which he became an avid IRED user, has publicly credited the device for the fact that he scored higher on all of his post-flight strength tests than he had before leaving for the station.

But Francis was just getting started. By the time the IRED made it to the space station, he had changed the name of his company to SpiraFlex Inc. and begun approaching fitness companies.

Benefits

Francis licensed SpiraFlex technology to Schwinn Cycling and Fitness Inc. and helped the company design a strength

> The biggest advantage of resistance-based workout equipment is that it enables the machine to be lightweight, take up less space, and be quiet."
>
> — Gregg Wilson, Nautilus

training machine, which it released in 2000 as the centerpiece to an international group fitness program for health clubs called the Resistance Performance Program (RiPP) (*Spinoff* 2001).

The following year, though, Nautilus Group—which had begun as Bowflex of America Inc.—purchased Schwinn Fitness, and RiPP was discontinued. A few years later, when Nautilus was looking for an alternative to its rod-based Bowflex home gym, the company didn't have to look far.

"I came along and presented my SpiraFlex technology and mechanical system, as well as a number of home gym configurations that incorporated the technology, and they developed the Revolution based on a combination of them," Francis says, noting that he holds patents not only for the SpiraFlex technology at the heart of the system but for all the machine's inner workings and many configurations.

The Bowflex Revolution, Nautilus' most successful home gym, was launched in 2005.

"The biggest advantage of resistance-based workout equipment is that it enables the machine to be lightweight, take up less space, and be quiet," says Gregg Wilson, director of product line management at Nautilus, which is now based in Vancouver, Washington. For example, he says, while the Revolution only weighs about 220 pounds, its leg press station can provide up to 600 pounds of resistance "and a range of power unheard of in a regular home gym."

Resistive equipment also eliminates the momentum free weights generate during lifting, which can be hard on joints and also allow the user to "cheat a bit" on the upswing, as Wilson puts it.

He notes that SpiraFlex offers an additional advantage over other resistance-based equipment, including the original Bowflex line, which

The popular Bowflex Revolution home gym uses SpiraFlex technology to provide up to 600 pounds of resistance, while the machine itself only weighs about 220 pounds.

relies on "power rods" that the user bends, and others that use springs or elastic bands. "Rod-based gyms are great, but the resistance is progressive, meaning that, as you move through the range of motion, it gets harder," Wilson explains.

FlexPacks, on the other hand, provide "linear resistance," meaning the effective "weight" stays the same from the start of each stroke to the end. "Working out on the Revolution feels more like true free weights, but without the dangerous inertia, and helps the user maintain better and more controlled form," Wilson says.

That quality, together with an innovative configuration, allows the Revolution to recreate the commercial gym experience with more than 100 aerobic and strength-training exercises.

"The Revolution has been our best gym, offering the most exercises and keeping people fit and strong for over 12 years," Wilson says.

Meanwhile, Francis has retained rights to his SpiraFlex techology and founded another company, OYO Fitness, to leverage the technology even further toward convenience and portability with a line of devices that weigh only two pounds but enable dozens of exercises (*Spinoff* 2018). And there's more to come.

"We have a line of new products we'll be introducing in all sizes, shapes, and price points," he says, adding that the company is also developing group exercise plans based on its products for health clubs, corporate wellness programs, and senior living facilities.

Francis notes that these commercial fitness devices that have benefited tens of thousands of users to date were enabled by the development work with NASA to keep astronauts in shape on the space station. "The funding from NASA enabled us to take the technology to the next level of development and commercialization, so SpiraFlex was greatly improved due to the NASA project." ❖

The SpiraFlex FlexPacks, originally developed for NASA, can be added or removed to adjust the Bowflex Revolution's resistance.

Spacesuit Air Filters Eliminate Household Pet Odors

NASA Technology

In a surprising turn, NASA-backed research on new spacesuit technology could improve air quality in the homes of pet owners, as well as keep cars smelling fresh and filter contaminants out of the air in microchip manufacturing facilities.

The technology has been under development for some time. After creating an air and water purification system as PhD students in the Materials Science and Engineering Department at the University of Illinois at Urbana-Champaign, James Langer and Weihua Zheng cofounded Serionix Inc. in 2011 to bring their research out of the lab and into the world. They quickly narrowed their focus to air purification.

"We found a special formula—our secret sauce—that was highly reactive to certain toxic or otherwise unwanted chemicals in the air," says Langer, who is now president of Serionix. The formula, the company's patent-pending Colorfil technology, involves polyelectrolytes—polymer substances with a permanent electrical charge on them. It applies the coating to the surface of a fabric-like nonwoven material. The material is breathable and easily installed, like a regular air filter, and the Colorfil coating removes toxic chemicals and kills viruses, bacteria, and mold.

Langer and Zheng were researching applications for their air purification technology when they came across a NASA solicitation for research on spacesuit air quality, primarily for the safety, health, and comfort of the astronauts.

Technology Transfer

Johnson Space Center awarded Serionix, located in Champaign, Illinois, a Small Business Innovation Research (SBIR) contract in 2016 that provided about $125,000 to design and demonstrate a lightweight, high-performing system for removing ammonia and formaldehyde from next-generation spacesuits.

Later that year, after proving the technology, the company won another $750,000 from Johnson in SBIR Phase II funding to tailor the filters to spacesuit and spacecraft requirements. An SBIR Phase III award from Johnson has enabled Serionix to focus on vehicle air quality challenges, mainly for Orion, which is NASA's first spacecraft designed to carry astronauts since the retirement of the Space Shuttle in 2011.

In a small, closed environment like the space station, keeping air clean and breathable is a serious chore. NASA astronaut Dan Burbank is shown here cleaning cabin air bacteria filters in the Tranquility node of the station in 2012.

"The challenges that we've been working on with NASA are mostly to do with the engineering challenges of actually incorporating the technology in the suit or in space vehicles," Langer says. "Weight and shape and ease-of-use constraints all become critical issues in these applications."

In a spacesuit, the suit itself could be the source of the air contaminants, or the human body could cause buildup of ammonia and toxins over time, just from offgassing. How much ammonia is present will vary depending on the age of the spacesuit and on the individual in it—their physical state, what they've eaten.

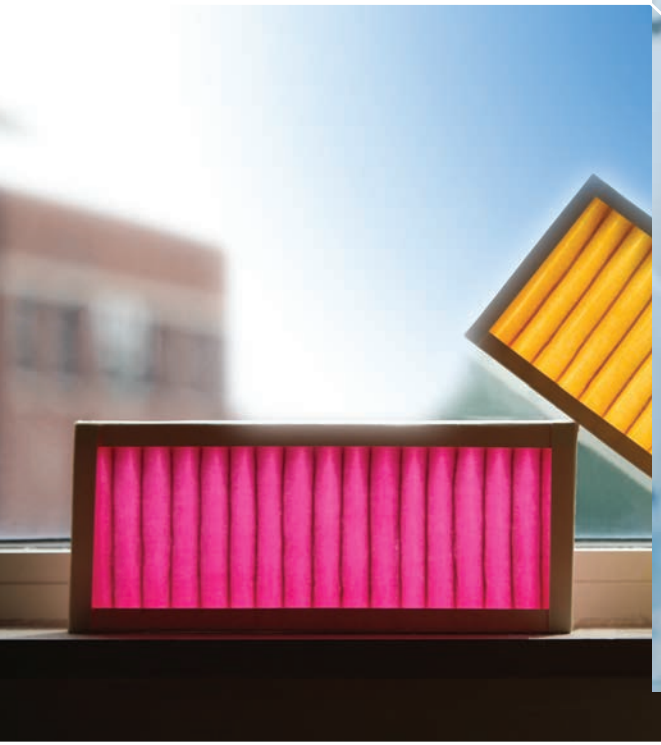
Serionix's Colorfil technology also changes color when a filter is spent, which prevents unnecessary changes, such as when filters are swapped at predetermined intervals. Unlike traditional filters that start out white and turn gray over time, Serionix filters change unambiguously from bright magenta to a drab yellow.

"The idea was to put a filter in a spacesuit or on the International Space Station or Orion that would give clear feedback to users when it needs to be replaced," Langer says.

"It could be that the first few uses of a new spacesuit might use up a new filter, but then later in the spacesuit's life, it might be more like 10 uses," Langer says. "So instead of having to arbitrarily replace it on a schedule, our filter would allow you to use a more rational approach, replacing it when needed."

Benefits

When Langer and his colleagues at Serionix began considering potential applications for their filters, two distinct directions emerged. They could go high-tech, filtering air in



Thanks to their chemical properties, Serionix Colorfil filters change from a vibrant magenta to a dull yellow when they need replacing, eliminating guesswork and saving money.

Because microchips' components are so small and sensitive, they must be manufactured in hyperclean environments, free of even tiny specks of dust or traces of harmful gases such as ammonia. Serionix is working with one microchip manufacturer to incorporate its filters in the company's facilities.

space, and they could target consumers directly. Ultimately, the company decided to pursue both paths.

"The aerospace direction for our technology was pretty straightforward," he says. "Interestingly enough, we found that on the far extreme, the consumer side of things, ammonia happened to be a real issue with pet owners in particular."

Unpleasant odors from cat boxes, hamster cages, and other pet spaces is due to ammonia and other related chemicals in urine that Serionix filters excel at removing. The company received encouraging feedback after conducting beta testing with consumers using their filters in air purifiers and HVAC filters.

Serionix currently sells these household filters directly to consumers through the company's website. Products include a Colorfil-branded air purifier, an HVAC filter, and a cabin air filter for automobiles. All the products incorporate Colorfil filter technology that changes from magenta to dull yellow and promises to remove chemicals and odors from the air that other filters can't.

> "The challenges of deploying the technology in space definitely serve us well in making a more robust product for our customers on Earth."
>
> — James Langer, Serionix

The company has also been working with a microchip manufacturer, because that process is also highly sensitive to ammonia and other corrosive gases. Langer and his team have also been in talks with an automaker to provide car cabin filters on a large scale.

Besides NASA, the company has received research funding from the U.S. Army and the National Science Foundation. But Langer says the NASA contracts in particular have contributed to the development of the consumer applications.

"All of the challenges that we have here are simply magnified up in space. That's the environment up there, and people's lives depend on solving those problems," he says. "The challenges of deploying the technology in space definitely serve us well in making a more robust product for our customers on Earth." ❖

NASA Research Sends Video Game Players on a Journey to Mars

NASA Technology

What would it be like to venture to another planet? To kick up red dirt on Mars and crawl through the lava tubes that wind beneath the surface? To build a shelter and plant a garden?

NASA has spent years imagining—and studying—just that, gathering images and data with satellites and rovers, using computer models to simulate alien environments, and even building mockups to test out ideas here on Earth.

Now anyone, from astronauts to school kids and in between, can experience the results of that research like never before, in an immersive virtual reality game set on Mars developed by Miami-based Fusion Media Group Labs.

Pat Troutman is the human exploration strategic analysis lead at Langley Research Center, whose work on NASA's Evolvable Mars Campaign provided much of the research underpinning the game. "In the opening scene, you start off in Mars orbit, and once you're entering and landing, it's pretty much what the Evolvable Mars Campaign was striving to achieve," he says.

Part of the challenge of the NASA campaign, says Troutman, was that "it had to be sustainable with resources we had been given. Instead of looking for the optimal approach to Mars, we asked, 'What could we do with what we have?'"

The most important change they made in their plan, versus earlier concepts, was that everything had to be reusable. That meant designing a spacecraft that could make multiple trips, designing a propulsion system and trajectory that minimized fuel needs, making full use of Martian resources onsite, and, crucially, returning to the same landing spot on Mars, where they could reuse habitats, rovers, and other supplies brought on previous missions.

The rover that astronauts would use to explore was also completely redesigned to make it more efficient and cost-effective. "It features a really cool concept we call 'suitports,'" Troutman explains. "Basically, the spacesuit has a hatch in the back of it" that can attach directly to the rover hatch. "If you open both at the same time, you can crawl out of the suit and into the rover without having to go through an airlock and without transferring any dust back into the rover."

That makes it easier to explore the surface, he says. "It's the best of both worlds—use the spacesuit for walking and grabbing, and use the rover to drive around. Plus, the rover is a mini camper. They can go for a week camping in that thing and go on long excursions far from base."

Technology Transfer

The Evolvable Mars Campaign was written up into a report for headquarters and is available to the public—but it's not particularly well known outside NASA.

In fact, what initially sparked the imaginations of the game developers back in 2014 was the launch of the highly publicized Mars One campaign, a private company's effort to develop the first permanent human settlement on Mars.

In light of the media attention given to the attempt, a quartet of Massachusetts Institute of Technology graduate students decided to analyze the plans to see if they were actually feasible. "We were looking to see if they had presented any analysis to justify some of the claims they were making on life cycle costs and logistics demands," explains Sydney Do, who now works at the Jet Propulsion Laboratory (JPL).

"We mined their website for every data point we could find and filled in the gaps with the NASA standard design reference manual."

Their findings: the plan wasn't realistic. But their report got a decent amount of public attention as well, including from Fusion Media Group Labs. Company representatives got in touch with Do and the others, asking for advice on

Astronauts, engineers, and geologists tested this Multi-Mission Space Exploration Vehicle concept in the Arizona desert in 2008. A vehicle like this might one day carry astronauts across the Martian surface.


When Fusion Media Group Labs was designing its virtual reality game, Mars 2030, it consulted extensively with NASA and modeled the experience closely on the Agency's proposals for sending humans to the Red Planet. The FMG Labs team even drove a model of the proposed rover (left), and designed their virtual rover to mimic it exactly (right).

making a Mars exploration game, one that showed a plan that could actually happen.

"I just found it so fascinating to approach it from the science," says Julian Reyes, director of virtual and augmented reality at the company. "Typically games have this conventional structure where you get points or are tasked with survival, the concept of a game itself, and we didn't want to make it a game, instead we wanted to use an interactive engine as a way to present scientific information."

Do and his fellow graduate students began funneling research to Reyes and his team and then helped them get in touch with the NASA researchers behind the science, including Troutman.

"After a year of conversations, we signed a Space Act Agreement and started work on Mars 2030," Reyes says. "This involved several trips to Langley Research Center, to Johnson Space Center and Michoud Assembly Facility to gather up as many resources as possible. We also collaborated with JPL to get the digital terrain models for the exterior."

The developers got a sense of what driving the Mars rover would feel like by driving a NASA model, and they even recorded audio to incorporate into the game. Then they took all that research and, over a year and a half, built it into a video game engine.

Benefits

The end result is a virtual reality that looks and feels like the real thing—and that's according to the experts. "We had Michael Gernhard, a four-time astronaut who designed the rover, he was driving in the game and said this feels like the real rover," recalls Reyes.

There are a few differences, Troutman insists. "The habitats are much bigger and airier and cleaner on the inside than they'd actually be." But he says, overall, the game is a great representation of the work he and his team did, from big things like the rover and the landing site, down to the tiniest details like the logo on the plant growth module.

Do says he thinks the experience will help increase public excitement around space exploration. "Something like this—someone who's excited about space exploration makes something that enables anybody to experience the same joy he does—I think that's just amazing."

And that, Reyes says, was largely the point. "We see this as an educational experience. Every single module has info about the systems NASA is working on," he notes. "We want this to be in the hands of the students to inspire that sense that we can make it to Mars, and hopefully some of them decide to become scientists themselves and try to elaborate on these concepts."

For that reason, the game was immediately available free of charge to educators and, as of March 2018, became free to all users through the NASA website. Moreover, in March, Fusion Media Group (FMG) Labs made the Editor tool of their game engine free and public as well, "so other developers and scientists can use our rover models and terrain data to develop their own concepts."

After all, "if NASA's information is free to the public, and our project is built with that data, ours should be too," Reyes emphasizes.

The company's hope is that it's creating a tool that can be used to simulate many other worlds and modes of exploration, as well as upgrade habitats and model different types of resource management on those worlds.

Within Mars 2030, everything is interactive, so users can build new technology and new habitats and see how they function within the Mars environment.

The new platform is exciting for the scientists too. For example, research results tend to look like columns of numbers and dots on graphs. Seeing that play out in a virtual reality game "makes you experience what the numbers are telling you, and that can help with physical intuition," Do says. "And it will probably improve the science and engineering just through that whole experience." ❖

Players can explore the surface of Mars like never before, even picking up samples to analyze with instruments modeled on real NASA technology. The spacesuit is also designed using concepts developed for real future Mars missions.

"We want this to be in **the hands** of the **students to inspire** that **sense** that we **can make** it to **Mars."**

— Julian Reyes, Fusion Media Group Labs

Memory Foam Supports and Shapes in Women's Apparel

NASA Technology

If there's one NASA spinoff that is almost guaranteed to have touched your life, it is memory foam. Even traditional spring mattresses typically have a layer of it these days, and the material is showing up in more and more unexpected items, from sneakers to car seats and even high-end bras.

But first the famously cushy foam was made for NASA, as part of a project to design safer seating for commercial airplane passengers.

Memory foam, also known as temper foam, was originally created for a project to improve passenger seats for airplanes, but the extraordinary impact absorption of the material ensured it was soon used for many other projects, including seats on the Space Shuttle.

It was the late 1960s, and commercial air travel was just starting to become more common. NASA, tasked with innovating in aircraft as well as spaceships, was looking for ways to improve safety in the event of a catastrophic emergency.

"At first, they were thinking of contracting for a study of a system that, if the plane was going to crash, it would blow off both the wings and have parachutes deploy off the top of the fuselage," explains Charles Kubokawa, now retired from Ames Research Center, where he was then a human factors engineer and later held several roles including assistant administrator.

But that proposal was quickly squashed. "Top administrators said, 'No, we don't want to shock passengers about the possibility of a plane blowing off the wings,'" Kubokawa recalls with a laugh.

So he and his team decided on a different plan. "We decided to design a crash-proof seat," he says, something that would protect a passenger even in an extremely rough landing.

The project, which reimagined everything about airplane seating, from the bolts attaching it to the interior aircraft flooring to the placement of the tray table, was a success. "We developed a chair that worked real nicely for up to 36 Gs of crash worthiness," he says, referring to forces equivalent to 36 times Earth's gravity—well beyond the 14 Gs the rest of the plane was built to survive.

The impact protection came from a combination of design elements, but one of the most important, Kubokawa recalls, was the foam cushion they integrated into the seat and back. The design called for something that wasn't flammable, would be comfortable, and most importantly could absorb high impact.

"We called it temper foam," Kubokawa says. "Once you sat on the foam, it conformed evenly with the contacted body surface and made you settle snugly into the seat. After you stood up from the seat, the foam would revert back to its original form with nothing on it."

And the foam also did a remarkable job of absorbing impact, something the team initially tested in a somewhat unorthodox way: "We put a piece of foam on the ground, and we dropped an egg on it and the egg didn't crack. And then we dropped heavy things, and it absorbed the G forces. Any kind of fragile things that were dropped on it didn't break." The team also did an official proof-of-concept crash test with an anthropometric dummy at the Civil Aeronautics Medical Institute in Oklahoma City, resulting in acceptable positive results.

Although the seats were never fully integrated into commercial jets, the original temper foam has found a wide range of uses, a payoff the inventors were quick to anticipate—and in fact, the engineer who worked with Kubokawa, Charles Yost, later became one of the first commercial manufacturers.

Technology Transfer

The first prototype of the NASA-designed airplane passenger seat used a different, pre-existing foam, but it had a critical flaw: it was flammable.

When the NASA team realized it needed to go back to the drawing board, Kubokawa went back to the seat designing company, Stencel Aero Engineering Corporation. There, he worked closely with Yost to design a new foam formula that would meet the project's needs. "Yost had the chemistry background" and was doing the actual mixing and fabricating, Kubokawa says, "but a lot of it was a hit-and-miss type of thing. There were many iterations of the foam composition, and he and I discussed what changes had to be made."

After the successful version was completed and detailed to NASA, Yost went into business for himself, opening Dynamic Systems Inc. in 1969. Besides airplane seats, Yost's company extended the uses of memory foam to a number of industries, including making a line of cushions that could be used in orthopedic seating and mattress pads to reduce the risk of bedsores and seat sores for wheelchair patients (*Spinoff* 2005).

“Memory foam really does **form to your body** like a **second skin.”**

— Ra’el Cohen, ThirdLove

Today, memory foam is one of NASA’s most widely used spinoffs. The material turns up in everything from mattresses to wheelchairs to protective gear—and even bras. ThirdLove adapted the material to enable it to be cast in thin layers for a bra that molds comfortably to the body while offering the right level of support.

But neither Yost nor Kubokawa ever patented the innovations pioneered in the seat, in part, Kubokawa says, because of a snafu that happened when he went away on vacation: while he was away, a public affairs colleague showed a reporter the ongoing project, allowing the reporter to take pictures that were later published.

U.S. patent law requires that a patent be filed within a year of an invention first getting written about publicly, and Kubokawa, unaware of the newspaper article published during his vacation, missed that deadline. “The patent officer came to my office and said, ‘I hate to tell you this but you’re one day after the year limit.’”

As a result, the foam, along with 26 other potentially patentable innovations, were never patented. In the 1980s, NASA released the formula for temper foam into the public domain, paving the way for many companies to use it in a variety of industries and consumer goods.

Benefits

When ThirdLove began designing a modern, high-end bra, the San Francisco-based company wanted to start from the ground up. “Part of that is, we don’t come from the traditional apparel industry, so when we decided to go into the market, we took a very Silicon Valley-like approach: how do we build a better company, a better system, a better product?” explains cofounder David Spector.

One of the areas they focused on, he says, was the foam layer that gives the cup its shape. “Memory foam really does form to your body like a second skin,” notes design chief Ra’el Cohen. Unlike other foams that are stiffer, memory foam softens with body heat, allowing for a shape that conforms to the body instead of the other way around.

Once the company settled on memory foam, however, it still needed to innovate: after all, the thick, heavy pad that works in mattresses would never do for a bra. “We knew we wanted to do something that was kind of revolutionizing the way memory foam was used,” Cohen says. “We wanted a thinner pad but also needed it to be supportive enough.”

The solution they found was to tweak the foam formula to make it lighter, less dense, and able to be cast in a very thin sheet. Then, unlike other bras, which use a separate foam pad between two layers of fabric, the company laminates the nylon fabric directly to the foam using a heat process. That adds extra structure to the foam, ensuring it is supportive enough while also minimizing the total amount of material and layers in the final garment.

“All of our bras in our collection have memory foam,” Spector says. “It’s something that ThirdLove has built the collection around—we find customers really love it.”

Although their products don’t need the high-force impact protection that memory foam was originally created to provide, the company did appreciate the NASA history behind the technology.

“It’s a wonderful technology, and there’s a lot of credit that goes to NASA for developing it,” Spector says. “It’s done tremendous things to enhance products across the board. And now, we’re really proud to be bringing it to the bra category.” ❖

Rocket Design Leads to Turbo-Charged Air Purifier

NASA Technology

The founders of Wynd, a start-up that makes personal air purifiers, didn't particularly have space exploration on the brain when they built their prototype. But the experience the engineers had calibrating sensors for launch pads and designing turbines for rockets proved crucial when designing their smart, portable device that not only cleans the air you breathe but also tells you just what was in the air in the first place.

The idea was sparked when Jason You planned to take his toddler daughter to China to visit family and worried about the effect of infamous air pollution there on her sensitive lungs.

Most air purifiers are designed to work inside a home or a building. But You wanted something he could take on a walk or in the car. He looked around but didn't find anything that did what he wanted, so he decided to rig something up himself.

"We brought it to China and a lot of my daughter's aunts and uncles loved it for their kids. We ended up making some prototypes for them," You says. But his relatives questioned whether the device actually cleaned the air as well as he said, so You hooked up some external sensors to prove the air was getting clean.

"That gave us the idea to put a sensor in the device itself," he says, "but I couldn't find anything small enough." So once again, he decided to build something new.

You had spent several years working for a company that built sensors and installed them around the launch pad at Kennedy Space Center to ensure the air quality remained safe after a rocket firing. "I was part of the team that checked the sensors to make sure they detect everything appropriately," You explains, including things like carbon dioxide and volatile organic compounds.

That experience was directly relevant when he began building a tiny air quality sensor for Wynd. "The Wynd sensor is a particulate matter sensor, but a lot of the physics and understanding of how things work derived from that NASA work," he recalls.

After building expertise in sensor design and turbopumps for NASA, engineers teamed up at start-up Wynd to build a small, portable air purifier that can be toted in a cup holder or placed on a desk or nightstand to reduce air pollution, allergens, and even viruses.

Moreover, he knew the pitfalls that could make a sensor less accurate, which he says saved him a great deal of time. Based on the experience at Kennedy, for example, he knew the sensors "would be sensitive to temperature and humidity and a slew of other things," so he could plan for it ahead of time instead of being surprised in later testing. "It allowed me to create a more robust system," he emphasizes.

Technology Transfer

You wasn't the only one at Wynd with NASA experience—Eric Munoz, the hardware engineer who designed the system that moves air through the filter and directs the clean flow back to the user, had built up his fluid mechanics expertise on rocket engines.

"The whole thing was designed around airflow," You says, and "the experience at NASA helped him understand how air flows and how to maximize that."

That's not a surprise, says Ralph Coates, a propulsion systems engineer at Marshall Space Flight Center with more than 30 years of experience at NASA and elsewhere. The basic idea of rockets is that they convert chemical energy, or the energy stored in molecular bonds, into kinetic energy, or movement—and some of the components that help direct that energy are turbines and pumps.

> “With our sensors that are out there, you can see data instantaneously. You can see what the air quality is actually doing.”
>
> — Jason You, Wynd

These simple machines, which extract energy from a fluid or add energy to it, are used in any number of systems, from windmills to car engines to rockets, and while the specific details—size, material, configuration—may vary, the same rules of physics apply.

There’s a lot more to it, of course, but Coates says the experience designing for liftoff would transfer easily into many other fields. “One of the things we’re always pushing for on rocket engines is that you want to keep things as light and as small yet as simple and efficient as you can. And those don’t always go together very well. You can make something light and fast, but maybe then it’s too delicate. Now it’s not quite as reliable as it was. So you have to beef it back up so it’ll last a long time,” he explains. “Learning to balance these important and often conflicting areas of emphasis is a tough but very useful training ground.”

Benefits

After You came back from China, he teamed up with fellow Wynd founder and CEO Ray Wu to develop a product that was ready to sell.

They built a portable device, about the size of a water bottle, that was rechargeable and, because of the smart sensors You designed, is able to conserve energy when the air quality is good and then ramp up the purifier when the air gets worse.

You says that the device is incredibly powerful for its size. “It can clean nine cubic feet of air per second, which for that size is way ahead of anything that’s out there,” he says, tying that efficiency directly to his colleague’s experience in rocket engines.

The Redwood City, California-based company launched an Indiegogo funding campaign in 2016 and immediately raised over $600,000, more than 12 times its initial funding goal. The company now sells the air purifier and air quality sensor online, either separately or packaged together, as well as replacement filters and a special holder designed to clamp the air purifier to a stroller frame.

The company also makes a removable sensor that monitors air quality in real time—and can send anonymized updates to a world map so users can check conditions where they need to go.

He says the customer base falls generally into three categories: people with kids, people who are particularly health conscious, and people with allergies. Because it streams clean air directly at the user, the Wynd device can be particularly effective at alleviating allergy symptoms and reducing pollution, and because the filter contains a silver liner that kills germs when oxidized, it can even help protect the user from getting sick during flu season or when other airborne illnesses are spreading.

The company is also launching a crowd-sourced global map of air quality, using data from the sensors in each device, with information displayed on the company’s free app. “Right now, there are air quality stations all around the world. But particulate pollution is very localized, so you can’t really get a good sense of pollution based on a sensor that’s several miles away,” You notes. Plus, those stations post a 24-hour average, but “air quality changes a lot faster than that.

“With our sensors that are out there, you can see data instantaneously. You can see what the air quality is actually doing,” he says.

That could mean better forecasting as well as real-time info on whether it’s safe to go to a certain park or what’s a good hotel to stay in. With pollution and air quality issues among the top health issues around the world, the Wynd team says it hopes to make an impact with its technology and products, and, You adds, is very thankful for the Space Program that helped pave the way to many of its innovations. ❖

Brainwaves Reveal Student Engagement, Operate Household Objects

NASA Technology

When we talk about operating "on autopilot," we usually mean acting with little thought or effort, often resulting in error. It turns out actual autopilot systems can cause actual pilots to behave in this way.

"Early in my career, the concern in aviation was about stress and workload, but automation was becoming more of a concern," says Alan Pope, who began his long stint at Langley Research Center in 1980. As automated flight control systems took over more and more of the moment-to-moment operations in the cockpit, pilots could grow bored, complacent, and disengaged—conditions that are just as dangerous as being overwhelmed, Pope explains.

By the mid-1990s, researchers at NASA and the Federal Aviation Administration, including Pope, were researching the causes of these "hazardous states of awareness" and ways to objectively identify and measure a pilot's cognitive state. "We worked on finding physiological signals that showed underload," he says.

Pope led a team looking for a way to use electroencephalographic (EEG) data—that is, brainwave readings—to quantify a subject's level of engagement. The result, which they described in a 1995 paper, was an "engagement index" that's still used today: the strength of high-frequency beta waves, which indicate attention, is divided by the combined power of lower-frequency alpha and theta waves, which come with relaxation, to arrive at a measure of engagement.

An incident later that year, in which a series of pilot errors ended with an American Airlines flight crashing into a mountain while preparing to land in Cali, Columbia, killing 159 people, intensified interest in the subject. The crash is mentioned more than once in a 2001 paper, in which Pope and two other researchers describe a collaboration between Langley and Old Dominion University to apply the engagement index to an attempt to train subjects to regulate their own engagement level.

In the 1990s, scientists at Langley Research Center studying pilot inattention established an "engagement index" that could be measured using brainwaves. They found that subjects who were shown their own engagement level in real time could learn to control it.

The training relied on what's known as a biofeedback loop. The researchers let the subjects in one group watch their own rating on the engagement index, on a 1-to-6 scale, while they performed a task, and told them to try to maintain a level of 3 or 4. Other groups were provided with incorrect feedback on engagement or none at all. After a week, all the participants were asked to perform the task again. The subjects in the group that had received the biofeedback training significantly outperformed the others while remaining closer to their baseline, "normal" engagement level. They also rated their workload markedly lower than those in the other groups did.

They had learned to regulate responses that are normally beyond our control. The paper concluded that this "physiological self-regulation" training could help pilots manage and maintain their attention.

Technology Transfer

When a group of Harvard University graduate students founded BrainCo Inc. in Cambridge, Massachusetts, in the

BrainCo's Focus EDU headband monitors the wearer's brainwaves to determine attention level. The device is marketed as an educational tool that lets teachers monitor student engagement in real time and with after-the-fact reports.

spring of 2015, they didn't know anything about NASA's work on monitoring and mitigating hazardous states of awareness. But they did know a little about EEG readings as they related to attention and biofeedback.

The fledgling company wanted to develop a practical way to use EEG readings to monitor students' attention in the classroom and, ultimately, to help people with attention deficit hyperactivity disorder (ADHD) gain more control over their concentration. A prototype EEG-reading, WiFi-connected headband had been built by the time Max Newlon was brought on board as a research scientist about a year later, but the company wanted to improve its software. Newlon was tasked with finding an algorithm to accurately determine cognitive state based on brainwave readings. He hit on the 2001 Langley/Old Dominion experiment and its use of Pope's engagement index formula.

"I did a pretty extensive literature review and found that the NASA algorithm was the best fit for what we were doing," he says.

BrainCo's Focus EDU is a classroom system that lets the teacher monitor a class's attention level in real time, as an average or as a "heat map" of the classroom, and it generates an after-class report on the group as a whole, as well as individual students' attention levels.

An LED light on the front of each student's headband can indicate one of three attention levels, although Newlon says the feature is generally turned off during class time. "You don't want to distract students with their friends' headband colors."

Focus Family uses the same hardware with a smartphone app to create a sort of digital study buddy for use at home, Newlon says, noting that students can see their attention levels in real time and generate a report after a study session. A couple of video games are included, which users control by modulating their brainwaves. These assess abilities like sustained attention and task switching. All the results can be shared and compared in an online community.

The soon-to-be-released LUCY product uses the same technology in a slightly different form. It is intended to use biofeedback to improve focus and attention control, much like the work Pope and colleagues describe in the paper Newlon came across. It will include video games for this purpose, but the app will also let users remotely pair the EEG-reading headband with real-world objects, allowing ordinary electronics to be controlled with the mind.

Benefits

BrainCo shipped its first order—20,000 Focus EDU and Family units—to a Chinese distributor in spring of 2018. The company's founder and several team members are from China and had connections there, Newlon says, noting that BrainCo is now working to break into the U.S. market, with pilot studies having begun in mid-2018.

The classroom version gives teachers overall student attention reports to see what's getting kids' attention, where they're getting lost, and even whether they're relaxed during breaks. Individual student reports let them see who's having trouble paying attention and when.

"If you go up a layer, an administrator can see who's good at engaging students and look into what they're doing well and how that can be shared with others," Newlon points out.

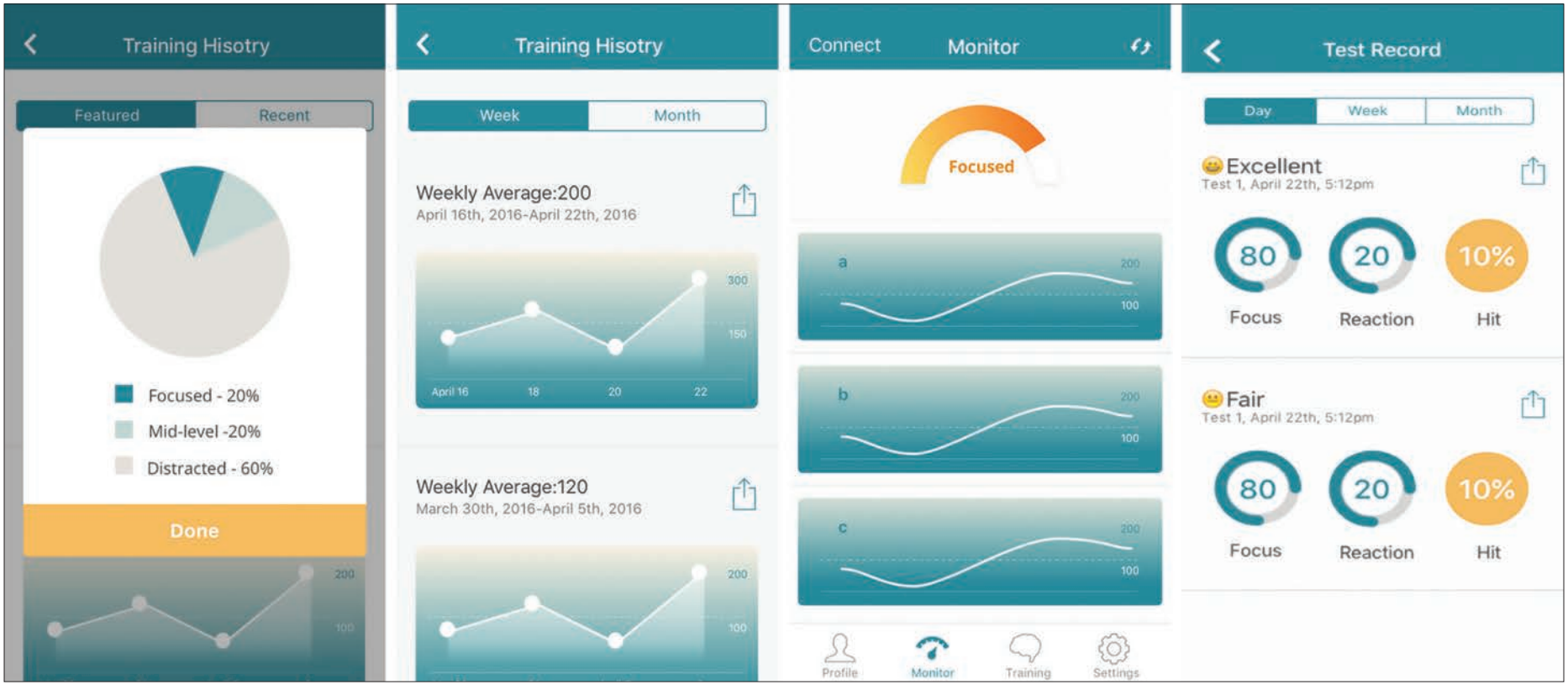
The home version can record students' brain activity while they study to create a report that allows insight into their distractibility, when they should schedule breaks, and what subjects engage them the most.

"One thing we're hoping to use this for is to detect users' interest," Newlon says. "There's a subjective component people already experience. We want to make it visible and put a number on it so people can learn more about what's going on in their brains."

The app also generates tips to improve studying.

BrainCo especially hopes LUCY can benefit those with ADHD, he says. "There's been some pretty good research on neurofeedback for ADHD, but we're aiming to be the first to get FDA approval." He specifies that the company wouldn't claim to treat or cure ADHD, but that anyone with trouble controlling attention could benefit. LUCY began in-house clinical trials in early 2018.

Pope partnered with Eastern Virginia Medical School to compare the effects of video game-based biofeedback and more standard biofeedback training on 22 children with



Focus Family uses a smartphone app to produce reports on students' engagement levels while they study or while they play video games that require them to control their attention level.

ADHD. While the video game training was rated to be more fun, a report the team gave in 2001 concluded that "both the video game and standard neurofeedback improved the functioning of children with ADHD substantially above the benefits of medication."

"It's a little-known secret that a lot of benefit can be drawn from biofeedback," says Pope, who used the technique in his practice as a clinical psychologist. "If someone has information about their internal state, they can learn to change it. It requires training over time and multiple sessions, but you can learn that skill."

"It's almost like flexing this mental muscle over and over again," Newlon says, noting that some studies have found that improvements in concentration can last months after training. He says the company hit on using brain waves to manipulate household objects because ADHD is most common in children. "What do kids want to do? They want to control stuff in their room. How cool is that?" To that end, the company has remotely paired prototypes with devices like lights and robots such that the devices respond differently to different attention levels.

In addition to its product line, though, BrainCo also sees a future in research. With multiple students using each device sent to schools, Newlon figures it won't take long for the first shipment alone to net a database of EEG readings from a million users, larger than any that exists today. "We think there might be a really big opportunity here. What can we learn if we do a big-data analysis?"

He emphasizes that the company will prioritize privacy and data security, having already started working with leaders in the field to ensure all applications meet the industry's top standards for protecting data.

The research could go in any direction. "What we really want to do is talk to the smartest people: 'We have all this data. What questions do you have, and how can we help answer them?'" Newlon says.

"And all of this is based on the NASA engagement index."

While NASA research on biofeedback lagged after the mid-2000s, Pope says, a new appreciation for the importance of crew cognitive states in the last few years has renewed interest in the field. Now retired and a NASA distinguished research associate, Pope is a consultant on the Crew State Monitoring project that began at Langley around 2013. The team is applying machine learning to EEG data, as well as other physiological signs like heartbeat and respiration, to further refine characterization of cognitive states and extract more information from the data. ❖

“What do kids **want to do?**
They want **to control stuff** in their room.
How **cool is** that?**”**

— Max Newlon, BrainCo

BrainCo’s LUCY headband can be paired with real-world objects, such as the pink light seen here, to allow them to be remotely controlled by the wearer’s brainwaves. This neurofeedback loop helps users learn to control their attention levels.

NASA Plant Research Offers a Breath of Fresh Air

NASA Technology

Try to name sources of air pollution. Most likely your first thoughts would be things like exhaust from burning coal or driving a car. But, perhaps counterintuitively, the air indoors is as much as 30 times more toxic than the air outside.

One solution, borne out by NASA research, is to bring some of the outside in: plants and associated microorganisms in the soil around them are "nature's life-support system," notes a study published by Stennis Space Center in 1989.

So get some houseplants—that's easy. But the study, led by B.C. Wolverton, head of Stennis' Environmental Research Lab, was interested in how to maximize the air-scrubbing ability of those plants. After all, space habitats present the toughest possible challenge for ensuring safe, breathable air, since they're entirely closed systems in an airless vacuum. There's no chance to get some fresher air by opening a window, and even if engineers were able to build a habitat free from any of the toxins and chemical pollutants we find on Earth, "man's own waste products would cause indoor air pollution problems," notes Wolverton.

Wolverton screened a dozen common houseplants from the gerbera daisy to the bamboo palm, and tested their ability to remove a variety of household toxins, like formaldehyde, from a sealed chamber. The goal was to find which plants did the best job with different pollutants.

But perhaps the most important finding, and one that surprised the researchers, was just how, and what part of, the plant was doing the bulk of the filtering: the roots and soil. As part of the experiment, the researchers removed all the leaves and learned that the air-purifying effect was only a tiny bit less than before.

Wolverton and his team used the results to create a design for a plant pot with an activated carbon filter to maximize its air-purifying abilities, based in part on wastewater treatment studies.

The design also incorporated an electric fan beneath the pot to draw in more air and direct it into the soil, where the carbon and roots could do their filtering: "smoke, organic chemicals, pathogenic microorganisms (if present),

We sometimes call Earth the "blue planet," but the green is equally key to supporting life. Plants not only take in carbon dioxide and return oxygen, but they are exceptionally good at capturing harmful toxins from the air. NASA research has delved into how plants do this, and how to potentially use plants to provide clean air on long-duration space missions.

and possibly radon are absorbed by the carbon filter," the study notes.

"Plant roots and their associated microorganisms then destroy the pathogenic viruses, bacteria, and the organic chemicals, eventually converting all these air pollutants into new plant tissue," it continues.

Technology Transfer

With the results of the study in the public domain, other researchers and engineers over the years have been able to use and adapt them to their own products.

One group to do just that was Hamburg, Germany-based AIRY GreenTech, which was interested in creating a stand-alone system that relied exclusively on the plant, soil, and related microorganisms to do the air filtering, with no need for a carbon filter or a fan.

"There are a lot of articles describing the air-purifying plants used by NASA," explains founder and managing director Peer-Arne Bottcher; anyone can use those plants in their home. He and his team wanted to capitalize on the second finding, that the most effective part of filtering was happening around the roots. "What we're doing with our part, our AIRY box, is to scale up the efficiency of the air-purifying plants even further by ventilating the root system."

It took a lot of engineering, he says, to solve problems like how to water a plant in a pot with ventilation all around the base without all the water pouring out. "We have three patents on our system internationally," Bottcher says. However, at its core, the design is "all based on the facts and the tests done by Dr. Wolverton and his team."

Benefits

The pot is deceptively simple, Bottcher says, but extremely effective.

First, vents around the pot draw air in, and that air gets basic filtration simply by passing through the soil.

The plant itself acts as the "second step," he says. As Wolverton proved in his research, the plant and the microorganisms that thrive in the soil around its roots extract organic compounds from the air and turn them into nutrients for the plants. "That's the most exciting part, that's the reason why humans are able to live on this planet, because plants have purified the air. And we are using this ability of the plant in our pots."

To create its plant pot, AIRY GreenTech used NASA's findings on the importance of roots and microorganisms around them in the soil for the plant's ability to extract toxins from the air. The design allows maximum airflow through the soil and around the roots, which increases the air-purifying capacity, while also helping the plant thrive.

Different plants are better than others at removing particular pollutants, Bottcher says and Wolverton's study results included a list of which plants were best in different circumstances. However, he notes, "the plant is quite flexible in which pollutants are transformed into nutrients," and it can actually detect the pollutants in a given space and adapt to some extent to make better use of those pollutants.

"The plant needs about two weeks to detect the pol-lutants and to build the different enzymes to metabolize them," he says. In the meantime, the plant is also helping improve indoor air quality by humidifying the air, because plants release water vapor as part of photosynthesis and respiration

And while the goal of the AIRY plant pot was to increase the air-filtration abilities, there is a side benefit for the plant: increased airflow around the roots helps the plant grow better. Add in the special water reservoir that ensures the plant gets as much water as it needs it without spilling through the ventilation holes, and, well, "you don't need a green thumb," says Bottcher. "The AIRY system takes care of your plant for you."

Currently, the company offers two models: an AIRY pot, designed for rooms around 172 square feet or smaller, and a larger AIRY box, designed for rooms around 322 square feet. For larger spaces, the company notes, customers can use multiple pots or boxes.

The company claims its system can neutralize nearly 100 percent of the most dangerous environmental toxins in a room in only 24 hours—though it notes that pollutants continue to evaporate all the while, so the air would never be completely toxin-free.

In the United States, the pots are available for sale through Amazon.com, and the company is looking for additional sales channels. Meanwhile, the products are also available in some 50 countries around the world, with partners in Asia, Europe, the Middle East, and Latin America. One distribution company in Chile and Brazil, for example, sells to schools and government facilities.

AIRY also sells directly to multinational companies like United Kingdom-based Ernest and Young, a tax and law firm that has installed plant pots in its offices around the world. "They're loving it, because it's very good for the health of the employees," says Bottcher. ❖

Light Research Aids Slumber

NASA Technology

In the age of smartphones and e-readers, with touchscreens and LED displays seemingly on every appliance and everywhere else, it has also become quite commonplace to talk about the problems of too much blue light from all those screens and how it is costing us sleep.

But that basic fact—that shorter wavelengths of light cue our body for alertness—is something that has only fairly recently become understood. And much of the fundamental research that led to these revelations owes its origins to NASA and the Agency's need to ensure rest for astronauts.

Back when astronauts only spent a few days at a time away from Earth, how they slept was not the biggest concern. And while the lack of gravity and a normal day/night cycle was clearly disruptive to the body's circadian rhythms, the elite men and women of the astronaut corps could "tough it out."

But by the 1990s, trips into orbit were stretching into weeks, and with the construction of the International Space Station, astronauts began regularly spending months at a time in space. Toughing it out was no longer a viable option.

To better understand just how spaceflight impacted rest and alertness, the Space Agency began its own research and supported outside studies, mainly through Johnson Space Center and the National Space Biomedical Research Institute, a nonprofit research consortium of NASA and more than 70 other agencies, universities, and institutions. One report, published in the Journal of Biological Rhythms in 1998, studied the sleep and circadian rhythms of four astronauts over 17 days of a Space Shuttle mission.

"Like other animals, in humans the circadian timekeeping is entrained to the correct period and temporal orientation by [environmental cues], the most important of which is the alteration of daylight and darkness," the authors noted.

But it wasn't until several years later that details began to emerge of the specific impact of short, or blue, wavelengths, which are abundant in daylight. In one of several NASA-funded studies, this one published in the Journal of Clinical Endocrinology and Metabolism in 2005, researchers found that "the efficacy of light in phase shifting human circadian rhythms is wavelength dependent and that the human circadian pacemaker is more sensitive to short (460 nanometers) versus long (555 nanometers) wavelengths of visible light."

The study also noted that the sensitivity was true even for subjects who were otherwise totally blind. Ultimately, NASA-funded studies found that there's a third type of photoreceptor in the eye that responds to blue light, in part by suppressing production of melatonin, which plays a role in governing our sleep and wake cycles.

Technology Transfer

As the picture clarified, NASA began working on tailoring LED lights to different wavelengths, in the hopes it could artificially create a day/night light cycle for astronauts to stimulate alertness and help them sleep when appropriate.

Here on Earth, a number of companies have done the same (*Spinoff* 2015, 2018), including one by the name of Headwaters Research and Development Inc., based in Marblehead, Massachusetts, and Ottawa, Canada, which developed a sleep mask with light cues to help wearers fall asleep faster and sleep more deeply throughout the night.

"It started probably back in 2011. We took over production of this simple mask that helped you meditate to go to sleep. It used some glow-in-the-dark strips inside of a sleep mask," explains Philippe Genereux, Headwaters' vice president of research and development. "People enjoyed that and found it useful," he says, but the developers thought they could make it even more useful.

Sleeping in orbit can be difficult, where the usual day/night circadian cues are absent. NASA research to help astronauts sleep better in space has led to discoveries about how short, or blue, wavelengths can increase alertness and impede sleep.

Genereux and his colleagues began researching different colors of light and came across the NASA research. "We learned that blue light improves alertness and it helps to overcome sleep inertia in the morning," he notes, and "we knew we wanted to avoid large amounts of blue light at night."

The team interviewed a NASA-funded researcher and read studies going back two decades, to design a brand-new "smart" sleep mask under their Sound Oasis brand, called Illumy. In addition to serving as a "sunrise" alarm clock by cuing short-wavelength, blue light in the morning, the mask also tries to do the opposite by using longer-wavelength, red light to cue sleepiness at night.

"Some researchers say that pure darkness, total darkness at night is the best situation to help people sleep," explains Genereux. "Our product does offer that option, but our experience with Illumy is that some people need a little extra help to get to sleep. Just like relaxing sounds can help some people get to sleep, we've found that a dimming red light is a similar tool that we use."

Benefits

In early 2017, Sound Oasis launched a crowdfunding campaign on Indiegogo to introduce its Illumy mask, quickly raising well over $50,000 and selling more than 500 of the first-generation product.

Since then, the company continues to make the mask more lightweight and flexible to improve the wearer's comfort. That includes improving the light panels, which are only a few millimeters thick, Genereux notes.

"One thing we learned with our first-generation sleep mask is that many people don't want their eyelashes touching the inside of the mask," he adds, so the company has built up the foam that lies against the wearer's face, to keep the mask away from the eyelashes.

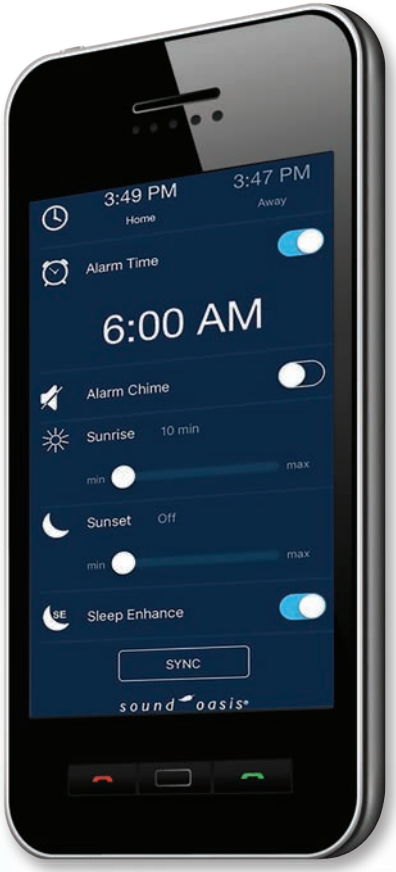
The company has also developed an app for Apple and Android devices that programs the mask to the users' individual settings, including when they aim to fall asleep and when they need to wake up.

And, in addition to simply tailoring light wavelength, the mask has the option of pulsing the light—slower red light at bedtime and quick, blue light in the morning—which the company says helps guide the wearer most effectively to sleep and to wake. And because the mask also blocks out all ambient light from the room, the company argues it is more effective than other nightlights or alarms that use light cues.

Ultimately, however, Genereux says it's really the NASA research on blue light and the cues it gives to the circadian rhythms—which is now becoming well known—that is driving the success of the mask. "That's ended up being the biggest point of interest from the press or from bloggers—they're really excited to see an application of all this talk of blue light and red light."

As a next step, the company is working on tailoring the device to help travelers tackle jet lag. And meanwhile, since the end of the crowdfunding campaign, Genereux says international sales have been excellent. "We've sold quite a few recently in Japan and Australia," he notes, adding, "We're happy with the initial launch and even happier to see the interest from all over the world to help us build out our sales channels."

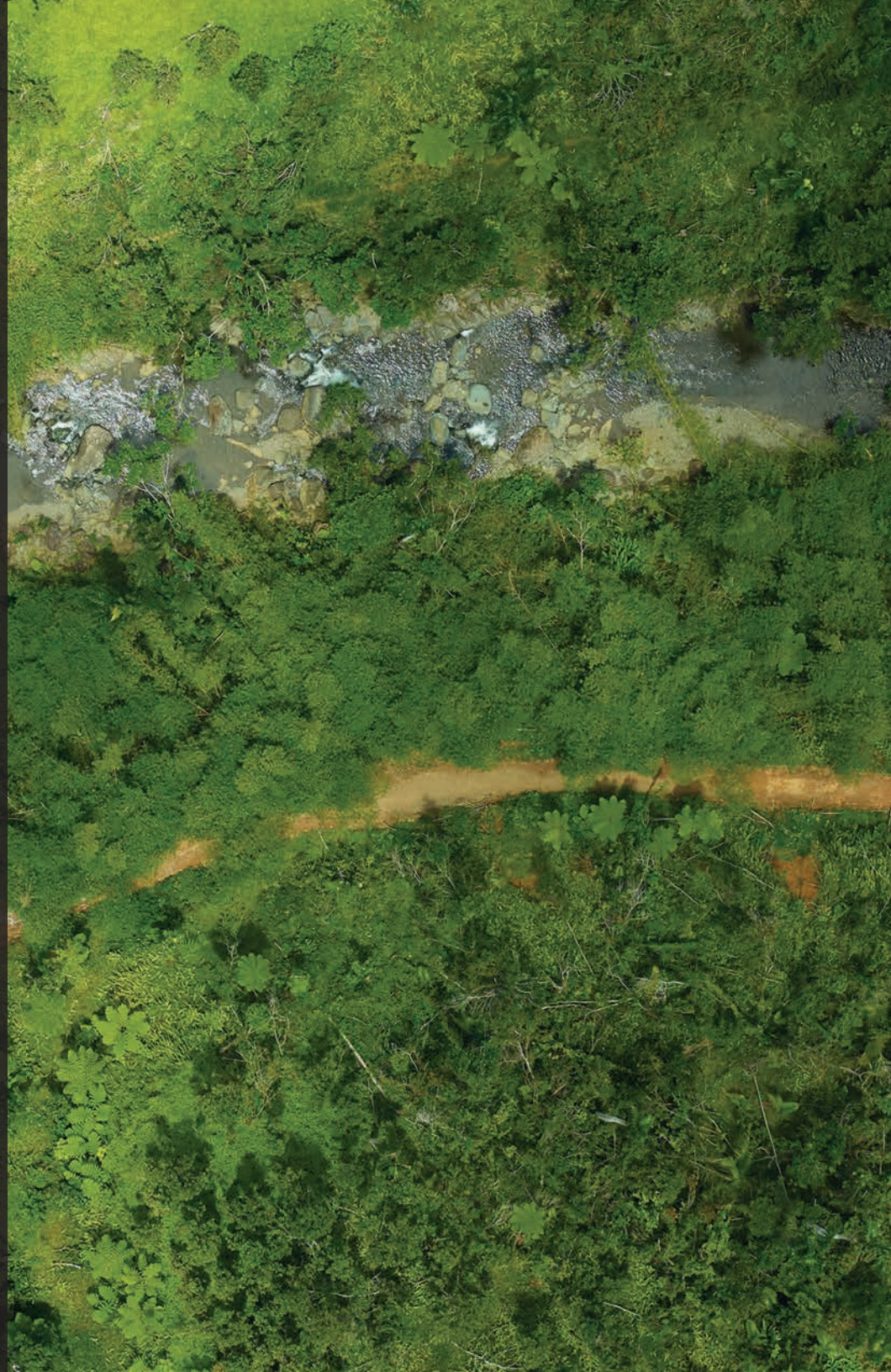
He credits NASA and its early research with a big role both in increasing the understanding of how light impacts circadian rhythms and with inspiring products like Illumy. "Some people may think the link from NASA to small companies like ours might be a long one, but because of NASA's visibility, a lot of engineers are looking to the work NASA's doing for inspiration." ❖



Headwaters Research and Development used NASA's published findings on light wavelengths and alertness to help create its "smart" sleep mask, which can be controlled with a smartphone app. Among other features, it can pulse red light at bedtime and blue light in the morning to help the wearer fall asleep and wake up.

Energy and Environment

Many of the challenges of space missions—from keeping healthy to making the best use of scarce resources—apply here on Earth as well. In this section, read about electricity-generating bacteria that could power future exploration and are already cleaning wastewater, as well as new ways to mimic sunlight with LEDs that could concentrate nutrients in vegetables grown in space—and on the ground. Other innovations make use of the long view of Earth from orbit to predict crop growth and provide new insights into our changing planet.



Electrified Bacteria Clean Wastewater, Generate Power

NASA Technology

NASA recently sent into space organisms that might sound like they came from space to begin with—microbes that can essentially breathe electricity.

In fact, all metabolism is powered mainly by electron transfer. Animals must breathe oxygen because, in their aerobic metabolism, electrons are picked off of molecules within the cell and go through a long chain reaction ending at the inhaled oxygen molecules, which take on the electrons and share them with hydrogen atoms to produce water. In most bacteria capable of anaerobic respiration, sulfate or nitrate might take the place of oxygen as the final electron acceptor. But the *Shewanella oneidensis* bacteria that traveled to the space station for study last February can, in the absence of oxygen, use a metal outside the cell as the final electron acceptor, transferring a charge.

Since *Shewanella* was discovered in 1988, scientists have found a host of similar microbes, known as exoelectrogens, that can "exhale" or "inhale" electrons or in some cases do both.

NASA, always looking to maximize efficiency, has taken an interest. There are a number of potential applications, though none has yet been made practical for space travel. One idea, says John Hogan, a scientist in the Bioengineering Branch at Ames Research Center who is overseeing the space station experiment, is to make fuel cells or electrolysis cells that would use genetically engineered varieties of these strange microbes as catalysts on their electrodes. These fuel cells could be used to process wastewater while generating energy and converting the waste into various products, from edible biomass to pharmaceuticals to bioplastics.

"The fuel cell is just a tool to make products we're interested in," says Hogan. "On one side you're making energy, and on the other side you're making products. That's one of the reasons it's interesting."

In 2006, graduate students at the Massachusetts Institute of Technology founded IntAct Labs, now known as Cambrian Innovation, with funding from a NASA Innovative Advanced Concepts (NIAC) grant to study "bioelectric space exploration." Among the ideas the company explored under the grant was a microbial fuel cell based on exoelectrogenic microbes and powered by wastewater.

"With the NIAC grant, we did a broad-based survey of what was going on in bioelectricity and how NASA could use it," says Matt Silver, founder and CEO of Cambrian Innovation. "There was a little lab work to validate that some of the things we were reading were true. What we learned led to what came next."

What came next were grants from the U.S. Department of Agriculture, the Environmental Protection Agency, the National Science Foundation, the Army, NASA, and others, mostly aimed at further developing the use of electrochemically active bacteria for wastewater treatment and power generation.

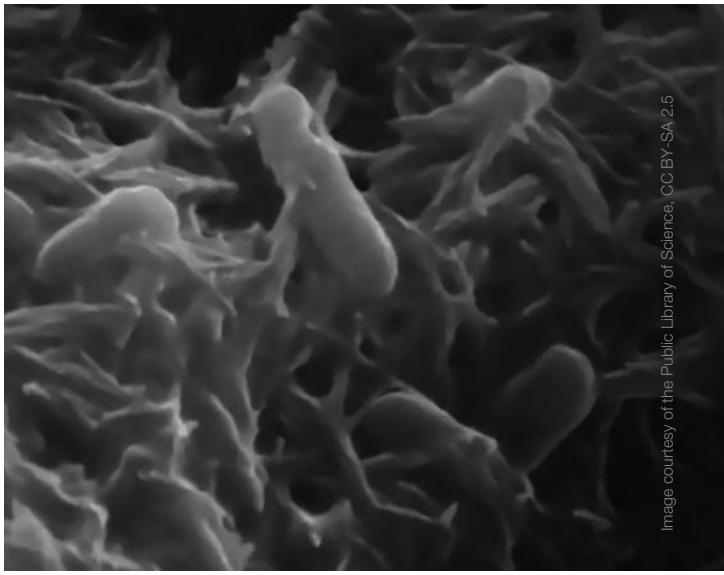
But NASA was interested in using the microbes to create more than just energy.

In 2011, Hogan oversaw a Small Business Innovation Research (SBIR) contract with Cambrian to fund the development a life-support system that would use exoelectrogenic microbes to extract carbon dioxide from the air in a spacecraft and generate oxygen, water, and methane. While NASA didn't plan to make direct use of the methane, its production was considered a possible future commercial application. The idea would prove to be prescient.

Technology Transfer

The year before Cambrian undertook the Ames work, it had worked on another SBIR contract with Johnson Space Center to build a reactor to treat wastewater while functioning as either a microbial fuel cell, converting wastewater to energy, or a microbial electrolysis cell, using input electricity to break down waste and create useful hydrogen or methane.

"We knew we could generate methane but thought it might be interesting to do all three—energy, hydrogen, and methane. And what if we could switch between them?" says Silver. That project resulted in a patent. It also resulted in a working cell and test data.



Shewanella oneidensis bacteria, discovered in 1988, were the first microbes known to be able to breathe by transferring an electric charge to a metal outside their cell membrane. NASA recently sent a batch of *Shewanella* to the ISS to see how they react to the spacecraft environment, as they could be useful for life-support systems.

"Across the board, we gained experience iterating on materials and inoculation methods," says Justin Buck, Cambrian cofounder and chief technology officer. He adds that the work validated that the basic concepts worked, as well as the benefits and efficiency of the technology and the conditions in which the microbes best performed.

Silver notes that NASA was skittish about the idea of relying on colonies of living organisms for life support, but the work showed that the biofilms the bacteria formed on the electrodes were reliable. "It validated that the biofilms are extraordinarily tough and resilient," he says, noting that this robustness and consistency is now a major advantage of the company's commercial product over alternatives.

Units of Cambrian Innovation's bioelectrically enhanced wastewater treatment system, the EcoVolt Reactor, can be stacked to meet a larger facility's needs. For businesses generating 10,000 to 15,000 gallons of waste per day, the EcoVolt MINI (inset) combines the EcoVolt Reactor, which removes most contaminants, with its more conventional EcoVolt MBR (Membrane Bioreactor), which polishes the water for reuse.

Benefits

In the fall of 2013, Cambrian announced that its bioelectrically enhanced wastewater treatment system, the EcoVolt Reactor, was available for sale. By then it had successfully field-tested one of its shipping container-sized units at a California winery over 18 months.

The prefabricated, modular system applies a small electrical charge to enable what Silver calls "biologically assisted electrolysis." Microbes on the anode break down waste to generate electricity, while different microbes on the cathode—electromethanogens—feed on that electricity, as well as carbon dioxide, to create methane-rich natural gas to be burned for power. The gas provides significantly more energy than the charge that's put into the unit, making it a net-positive energy generator.

Wineries and breweries were the first industrial facilities the company targeted for adoption of its technology because they produce large amounts of highly contaminated wastewater—around five gallons of wastewater for every gallon of wine or beer produced. That wastewater is also far more concentrated than what households produce and what municipal treatment facilities are designed to treat, averaging about 30 times more concentrated than domestic waste and forcing beverage producers to come up with their own solutions or face steep fees.

Low-tech aerobic treatment options, such as wastewater treatment ponds, require a huge footprint, while more advanced aerobic options produce large amounts of solid waste and use a lot of energy. Traditional anaerobic alternatives generate renewable energy and produce less solid waste but are sensitive to fluctuations in input and other environmental changes and tend to require careful oversight and management.

With the help of its living electrodes, the EcoVolt Reactor can reliably process more variable loads of wastewater than other anaerobic systems with minimal oversight, all while achieving high treatment and methane production rates, the company says.

"A really big advantage is that it's a very consistent and stable treatment process," says Silver. "It works continuously with very little down time."

The natural gas it produces is 70 to 80 percent methane, which he says is higher than alternatives can produce. Because the system is prefabricated, he adds, it can be transported by road and is easy to set up, and if a facility expands its operations, it can scale up treatment by adding another unit.

The bioelectrically enhanced system removes enough contaminants for a brewery or winery to discharge the output into a municipal treatment system without surcharges. For those that want to reuse the treated wastewater, the EcoVolt Reactor can be followed by the company's EcoVolt MBR (Membrane Bioreactor), a more traditional aerobic system that further polishes the wastewater, removing more than 99 percent of contaminants. This is especially attractive to

“We see a **big trend associated** with **extracting resources** from **waste—treating** it more as **a potential source** of **value than** a **cost burden.”**

— Matt Silver, Cambrian Innovation

For every gallon of wine it produces, a winery creates about five gallons of wastewater that’s 30 times more concentrated than household wastewater. Breweries generate similar levels of waste. This makes them a natural market for Cambrian’s bioelectrically enhanced wastewater treatment systems, although the company is also targeting dairy producers, juice processors, and the wider food and beverage market.

companies located where water use is restricted. Producers there often face water-use caps that can limit production, and they may also pay high prices for water.

“We definitely saw the most interest in California at first, but now we’re seeing interest across the country,” says Claire Aviles, marketing and communications manager at Cambrian.

For companies producing less than 15,000 gallons of wastewater per day, there’s also the EcoVolt MINI, which combines EcoVolt Reactor and EcoVolt MBR technology in a single unit.

And in late 2015, the company established its WEPA (Water-Energy Purchase Agreement) option, whereby Cambrian installs, owns, and operates its EcoVolt solutions on behalf of an industrial facility, charging a monthly service fee based on wastewater treated and clean water and energy returned to the facility.

Having made its first sale in 2014, Cambrian now has industrial-scale projects at more than 10 different wineries and breweries. The company has helped facilities treat more than 70 million gallons of wastewater and recycle more than 20 million gallons to date. It has grown to 40 employees and added a new office in California, in addition to its headquarters in the Boston area.

One of Cambrian Innovation’s brewery customers uses two EcoVolt Reactors to transform its wastewater stream into value by generating up to 95 kilowatts of electricity (the average U.S. home consumes two kilowatts of power at any given time). This allows the brewery to eliminate over 4,000 metric tons of carbon dioxide emissions per year through energy savings. Other customers reuse treated wastewater in industrial processes such as rinsing equipment.

“NASA was critical to the company getting started,” Silver says. “It’s hard to get into the market without an initial validation, and that usually can’t be supported by the private sector.”

Now he sees the company’s work as part of a growing movement. “We see a big trend associated with extracting resources from waste—treating it more as a potential source of value than a cost burden. That’s very similar to how it’s looked at for space travel.”

And those *Shewanella* microbes that recently traveled to the space station will help determine whether technology like Cambrian’s might commodify waste in space. ❖

Building-Monitoring System Provides Insights for Sustainability

When Ames Research Center built Sustainability Base, it wanted the building to produce at least as much energy as it consumed. To attain that goal, it included solar panels, a fuel cell, and even a small wind turbine. It also incorporated a monitoring system to show energy going in and out.

NASA Technology

When we talk about "green buildings," the conversation is generally about reducing consumption. That's because buildings and their occupants consume lots of energy: people turn on lights and computers, appreciate air conditioning, ride in elevators, and take advantage of any number of other conveniences powered by electricity from the grid.

But there is a flip side to the equation. In addition to reducing consumption, another way to lessen a building's draw on the grid is to produce renewable energy onsite.

When Ames Research Center won the funding to build Sustainability Base, the most environmentally friendly building in the Federal Government, that was a critical part of the plan. In addition to incorporating all manner of energy-saving technology, from skylights to reduce the need for artificial lighting to cutting-edge climate control systems and more, the engineers also included solar panels, a highly efficient fuel cell, and even a small wind turbine to power the building's needs.

"Part of the goal was just to be able to show ourselves and show the public that in fact it's possible, in a building on planet Earth, using modern technology and some NASA aerospace technology, to build a building that can produce more than it consumes," emphasizes Steve Zornetzer, Ames' recently retired associate director for research and development, who spearheaded the effort to build Sustainability Base.

To prove that it was really accomplishing what it promised, the building needed a system to monitor what energy was coming in and what was going out. "We went around Silicon Valley at the time"—this was around 2009 or so—"looking for best practices," Zornetzer recalls.

That work led them to San Ramon, California-based Integrated Building Solutions Inc. (IBS), which was already developing an energy dashboard, a way of quickly visualizing the energy-consuming and energy-saving activities.

> "One of our intentions was to make it an intelligent building and create an environment that would inspire other people to do similar kinds of things."
>
> — Steve Zornetzer, Ames Research Center

"Ames used us as the single pane of glass so we can see the performance and how they are all working as a system. They were talking about air conditioning, lighting, real-time metering, solar-panel system, fuel system, occupancy control, about a dozen different systems," explains IBS owner Eugene Gutkin. "The goal was pulling the data from their systems, putting it in one interface, and making sure the building is working as efficiently as possible."

The results are now prominently displayed in the lobby of Sustainability Base, and "typically what it shows in the dashboard is that at virtually any moment, the building produces more than it is consuming," says Zornetzer.

Technology Transfer

With help from Ames' computer scientists, IBS was able to add an important additional feature to its dashboard: fault detection. "It's a technology we've developed for aerospace and flown in high-performance military jets, NASA planes, and spacecraft," says Zornetzer.

To detect a problem, the system starts by understanding how a device is supposed to operate, from its temperature to vibrational patterns and a host of other parameters. "Then you monitor the measurement of those parameters in real time, and constantly compare it to the optimal state in the model. Fault detection algorithms enable you to detect when there's deviation between nominal and actual," he explains.

With this system in place, the building operators can avoid the expense of unnecessary maintenance but still note when a component is acting suspiciously and replace or fix

it before it fails, he says. "Unlike the energy consumption dashboard, this is not something that's on public display, but it's something our maintenance people use every day."

In addition, says Gutkin, the system adds depth to the energy consumption picture: "When something is not working, we're able to track the cost of this malfunction from the energy perspective."

To accomplish the project, NASA and IBS signed a Space Act Agreement to share information back and forth. "I don't think very much money, if any, changed hands," says Zornetzer. "They saw the opportunity to learn from the experience at NASA and improve their own tech and at the same time provide us something that would be very beneficial. It was win-win for both sides."

For the fault detection component, in particular, "we met with Ames' engineers multiple times, and they showed us how their system works," recalls Gutkin. Using that foundation, IBS was able to build a system tailored to Sustainability Base's systems, including lighting, the solar panels, various meters, and more. "And once it was built, those engineers participated in the testing, trying to monitor the various components and ensure it would catch problems."

Benefits

Today, fault detection is a standard component of the Intelligent Building Information System (IBIS), which has been installed at a number of corporate campuses across Silicon Valley, as well as in other government buildings. Gutkin credits NASA directly with helping the company expand its business.

"Our exposure to NASA, the experience we gained working with them on the diverse systems, helped us to get the trust and the technology that we have used in government jobs and quite a few other projects," he says.

One project that came almost immediately following Sustainability Base was for the U.S. General Services Administration. Since then, IBS has also installed systems at PayPal, Oracle, General Dynamics, and Intuit, among others.

Integrated Building Solutions improved its energy-monitoring dashboard for Sustainability Base and now installs the upgraded system at corporate campuses across Silicon Valley as well as in other government buildings. Among other features, it enables a building manager to look at how energy consumption differs across different zones, even on the same floor.

Like at Sustainability Base, IBIS provides a way to monitor energy consumption of critical building systems, like air conditioning, lights, and renewable energy, while also providing alerts to any abnormalities. "They're using this to save energy, also for critical system monitoring, so they can have a quick response if something fails," Gutkin emphasizes.

For older buildings looking to reduce their environmental footprint, IBS notes, its system can provide important insights as well as help various "smart" systems integrate most efficiently. At Oracle, for example, a sprawling campus that includes 17 buildings and 84 acres of landscaping originally built in 1997, the installation of IBIS was part of a two-year sustainability initiative starting in 2015. The results of the campaign, all reflected in the energy dashboard, saw electricity consumption drop 28 percent in the first two years, irrigation water use drop by 29 percent, and annual savings of $3.86 million—a 190 percent return on investment.

Zornetzer says he is pleased to see the work done for Sustainability Base spreading to other government buildings and beyond.

"One of our intentions was to make it an intelligent building and create an environment that would inspire other people to do similar kinds of things," he says. ❖

Space Station Garden Shines Light on Earth-Based Horticulture

NASA Technology

Astronauts have been gardening on the International Space Station for years to learn how plants grow in microgravity, with the idea that space crops will one day help sustain humans on long-duration missions such as to the Moon or Mars.

The Phytofy system's lighting capability and range of choice allow NASA researchers on Earth to simulate the lighting capabilities of the Advanced Plant Habitat, a growth chamber that astronauts began using on the ISS in early 2018.

As on Earth, plants in space require nutrients, water, air, and light. Rather than resting in a soil garden bed, space station plants grow in a pillow-like container, which holds a ceramic growing medium with controlled-release fertilizer that provides nutrients over time. The pillow system is designed to be a passive watering apparatus, but astronauts can also inject water directly as needed.

An LED lighting system enables the crew to grow crops independent of sunlight.

Different light color combinations, or "light recipes," can have dramatic effects on plant size, shape, texture, and appearance. This happens on Earth as well: the angle of the sun in the sky changes the light color and intensity of its rays on the ground, providing a cue for plants to respond to the light environment and adjust their growth to the available light quality. As a result, plants can develop biological rhythms to detect time of day and time of year.

Matthew Mickens, a NASA postdoctoral research fellow at the Kennedy Space Center, investigates how different light recipes affect crop yield, as well as the nutrient content and flavor of plants.

"There is a light recipe that will maximize the yield of a crop, in terms of total edible biomass," he says, "and there's also a light recipe we can use to keep plants short—a process known as dwarfing. I've observed that when plants stay small throughout their growth cycle, the rate of nutrient uptake is still the same, so they're actually concentrating higher levels of nutrients within the leaf tissues by staying small. The trick is to find the recipe that balances both yield and nutrients."

The space station crew members currently use three growth chambers for gardening: two simple Vegetable Production Chambers, more commonly referred to as Veggie units, and a newer plant growth system called the Advanced Plant Habitat (APH), which joined the space station's Veggie units in the fall of 2017 and was initiated in January 2018.

Like the earlier growth chambers, the APH secures seeds in a growing medium. However, unlike the Veggie units, APH allows users to exercise complete control of the plant's environment. At about the size of a minifridge, it's larger than the Veggie units. It's more automated as well, with many functions driven by a computer on board—minimizing the amount of time astronauts have to spend gardening.

It also has an improved custom-designed LED system that offers a greater variety of light colors and intensities. The Veggie habitats are equipped with red, green, and blue LEDs, while the APH adds white and far-red, a light color between red and infrared barely visible to the human eye but detected and used by plants.

The APH has already been used on the space station to grow dwarf wheat and a flowering plant related to cabbage and mustard, using light recipes and other techniques NASA scientists first designed and thoroughly tested on Earth.

Technology Transfer

Controlling light for crop growth is also a terrestrial horticultural focus, where there is growing interest in vertical farming—techniques enabling food and other crops to be grown indoors in places like skyscrapers, old warehouses, or even shipping containers. The idea is to establish year-round fresh and local food options in urban and other areas that don't have easy access to farmland.

OSRAM, a high-tech German lighting company with U.S. headquarters in Wilmington, Massachusetts, has been working on a horticulture lighting solution to improve research in this field through a project headed by Steve Graves, strategic program manager for urban and digital farming in the company's innovation group.

The OSRAM solution, Phytofy RL, is a tray-like fixture with a network of LED lights, temperature control, and a software-controlled panel to adjust settings. OSRAM has worked with academics and others to design it according to researchers' needs.

Aware of both NASA's plant projects and OSRAM's technology, vertical farming specialist Chris Higgins, founder of Hort Americas (a company that works with

OSRAM's Steve Graves (right) and NASA's Matthew Mickens install a prototype of the company's LED lighting system Phytofy in a reach-in growth chamber at Kennedy Space Center. NASA is researching the effects that light color, duration, and intensity have on plants on the ISS. Controlling light to affect crops is also a focus of horticulture that stays on Earth, where there is growing interest in growing crops indoors in places like skyscrapers, old warehouses, or even shipping containers.

commercial greenhouse growers), introduced the Kennedy researchers to OSRAM's developers in 2017.

"It turns out that our fixture is very compatible with what Kennedy Space Center is doing to develop light recipes or protocols that might be useful for the Advanced Plant Habitat," Graves says.

Later in 2017, Mickens and other Kennedy researchers began using a Phytofy prototype provided by OSRAM to conduct ground-based studies and preliminary research for in-space APH experiments. Mickens and the OSRAM team installed the Phytofy in a reach-in growth chamber, and eventually plan to use the lighting fixture in Kennedy's walk-in growth chambers as well.

Mickens says OSRAM's device offers choices in light wavelength, which determines light color, that are similar to the APH. "The Phytofy gave us the capability to simulate the Advanced Plant Habitat lighting environment without necessarily needing to go buy a second APH unit."

Mickens and Graves remained in close communication during what was essentially beta testing of Phytofy, with Mickens offering feedback and describing his research. The exchange with NASA has helped the OSRAM team feel confident enough to sell Phytofy commercially, with an expected product launch in late 2018 or early 2019.

"It's served as validation," Graves says, "but we also receive useful feedback from Matt in regards to the research he's doing. The result is new light recipes for NASA, and we are hopeful that their success percolates into controlled environments on Earth, which will aid our mission to overcome food insecurity worldwide."

Benefits

OSRAM is initially marketing a Phytofy solution featuring a configurable lighting system with real-time controls, as well as scheduling capabilities, to plant scientists in academia and in commercial growers' research and development departments. Graves expects future versions will add additional automation and sensor options to help reduce the large amount of human observation that plant science now requires. All settings can be controlled through a graphical user interface.

OSRAM has designed Phytofy's current light spectra—light wavelength (color) and intensity—specifically for researching plant light recipes, including the far-reds that mimic end-of-day sunlight, brief UV light, and night interruption light that can also affect how plants grow.

While pharmaceutical companies and flower growers have shown an interest in this type of research, much of the early interest is in food crops. Light recipes give growers—in space and on Earth—the ability to affect plants in ways that were not previously possible.

"The use of LEDs provides complete control over the wavelengths—or colors—of light that we use to grow the plants," Mickens says. "This allows us to strategically alter the plant's physiology in all kinds of ways."

This type of plant research, with the help of devices like Phytofy, is laying the scientific foundation for feeding humans on the Moon or Mars—or even back on Earth, where vertical farmers hope to resolve some of the food supply challenges we'll face in the coming decades.

Graves says the Space Agency's researchers are consistently on the cutting edge in horticulture and that their work informs OSRAM's. "They serve as pioneers for the tools that we're developing," he says, "and they also provide input into our product roadmap. I hope this is just the beginning." ❖

Carbon Capture Process Makes Sustainable Oil

NASA Technology

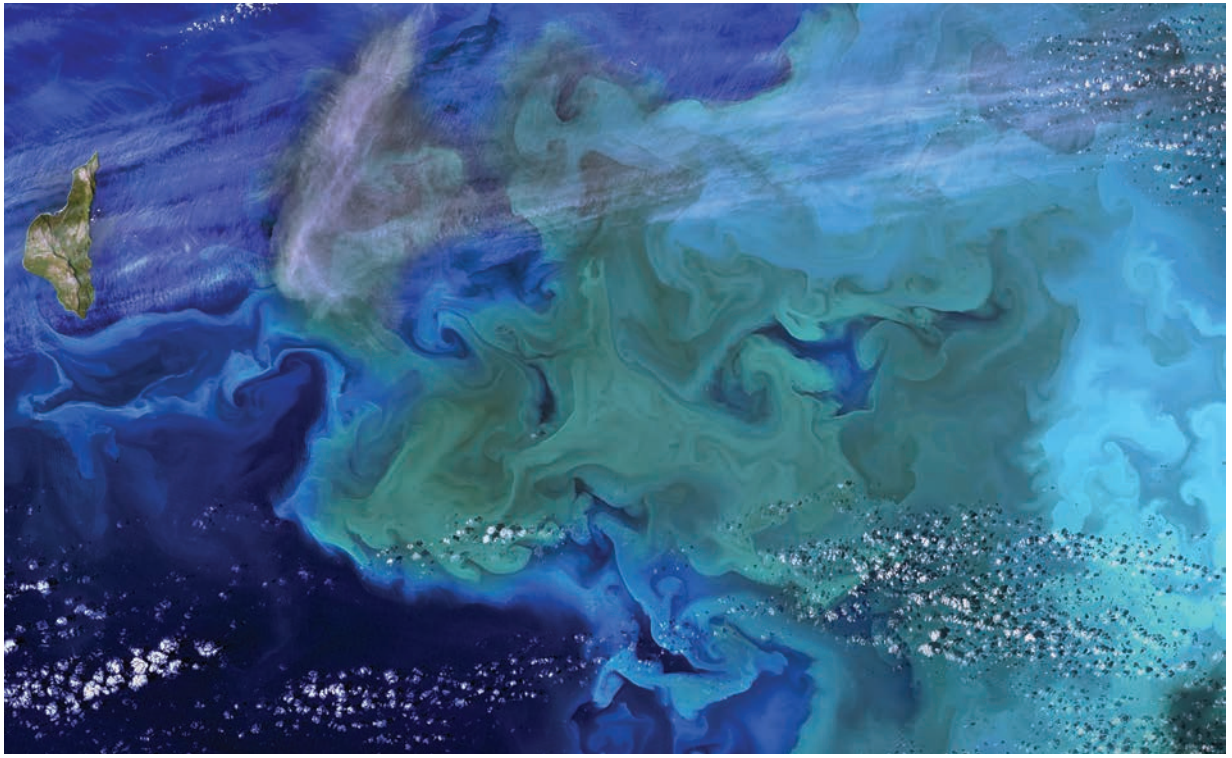
NASA has many researchers focused on the carbon cycle on Earth—and how it contributes to climate change—but the Space Agency has also spent plenty of time delving into what to do with excess carbon in the closed environment of a spacecraft. Now, thanks to an innovative start-up, that life-support research could provide part of the solution to Earth's climate problems, too.

As far back as the 1960s, even before Neil Armstrong stepped on the Moon, NASA was envisioning missions deeper into space. And for just as long, the Agency has known it needed "life-support systems that minimize as much as possible the expendable materials carried in the spacecraft," Lockheed Missiles and Space Company's R. B. Jagow and R. S. Thomas wrote in a paper from a 1966 report published by Ames Research Center.

Among other challenges, any life-support system needed to find a way to make good use of the waste products the astronauts would produce. As that same report noted, "metabolic wastes—mainly evaporative water loss, urine, utility water, expired carbon dioxide, and feces—amount to 10 to 14 pounds per man per day. For a 10-man, three-year mission, this amounts to over 100,000 pounds without considering the weight of containers."

The 1966 report, titled "The Closed Life-Support System," devoted nine chapters, each written by a different team of researchers, to studying various options for and challenges in taking waste products and turning them into breathable air, clean water, and food. One of the most promising, both for its high efficiency in recycling carbon dioxide (CO_2) into useable by-products and for its low power and space requirements, relied on hydrogen-fixing bacteria, focusing particular study on a genus of bacteria called *Hydrogenomonas*.

"First hydrogen and oxygen are combined to obtain energy; then CO_2 is reduced to form cell material," Jagow and Thomas explain. Unlike algal and other plant systems that require light for photosynthesis, the bacteria could grow in the dark. That, along with its higher use of CO_2 than algal systems, meant it was up to 15 times more efficient overall.



This Landsat snapshot, of a phytoplankton bloom off the coast of Alaska, offers a glimpse of Earth's life-support system. Microorganisms, like phytoplankton, take carbon dioxide (CO_2) and turn it into something else—in this case, oxygen and food for marine wildlife. NASA research has studied how to harness these natural processes to improve conditions for astronauts on long-duration space missions.

The report notes that NASA had already studied *Hydrogenomonas* for three years, in part to work on maintaining a continuous, high growth rate operating at the highest efficiency. A chapter by John F. Foster and John H. Litchfield of the Battelle Memorial Institute notes that further research into continuous cultures was needed but says it "should then be possible to maintain continuous cultures at high efficiencies for very long periods of time."

Technology Transfer

Although NASA has yet to send any astronauts on any years-long missions without resupply, the work the Agency did to advance life-support systems has inspired some entrepreneurs right here on Earth.

Earth is much larger than a spaceship, of course, but it is ultimately still a closed system, and like on that theoretical space journey NASA was working on all those years ago, accumulated CO_2 is a growing problem.

It was with this in mind that Lisa Dyson and John Reed, cofounders of San Francisco Bay area-based Kiverdi,

came across the NASA research on life support in 2008. "We were very interested in developing technical solutions that would help us combat climate change," Dyson recalls, and "we thought the idea to use microbes that grow in the dark on carbon dioxide, with higher efficiency, and using minimal space, was a great idea."

Dyson cites the 1966 report, along with additional NASA-funded studies published in 1968 and 1974, as influential on her and Reed. "What we did at Kiverdi was pick up where they left off," says Dyson. "Since that time there have been so many advances in biotechnology, we asked the question: can we apply modern tools of biotechnology to this old research? We happily discovered it was possible. We have really leveraged a lot of that NASA work."

Benefits

Kiverdi relies on microorganisms to convert CO_2, along with other simple mineral nutrients and gases, into raw materials for everyday products, such as food, clothes, personal care items, industrial goods, and, ultimately, biofuels, Dyson explains.

Basically, they mix the CO_2 and other ingredients into a large vat, where the gases are consumed by microorganisms, which grow and produce proteins and oils. "You can think about the process as being similar to brewing beer, but instead of making alcohol with yeast and sugar, we are brewing, for instance, oils and proteins with carbon dioxide, water, and, in some cases, renewable energy," Dyson explains.

The proteins and oils can be used in a variety of industries, she notes, from feed for fish farms to a substitute for palm oil in anything from soap to ice cream. And not only does the production use up waste products like CO_2, but the process is far more efficient than traditional agriculture that produces soybeans for fish feed or palm trees for palm oil.

Both palm oil and soybeans have become so ubiquitous that the efforts to grow them have huge environmental impacts. Palm oil, for example, is now the world's most common vegetable oil—and one of the primary drivers of deforestation, as farmers clear acres upon acres of tropical forests, largely in Indonesia and Malaysia, to produce it. Likewise, millions of acres in Latin America and around the world have been cleared to make way for industrial soybean agriculture, which also uses heavy-duty pesticides and fertilizers.

> "We need alternatives that require less land and water while still enabling us to create crops that feed people and power industry."
>
> — Lisa Dyson, Kiverdi

Currently, Kiverdi's products include a high-protein, high-nutrient flour and PALM+, a sustainably produced palm oil alternative, but the company has plans to increase its offerings, based on where it sees a need. The company has won three grants from the Department of Energy, including a $2 million award in 2015, as well as funding from the California Energy Commission and the state of Iowa, to further work on its processes to generate hydrocarbons with bacteria, and in 2017, it received additional funding as part of the Valorisation Carbone Québec project.

"We believe our solution can address a number of problems simultaneously, including a lack of beneficial uses for CO_2 and a lack of sustainable high-protein sources to meet the demands of a growing world population," Dyson says.

With the world population set to reach 10 billion by around 2050, current methods of growing food are likely to be insufficient, she explains, and the "green revolution" that has enabled agriculture to scale up so much in recent decades is reaching its limits.

Much like the NASA life-support studies concluded 50 years ago, Dyson says, "we need alternatives that require less land and water while still enabling us to create crops that feed people and power industry." One answer that seemed promising for missions into space was hydrogen-fixing bacteria. Dyson thinks the same answer applies here on Earth. ❖

Kiverdi, after studying research and reports from NASA, developed a process using microorganisms to capture carbon dioxide and create useful oils and proteins. These by-products can reduce excess CO_2 in the atmosphere, while also decreasing the environmental impact of producing ingredients like palm oil, which is a leading cause of deforestation.

Emissive Coatings Cut Industrial Costs, Emissions, Fuel Consumption

NASA Technology

It's no surprise that the experimental X-Plane Program has led to improvements in commercial flight, but the program also produces breakthroughs in other fields entirely. Without even leaving the ground, the X-33 and X-34 aircraft sparked the development of a high-heat coating that has helped industrial plants save money and cut down on harmful emissions.

X-Planes, experimental aircraft usually built by NASA or its predecessor, the National Advisory Committee for Aeronautics, together with the U.S. Air Force, routinely test new ideas and overcome new problems.

The X-33 and X-34 were planned prototypes for commercial high-speed spaceplanes that would fly up to 15 times the speed of sound. At such high speeds, these planes would require thermal protection systems even more advanced than what was used on the Space Shuttles. In preparation for what would come to be known as the Reusable Launch Vehicle Program, scientists at Ames Research Center set out to address the problem in the early 1990s.

They needed a flexible coating that could withstand temperatures up to 3,000 °F, nearly double the maximum temperature rating of the Shuttle's flexible coating, the Advanced Flexible Reusable Surface Insulation (AFRSI), which became unstable at 1,800 °F. The spaceplanes also required a coating that was lightweight and durable, wouldn't release organic compounds, and could be used as a high-temperature adhesive.

The Ames researchers found that by mixing the two forms of silicon that make up the AFRSI coating with one or more emissivity agents—preferably silicon hexaboride—they got a coating that met all their criteria.

Dubbed Protective Coating for Ceramic Materials (PCCM), the result was paper-thin and highly stable, weighed little, and was excellent at emitting heat from the ceramic fiber insulation it coated, preventing the thermal protection system from combusting under extreme temperatures.

The planned X-33 and X-34 experimental spaceplanes, which would fly at up to 15 times the speed of sound, required even more robust thermal protection systems than existing spacecraft. Ames Research Center scientists responded by creating the flexible, paper-thin, highly emissive Protective Coating for Ceramic Materials (PCCM), capable of withstanding temperatures up to 3,000 °F.

Technology Transfer

Ames patented PCCM and licensed it exclusively to Wessex Inc., now Emisshield Inc., of Blacksburg, Virginia. The company adapted it for metals, gave it a much longer shelf life, and made it easier to spray onto surfaces, first selling PCCM-based coatings to building material manufacturers for fireproofing (*Spinoff* 2001). Soon its Emisshield line was coating high-heat race car parts, where it increased both horsepower and fuel mileage, and the company began to look at industrial applications like refractories, kilns, boilers, and furnaces (*Spinoff* 2004).

By 2016, Emisshield coatings could be found in a range of high-heat industrial applications (*Spinoff* 2011), as well as in consumer goods like a line of clothing (*Spinoff* 2016), and the company was working to extend its reach into food production equipment and solar concentrators.

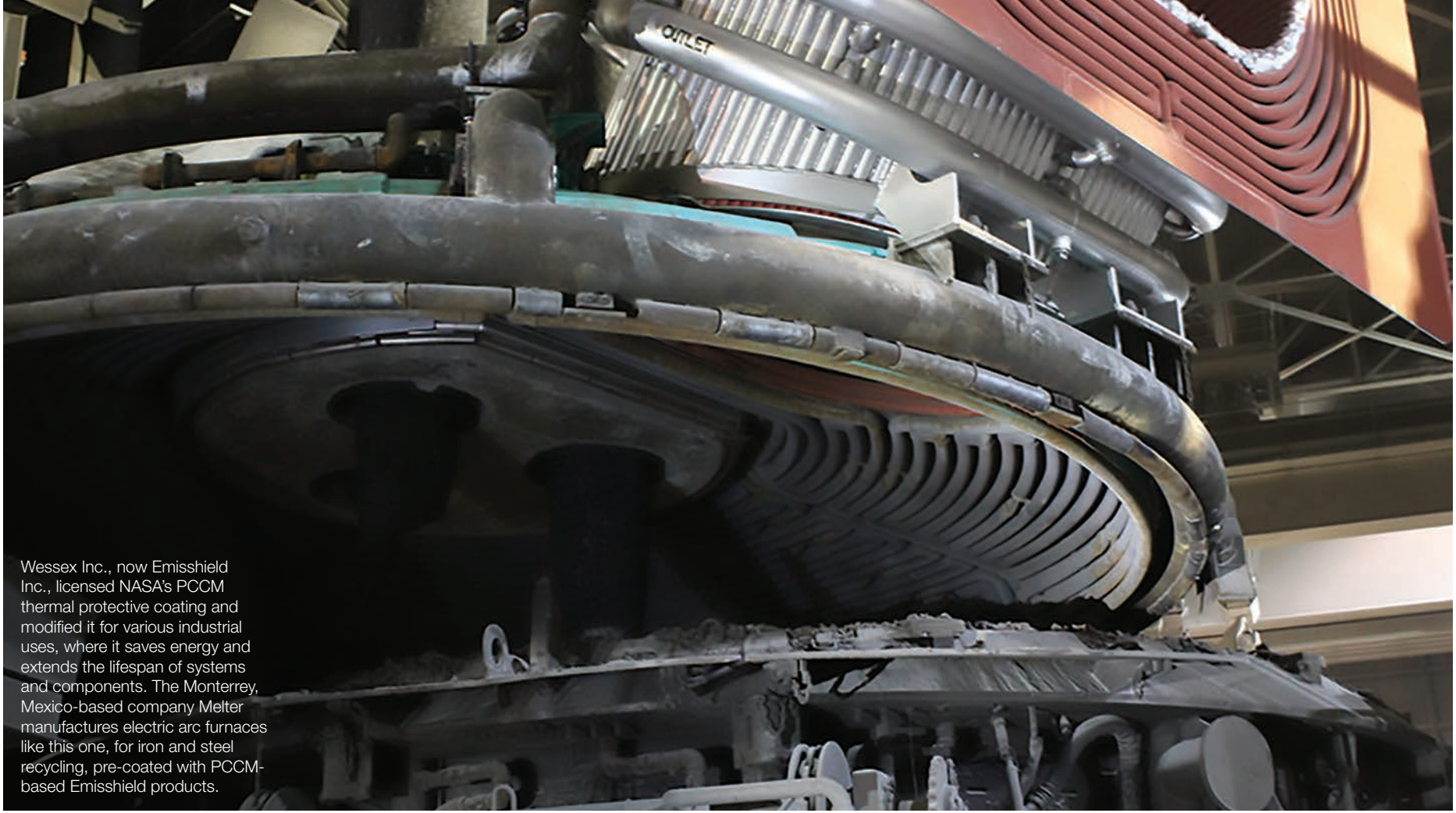
Benefits

Emisshield has now firmly entrenched itself in a wide range of industrial applications, where the company has focused its energy in recent years, expanding its product line to about 40 different coatings and partnering with a number of original equipment manufacturers. In these applications, the coatings generally improve efficiency—which reduces costs and greenhouse gas emissions—and extend systems' lifespans.

As major corporations have become more focused on sustainable practices, especially in Europe, where governments are tightening restrictions on emissions, the coatings have attracted more interest, says Justin Jackovic, director of marketing at Emisshield. Rather than just convincing a plant manager to coat a particular incinerator, say, to reduce down time, Emisshield now persuades a vice president of sustainability that the company can meet its environmental goals by applying the coatings across multiple processes and facilities, he explains.

"Presenting our expanded knowledge of high-emissivity materials to corporate sustainability boards has led to an understanding of Emisshield's substantial effect in reducing a process's carbon emissions. We're talking millions and millions of dollars these companies are saving, and that correlates with reduced emissions."

He estimates Emisshield products are in twice as many industrial plants now as they were just a couple of years ago, including more than 150 glass plants, 50 to 100 petrochemical plants, and nearly 200 iron- and steel-producing facilities. But they're also being applied much more extensively throughout each of these.



Wessex Inc., now Emisshield Inc., licensed NASA's PCCM thermal protective coating and modified it for various industrial uses, where it saves energy and extends the lifespan of systems and components. The Monterrey, Mexico-based company Melter manufactures electric arc furnaces like this one, for iron and steel recycling, pre-coated with PCCM-based Emisshield products.

As it worked its way into more industries, the company continued to develop new formulas for different environments and applications. It altered the binders in coatings to expand the range of substrates it can be applied to and increased its abrasion-resistant properties. It also continued to improve emissivity, or the ability to emit heat radiation, which is key to the coatings' functionality. In a furnace, for example, it makes the heating element more efficient. Applications to furnace walls increase the ability of radiant and convective energy from the burners and hot furnace gases to be absorbed at the surface of the coating and re-radiated to the cooler furnace load. This property is measured on a scale of 0 to 1, and Emisshield coatings can now achieve up to 0.98 emissivity.

And as more customers stopped replacing their systems as often, the coatings came to the attention of equipment manufacturers, some of which now partner with Emisshield to coat their products during the manufacturing process.

"Our equipment-manufacturing partners work to bring innovative products to their customers and put their competitors out of business," says John Olver, owner of Emisshield. He says a lot of his company's recent success has come as more and more of these manufacturers realize that the use of high-emissivity composite materials throughout industrial processes brings multiple benefits, reducing emissions by improving performance. "Ten years ago, if you made this pitch at a petrochemical plant, they looked at you cross-eyed," Olver says.

For example, he says, a glass plant furnace coated with an Emisshield product will save 7 to 12 percent on energy, with correlating reductions in cost and emissions. But the cost savings continue to grow as the coating also makes the furnace last up to twice as long.

Or in the baking industry—which Emisshield broke into, for example, with a company that produces cookies and crackers in Europe and Turkey—an Emisshield-coated

oven cooks the products twice as fast. "An equipment manufacturer can make an oven half the size, sell it for the same capacity, and undercut his competitor," Olver says.

Around 2016, a Dutch manufacturing partner got Emisshield involved with a European project called Integrated Model-Guided Process Optimization of Steam Cracking Furnaces (IMPROOF), led by Ghent University in Belgium. The project aims to drastically improve energy efficiency in steam cracking furnaces and reduce their greenhouse gas and nitrogen oxide emissions by 25 percent. Emisshield's selection led to a $9.1 million grant, authorized by the European Commission.

Steam cracking, which uses steam and a flash of extreme heat to break large, saturated hydrocarbons into smaller, more useful ones, is the chemical industry's most energy-consuming process. The two coatings Emisshield developed for the project represent one of several solutions participants are proposing to modernize the process.

Applied to the radiant coils and furnace walls, the coatings are expected to reduce energy consumption and emissions by 15 percent or more.

They're also expected to spread heat more evenly, reducing the hot spots that accelerate coking, a form of carbon buildup, which degrades heat-transfer efficiency. A steam cracking furnace typically has to shut down every 30 to 60 days for decoking. "During the decoking cycle, the unit is unproductive, causing undue degradation to the equipment," says Jackovic. "It's also a huge hindrance as far as how much it costs."

IMPROOF plans to demonstrate its technology in 2020, and Jackovic says testing so far has met expectations and confirmed the company's own marketing claims.

Meanwhile, the company continues to seek out new markets. GE and Siemens have taken out patents for using Emisshield coatings on jet engine turbines, which enables an engine to run hotter and achieve the performance of a larger model. And a major inefficiency in the power grid is energy lost from high-voltage power lines in the form of heat, says Olver, noting that the company experimented with coating one. "It reduced the temperature by 30 percent, which means it's carrying 30 percent more power." While it seems like an obvious improvement, he says, he foresees another battle to get an industry to change. After all, he's still trying to break into the equally obvious solar concentrator business.

"I don't think we're done yet. We have ongoing R&D," says Olver. "I'd say we're about 30 to 40 percent into the final expansion of this technology." ❖

"We're talking **millions** and **millions** of **dollars** these **companies** are **saving,** and that **correlates** with **reduced emissions."**

— Justin Jackovic, Emisshield

A major inefficiency in the power grid is energy lost from high-voltage power lines in the form of heat. Emisshield recently experimented with coating these lines with its products and found a 30 percent reduction in heat and energy loss. With such new applications continuing to emerge, the company estimates it hasn't covered even half the potential market for its NASA-based coatings.

Pointing Platform Enables Earth Imaging from Space Station

NASA Technology

Most people think of the International Space Station (ISS) as a place to learn about space, but in recent years the modules of humanity's only outpost in space are also becoming halls of commerce, where companies experiment with materials in the space environment or 3D print nanosatellite parts.

A less obvious commercial use taking shape is Earth imaging. While low-Earth orbit is increasingly populated with downward-looking satellites, the space station can present a more affordable option for anyone looking to fly or at least try out science-grade imaging instruments. Since the station is already a satellite in orbit, a client only needs to send up the instrument itself.

Until recently, though, there was nowhere to put such an imager, and even if there were, there would have been no way to point it precisely: the space station only calculates its orientation to within about a degree of accuracy, but for a camera looking down on Earth from that 250-mile-high perch, turning just a hundredth of a degree means a difference of almost 200 feet on the ground.

"Before, you couldn't track a spot on the ground or hold on a spot as you passed over it," says Mike Read, who manages the ISS's National Laboratory from Johnson Space Center.

To overcome this deficiency, Read's office partnered with Huntsville, Alabama-based Teledyne Brown Engineering to outfit the station with its new Multi-User System for Earth Sensing (MUSES), which flew to the ISS in June of 2017 and went into full operation that September.

"We thought there was probably a market out there for various types of instruments that could be Earth-pointing," he says, noting that the facility also fills a gap in NASA's research capabilities.

This sort of thinking arises in part from a 2010 mandate from Congress that half of the National Lab's resources be used by entities outside NASA, including commercial, academic, and governmental organizations.

Teledyne Brown Engineering's Multi-User System for Earth Sensing (MUSES) has introduced a new level of precision pointing and tracking for Earth-imaging devices on the ISS. Through a cooperative agreement, the company built the facility and now rents space aboard it.

Technology Transfer

Teledyne Brown was one of the first companies to enter into a cooperative agreement with the Space Agency to carry out commercial activities on the space station, signing the MUSES contract in 2012.

The company was accustomed to working with NASA but found as it was developing MUSES that if it wanted to turn a profit it had to reduce some of the redundancies and complexities the Agency had normally required, says Jack Ickes, vice president of geospatial solutions for Teledyne Brown. "Our challenge was to be able to make that product in space at such a cost that we would have a shot at return on investment."

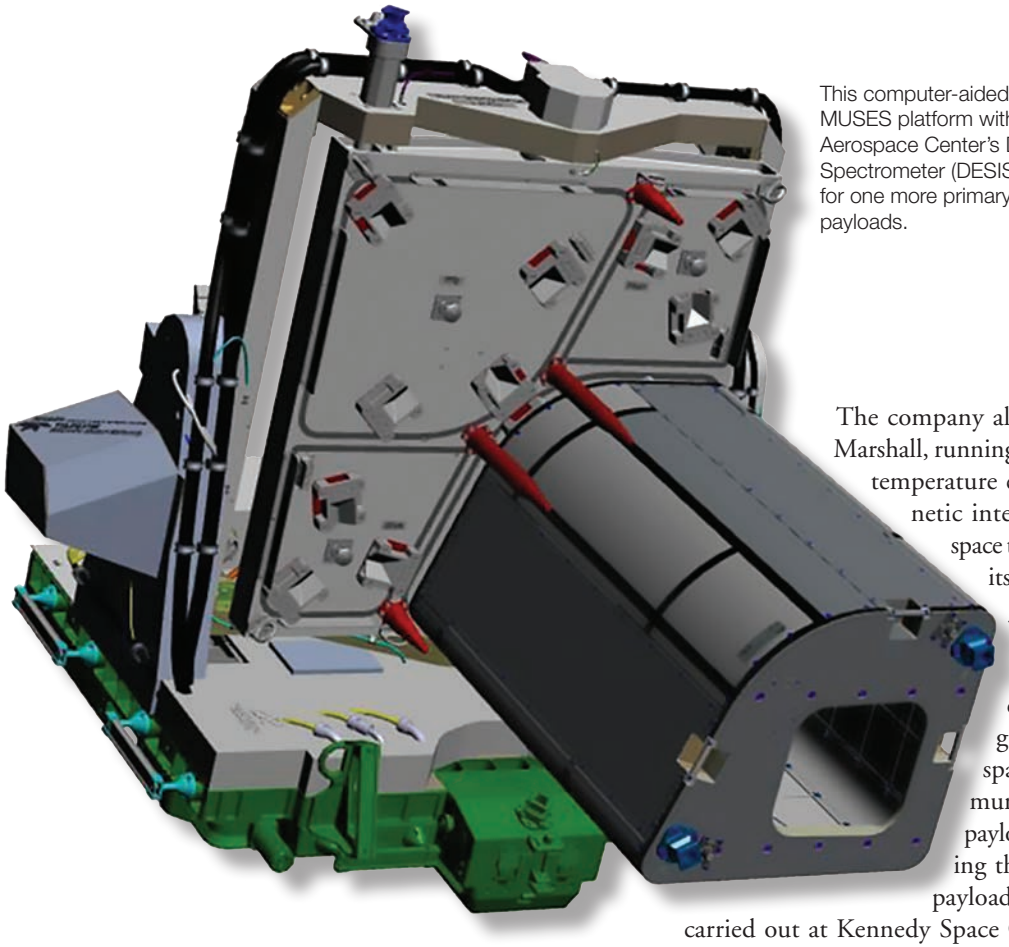
He says the agreement worked because NASA was willing to leave the system's success up to the company, writing requirements only for crucial factors like safety. At first, he says, the Agency's engineers often had to be reminded of that new approach, but it's now become the National Laboratory's standard practice for partnering with companies.

"We're trying to make sure we only levy those requirements that are necessary," says Read. "We've got a major undertaking going on to shift our culture to be more responsive to commercial best practices."

Designed to fit on one of the space station's four external ExPRESS (that's Expedite the Processing of Experiments to the Space Station) Logistics Carriers, MUSES consists of two 18-by-36-inch canisters and two that are 10 by 36 inches. All four can house multiple payloads, depending on customers' needs.

To enable precision pointing, it uses a star tracker that orients itself by the stars, as well as enhanced GPS and miniaturized inertial measurement devices. It's accurate down to less than a thousandth of a degree.

Randy Miller, operations manager for geospatial solutions at Teledyne Brown, says the system is so sensitive it can detect the vibrations caused by an astronaut exercising



This computer-aided design drawing shows the MUSES platform with its first tenant, the German Aerospace Center's DLR Earth Sensing Imaging Spectrometer (DESIS). There is room remaining for one more primary payload and two secondary payloads.

inside the space station. By sensing such disturbances, the system can correct for them on a pixel-by-pixel basis.

MUSES has deep roots in the Space Agency, well beyond the cooperative agreement and the know-how Teledyne Brown has accumulated over decades as a NASA contractor. The company's chief technologist and "father of the MUSES design," Mark Whorton, was a 20-year NASA veteran who had retired as chief of the Guidance, Navigation, and Mission Analysis Branch at Marshall Space Flight Center, notes Ray Perkins, Teledyne Brown's business development manager for geospatial solutions. "So he had a very extensive background in space-based control and pointing systems."

The company also spent about a week at Marshall, running the hardware through the temperature extremes and electromagnetic interference it would face in space to qualify it and characterize its performance. Meanwhile, Johnson engineers helped test the communications interfaces that let MUSES downlink as much as 225 gigabits per day over the space station's wireless communications system. And the payload rack checkout unit testing that's required for external payloads on the space station was carried out at Kennedy Space Center. "When we had a challenge, we worked with NASA at all three of these Centers to overcome it," Perkins says.

Benefits

The first customer for MUSES was the German Aerospace Center, Deutsches Zentrum für Luft- und Raumfahrt (DLR), which signed on in 2014 to place its DLR Earth Sensing Imaging Spectrometer (DESIS) onto the platform. The hyperspectral imager, installed in early 2018, has a 30-meter resolution and "sees" Earth through 235 channels in the visible and near-infrared wavelengths. It can sense changes in surface coverage, oceans, and the atmosphere and is intended to help inform Germany's decisions around problems like environmental and climate protection and food security.

Teledyne Brown expects that a major customer base for MUSES will include entities that want to try out their technology in space before putting it on a satellite. The DESIS spectrometer, for example, is planned for the German Environmental Mapping and Analysis Program satellite that's supposed to fly in 2019. But the one on MUSES required a lot less engineering and reinforcement than the satellite version will.

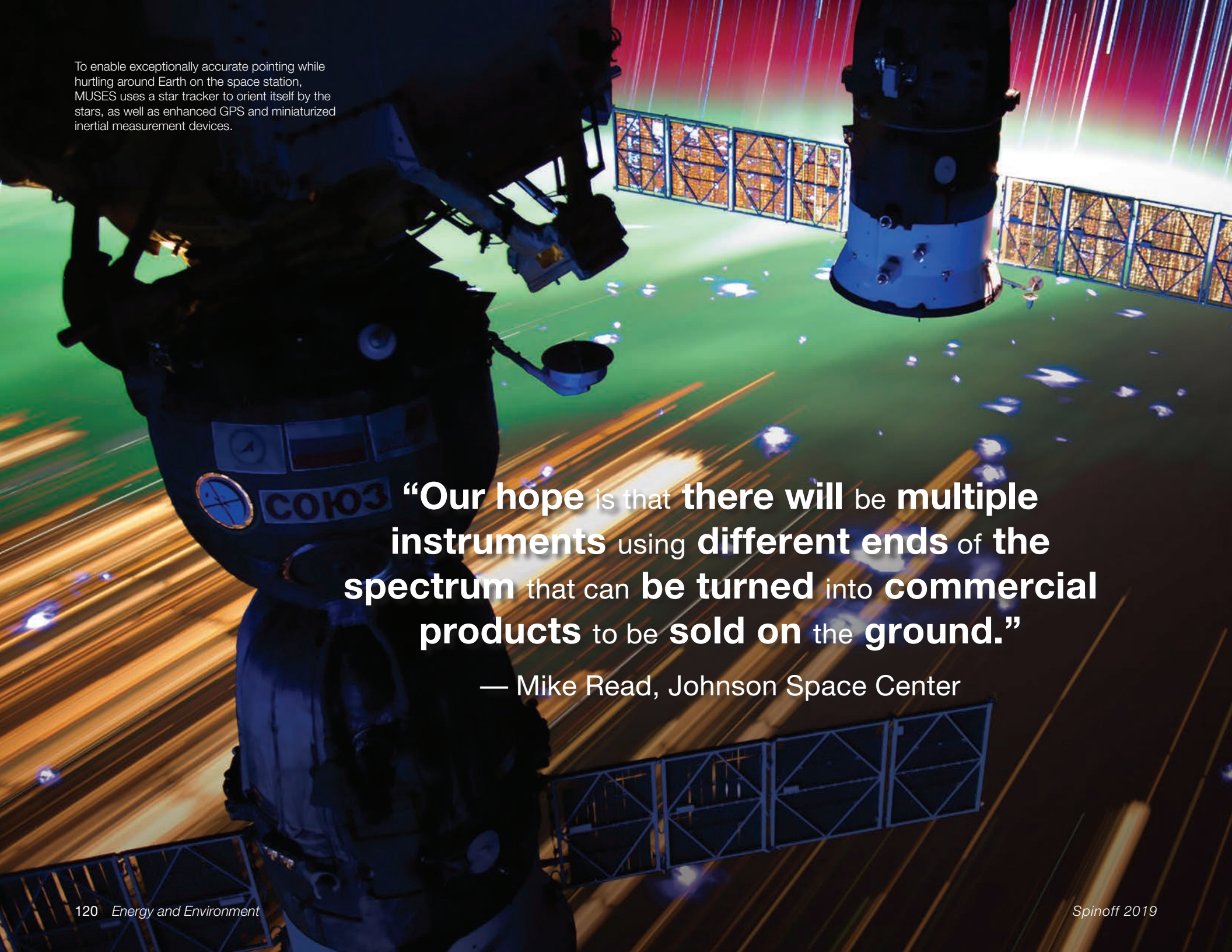
Satellites being sent to space are attached to the frame of the spacecraft carrying them and experience all the jarring vibrations of liftoff, so it takes a lot of engineering to ensure all their components will survive launch, Perkins says. But smaller components being sent to the space station can be packed away and insulated from vibration. "It's the difference between driving a dump truck and driving a Cadillac."

Without the need to withstand violent shaking, builders can use more inexpensive, off-the-shelf components. Test articles are sent up with resupply missions and installed on the MUSES platform via robotic arm, cutting down on expenses, and they can later be returned to Earth.

Jessica Sanders, director of marketing and communications for Teledyne Brown, says 30-40 percent of CubeSats that go into orbit don't perform as expected—succumbing to glitches that might be discovered on a test flight on MUSES. "To be able to do an incremental test flight of your prototype, that's a significant cost saving."

Other clients might send a final product to carry out a mission—imaging or otherwise—on the platform. "Whether it's a test flight or a mission, MUSES is more cost-effective than a dedicated satellite launch," Sanders says. "It's almost like a payload hotel, and you can check in and check out when you want."

Secondary customers, meanwhile, can simply buy imagery from Teledyne Brown, which retains commercial rights to the data DESIS gathers. NASA is among these



To enable exceptionally accurate pointing while hurtling around Earth on the space station, MUSES uses a star tracker to orient itself by the stars, as well as enhanced GPS and miniaturized inertial measurement devices.

"Our hope is that **there will** be **multiple instruments** using **different ends** of **the spectrum** that can **be turned** into **commercial products** to be **sold on** the **ground."**

— Mike Read, Johnson Space Center

customers: its Earth Science Division paid for access to any data the Space Agency or a university has a use for.

In preparation for multiple data streams coming from MUSES, Teledyne Brown created what it calls the Teledyne Cloud, to store image archives, process data, and support collaboration between users. It already holds data from the U.S. Department of Agriculture's National Agriculture Imaging Program and will soon incorporate a growing DESIS archive.

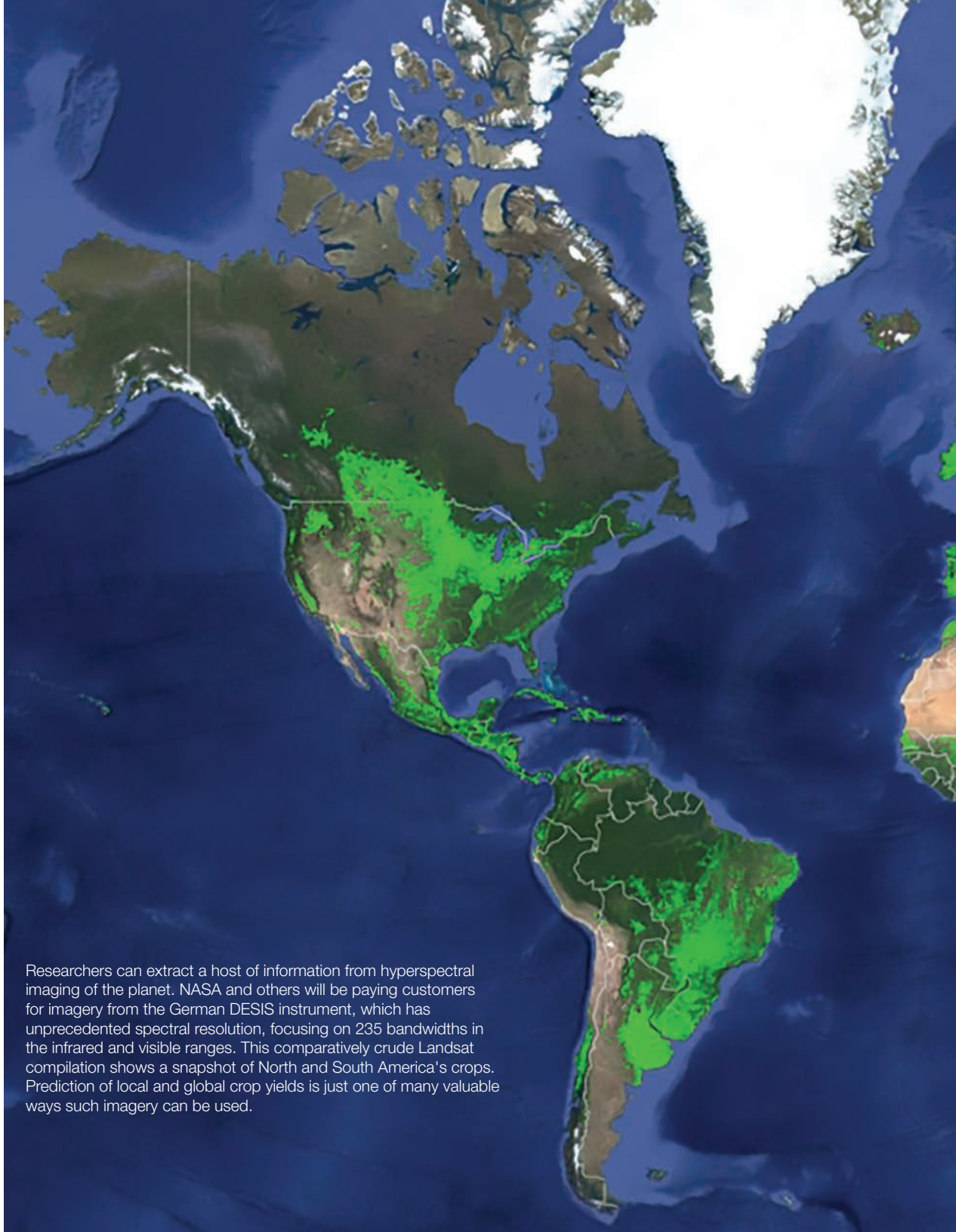
"If you place an order for images of a particular area, and that imagery already exists, you can get it right away," says Johnny Miller, director of media services for Teledyne Brown. Otherwise, it will be captured on the space station's next pass.

Perkins says state and local natural resource managers have expressed interest in using the hyperspectral data to calculate the area, type, and health of forest cover. Even some state budget offices could benefit from such data, depending on how much of a state's tax revenue comes from lumber sales. Others are interested in monitoring water quality or pollutants in the atmosphere. One application likely to find government and commercial applications is taking inventory of crops and forecasting their yields.

Different wavelengths are useful for identifying different characteristics and features, and with DESIS differentiating between 235 spectral bands, Perkins says, a wealth of information can be extracted from the data it generates. "No instrument has flown in space with that level of spectral resolution before," he says. "This is designed for government and commercial users to make significant decisions based on information extracted from data."

And the DESIS imager is just the first of many potential tenants aboard MUSES, Read emphasizes. "Our hope is that there will be multiple instruments using different ends of the spectrum that can be turned into commercial products to be sold on the ground," he says.

MUSES, in turn, is just one of several commercial partnerships taking shape on the ISS in recent years. "We want to see a viable economy in low-Earth orbit, and we want to be a customer," Read says. "Helping companies learn they can make money in orbit is critical to growing that economy." ❖



Researchers can extract a host of information from hyperspectral imaging of the planet. NASA and others will be paying customers for imagery from the German DESIS instrument, which has unprecedented spectral resolution, focusing on 235 bandwidths in the infrared and visible ranges. This comparatively crude Landsat compilation shows a snapshot of North and South America's crops. Prediction of local and global crop yields is just one of many valuable ways such imagery can be used.

Algorithms to Detect Clouds Forecast Global Crop Production

Automated software that GDA Corporation started with NASA funding pulls images from various satellites, identifies staple crops all over the world, and determines their health and stages of growth. A wealth of information can be gathered from this data, including total global crop yield forecasts.

NASA Technology

It started as an algorithm to detect clouds in satellite imagery, but now the software is being used for everything from increasing food security in the developing world to guiding futures trading on Wall Street.

Satellites like the Landsat series don't just take pictures of Earth—they're used to monitor forest and crop health, ice cap and glacier coverage, surface moisture, and a host of other surface conditions. Crucially, however, pixels capturing clouds and their shadows throw off all this data, so those pixels have to be discarded before any calculations are made.

"On a global scale, this is labor intensive, so you've got to be able to do it in some sort of automated fashion," says Tom Stanley, technology transition lead at Stennis Space Center.

Initial plans for the Landsat 8 Earth-imaging satellite didn't include a thermal sensor, which was how its predecessors had detected cloud cover. Instead, engineers at Stennis put out a Small Business Innovation Research (SBIR) solicitation for software capable of detecting cloud cover, which Stephanie Hulina, then a contractor at Goddard Space Flight Center, cofounded a company to win.

Stanley, who was the contracting officer's technical representative for the SBIR work at Stennis, notes that Hulina was doing remote sensing and global information systems work at the time. "She was already highly knowledgeable about the Earth Science Program and looking for her niche so she could start her own business."

Thus, Geospatial Data Analysis (GDA) Corporation of State College, Pennsylvania, was born.

Technology Transfer

Landsat 8 ultimately incorporated a thermal imager and didn't require the software, but by then Hulina and her company had long moved beyond cloud detection and into broader territory. "A lot of what we were doing for cloud detection was really feature detection, so we just applied it to crops," she says.

Further SBIR contracts with Stennis in 2004 and 2005 focused on analyzing satellite images in visible and infrared spectra to identify surface features such as crop coverage and health, as well as soil conditions, forest fires, and gypsy moth outbreaks.

"This definitely fits in with the goal of taking NASA science and capabilities and applying those to areas of public need," Stanley says, noting that the Space Agency has a longstanding interest in monitoring and forecasting conditions on Earth, such as food productivity, climate change, and the impacts of droughts and disasters. "Certainly, we want to know what the overall agricultural productivity is. And the whole Earth Science Program is focused on Earth dynamics for purposes like ecological forecasting and disaster management."

Hulina says the SBIR funding from Stennis was crucial in building the company. "It gave us the opportunity to really research and develop what we call scientific-quality algorithms without the pressures of the commercial marketplace." Clouds are just one type of interference that creates noise in the satellite data, and the company had to develop algorithms not just to identify crop types and health but to correct for factors like topographical effects on lighting or the differences in angles between the center of an image and the edges.

> "This definitely fits in with the goal of taking NASA science and capabilities and applying those to areas of public need."
>
> — Tom Stanley, Stennis Space Center

GDA also used the opportunity to automate its systems, which regularly pull, correct, and analyze data from several Earth-imaging instruments, and it built a 200-terabyte cloud to also allow mining of historical and most current crop statistics from various agricultural monitoring entities to answer specific queries with tables, charts, maps, and other products.

"As far as we know, this is the only operational repository of global agricultural statistics and crop-relevant data," says Dmitry Varlyguin, GDA's vice president and chief scientist. "The SBIRs gave us time to develop all this and have a long-term plan."

Benefits

Calculations of crop coverage, type, health, and growth, and especially forecasts of crop productivity interest organizations like the U.S. Department of Agriculture's (USDA) Foreign Agricultural Service, which provides unbiased commodity estimates and forecasts to create a marketing edge for U.S. producers in world markets.

As GDA amassed enough global crop data to develop commercial products, the agricultural service became its biggest customer, but others, such as agricultural insurance companies, grain and commodity traders, and food transporters, also became clients, Hulina says. "Anybody who really needs to know where crops are, how they're progressing through the growing season, and what the output will be" is a potential customer, she adds.

For commercial customers, GDA offers real-time and historical image-based data for 16 major crops around the world. This "agricultural intelligence" includes maps of crop coverage, acreage totals, ground conditions, crop health, and forecasts of yield per acre and overall global production. These can also be broken down to national and state levels.

The system pulls imaging from multiple sensors on several satellites, which vary in resolution, spectral bands, how wide a swath they can see, and how often they pass over a given area, letting the company tailor products to meet a wide range of needs. GDA says it's the only company to combine all these capabilities on a global scale.

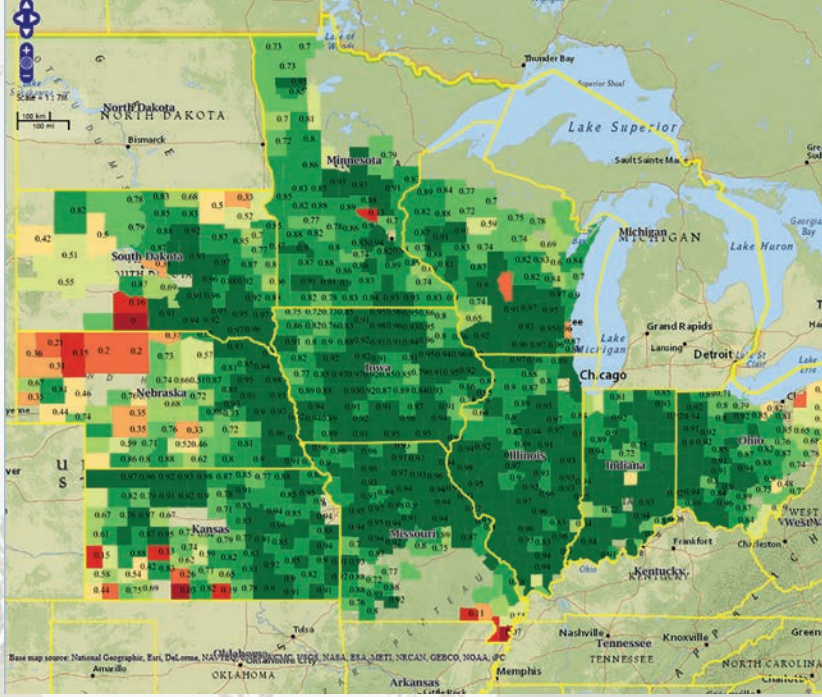
Its relatively new GeoSynergy webGIS service puts them all in one place to let the user manipulate and analyze calibrated, full-resolution current and historical imagery and data.

Varlyguin says the company plans to continue adding new capabilities, as well as new sources of imagery as they become available.

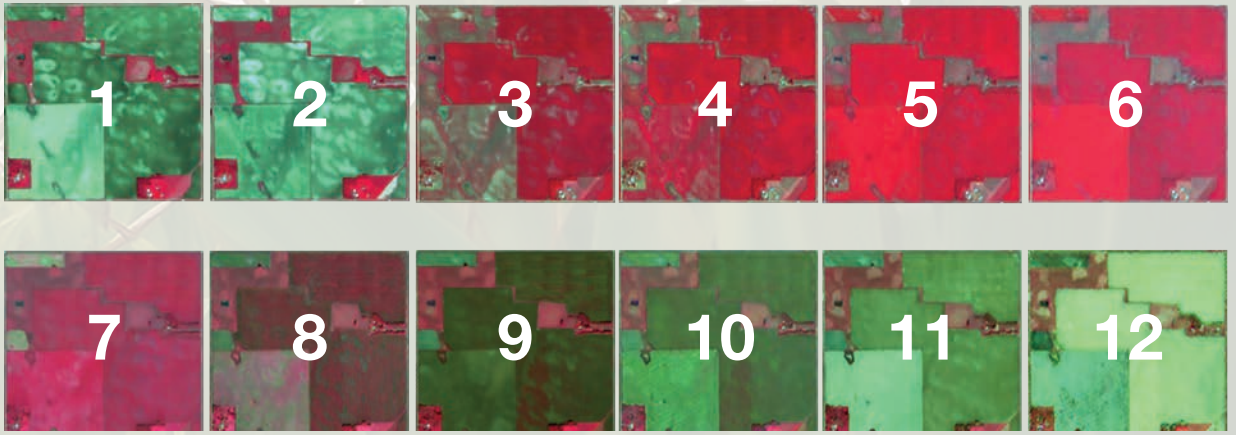
The Foreign Agricultural Service uses GDA's tools, among other sources, to create its monthly production estimates for all major commodity crops, and Hulina notes that crop futures markets move according to those estimates. "We are the only remote sensing firm supplying that line of evidence," she says. The estimates also help the service predict shortages to help direct its food aid programs.

The company also counts the U.S. Geological Survey (USGS), the U.S. Forest Service, and the USDA's National Agricultural Statistics Service among its customers.

But the company's success wouldn't be possible without two important Government initiatives, Varlyguin says. Earth-imaging analysis on a global scale wouldn't be feasible without free satellite imagery. Landsat images, for example, cost hundreds to thousands of dollars per scene until the USGS decided in 2008 to make them free. And the SBIR program, he says, "is extremely beneficial, not just to GDA but to overall research and development. Without that, a lot of companies, including GDA, would be very different than they are." ❖



This map shows the correlations between GDA Corporation's crop yield forecasts and the U.S. Department of Agriculture's forecasts at the county level between 2005 and 2017 in the American Midwest, with deeper greens indicating higher correlation and reds showing less correlation. Areas with more complete historical data generate more consistent and accurate forecasts.



Infrared satellite imagery captures the stages of an entire growing cycle for multiple crops in several fields. Red hues indicate vegetation, with deeper reds showing heavier crop coverage. Image three shows that one crop type is planted earlier than another. By the ninth image, all crops have been harvested, and the fields slowly dry out thereafter.

Information Technology

Software and information technology are already woven deeply into the fabric of daily life. Engineers use computer software to more quickly design new, and safer, aircraft. Digital communications make it easier for teams of doctors across specialties to care for patients. And even the ads we experience online are placed there through complex algorithms that work unimaginably fast. These advances and more improve our daily lives, and they got their start at NASA.


6

Space Mission Planning System Targets Advertising with Precision

NASA Technology

Most Internet users may not know that every time they see an online ad, it was placed there after a near-instant auction for that slot. Each slot gets sent for bidding to several thousand interested advertisers by a handful of advertising exchanges, and the ad is sold by the time the page loads. The entire process is automated and takes about a tenth of a second.

One of the leading companies now driving that process uses software based on an approach its founders helped invent for planning NASA missions to the Moon and Mars.

In 2004 and 2005, NASA funded several aerospace contractors to study possible architectures for missions to send astronauts to the Moon or Mars. But the study, funded by what was then called the Office of Program Analysis and Evaluation at NASA Headquarters, also brought an academic counterpart on board—a team of faculty and graduate students in the Massachusetts Institute of Technology's (MIT) Department of Aeronautics and Astronautics, partnering with Draper Labs. The MIT team started with an entirely different method than others used.

"We took the approach of not making any assumptions about equipment, number of crew members, trajectories, or anything and instead looked at all options," says Willard Simmons, who had just joined the graduate program at the time and is now chief technology officer for the Boston-based company dataxu.

Using previous mission plans for background, they narrowed the major decisions that had to be made down to about 35 choices and created software based on a meta-language—that is, a language for talking about a language—to articulate mission phases, the different module types necessary for any mission carrying humans to a planetary body, the destinations for each of those modules, and other aspects of a mission. For example, some plans might pre-deploy a habitat and other resources to the surface of the Moon or Mars; others might temporarily park elements in Earth orbit. This meta-language formed the basis for a set of algorithms the team called the Object Process Network.

The result yielded about 30 billion possible combinations—though most were impossible in practice and automatically eliminated by the rules of the Object Process Network's syntax. For example, a vehicle pre-deployed to the extraterrestrial surface for the astronauts' return had to be paired with a propulsion system. And any interplanetary propulsion system had to be disposed of after its trip.

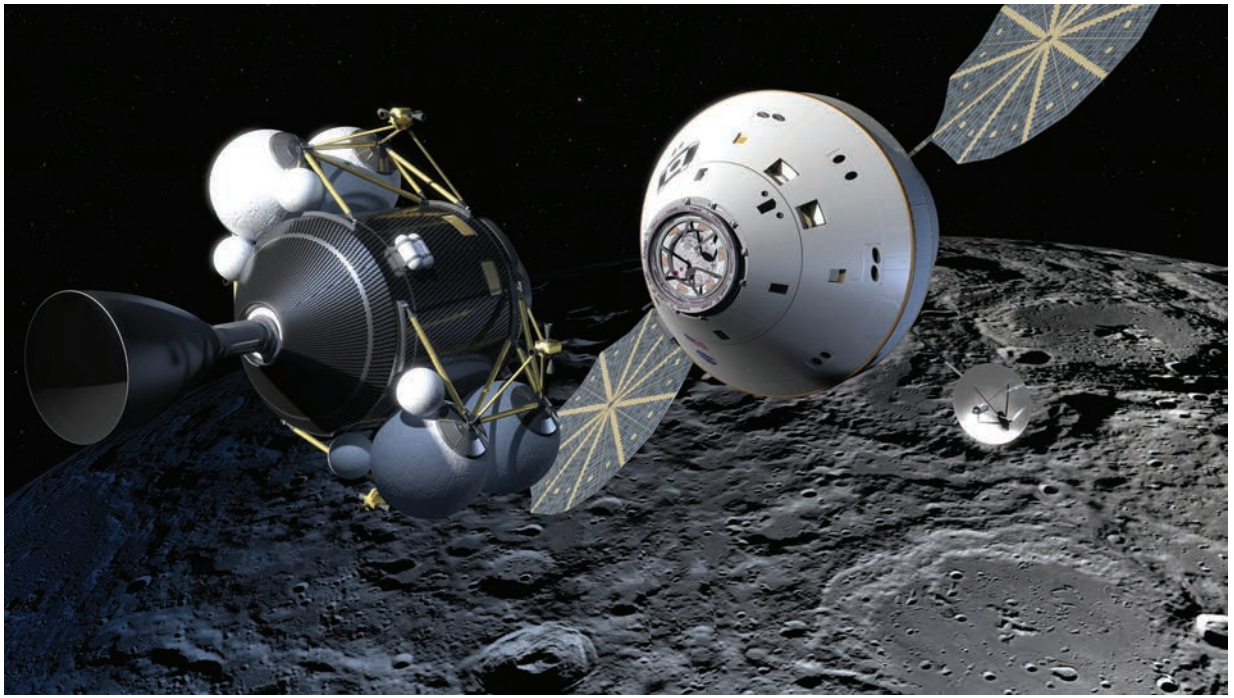
The team ended up with 1,162 possible mission architectures, which could be evaluated and sorted for weight, cost, risks, and other factors.

"The big companies each described their one mission using their own vehicles," Simmons recalls. "We were able to give a nonbiased report with a massively more comprehensive understanding." Theirs was the only effort that received further funding, but it too was eventually shelved.

"That was the moment that inspired us to think about other commercial opportunities for this approach," Simmons says.

Technology Transfer

"'Big data' wasn't a catch phrase yet at the time, but we thought we could use this approach for big computational planning in the real world," Simmons says. The company was founded in 2007 by Simmons and Sandro Catanzaro, also a student on the MIT project, who is now chief innovation officer at the company.



The software that dataxu now uses to place advertisements was originally created to select architectures for missions to the Moon and Mars, making decisions like whether a habitat such as the lander pictured here would include an ascent stage and dock with a capsule left in orbit after leaving the surface.

They spent two more years researching industries, building prototypes, and talking to companies before they found their niche. They discovered that digital advertising, although a major and fast-growing business, had "massive room for innovation and massive inefficiencies," Catanzaro says. They saw an opportunity.

When real-time bidding, the modern format for online ad sales, was born in 2009, dataxu was one of the companies that made it possible, and Simmons led the effort to launch the OpenRTB (for "real-time bidding") protocol standardization for these automated transactions.

Benefits

Every second, there are three million chances to place an ad online, says Catanzaro. While dataxu isn't the only platform watching those opportunities, he thinks it's the best at choosing them. This is because its algorithms, based on the approach originally developed for space mission planning, very quickly narrow down the possibilities for a given ad space to about 20 ads, based on factors like the size and shape of the space, the content it appears alongside, the content of available advertising, and user data. Then the platform uses a more advanced mathematical formula to determine the probability of the user responding to each of these ads. It selects an ad and, based on the calculated probability of the user taking action and the value of the product advertised, makes a bid on the slot, which it may or may not win.

"Our model is much more accurate because it's evaluating every possibility, therefore it's much more valuable to the advertiser," Catanzaro says.

The system's algorithmic engine self-corrects to improve future results, based on whether consumers visited the advertiser's site as a result of ads being shown.

The industry measures performance in terms of the amount of investment to drive a single visit to the advertiser's website, also known as "cost per action," and by that standard, Catanzaro says, dataxu's service is 35-40 percent more efficient than competitors. It's also one of the only platforms that's buy side-only. Most online ad exchanges act as both the auctioneer and the bidder.

Simmons traces the technique back to a philosophy typical to MIT—starting without a bias for any outcome and letting the data decide, whether it's how much to pay for an ad or what fuel to use in a rocket.

The online ad-bidding service dataxu offers is 35 to 40 percent more efficient, in terms of cost per action, than competitors, the company says.

In the last few years, the company has also broken into the television advertising business. This can mean placing targeted ads based on a show's ratings and the channel's demographics, but the tools are becoming increasingly sophisticated. In 2014, the company started placing advertising on what's known as addressable TV. Cable providers for more than 50 million households in the United States are now able to use data from viewers' set-top boxes to target different ads to different households in the same timeslots. And in 2017, the company started placing ads within streaming television content.

There's no bidding in television advertising, so success is measured by the number of viewers reached within a given budget, and Catanzaro says dataxu's system can find three times the audience that competitors can for the same cost by strategically choosing which slots to buy.

"All these technologies are integrated into our platform—computers, smartphones, TV," says Catanzaro. "We just make it simple."

The system can even help the advertiser decide how to optimally distribute resources across television and Internet campaigns.

Catanzaro says there's also a benefit to viewers and users. "If we're doing our job correctly, and ads are more relevant to consumers, then there don't need to be as many ads," he says. "Down the road, commercial interruptions should be shorter. That's something that should be interesting on the consumer side."

From a little start-up founded by aerospace PhDs, dataxu has grown to a company of about 350 employees in 16 offices across North America, Europe, and Asia. Its customers include Lexus, Pandora, Hewlett-Packard, Sky, the BBC, Universal Pictures, and other household names. ❖

Tiny Star Trackers Help Spacecraft Find Their Place

NASA Technology

NASA tackles some of the biggest questions in the universe, and the tools needed to look for answers are often, themselves, big, in both size and cost. But one small aerospace company has designed a modern take on an ancient navigation device that is tiny, cheap, and potentially revolutionary for NASA and private companies that explore the universe.

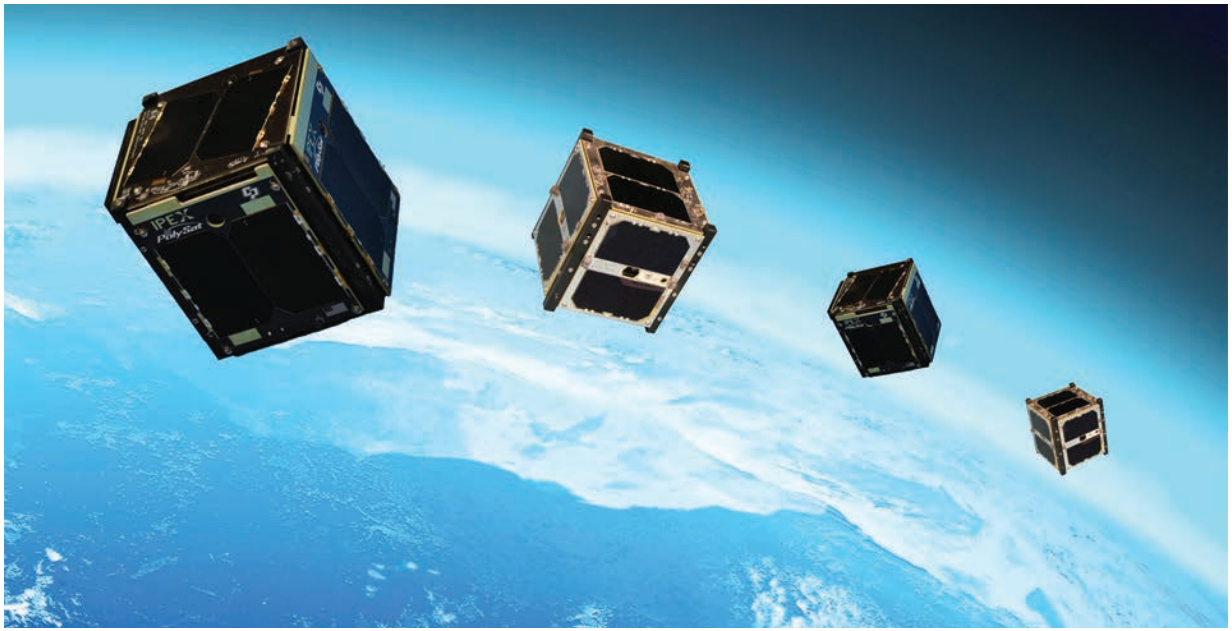
For millennia, travelers relied on the stars to pinpoint their location on the globe. Once humans took to space, they adapted Earth-proven technologies for the new environment. Starting with the earliest missions, many spacecraft have used specially designed sextants to measure the angle between different celestial bodies in relation to each other or the horizon.

These star trackers are important not just for navigation but because "the better we can point our satellites, the better images and science data we can get," explains Alice Liu, attitude control system engineer at Goddard Space Flight Center. "We need to be able to point at a direction where we want to take a picture and have to be stable while we take it."

NASA's flagship missions often require the most cutting-edge technology available, which often hasn't been around long enough to be miniaturized, explains Jason Mitchell, assistant chief for technology in Goddard's Mission Engineering and Systems Analysis division. But that is starting to change. Satellites are getting smaller and less expensive, and it is becoming possible to get scientific results in a new way—if the instruments aboard are powerful enough.

That's where a new star tracker, designed by Adcole Maryland Aerospace, might come in.

The device is small enough to fit inside a CubeSat—each side is only two inches long—and yet is capable of pointing a spacecraft to high-level accuracy, down to about 0.1 degrees of error, matching the performance of much larger instruments.



Small satellites, often called CubeSats, are far less expensive to build and launch than traditional satellites, but to use them for important scientific research, engineers have had to develop new tools that are small and inexpensive but still precise and powerful enough to get good results.

"We're talking about crossing a boundary into bringing that capability into a new class of mission," says Mitchell. Where before, NASA might have spent tens or even hundreds of millions of dollars for a sun-observing satellite to get the kind of resolution it needs, with less-expensive CubeSats, it is far more feasible for researchers to, for example, deploy two units to observe from different angles.

"Think about your eyes, stereo vision. Now you can have stereo pictures of the sun," he says.

More broadly, "the number of measurements can go up. With the cost savings, multiple spacecraft can do the same thing but in different locations. And, if something fails, the mission isn't lost completely," Mitchell adds.

"It really does revolutionize the way that you can think about generating measurements. It enables many new possibilities for science."

Technology Transfer

The partnership between NASA and Adcole Maryland Aerospace, based in Crofton, Maryland, started with several Small Business Innovation Research (SBIR) contracts.

In 2012, explains Liu, who specializes in fine pointing and tight stability for space missions, "CubeSat work had started to gain interest, and Goddard was getting ready to be part of the CubeSat world. I was reviewing proposals that would give us better pointing stability."

She came across the company's proposal and "was very impressed," she recalls.

Previous pointing devices often used magnetometers and horizon sensors to orient a CubeSat in relation to the Earth's magnetosphere or horizon. But accuracy was only good to about one degree at best, says company president Glen Cameron.

Instead, Adcole Maryland Aerospace proposed star trackers that use a camera to take an image of the starscape. Then, software analyzes the image to calculate orientation. "If you have two bright stars in the night sky, the angular separation between those two stars is unique. There's no pair of bright stars with exactly the same separation," explains Steve Fujikawa, the company's principal investigator on the project. The star tracker uses the angle of separation to identify which stars the camera is pointing at; using that information, the CubeSat can orient itself in space.

This is essentially the same process sailors have long used with sextants, but of course on a CubeSat, there is no person to do the calculation. So, as part of the work done under the SBIR contracts, Fujikawa mined publicly available star catalogs to create a database of "star separations"—some 70,000 of them, based on around 1,825 stars.

That sounds like a lot, but it's actually a carefully curated selection, designed to cover the entire sky while minimizing the processing load, so calculations can be done quickly and with minimal demands on memory and power.

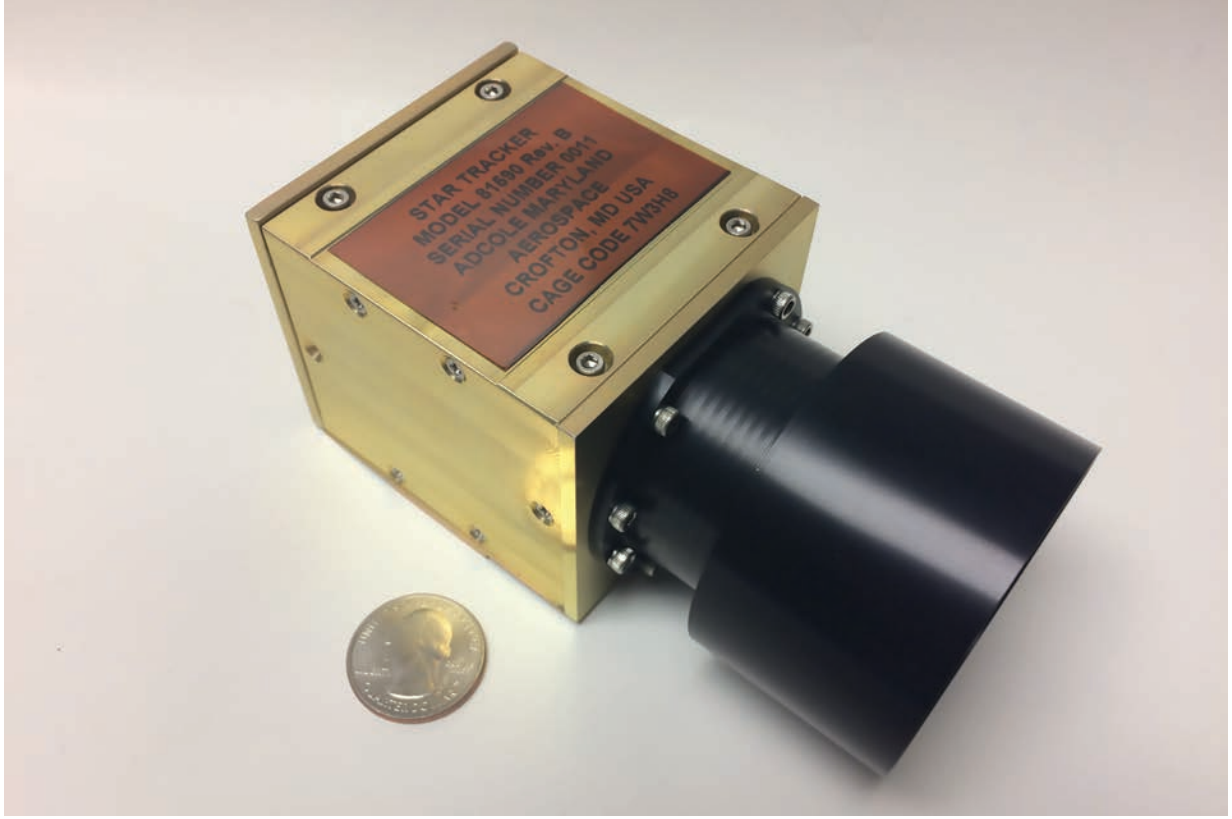
The company also developed a miniature optical system that is small enough to fit easily in a CubeSat and is radiation-hardened to be able to perform in the space environment.

The original contract enabled them to develop a single-camera star tracker and its related software, and a subsequent SBIR contract enabled the development of a two-camera system that provides greater flexibility, says Cameron. If one camera is pointing toward the sun, which is bright enough to block the view of other stars, the second will be pointing elsewhere, meaning the star tracker is always able to find its orientation.

Benefits

The company now sells these components in three different configurations, Cameron says. Customers can buy a stand-alone star tracker, a single-camera package that includes the star tracker and the attitude control system, or a double-camera package. By the end of 2017, they had already sold around 20 units across all three models, he adds, which is a big success for the first year.

Part of the success, Fujikawa says, could be linked to the relatively affordable price—ranging from around $32,000 for the stand-alone star tracker to around $100,000 for the dual-camera package—something the company links directly to its SBIR funding. "We have a tremendous advantage, because NASA funded the development, so we don't have to amortize the development cost over any production," he emphasizes.



This tiny device fits inside a CubeSat and contains all the hardware and software to precisely point the miniature satellite—within 0.1 degrees of error. Developed by Adcole Maryland Aerospace with funding from several SBIR contracts, it is at least an order of magnitude more precise than previous pointing devices for CubeSats.

Mitchell and Liu say this notches a big success for the SBIR program as well: Adcole Maryland Aerospace's team "not only achieved the performance they promised, but they have also expanded it to commercializing the components. It's going to be a sustainable technology going forward."

And, adds Mitchell, by creating "a brand-new capability, it encourages other people to look into it. We end up with not only healthy small businesses, but it also generates competition that helps us, because now there's a healthy market and we have more choices."

The primary application for now is Earth-observation missions, such as monitoring deforestation: "Say an image was done six months ago of a certain spot in the Amazon, and you want to get the exact same image so you can get a comparison," Cameron explains. Or perhaps a company wants to monitor methane emissions from an oil refinery: "You need to point your instrument exactly at that place to get that imagery," he says.

Another customer, however, is using the star tracker for a project to detect planets around distant stars, Fujikawa says. "To do that, you have to point the spacecraft really precisely at the other star. This kind of mission is only enabled by a sensor like this."

Looking forward, he adds, for interplanetary missions and CubeSats orbiting planets other than Earth, there will be no possibility of using the Earth's horizon or magnetic field for orientation, so star trackers like these will be crucial. ❖

Software Toolkit Steadies Rockets

NASA Technology

"Combustion instability is the part of rocket science that makes rocket science hard," says Paul Gloyer, actual rocket scientist and cofounder of a company that hopes to help make getting into space as common as flying across the Atlantic.

Gloyer has worked closely with NASA to design and test a software toolkit that implements a new process to predict combustion instability, which he describes as pressure, oscillations, and vibrations that build up and cause an engine to explode—"the bad kind of exploding."

Combustion instability is a big problem, agrees Matt Casiano. "It's probably one of the highest risks that we encounter when we design an engine." Casiano is an aerospace engineer at Marshall Space Flight Center and part of a team that worked with Gloyer's company, Gloyer-Taylor Laboratories LLC (GTL), to test one component of the toolkit.

At the time, Casiano was part of a separate, Air Force-funded project to develop tools to help solve combustion instability issues. Marshall's role was to build a rocket engine specifically designed to have problems. For example, he recalls, "we purposely designed the injector to see an instability, and that's a very hard thing to do."

The engine was also instrumented throughout with sensors so engineers could gather as much data as possible about just what happened when the rocket fired, and especially when it became unstable.

The Air Force-funded combustor was the perfect test bed for the Tullahoma, Tennessee-based company's toolkit, which was still in the early stages of development at the time. "One of the things that goes into their analysis tool is a CFD simulation," Casiano explains, referring to computational fluid dynamics, computer simulations of how liquid and gas flow through and around the system.

GTL was able to use its CFD post-processing tool to analyze the Air Force combustor—or try to.

"When they originally worked the problem the way their code was intended, it was intractable: it would take years,"

NASA test fires one of the Space Lauch System's boosters, which one day could help propel humans to the Moon and beyond. When designing a new rocket, one of the biggest risks is combustion instability from the engine, when the vibrations resonate and amplify until it explodes. Historically, these instabilities have mainly been identified during late-stage testing, but it would be far easier and less costly to fix any problems earlier in the design phase.

Casiano explains. That's because the number of elements that needed to be simulated was orders of magnitude larger than they were used to, he says, a common difference between academic simulations and real-life rockets. "That was a huge development challenge, and they were able to solve it" by implementing some new algorithms to speed up the processing.

Marshall also had GTL test its Simulation Data Analysis Tool (SimDAT), which breaks apart the problem into physical mechanisms and can provide the design engineer with information about what caused the instability.

Overall, Casiano says, "it wasn't a full checkout of their tool but a demonstration of its capability and how it can provide information to design engineers," and on that level it was a success. For Marshall, too, it was a useful collaboration, he says.

"We definitely helped them further develop their tool. I know they improved the efficiency enormously in our configuration," Casiano notes, and on his end, "we're always on the lookout for capability improvements, to make sure we're using the best tools out there in our work."

Technology Transfer

The collaboration was funded through a Small Business Innovation Research (SBIR) contract. It was one of several awarded to GTL by various NASA Centers, as well as other Government agencies, to help develop its Universal Combustion Device Stability (UCDS) process and toolkit over the last decade.

The work, however, began earlier when Gary Flandro, a former NASA engineer and later a professor at the University of Tennessee Space Institute, made a breakthrough in understanding combustion instability, using an energy framework and fluid mechanics equations, explains Gloyer.

Combustion instability is essentially a resonance issue. Due to the shape and other characteristics of a structure, certain vibration frequencies amplify themselves in a feedback loop that can end up turning destructive: think of a soprano hitting that high note that causes glass to shatter. But in a rocket engine, there's far more than simple sound waves reverberating; there's vortical and thermal entropic energy and more all interacting in different and very complex ways.

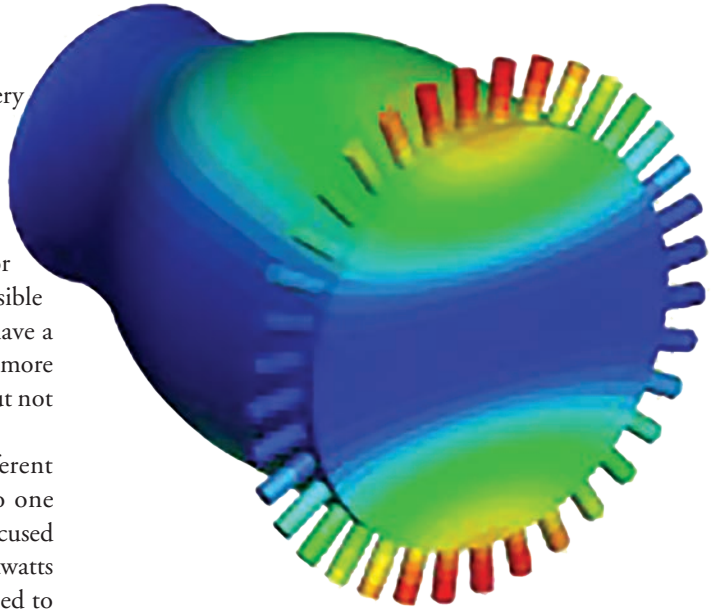
Historically, Gloyer says, people would try to simplify the problem to solve it—but, he notes, "when you're simplifying, you're basically throwing out some of the physics." The results were not accurate or particularly helpful, which meant it was nearly impossible to determine ahead of time if a new rocket would have a combustion instability problem—or, as CFD became more common, engineers might see there was a problem but not know how to pinpoint the source.

"Basically, what Gary found was, using a different technique, he could finally put all the pieces into one mathematical solution," Gloyer says. His approach focused on energy. "A rocket engine releases megawatts to gigawatts of energy, huge amounts of energy. It's what you need to accelerate and lift all that stuff into space," he explains. "But if even a tenth of a percent of that energy goes into one of those resonant modes, it can destroy the rocket."

UCDS calculates all the sources of energy flowing into resonant modes. This includes not only just simple acoustics, but vorticity, combustion, thermal effects, and more. "And when we combine it all together, we get a clear picture of all the physics," he says. "Because we can see how all these pieces fit together, we can go in and look at an engine and see exactly why it's behaving the way it is."

GTL received NASA SBIR funding to help build up those layers of software and test it against real-life rockets to see if the predictions bore out. Under one early contract, GTL was hired to use its first-generation software tools to analyze the large five-second solid rocket motor of the since-cancelled Ares 1 rocket, which had a combustion instability problem.

"They were looking at trying to put a Band-Aid on; our approach was, let's look at the source of the problem and make it go away. We were able to show a very small change in the motor would make it go away," Gloyer recalls, and ATK, now Northrop Grumman, which served as the prime contractor on the Ares project, gave the company a letter commendation for the work.

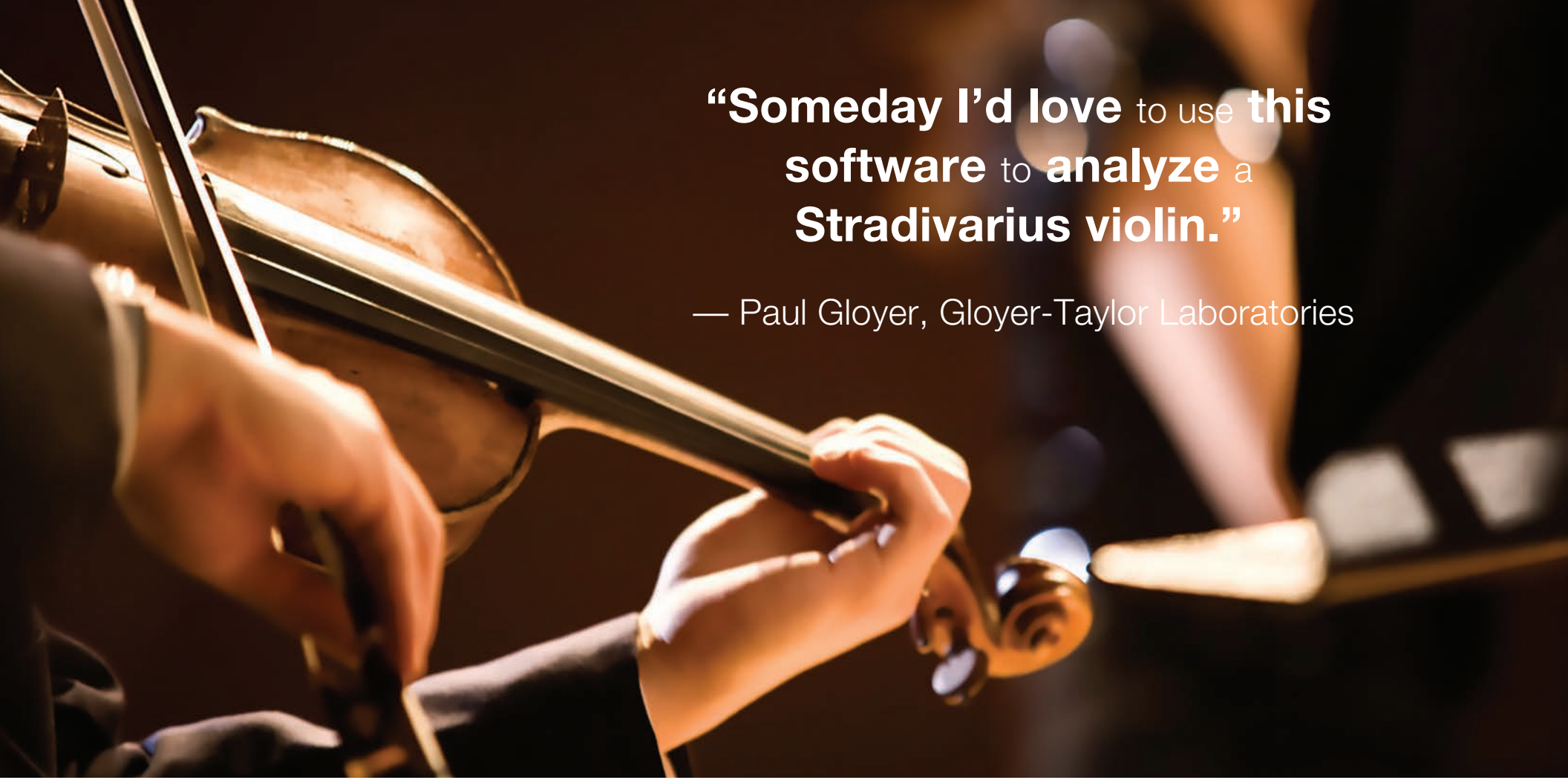


Gloyer-Taylor Laboratories (GTL) has created a software toolkit that models and analyzes structures for combustion instability, calculating the bulk flow of energy and then continuing on in layers, analyzing acoustics, vorticity, and then the thermal entropic energy. The company received multiple SBIR contracts from NASA to help design and test the toolkit, including the acoustics component called Resonance, which generated the image here.

During another SBIR contract with Langley Research Center focused on subsonic and supersonic airflows of scram jets, GTL improved its acoustics analyzer, which it has dubbed Resonance. Other contracts have enabled the company to continue to upgrade all of the software layers—the company is currently near completion on the fourth generation—as well as to test fire its own UCDS-aided rocket engine design. The company also validated UCDS predictions on a new engine at Glenn Research Center: "We said it's going to be unstable at this frequency," Gloyer says, "and they said, 'You nailed it. We put it on the stand and it melted.'"

Benefits

Gloyer says the UCDS software has the potential to cut rocket costs by a huge margin, because it can simplify the design process so significantly. "Combustion instability,



Stradivarius violins are famously the best, but what differentiates them from the less expensive models? It comes down to resonance and acoustics—due to tiny differences in materials and shape. Although GTL’s toolkit was originally designed for rockets, the physics of musical instruments is essentially the same, and the toolkit could help uncover the mysteries of just what makes for beautiful sound.

depending on how you look at it, accounts for about half the money the United States has spent on rockets, in terms of cost overruns, hardware damage, testing, and program cancellation,” he says.

Typically, he says, engineers discover a problem late in the design stage and then use trial and error to try to solve it—a hugely expensive process. But with UCDS, they can discover any problems early in the program in the design phase and design the rocket engine to be stable to begin with.

In 2014, GTL released its Resonance software as a stand-alone program, and it has sold a few licenses to commercial aerospace firms as well as government agencies. The company also plans a spring 2019 release of the full UCDS software toolkit, in the fourth generation, now that it’s had more time to develop and validate it.

The market is small, Gloyer says, but he sees a fair amount of growth potential, not just in rocket design but for jet engines and even power plants. “Gas turbine power plants are basically giant jet engines,” Gloyer notes.

To get emissions down, the power plant needs to operate as efficiently as possible, he explains, but “the primary thing preventing them from running the power plants at lean conditions is combustion instability. As you get to that, you start to pick up these oscillations.”

His team is also working on adapting the software to help design better, more efficient internal combustion engines, like those in cars, and there is even potential to use the software in other kinds of research as well—like understanding why certain musical instruments resonate so much more powerfully than others. “Someday I’d love to use this software to analyze a Stradivarius violin,” Gloyer says. ❖

Low-Cost Transceiver Will Allow First Laser Mass Communication

NASA Technology

Since the advent of the laser in the 1960s, engineers have struggled to use light beams in free space to send information the way we use radio waves. No one could have expected a solution for mass communication by laser to come from a former aviation data executive like Mark LaPenna—least of all him.

LaPenna left a comfortable job in 2014 to start an aircraft tracking company. "I sold everything I owned—Ferrari, nice condo, nice life," he says. Then he ran into a problem.

"We realized we were going to create four petabytes of data per day," he says. (A single petabyte could contain enough MP3 audio files to play continuously for about 2,000 years.) Much of that data would have to be collected by satellites, rather than ground stations, and there was no way to send that much data back down to Earth via radio frequency, in part because the radio spectrum has limited capacity and is becoming increasingly crowded and expensive.

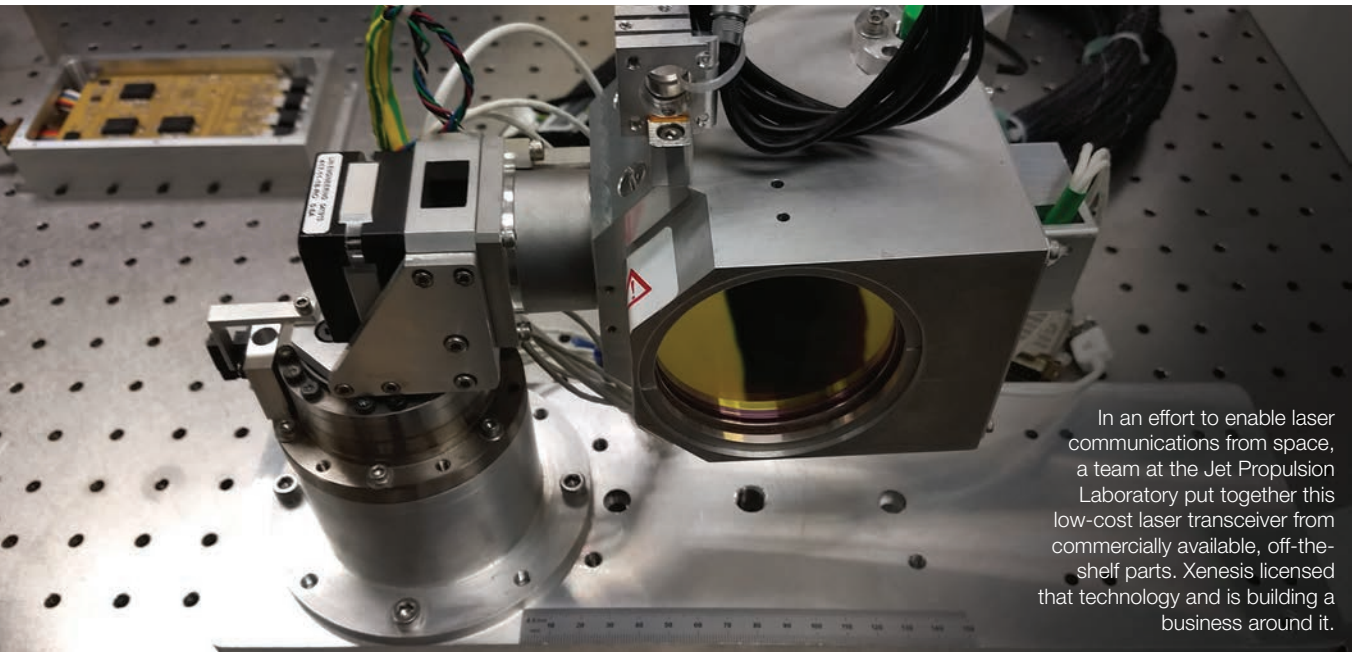
With this kink in its business model, the company's progress almost ground to a halt. "I was within a week of dissolving the company and looking for a job," LaPenna recalls. Then a friend at NASA suggested he check out a technology NASA's Jet Propulsion Laboratory (JPL) had available for license.

NASA, too, has chafed at the limited capacity of radio for transmitting data from space to Earth. So a team at JPL had received three years' worth of funding, ending in 2012, to come up with a simple, low-cost laser communications transceiver that could end those constraints.

While radio waves range in length from 10 meters to 10 kilometers, light wavelengths are measured in the hundreds of nanometers. This more concentrated beam means light has a vastly greater capacity to carry information. Fiber optics take advantage of this characteristic through the use of glass threads that guide the laser, but engineers have had difficulty transmitting light signals without the fibers.

The goal of the JPL program was to enable transmission of 10 gigabits per second from low-Earth orbit and to do it cheaply and efficiently. To that end, the team forsook space-qualified parts and went entirely with existing components. "The innovation was to make it as small and simple as possible with off-the-shelf parts," says Joe Kovalik, a JPL engineer who worked on the team.

"Everything together is sort of the innovation, but there's no one thing that's new," Kovalik says. "I'm actually a little surprised they patented it."



In an effort to enable laser communications from space, a team at the Jet Propulsion Laboratory put together this low-cost laser transceiver from commercially available, off-the-shelf parts. Xenesis licensed that technology and is building a business around it.

Technology Transfer

Upon learning of the transceiver, which JPL had by then tested and proven, LaPenna scrapped his plans for aircraft tracking, realizing that high-speed mass communication could meet an even larger need. He licensed the technology.

While others have tried to create large-scale satellite laser communication systems, none have succeeded. The obstacles are daunting: Clouds, snow, and haze can interfere with the laser signal. There are not many optical receivers on the ground, let alone the infrastructure to connect receivers to users. And a constellation of satellites is necessary for uninterrupted communication.

For these reasons, Xenesis, LaPenna's Atlanta-based company, won't start with space-to-ground communications but rather with communication over land. Rather than burying fiber-optic cables, a client will be able to beam laser signals above ground from one point to another across a network of ground transceivers. As the system is built out, satellites will extend its reach, for example enabling intercontinental laser communication.

Meanwhile, the company is building partnerships to encourage and gain access to a future ground network capable of receiving and disseminating satellite laser transmissions. And Xenesis is working with industry leaders to create a global set of standards for laser communications.

Ultimately, the company plans to launch its own Intercessor constellation of low- and middle-Earth-orbit satellites.

Benefits

A major problem for hospitals, banks, and others handling vast amounts of sensitive information is secure data communication. These entities are constantly sharing information between branch locations, and every access, transfer, and switch point on Internet networks presents an opportunity for hackers to intercept or corrupt it.

Wireless laser communications, however, can be made unhackable. A mirror could intercept the beam, but the signal in the reflected beam would collapse and become incomprehensible.

"It also sidesteps tens of millions of dollars in burying cables," LaPenna adds.

He considers this ground-to-ground communication to be the low-hanging fruit for the laser communication market, which others trying to commercialize the technology have overlooked. "The number-one reason others haven't succeeded is that engineers aren't business people," he says. "In business, a lot of times, people don't realize what they need until you show it to them."

Just two months after acquiring the license in 2017, Xenesis had already racked up more than $10 million in letters of intent from companies interested in investing.

Meanwhile, an agreement between Xenesis, several universities, and Nanoracks—the company that manages much of the science equipment on the International Space Station—will try out one of the units on the space station in 2019.

For the long term, the company is partnering with businesses like Atlas Space Operations that are jointly developing networks of laser-communication ground receivers. Such an array of receivers, using wide-area apertures, would overcome the problem of weather interference. Construction of the network began in 2018 and is expected to take several years.

Xenesis is also partnering with the company Laser Light Communications, which is in turn partnering with NASA's Near Earth Network to build laser communications capabilities in space. And Xenesis, another high-tech company, and Florida's space development authority, Space Florida, are slated to build a manufacturing facility at Kennedy Space Center.

Following the run on the space station, Xenesis plans to launch the first two payloads in its constellation in 2020, to be followed by hundreds more.

LaPenna says there are more satellites currently in development around the world than have been launched since Sputnik. Like those already in orbit, a main function of all these satellites will be to transmit data to Earth, causing radio frequencies to reach full capacity in the coming years. Laser communication, on the other hand, is limited only by the number of satellites in orbit and stations on the ground.

"In other words," he says, "optical communications are fully scalable and are capable of creating abundance from scarcity—the basic formula for 'disruption.'"

Transmissions will also require little power and have four to five times the capacity of high-end radio transmissions and a shorter latency period. Within five years, LaPenna says, he expects to have enough satellites in space to be able to uplink via laser, which is harder because satellite transceivers are limited in their aperture size.

All of this will enable ultra-secure, high-speed satellite Internet access. "What we represent to broadband is what broadband represented to dial-up," he says. "The market is going toward this, and the first company that has a scalable network will lead the industry."

What Xenesis ultimately plans to sell is cheap and abundant access to that network.

LaPenna notes that a number of other companies are building optical terminals, but their research and development costs are reflected in their prices, whereas his technology was already developed. Licensing the technology "was the easiest process I've ever been through in terms of working with the Government directly," he says, adding that the company is already exploring other possible JPL licenses.

"I'm sure one day people will say, 'They couldn't have done it without NASA,' and they'll be 100 percent right. We absolutely couldn't have." ❖

In the future, Xenesis plans to use laser communications to offer large-scale, ultra-secure, high-speed satellite Internet access. But in the short term, the company will start with over-land laser communications, providing unhackable connections, for example for hospitals and banks, which transmit large amounts of sensitive information between their various locations.

NASA Code Speeds Nation's Aircraft, Spacecraft Design

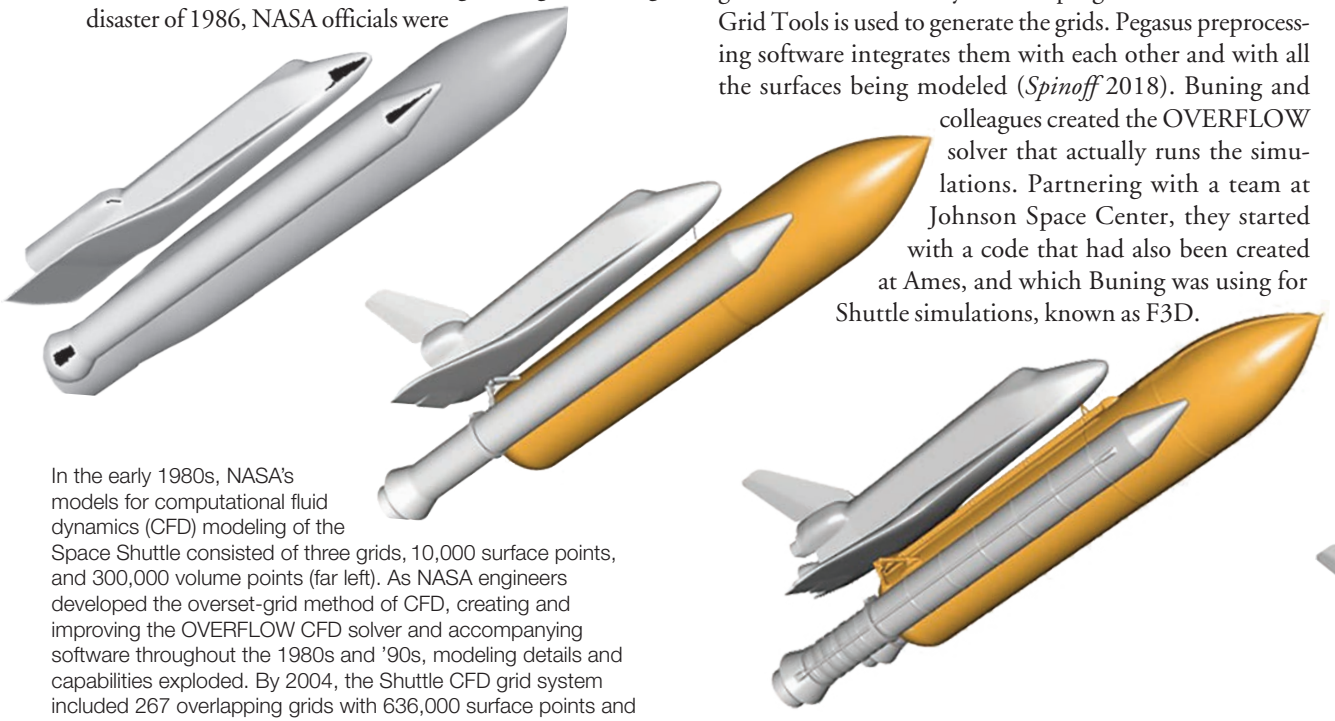
NASA Technology

In the late 1980s, NASA engineers were working to improve software to simulate how air flowed around vehicles in flight. But the Space Shuttle posed a distinct challenge. At liftoff, the craft was attached to a huge external fuel tank, which in turn carried two solid rocket boosters. Each of these four bodies generated airflows, which interacted with each other in complex ways. What's more, as they separated from each other and began moving at different speeds, it got even harder to simulate the air rushing around and between them.

"Simulation of the orbiter detaching from the external tank was the original problem," says Pieter Buning, who was with the Applied Computational Fluids Branch at Ames Research Center at the time. Following the tragic Challenger disaster of 1986, NASA officials were interested in exploring the possibility of dropping the boosters before they burned out, in case of a malfunction. To better model the fluid dynamics of multiple bodies, Buning and his team lead Joseph Steger proposed using an improvement to computational fluid dynamics (CFD) that is now used by most air- and spacecraft designers in the United States: the overset-grid method.

All CFD software breaks down complex geometries into grids of simple shapes, including breaking up the air around the vehicle model into tiny, three-dimensional bins. Early Shuttle CFD work generated these grids around each major component and then patched them together. Overset grids, on the other hand, overlap and interact with each other, as real airflows would, resulting in more realistic simulations.

NASA developed a suite of software that enables overset grids and is now widely used: A program called Chimera Grid Tools is used to generate the grids. Pegasus preprocessing software integrates them with each other and with all the surfaces being modeled (*Spinoff* 2018). Buning and colleagues created the OVERFLOW solver that actually runs the simulations. Partnering with a team at Johnson Space Center, they started with a code that had also been created at Ames, and which Buning was using for Shuttle simulations, known as F3D.



In the early 1980s, NASA's models for computational fluid dynamics (CFD) modeling of the Space Shuttle consisted of three grids, 10,000 surface points, and 300,000 volume points (far left). As NASA engineers developed the overset-grid method of CFD, creating and improving the OVERFLOW CFD solver and accompanying software throughout the 1980s and '90s, modeling details and capabilities exploded. By 2004, the Shuttle CFD grid system included 267 overlapping grids with 636,000 surface points and 34.8 million volume points (far right).

"I rewrote it, cleaned it up, made it more user-friendly, and incorporated algorithms from lots of people," Buning says. "My role has sort of been technology integrator, making it as useful as possible for as many projects as possible."

Early areas of interest for multi-body CFD beyond spacecraft were helicopters, which might have air moving near the speed of sound over the tips of the blades but relatively gentle airflow around the body, and the release of fuel tanks or missiles, which, under the wrong conditions, could return to hit the aircraft.

Technology Transfer

In the 1990s, Buning transferred to Langley Research Center, where he is now in the Computational AeroSciences Branch. There, he worked for a number of years on commercial transport airplanes and developed relationships with a variety of aircraft companies. OVERFLOW became available through software usage agreements with Langley and was widely acquired throughout the industry and the Department of Defense.

"Getting it out to a lot of organizations helps get me feedback on what people want to do that they can't do, and I'll try to get that capability working," Buning says, noting that this has made the program more flexible, leading to wider adoption. "I worked very hard to make the code user-friendly and put in options a lot of people are interested in."

Further additions to the software resulted from various NASA projects, such as work on space capsule dynamics, reusable launch vehicles, and rotorcraft. For

example, automatically adding grid points to help simulate the tiny whirlwinds that are generated at the tips of helicopter blades also proved useful for other applications.

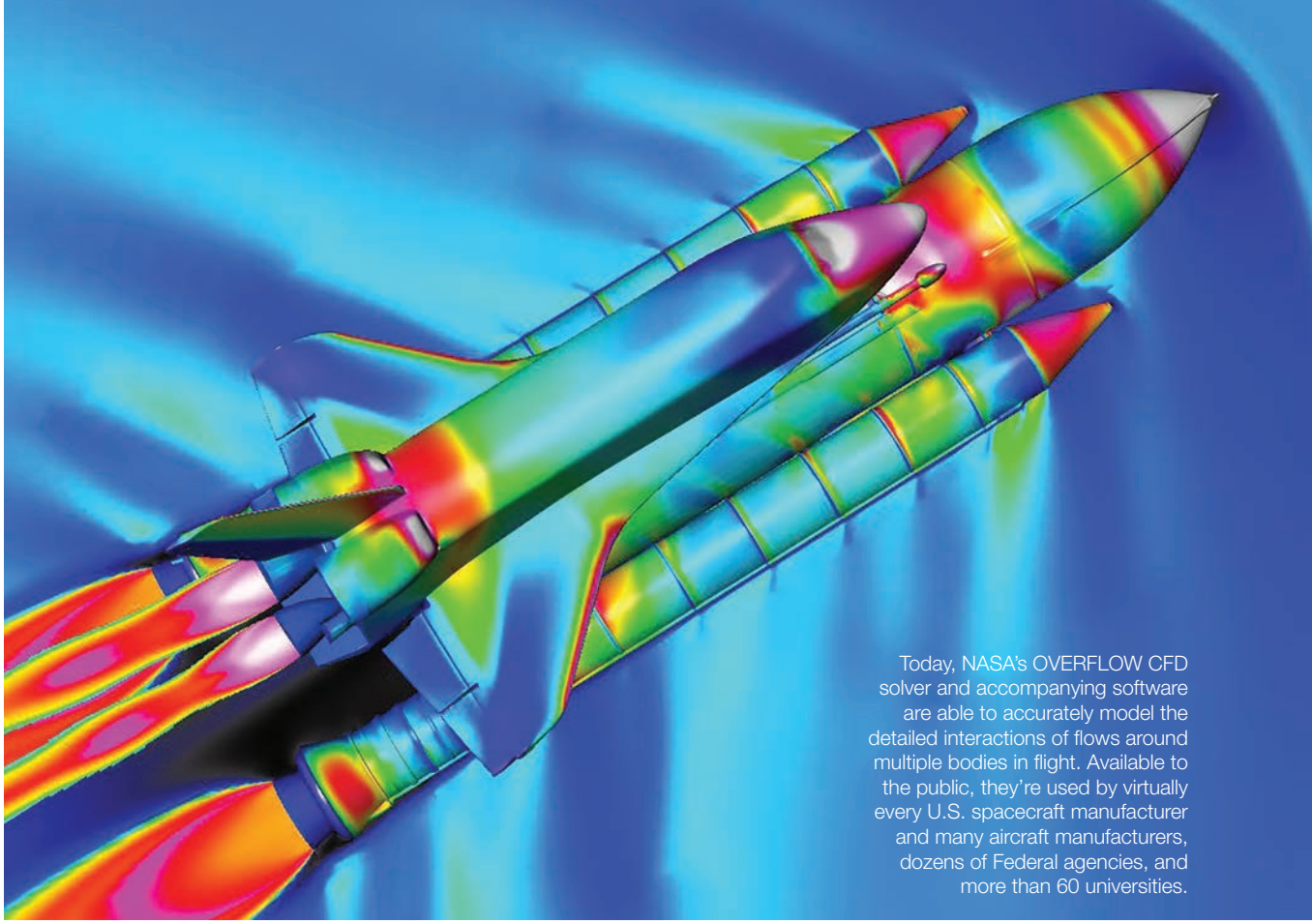
OVERFLOW is optimized for transonic speeds—velocities approaching or somewhat exceeding the speed of sound—making it applicable to most airline and military applications. Even military jets that fly at twice the speed of sound or more are within OVERFLOW's range. Only atmospheric reentry speeds are beyond it. While versatile, though, it only uses structured grids, which require less computer memory and processing power than unstructured-grid CFD, although the latter simplifies grid generation for complex shapes. For unstructured-grid CFD, users can obtain programs like FUN3D, also available from Langley.

Benefits

One early adopter of OVERFLOW and the rest of the Chimera Grid Tools suite was Boeing, which now uses the software throughout its commercial, military, space, and research and technology operations for development of planes, rotorcraft, spacecraft, and advanced concepts and hypersonic flight. "The method was proven on the Space Shuttle Launch Vehicle and has been matured over the past 25-plus years. It is an integral part of the Boeing CFD tool set," says Robb Gregg, chief aerodynamicist at Seattle-based Boeing Commercial Airplanes. He adds that the code provides "exceptionally efficient and accurate flow solutions supporting virtually every product in the company."

To illustrate the software's efficiency, Gregg notes that in 1990, it took two-and-a-half years to build a Space Shuttle launch configuration grid system with 16 million points across 20 zones, and another three weeks to run the simulation on a supercomputer. Today, he says, it only takes three weeks to build the grid system for a high-lift commercial transport plane, which includes 300 million points over more than 250 zones, and its simulation can be run in two days.

Other users include about three dozen Department of Defense and other Federal offices; most major defense contractors; more than 60 universities; virtually every U.S. spacecraft manufacturer; aircraft manufacturers like Learjet, Sikorsky, and Honda Aircraft Company; and computer giants such as Microsoft, IBM, Intel, and Hewlett-Packard, which mainly use it to benchmark computers' CFD performance. Buning says the latest version, released in 2017, went out to about 200 users.



Today, NASA's OVERFLOW CFD solver and accompanying software are able to accurately model the detailed interactions of flows around multiple bodies in flight. Available to the public, they're used by virtually every U.S. spacecraft manufacturer and many aircraft manufacturers, dozens of Federal agencies, and more than 60 universities.

He even recalls helping one engineer from a major manufacturer use OVERFLOW to design a screw compressor for industrial air conditioning units. "If I've done my job right and designed the code so it's general-purpose, hopefully it's applicable to this kind of problem without too much work," he says.

In addition to speed, accuracy, and flexibility, Buning says, NASA's support is another reason the software has caught on. He and colleagues answer users' questions, help them get started, and troubleshoot problems.

Gregg notes that the code has fostered a mutually beneficial relationship between NASA and Boeing, with the Space Agency making improvements at the company's suggestion and Boeing's engineers adding upgrades that find their way into newer versions of the program. "The support we get from NASA has been tremendous," he says. "The continuous improvement of this technology by NASA, often driven by customers like Boeing, fuels our continued reliance on the tool suite."

"By disseminating it, we get a lot of feedback, and we learn what people are doing with it and what works and what doesn't," Buning adds. ❖

Tiny Springs Improve Electronic Reliability

NASA Technology

Space exploration comes with many giant challenges, but some of them are downright tiny. One project to solve a connection issue in printed circuit boards has resulted in a miniature solution—a micro-coil spring less than half a millimeter in diameter—that could have an outsized impact on electronics for spacecraft and here on Earth.

Printed circuit boards are layered boards with copper lines and pads that connect various electronic components. For example, a computer motherboard is a printed circuit board that connects components to a microprocessor. Typically, the components are soldered to the board, which provides a strong adhesion and allows electricity to pass through.

However, those joints can break when things heat up—a particular problem in space, where temperature swings between sun-facing and shaded orientations can be extreme, and where repairs and replacements are hard to come by. Because the circuit board and the electrical components are generally made of different materials, explains Marshall Space Flight Center aerospace engineer Jim Hester, "the materials both expand, but the integrated circuit expands less than the circuit board does, and that tries to shear that solder joint."

The current state of the art is to create a "solder column" at the joint. The increased length allows a degree of flexibility, but it's still fairly brittle.

"We wanted something that might be a little more robust from a handling perspective, with higher reliability from a thermal perspective," says Hester's co-inventor Mark Strickland, a fellow engineer at Marshall.

After considering a variety of interconnections, they decided on a tiny spring. "The real challenge comes from taking the spring and mounting it onto the circuit board," he notes. "If you look at a spring from the side, you have a nub that sticks out: the bottom is not flat," which makes it difficult to attach perpendicularly to the board.

Strickland and Hester devised a method and tested the resulting connections under extreme conditions, cycling back and forth from -70 °F to nearly 260 °F. Compared to solder columns, the spring connections lasted at least twice as long on ceramic devices, based on first failure for space applications, with improved consistency and uniformity, and at least five times longer on plastic devices, and could withstand vibrations at forces of up to 10 Gs.

"The springs are also just more robust from a handling perspective during assembly," Strickland adds, "so they're not as fragile if you are touching the part."

Tiny springs like this one help connect electronic components to circuit boards. Because they are flexible, they make stronger, longer-lasting connections, which is great for space—and high demand applications on the ground.

Technology Transfer

In 2014, Strickland and Hester's innovation won the top prize in the electronics category of *Tech Briefs*' Design the Future challenge, and Marshall saw potential for the invention outside aerospace—after all, printed circuit boards are used in a wide array of contexts. Strickland and Hester pursued a patent, and meanwhile Marshall's Technology Transfer Office approached Milledgeville, Georgia-based Topline Corporation.

When licensing manager Sammy Nabors showed him the details, says Martin Hart, Topline CEO, "the light bulb instantly went off. I understood the product could fit into our general product line."

Topline negotiated a license to produce and sell the micro-coil spring interconnectors, and although a patent was ultimately not granted to NASA, the company continues to sell the spring interconnectors to its clients.

Benefits

"We're selling the springs, and we're also attaching the springs to test components that the industry is using to make their own tests and verifications," Hart says. The company offers a variety of sizes, from 0.2 mm diameter by 0.5 mm in length up to 0.5 mm diameter by 1.27 mm long.

To attach a component, he notes, would typically take an array of 1,000 to 2,000 springs, and he emphasizes that the process for attaching springs had to be perfected and streamlined in-house. "NASA does a great job at figuring out a better way to do things, but it's not a blueprint."

The target application "is large ceramic-substrate components that will fail if you use a solder ball, ball grid array," he says, because the larger the part, the more extreme the heat expansion differences will be.

The applications are "any where there are large temperature swings: downhole drilling or automotive where the assembly fits in the engine compartment, or even a desktop computer where there are large ceramic parts."

He sees potential in medical devices, like hearing aids, but notes, "We're still at the beginning of discovering the market."

But he says the NASA origins have helped open doors: "When the customer realizes that the invention was made at NASA, they're more willing to listen, read about it, consider buying it." ❖

Collaborative Platform Trains Students in Simulation and Modeling

NASA Technology

It's the 2050s. On the far side of the Moon, in the vast, pockmarked South Pole-Aitken Basin impact crater, groups of college students from around the world are building an outpost.

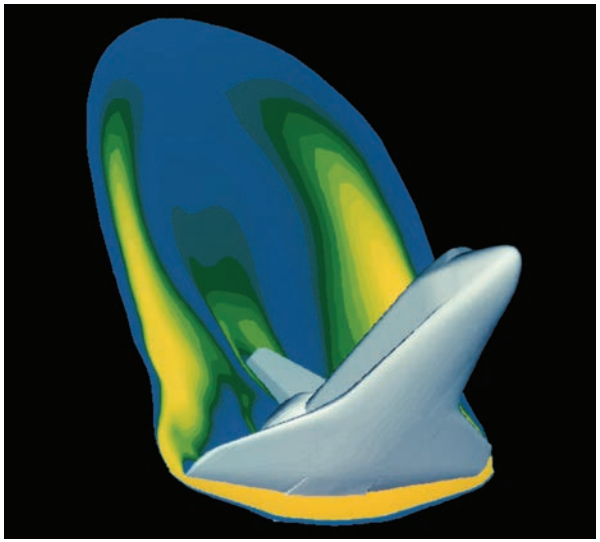
In the southern sector of Moon City, a French team outfits a supply depot with smart technology. Just north of the depot is a waste management facility that a Canadian team built out of bricks made from 3D-printed Moon dust. The outpost recently began receiving tourists via the Tourism and Commercial Spaceport that Bulgarian students constructed in the Launch, Landings, and Communication area. In the Moon City Center, where most of the outpost's 100 or so residents live and work, drones tend to crops in a greenhouse built by students from Italy.

Of course, none of this would be possible without NASA technology.

Moon City exists in a simulation and is visible through the Distributed Observer Network (DON), a simulation viewer created by NASA. The students are all in fact at their respective universities, in the present day, collaborating to build the virtual lunar city as part of the Simulation Exploration Experience (SEE). It's a program that introduces them to collaborative modeling and simulation, a subject rarely taught in schools. Around 60-80 students participate each year.

Many organizations use computer modeling and simulation nowadays, but few more than NASA. "Simulations let us learn and not make mistakes once we have multibillion-dollar pieces of equipment," says Mike Conroy, who oversaw DON from its creation in the IT Advanced Concepts Lab at Kennedy Space Center in 2008 until his retirement at the end of 2017.

The idea from the beginning was to capture data from simulations and make them portable, to allow them to be preserved and shared. NASA teams running simulations were creating massive datasets using tools ranging from supercomputers to spreadsheets. The data was difficult to use outside the original tool, requiring the long-term preservation of the simulation system itself. DON was developed to solve this problem, allowing rich, immersive access to simulation data outside the original tools.



NASA uses a variety of tools to create simulations, including the computational fluid dynamics software used to simulate the aerodynamics of Space Shuttle descent here. The Distributed Observer Network (DON) can read and display any of those simulations.

The viewer was built to work alongside a commercial game engine, allowing the integration of modern tools, development methods, and the latest 3D technologies. Supporting the DON visual environment is the Model Process Control (MPC) specification. MPC defines a data format that is easy for simulation tools to implement and for people to understand. Coupled with DON, MPC allows the capture of any simulation information for review, analysis, or even use by another simulation, in real time or decades later.

Conroy likens this capability to Adobe Acrobat, where data from multiple sources can be viewed and shared without the need for the original tools.

The current version of DON runs alongside the Unity 5 game engine—the same one that supports PlayStation, Xbox, iOS, Android, Windows, and most other modern platforms—but DON is versatile enough that it can and does switch game engines.

Conroy says NASA has used DON in scores of simulations across its various facilities, saving untold time and money and improving outcomes. "The more eyes on the data, the better product you're going to get," he says, noting that a team or engineer wanting input from another NASA group can easily share entire simulations rather than a handful of screenshots. "With DON, you can easily get a large group of people looking at the data, work around everyone's schedule, and end up with the knowledge to make better decisions."

The software was a runner-up for NASA Software of the Year in 2017 and is now available to the public for free download through the Agency's software catalog, along with the accompanying MPC standard.

Technology Transfer

At a simulation standards workshop in 2009, Priscilla Elfrey, who works on simulation outreach at Kennedy, and Edwin "Zack" Crues of Johnson Space Center found themselves in a conversation with other simulation experts from industry and government "about how very few people applying for work in simulation knew anything about it," she recalls.

Crues had the idea of putting college students to work on a simulated lunar mission, the inspiration that led to SEE, which he still advises. Elfrey started planning. After two years of development and with support from industry groups and several companies, students from six universities met the first challenge in 2011.

In addition to DON, NASA supplies the teams with High-Level Architecture-based software that enables the solar system model and ensures the accurate trajectories and positioning of the planetary bodies. The detailed model of the Aitken Basin that provides the challenge's virtual

setting was created at NASA's Jet Propulsion Laboratory. And various NASA personnel serve as committee members and advisors, including Conroy, who is SEE's technical chair.

But the most support for SEE comes from the faculty at each school. "We try to make it support whatever the faculty is teaching, and they've been able to take what we're doing and meld it into their own programs," says Elfrey. "Part of the students' assignment is that they have to come up with what they're going to do." Each team submits a 50-word synopsis of its project for the year. Teams then coordinate their projects, communicating not only via DON but also through video conferencing.

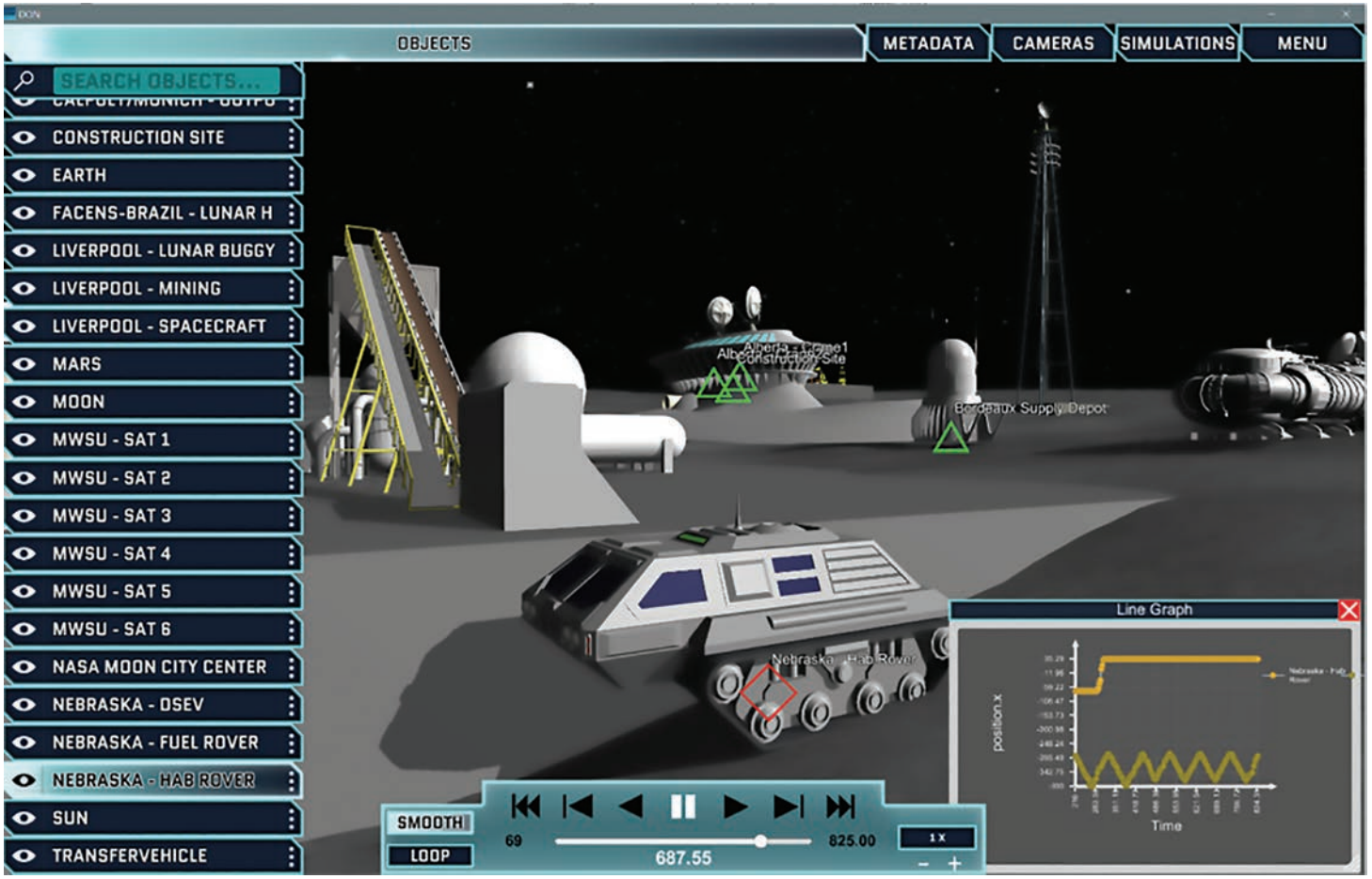
About 26 universities have been involved over the years, including many that have participated year after year. The University of Genoa in Italy has taken part since the beginning, while two schools in Pakistan were newcomers in 2018. Five teams went to Sofia in Bulgaria for SEE 2018 and were joined remotely by 11 more.

Benefits

There are few simulation programs or departments in American universities, especially at the undergraduate level. In 2013, Old Dominion University in Virginia graduated the first four students in the country with undergraduate degrees in modeling and simulation. "That's when we realized we had an even bigger problem than we knew," says Elfrey.

SEE's overarching goal is to enhance students' employability. Given the dearth of simulation courses and how essential the technology has become to so many workplaces, guided, hands-on experience goes a long way to that end.

"With space, we have no choice but to use simulation, but there are many professions using dynamic modeling and simulation today," Elfrey says. She points to the widespread use of human patient simulators in medical education, the emergence of collaborative construction design software, and even the visual simulations financial companies use to display portfolios, let alone the military's long and widespread use of simulations.



A rover passes in front of part of Moon City, the simulated lunar outpost constructed by teams of students from around the world in the Simulation Exploration Experience.

Four people who participated in the program as students are now teaching simulation in colleges and participate in SEE as faculty, says Elfrey. "We're kind of growing our own. That was not something we had anticipated." Another alumnus now works at NASA.

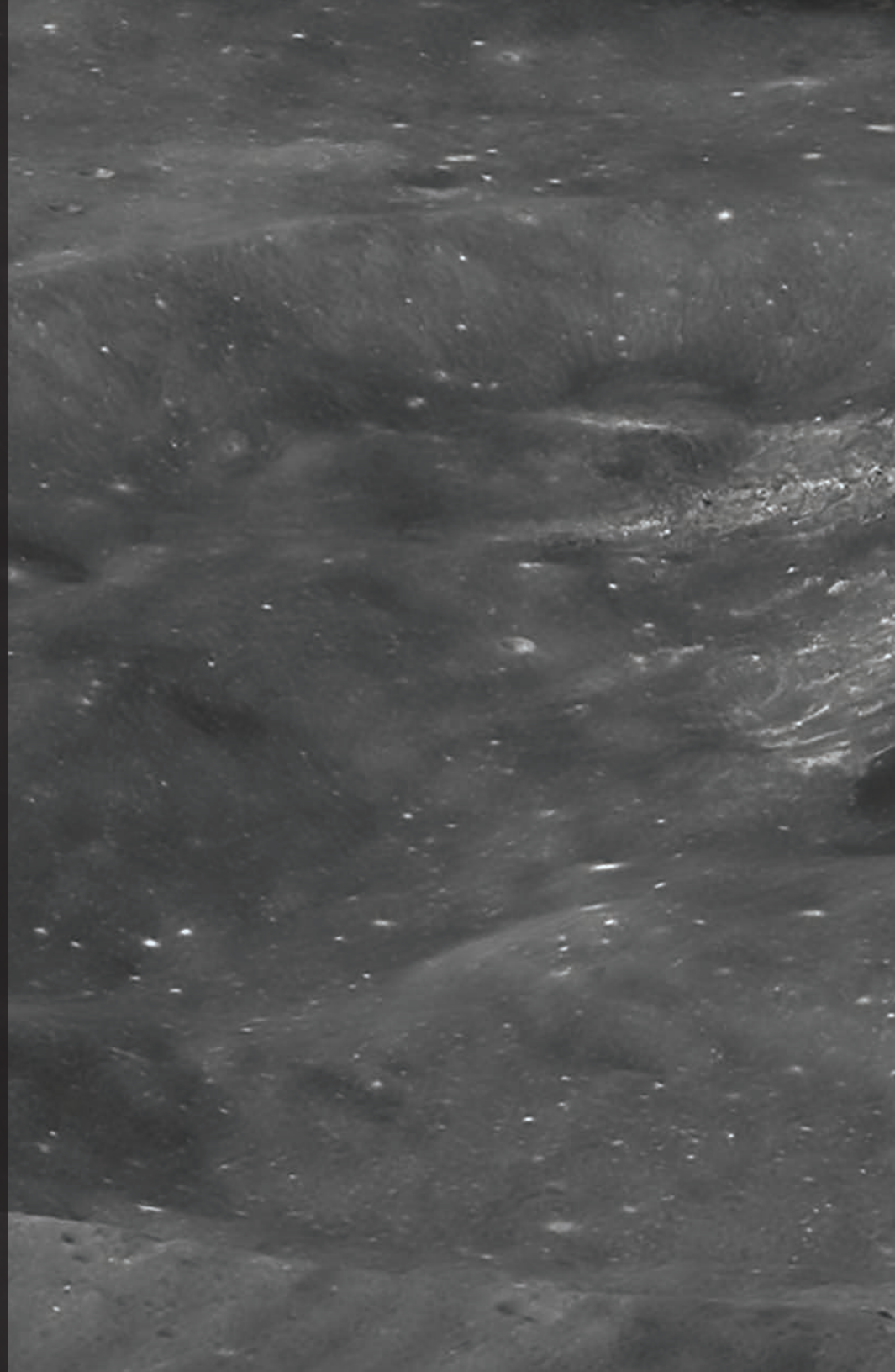
A major benefit of the software to NASA and other potential users is that it makes simulations portable not just across distances but also across time, Conroy says, noting that this is important for an entity like NASA that carries out big plans with multi-decade timelines.

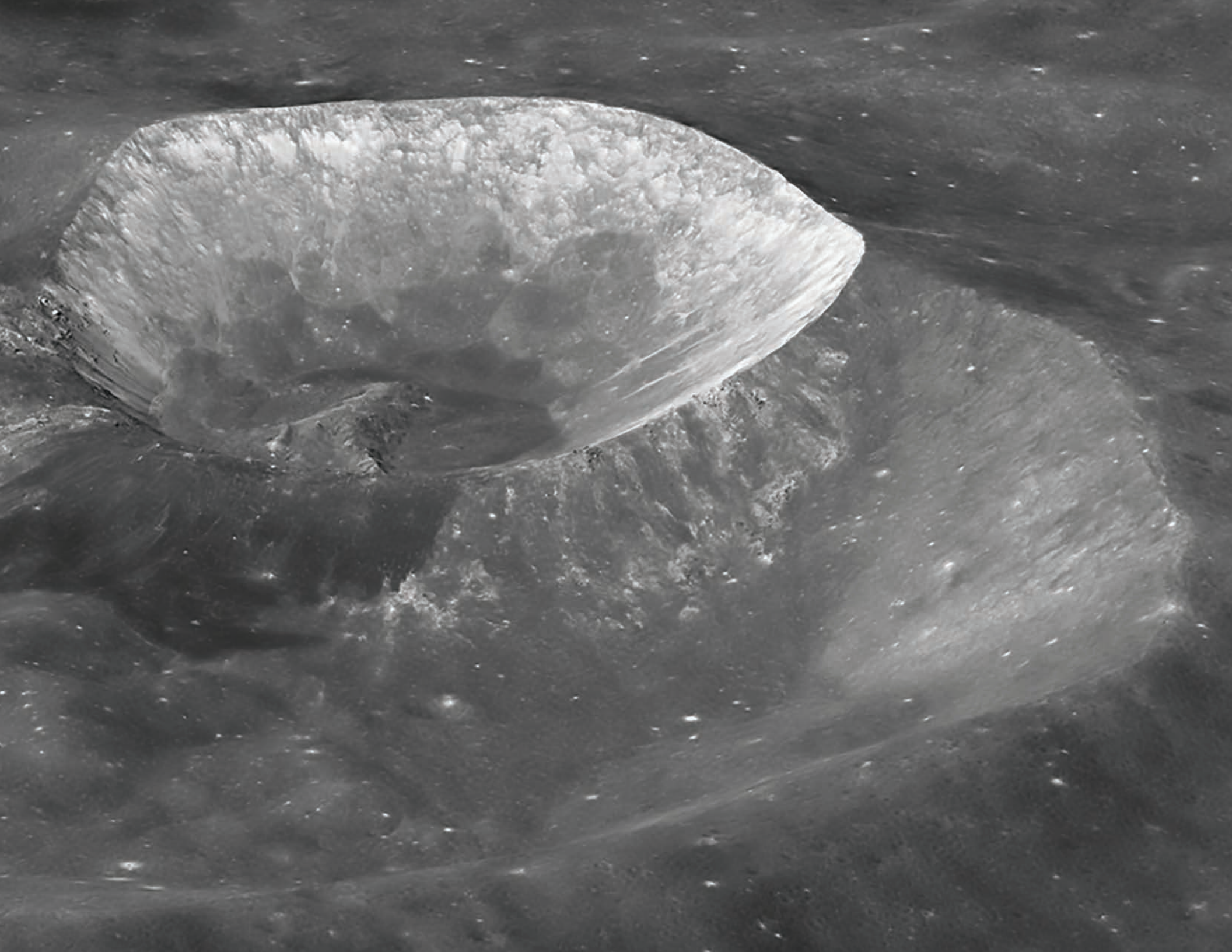
Other organizations are building their own, similar software—possibly following NASA's example. "The first time we showed DON at an international conference, we were the first to have used game engines that way," Conroy says, noting that two years later, "almost everyone" was doing it.

But DON remains unique in its ability to manage large numbers of complex models that span distances of hundreds of millions miles. ❖

Industrial Productivity

To ensure everything goes right in space—and to fix any problems that arise—NASA pioneers cutting-edge technology that then finds uses in every industry, in every phase of manufacturing. These innovations improve the cars we drive, help pioneer new television screens, advance 3D printing, and make Earth-bound telescopes more powerful.





Spray Analyzer Turns Up in Cars, Planes, Medicine, Cutting-Edge TVs

NASA Technology

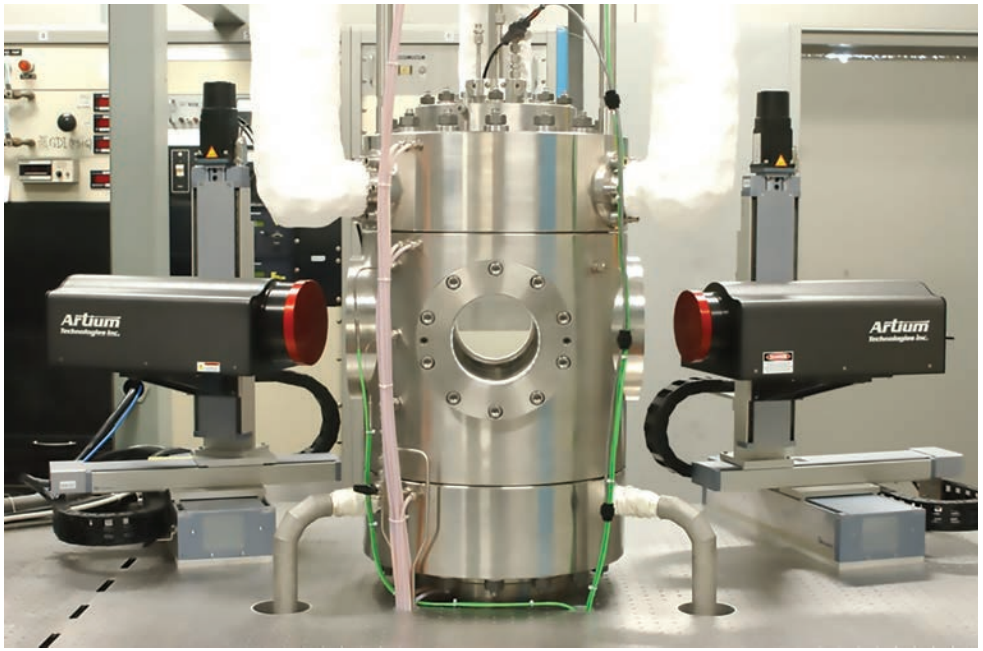
At first, NASA just wanted a way to characterize fuel sprays in a turbulent environment such as a jet engine. What William Bachalo created to meet this need in 1984 has since been used for automobile engines, aircraft testing, inkjet printers, medicine, agriculture, and now the latest cutting-edge development in smartphone and television screens.

Bachalo did his postdoctoral work at NASA's Ames Research Center, studying turbulent airflow separation around airplane wings and helicopter rotors. To visualize and characterize the behavior of these flows, he developed innovative techniques for measuring the Doppler shift in laser beams to make detailed observations of flow speeds and movements. He also developed a way to use holography to record the features of large flow fields at or around the speed of sound. The results were detailed visualizations and quantitative data on flow contours, pressure distributions, and speeds.

Following his work at Ames, Bachalo founded the company Aerometrics Inc., which won its first Small Business Innovation Research (SBIR) contracts from Lewis Research Center, now known as Glenn Research Center, to build on his earlier work. With that funding, the company invented and developed a device that could characterize the interaction of atomized fuel and air in terms of droplet sizes, velocity distribution, turbulence intensity, and fluctuations in turbulence. He called it the Phase Doppler Particle Analyzer (PDPA), and it remains the standard for spray characterization to this day.

The PDPA measures the velocity of particles in a spray based on the Doppler difference in frequency and phase shift in the light they scatter when passing through the intersection of two laser beams. It determines particle size based on the phase difference in scattered light received by three different photodetectors. Bachalo first developed the method with the help of his partner at Aerometrics, Michael Houser.

This technology, along with work on using lasers to characterize soot emissions, also funded by Glenn, formed the basis for the products offered by his current company, Sunnyvale, California-based Artium Technologies Inc. In addition, the company has developed high-speed imaging under Glenn SBIR funding, used to characterize mixtures of liquid drops and ice particles for aircracft icing research and development.



Artium's Phase Doppler Interferometer is used to test fuel injectors at a General Motors facility. Most automakers use Artium technology, which was originally created to test rocket and jet engines.

Technology Transfer

A series of SBIR contracts with NASA, the Department of Defense, the Department of Energy, and the National Science Foundation refined and expanded the technology's capabilities and applied it to various problems. Two such contracts with Glenn, which funded most of the company's NASA work, added the capability to determine droplet temperature using a linear array of charge-coupled device image sensors to capture each droplet's refractive index, which is a function of its composition and temperature.

That added capability made the technology the only instrument that could measure droplet temperatures in a spray flame, such as may be found in a combustion engine. That and its ability to simultaneously gauge particle size and velocity allowed the devices to test and validate advanced models for fuel-efficient combustors (*Spinoff* 1998).

In early commercial applications, the technology was used to design or monitor spray nozzles for paint, agricultural products, fire sprinklers, and fuel sprays into combustors (*Spinoff* 1994). An adapted version characterized sprays of nebulizers, aerosols, and mists.

In 1995, Aerometrics, whose staff had grown to about 50, merged with a competitor, and in 1998, Bachalo cofounded Artium. The company has continued to work with NASA, especially Glenn, mostly on technology to measure particulate emissions from various combustion sources and to study airframe and jet engine icing.

Benefits

A widespread commercial application to this day is developing and testing automobile fuel injectors. "Most auto companies have our instruments or work with a university using our instrument," Bachalo says, adding that the advent of direct fuel injection was enabled in part by his technology's ability to characterize gasoline direct-injection sprays.

Car manufacturers have also used the instruments for vehicle body painting, although it's not a major source of business for the company. "When you paint a vehicle, you've got to get the right-sized droplet so you produce a nice, smooth, even coat," Bachalo says. Likewise, pharmaceutical companies use it in spray-coating medicine tablets. At least one customer has used it to develop nozzles for spraying crops. Companies making inkjet printers use PDPA technology for product development and quality control.

"Aircraft icing is not a big market, but it's important," Bachalo says, noting that Artium products help certify airplane and helicopter parts in wind tunnels by showing how supercooled liquid droplets behave when impacting these components. These are demanding environments, where instruments have to work at temperatures ranging down to -40 °F in winds of 200 or 300 mph. Icing is a major flight hazard and one that Artium and NASA are still working on. Droplets of supercooled water can freeze on wings, causing them to lose their aerodynamic shape, or in engines, causing flameout and loss of power.

In 2014, the Federal Aviation Administration issued new certification standards for dealing with supercooled large drops. Bachalo says such conditions are difficult to recreate and mitigate, but Artium is helping Glenn develop solutions. The two entities are also working on high-speed imaging of ice crystals. Because the crystals are shaped irregularly, Artium's usual PDPA technology cannot characterize them. With NASA funding, Artium has developed a specialized instrument that's currently in development. "It's part of that whole process of keeping flying safe," Bachalo says. "It's required lot of innovation and effort from our team."

PDPA technology recently found a new—and lucrative—market in the organic LED, or OLED, display business. These new screens, used in smartphones and televisions, with their deep blacks and rich colors, are made with organic dyes that light up in a particular color when hit with a voltage. Initially, the pixels were created through a lithographic process, but manufacturers are now working to print the screens with inkjet printer technologies, Bachalo explains. Such a printer might have 1,024 jets, and each must produce droplets of a precise size and hit a precise target. "You've got to know if they're all working right, because the dye and printing process are extremely expensive." So PDPA instruments provide the screen manufacturers with the necessary quality control. He notes that the work should bring down the prices of OLED displays significantly.

Organic LED, or OLED, displays are known for their rich colors and deep blacks, as well as for being thin and often flexible. But they're also expensive. Manufacturers are working to bring down the cost by applying the screens' organic dyes via inkjet printer, a process that uses Artium's spray characterization technology for quality control.

OLED products already represent a market of tens of billions of dollars, Bachalo says, and Artium's revenues have doubled in the last year. The company still only has about 15 employees. "I prefer to be profitable rather than large," he explains.

Taking a technology that started with NASA jet and rocket engines and applying it to so many areas didn't come easily, Bachalo says. "It's tough, because it spreads us thin when we've got to know about the technology in all these different fields." His various leadership positions with the Institute for Liquid Atomization and Spray Systems have helped, he says.

"People kind of trivialize sprays, but they're one of the more complicated problems in fluid mechanics." ❖

Deep-Space Food Science Research Improves 3D-Printing Capabilities

NASA Technology

Crew health is critical to any successful mission, and maintaining astronauts' nutrition gets harder the farther they get from Earth and any chance of a resupply mission. A crewed mission to Mars, for example, will have to pack food for up to five years in space. The food must stay as fresh as possible, provide precise amounts of needed nutrients, create as little trash as possible, and be appetizing enough for the crew to keep eating it.

NASA currently supplies the International Space Station (ISS) with individually wrapped, shelf-stable dishes, many of which simply require heating in the ISS food warmer. Space station astronauts can also choose from a variety of single-serving, freeze-dried side dishes and beverage packets that require hot or cold water be added. But these options are designed to last only six months in space, where food refrigeration would be an inefficient use of precious resources. The meals take up storage space before they're eaten, and their packaging then becomes waste.

In its continuing search for new ways to provide nutrients and variety to astronauts on long-duration missions, NASA in 2013 awarded a Small Business Innovation Research (SBIR) contract to an Austin, Texas-based company with a novel idea. Systems and Materials Research Corporation (SMRC) proposed building food from scratch with a 3D printer that could deliver starch, protein, and fat, creating properly textured edible structures that would be supplemented with micronutrients, flavor, and aroma delivered by inkjet technology.

Unflavored macronutrients like protein and starch would be stored as dry powders and fed directly to the 3D printer, where oil or water would be mixed in at the printhead. The micronutrients and flavors, stored in packets as liquids or pastes, would then be delivered by inkjet.

NASA astronauts Chris Ferguson (left) and Doug Hurley participate in a food tasting session in the Habitability and Environmental Factors Office at Johnson Space Center. As NASA looks to long-duration manned missions to the Moon, Mars, and beyond, it's researching how to preserve food's freshness, nutrient profile, and taste so that astronauts can both benefit from and enjoy the food they eat while they are far from home.

These nutrients, even in powder form, break down over time, so NASA's food scientists needed a way to deliver precise amounts of nutrients, accounting for the inevitable degradation. Adding too much could result in nutrient toxicity, while too little could mean deficiency.

Technology Transfer

Anjan Contractor, then a senior engineer at SMRC, was behind the company's proposal. The intent was to eventually provide astronauts with precise, personalized, 3D-printed nutrition in microgravity, where crew time is limited and cooking is not an option. The connection was natural for Contractor, whose educational background is in mechanical engineering, with a focus on additive manufacturing, robotics, automation, and some software development.

As with most Phase I SBIR projects, the SMRC proposal was just an idea in its very early, conceptual stages. With the NASA funds, Contractor and his colleagues successfully developed a system capable of printing some basic foods from powdered nutrients, oil, and other liquids.

When Phase II SBIR funds to improve the nutritional components didn't immediately follow, Contractor started to think about other applications for 3D food printing. It seemed unlikely that earthbound consumers would be interested in foods derived from powders, so he turned his attention to fresh ingredients instead. He began working on a 3D printer that could put together customized pizzas, with traditional (or even gluten-free cauliflower) dough, sauce, cheese, and toppings, one at a time. Pizza was a natural fit for 3D printing, which builds things layer by layer.

"It was basically the work I did for the NASA deep-space missions that led to this idea," Contractor says. "Out of that knowledge and technology, I made my first prototype at home."

In 2016, he founded his own company, BeeHex, with the initial strategy of traveling around with the prototype doing tech demos—and selling the results to people for lunch. After one such event—a football game at his alma

One application for BeeHex's technology, developed in partnership with the U.S. Army, is collecting and analyzing physiological data to create custom breakfast or lunch bars tailored to a person's needs.

One of BeeHex founder Anjan Contractor's first forays into 3D printing food began with customized pizzas built from dough, sauce, cheese, and toppings applied layer by layer. He credits NASA SBIR funding to explore printing basic foods from powdered nutrients, oil, and other liquids for the knowledge and technology that made his 3D-printed pizzas possible.

mater, Ohio State University—local media picked up the story, including a front-page story the next day in *The Columbus Dispatch* titled "3D Printer Promises to Change Way Food Is Made."

That story drew BeeHex's first seed funding—nearly $1 million from the owner of a restaurant chain who saw endless applications for the technology, from breakfast bars to confections and baked goods, in addition to pizza.

Benefits

"Since then, we've come a long way," Contractor says. He moved BeeHex to Columbus, Ohio, and began working on a production-level prototype of his machine that could be customized for different tasks.

For one thing, he adapted it to decorate cookies and cakes. While BeeHex isn't the first to use 3D printing technology to make food and decorate cakes and confections, Contractor says his approach was informed by his work for NASA, through SMRC.

The BeeHex printer, dubbed Chef 3D, can create protrusions and texture—the ribbon on the edge of a cake, a flower, or seasonally themed cookies, for example—designs that traditionally require skilled cake decorators.

BeeHex is trying a variety of business models. One route is a stand-alone machine that bakers can use to design on-demand confections. The company deploys the machine at minimal cost to bakers and charges only for the duration of use.

"We will have one in a popular cookie shop in Columbus," Contractor says. "Any customer can go, select a shape, print their cookie, and right there get a fresh customized cookie on the spot."

BeeHex has other 3D-printed food technology in the pipeline as well. For example, Contractor is working on a recovery bar machine that can personalize a breakfast or late lunch nutrition bar depending on a person's individual needs, such as genetics, metabolism, and blood markers.

"We are trying to connect it to physiological data like heart rate, calories burned, hydration levels," says Contractor, who is in talks with Columbus-area gyms about hosting such a device. "Right after a workout, people can get a personalized bar that covers 30 percent of daily recommended nutrition values."

The breakfast bar got a boost from research BeeHex is working on with the U.S. Army. "With that project, we collect the personal profile of soldiers—genetics, lactose intolerance or a gene presence that may trigger it, diabetes, physical activity over the last seven days," Contractor says. "Then we make the recovery bar."

Even with so much potential on Earth—BeeHex has two patents pending for its Chef 3D device—Contractor believes the truly revolutionary 3D-printing developments will occur back in space, where human tissue may one day be printed in layers without concern that the bottom layers will get squashed by the top ones.

"I'm very confident that this is going to happen sooner or later," Contractor says. "Tissues and organs needed for drug discoveries or human parts can be grown in space. It could be 30 or 60 or 100 years, but it's very likely this will happen. The foundation is in the 3D printing—the same thing we're doing." ❖

Simulated Space Dirt Supports Future Asteroid Mining

NASA Technology

When companies finally begin mining asteroids in space, they probably won't be looking for precious metals, nor anything else normally mined on Earth. Some space rocks do contain such materials, but priorities change in the harsh space environment, where water becomes the most valuable substance.

"Water is like gold in deep space," says James Mantovani of Kennedy Space Center's Granular Mechanics and Regolith Operations Lab. Water is not only necessary to sustain life, but it contains that other necessity, oxygen, which along with water's other ingredient, hydrogen, can be turned into a common rocket fuel: liquid hydrogen oxidized by liquid oxygen. So the first missions to return with asteroid-mined resources will likely be carrying tons of water into Earth orbit rather than bringing rare metals to the surface.

Deep Space Industries (DSI), a San Jose, California-based company, is one of a handful of businesses working to develop capabilities for space mining, an activity still several years in the future. In the interest of these long-term goals, in 2015 DSI leapt at NASA's solicitation to develop soil and crust that simulate the soil composition of four different types of asteroids. Any equipment for mining or even landing on an asteroid would benefit from testing with such simulants.

The first asteroid NASA wanted to mimic was Near Earth Asteroid 2008 EV5, which was the prime candidate for the Agency's now-cancelled Asteroid Redirect Mission, a plan to robotically capture a large boulder from an asteroid and put it in orbit around the Moon for human study. Like the other asteroid types DSI was ultimately contracted to imitate, 2008 EV5 is a variety of carbonaceous chondrite, a class of asteroids that contain abundant carbon, as well as water and organic compounds, all useful for space travel.

NASA has never returned a sample from an asteroid, but, says Stephen Covey, cofounder and director of research and development at DSI, "it turns out we have small samples of a lot of different asteroids on Earth." Meteorites—the remains of asteroids that fall to Earth—have been recovered all over the world and analyzed to determine their composition. These include at least nine types of carbonaceous chondrites.

Technology Transfer

DSI ultimately delivered a total of more than 11,000 pounds of four different asteroid simulants by the spring of 2018, working under two different Small Business Innovation Research contracts issued at Johnson and Kennedy and overseen by Mantovani at Kennedy.

The company produced simulant in both loose, granular form and in hardened "cobbles" that Mantovani compares to dried mud, as well as packages of each asteroid type's individual mineral components. "We might want to play with the recipe, so that's an added benefit," Mantovani says.

The Kennedy scientist's lab studies the mechanics of handling surfaces of other worlds, known as regoliths—from transporting surface material to dust management. For the Asteroid Redirect Mission, researchers wanted to use the simulants to test new tools and train astronauts for challenges like how to anchor to a given asteroid. Asteroids have very little gravity, so landing and digging on them requires reliable anchoring. Collecting samples presents challenges as well, since there is little to hold the dirt in a shovel.

"Whatever your application is, you want to try to refine it on Earth before launch," Mantovani says.

Researchers know a lot about asteroids from studying the ones that have fallen to Earth. The Murchison asteroid, a piece of which is shown here, struck near Lake Murchison in Australia in 1969. This is a CM-type carbonaceous chondrite, predominantly made up of clays and rich in organic compounds. CM-type asteroids present a potential source of water, shielding materials, and other resources and are one of four types Deep Space Industries (DSI) simulates.

Image courtesy of Wikipedia user Basilicofresco, CC BY-SA 3.0

DSI customers can buy raw asteroid simulant powders or mixes of a range of grain sizes.

For accurate simulants, DSI not only matched the chemical composition of known meteorites but tried to recreate the compaction, porosity, and granularity of their original surfaces, which had burned off in atmospheric entry. "We're extrapolating from what we know of the behavior of materials on Earth and what we've seen on the Moon and Mars," Covey says.

While Asteroid Redirect was scrapped, interest in asteroids remains high at NASA, whether among planetary scientists studying the evolution of the universe, mission planners who want to know what a spacecraft might encounter on its way to the outer solar system, or in-situ resource utilization engineers looking at ways to process surface materials to make water, air, fuel, and spare parts.

"At all the NASA Centers, there are people doing something with regolith, and they would like to use really good, high-fidelity simulants to develop their techniques," Mantovani says. In 2018, his team began reaching out to the other NASA field centers and shipping out orders.

DSI, meanwhile, is also filling orders.

Benefits

A number of universities have purchased the simulants DSI developed for NASA, as have other space agencies and a handful of companies that are also interested in space mining. A standard order is about 20 pounds, which Covey says is "enough to get started" on some basic research.

Mining asteroids is a long-term goal, one that Covey believes is at least five years out but promises to eventually pay hefty dividends. "The interest in asteroid mining is due to the fact that it's so expensive to put anything in space," he explains, pinning the cost at more than $11,000 per pound. Most of that weight is fuel.

DSI imagines extracting a couple thousand tons of water from an asteroid and using half of it as fuel to carry the rest back into Earth orbit. There, it would be available for sale as fuel for any passing spacecraft.

Boeing has already signed a letter of intent to buy a hundred tons of water whenever DSI can harvest it and make it available in orbit. "And there are a bunch of people at [the Jet Propulsion Laboratory] drooling over the idea of what NASA could do if DSI could bring a thousand tons of water to Earth orbit," Covey says.

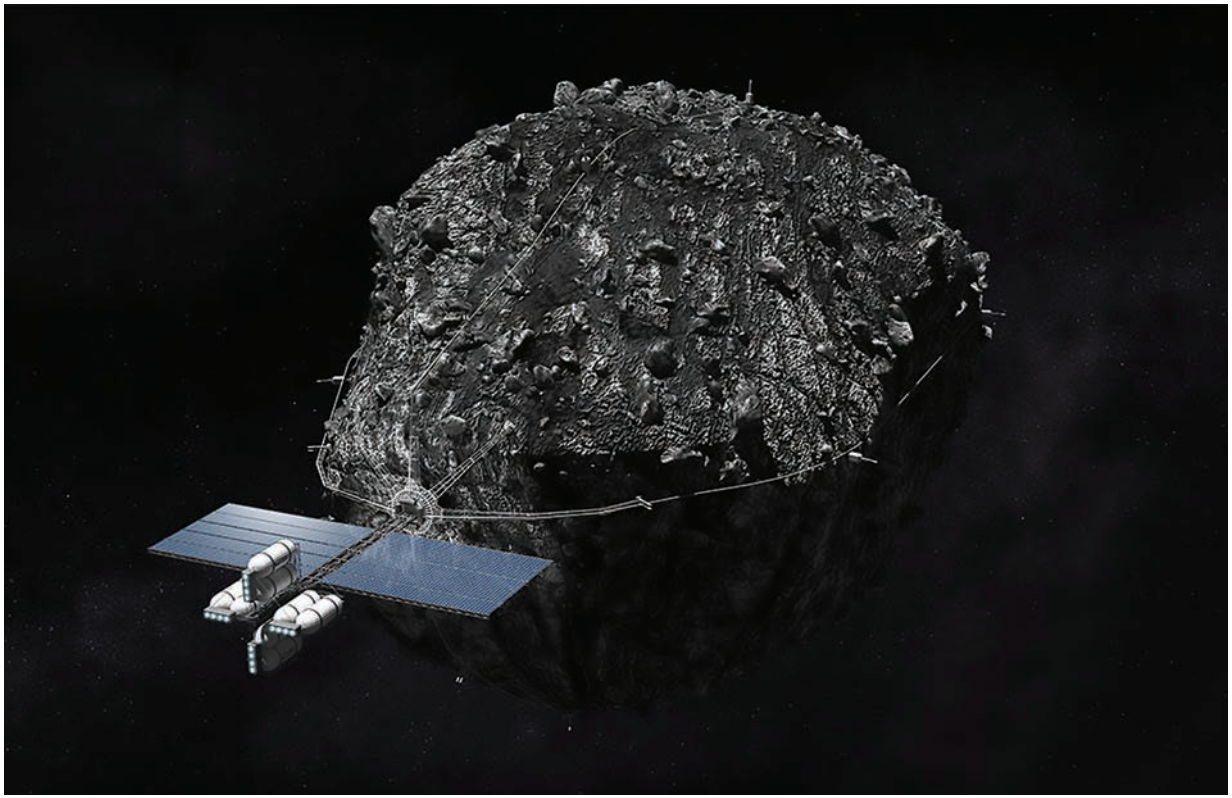
This water could also fuel a space tug lifting a satellite from low-Earth orbit. Launch to geostationary orbit costs several times what it costs to put a payload in low-Earth orbit. But a space tug using asteroid-harvested fuel could pull a satellite from a few hundred miles above Earth to 22,000 miles out relatively cheaply. "That's a viable business for someone," Covey says. "We want someone else to build the tug, and we'll provide the fuel."

That said, the company is working on other technology that could help enable such a tug, such as thrusters that derive their fuel from water, a spacecraft designed to launch from low-Earth orbit into deep space, and aerobrakes for return to Earth orbit.

Beyond water, DSI also wants to eventually use elements harvested from asteroids to manufacture parts in space. "If we could build all the heavy, dumb parts of a satellite in space and just send up the expensive, high-tech electronics from Earth, there would be a big market for that," Covey says, adding that solar panel cells built in space would find an even larger customer base.

And for NASA, DSI imagines its technology extending deep-space research missions that could hop from one asteroid to the next, continually refueling.

But all these ambitions hinge on basic research, some of which depends on the same crust and dirt NASA needed for planning. "To test our own excavation technology, we need asteroid simulants ourselves," Covey says. "It's great that our goals have matched enough with NASA's needs that we could help NASA while helping ourselves and a few others along the way." ❖



DSI ultimately wants to set up asteroid mining operations with spacecraft like this harvester concept. Any machinery bound for an asteroid, though, first needs to be tested in asteroid simulant to see how it will perform.

Vibration Isolator Steadies Optics for Telescopes

NASA Technology

Anybody who has ever tried to hold a camera steady for a long exposure in low light knows exactly what inevitably happens: the camera shakes, and the image blurs. The same can happen with images from telescopes or any other long-range image. In fact, for some very sensitive optics, even ordinary ground vibrations can be enough to throw off the results.

That's why, explains Serge Dubovitsky, instrument system engineer at the Jet Propulsion Laboratory (JPL), NASA often needs a tool called a vibration isolator. These work in a few different ways but essentially create a more stable platform where external vibrations won't interfere with sensitive measurements.

Dubovitsky often works on optics, including systems of mirrors for observational missions like telescopes. The mirrors reflect light in different wavelengths, concentrating it into an image that can be analyzed by other instruments. But before these optics are installed, they have to be tested to ensure they perform as intended.

Scientists hope to use the James Webb Space Telescope to peer deeper into the universe than ever before. To ensure the instruments get crisp images out in space, Webb has undergone months and months of tests, some of which required a "vibration isolator" to hold it extremely steady.

"For optics that operate in roughly visible wavelengths," says Dubovitsky, "any motion on the scale of one micron [that is, one-millionth of a meter], or in some cases even much less than that, disturbs the image quality."

Optics testing is also often done in a vacuum, with ramifications for vibration isolators. "Vacuum is important in verifying optics, because air interferes with light. If you are aiming at space applications, on the ground you need vacuum," Dubovitsky explains. Even when working with optics that will remain on the ground, a vacuum can be helpful for testing.

Vacuum creates its own challenges, though, especially for vibration isolators, which often use air to make the platform "float" and tend to include hoses and bladders made of rubber, which can outgas or leak, releasing lightweight molecules that could interfere with the vacuum. Air systems also have to be able to vent exhaust gases without compromising the vacuum. Other systems that use electricity risk overheating, because there is no airflow to help dissipate heat.

Faced with a recent project that required an isolator for testing space-ready optics, which requires a fairly high degree of vacuum compared to typical industry standards, JPL turned to a company called Minus K Technology.

Technology Transfer

NASA has bought several vibration isolators from Minus K over the years—including a system for the James Webb Space Telescope of six isolators, specially built to hold up to 10,000 pounds each. That's a larger capacity than Minus K had ever built before, and, the company believes, the largest-capacity vibration isolator anywhere for this type of application

"Six of our isolators are now on top of a chamber at Johnson Space Center supporting that project," says engi-

> When building chips and measuring chips, they need to have as close to no vibration as possible."
>
> — Erik Runge, Minus K Technologies

neering director Erik Runge, adding that "now that we have the design, we could adapt it for other customers too." He says there has already been interest from customers.

And although Minus K has a good deal of experience building vibration isolators for vacuum, Runge says the JPL project also required innovation. "Even if you have someone that needs a vacuum system," he notes, "there are different levels of vacuum. Some have a very slight vacuum, some have a very hard vacuum. There are different requirements for materials that can be used, types of coatings that are OK, and so on. We learned about what special requirements were needed at high vacuum levels."

Among other tweaks, he explains, the company had to test special greases and parts to find what would work best in a hard vacuum and not outgas. "As a result of some of the things we've learned, we can make all of our vacuum-compatible isolators to work at a higher level of vacuum, when needed," Runge says.

Benefits

Part of the reason Minus K's isolators work so well in vacuums is because they are designed differently than many other devices, Runge explains. "Our isolators use no air and no electricity. They are happy as can be in a vacuum."

The isolators work through negative stiffness mechanisms, essentially mounting the platform on a network of springs or flexures "loaded in such a way that we can control the net stiffness of an entire system," Runge says. "If you can control the stiffness, you have direct control of the resonant frequency of the system, and the resonant frequency of the system is what determines the isolation performance."

To visualize how this works, he says, imagine a rubber band stretched with a heavy weight attached. If you shake the rubber band up and down slowly, the weight will move at about the same rate as your hand; move it at exactly the right speed, and you'll hit the resonant frequency, where a small input amplifies in a recurring cycle. But if you shake the rubber band faster than that, the weight will remain steady. "You're going to see your hand moving, but the weight won't move," Runge says.

For a project with the Jet Propulsion Laboratory, Minus K Technology built a vibration isolator that worked well in a hard vacuum. The company now sells similar models to other customers, including to run quality control testing on silicon chips.

Minus K's isolators are able to maintain vertical isolation with those springs and flexures, and they achieve isolation horizontally through a set of columns. "You can kind of think of them as inverted pendulumns," he says. "The more mass you put on them, the lower the resonant frequency will be, until at some point there's too much weight and they won't be able to restore themselves. By keeping the weight close to that upper limit, we can adjust the resonant frequency horizontally."

Runge says Minus K isolators are used to steady electron microscopes, optical microscopes, and other scientific instruments, but the vacuum-compatible isolators are also used to assist quality control in manufacturing semiconductors. "When building chips and measuring chips, they need to have as close to no vibration as possible," he says.

Other companies have bought the vacuum-compatible isolators for optics, he adds, and others have not specified the final purpose, in part because many of the applications are related to defense work. "Vacuum chambers large enough for an isolator tend to be pretty expensive," he notes, which means "not many people have them."

But for customers like NASA, the Department of Defense, and the National Laboratories, Minus K's vacuum-compatible isolators are a great tool, says Dubovitsky, and he expects NASA will continue to call on Minus K for future projects as well. "They have a unique product that provides very clean isolation." ❖

IonCCD Enables Fast, Reliable, Inexpensive Mass Spectrometry

NASA Technology

NASA's Jet Propulsion Laboratory (JPL) has a long history of pioneering the use of the charge-coupled device, or CCD, which it used to build some of the world's first digital cameras.

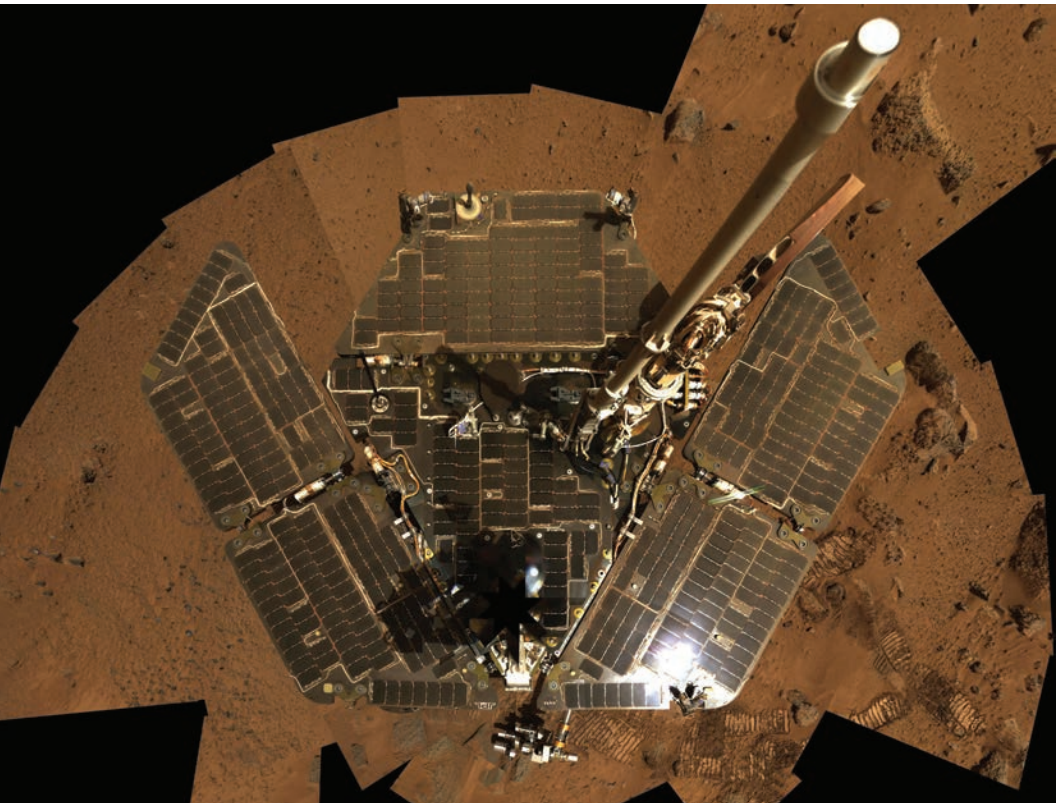
Almost as soon as the technology—an integrated circuit etched onto a silicon semiconductor—was demonstrated in 1970, it became apparent that CCDs might be used for image capture. In 1972, JPL established a program to work on digital imaging, and three years later it captured what is thought to be the first astronomical image made with CCD technology—a view of the south pole of Uranus.

Today, legacy CCD imaging technology has been largely supplanted by complementary metal oxide sensor, or CMOS, imagers, invented at JPL in the mid-1990s. But around the same time, two other JPL engineers identified a way to replace traditional film with CCDs in a totally different application.

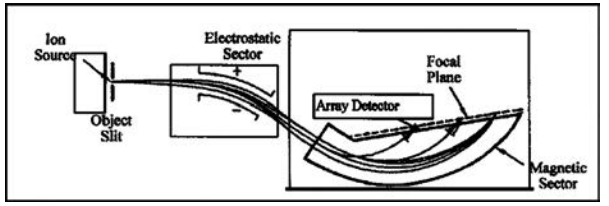
"Mahadeva Sinha was the principal investigator for the miniature Mattauch-Herzog mass spectrometer, starting in the early 1990s," recounts Evan Neidholdt, who worked in the same spectrometry lab Sinha once did. "He and Mark Wadsworth were using a certain kind of detector for the mass spectrometer, and then they identified their desire for this new type, based on CCDs."

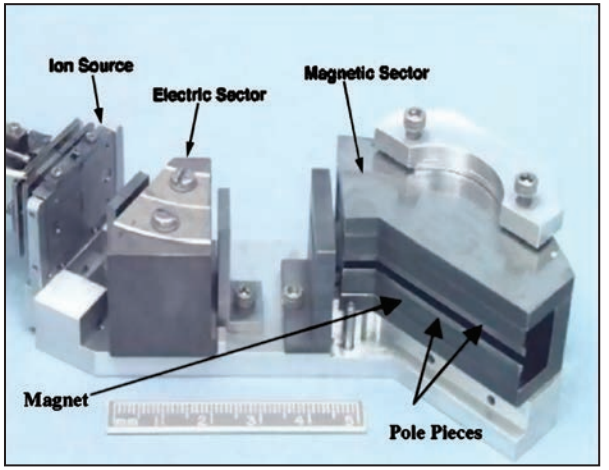
Mass spectrometers identify the ratios of various isotopes in a material sample, which can reveal information about its age, formation, and more. Sinha wanted a small, durable mass spectrometer to enable a lander to determine the age of a comet. Wadsworth was custom-building specialized CCD imagers for the Spirit and Opportunity Mars rovers at the time.

The Mattauch-Herzog configuration, named for the professors who invented it, is a type of sector field mass spectrometer. A sector field mass spectrometer applies electric and/or magnetic fields to ionized sample molecules passing through the device. Different isotopes of a substance



Imagers on the twin Spirit and Opportunity rovers, including the Pancam that took this self-portrait, had to meet rigorous requirements, obliging Jet Propulsion Laboratory (JPL) engineer Mark Wadsworth to custom-build specialized imagers based on charge-coupled device (CCD) arrays. These highly photosensitive, low-power, low-noise, high-speed yet simply designed CCD arrays came in handy when a colleague needed help designing a mass spectrometer with a CCD array for a focal plane, although they required more modifications.





In the Mattauch-Herzog mass spectrometer configuration, ions are deflected first by an electrical field and then by a magnetic field to sort them by weight before they strike a focal plane that detects all the ions simultaneously. The CCD-based prototype created at JPL accomplished this within a small, rugged, inexpensive, energy-efficient device.

have different masses, and the magnetic or electric field deflects lighter ones more than heavier molecules. A detector at the end of the device senses the particles that hit it by their electric charge, which is why they've been ionized.

Many sector field mass spectrometers have only a single detector to count one isotope at a time. A Mattauch-Herzog mass spectrometer, on the other hand, deflects all isotopes of interest onto a broader focal plane and counts them all at once, calculating their molecular weight by where they hit the plane.

Sinha had helped develop a mass spectrometer that used a CCD array in its focal plane—much easier to use than predecessors that had camera film in their focal planes—but it was complex and required high voltage. It essentially converted ions to electrons to photons, then back to electrons and finally to a digital signal, and every conversion added noise to the signal and blurred the focus of the ion beam.

Working together, Wadsworth and Sinha came up with a simpler design. By coating each silicon pixel with a tough, conductive coating of metal oxide, they could make the CCD blind to light but able to directly receive a charge from an ion striking the sensor. The device would be enabled by some of the refined circuitry and strong separation between pixels that Wadsworth had developed for Mars rover cameras.

But they didn't have the funding to build it. That's when a small start-up company called Intelligent Ion got involved.

Technology Transfer

"The founder of the start-up company had a similar technology developed, but reading the detected signal and processing the information turned out to be challenging, and he was looking for something else. That's how he found Mahadeva Sinha and Mark Wadsworth at JPL," says Gottfried Kibelka, who was a scientist at Intelligent Ion at the time. "In the end, it was much cheaper for JPL to call us and ask, 'Can you build this for us? Can you sell us one?' It was a win-win situation at that point."

Intelligent Ion licensed the intellectual property from the California Institute of Technology, which manages JPL, and worked directly with Wadsworth to build the first prototypes on its own budget. "And without Sinha's help and input, it would not have worked, so this really was a very fruitful cooperation between all involved," Kibelka adds.

"In October 2003 we saw the first ions. I was there."

Following testing and validation, the company built and sold a handful of mass spectrometers based on the CCD focal plane detector, which it named IonCCD. A few years later, OI Analytical, based in College Station, Texas, purchased the company and launched the first official commercial line based on the technology.

"OI Analytical started selling mass spectrometers, having this chip technology, and after a while realized that the IonCCD in itself is a product many researchers would like to have in their portfolio in mass spectrometer development and research," says Kibelka, who still manages the technology. "Now we are talking to some other companies that want to use it as their standard detector in commercially available mass spectrometers."

In 2011, around the time OI became a subsidiary of the water technology company Xylem, it stopped developing mass spectrometers and started offering IonCCD as a stand-alone product. That year, the company also packaged it with a camera controller and power supply to create the first series of the IDS 2030 Charged Particle Detector.

Benefits

Besides the benefits afforded by any Mattauch-Herzog mass spectrometer—the simultaneous counting of all isotopes of interest on a single sensor for fast, accurate results—IonCCD is also small, inexpensive, and rugged and requires little power.

"The biggest selling point is that it doesn't need high voltage," Kibelka says. Other similar devices require about 1,000 volts, while the IDS 2030 runs on 24 volts. This is in part because it doesn't require particles to be accelerated and can operate at normal atmospheric pressures. Most other mass spectrometers can only operate at low internal pressures, necessitating the use of costly vacuum pumps.

Not all mass spectrometry applications need a detector array, but a number of researchers and mass spectrometer manufacturers are purchasing the technology for applications that can benefit from it, says Kibelka. These include analytical chemists, the pharmaceutical industry, and the military's threat detection applications. The IDS 2030 has customers in spatially resolving ion-mobility spectrometry, often used for drug and explosive detection.

OI Analytical's IDS 2030 Charged Particle Detector is based directly on technology licensed from JPL for a CCD-based mass spectrometer. The small, affordable, robust, and efficient device offers quick, accurate results and has found applications among analytical chemists, the pharmaceutical industry, military threat detection, and more.

But researchers are also using the technology outside of mass spectrometers for applications such as ion beam experimentation and solar wind detection.

The company recently released a next-generation version of the IDS 2030, which was improved through a partnership with Kennedy Space Center to outfit the lunar rover Resource Prospector with an IonCCD-enabled mass spectrometer that will help it look for water on the Moon.

As a part of the project, the company merged the hardware from two traditional printed circuit boards onto a ceramic board to make the IDS 2030 smaller and minimize volatile compounds that could evaporate from the circuit board. "There was good technology advancement on the IonCCD, making it the most advanced of its kind," says Neidholdt. ❖

Beryllium Blazes New Trail for Telescopes

A radiographer at Brush Wellman, now Materion Corporation, prepares a beryllium mirror blank for an X-ray radiograph. The slab was later machined down to create a mirror for the James Webb Space Telescope.

NASA Technology

The James Webb Space Telescope is a mechanical eye so penetrating it will look back in time to the dawn of the universe. And its cornea of lightweight, durable mirrors is largely to thank for all we'll learn from the images it sends back to Earth.

The telescope, scheduled to launch in 2021, will peer into space from almost a million miles from Earth, orbiting a Lagrange point, where the combination of the sun's and Earth's gravity creates a relatively stable parking spot. For observations, it will rely on a set of gold-coated mirrors capable of handling punishingly cold temperatures to collect radiation emitted by the earliest stars.

NASA couldn't use glass for Webb's mirror as it did for the Hubble Space Telescope's mirror, which operates at room temperature. Detection of faint infrared light—actually heat emitted billions of years ago—requires the near absence of heat in its instruments. The Agency needed a lightweight, durable material that would maintain a stable shape at temperatures approaching absolute zero and that could withstand the hazardous journey into space.

"We had to pick a material we knew we could make at room temperature, and we knew it would change shape as it went cold but would do so in a predictable and consistent way every time," recalls Paul Geithner, a deputy project manager for Webb based at Goddard Space Flight Center. "Beryllium is a really good material for that. It's really stiff and, once it gets below about -300 °F, it basically stops shrinking."

This is important because Webb, insulated by a sun shield, will operate at about 30 K (-406 °F) and only experience temperature swings of plus or minus 30 K, never reaching a temperature that would cause it to expand.

Beryllium also has a higher stiffness-to-mass ratio than other materials, "which wasn't a selection criteria but is an advantage, as it means you get a lighter mirror, better able to withstand the high vibro-acoustic levels during takeoff," notes Lee Feinberg, the telescope manager for Webb at Goddard.

When NASA was planning the telescope, Mayfield Heights, Ohio-based Brush Wellman, now known as Materion Corporation, was one of the top beryllium-producing companies in the world. The company owns a major bertrandite mine in Utah and had perfected the process of treating beryllium and crafting it into the kind

The James Webb Space Telescope mirrors are removed from Marshall Space Flight Center's X-Ray and Cryogenic Facility following testing. The mirrors are made of beryllium in part because the material will deform predictably when taken from room temperature to near absolute zero.

of light but sturdy mirrors NASA needed for Webb. After a bidding process, Materion won the contract to build the mirrors.

Technology Transfer

The mirrors began as a powder. But unlike other beryllium powders, which are made up of block-like grains, Materion's is gas atomized to be spherical, allowing for a uniformity in its properties in all directions, adding to the mirrors' quality and durability, explains Jason Clune, manager of applications and business development for Materion Beryllium and Composites. To create the mirrors, the powder is poured into a "large pressure vessel that reaches really high pressures and temperatures. Under those conditions, the powder is pressed in all different directions at the same time, fusing it together." It's a process known as hot isostatic pressing (HIP).

This produces mirror blanks with a homogeneous microstructure, resulting in repeatable and predictable shape change—just the thing that was required for Webb.

The mirror blanks Materion created weighed just under 600 pounds, but other NASA contractors subsequently machined them down to roughly 46 pounds. Together, the 18 individual mirrors make up the massive 21-foot, 4-inch primary mirror.

As work continued, Materion won contracts to make additional components, including the secondary and tertiary mirrors, along with other features that were originally planned to be made from carbon composites, Clune says.

"For us, it was the first time that we had to manufacture the spherical powder in very large quantities," he says. "That was a challenge, but we were highly successful at doing it."

Materion won several awards for the HIP tools it created to make the mirrors, which adapted the process to ensure the mirror blanks wouldn't fold or otherwise deform permanently when cycled through cryogenic temperatures.

The Webb mirrors "are some of the most precise large components manufactured in the United States," Clune adds. NASA received the mirrors ahead of schedule, which Clune thinks might have helped keep the project alive amid shifting budget priorities.

Benefits

As a result of the Webb work, Materion developed an industrial standard for the gas-atomized spherical beryllium powder. "We developed a quality production document just for these mirrors, and after this project, we moved our entire system to what's called an aerospace requirement, AS-9100," Clune says, referring to official standards of the Society of Automotive Engineers and the European Association of Aerospace Industries. "We transformed ourselves into an aerospace-certified business, so now all of our materials are made that way. Anyone can come to us and get the same high-quality product. The requirements are pretty stringent and, as a result, the products are consistent."

Beryllium is used in military satellites and other Department of Defense equipment, but Robert Michel, manager of market development for Materion Beryllium and Composites, says it's nice to have the NASA work in the company's portfolio of successes. Materion has also provided components for both of the Agency's Ice, Cloud, and Land Elevation Satellites, as well as the Cloud-Aerosol Transport System on the International Space Station.

Back on land, beryllium is used in most X-ray and mammogram machines, as the material is "almost transparent to X-rays, so technicians can use a much lower dose of radiation on their patients," Michel says.

Both Michel and Clune anticipate Materion and beryllium's profile will grow as other applications are embraced. "There are already talks about the next James Webb and what materials will be used," Clune says. "We want to leverage what we did in the past to work on the next-generation program. That's one of the strengths of our company and our work with NASA."

NASA has been impressed with Materion's work. "To my knowledge, there's no other place in the country that could've made beryllium of this quality," Feinberg says. "The option of making beryllium mirrors would not have been very feasible" without the company. ❖

Phase-Change Coating Absorbs Heat from Rockets, Pipes, Beer

NASA Technology

Most people enjoy an icy drink on a hot summer day without thinking about the physics happening inside the glass. But the phase-change reaction—in this case, as the ice absorbs heat from the drink and melts—is a powerful one. It's one NASA has harnessed for far more extreme environments, and now a coating the Agency created to take advantage of that same reaction could turn up on passenger planes—or be the key to an ice-free cooler.

The magic of phase changes, notes Marshall Space Flight Center materials scientist Raj Kaul, is that the temperature holds steady at exactly the point of transition. "If you freeze a thermometer in a block of ice and start heating it," he explains, "the temperature will stay at 32 °F, even in the already melted part. Only once the ice is completely melted will the water start raising its temperature."

For water, the melting/freezing point is 32 °F, but NASA has developed a suite of materials with different melting points. Initially, the plan was to use these materials inside spacesuits, which can get uncomfortably hot as body heat accumulates inside the sealed garments.

In the early 2000s, however, Kaul began researching a way to use phase-change materials on the outside of spacecraft, in particular the Shuttle. The solid rocket boosters were protected by a material called MCC-1 (for Marshall Convergent Coating), which was "basically a mixture of cork and epoxy," Kaul says. "The cork will burn, and that burning process also removes the heat. Plus, it ablates—the layer will just come off, so new material will be exposed, and then go through that again."

Because the coating was designed to burn off, however, there remained a danger that the process would cause damage. So Kaul was working on a new idea for a protective coating that would not ablate and would still maintain a safe temperature underneath.

He turned to NASA's previous work with phase-change materials and decided to use them in this new context. The key innovation was incorporating the material into a coating that could be applied like paint, Kaul says, which required determining the right ratio of phase-change material to coating to get the best results, as well as the most effective binders and other ingredients.

Ultimately, Kaul developed a material that "is encapsulated in a plastic. When it sees heat, it absorbs that heat to go through the solid to liquid phase," he explains. "As a result, the heat cannot go through to the substrate—it all goes through this phase-transformation process." Thanks to the phase change material, the solid rocket booster wouldn't melt from the extreme heat of launch. And thanks to the epoxy binding the coating to itself and the rocket, the phase-change material wouldn't drip off when it melted.

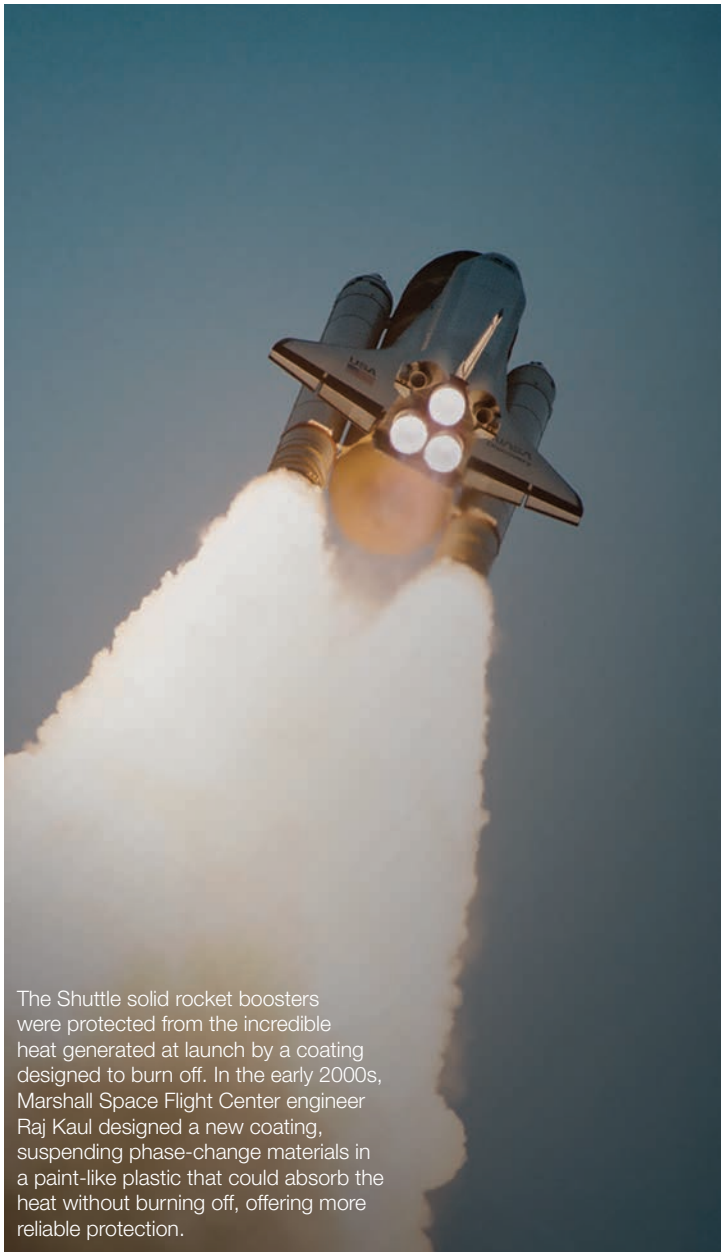
This new thermal-management coating was more reliable than the previous ablative coating, Kaul says, and because it didn't burn off, it was effective with a much thinner layer. "Another advantage," he adds, is that "it could be reused. After it goes through transformation, when it starts cooling, the material inside will go back to solid so then you can reuse the coating."

After extensive testing by NASA, the material was approved for use on spacecraft. Unfortunately, by the time that was completed, the Shuttle program had been discontinued. However, the coating continues to be available for future spacecraft, and there has even been interest from commercial aerospace companies, says Kaul.

Technology Transfer

Aerospace is hardly the only arena where such a coating might prove useful, so NASA advertised the patent for commercial licensing—and it was quickly snapped up by entrepreneur Chris Bilec.

The Army veteran was pursuing a master of science in technology commercialization at the University of Texas at Austin McCombs School of Business, which introduced him to NASA's Technology Transfer and Patent Licensing programs. Bilec was excited about the opportunity to start a business with proven technology, but he wasn't sure which



The Shuttle solid rocket boosters were protected from the incredible heat generated at launch by a coating designed to burn off. In the early 2000s, Marshall Space Flight Center engineer Raj Kaul designed a new coating, suspending phase-change materials in a paint-like plastic that could absorb the heat without burning off, offering more reliable protection.

> “He asked me, ‘Can this paint insulate my airplanes?’ … And that was how the whole process began.”
>
> — Chris Bilec, PrimeBilec

of the many patents he should start with, so he turned for advice to a hockey teammate with a successful track record in business and aviation.

That friend homed in on the thermal-management coating. “He asked me, ‘Can this paint insulate my airplanes?’ So that was the fundamental question. I said, ‘I don’t know, I’ll go find out.’ And that was how the whole process began.”

Bilec started a company, Austin-based PrimeBilec, to acquire an exclusive license for the patent, and Marshall’s Technology Transfer Office connected him with Kaul so the inventor could answer questions and share ideas for the material. Kaul suggested the coating had potential for exterior house paint or as a coating on the roof, “so that in the daytime, it will absorb heat, and in the nighttime, it will release that heat and go through the cycle. It would make the house more energy-efficient.”

Bilec struggled with creating a residential paint that fit within the bounds of the patent, he says, but he already had other ideas for commercial applications, including the one suggested by his hockey teammate, to insulate airplanes.

Benefits

For airplanes, Bilec explains, the idea would be to coat the back end of the plane, to prevent heat damage from the jet engines. “For aviation, we’re setting the phase-change material at 24° C,” or approximately room temperature, Bilec says, because that is the temperature the airline wants to maintain in the cabin for passenger comfort. By using that temperature, in addition to protecting the exterior from heat damage, the coating will also absorb heat that would raise the internal temperature.

After licensing the patent for the phase-change coating from Marshall, entrepreneur Chris Bilec founded a company, PrimeBilec, and is working on a number of products, including an iceless cooler.

Bilec has sent samples to aeronautic coatings manufacturer EnvirosafePaint Company for testing, and his company hopes to begin production in 2019.

In the meantime, he has also seen interest from a company that makes heat traps for Veterans Affairs hospitals. “They monitor the heat coming off the pipes in the hospital,” Bilec says. “When these pipes get too hot, they overheat and burn their sensors. Our products will extend the lifespan of their heat traps.”

The heat trap company now plans to include the coating when it bids for contracts, Bilec says, “because it will differentiate their contract from their competitors.”

Bilec has another idea in development as well, to create an “iceless cooler” along with smaller containers for lunches and leftovers. “The idea came to me when I was watching some people buy beer and saying they didn’t have enough room for the ice. I thought, ‘I’ve got the perfect solution.’”

For the containers, PrimeBilec embeds the phase-chase material in food-grade polyester to coat the container—the polyester is already FDA approved for products that touch food, Bilec notes. With the coating, the food—or beer—inside the container “will stay colder for about two to four hours longer,” he says, depending on the temperature outside. ❖

Spinoffs of Tomorrow

Inspired? We hope so, because we've got hundreds of innovations in our portfolio ready to become the next generation of spinoffs. NASA relies on American businesses and entrepreneurs to ensure its inventions see the widest possible use on Earth. This section features 20 technologies available for licensing 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

Multispectral Imaging, Detection, and Active Reflectance (MiDAR)

A novel next-generation remote sensing instrument

Ames Research Center has developed a novel next-generation remote sensing instrument with advanced scientific capabilities for multispectral imaging, detection, and active reflectance (MiDAR). The MiDAR transmitter and receiver demonstrate a novel and cost-effective solution for simultaneous high-frame-rate, high-signal-to-noise ratio multispectral imaging—with potential for hyperspectral imaging. The technology can transmit high-bandwidth one-way communication while imaging.

The use of algorithms enables the creation of three-dimensional multispectral scenes and high-resolution underwater imagery, ideal for use in future scientific airborne field campaigns.

Benefits

- Cost-effective, high-resolution imaging
- Not limited by ambient light
- Can be used underwater
- Transmits high-bandwidth one-way communication while imaging

Applications

- Remote sensing from aircraft, robotic explorers, and spacecraft
- Noninvasive medical imaging and diagnosis
- Semiconductor imaging and structural analysis
- Simultaneous optical communications

Affordable Vehicle Avionics

Common, modular avionics system for nano-launchers, offering affordable access to space

Small satellites, or smallsats, are becoming ever more capable of performing valuable missions for both government and commercial customers. However, currently these satellites can only be launched affordably as secondary payloads, which makes it difficult for smallsat missions to launch when needed and reach their desired orbit with acceptable risk.

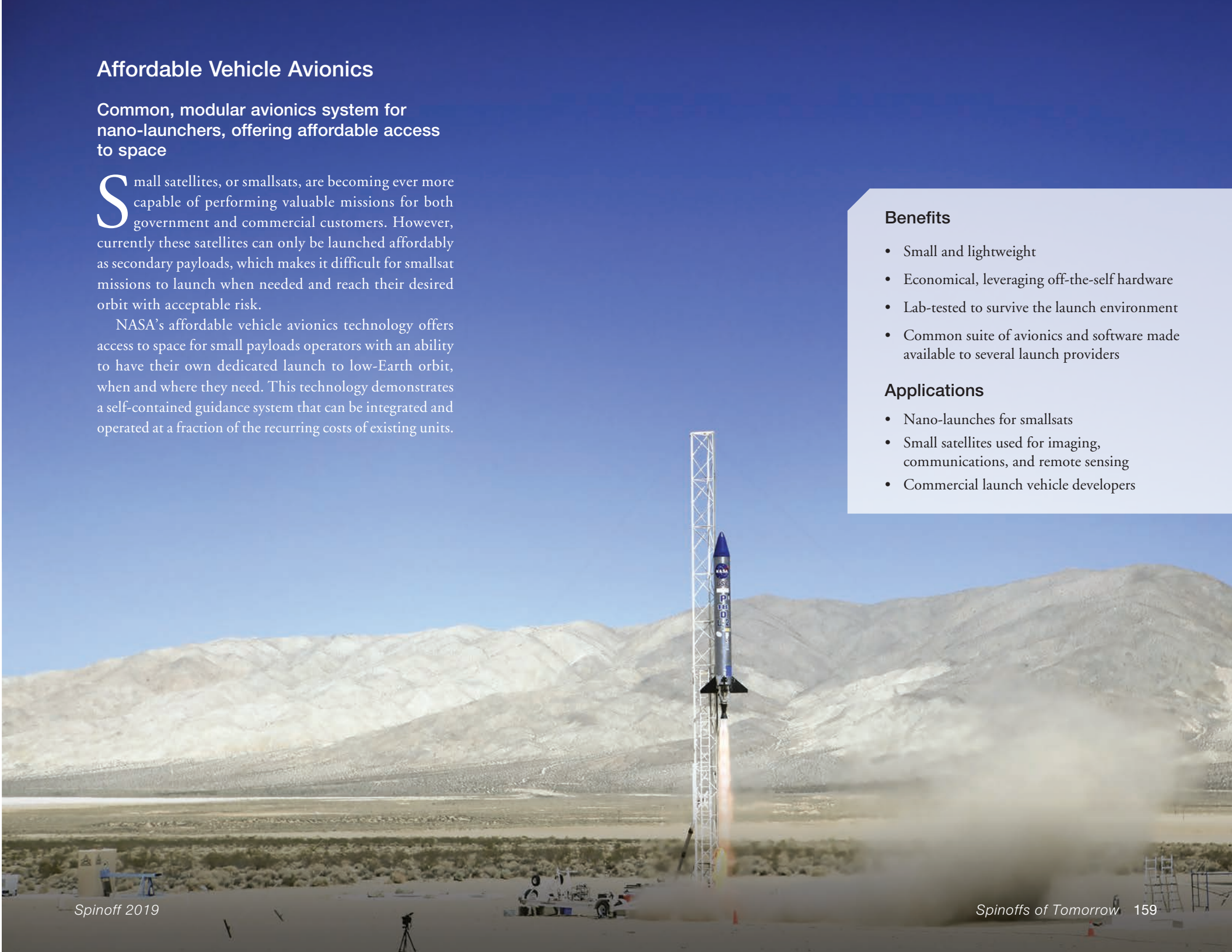
NASA's affordable vehicle avionics technology offers access to space for small payloads operators with an ability to have their own dedicated launch to low-Earth orbit, when and where they need. This technology demonstrates a self-contained guidance system that can be integrated and operated at a fraction of the recurring costs of existing units.

Benefits

- Small and lightweight
- Economical, leveraging off-the-self hardware
- Lab-tested to survive the launch environment
- Common suite of avionics and software made available to several launch providers

Applications

- Nano-launches for smallsats
- Small satellites used for imaging, communications, and remote sensing
- Commercial launch vehicle developers



Armstrong

Wireless Sensor Gateway

Wireless platform reduces cable weight, speeds up flight testing timelines

Wireless sensors are attractive because they do not add cable weight and take less time to install than wired sensors—which makes it easier and faster to take advantage of the latest upgrades in wireless sensor technology. Engineers at Armstrong Flight Research Center have developed a wireless gateway platform that allows aircraft test engineers to integrate emerging wireless sensors into pre-existing hardwired flight-test sensor networks.

The gateway uses a software-defined radio to control the flow of information between dissimilar wireless devices and a vehicle's avionics. This single universal access point time-stamps sensor data, synchronizes the information between new wireless and legacy wireless sensors and hardware, and feeds the information to storage devices.

Benefits

- Easy to implement and integrate updated sensors
- Reduced weight frees up payload capacity
- Saves time and reduces costs while preserving investment in legacy networks
- Expands sensor placement options
- Software updates can accommodate future wireless sensor technology

Applications

- Aeronautic and automotive vehicle testing
- Monitoring the health of systems in long-term storage
- "Internet of things" for industry

Propeller Blade Shape

A new twist makes rotating machinery more efficient and quieter

A new shape for propeller blades dramatically increases their efficiency while reducing noise. Based on improvements achieved through a new wing design known as PRANDTL-D, this innovative propeller incorporates a nonlinear twist to the propeller blade. The twist moves the load inward and dissipates the tip vortex over a wider area, minimizing its effect on drag.

The changes result in a more than 15 percent improvement in propulsive efficiency and significantly reduced noise, which enables lower power consumption for propeller aircraft.

Benefits

- Reduces power consumption while producing the same thrust
- Cuts fuel costs
- Lowers noise levels dramatically
- Can be coupled with laminar flow or supercritical airfoils

Applications

- Aircraft and marine propellers
- Industrial fans
- Axial compressors in air separation plants and blast furnaces
- Power turbines, such as those used to generate nuclear, hydroelectric, and wind power

Glenn

Superelastic Tire

A viable alternative to the pneumatic tire

The Superelastic Tire, developed for future Mars missions, is a viable alternative to pneumatic tires here on Earth. This technology represents the latest evolution of the Spring Tire, which was invented by Glenn Research Center and Goodyear and inspired by the Apollo lunar tires.

Instead of rubber or other elastic materials, the tire uses shape-memory alloys as load-bearing components. These shape-memory alloys can undergo significant reversible strain (up to 10 percent), enabling the tire to withstand an order of magnitude greater deformation without being damaged compared to other nonpneumatic tires.

The Superelastic Tire offers traction equal or superior to conventional pneumatic tires and eliminates the possibility of puncture failures, thereby improving automobile safety. This tire design also eliminates the need for an inner frame, which both simplifies and lightens the tire-wheel assembly.

Benefits

- No risk of puncture failure
- Strong, lightweight, and versatile
- High traction
- No need for air

Applications

- All-terrain vehicles
- Military and aircraft tires
- Construction and heavy equipment
- Consumer automobiles
- Agricultural vehicles

Secure Optical Quantum Communications

Novel production and use of entangled-photon pairs enhances quantum communications capability

Quantum communications systems rely on photon pairs for highly secure communications. But prior systems to produce those pairs were too large to be portable. Glenn Research Center has developed a method of using entangled-photon pairs approximately a million times more efficiently than conventional sources, in a system that is small and light enough to be portable.

Because this method transmits digital information by detecting small temporal shifts between entangled photons, it has a superior signal-to-noise ratio, which facilitates highly secure communications in very noisy free space and fiber-optic environments.

Originally developed for microrobots used in space exploration, this technology represents a breakthrough for a wide variety of terrestrial, scientific, military, and other field-deployable applications including fiber-optic and satellite communications.

Benefits

- Highly secure
- Transmits information at very low power levels
- Can be used in free space and with fiber-optic cables
- Works with low-cost, off-the-shelf optical coatings and components
- Compact and transportable

Applications

- Satellite communications
- Defense technologies
- Airborne communications
- Surveillance systems
- Secure line-of-sight optical communication links

Goddard

Miniaturized High-Speed Modulated X-Ray Source

Small, low-cost option for high-speed modulation of X-ray intensity

This miniaturized X-ray source can be modulated in intensity from completely off to full intensity in sub-nanosecond timescales. The high-speed switching capability and miniature size make possible many new technologies, including X-ray-based communication, compact time-resolved X-ray diffraction, novel X-ray fluorescence instruments, low-dose medical X-rays, and more.

The device is more compact, rugged, and power-efficient than standard X-ray sources. It can be manufactured using commercially available components and 3D-printed housing. Unlike traditional X-ray sources, this technology does not require a filament or vacuum and cooling systems. Most importantly, rapid and arbitrary modulation allows the use of X-rays in the time domain, a new dimension to X-ray applications.

Benefits

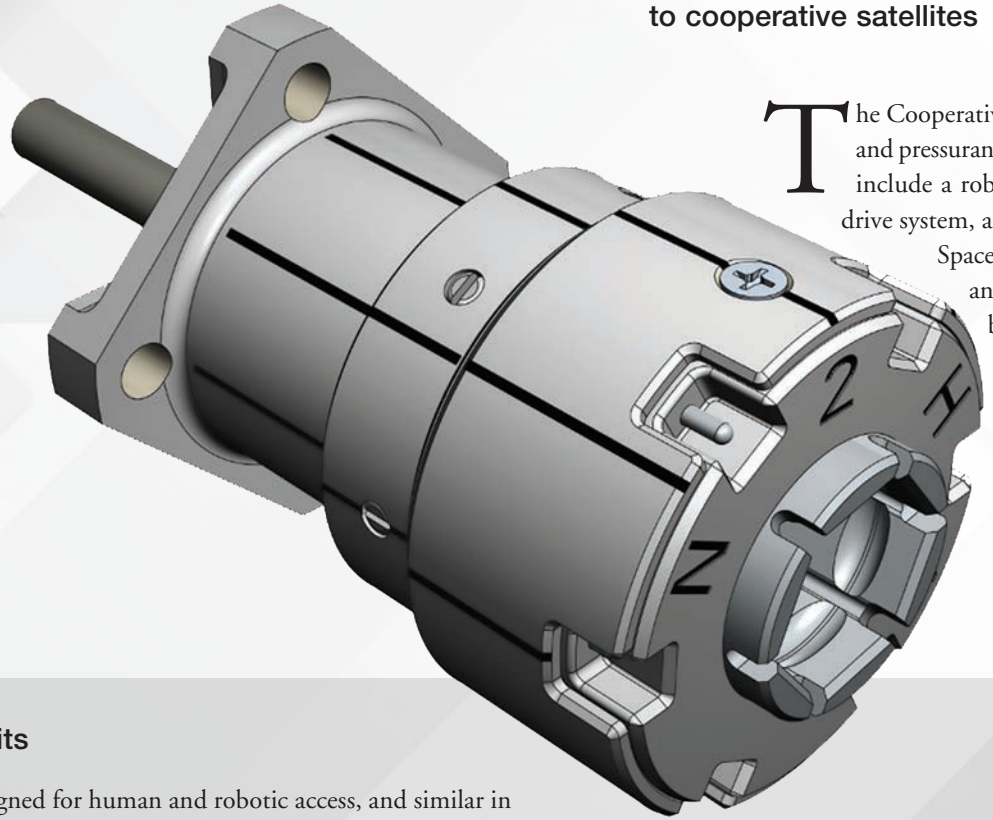
- Arbitrary modulation up to 100 kiloelectron volts within a nanosecond
- Small size, rugged
- Low cost to produce
- Energy-efficient
- Secure, fast, and long-range
- Works with hypersonic aircraft in atmosphere

Applications

- Secure, power-efficient X-ray-based communications
- In-flight calibration of X-ray detectors
- Compact, time-resolved X-ray diffraction and fluorescence
- Precise and low-dose medical X-ray imaging
- Chemical and material analysis

Cooperative Service Valve for In-Orbit Satellite Fueling

Telerobotic-operated resupplies of media, such as propellants and pressurant, to cooperative satellites



The Cooperative Service Valve (CSV) facilitates the resupply of media, such as propellants and pressurants, to satellites, replacing a standard spacecraft fill-and-drain valve. Advantages include a robotic interface, three individually actuated seals, a self-contained anti-back drive system, and built-in thermal isolation.

Spacecraft outfitted with the CSV can be serviced in orbit with less risk, lower costs, and a much higher chance of success. The tools used to interface with the CSV, both on the ground and in space, were also designed and tested by NASA.

The CSV architecture and approach can be extended to all space assets that could potentially be fueled or refueled on and off the ground, including crew vehicles, planetary rovers, and space habitats.

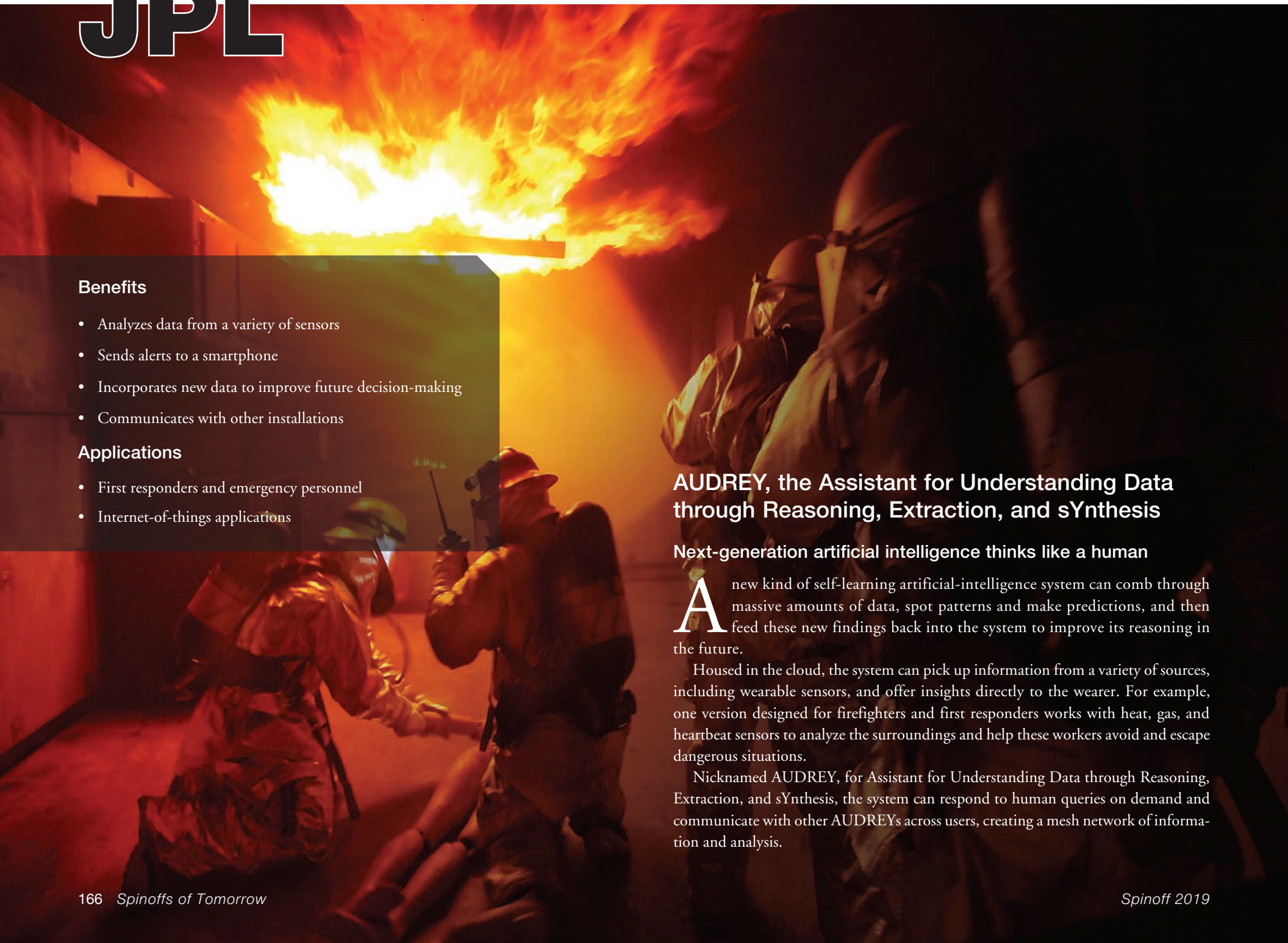
Benefits

- Designed for human and robotic access, and similar in size to standard valves
- Requires no caps or wires
- Inherent thermal isolation
- Compatible with common spacecraft propellants and pressurants including xenon
- Self-locking against inadvertent actuation

Applications

- Ground and launch pad fueling
- In-space satellite refueling and repair

JPL



Benefits

- Analyzes data from a variety of sensors
- Sends alerts to a smartphone
- Incorporates new data to improve future decision-making
- Communicates with other installations

Applications

- First responders and emergency personnel
- Internet-of-things applications

AUDREY, the Assistant for Understanding Data through Reasoning, Extraction, and sYnthesis

Next-generation artificial intelligence thinks like a human

A new kind of self-learning artificial-intelligence system can comb through massive amounts of data, spot patterns and make predictions, and then feed these new findings back into the system to improve its reasoning in the future.

Housed in the cloud, the system can pick up information from a variety of sources, including wearable sensors, and offer insights directly to the wearer. For example, one version designed for firefighters and first responders works with heat, gas, and heartbeat sensors to analyze the surroundings and help these workers avoid and escape dangerous situations.

Nicknamed AUDREY, for Assistant for Understanding Data through Reasoning, Extraction, and sYnthesis, the system can respond to human queries on demand and communicate with other AUDREYs across users, creating a mesh network of information and analysis.

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 (RHEAS), 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 models 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

The Jet Propulsion Laboratory (JPL) is a Federally Funded Research and Development Center run under contract for NASA by the California Institute of Technology. If your company is interested in these or other JPL/Caltech technologies, visit http://scienceandtechnology.jpl.nasa.gov/opportunities.

Johnson

Pre-Treatment Solution for Water Recovery

Increase water recovery, prevent mineral scaling, and reduce the volume of brines by half

The Pre-Treatment Solution for Water Recovery technology was developed by Johnson Space Center innovators to increase the amount of potable water recovered from the International Space Station's urine processor assembly system.

Turning wastewater, urine, or seawater into drinking water requires three important steps: pre-treatment, distillation or membrane filtration, and transportation and storage of potable water and brine. This solution is added during the first step, consequently improving the next steps in the process primarily by reducing the formation of solid precipitates. By reducing these precipitates, there is less surface scaling and clogging in the distillation systems and more potable water can be recovered. Also, the solution contains a biocide to prevent the growth of bacteria, thereby increasing storage time and the amount of water recovered.

Benefits

- Simple process
- Increased water recovery rate
- Works for urine, wastewater, and seawater
- Scalable from small- to large-scale operations

Applications

- Desalination plants
- Brackish water treatment
- Mining water treatment
- Urine recycling as a water source
- Water supply for oil and gas exploration and production
- Transportation and storage of concentrated waste product
- Membrane wastewater treatment systems

Battery Management System

Simple, reliable, safe battery management for high-voltage systems

Innovators at Johnson Space Center have developed a simple and reliable circuit that detects a single bad cell within a battery pack of hundreds of cells and can monitor and balance the charge of individual cells in series. The Battery Management System is cost-effective and can enhance safety and extend the life of critical battery systems, including high-voltage lithium-ion batteries that are used in electric vehicles and other next-generation renewable energy applications.

Cell balancing in multi-cell battery strings compensates for weaker cells by equalizing the charge on all the cells in the chain, thus extending battery life. Voltage sensing helps avoid damage from over-voltage that can occur during charging and from under-voltage that can occur through excessive discharging.

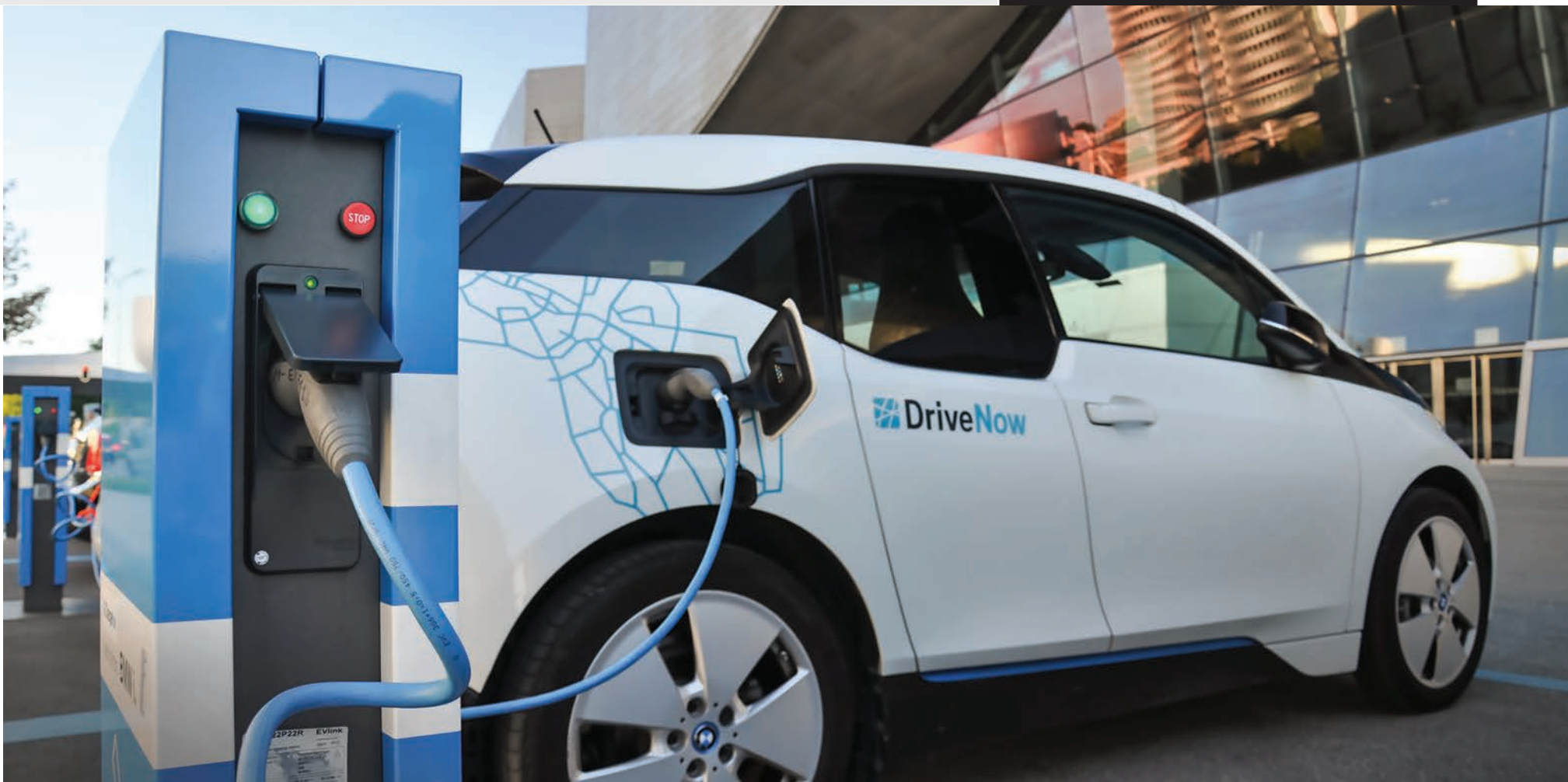
Another benefit: Johnson's Battery Management System uses fewer connections (pins) than competing technologies, which reduces complexity and improves reliability.

Benefits

- Reliable and low-cost
- Lowers risk of thermal runaway
- Extends battery life
- Balances cells by adding charge to individual cells

Applications

- Electric, plug-in hybrid, and hybrid electric vehicles
- Telecommunications backup systems
- Space mission critical battery backup systems



Kennedy

Ammonia Recovery System for Wastewater

Closed-loop system for recovering ammonia from wastewater

This ammonia recovery system for wastewater was developed for potential use to recycle water on the International Space Station. The system uses an affordable media that can reduce ammonia concentrations in wastewater from as high as 100,000 parts per million (ppm) to less than 1 ppm. Following treatment, the media is regenerated for reuse in the system, and ammonia is captured as a by-product.

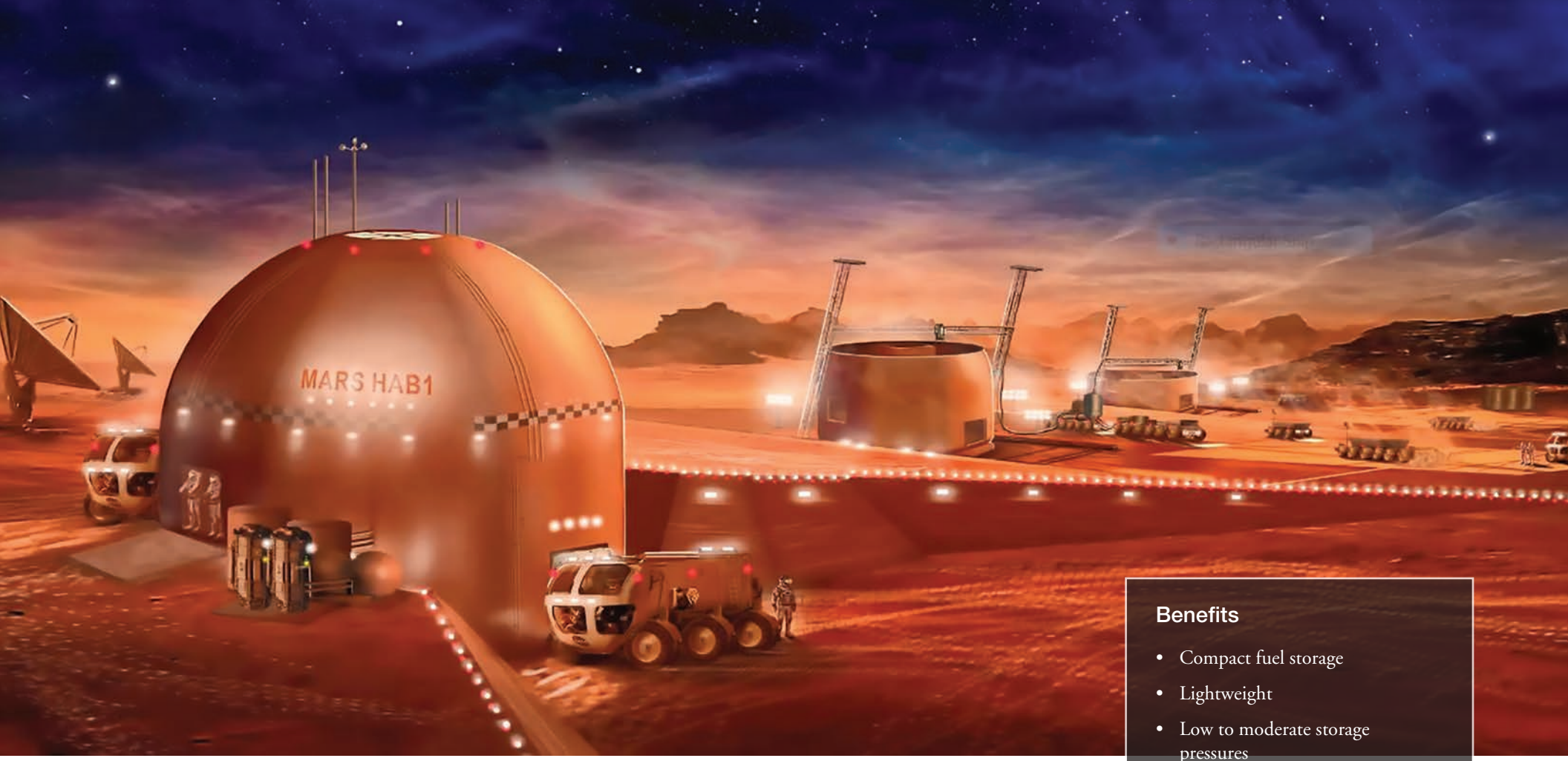
Although the NASA system is being developed for smaller-scale, space-based applications, the technology is scalable for larger industrial and municipal wastewater needs.

Benefits

- High capacity
- Complete removal in just 20–30 minutes
- Low-cost system, media can be reused
- Ammonia can be recycled or sold

Applications

- Agricultural wastewater
- Food processing plants
- Fertilizer and chemical plants
- Textiles (wool)
- Electroplating
- Municipal wastewater



Cryo-Fluid Capacitor

A device for solid-state storage and on-demand distribution of cryogenic fluids

Storage and transfer of fluids such as oxygen, hydrogen, natural gas, nitrogen, and argon is a necessity in many industries. The goal is to store as many fluid molecules as possible in the smallest, most lightweight volume—and to supply those molecules on demand in the end-use application.

Kennedy Space Center has created a cryo-fluid capacitor that capitalizes on the energy storage capacity of liquefied gases and the relative simplicity of high-pressure gas bottles while limiting their drawbacks. By exploiting a unique attribute of nano-porous aerogel, some fluids can be stored at densities on par with liquid, at low to moderate pressure, and then supplied as a gas, on demand, to a point of interest.

Benefits

- Compact fuel storage
- Lightweight
- Low to moderate storage pressures
- Fast charge-up times
- On-demand, fast discharges

Applications

- Spacecraft
- Space habitats
- Aircraft and transportation
- Fuel cells
- Medical industry

Langley

Anti-Insect Coating for Aircraft and More

Hydrophobic epoxy coating keeps insect remains from adhering

Langley Research Center has developed fluorinated alkyl ether-containing epoxies designed as an anti-insect coating. It was developed as a hydrophobic and non-wetting coating for aerodynamic surfaces to prevent accumulation of insect remains, which can lead to airflow disruption and create inefficiencies in aerodynamics.

The coating could be useful in a variety of applications besides aircraft where reduction of insect residue adherence is desirable, such as in the automotive and wind-energy industries.

Benefits

- Inexpensive and simple to apply
- Commercially available precursor requires only two chemical reactions
- Several formulations already flight tested

Applications

- Aerospace
- Marine
- Automotive
- Wind energy

Safe2Ditch

Autonomous crash management to a safe, clear ditch site for small drones

Highly capable small unmanned aerial vehicles (UAVs) provide substantial business opportunity, especially if allowed to operate in the suburban market. However, reliability issues mean there needs to be a safety pilot for each vehicle, which is cost-prohibitive for large-scale commercial applications and limits the use of these vehicles to line-of-site operation.

Safe2Ditch is a crash management system that resides on a small onboard processor. The system's exclusive mission is emergency management: to get the vehicle safely to the ground in the event of an unexpected critical flight issue.

Safe2Ditch uses its intelligent algorithms, knowledge of the local area, and knowledge of the disabled vehicle's remaining control capacity to select and steer to a crash location that minimizes risk to people and property. As the UAV approaches landing, it uses machine vision to inspect the selected site and ensure that it is clear as expected.

Benefits

- Compact, lightweight, and low-cost
- Designed to operate with autopilot systems favored by the UAV market

Applications

- Home and business deliveries
- Live remote transmission
- Real estate management

Marshall

Lower-Chatter Friction Pull Plug Welding

New plug design reduces chatter and stalling

In friction stir welding, the heat that melts the metal to create the joint is created by friction, as the stud or other piece is spun extremely quickly. But the pin tool of the welder, which holds and spins the stud, leaves a hole that must be filled.

Friction pull plug welding is the process that fills that hole. When the plug enters the hole, there is often chatter, and sometimes the machine stalls completely. Engineers at Marshall Space Flight Center discovered that by optimizing the design of the pull plug, it can be made to contact the hole in such a way that the chatter issue is improved.

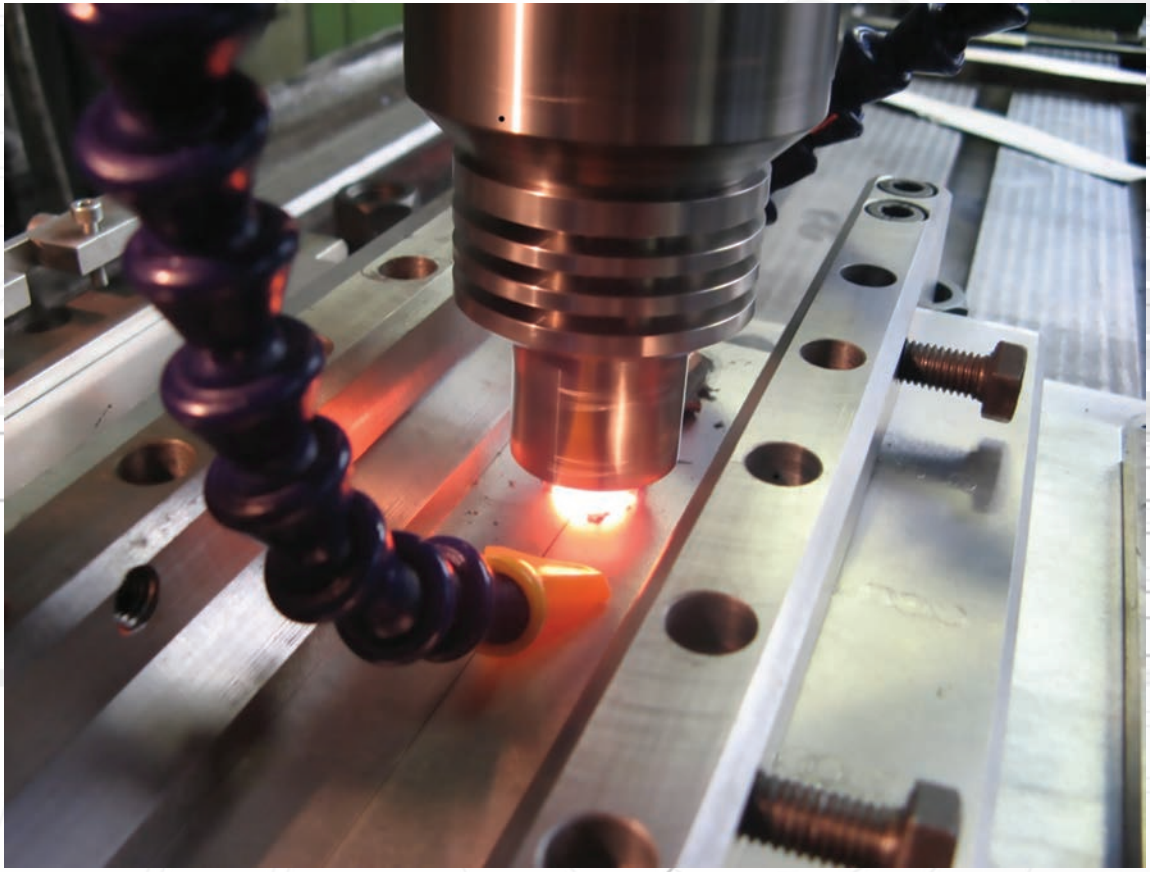
This new design makes friction pull plug welding more practical, perhaps even as a future rivet replacement. It has already been used to make space-qualified parts at NASA.

Benefits

- Eliminates stalling
- Enables friction pull plug welding on thicker plates
- Works with more alloys

Applications

- Potential rivet replacement
- Aerospace
- Naval ships, commercial aluminum ships
- Army lightweight vehicles and hybrid armor
- High-speed trains made of thick aluminum



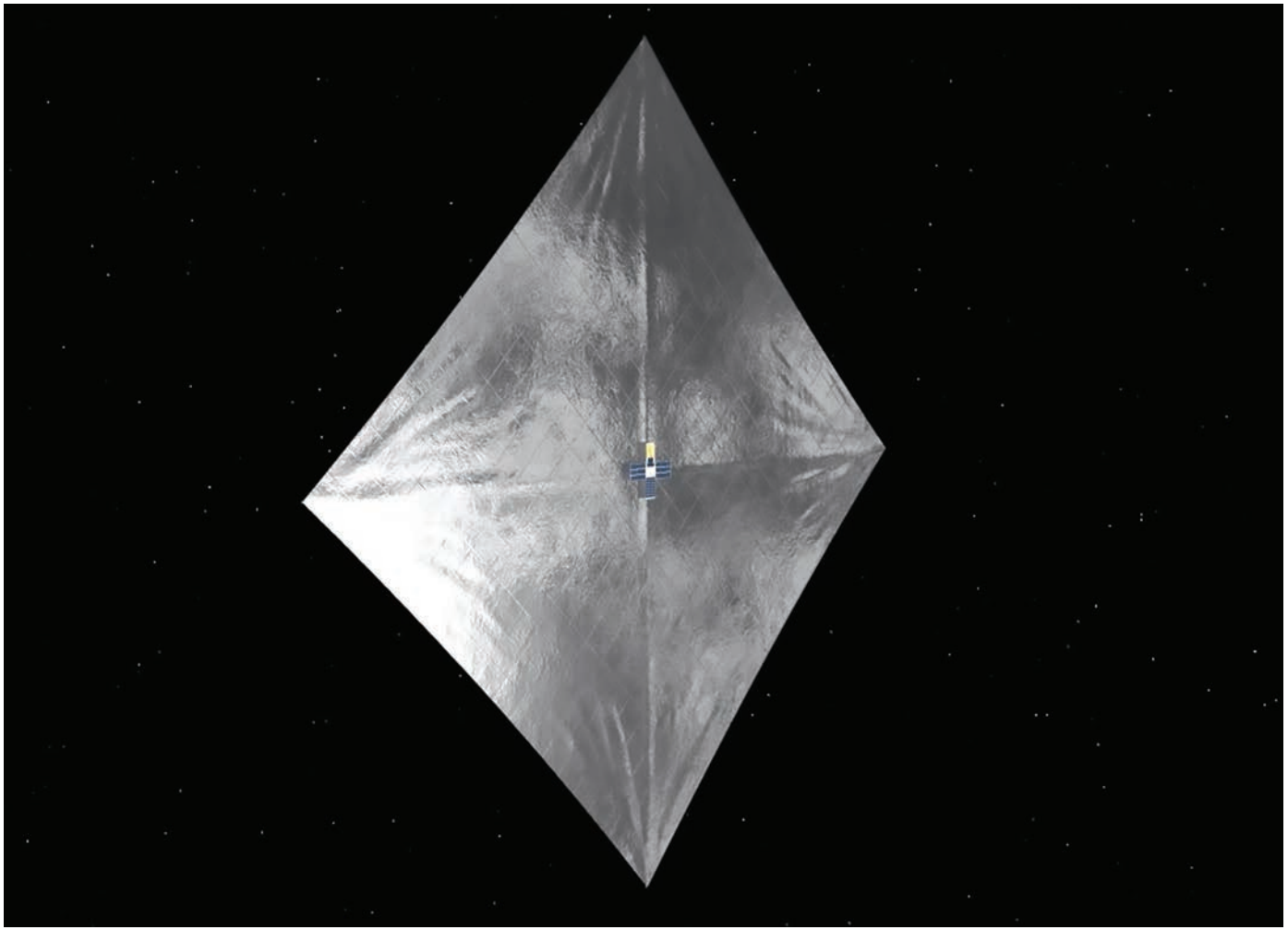
Efficient Packaging Process for One-Piece Deployable Thin Membrane

Improves packing efficiency to conserve volume and reduces fold count

This technology consists a method for folding a 3-micron-thick polyimide solar sail to fit into a 4- by 6- by 8-inch space. Once in orbit, the solar sail is deployed uniformly from a central hub to power a CubeSat.

Increasing packing efficiency by 25–30 percent, the bowtie folding process avoids pocket voids by folding the sail in a Z-fold along its edge. Once the Z-fold is complete, the material is then rolled onto the center hub. The smaller footprint of the stowed solar sail makes the process more practical and economical.

The folding style, which has not been previously documented, leaves all four corners of the sail exposed. The method is also beneficial for reflective surfaces and avoids the weakening risks associated with traditional folds.



Benefits

- Cost- and power-efficient
- Elegant, reproducible
- Reduces creases
- Fully tested on Earth, with flight tests scheduled

Applications

- Solar sail deployment
- Antenna deployment
- Tent or habitat packaging
- Parachute or hang glider packaging
- Umbrella design

Stennis

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

PowerFelt

Power-generating coverings and casings fit irregular shapes, draw down heat

Advances in nanomaterials have made it possible to create thermoelectrics using high-temperature polymer composites. These are able to easily conform to large, irregular shapes and can scavenge energy from both movement and heat.

The combination of thermal and vibrational power production is synergistic, generating more power than the sum of the components.

Piezo-thermo-electric PowerFelt can supplement or repace batteries by harvesting energy from heat sources and movements or vibrations. It can remove heat to stabilize temperatures of sensitive components. And it can use thermoelectrics to drive down component temperatures to increase the sensitivity of imagers, solid-state lasers, and other sensors. PowerFelt can provide systems with supplemental or backup power. It can be incorporated into clothing, cell phone holsters, tents, backpacks, and vehicles and can provide power during emergencies.

Benefits

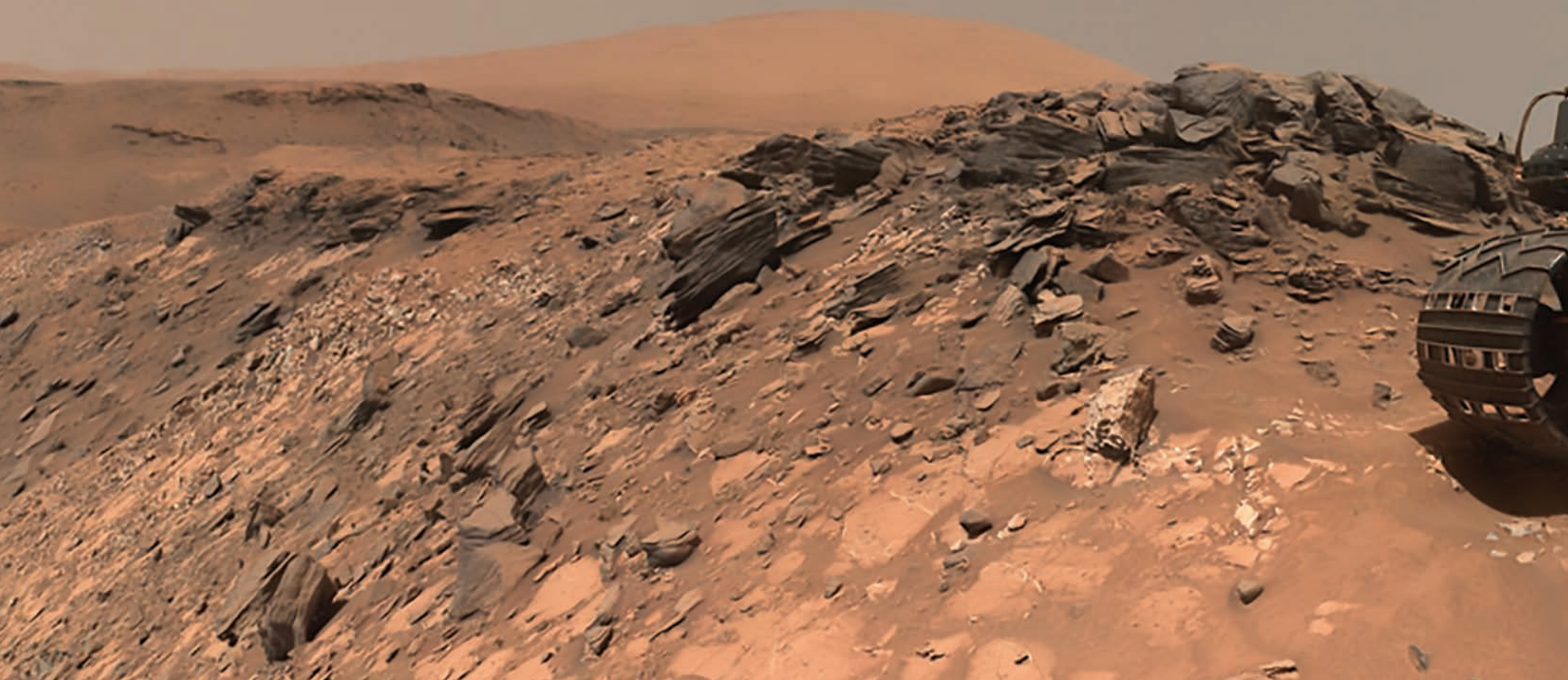
- Easily conforms to irregular surfaces
- Combines energy scavenged from movement and heat
- Endless, renewable energy source
- Eliminates or supplements batteries
- Cools components for stability or increased detector sensitivity
- Zero emissions

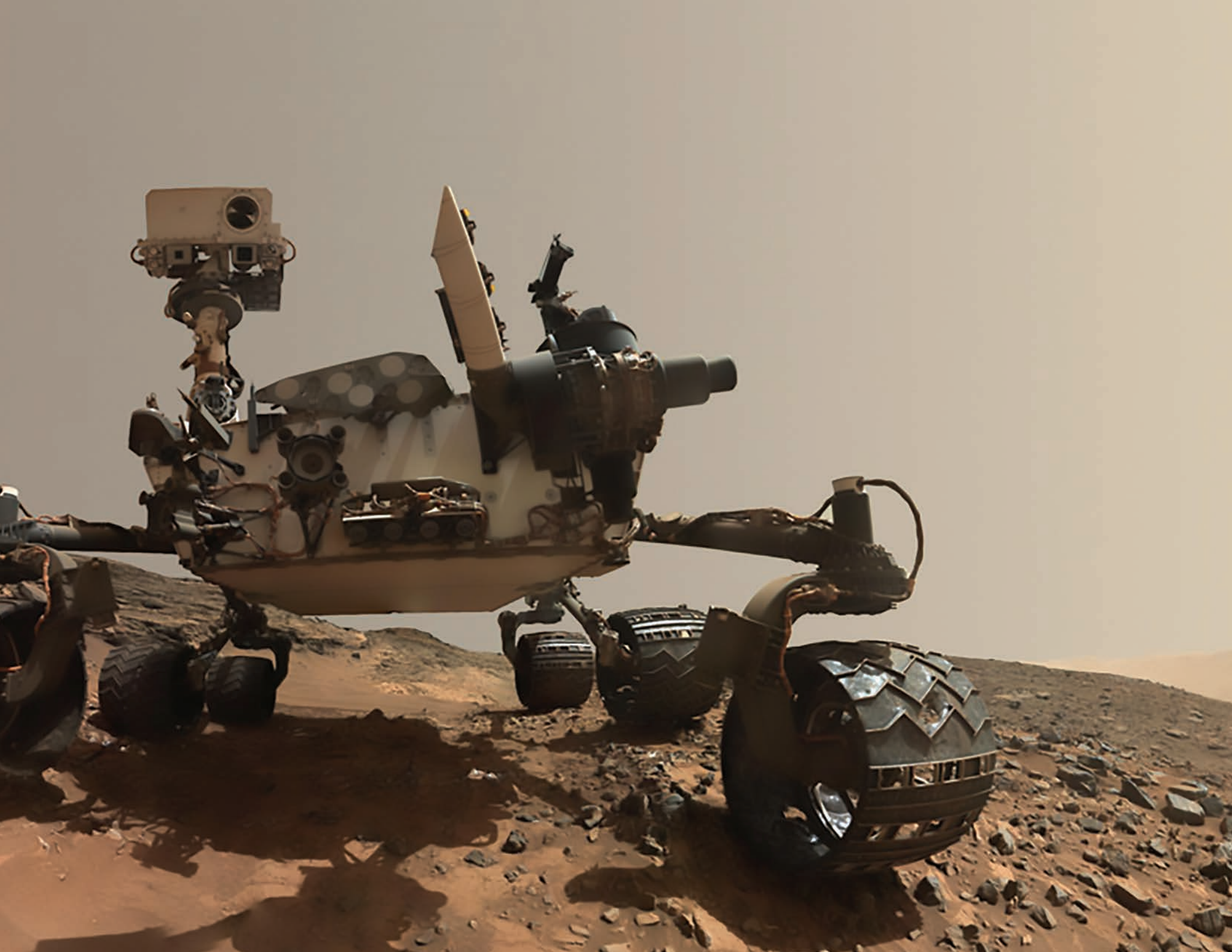
Applications

- Clothing and accessories to power devices
- Vehicles
- Emergency backup power
- Detectors, imagers, lasers
- Aerospace
- Military

NASA's Technology Transfer Program

For more than 50 years, NASA's Technology Transfer Program has worked behind the scenes to publish new discoveries, patent and license valuable inventions, and collect and distribute software codes. Thanks to this program—the Agency's longest-running mission—NASA research, technology, and innovations spread into American industry as much as possible.





NASA's Technology Transfer Program

Bringing NASA Technology Down to Earth

NASA has a well-earned reputation for leading the Federal Government in technology transfer. From cell phone cameras and memory foam to aerogel insulation and modern truck designs, NASA inventions are widespread—and stick out for the public as examples of taxpayer dollars returning spinoff benefits.

As mandated by Congress, as far back as the 1958 Space Act that created the Space Agency, NASA has worked to ensure the results of its space and aeronautics activities benefit the whole of humanity. To that end, NASA's Technology Transfer Program serves as the nation's curator of aerospace technology assets, identifying and protecting inventions and ensuring they are distributed to individuals, academia, and industry as widely as possible. The program processes more than 1,500 new technologies created by NASA innovators each year, assessing each for its commercial potential and patenting those that are particularly promising. It manages the Agency's technology portfolio, negotiates license agreements, and handles requests for NASA software.

The program also communicates the societal benefits of NASA's work to the public through its annual *Spinoff* publication, which has featured more than 2,000 successfully commercialized space technologies since its first issue in 1976.

Over the past decade, NASA's effective marketing and promotion of its portfolios has led to a steady increase in public and government interest in NASA technology for secondary applications. Managing this increased interest requires constant and continuous process improvements across all areas of the technology transfer pipeline—from new tools to help NASA innovators publish their discoveries and inventions internally to public websites and mobile applications everyone can use to discover and acquire NASA technology. The Technology Transfer Program develops and maintains these tools while also conducting public outreach

Representing NASA's Technology Transfer Program, Marshall Space Flight Center's Jordan Larsen and Tom Knight staff a program booth at the Offshore Technology Conference in 2018.

through media, conferences, and other interactions with government, university, and commercial organizations.

From a record number of new licenses and software usage agreements to numerous big-impact commercial spinoff success stories, NASA remains on the forefront of government agencies sharing its intellectual property and technology with the private sector.

Invention Disclosure

New technology reports are the first step to technology transfer success. They include any invention, discovery, improvement, or innovation that was either conceived or first put into practice in the performance of NASA work. NASA employees are required to disclose their inventions to the public, although it is a perennial challenge to ensure they are aware of this requirement and follow through with action.

Recently, in an effort to encourage Agency invention disclosures, NASA has created popular incentives for inventors, including challenge coins minted using metal that was flown in space. Additionally, the program continues to coordinate Agency in-reach events: in 2017, alone, it hosted more than 130 training sessions across all 10 NASA Field Centers. These events educated approximately 4,300 innovators on their duty to report new technologies and made them aware of new tools designed to ease the process. These include, among others, a simplified web-based portal for reporting and tracking new technologies.

Patent Licensing

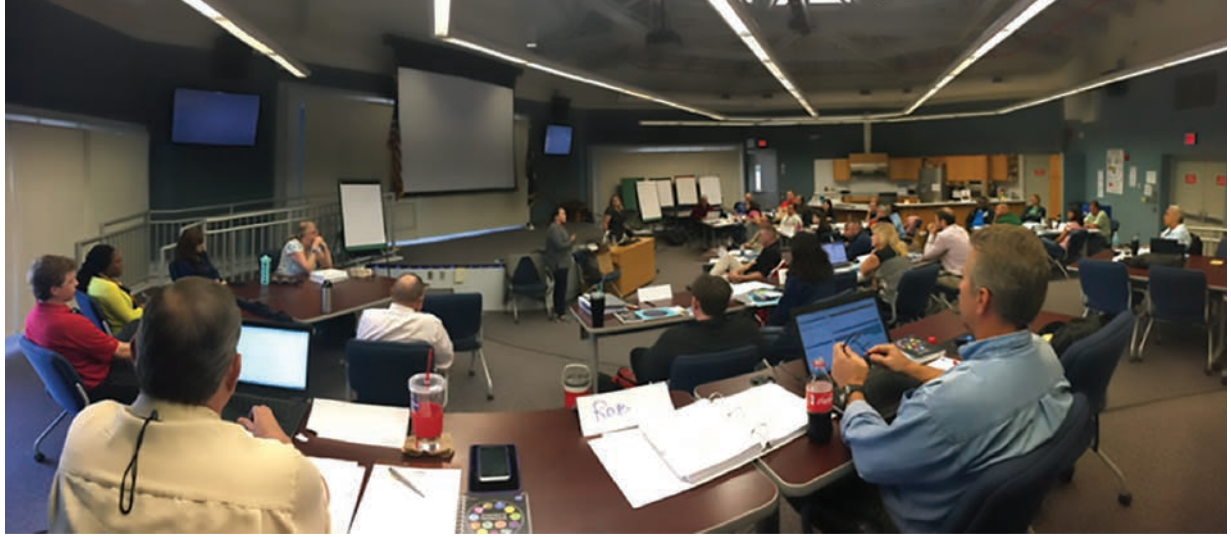
NASA's innovative patent-licensing strategy has matured over the course of several years following a program reform in 2011 that centralized the Agency's intellectual property into a single portfolio. The result? Patent licensing by NASA has increased nearly five-fold in the last eight years. Currently, there are about 500 active licenses for NASA-patented technologies, with 119 new licenses executed in the past year. Also in the last year, NASA filed 165 new patents on technology with an eye toward near-term commercialization.

NASA is still the only Federal agency with a consolidated intellectual property portfolio marketing approach. Users can find all available NASA inventions on a single, public-facing, fully searchable website (http://technology.nasa.gov/patents) that is always up to date. Every one of the thousand-plus technologies in this database has a corresponding fact sheet online containing a plain-language description of the technology, lists of its advantages and potential applications, and NASA contacts for further information.

Individuals and businesses interested in using these NASA technologies can now apply for a license through a simple, intuitive, and automated online application system known as ATLAS. Commercial licenses are negotiated on a case-by-case basis, but NASA also offers a few licenses that have low or no up-front costs for start-up companies or businesses interested in evaluating a technology before committing to it. Thanks to these special licenses and NASA's promotion of its assets to entrepreneurs, about 30 start-ups founded in the last three years are building products using NASA technology.

There are also thousands of formerly patented technologies that NASA has gifted into the public domain—again, with a central, searchable database developed within the last few years (https://technology.nasa.gov/publicdomain). Anyone can pursue product development using these technologies for free, with no requirement to contact NASA.

Of notable value among these patents are a large number of space-based technologies—for example, in propulsion—that will help foster increasing competition in America's growing commercial space sector.



Recent successes of the Technology Transfer Program include effective in-reach to NASA inventors. Pictured here is a recent training event for approximately 30 NASA employees held by the Kennedy Space Center Technology Transfer Office and NASA patent counsel representatives.

Software Release

Today more than ever, people are using NASA software to solve their technical challenges. In 2017, software releases—that is, acquisitions of software following a request and NASA approval—increased by an astounding 193 percent, part of an overall 473 percent increase in software releases since 2011.

NASA's software release practices have become a model for other Federal agencies, showing them how to capture, track, review, and release code to the public.

A key element of NASA's software release success is the software catalog, which is kept up to date on a single public-facing website (http://software.nasa.gov/). As of the end of 2018, the catalog contains more than a thousand software packages, all of which are available free of charge and can be downloaded from the site using an automated request system. This catalog, first released in 2014, was the first of its kind among all agencies of the Federal Government, the world's largest creator of custom code.

The Space Agency never stops looking for new ways to surpass its original technology transfer mandate and extend the reach of its continuous technological innovation to improve the quality of life on Earth. This issue of *Spinoff* alone represents dozens of tangible examples of its successes, with many more to come. ❖

Daniel Lockney, NASA's Technology Transfer Program Executive, is shown during a panel at the Space Foundation's annual Space Symposium.

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.

NASA Headquarters provides leadership, policy, strategy, resource allocation, and media relations for technology transfer activities Agency-wide.

Technology Transfer Program Offices at each of NASA's 10 Field Centers represent NASA's technology sources and manage Center participation in technology transfer activities.

MAP KEY

NASA HQ — NASA Headquarters
ARC — Ames Research Center
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

NASA Headquarters

National Aeronautics and Space Administration

Technology Transfer Program Executive:
Daniel Lockney
Phone: (202) 358-2037
Email: daniel.p.lockney@nasa.gov
300 E Street, SW
Washington, DC 20546

Field Centers

Ames Research Center
Technology Transfer Office Chief:
Tony Strawa
Phone: (650) 604-3437
Email: anthony.w.strawa@nasa.gov
Moffett Field, California 94035

Armstrong Flight Research Center
Technology Transfer Office Chief:
Laura Fobel
Phone: (661) 276-3967
Email: laura.j.fobel@nasa.gov
4800 Lilly Drive, Building 4839
Edwards, California 93523-0273

Glenn Research Center
Technology Transfer Office Chief:
Harvey Schabes
Phone: (216) 433-8047
Email: harvey.l.schabes@nasa.gov
21000 Brookpark Road
Cleveland, Ohio 44135

Goddard Space Flight Center
Technology Transfer Office Chief:
Nona Cheeks
Phone: (301) 286-5810
Email: nona.k.cheeks@nasa.gov
8800 Greenbelt Road
Greenbelt, Maryland 20771

Jet Propulsion Laboratory
Technology Transfer Office Chief:
Debora Wolfenbarger
Phone: (818) 354-3829
Email: debora.l.wolfenbarger@jpl.nasa.gov
4800 Oak Grove Drive
Pasadena, California 91109

Johnson Space Center
Technology Transfer Office Chief:
Charlene Gilbert
Phone: (281) 483-0474
Email: charlene.e.gilbert@nasa.gov
2101 E. NASA Parkway
Houston, Texas 77058

Kennedy Space Center
Technology Transfer Office Chief:
Dave Makufka
Phone: (321) 867-6227
Email: david.r.makufka@nasa.gov
Kennedy Space Center, Florida 32899

Langley Research Center
Technology Transfer Office Chief:
Kathy Dezern
Phone: (757) 864-5704
Email: kathy.a.dezern@nasa.gov
Hampton, Virginia 23681-2199

Marshall Space Flight Center
Technology Transfer Office Chief:
Terry Taylor
Phone: (256) 544-5916
Email: terry.taylor@nasa.gov
Huntsville, Alabama 35812

Stennis Space Center
Technology Transfer Office Chief:
Duane Armstrong
Phone: (228) 688-2180
Email: curtis.d.armstrong@nasa.gov
Stennis Space Center, Mississippi 39529

Spinoff Program Office
Email: spinoff@nasa.gov

Daniel Coleman, Editor-in-Chief
Phone: (301) 286-4058
Email: daniel.p.coleman@nasa.gov

Mike DiCicco, Senior Science Writer
Naomi Seck, Senior Science Writer and Social Media Manager
John Jones, Senior Graphics Designer

Goddard Space Flight Center, Building 35
8800 Greenbelt Road
Greenbelt, Maryland 20771

NASA

HOME & CITY

There's more SPACE in YOUR LIFE than you think.

Visit Home & City to trace space back you:

homeandcity.nasa.gov

NASA **TECHNOLOGY TRANSFER** PROGRAM

National Aeronautics and Space Administration

Technology Transfer Program
NASA Headquarters
Washington, DC 20546

www.nasa.gov

NP-2018-08-2611-HQ