National Aeronautics and Space Administration

Spinoff

2019

Introduction

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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 are 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 this iPad app, you can read about the latest success stories of commercialized NASA technology, along with videos and image galleries that let you explore the benefits of space in your life.

If you'd like to learn more about any of the technologies in this app, or if you'd like to request your own free print version of *Spinoff*, please visit us at http://spinoff.nasa.gov. To learn more about NASA's Technology Transfer Program, where spinoff technologies get their start, please visit http://technology.nasa.gov.

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.

Unique Polymer Finds Widespread Use in Heart Devices

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

In the 1990s, working under the High-Speed Research Program, Langley Research Center scientist Robert Bryant was screening various polymers for use as advanced composites and adhesives when he came across a substance with a unique set of qualities. This polyimide—a class of highly durable materials that make great electrical insulators, among other properties—remained soluble when it shouldn't have and, unlike most polyimides, could be melted even after it was insoluble. It resulted in different useful products at all of the three steps in the polymerization process. These could be applied to a substrate in many different ways.

Bryant helped Langley patent the formula and process as LaRC-SI (Langley Research Center-Soluble Imide).

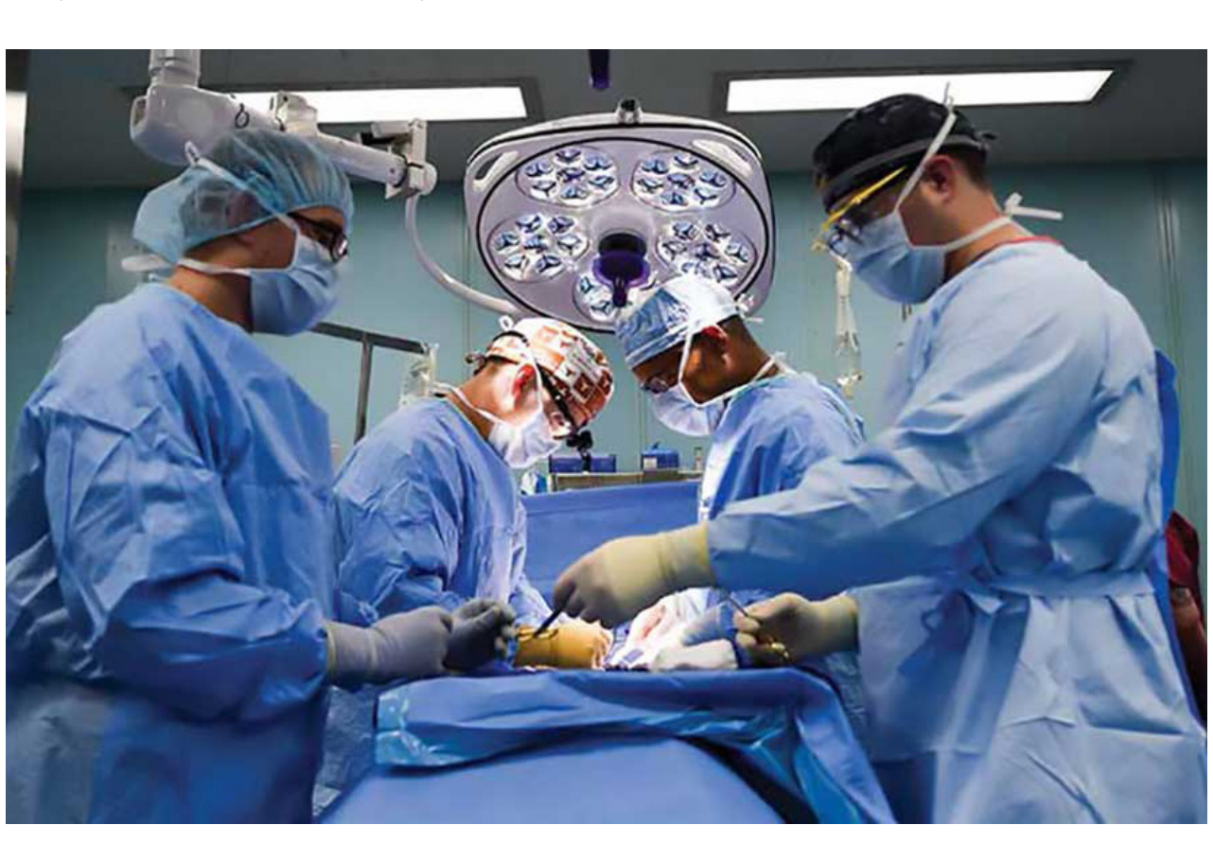
In 2004, Minneapolis-based Medtronic licensed LaRC-SI, and the company eventually brought Bryant on as a consultant, a role he still fills. They spent years developing a process to use the material as a coating and electric insulator for the thinnest left ventricular leads available.

Traditional pacemakers address a slow heartbeat by delivering a tiny electrical charge to the heart's right atrium and right ventricle. About 40 percent of patients with congestive heart failure or cardiomyopathy, however, lack coordination between the left and right ventricles. This significantly reduces pumping efficiency and isn't addressed by a regular pacemaker.

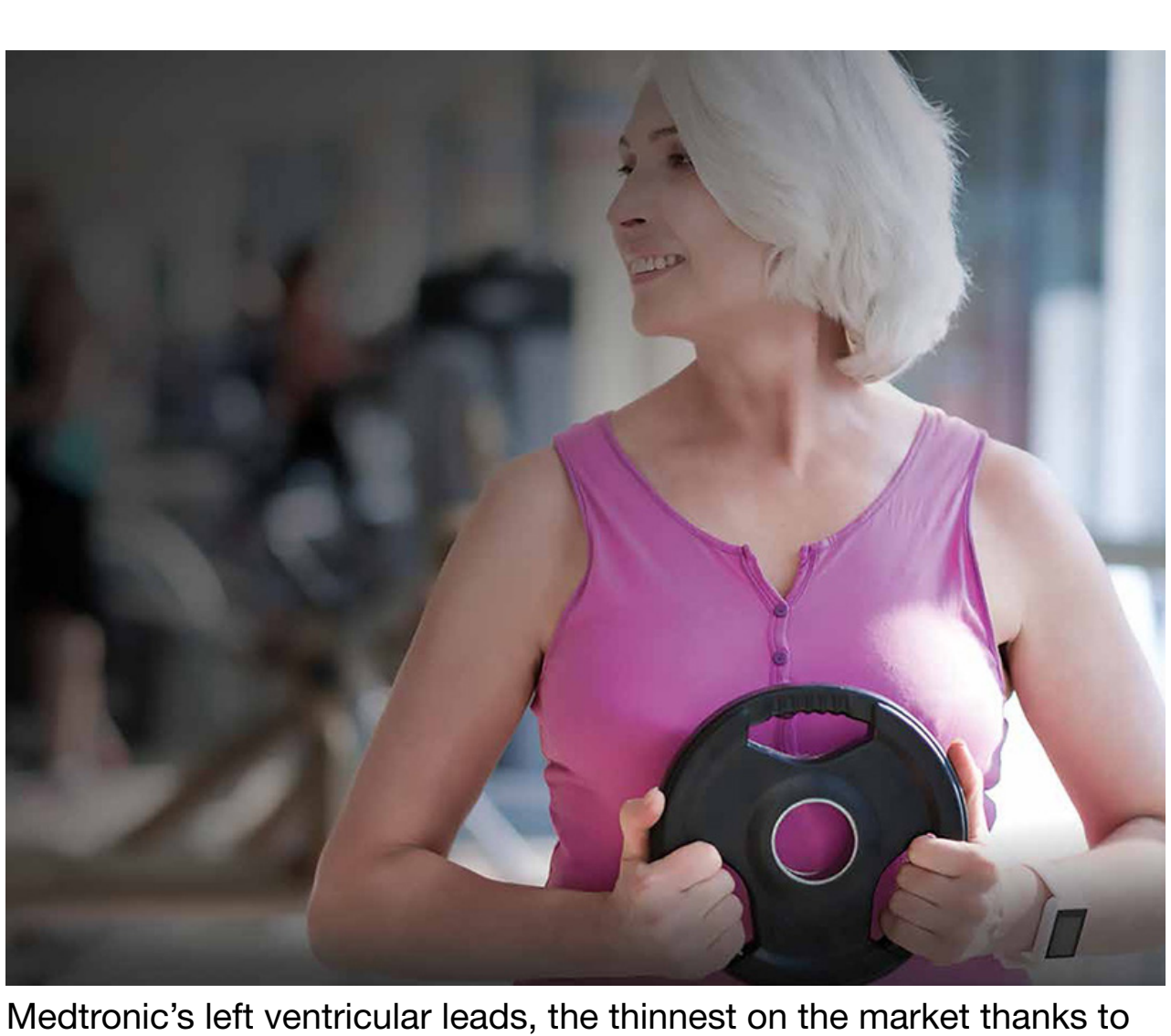
Cardiac resynchronization therapy addresses this problem by running a third electrical lead to the left ventricle. It's a challenging procedure, because the lead has to be threaded through a vein that's often convoluted in a small space.

Using LaRC-SI as its insulator lets the lead be exceptionally thin and flexible without sacrificing strength or reliability, making Medtronic's left ventricular leads some of the safest and easiest to implant on the market.

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.



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. Image courtesy of the U.S. Navy



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

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, formerly of the Jet Propulsion Laboratory (JPL).

"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 bringing back a sample requires putting it in a container with 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. That can interfere with the seal.

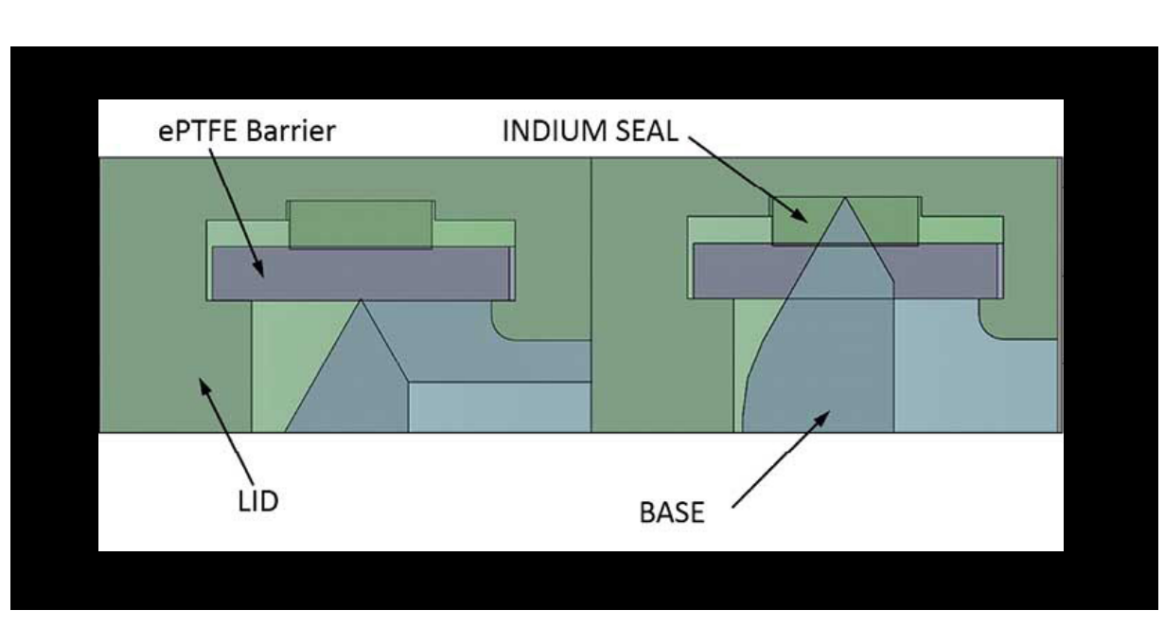
Stanley, vice president of technology at a small company called Techno Planet Inc., was building a Mars sample-return canister with Small Business Innovation Research funding from JPL and turned to Orangeburg, South Carolina-based Zeus Inc. for one important component. Zeus innovated a new process to extrude and expand PTFE (polytetrafluoroethylene, commonly called Teflon) to create a barrier that would wipe dirt off the canister edge before it pushed into soft metal around the inside of the lid that would block any cross-contamination.

Since then, the company has found numerous uses for the extruded material, including as sutures used for delicate operations, like heart valve repairs.

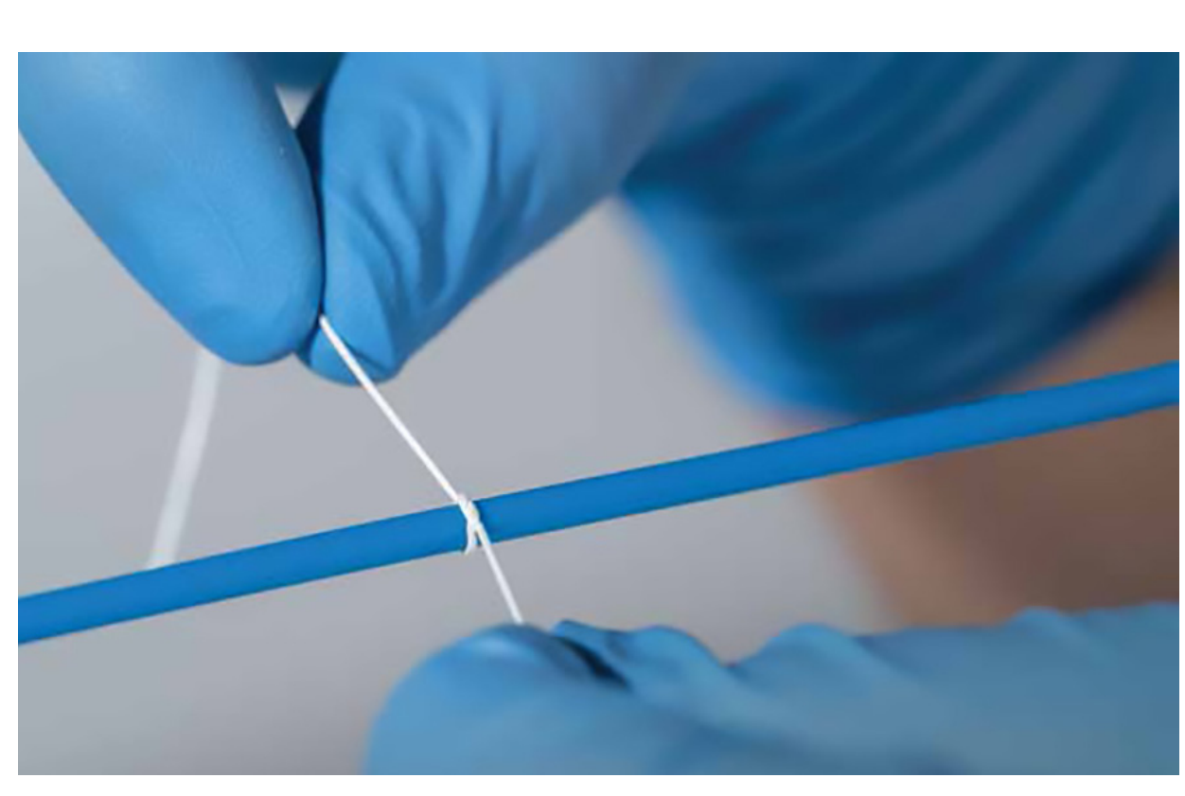
"This material is unique, because it's soft, flexible, and strong—and it's also biocompatible. It's a material that can safely interact in the body and can be safely implanted in the body," notes Global Business Development Manager Wayne Black.

The material is also used to encapsulate stents also used in heart surgery, as well as in fiber optics and to coat cables for aerospace.

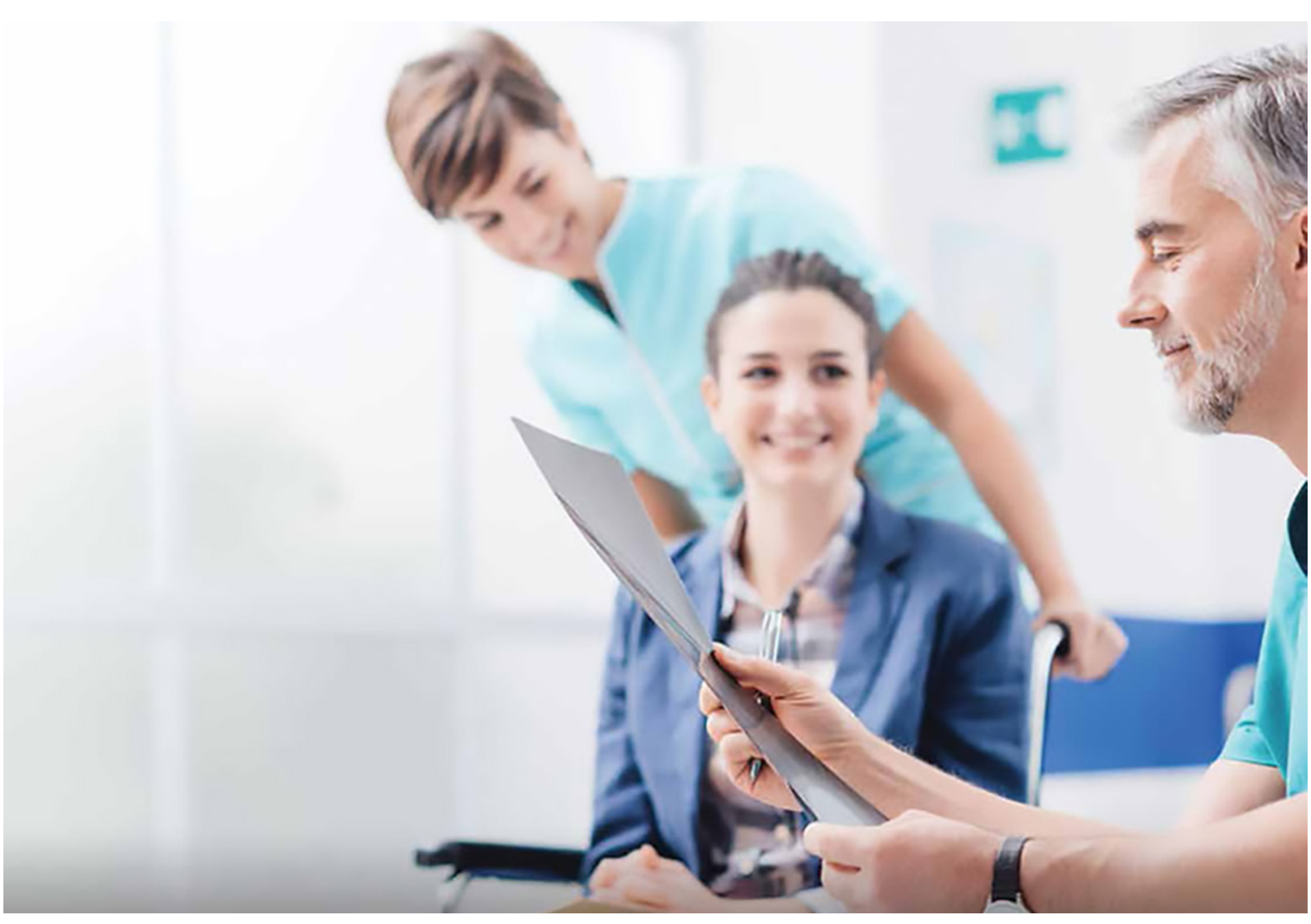
This photo by NASA's Curiosity rover shows the Windjana rock site, where the rover's tools drilled down for a sample to analyze. NASA learns a lot from these rovers, but it could learn even more by bringing a rock sample home for deeper analysis in Earth-based labs.



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.



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.



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

A new technique for detecting chromosome damage 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 soon put them at the forefront of a revolution in genetics.

That same year, unbeknownst to the founders of KromaTiD Inc., a team in France demonstrated that a feature of bacterial DNA called CRISPR, for clustered regularly interspaced short palindromic repeats, serves as an adaptive immune system. Researchers have since found that these snippets of DNA can be used to turn genes on and off and to add DNA 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 damage, are understood.

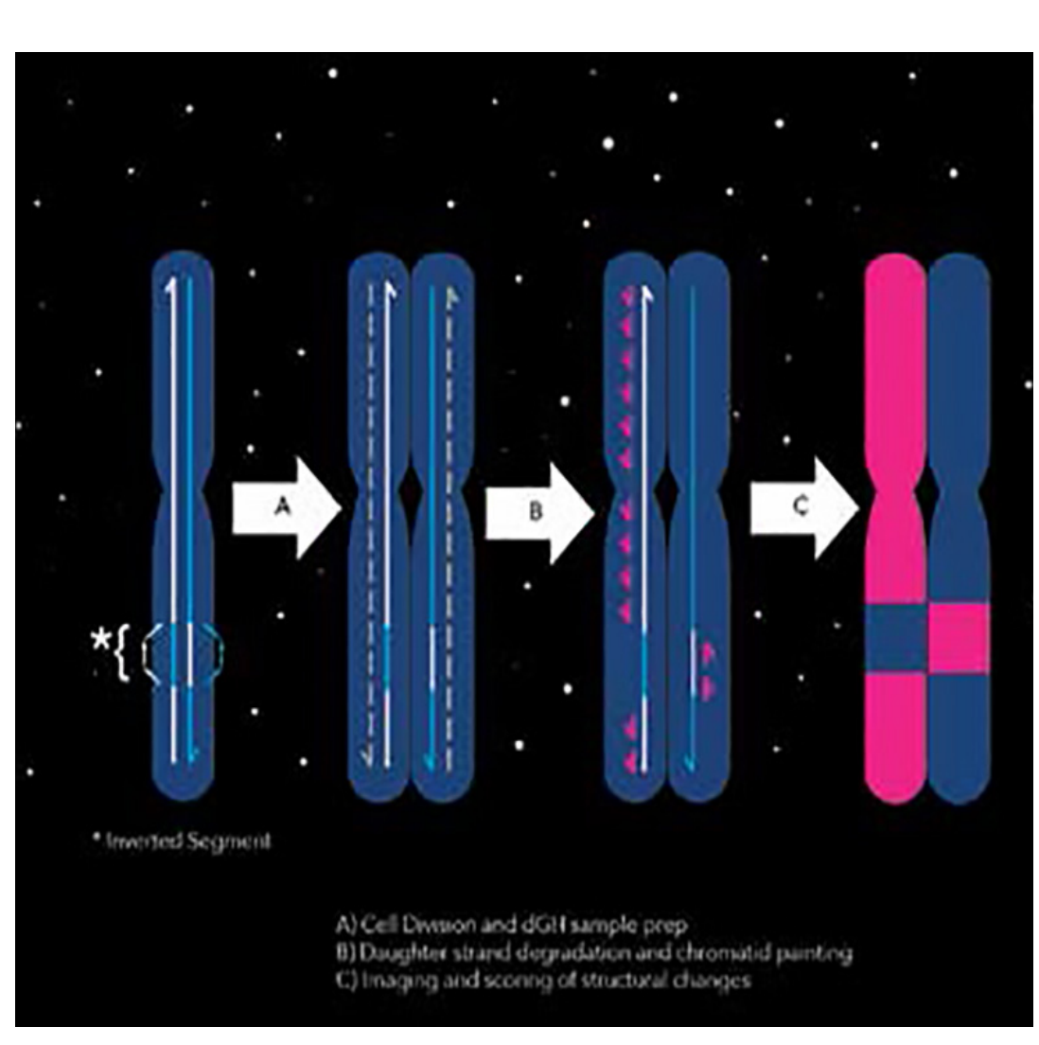
NASA has studied DNA damage because astronauts are exposed to charged particles that can rip through DNA, inflicting random harm. For years, doctors at Johnson Space Center took blood samples from every astronaut before and after trips into space, checking for genetic damage.

Although they could detect the translocation of DNA—when a bit of one chromosome ends up fused to another—they couldn't see subtler forms of damage. KromaTiD's technique promised the ability to spot inversions within a chromosome, where a stretch of DNA gets flipped backwards.

In 2008, Johnson awarded two Small Business Innovation Research contracts to the Fort Collins, Colorado-based company. It was KromaTiD's first funding, and it helped prove and refine the technique it calls directional Genomic Hybridization.

KromaTiD's DNA probes can help doctors select and tailor cancer treatments and help researchers identify patients for clinical trials. They've found the DNA variations responsible for undiagnosed conditions. And they can help agencies determine radiation levels and exposures in nuclear disasters.

But the company sees its biggest opportunities in the field of gene editing, which holds enormous possibilities for health and industry but requires refinement, studies into unintended consequences, and the establishment of standards and guidelines.


A
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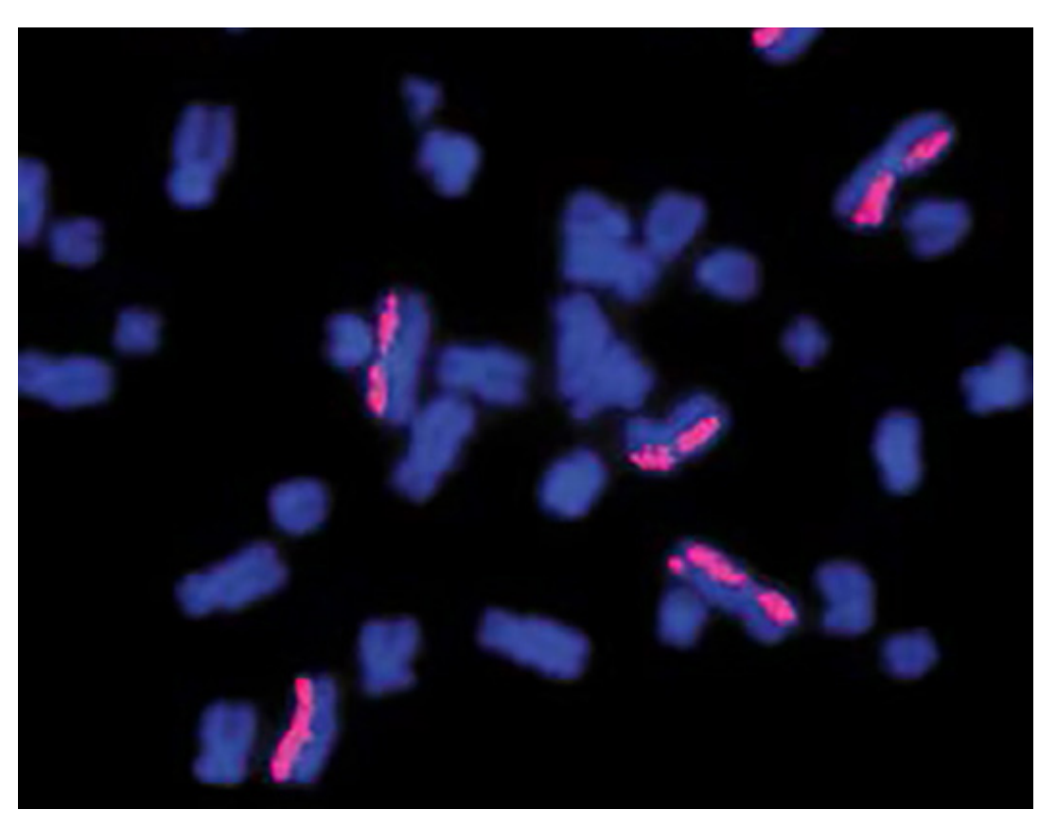
* Inverted Segment
A) Cell Division and dGH sample prep
B) Daughter strand degradation and chromatid painting
C) Imaging and scoring of structural changes

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.

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.

Image-Analysis Software Sees Cancer in 3D

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.

But even with decades of study on health risks, notes Craig Kundrot, division director for NASA's Space Life and Physical Sciences Research and Applications, there are still unknowns. For example, "when we went from two-week Shuttle missions to six-month space station missions … 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 what risk they pose, researchers believe they are related to blood flow changes in microgravity, which is something that has been studied extensively.

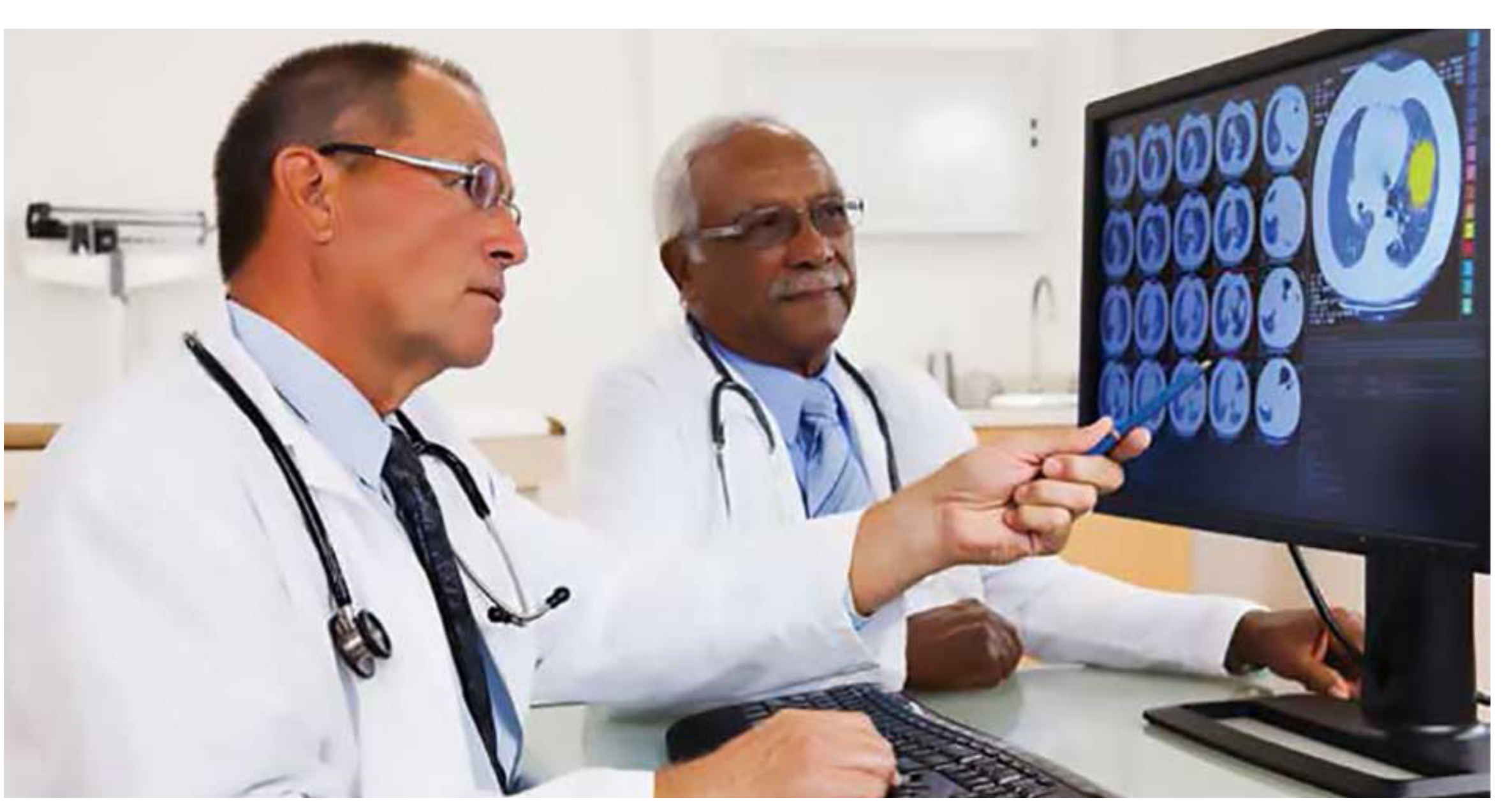
In one 2011 study on vascular changes in microgravity, funded by Ames Research Center, lead researcher Ron Midura aimed to test the hypothesis that these changes impact muscle and bone loss. Part of his study included analyzing images of tissue samples from the hind legs of mice that had flown on the Shuttle, to count the blood vessels and measure their thickness and shape.

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," Midura notes.

Instead, Midura decided to turn to computer analysis software made by Image IQ, now owned by Philadelphia-based ERT. 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 software has since been used for many clinical studies. One potentially life-saving example: using the filters and algorithms created for Midura, researchers can identify the three-dimensional shape of a tumor, which can give better insight into whether it is growing and whether it is metastatic or benign.

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.



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

Nobody has ever directly seen dark matter or dark energy, yet physicists and astronomers observe their effects all around us. Researchers are working to better understand these mysterious phenomena—and NASA is helping design the next generation of powerful instruments that will hopefully lead to big discoveries.

One instrument that could offer important new clues, built with the help of engineers from the California Institute of Technology and the Jet Propulsion Laboratory (JPL), is due to be installed on Japan's Subaru Telescope in Hawaii in 2020.

The tool, called a fiber-fed spectrograph, measures the expansion of the universe by looking at the red shift of distant galaxies. Each of some 2,398 fibers lines up with a spot on the image to analyze its color spectrum.

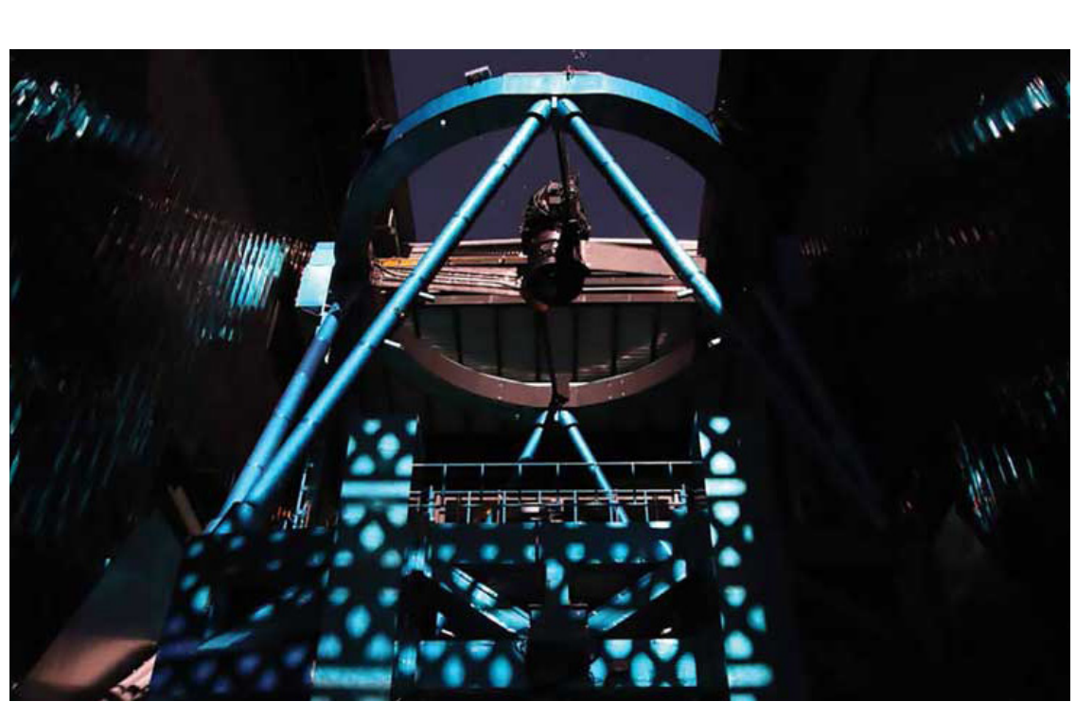
That requires thousands of miniature positioners, powered with tiny piezoelectric motors, to move each fiber into the right spot. JPL worked with Victor, New York-based New Scale Technologies to perfect the rotary motors. Importantly, the company reduced the required power to less than 10 volts and improved its precision manufacturing to ensure each product was identical.

Today, "everything we do now is at 10 volts or below," emphasizes New Scale CEO David Henderson. "Even some of our more powerful products are now using reduced-voltage drives. It's essential for our mini-mechatronic solutions."

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.

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. The company is also getting interest for implantable devices to use in robotic surgery.

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.



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.

NEW SCALE TECHNOLOGIES

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.

Biometric Sensor Tracks Vital Signs for Health

Many people already keep track of their 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.

In particular, Velo was interested in 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.

Funded by Small Business Innovation Research (SBIR) contracts from Johnson Space Center, Velo developed a tiny PPG (photoplethysmography) sensor that tracks heart rate variability, a measure of the spaces between beats that can indicate stress level.

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.

Now Newark, California-based Salutron sells the sensor to wearable-makers and directly to consumers. One model that incorporates the PPG sensor, available from Salutron's website, is the Zoom HRV. It also incorporates actigraphy—monitoring rest-activity cycles—and sleep sensors (the latter were developed under separate SBIR contracts with NASA).

For now, Velo says, the core audience appears to be people interested in tracking fitness—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.

Battery Innovations Power All-Electric Aircraft

The X-planes, experimental aircraft built by NASA and the military, started out by breaking the sound barrier and have been pushing through invisible barriers ever since. The latest, known as the X-57 Maxwell, aims to make all-electric passenger aircraft a commercially viable reality.

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.

The plane is a highly modified Tecnam P2006T, a four-person, twin-engine craft. Engineers at Armstrong Flight Research Center are replacing its gas-powered engines with two electric cruise motors on the tips of the wings, reducing drag from wingtip vortices. Six smaller motors along the leading edge of each wing add to the airflow, increasing lift during takeoff and landing.

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.

One big challenge is safely delivering enough power to the motors. Engineers called on Electric Power Systems (EP Systems), based in Industry, California, to build the battery pack, funding the effort with Small Business Innovation Research contracts.

The 850-pound pack holds thousands of lithium-ion cells, each a little bigger than an AA battery. The downside to lithium-ion cells is that they can short-circuit and fall into "thermal runaway," ending in combustion, so the pack had to ensure that if one cell burst into flames, it wouldn't set off a chain reaction—which is exactly what happened when a cell in the first pack was short-circuited for testing.

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.

Armstrong brought in NASA battery and safety experts, who contributed equipment, innovations, and know-how that EP Systems incorporated, along with its own improvements, into the next battery pack, which proved successful.

In March of 2018, the company Bye Aerospace announced that EP Systems' batteries would power its all-electric Sun Flyer trainer, which made its first flight the following month. EP Systems says the batteries it's providing to Bye are similar to the one it developed for the X-57, incorporating many of the same improvements.

EP Systems says it has received considerable interest—and yet-unannounced contracts—from companies looking to build all-electric aircraft for short flights between small airports and vertical-takeoff and -landing vehicles for transportation within cities.

Without the assist from Armstrong, says Nathan Millecam, president and CEO of EP Systems, electric propulsion batteries might not have gotten off the ground. "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."

Shuttle Tire Sensors Warn Drivers of Flat Tires

How many people have been surprised to realize their car tire was dangerously low on air? It was something the Space Shuttle engineers worried about too.

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.

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.

Originally, an externally mounted strain gauge monitored tire pressure in flight, he says, but it only gave a very rough estimate of pressure. Instead, Shuttle engineers relied on extensive pre-flight ground testing to learn the rate at which the tires lost air, so they could prepare the tires with enough margin to be safe during landing.

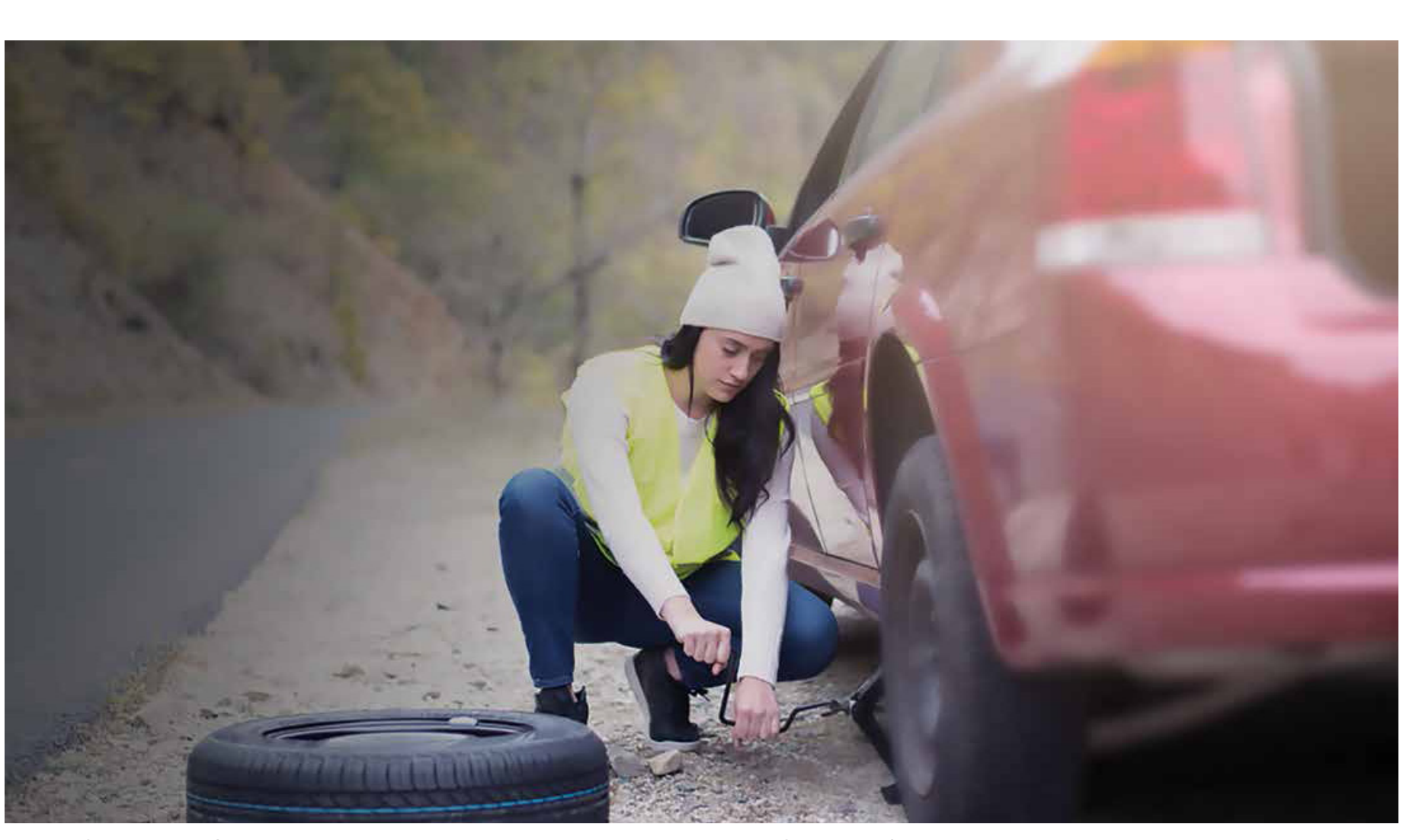
Looking for something better, in the 1990s, Kennedy partnered with a then-start-up called NovaSensor to build a tiny pressure sensor on a silicon chip, powered by a small battery, that alerted pilots if the pressure was low.

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.

The company, now part of the much larger St. Marys, Pennsylvania-based Amphenol Advanced Sensors, soon adapted the sensor for car tires and sold many millions, most of which ended up on U.S. passenger vehicles, including those by Ford and GM.

Today, U.S. law mandates a pressure gauge on every car tire, and that's because of the increased safety pressure sensors like these enable. Even when the pressure isn't low enough to cause a blowout, adds Amphenol's Mark Ready, low tire pressure makes the car run less efficiently, using more fuel and wearing through the tires faster.

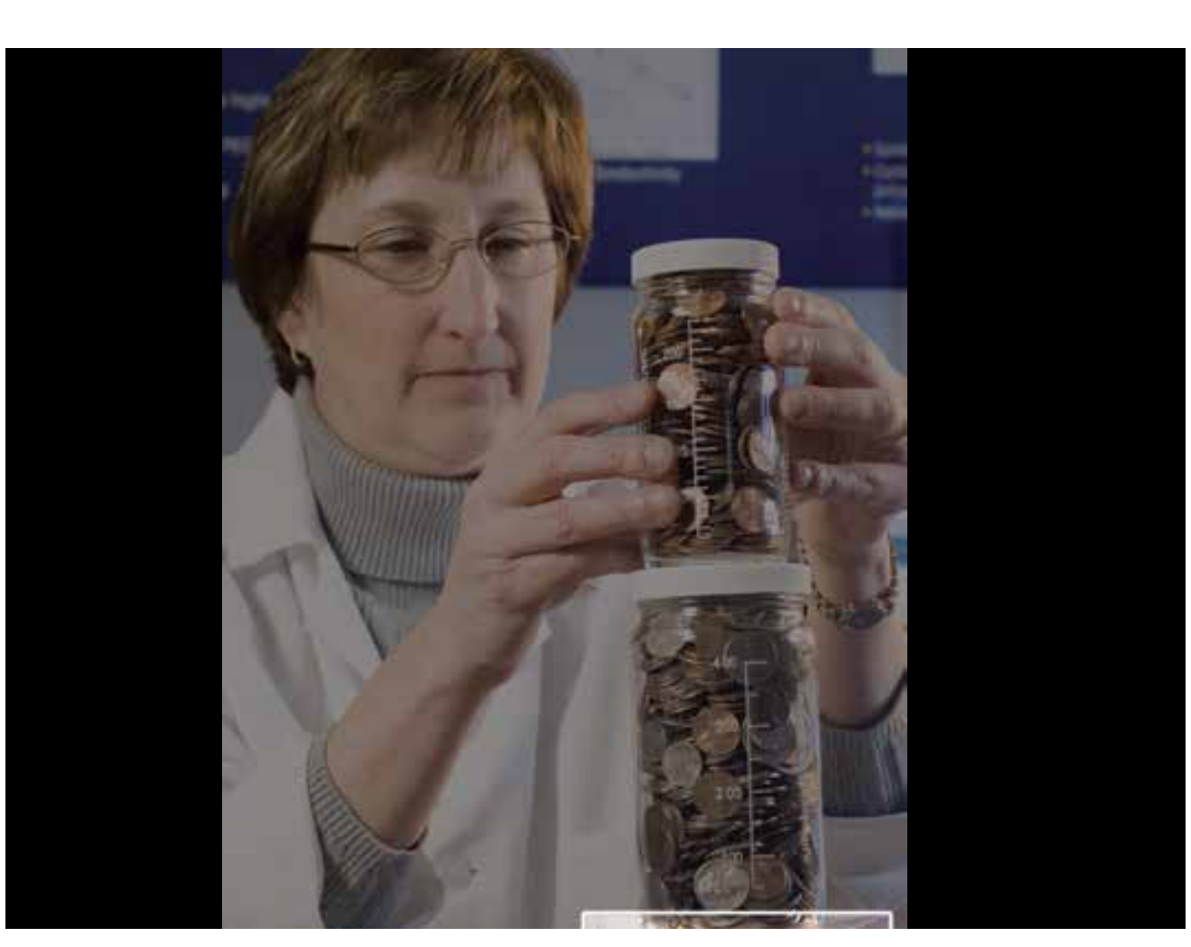
Amphenol continues to sell the NovaSensor P1602, which, despite upgrades, is essentially the same product created 25 years ago. Though no longer a huge part of Amphenol's business, Ready says, the tire pressure sensors "definitely played a critical role in first making us profitable—it helped us turn 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 Insulator Evolves to Replace Plastic and Save Weight

When aerogels were first invented in the 1930s, nobody had much use for them. 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 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.

Aerogels are made by creating a gel and then carefully removing all the liquid. The delicate structure that remains is the world's lightest solid—in some cases over 99 percent air, contained within nanopores distributed throughout a sponge-like material.

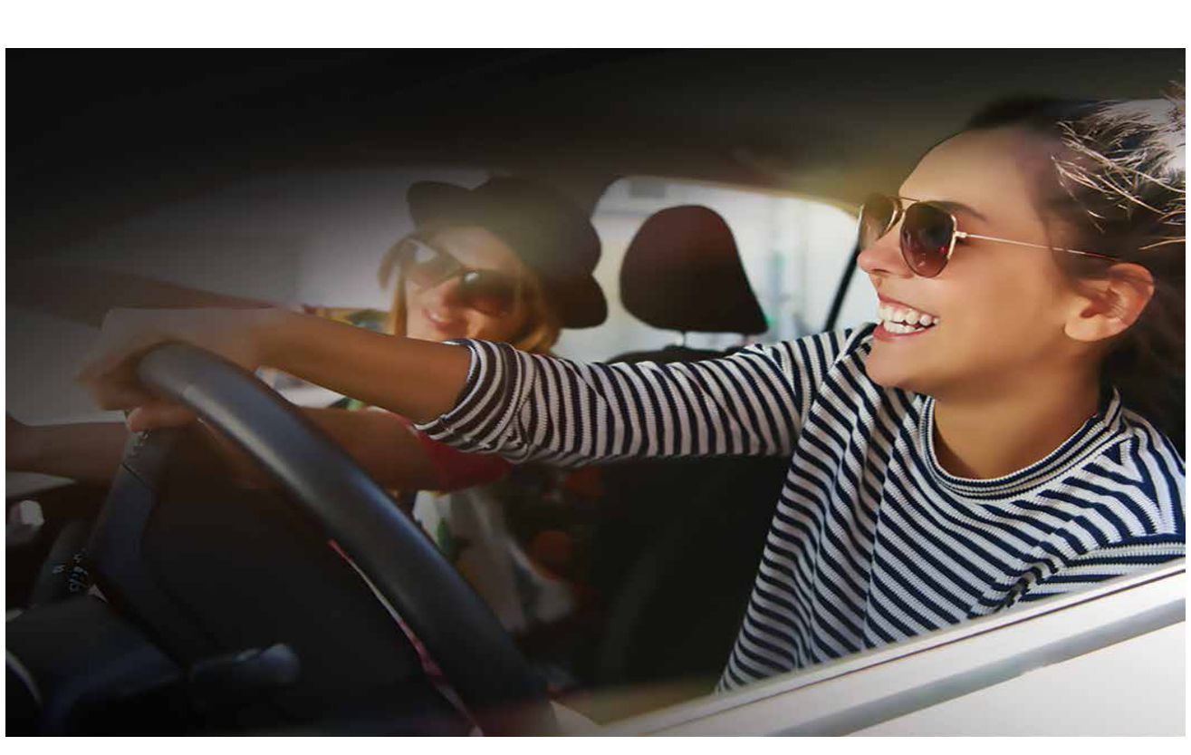
The commercial potential of aerogels only really got a jumpstart after a NASA-funded project figured out how to turn the famously brittle material into something useful. In the 1990s, a Small Business Innovation Research contract funded the development of aerogel-infused blankets, which were durable,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

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.

Since then, NASA has continued funding research into the materials. Most recently, says Glenn Research Center's Mary Ann Meador, "we've been working on using aerogels as a substrate for antennas."

But Meador is among the first to say the aerogels she has helped create have many other potential applications, including well outside NASA. That's why Glenn made its aerogel patents 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." Now, after additional in-house R&D, the Boston-based company is selling the material, which it has branded as "Airloys," to a variety of industries, including airplane and car manufacturers.



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

"Because they have plastic-like properties, our products are able to go into cars and airplanes to make them lighter—which can make them tremendously more fuel efficient," he emphasizes.

Software Helps Design Artery Stents, Lawn Mowers, Airplanes

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 died. Because the Boeing 737 was designed to resist exactly this type of cracking, and it was unclear how the damage occurred.

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.

Image courtesy of the National Transportation Safety Board

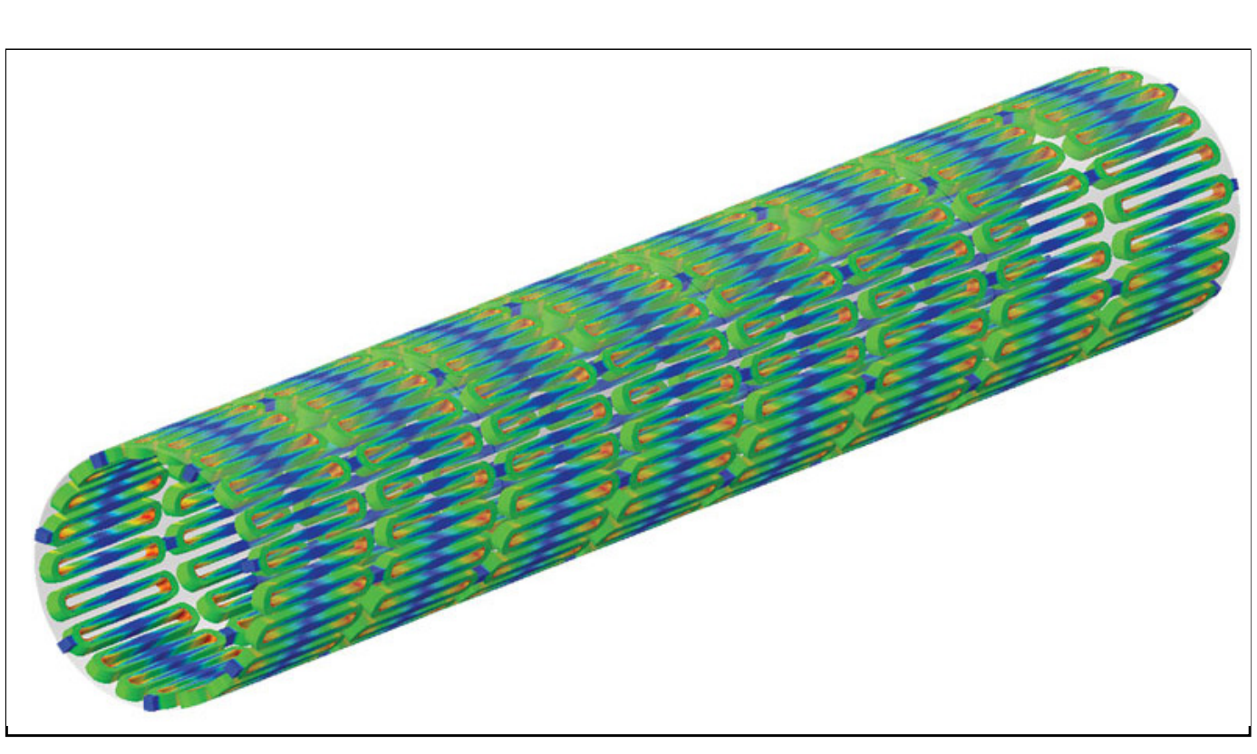
Researchers at Langley Research Center tasked with supporting the aeronautics industry created models of the fuselage joints using the Structural Analysis of General Shells (STAGS) code that Lockheed Martin was developing under a contract from the center. STAGS was one of several improvements being made at the time to finite element analysis (FEA) software, which breaks a structure down into tiny elements to analyze it and simulate its behavior.

One such software suite is Abaqus FEA. When French software company Dassault Systèmes bought Johnston, Rhode Island-based Abaqus Inc. in 2005, the programming needed to be updated to account for new composite materials and manufacturing processes. Its developers created a Fracture Customer Review Team that included NASA engineers, with whom it met regularly for the next decade.

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.

Image courtesy of Ariens Company

Among other improvements, developers added many capabilities of the STAGS code. As the company issued updates, NASA engineers often helped test them and ensure they met the Agency's needs. 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.



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

Image courtesy of Craig Bonsignore, CC BY 2.0

Today, a host of industries use Abaqus FEA software. Engineers have used it to develop 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, which has 50 percent fewer parts and lower production costs than predecessors. And students at the Norwegian University of Science and Technology are designing award-winning Formula Student race cars with the software.

Super-Accurate Atomic Clocks Could Aid in Navigation, Communication

Being able to measure time accurately and consistently is fundamental to advanced scientific research, but it could also be the key to what comes next after GPS.

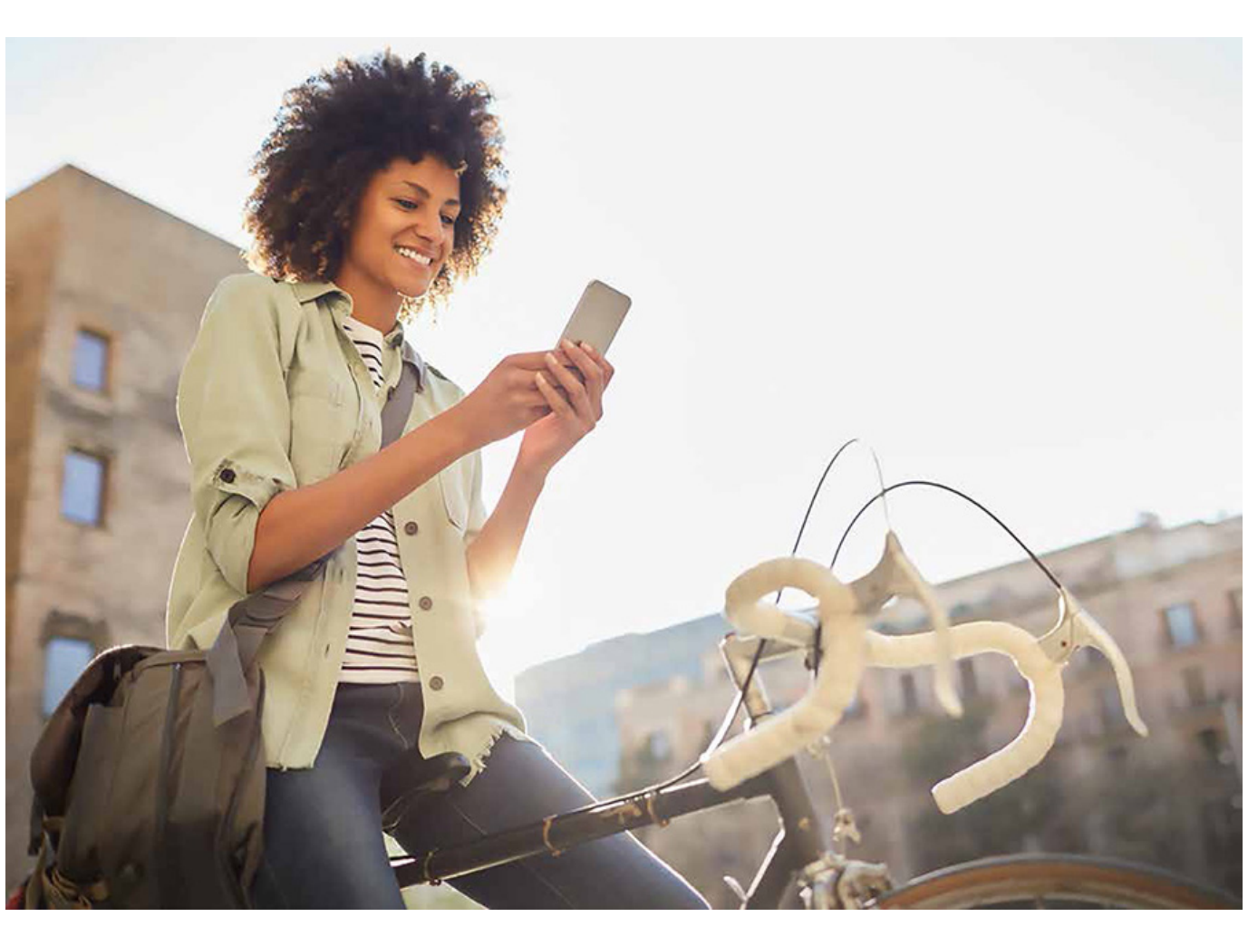
The best atomic clocks currently made "won't lose a second in the entire life of the observable universe," says Goddard Space Flight Center's Gregory Heckler. Unfortunately, those clocks tend to fill up an entire laboratory.

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.

One company working on making them portable is Sunnyvale, California-based AOSense Inc., with the help of several Small Business Innovation Research (SBIR) contracts from NASA, most with Goddard.

"We're doing the engineering necessary to make [optical atomic clocks] a lot smaller, a lot more robust, and able to operate autonomously and at low power," says AOSense's former vice president of strategic planning, Jamil Abo.

AOSense has already completed a compact laser-cooled atom source that operates on less than five watts and is "small enough to fit in a shoebox"—all while outperforming the large academic versions.



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.

That means "the academic labs aren't building their own anymore—they are buying ours," Abo says. Sales are just in the tens per year, he says, "but it helps sustain our engineering efforts."

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.

They anticipate a larger market for the completed clock—and a wider impact. Already, people rely 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.

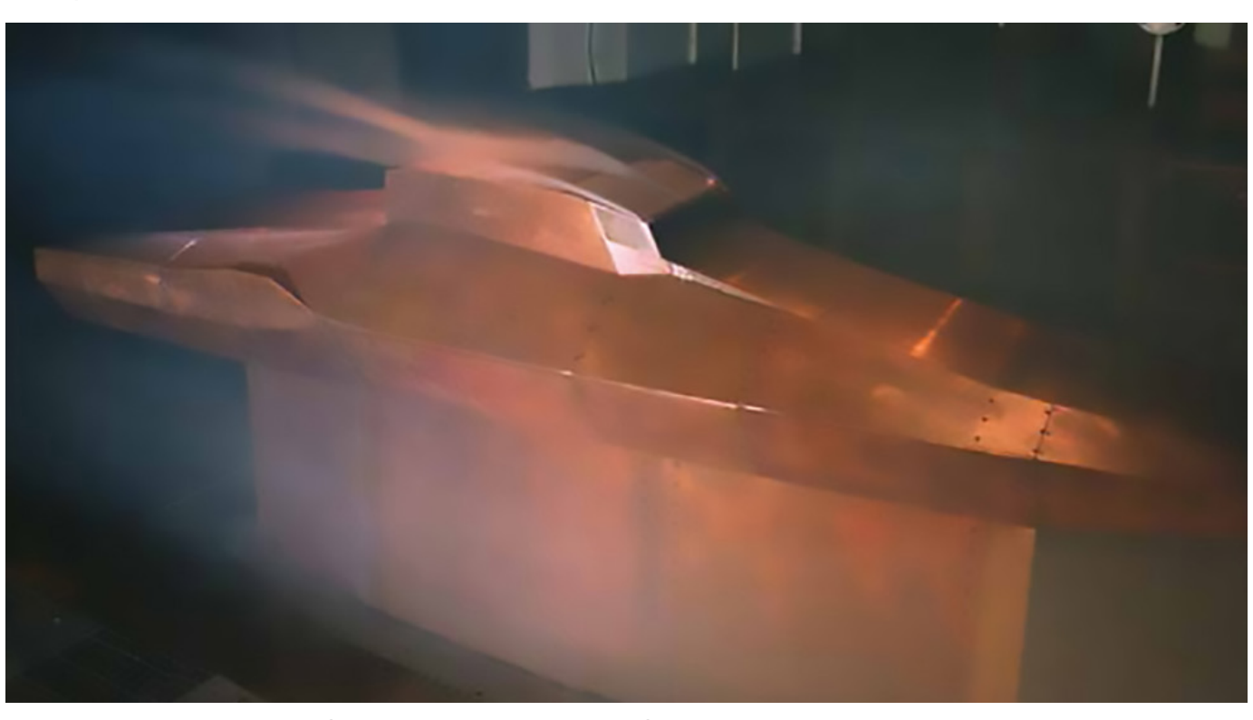
This laser-cooled atomic source "powers" an optical atomic clock. Unlike lab-size versions, this source consumes less than five watts and fits in a shoebox, while actually outperforming its larger predecessors.

Right now, the GPS satellites that provide this timing reference synchronize with atomic clocks at the Naval Observatory, but AOSense sees a future where each satellite could have its own. Likewise, an inertial navigation system built into the vehicle, using an atomic clock, would be safer than relying on jammable and hackable GPS.

Probes Characterize Air and Water Flows over Aircraft, Yachts

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

Anemometers are devices for measuring fluid speed, and Tao Systems Inc., based in Hampton, Virginia, first pioneered the constant voltage anemometer (CVA) under two Small Business Innovation Research contracts with Langley Research Center in 1992, releasing it as a commercial product soon after.



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.

The CVA, as well as constant temperature and constant current anemometers, usually use probes consisting of a tiny wire 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 wire's resistance decreases at lower temperatures, the anemometer can derive wind speed from the resistance in the wire. Unlike its cousins, the CVA holds input voltage constant, deriving flow velocity from output voltage.

Capable of up to 1 million readings per second, the CVA is especially advantageous for high-speed wind tunnel testing. Measuring small aerodynamic structures at high speed requires extremely high frequencies. The probes can also detect temperature fluctuations, becoming sensitive to temperature only at low voltage levels too weak to heat the sensor.

Because it can rapidly shift back and forth between low voltages that detect temperature and higher voltages that sense velocity, the CVA yields much faster results than other anemometers. Conventional systems use multiple sensors at different dedicated temperatures and risk burning out if temperatures change too rapidly. The CVA also produces a cleaner, less noisy signal.

Langley is currently testing the CVA against other anemometers in wind tunnel testing.

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, multichannel Model 4-600 (inset) is currently under testing at Langley to compare the CVA with other types of anemometers.

Image courtesy of Dale Frost, CC BY 2.0

While the primary users for the technology will likely continue to be NASA, the military, and aircraft manufacturers, the CVA has other applications, such as monitoring heat flows in fuel cells and characterizing the fluid dynamics of yacht designs. It's even been used to design America's Cup-winning yachts.

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

The Jet Propulsion Laboratory's (JPL) experience using signals from distant quasars to determine the precise locations of a network of radio telescopes was what initially led the center to begin supporting another location-based system: GPS.

In the 1980s, as the U.S. Air Force was launching GPS satellites, JPL started building its GPS tracking network, collocating the first ground stations with these radio telescopes.

But GPS data can be off by 30 feet if not calibrated for errors and delays. GIPSY-OASIS, the software JPL developed early on to correct for these errors, became one of NASA's most widely licensed software programs. When the Internet became widespread in the 1990s, JPL developed Real-Time GIPSY (RTG) software to make these corrections live. A host of possibilities opened up.

An early investor was the Federal Aviation Administration, which made RTG the prototype for its Wide Area Augmentation System, which tens of thousands of smaller planes now use for navigation and guided landings.

As word spread of what came to be called Global Differential GPS (GDGPS), in 2002, the Air Force sponsored a dedicated service to provide a wealth of information about the satellites and signals to its GPS operators, which JPL still continues in support of the entire GPS enterprise.

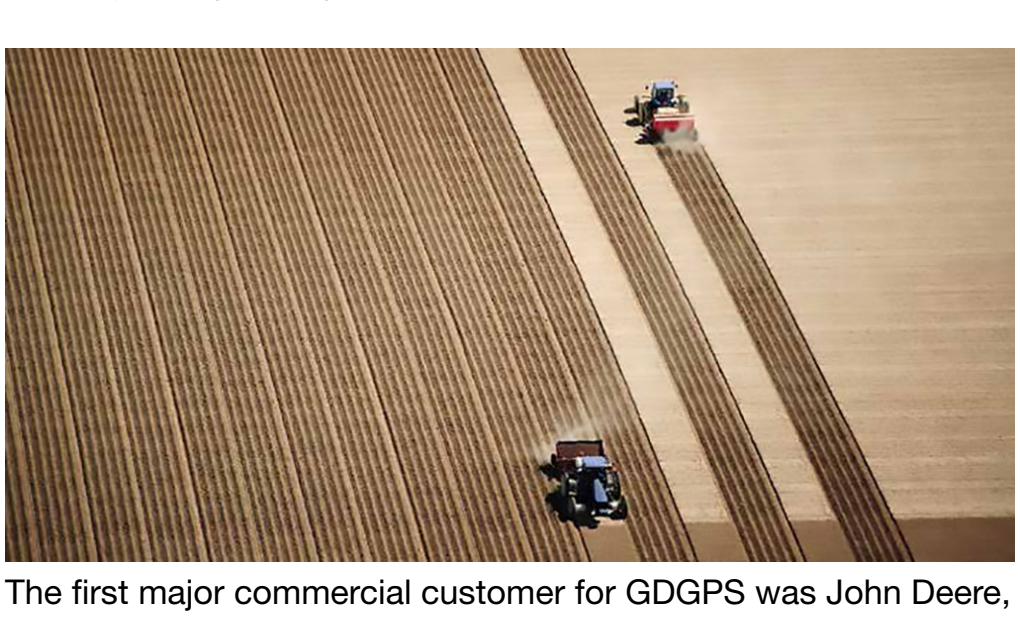
One early adopter of GDGPS was Long-Island-based Comtech Telecommunications Corporation. Today the company uses that data to provide locations to 911 responders for calls from about half of cell phone users in the United States and millions of others around the world. Comtech and other companies' use of GDGPS is also the reason navigation apps on smartphones immediately acquire satellite connections. And Comtech and others use it for asset tracking, navigation, and location-based social media.

GDGPS enabled the first self-driving farm equipment, giving rise to precision agriculture globally. It's also commonly used in offshore oil drilling, mapping, surveying, construction, and Earth sciences. NASA has demonstrated how it can be used to detect earthquakes and warn of tsunamis. And GDGPS now supports the world's other navigation satellite systems.

While NASA has always been a key user of GDGPS, its ongoing development has been funded almost entirely by these many other government and commercial users.

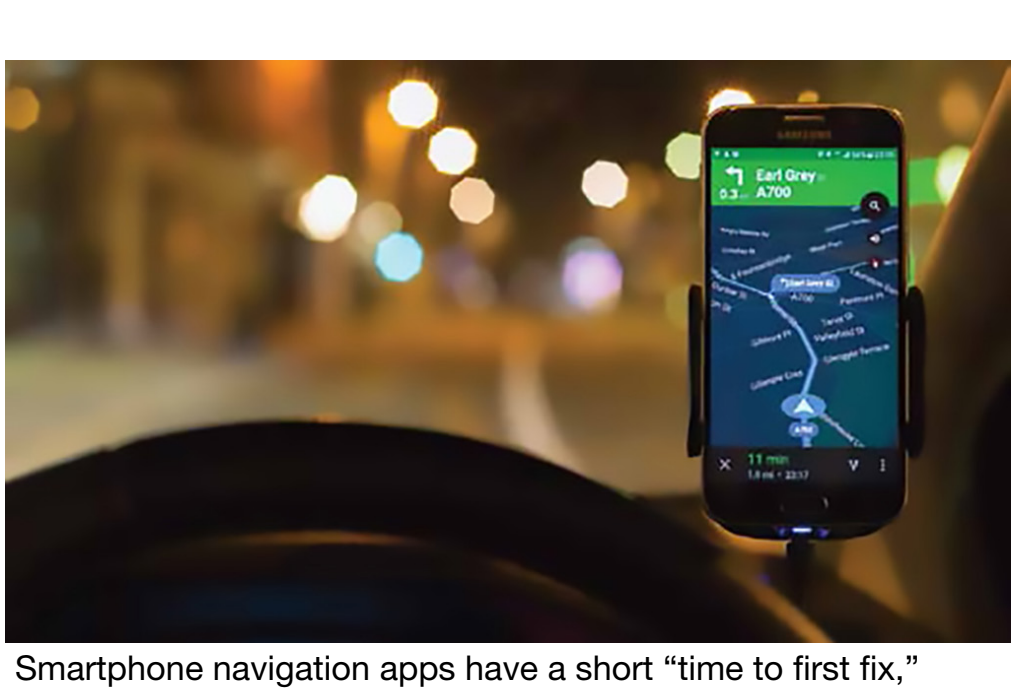
The Jet Propulsion Laboratory (JPL) got involved with the Global Positioning System (GPS) in the system's early days because JPL researchers had experience tracking radio signals from quasars, some of the brightest objects in the universe, to precisely locate radio telescopes on Earth's surface, giving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

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.



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.

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.

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.

Gas Regulators Keep Pilots Breathing

In 1962, John Glenn became the first American to reach orbit—and he was able to breathe thanks to technology created for that historic flight. All U.S. astronauts since have used a derivation of the same technology—and commercial airline pilots rely on backup oxygen systems that also trace back to the one invented for Glenn's flight.

It started with a jet engine issue that no longer exists.

"Early jet engines had problems with flameouts," explains Jim Talty, vice president of engineering at Cobham Missions 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: too much, too fast would cause another flameout, but not enough and the ignition wouldn't catch.

For astronauts breathing canned air, the same is true: too much too fast will hurt the astronaut, but too slow and the astronaut could asphyxiate.

The solution Cobham built is a small mechanical system with a spring-loaded valve that opens when the pressure lowers enough to relax the load on the spring. Previous versions were too big and heavy for space, and also didn't meet NASA's strict oxygen safety standards.

Cobham (then operating as Carleton Controls) innovated by combining two different springs in a new way, which maintained performance in a smaller size. It also learned from NASA how to best choose materials for oxygen safety.

Today, the company still uses the spring arrangement and its oxygen safety expertise in its latest products, including breathing regulators used in emergency oxygen systems for pilots of most major airlines.

"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," says Talty.

Other applications include military planes and submarines, as well as for elite military parachutists jumping from high altitude. Cobham also used its oxygen safety expertise to create a product that produces high-purity oxygen—between 99.5 and 99.99 percent pure—from room air for a variety of settings, including wastewater treatment and offshore drilling.

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.

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.

RoboMantis Offers to Take Over Dangerous Missions

At the 2015 DARPA Robotics Challenge, working slowly and deliberately, the Jet Propulsion Laboratory's (JPL) RoboSimian drove a vehicle, cleared a path through rubble, cut a hole in drywall, and opened and navigated doors, among other challenges. Carrying its white, tub-like body on four black, tubular limbs, the headless automaton navigated its surroundings with several sets of dual video cameras and a lidar device. The actuators powering its joints include brakes that let the robot hold long, awkward poses at low power to make it "patient." Its semi-autonomous operating system assumes that speed comes not from rapidity but rather from avoiding mistakes.

RoboSimian ranked fifth out of 23 robots in the competition.

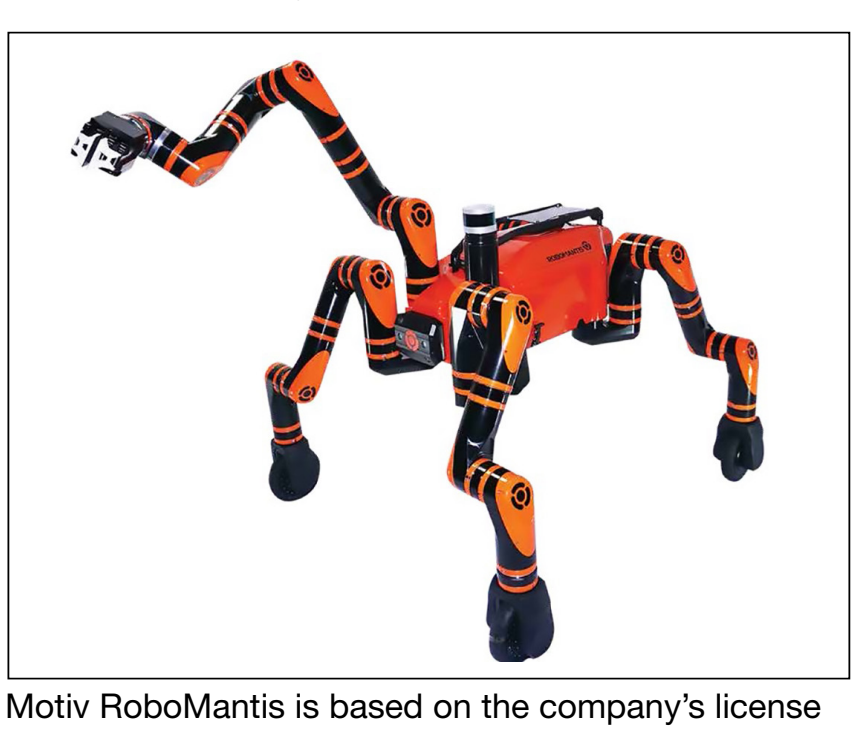
Even before the finals, the California Institute of Technology, which manages JPL, made the entire robot available for license as a package, an entire toolbox of robot technology. Robotics company Motiv Space Systems of Pasadena, California, soon licensed the technology, using it as a starting point for a next-generation version. That robot, the alternately five- or six-limbed RoboMantis, was unveiled in January of 2018.

For this 2.0 version, the company created new software, module interfaces, and actuators, as well as a new power system. While RoboSimian is so stable that its creators didn't need to program it to deal with falls, RoboMantis is even more so, with its ability to keep four limbs on the ground while working.

Motiv's target clientele for the robot is any company or organization that works in hazardous environments—from disaster relief to the oil and gas industry—where it can stand in for a human. The company hopes to see RoboMantis in chemical plants, power plants, oil fields, subterranean operations, and other industrial settings. Military applications like bomb disposal represent another possibility.

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.

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.



Motiv 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.

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.

Image courtesy of the U.S. Air Force

Wrapped Tanks Cut Weight on Everything from Buses to Paintball Guns

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.

The invention was a tank that could store gases and liquids at higher pressures than previously possible. Known as composite overwrapped pressure vessels (COPVs), they comprise a liner wrapped in a resin-embedded filament, and they can weigh 50 percent less than all-metal pressure tanks. The higher pressure allows the same amount of gas to be stored in a smaller cylinder.

Lewis Research Center, now Glenn Research Center, spent years exploring different combinations of liners, fibers, and resins, as well as various winding patterns and testing methods.

Aerojet General Corporation carried out much of this work at Lewis, and in 1971, four Aerojet engineers formed Structural Composites Industries (SCI) to continue that work. SCI would become the first company to manufacture the tanks for commercial use.

An early application improved firefighters' breathing apparatuses: COPVs stored oxygen at twice the pressure of their predecessors. Boeing soon used SCI's cylinders to store the gas that would fill emergency escape chutes on airliners. Both uses, and many others, are now commonplace.

SCI was purchased by Worthington Industries in 2009, but its production facilities in Pomona, California, remain among the leading COPV manufacturers.

Worthington sells 60,000 to 80,000 COPVs per year.

They hold the oxygen for airplanes' emergency breathing systems and the gas that ejects their landing gear in an emergency. On helicopters, they provide breathable air for pilots and, in emergencies, blow doors open and inflate floats.

The largest COPVs hold compressed and liquid natural gas on buses and other vehicles. Others are in breathing apparatuses for aviation, life support, deep sea diving, and high-altitude parachuting. They're popular in military applications, like air-powered Phalanx guns and lightweight drones. Even high-end paintball guns use them to pack more pressure.

And they're found on almost all spacecraft.

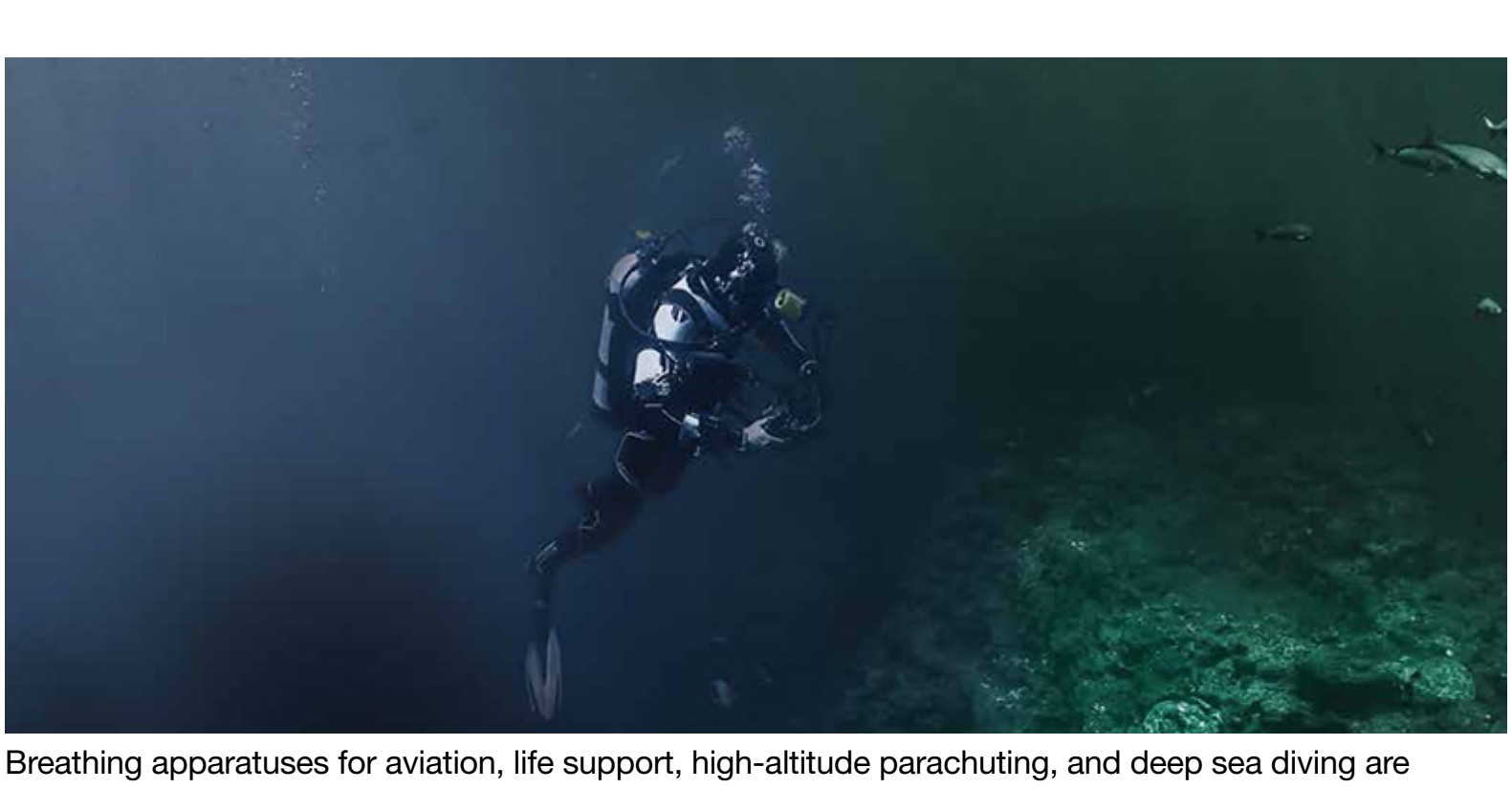
High-end paintball guns use composite overwrapped pressure vessels (COPVs) to pack more air pressure into the same-sized tank.

Image courtesy of the U.S. Air Force

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

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. Air Force



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

Image courtesy of Piro4D, CC0

Membranes Mimic Kidneys to Filter Water

When tackling a tough problem, engineers often 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 Aquaporin A/S.

One problem NASA has always faced is the need to clean water efficiently. On the International Space Station (ISS), all moisture, from humidity to urine, is purified and reused—but the filtration system is heavy, needs frequent replacement, and fails to remove certain contaminants.

An encounter at a seminar in 2007, where Jensen met Michael Flynn, lead for the Advanced Water Recycling group at Ames Research Center, introduced a possible solution. Jensen and colleagues at Aquaporin, of Copenhagen, Denmark, had been developing filters based on aquaporins—the proteins that transfer water through the membranes of all living cells.

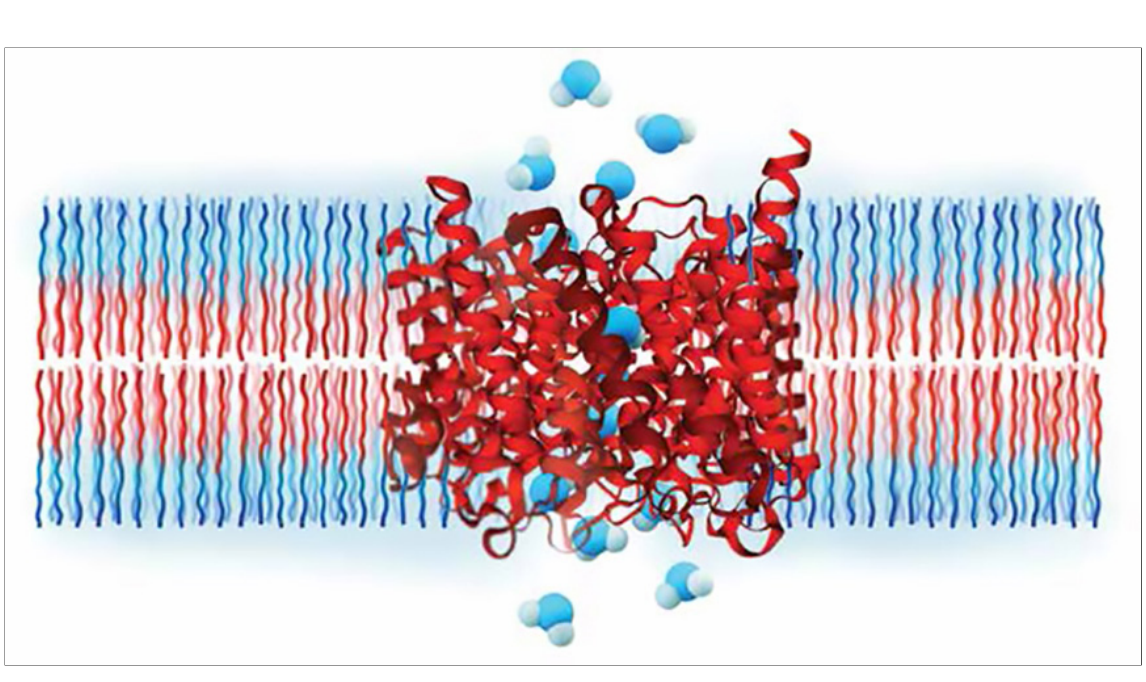
Aquaporins allow human kidneys to filter about 45 gallons of fluid per day, for example, and are highly selective, meaning only water passes through, not contaminates.

Flynn ordered prototypes, and with Ames funding, the company managed to overcome the challenge of incorporating the proteins into a membrane. The filters proved successful in testing at Ames and aboard the ISS for forward- and reverse-osmosis filtration.

In reverse osmosis, water is pushed through a filter, whereas forward osmosis is more efficient and relies on the physics of entropy. But the system on the ISS, like most filtration systems, is built for reverse osmosis.

The company now sells household under-sink modules made with its Tap Water Reverse Osmosis Membrane to distributors abroad, especially in China and India, where there is a huge market for home water purification. Jensen says the membranes filter water about twice as fast as other home purifiers and recover nearly twice as much water.

But Aquaporin mainly has industrial uses in mind for forward osmosis, which can handle highly contaminated wastewater efficiently and without clogging, eliminating pre- and post-treatment steps. The company is partnering with more than 50 wastewater treatment companies that are pilot-testing these membranes.



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.

Illustration courtesy of Vossman, CC BY-SA 3.0

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. Image courtesy of the European Space Agency

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

Dutch 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.

Detailed Spectrometry Makes Dangerous-Materials Testing Safer

In Chris McKay's search for signs of life on other worlds, some of the strongest clues come from identifying isotopes.

Isotopes are varieties of a single element with varying numbers of neutrons. For example, by analyzing the ratio of different isotopes in a carbon sample, McKay explains, researchers can determine whether it's a product of biology. Likewise, water carries isotopic evidence of its many phase changes.

The Mars Curiosity rover, for which the Ames Research Center scientist is a co-investigator, has a mass spectrometer that can identify some of these isotopes, but it needs to create a vacuum to analyze a sample. Due to that difficulty, Curiosity only used the mass spectrometer about 15 times in five years.

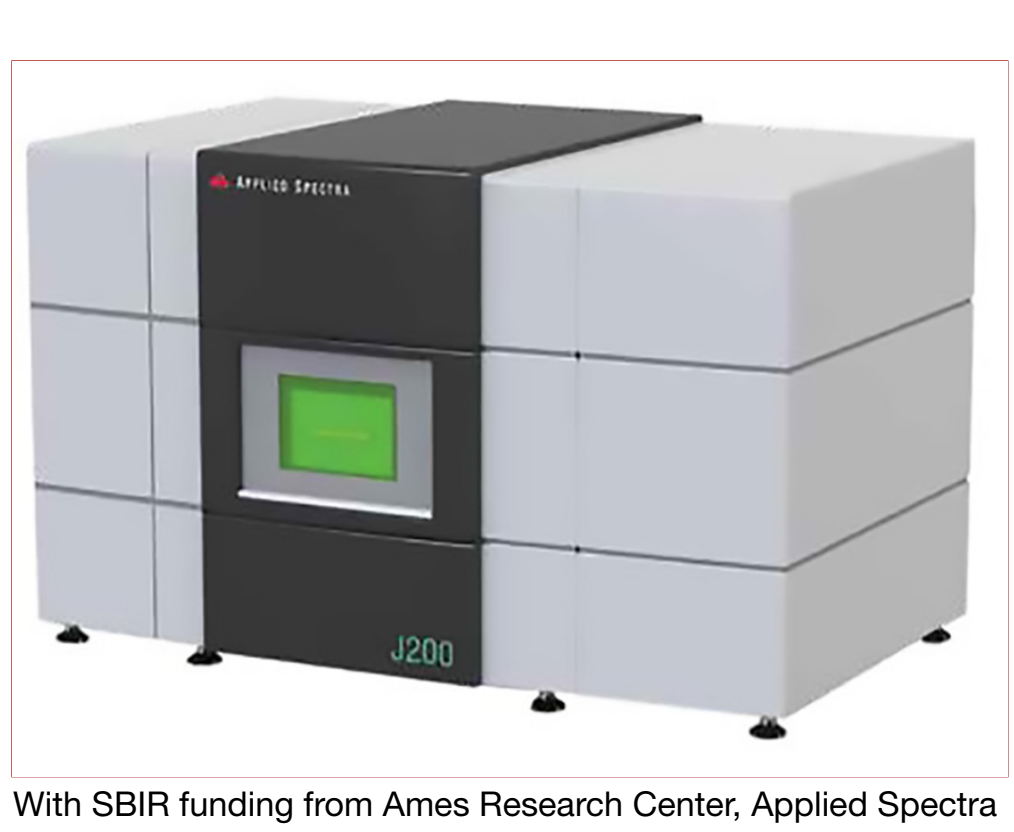
By contrast, another of the rover's tools has run more than 15,000 analyses. The laser spectrometer can zap any surface from a distance and determine its chemical content by observing the resulting flash, using a technique known as laser-induced breakdown spectroscopy (LIBS). But a laser spectrometer can only identify elements, not their isotopes.

So in the early 2000s, Alexander Bolshakov, then a senior researcher at Ames, proposed fine-tuning LIBS to the point that it could recognize even the slight shifts in electrons that identify isotopes.

"Nobody actually believed that this was possible," Bolshakov recalls. He managed to get a grant to start the work at Ames. In 2007, he left NASA to join Fremont, California-based Applied Spectra, which won a series of Small Business Innovation Research (SBIR) contracts with Ames to continue the project.

By fine-tuning the laser, the spectrometer, and the programming, the company was able to do what even McKay, who oversaw the SBIR contracts, doubted was possible. Applied Spectra calls the result Laser Ablation Molecular Isotopic Spectrometry.

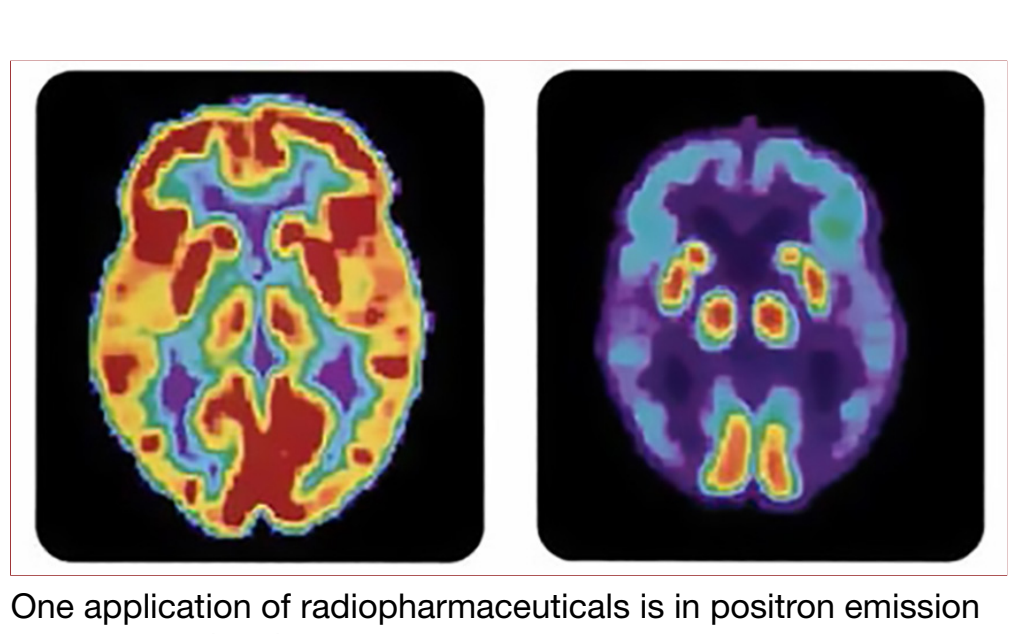
The technology should prove useful for various applications, but its big advantage over existing technology is that it can analyze samples without collecting them, making it attractive for characterizing radioactive material used in fields like nuclear energy and nuclear medicine.



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.

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 Dean Calma, International Atomic Energy Agency



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.

Image courtesy of the National Institute on Aging

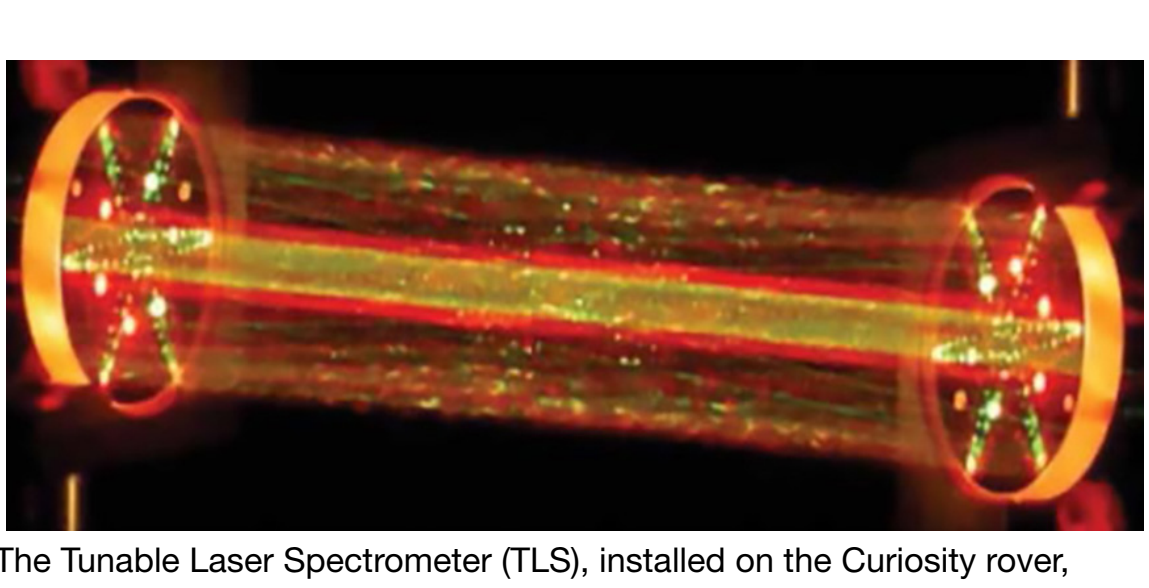
Methane Detector Sniffs Out Leaks

Methane is the main ingredient in natural gas fuel—and a potent greenhouse gas. It's also interesting as a sign of life: the biggest producer of it, on Earth at least, is bacteria. That means when NASA planetary scientists caught a glimpse of methane on Mars, it merited a closer look.

So a team at the Jet Propulsion Laboratory (JPL) built a tunable laser spectrometer (TLS) that can detect even minute traces of methane, as well as of carbon dioxide and water vapor, and installed it on the Curiosity rover, which landed on Mars in 2012.

Building a powerful enough space-ready spectrometer that was still small enough in size, weight, and power consumption required innovation—and it also drew on advances NASA had already made in things like efficient, miniature, mid-infrared lasers.

After the Curiosity work, JPL scientist Lance Christensen redesigned the TLS for Earth applications, especially in the natural gas industry. By trading off a bit of sensitivity, he made it even more lightweight—so it could be mounted on drones—and faster, able to run analyses 10 times a second.



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.

Andrew Aubrey, who also worked on the project, and Christensen decided to leave JPL and license the technology to create Pasadena, California-based SeekOps in 2017.

"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." A full well-pad inspection can take as little as 15 minutes using the drone-mounted SeekOps system, which is 1,000 times more sensitive than competing technologies.

The company also sells its system as handheld and vehicle-mounted devices.

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

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

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.

In the late 1990s, scientists at Langley Research Center, concerned with pilots' distractibility, came up with an index for measuring engagement by observing brainwave outputs. Then they let subjects monitor their own attention index—and try to control it.

The team found that subjects who were shown their attention level, as determined by brainwave output while performing a task, were able to learn to control it. They were responding to a "biofeedback loop." They also outperformed peers on the same tasks weeks later, even without feedback.

The engineers used these findings to build two inventions. First came a mechanical putting green. Based on the premise that golfers putt best with a quiet mind, the course physically undulated until electrodes on the golfer's forehead indicated strong alpha brainwave output, associated with an idling mind and meditation.

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.

Then they made MindShift, a first-person shooter video game that encouraged a different state of mind. The team found a way to compromise the signal from a Nintendo Wii controller, causing the cursor to circle, until the player's brain emitted dominant levels of beta waves, indicating alertness.

J&F Alliance Group of Hampton, Virginia, was working on virtual and mixed reality for training when the company heard about Langley's biofeedback technology in 2016. J&F licensed the golf and video game products, and the now-retired Langley engineer who had led their development joined the company as a consultant.

The team plans to sell both products but is first using the technology for a different application: virtual reality for military weapons training, with likely spinoffs for law enforcement and security personnel.

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. Image courtesy of the U.S. Army

Department of Defense agencies have put out calls for virtual reality training, which J&F planned to answer by late 2018 with a virtual reality shooting environment combining the MindShift concept with off-the-shelf equipment. The company calls the trainer the Biocyber Physical System, or BioPhyS.

"Improving mental readiness overall can significantly reduce avoidable incidents in military situations, both in training and real combat scenarios," says JarMarcus King, the company's chief operations officer.

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

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. Instead of dumbbells or cast-iron plates to provide resistance, he fashioned an elastomer compound into spiral-shaped torsional springs of various dimensions.

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.

At the time, NASA was struggling to combat the muscle and bone loss that plagued astronauts after prolonged weightlessness. Tying them to treadmills and stationary bikes wasn't sufficing, and traditional weights are useless without gravity. When Francis learned of this, he contacted Johnson Space Center. After he demonstrated his technology, now known as SpiraFlex, Johnson asked him to work with Lockheed Martin to build an astronaut exercise system.

A year and a half of development and testing resulted in the Interim Resistive Exercise Device, which astronauts used on the International Space Station for a decade. Francis now had a fully developed, tested, and validated mechanical system.

In the early 2000s, when Nautilus Inc., based in Vancouver, Washington, was looking for an alternative to its rod-based Bowflex home gym, Francis presented the company with his technology and several possible configurations, and he ended up helping the company design the Revolution based on SpiraFlex. It launched in 2005 to become Nautilus' most successful home gym.

"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 the company.

While the Revolution only weighs about 220 pounds, its leg press station can provide up to 600 pounds of resistance. It also takes up less space and is quieter than a traditional weight-based gym. Resistive equipment also eliminates the momentum free weights generate during lifting, which can be hard on joints and allow the user to cheat a bit on the upswing.

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.

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

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.

After creating an air and water purification system as PhD students, James Langer and Weihua Zheng cofounded Serionix Inc. in 2011, settling on air purification. In their systems, the company's patent-pending Colorfil technology uses a fabric-like nonwoven material coated with polyelectrolytes—polymer substances with a permanent electrical charge. The coating removes toxic chemicals and kills viruses, bacteria, and mold.

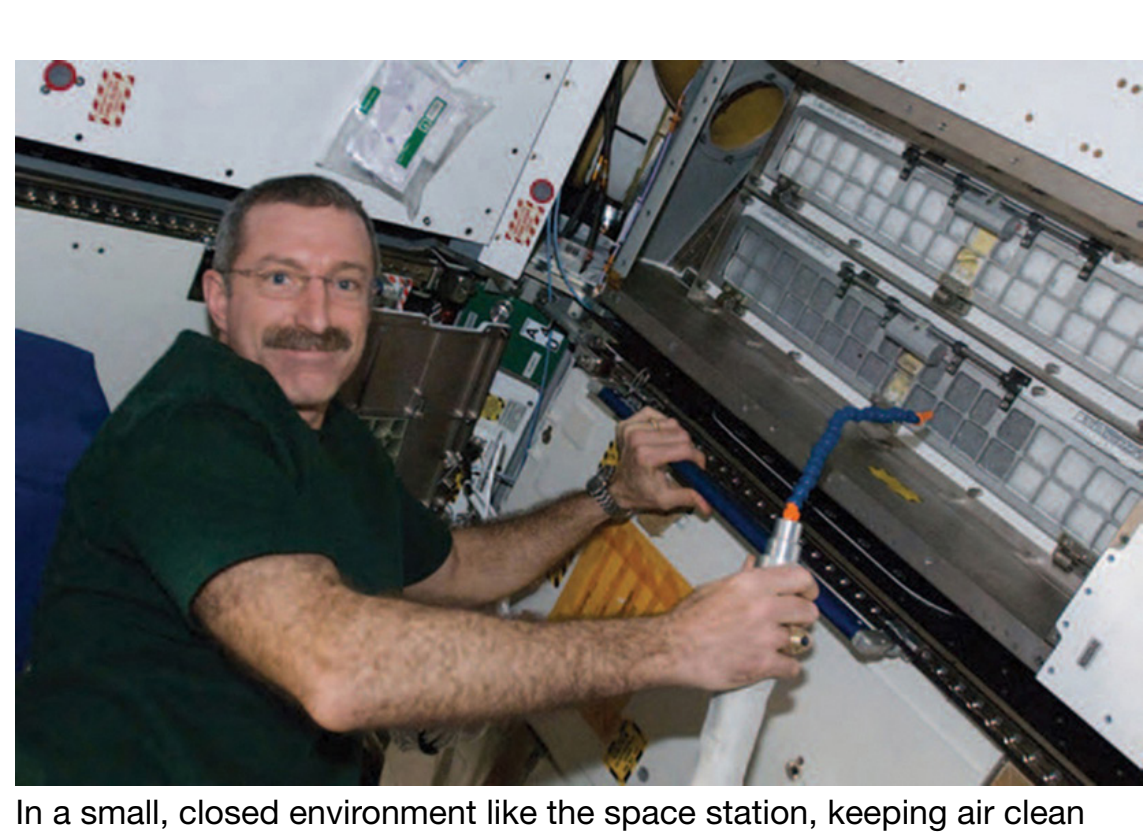
Johnson Space Center awarded Serionix, located in Champaign, Illinois, a Small Business Innovation Research (SBIR) contract in 2016 to fund a system for removing ammonia and formaldehyde from next-generation spacesuits. Further Johnson SBIR contracts focused not just on spacesuits but also spacecraft air quality.

Serionix's Colorfil technology also changes color from bright magenta to a drab yellow when a filter is spent, which prevents unnecessary filter changes.

In the consumer market, ammonia happens to be an issue with pet owners. Unpleasant odors from litter boxes and other pet spaces is due to ammonia and related chemicals in urine that Serionix filters excel at removing.

The company's commercial products now include a Colorfil-branded air purifier, an HVAC filter, and a cabin air filter for automobiles. Serionix has also been working with a microchip manufacturer, because that process is highly sensitive to ammonia and other corrosive gases.

Langer says the NASA contracts in particular have contributed to the development of these consumer applications. "The challenges of deploying the technology in space definitely serve us well in making a more robust product for our customers on Earth."



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.

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.

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?

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 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 (FMG) 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.

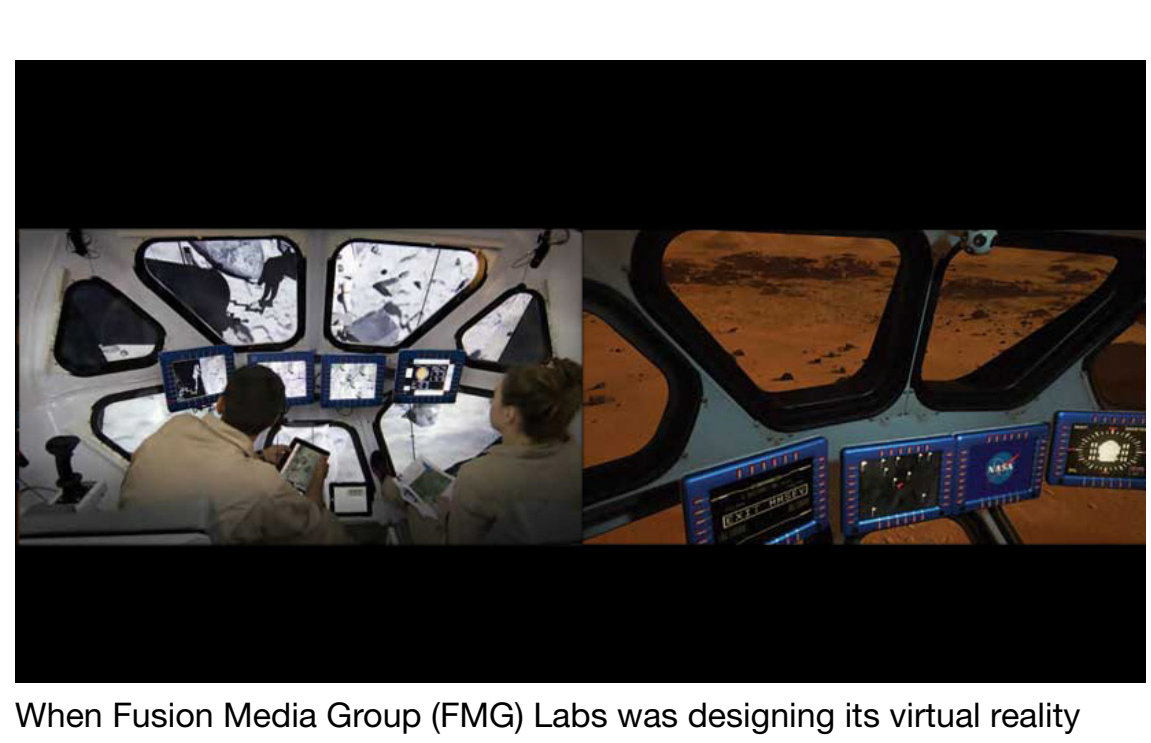
That was the goal, explains Julian Reyes, director of virtual and augmented reality at FMG Labs. "Typically, games have this conventional structure where you get points or are tasked with survival, the concept of a game itself, and we didn't want to make it a game, instead we wanted to use an interactive engine as a way to present scientific information."

The developers read Troutman's research, visited NASA centers to gather more resources, and collaborated with the Jet Propulsion Laboratory to get their hands on digital terrain models. They even drove a model Mars rover and recorded audio to incorporate into the game.

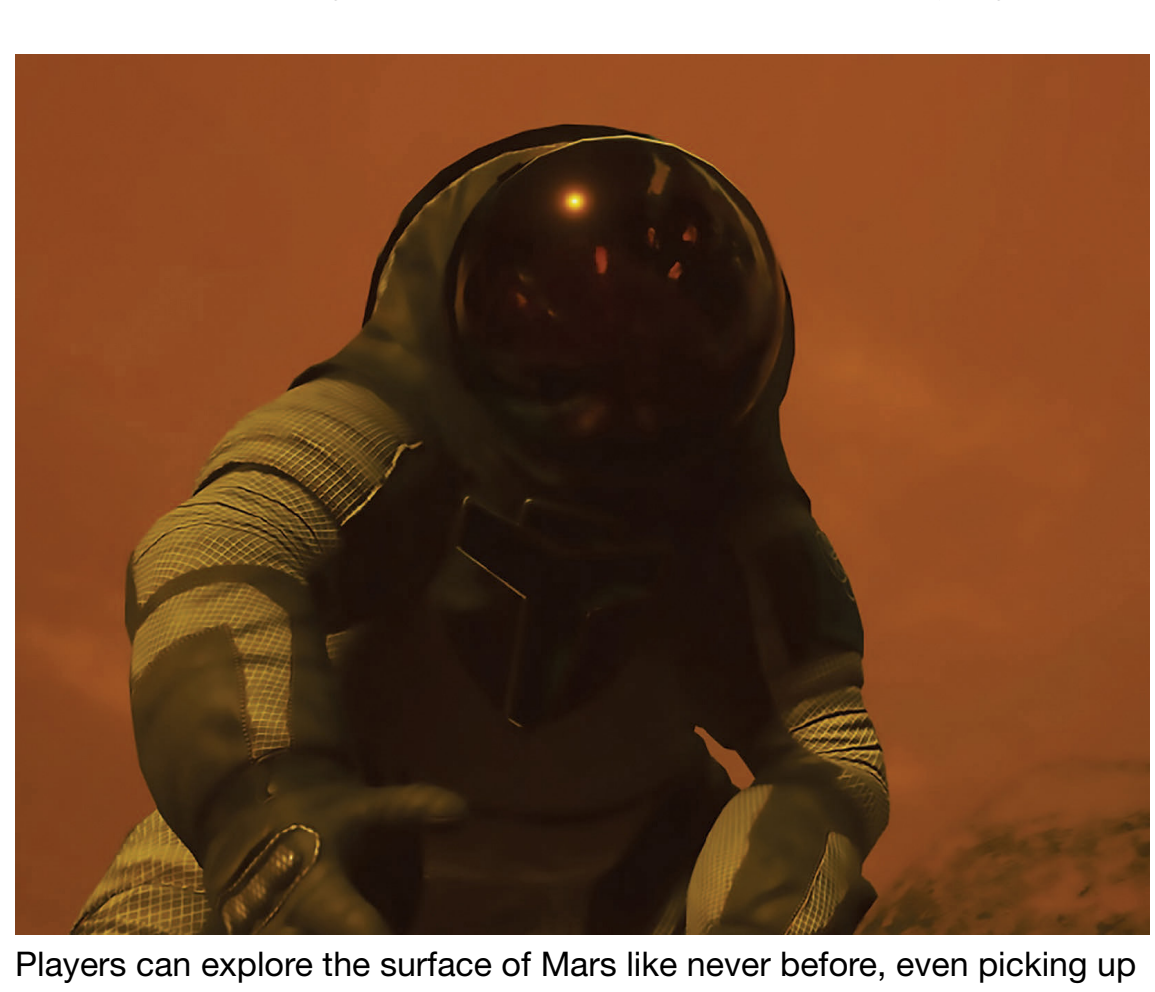
Today Mars 2030 is available for download and free for educators. Its Editor tool is also free to the public, so others can build new simulations.

"We want this to be in the hands of the students to inspire that sense that we can make it to Mars," says Reyes. "And hopefully some of them decide to become scientists themselves and try to elaborate on these concepts."

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 (FMG) 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).



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.

Memory Foam Supports and Shapes in Women's Apparel

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

But first the famously cushy foam was invented for a 1960s project to improve airline seating safety. "We decided to design a crash-proof seat," explains Charles Kubokawa, now retired from Ames Research Center, where he managed the project.

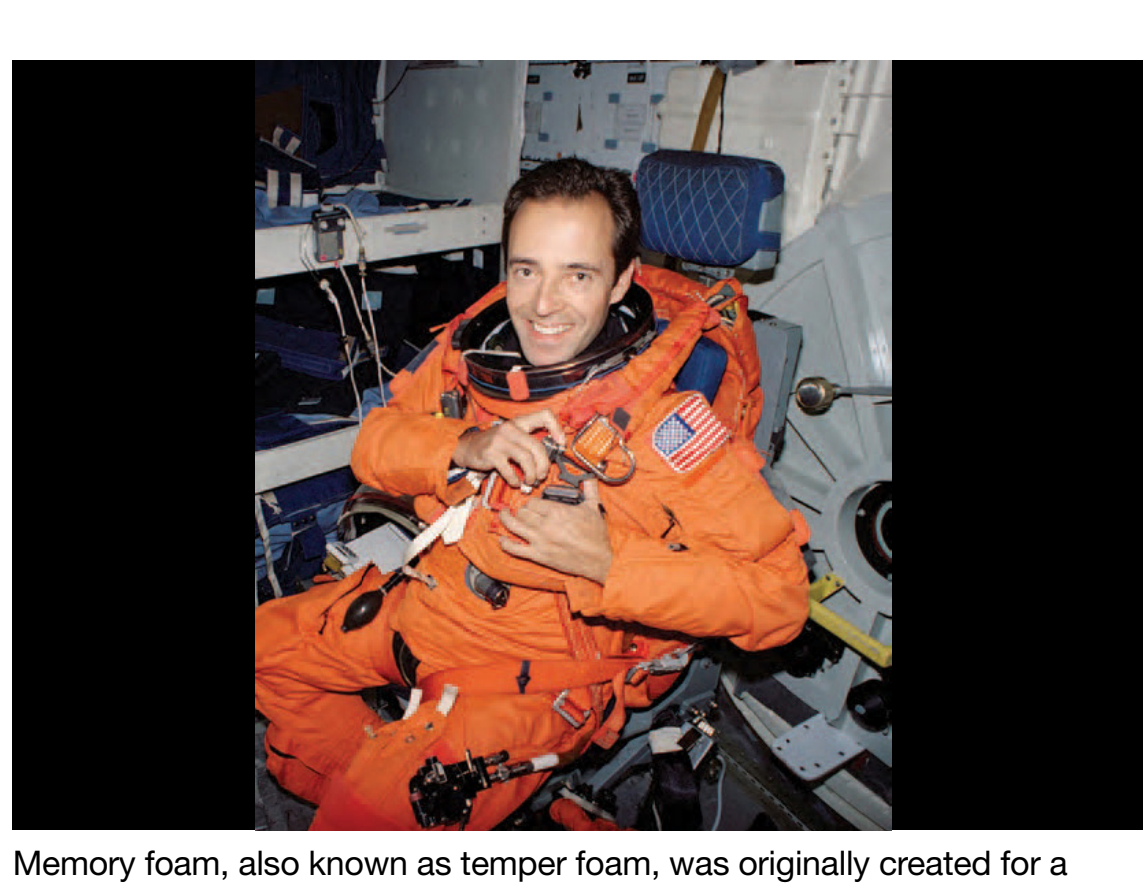
One of the most important innovations, Kubokawa recalls, was the foam cushion they integrated into the seat and back: "We called it temper foam." It did a remarkable job of absorbing impact, something the team tested with an anthropometric dummy at the Civil Aeronautics Medical Institute.

Although the seats were never fully integrated into commercial jets, the original "temper foam"— more commonly known today as memory foam—has found a wide range of uses, including cushions for orthopedic seating and mattress pads to reduce the risk of sores among wheelchair patients.

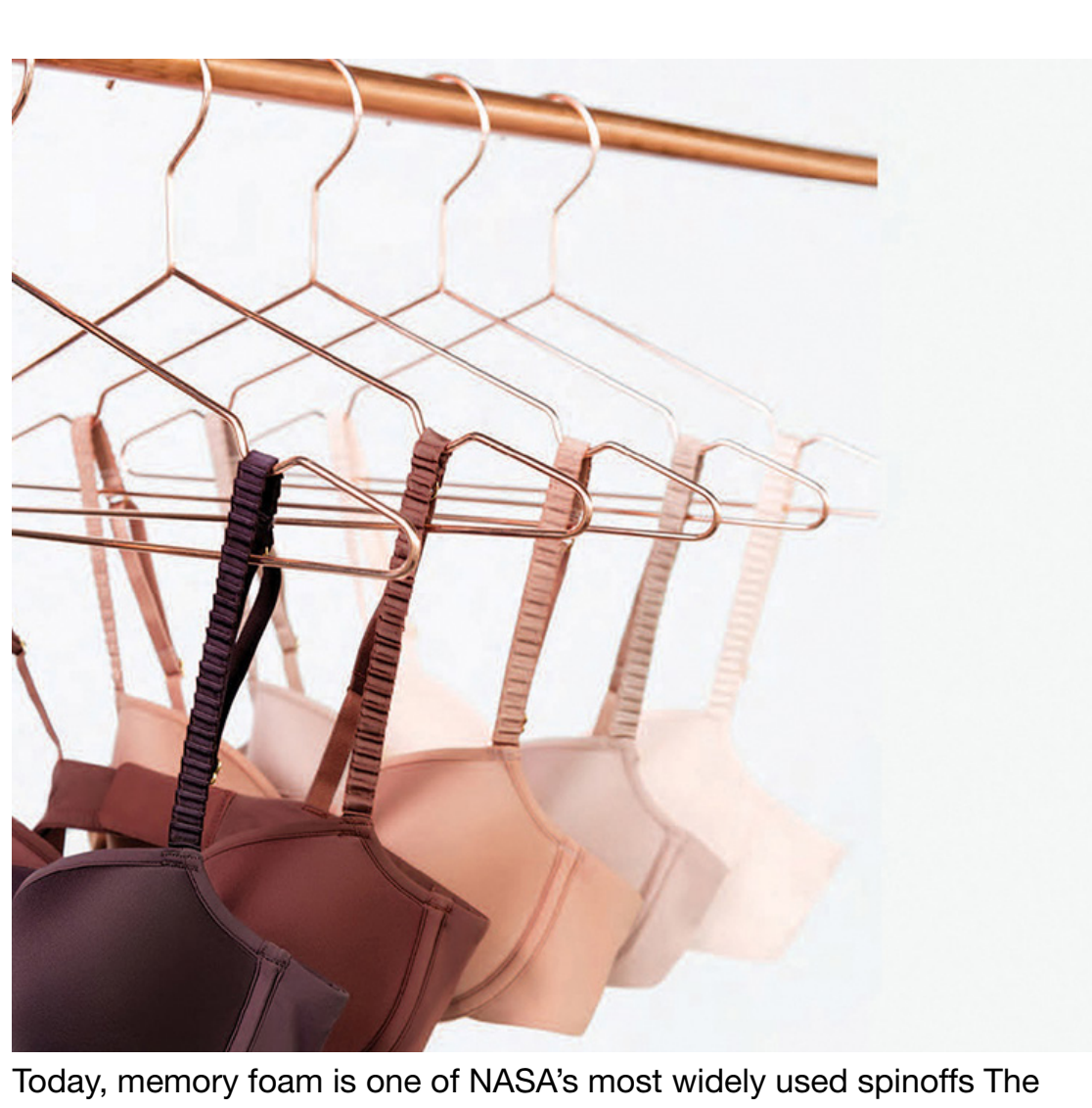
More recently, the material has found a place in San Francisco-based start-up ThirdLove's high-end bras, which take advantage of the foam's ability to soften with body heat and conform to the body. But the company still needed to innovate: "We wanted a thinner pad, but also needed it to be supportive enough," says design chief Ra'el Cohen. "Memory foam really does form to your body like a second skin."

The company tweaked the foam formula to cast it in lighter, less dense, thin sheets. And, unlike other garments that use a separate foam pad between layers of fabric, the company heat-laminates the nylon fabric directly to the foam. That adds extra structure to the foam, while also minimizing the total material and layers in the final garment.

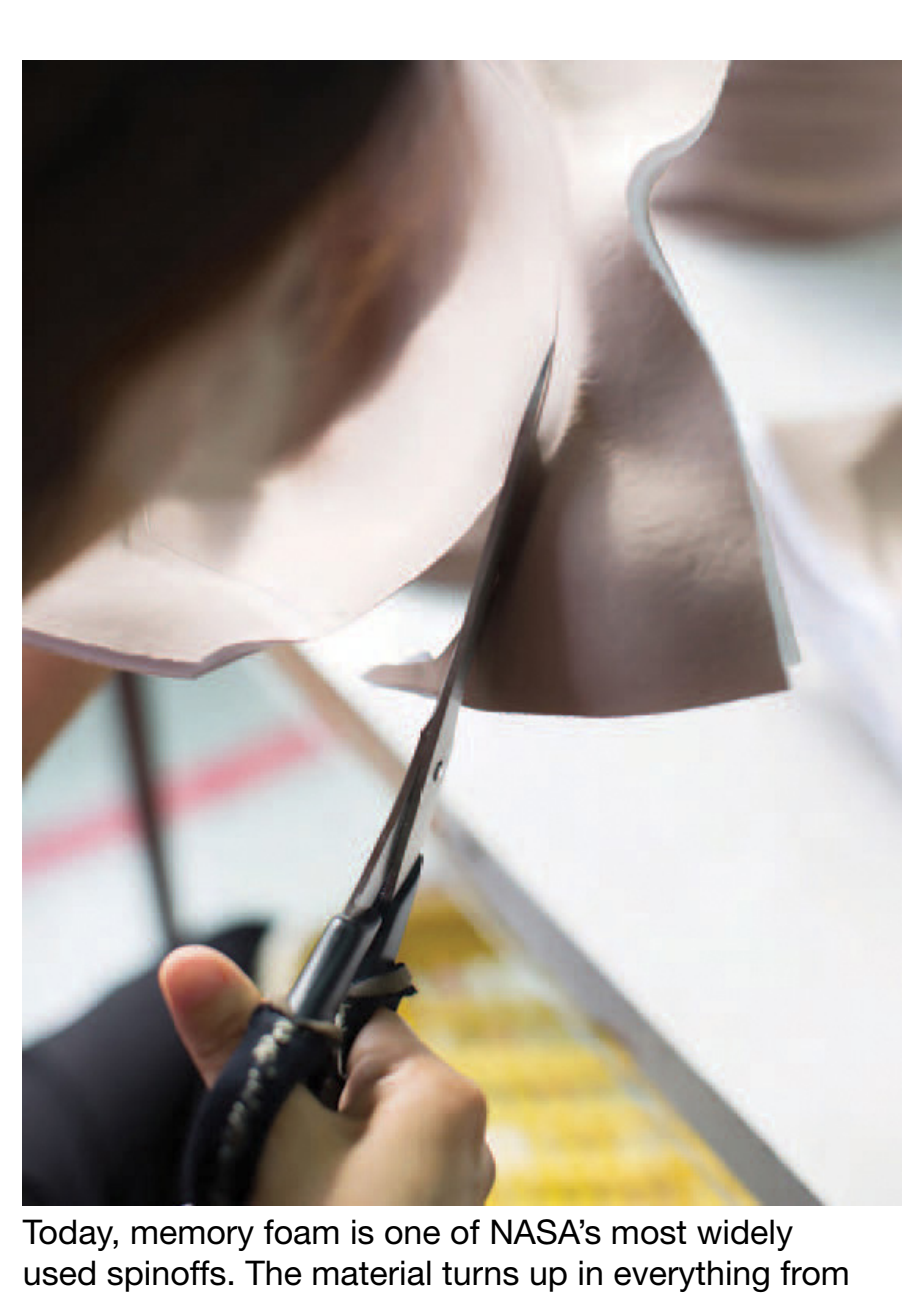
"All of our bras in our collection have memory foam," says company cofounder David Spector. "It's something that ThirdLove has built the collection around—we find customers really love it."



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.



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.



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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.

The idea was sparked when Jason You planned to take his toddler daughter to China to visit family and worried about the infamous air pollution. 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.

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.

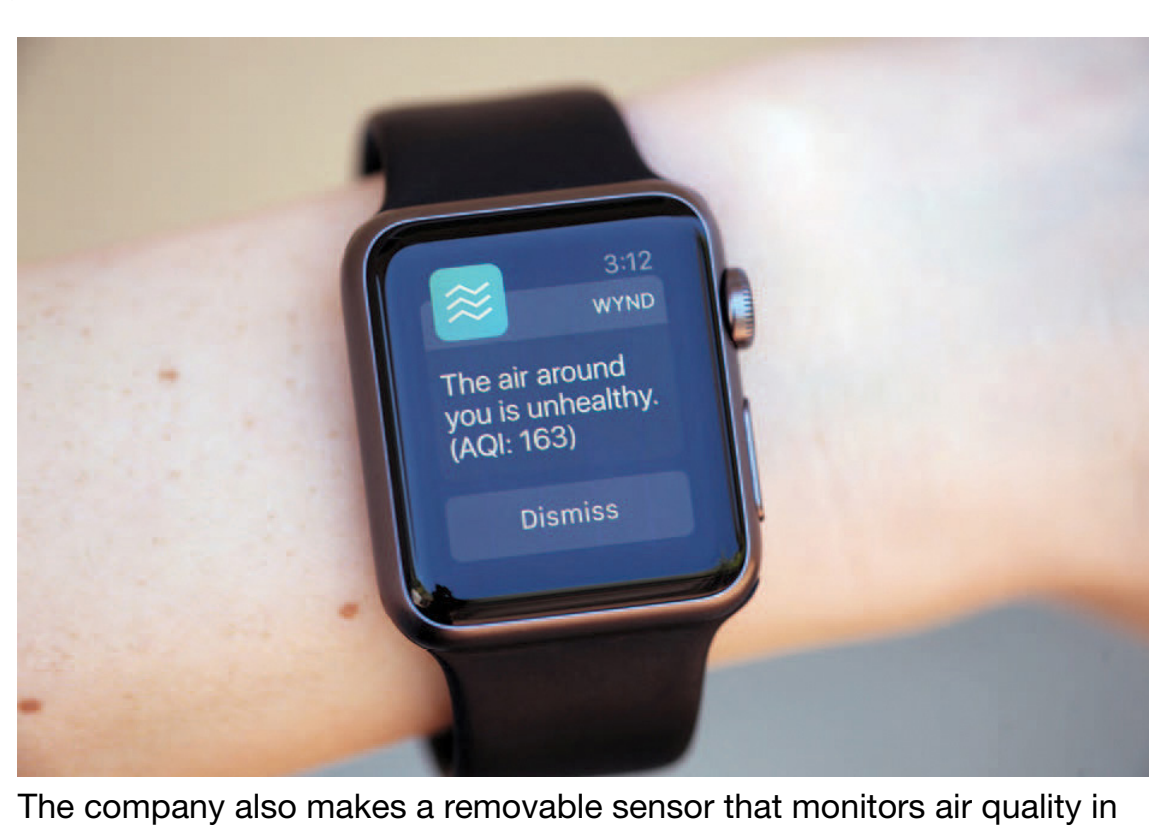
He couldn't find anything to fit the bill, so he built one himself. And, after returning from China, he teamed up with fellow Wynd founder and CEO Ray Wu to develop it into a product that was ready to sell.

You had spent several years working for a company that built sensors installed around the launch pad at Kennedy Space Center to ensure the air quality remained safe after a rocket firing. That experience was directly relevant when he began building a tiny air quality sensor for Wynd. Likewise, hardware engineer Eric Munoz had built up his fluid mechanics expertise on NASA rocket engines.

Together, the company built a portable, rechargeable device about the size of a water bottle. And, because of the smart sensors You designed, it is able to conserve energy when the air quality is good and then ramp up the purifier when the air gets worse.

"It can clean nine cubic feet of air per second, which for that size is way ahead of anything that's out there," You emphasizes, tying that efficiency directly to Munoz's experience in rocket engines.

The Redwood City, California-based company launched an Indiegogo funding campaign in 2016 and immediately raised over $600,000. 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.

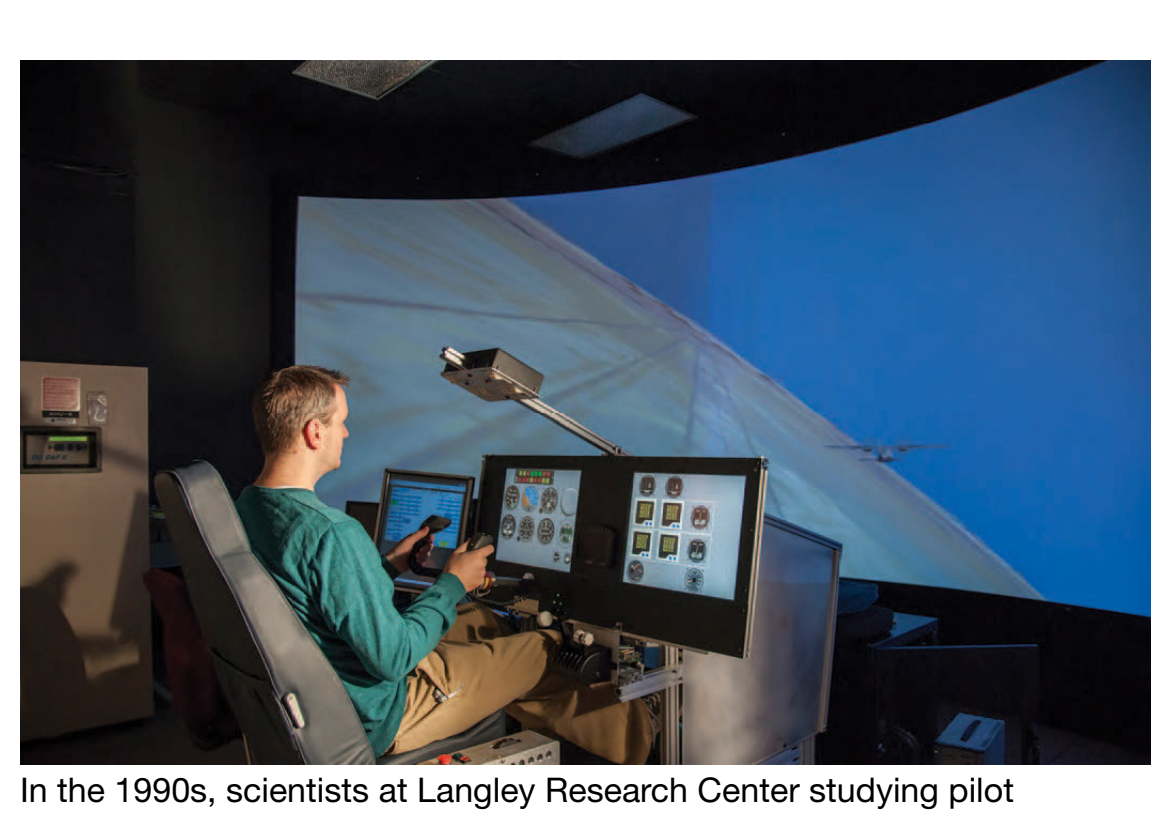


The company also makes a removable sensor that monitors air quality in real time—and can send anonymized updates to a world map so users can check conditions where they need to go.

Brainwaves Reveal Student Engagement, Operate Household Objects

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.

As automated flight control systems took over more and more operations in the cockpit, pilots could grow bored, complacent, and disengaged—what researchers called "hazardous states of awareness." By the mid-1990s, scientists at Langley Research Center were looking for ways to identify and measure a pilot's cognitive state using brainwave readings.



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 result was an "engagement index" that's still used today: beta wave output, which indicates attention, is divided by the combined power of alpha and theta waves, which come with relaxation, to arrive at a measure of engagement.

The team found that subjects who were allowed to monitor their engagement levels were able to control that engagement, creating what's called a biofeedback loop. They also found that learning to control attention levels improved performance, even in the long term.

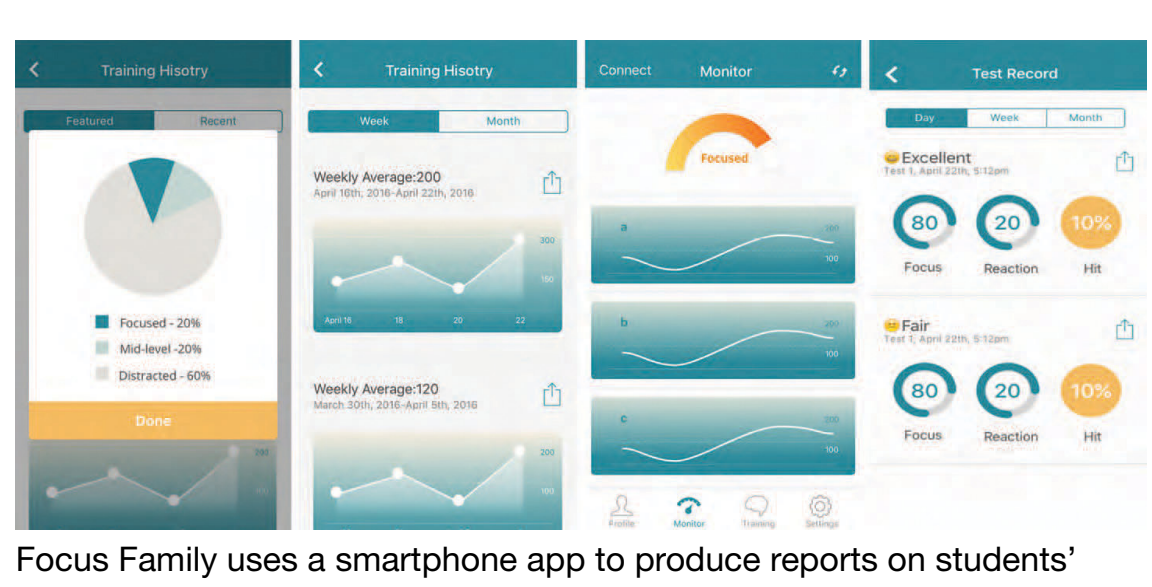
In 2015, a group of Harvard University graduate students founded BrainCo Inc. in Cambridge, Massachusetts, intending to use brainwave readings to monitor students' attention and, ultimately, to help people with attention deficit hyperactivity disorder (ADHD) gain more control over their concentration.

As the company was trying to improve its software, one of its research scientists, Max Newlon, came across the Langley experiments and engagement index, which became the basis for the company's product line.

BrainCo's Focus EDU lets a teacher monitor a class's attention level in real time and generates after-class reports. Focus Family uses the same hardware with a smartphone app to create a sort of digital study buddy for home use. And the soon-to-be-released LUCY uses the same technology for biofeedback training—with the right brain waves, users can manipulate household objects, for example turning on a lightbulb.

BrainCo shipped its first order of 20,000 units to a Chinese distributor in spring of 2018 and is working to break into the U.S. market.

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.



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.

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

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.

Aiming to improve air quality inside spacecraft, Stennis Space Center researcher W.C. Wolverton studied in the 1980s how to maximize the air-scrubbing potential of houseplants. Wolverton screened a dozen common house plants, 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.

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.

But perhaps the most important finding, and one that surprised the researchers, was that the roots and soil were doing the bulk of the filtering—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.

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 new products, including Hamburg, Germany-based AIRY GreenTech.

"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."

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. The products are available in some 50 countries around the world, and the company claims their system can neutralize nearly 100 percent of the most dangerous environmental toxins in a room in only 24 hours.

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.

Light Research Aids Slumber

When astronauts only spent a few days in orbit, sleep was not the biggest concern. As stays stretched longer, however, "toughing it out" was no longer a viable option.

So to better understand just how spaceflight impacted rest and alertness, Johnson Space Center and partner nonprofit National Space Biomedical Research Institute began studying rest and alertness in orbit.

The work showed different light wavelengths help govern sleep and wake cycles. Details began to emerge that short, or blue, wavelengths, which are abundant in daylight, had a particularly important effect in promoting alertness. The study noted that the sensitivity was present even in subjects who were otherwise totally blind.

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 used NASA's research and results to do the same, including Headwaters Research and Development Inc., based in Marblehead, Massachusetts, and Ottawa, Canada. 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, with light cues to help wearers fall asleep faster and sleep more deeply throughout the night.

Philippe Genereux, Headwaters' vice president of research and development, 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."

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.

6:00 AM
Alarm Time
Alarm Chime
Sunrise
Sunset
Sleep Enhance
SYNC
sound oasis

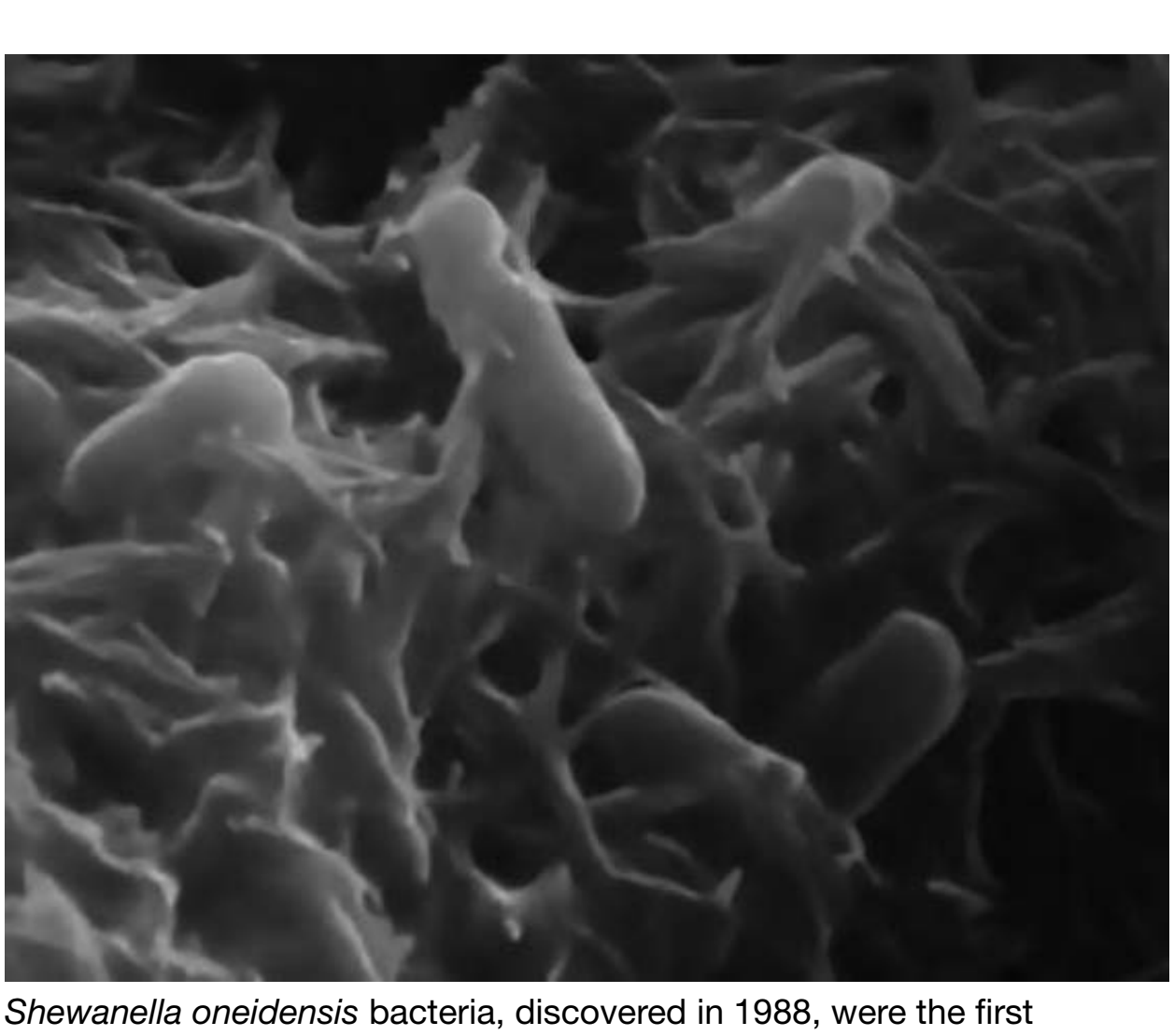
Headwaters Research and Development used NASA's published findings on light wavelengths and alertness to help create its "smart" sleep mask, which can be controlled with a smartphone app. Among other features, it can pulse red light at bedtime and blue light in the morning to help the wearer fall asleep 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

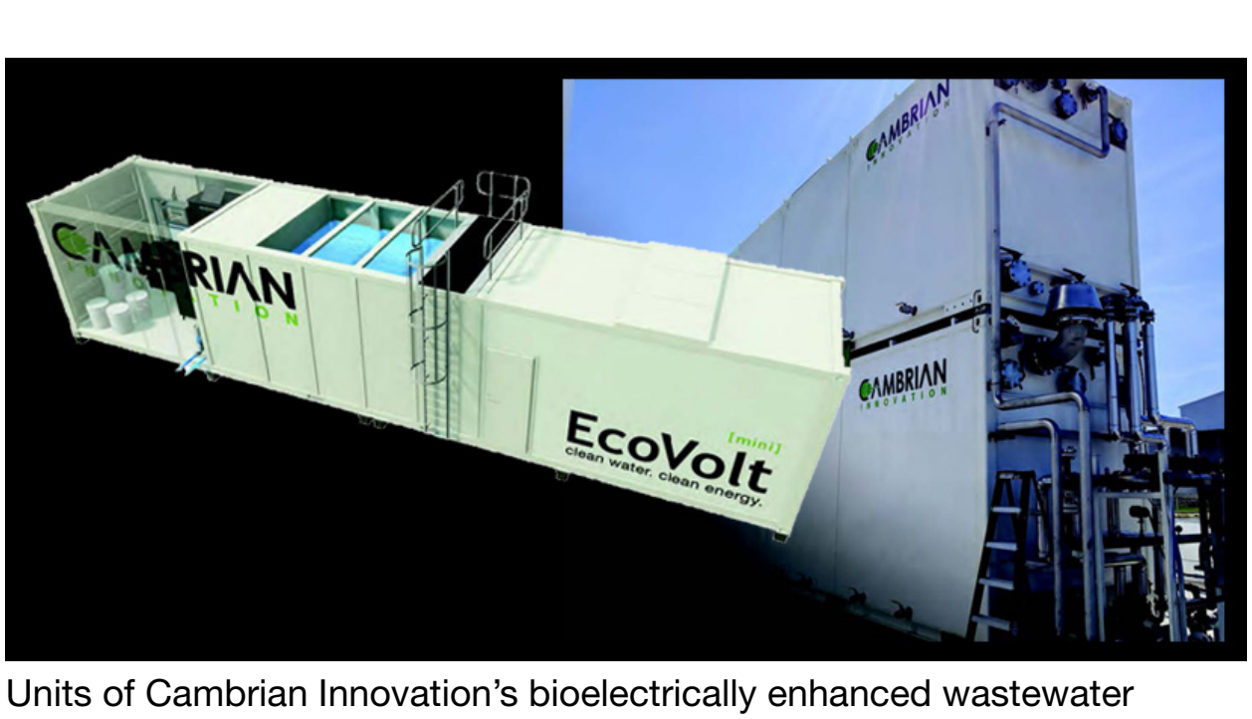
NASA recently sent into space organisms that might sound like they came from space to begin with—microbes that can essentially breathe electricity.



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.
Image courtesy of the Public Library of Science, CC BY-SA 2.5

The *Shewanella oneidensis* bacteria that traveled to the space station last February can use a metal outside the cell, instead of oxygen, as the final electron acceptor in its metabolic process, transferring a charge. A host of similar microbes, known as exoelectrogens, can "exhale" or "inhale" electrons or do both.

In 2006, graduate students at the Massachusetts Institute of Technology founded IntAct Labs, now called Cambrian Innovation, with NASA funding to study "bioelectric space exploration." Among the ideas explored was a microbial fuel cell based on exoelectrogens and powered by wastewater.



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.

The work led to further grants from several agencies, including NASA. A Small Business Innovation Research (SBIR) contract with Ames Research Center funded efforts to build a bioelectric life-support system that would extract carbon dioxide from the air and generate oxygen, water, and methane. Another SBIR contract with Johnson Space Center funded work on a reactor to treat wastewater while functioning as either a power-generating microbial fuel cell or an electrolysis cell that would break down waste and create hydrogen or methane.

Much of the work played into Cambrian's eventual commercial line. In 2013, the company's bioelectrically enhanced wastewater treatment system, the EcoVolt Reactor, became commercially available.

With a small charge applied, microbes on the anode break down waste to generate electricity, while different microbes on the cathode feed on that electricity to create natural gas to burn for power.

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.
Image courtesy of Jairo BD, CC BY-SA 2.0

Wineries and breweries were the first facilities the company targeted, because they produce large amounts of highly concentrated wastewater. "We see a big trend associated with extracting resources from waste—treating it more as a potential source of value than a cost burden," says Matt Silver, founder and CEO of Cambrian.

Unlike other options, the EcoVolt is compact and requires little oversight, in addition to producing fuel.

Following treatment, facilities can prepare wastewater for reuse with the company's EcoVolt MBR, a more traditional system that further polishes the water, removing more than 99 percent of contaminants.

Cambrian now has installations at more than 10 facilities.

Building Monitoring System Provides Insights for Sustainability

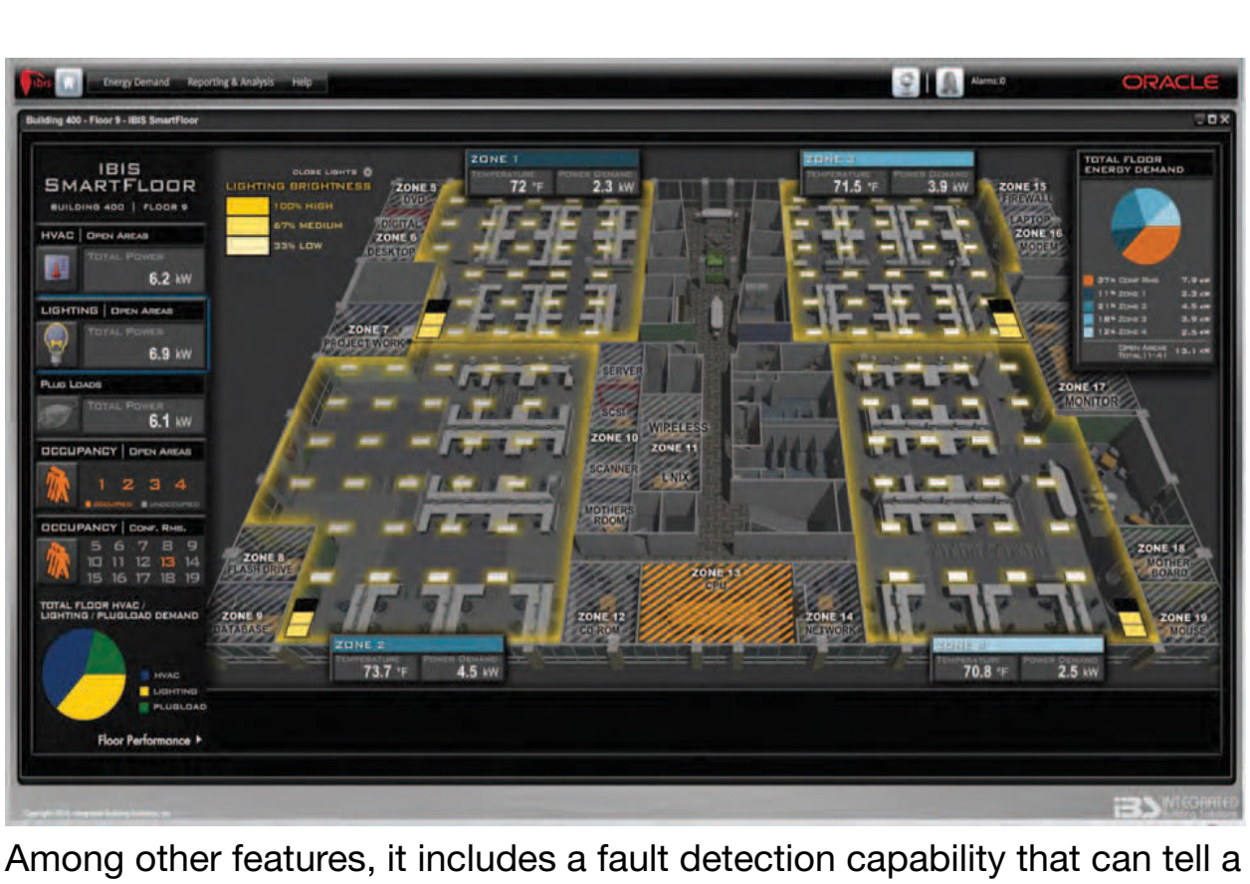
When Ames Research Center built Sustainability Base, the "greenest" building in the federal government, it counted on not just reducing its energy consumption but offsetting that consumption by producing sustainable energy.

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.

"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. For that, it turned to 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.

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.



Among other features, it includes a fault detection capability that can tell a building manager when a system isn't working optimally. Ames computer scientists helped the company develop this capability.

This allows maintenance staff to detect when building systems aren't working optimally—which could indicate a breakdown is coming, and in the meantime likely means it is consuming additional energy.

Today, that's a standard component of its Intelligent Building Information System, which has been installed at corporate campuses across Silicon Valley and beyond.

"Our exposure to NASA, the experience we gained, working with them on the diverse system, helped us to get the trust and the technology that we have used in government jobs and quite a few other projects," says IBS owner Eugene Gutkin.

Space Station Garden Shines Light on Earth-Based Horticulture

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 deep-space missions.

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.

One factor they experiment with is the use of different light color combinations, or "light recipes," which can have dramatic effects on plant size, shape, texture, and appearance.

"There is a light recipe that will maximize the yield of a crop, in terms of total edible biomass, and there's also a light recipe we can use to keep plants short—a process known as dwarfing," says Matthew Mickens, a NASA postdoctoral research fellow at Kennedy Space Center who investigates how different light recipes affect crops.

The space station's latest plant growth system, called the Advanced Plant Habitat (APH), is more automated than its predecessors and includes a custom-designed LED system.

Controlling light for crop growth is also a terrestrial focus, where there is interest in vertical farming—techniques enabling crops to be grown indoors. OSRAM, a German lighting company with U.S. headquarters in Wilmington, Massachusetts, has been working on such a lighting solution. Its Phytofy RL is a tray-like fixture with a network of LEDs, temperature control, and a software-controlled panel to adjust settings.

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.

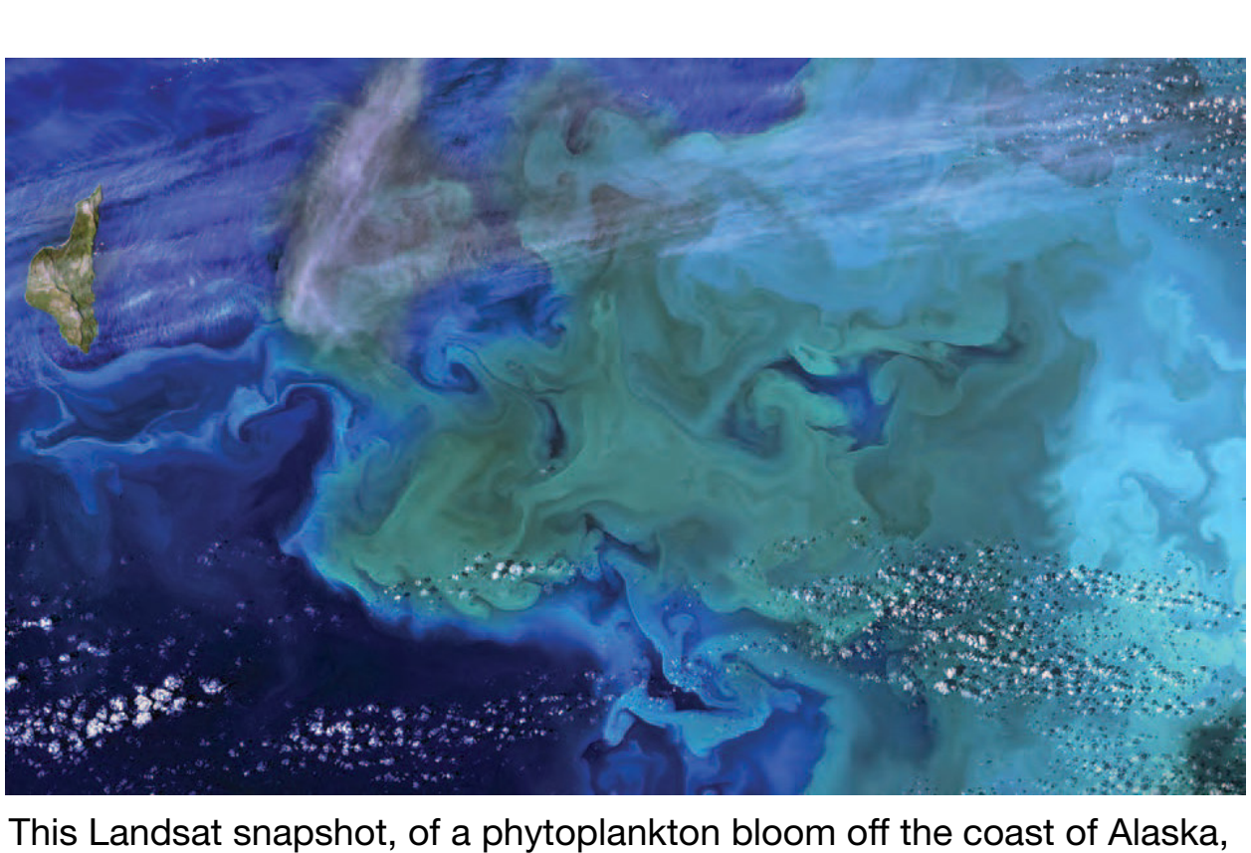
After the Kennedy researchers were introduced to OSRAM's developers in 2017, they began using a Phytofy prototype to conduct studies and preliminary research for in-space APH experiments. The exchange with NASA helped OSRAM feel confident enough to sell Phytofy commercially, with an expected product launch around early 2019.

"It's served as validation," says Steve Graves, strategic program manager for urban and digital farming at OSRAM, "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."

Phytofy is designed specifically for researching light recipes and is targeted to plant scientists in academia and in commercial growers' research and development departments.

Carbon Capture Process Makes Sustainable Oil

Even before Neil Armstrong ever stepped on the Moon, NASA began envisioning missions deep 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" by recycling waste products, 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.



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.

One of the most promising systems identified and analyzed in that report relied on hydrogen-fixing bacteria, in particular a genus of bacteria called *Hydrogenomonas*. The bacteria recycles carbon dioxide (CO_2) into useable by-products at a high rate, and, unlike algal and other plant systems that require light for photosynthesis, can grow in the dark.

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.

Earth is much larger than a spaceship, of course, but it is ultimately still a closed system—and accumulated CO_2 is a growing problem.

It was with the idea of fighting climate change that Lisa Dyson and John Reed, cofounders of San Francisco Bay area-based Kiverdi, came across the NASA life-support research in 2008. "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."

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.

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.

Emissive Coatings Cut Industrial Costs, Emissions, Fuel Consumption

It's no surprise that the experimental X-Plane Program has led to improvements in commercial flight, but it also produces breakthroughs in other fields entirely. For example, a high-heat coating that has helped industrial plants cut emissions and save money owes its start to the program.

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.

The X-33 and X-34 were planned prototypes for commercial spaceplanes that would fly up to 15 times the speed of sound. Such high speeds would require thermal protection even more advanced than that of the space shuttles.

The coating needed to be thin, stable, lightweight, highly emissive, flexible, and able to withstand temperatures up to 3,000 °F. Scientists at Ames Research Center discovered a formula that met all these needs, naming the result Protective Coating for Ceramic Materials and patenting it.

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.

Ames licensed the patent exclusively to Wessex Inc., now Emisshield Inc., of Blacksburg, Virginia, in the 1990s. After making its own improvements, the company first sold it to building material manufacturers for fireproofing. Soon the Emisshield line was coating high-heat race car parts. By 2016, the coatings could be found in a range of industrial applications like kilns, boilers, and furnaces, as well as in consumer goods like a line of clothing.

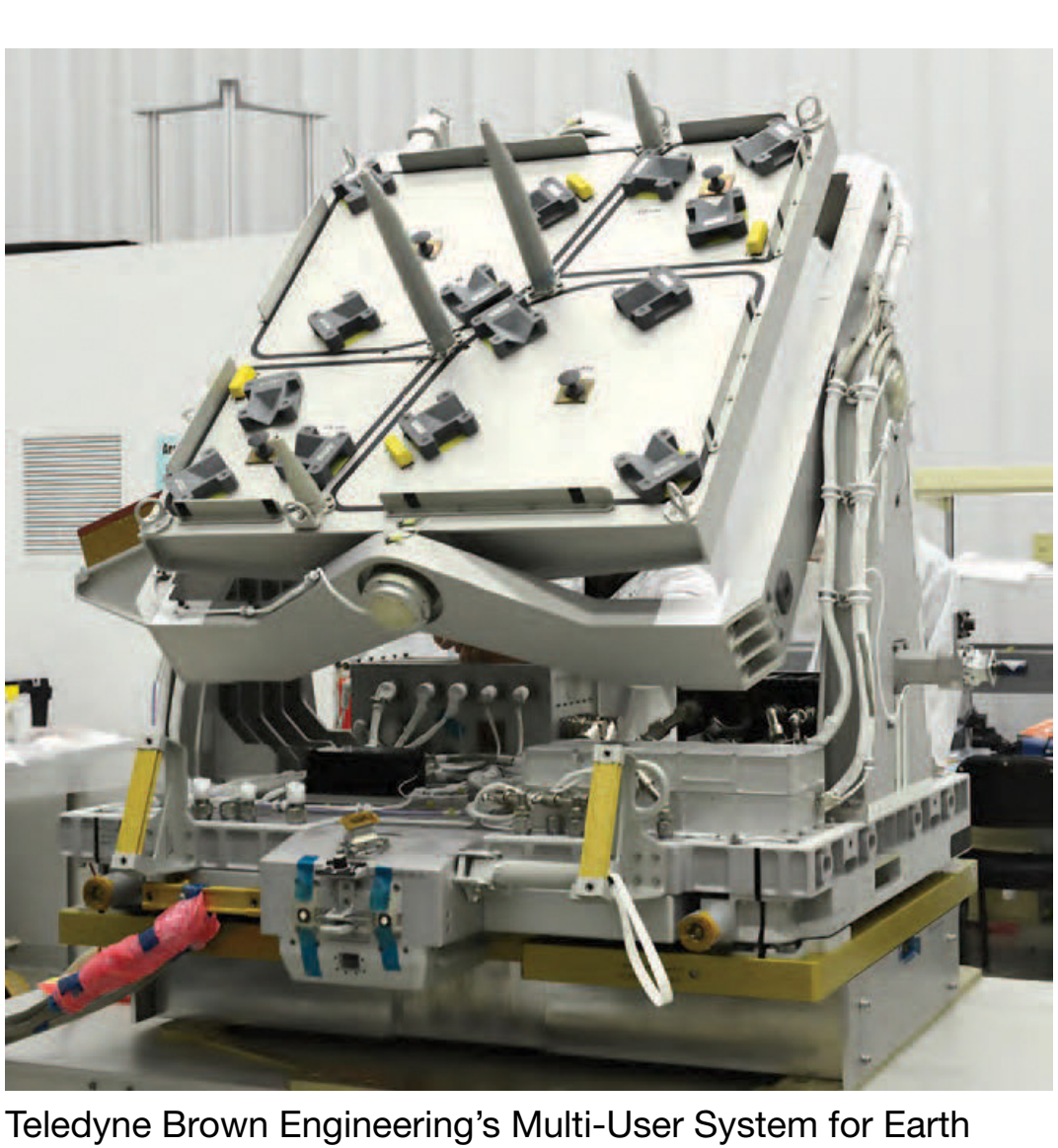
Emisshield has now entrenched itself in a wide range of industrial applications, expanding its product line to about 40 coatings and partnering with original equipment manufacturers. The coatings improve efficiency, which reduces costs and greenhouse gas emissions, and they extend systems' lifespans.

The company estimates its products are in twice as many industrial plants 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. And they're also being applied much more extensively throughout each of these.

Emisshield recently got involved with a European project called Integrated Model-Guided Process Optimization of Steam Cracking Furnaces, which aims to drastically improve energy efficiency in steam cracking furnaces and reduce their emissions by 25 percent.

Pointing Platform Enables Earth Imaging from Space Station

Most people think of the International Space Station (ISS) as a place to learn about space, but humanity's only outpost in space is also becoming a hall of commerce.

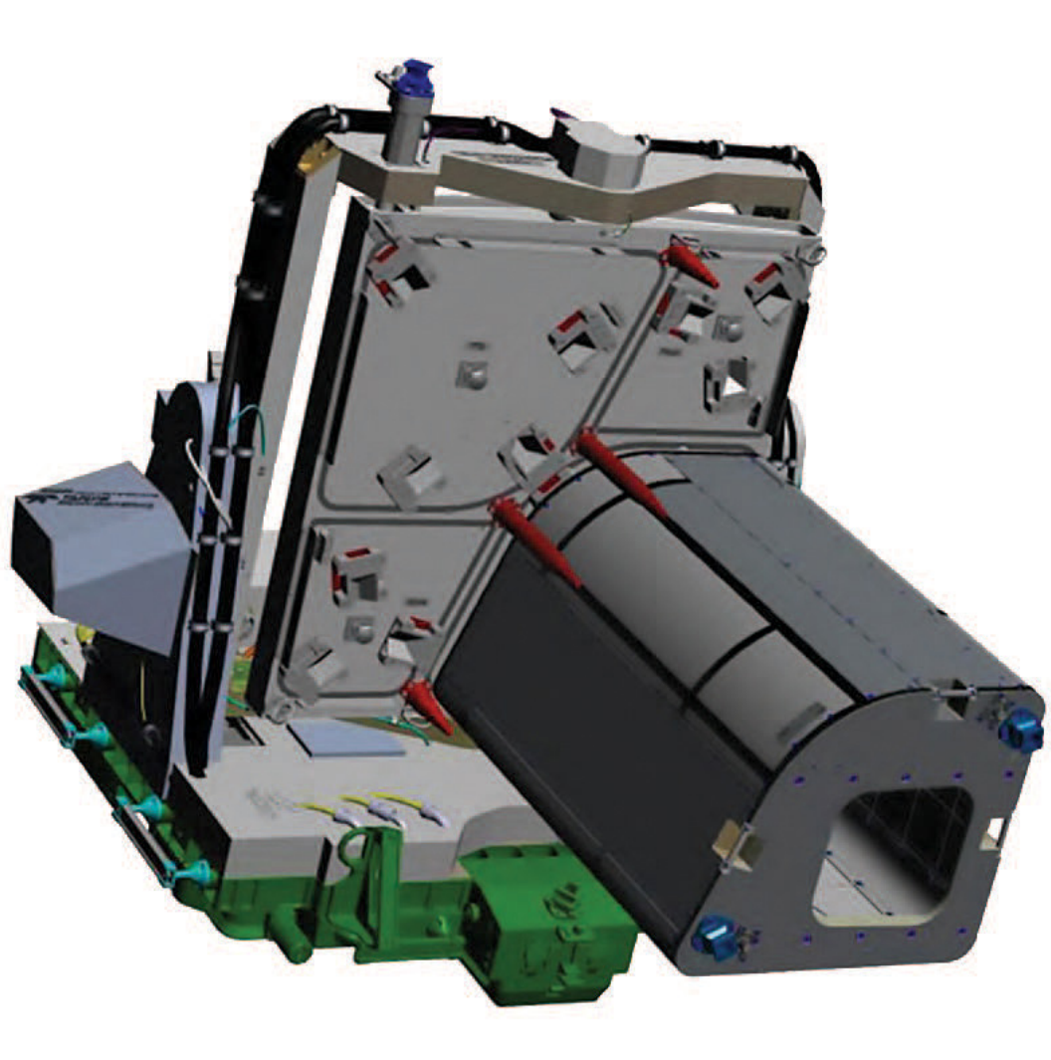


Teledyne Brown Engineering's Multi-User System for Earth Sensing (MUSES) has introduced a new level of precision pointing and tracking for Earth-imaging devices on the ISS. Through a cooperative agreement, the company built the facility and now rents space aboard it.

Teledyne Brown, based in Huntsville, Alabama, was one of the first companies to enter into a cooperative agreement with Johnson Space Center to conduct commercial activities on the space station. The result of that agreement, the Multi-User System for Earth Sensing (MUSES), flew to the ISS in 2017.

Mounted on the exterior of the space station, MUSES consists of four canisters that can each hold multiple payloads. Intended mainly for Earth-imaging devices, the platform provides a more affordable option than building and launching an entire satellite. Companies can also test a device on MUSES before putting it on a satellite.

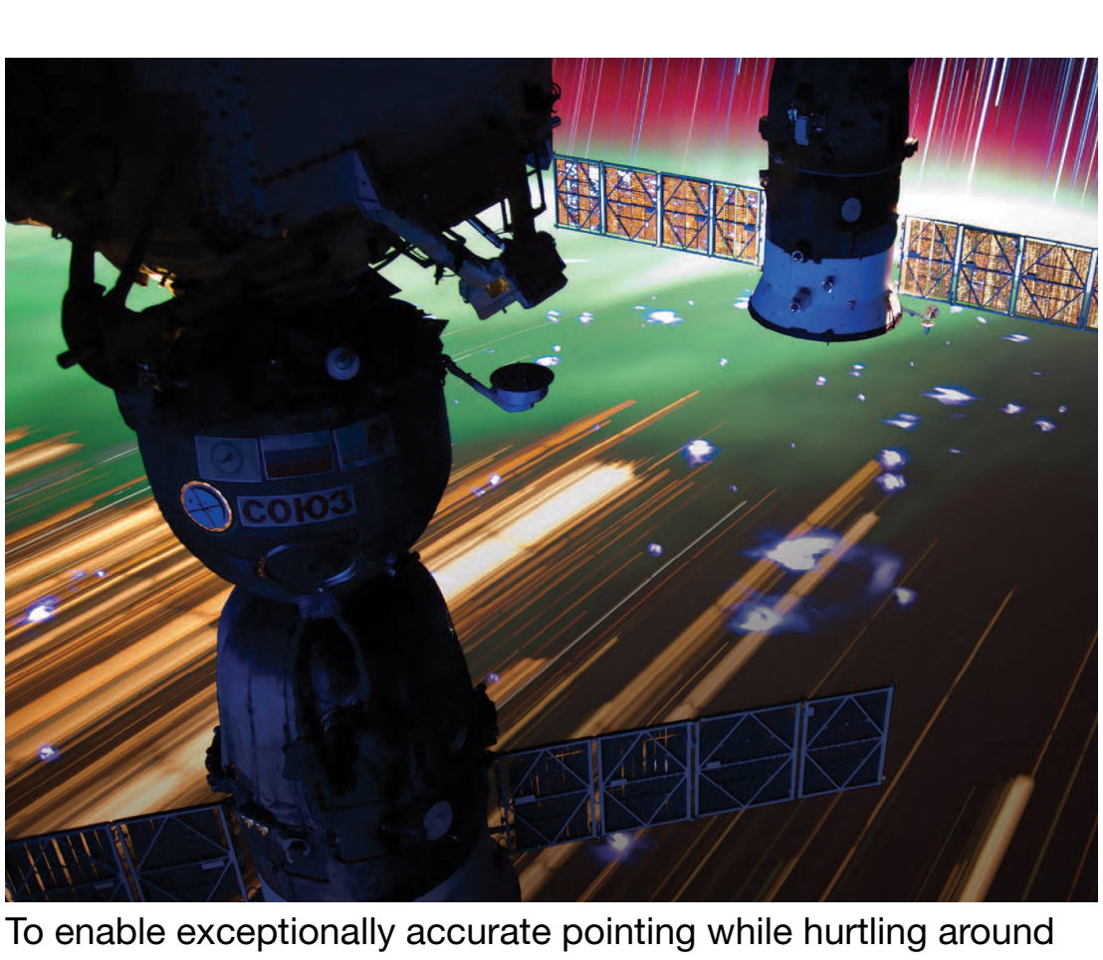
To enable precision pointing, a capability that didn't exist on the ISS, it uses a device that orients itself by the stars, as well as enhanced GPS and miniaturized inertial measurement devices.



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.

The first customer for MUSES was the German Aerospace Center, Deutsches Zentrum für Luft- und Raumfahrt (DLR), which put its DLR Earth Sensing Imaging Spectrometer on the platform. The hyperspectral imager, installed in early 2018, "sees" Earth through 235 channels in the visible and near-infrared wavelengths, providing unprecedented spectral resolution. It can sense changes in surface coverage, oceans, and the atmosphere and is intended to inform Germany's decisions around problems like environmental and climate protection and food security.

Secondary customers, meanwhile, can buy imagery from Teledyne Brown, which retains commercial rights to the data the spectrometer gathers. The company says natural resource managers have expressed interest in using the data to calculate the area, type, and health of forest cover. Even some state budget offices could benefit from such data, depending how much of a state's tax revenue comes from lumber sales. Others want to monitor water quality or air pollution. One application likely to find government and commercial applications is taking inventory of crops and forecasting their yields.



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.

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.

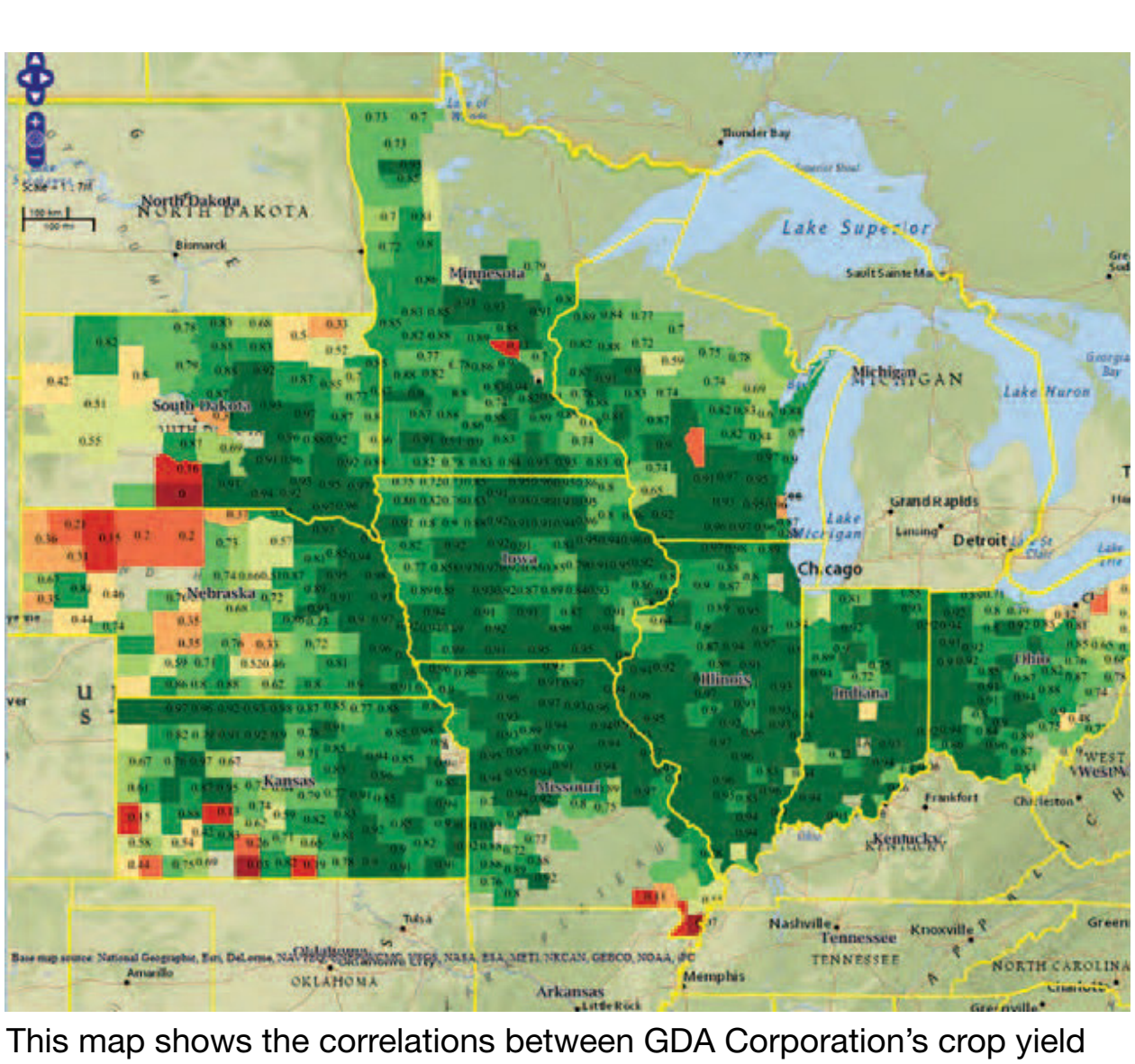
Algorithms to Detect Clouds Forecast Global Crop Production

It started as an algorithm to detect clouds in satellite imagery, but now it's being used for everything from ensuring food security in the developing world to guiding futures trading on Wall Street.

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.

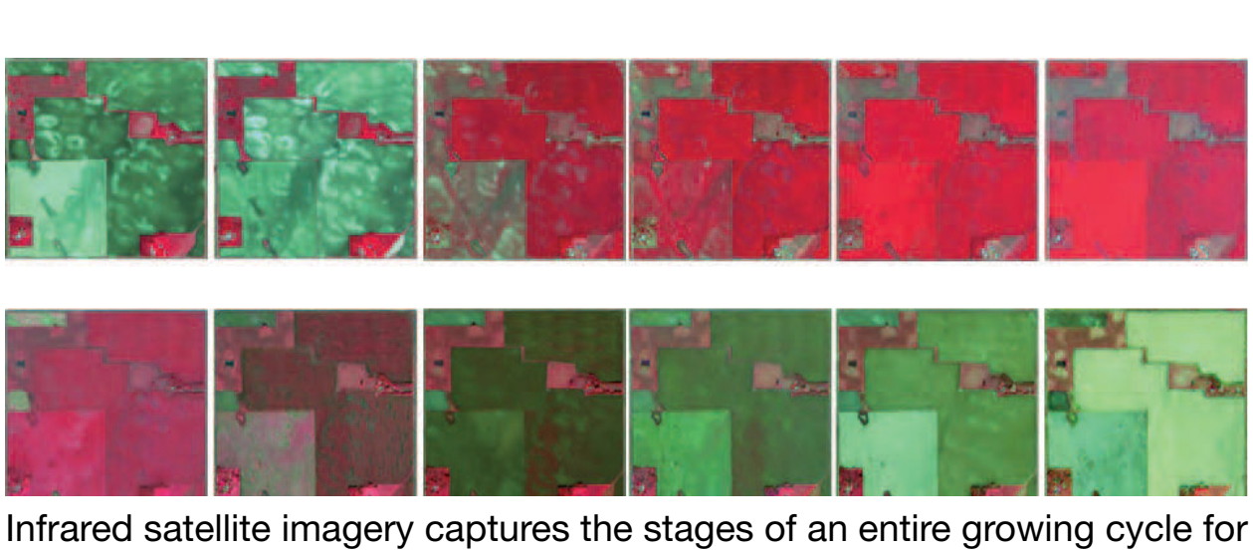
Earth-imaging satellites monitor forest and crop health, icecap and glacier coverage, and a host of other surface conditions. Pixels capturing clouds and their shadows throw off all this data, though, so those pixels must be discarded before calculations are made.

In 2002, in preparation for the Landsat 8 satellite, engineers at Stennis Space Center put out a Small Business Innovation Research (SBIR) solicitation for software capable of detecting cloud cover, which a contractor at Goddard Space Flight Center cofounded a company to win. Thus, Geospatial Data Analysis (GDA) Corporation of State College, Pennsylvania, was born.



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.

Further SBIR contracts with Stennis in 2004 and 2005 focused on analyzing satellite images to identify surface features such as crop coverage and health, soil conditions, forest fires, and more. GDA also used the funding to automate its systems, which regularly pull, correct, and analyze raw data from several Earth-imaging instruments, and it built a 200-terabyte cloud to allow mining of historical and current crop statistics from various agricultural monitoring entities.



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.

Calculations of crop coverage, type, health, and growth, and especially forecasts of crop productivity, interest organizations like the U.S. Department of Agriculture's Foreign Agricultural Service, which regularly provides commodity estimates and predictions to give a marketing edge for U.S. producers. The agricultural service became GDA's biggest customer, but others, such as agricultural insurance companies, grain and commodity traders, and food transporters, also became clients.

The Foreign Agricultural Service uses GDA's tools, among other sources, to create its monthly estimates for all major commodity crops, and crop futures markets move according to those estimates. They also help the service predict shortages to direct food aid programs.

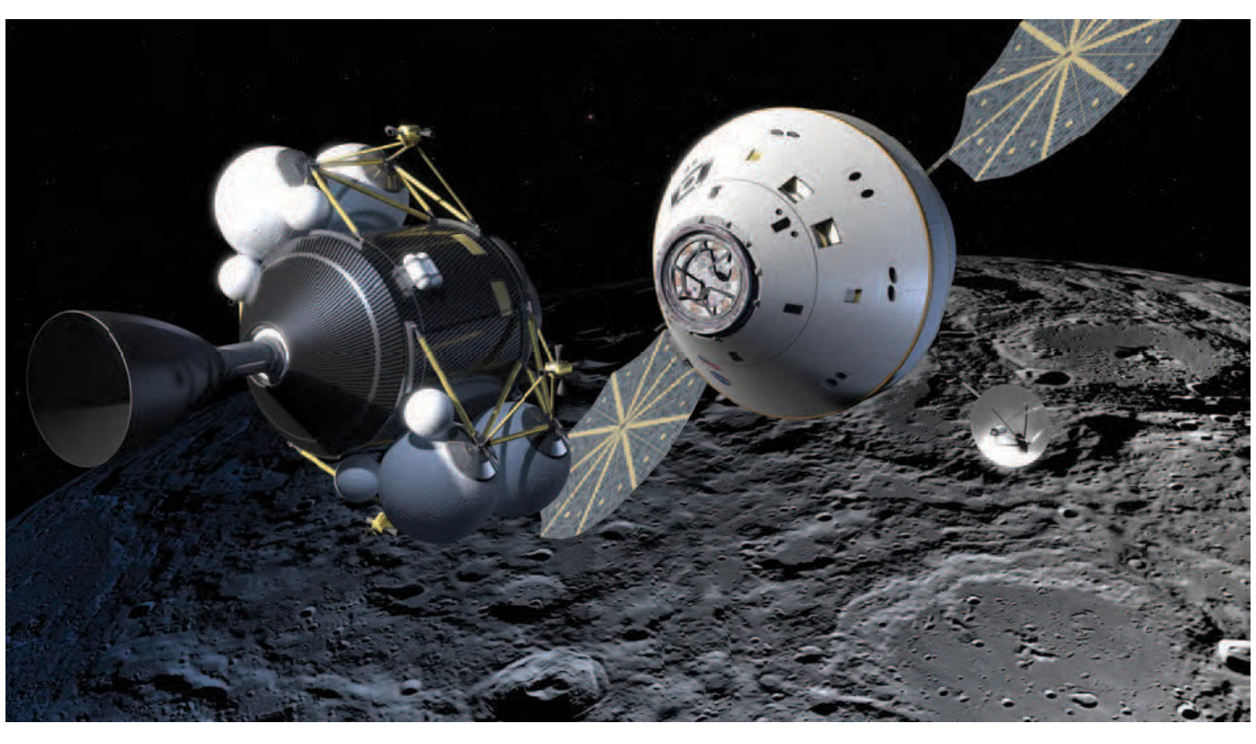
"This definitely fits in with the goal of taking NASA science and capabilities and applying those to areas of public need," says Tom Stanley of Stennis.

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.

Space Mission Planning System Targets Advertising with Precision

Most people don't realize that every time they see an online ad, it was placed there after a near-instant auction for that slot. The entire bidding and selling process is automated and takes about a tenth of a second.



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.

One of the leading companies now driving that process uses software based on an approach its founders helped invent for planning NASA missions.

Around 2004, NASA Headquarters paid several contractors to study possible architectures for an astronaut mission to the moon or Mars. The study also included a team of faculty and graduate students at the Massachusetts Institute of Technology (MIT). The MIT team started with an entirely different method than others used, looking at all options without any underlying assumptions about the mission.

The team created the Object Process Network, a meta-language based on about 35 major decisions needed for any crew mission to a planetary body. They ended up with 1,162 possible mission architectures, which could be evaluated and sorted for weight, cost, and other factors.

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.

Two of the team members then founded Boston-based dataxu and identified digital advertising—a fast-growing field that still had glaring inefficiencies and lots of room for improvement—as a great market for the software they'd helped develop.

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.

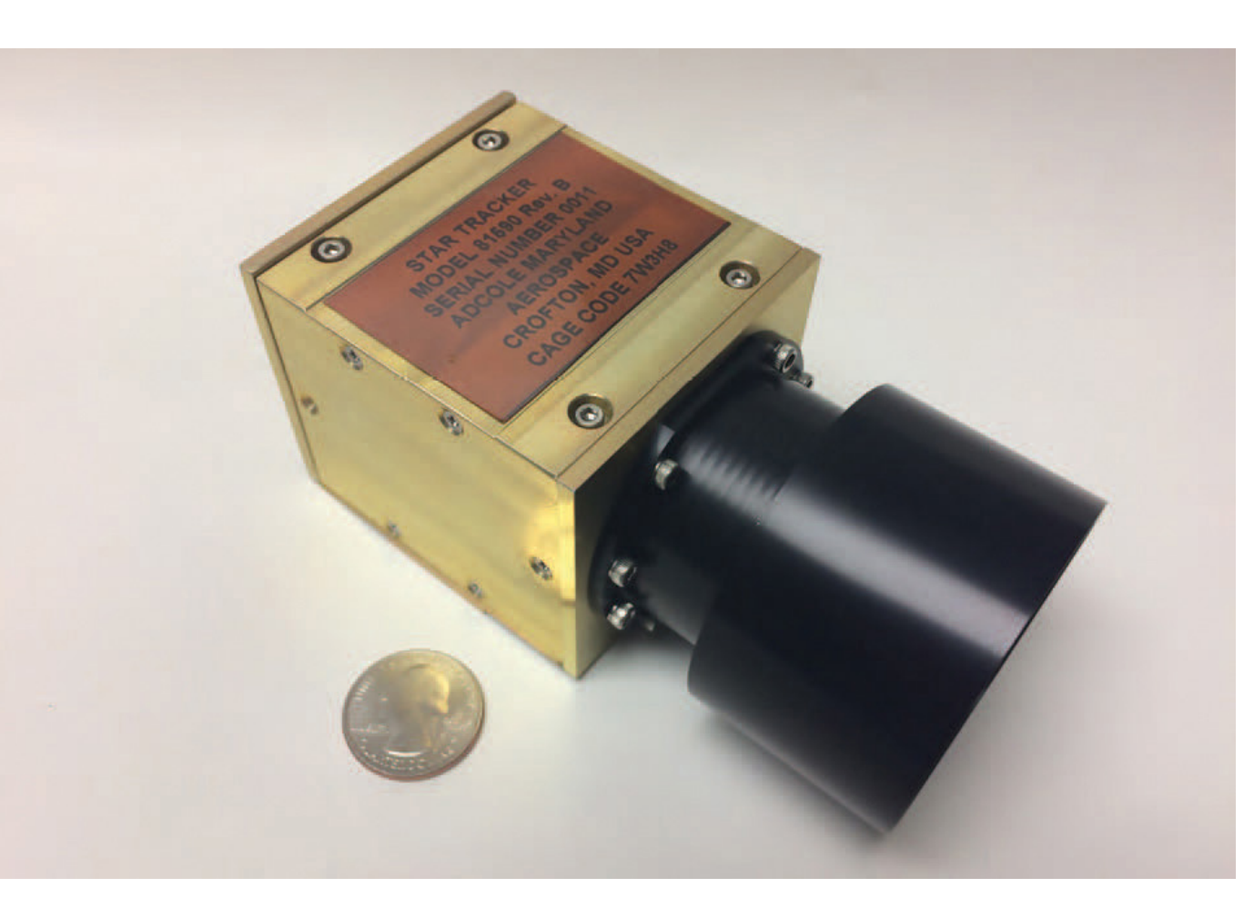
The company's algorithms consider all options for a given ad slot and immediately narrow down to about 20 contenders, based on factors like size and content. The platform then uses a more advanced formula to determine the probability of the user responding to each ad and selects one.

The company says its service is 35 to 40 percent more efficient than its competitors in terms of cost per click-through. Recently, dataxu broke into television advertising, where it says it finds three times the audience competitors do for the same price.

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 Small Business Innovation Research (SBIR) funding, has designed a modern take on an ancient navigation device that is tiny, cheap, and potentially revolutionary.

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.



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.

The device, a "space sextant," fits inside a CubeSat but can track stars with the accuracy of much larger instruments.

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, which funded the SBIR work. "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."

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 and accurate star trackers, it is far more feasible for researchers to, for example, deploy multiple units to observe from different angles.

"The number of measurements can go up. And, if something fails, the mission isn't lost completely," explains Jason Mitchell, assistant chief for technology in Goddard's Mission Engineering and Systems Analysis division.

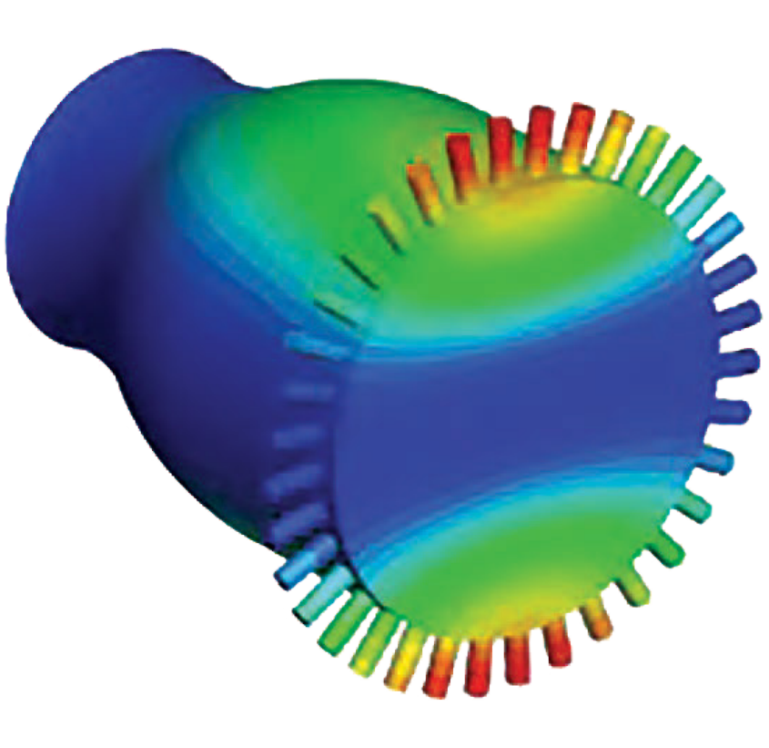
"It really does revolutionize the way that you can think about generating measurements. It enables many new possibilities for science."

The company now sells its space sextants in a variety of configurations and as stand-alone devices, primarily for Earth-observation satellites.

Software Toolkit Steadies Rockets

"Combustion instability is the part of rocket science that makes rocket science hard," says rocket scientist Paul Gloyer—and he's not joking. The phenomenon, in which oscillations or vibrations build up, can cause an engine to explode.

NASA test fires one of the Space Lauch System's boosters, which could help propel humans one day 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.



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.

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.

"It's probably one of the highest risks that we encounter when we design an engine," agrees Matt Casiano, an aerospace engineer at Marshall Space Flight Center.

Gloyer's company, Tullahoma, Tennessee-based Gloyer-Taylor Laboratories (GTL), has developed a tool—the company refers to it as the Universal Combustion Device Stability (UCDS) process and toolkit—to try to lower that risk. Based on an insight that breaks the problem of combustion instability into different layers, it can predict how an engine will behave and why, enabling engineers at NASA and beyond to change problematic factors during the early design phase.

Casiano was part of a team that worked with GTL to test one component of that toolkit. 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."

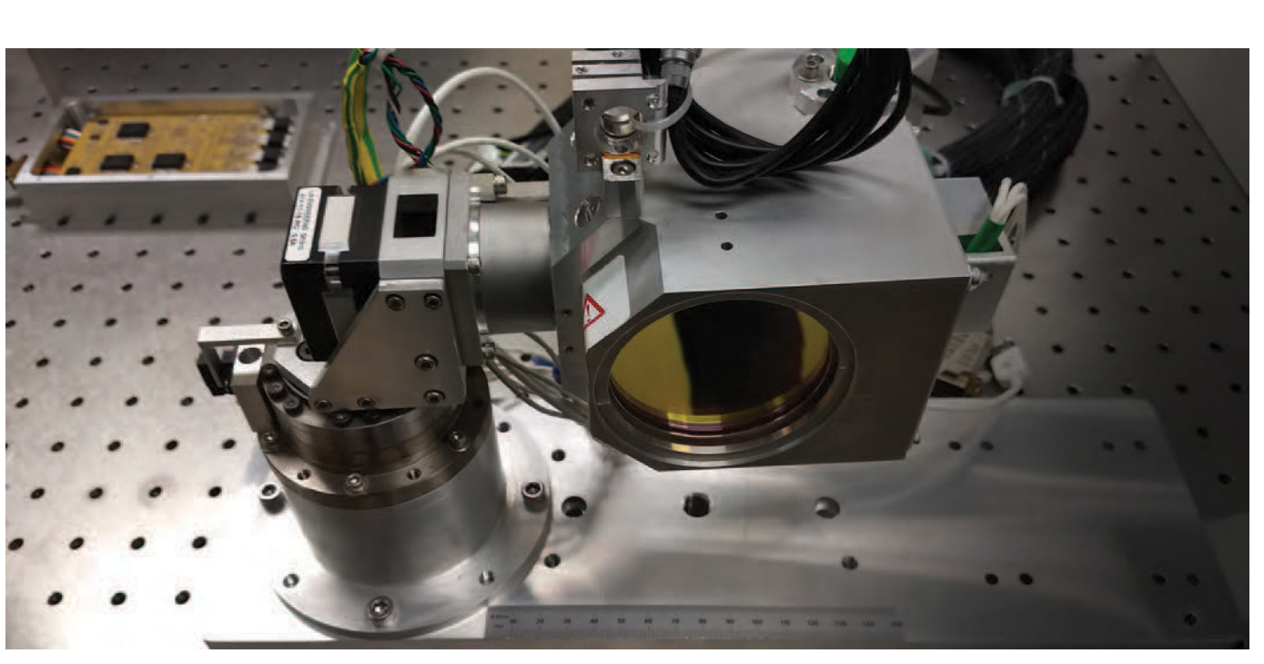
Gloyer says the UCDS software has the potential to cut rocket costs by a huge margin, because it can simplify the design process so significantly. "Combustion instability, depending on how you look at it, accounts for about half the money the United States has spent on rockets, in terms of cost overruns, hardware damage, testing, and program cancellation," he says.

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.

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. No one could have expected a solution to come from a former aviation data executive like Mark LaPenna—least of all him.



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.

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.

LaPenna left a comfortable job in 2014 to start an aircraft tracking company. Then he encountered a problem. The work would have required satellites to gather far more information than they could possibly beam down to Earth via radio, because the radio spectrum has limited capacity and is becoming overcrowded. He was about to dissolve the company when a friend at NASA suggested he consider a technology the Jet Propulsion Laboratory had available for license.

A team there had come up with a simple, low-cost laser communications transceiver that could end the constraints of radio communications. While radio waves are 10 meters to 10 kilometers long, light wavelengths are measured in microns. This more concentrated beam gives light a vastly greater capacity to carry information.

Upon learning of the transceiver, LaPenna scrapped his original plans, realizing that laser communications could meet a larger need. He licensed the technology.

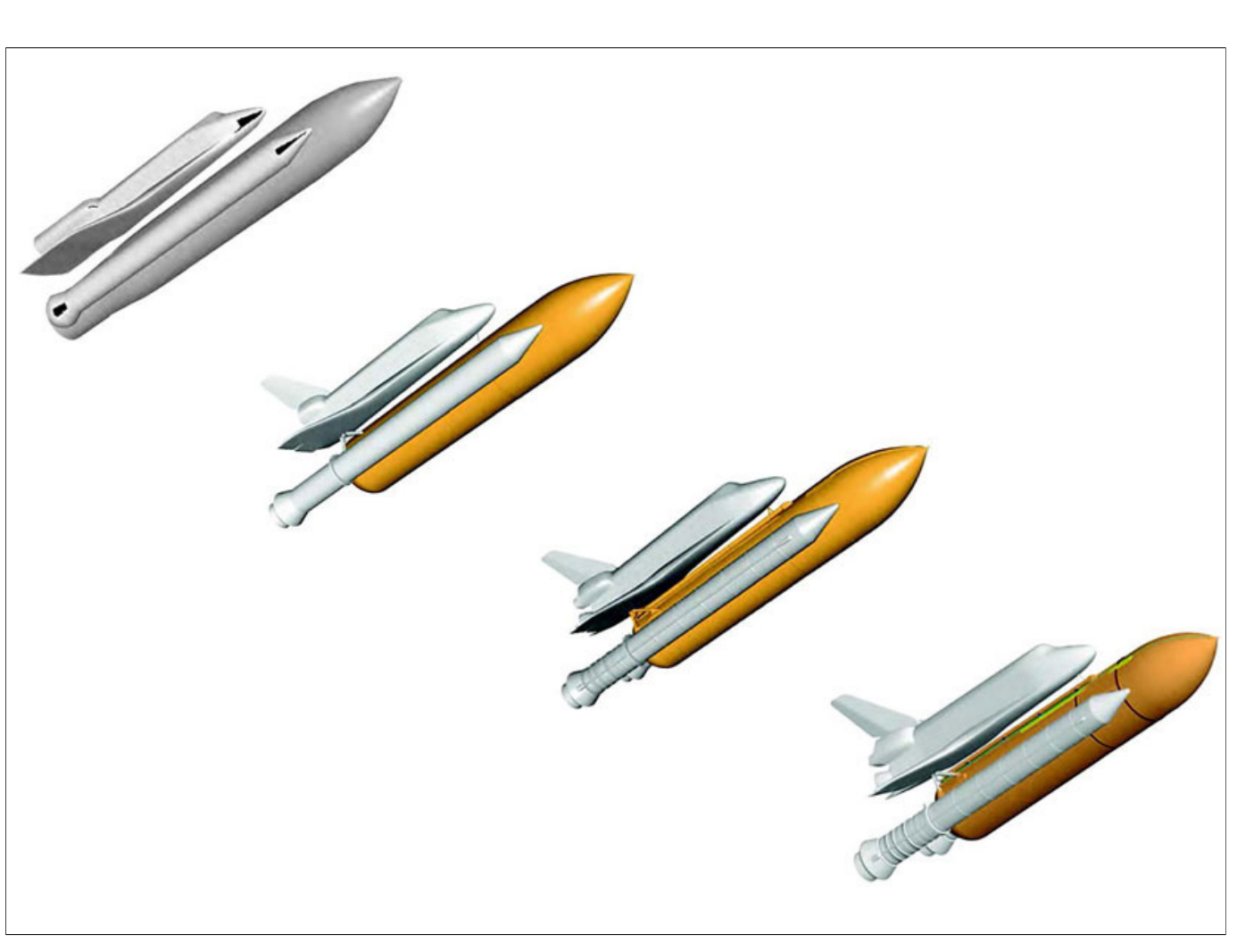
Obstacles like weather interference, a lack of ground stations, and the need for an entire constellation of satellites have scuttled other attempts at large-scale satellite laser communications. So, while LaPenna's Atlanta-based company, Xenesis, builds partnerships to encourage and gain access to a future network of ground transceivers, it will start by offering unhackable laser communication over land.

This will let banks, hospitals, and other entities that transmit large amounts of sensitive data to do so more securely than is currently possible.

For the long term, the company is partnering with businesses that are jointly developing networks of laser-communication ground receivers and space capabilities. Xenesis plans to launch the first two payloads in its constellation in 2020, to be followed by hundreds more. All of this will one day enable ultra-secure, high-speed satellite Internet access.

NASA Code Speeds Nation's Aircraft, Spacecraft Design

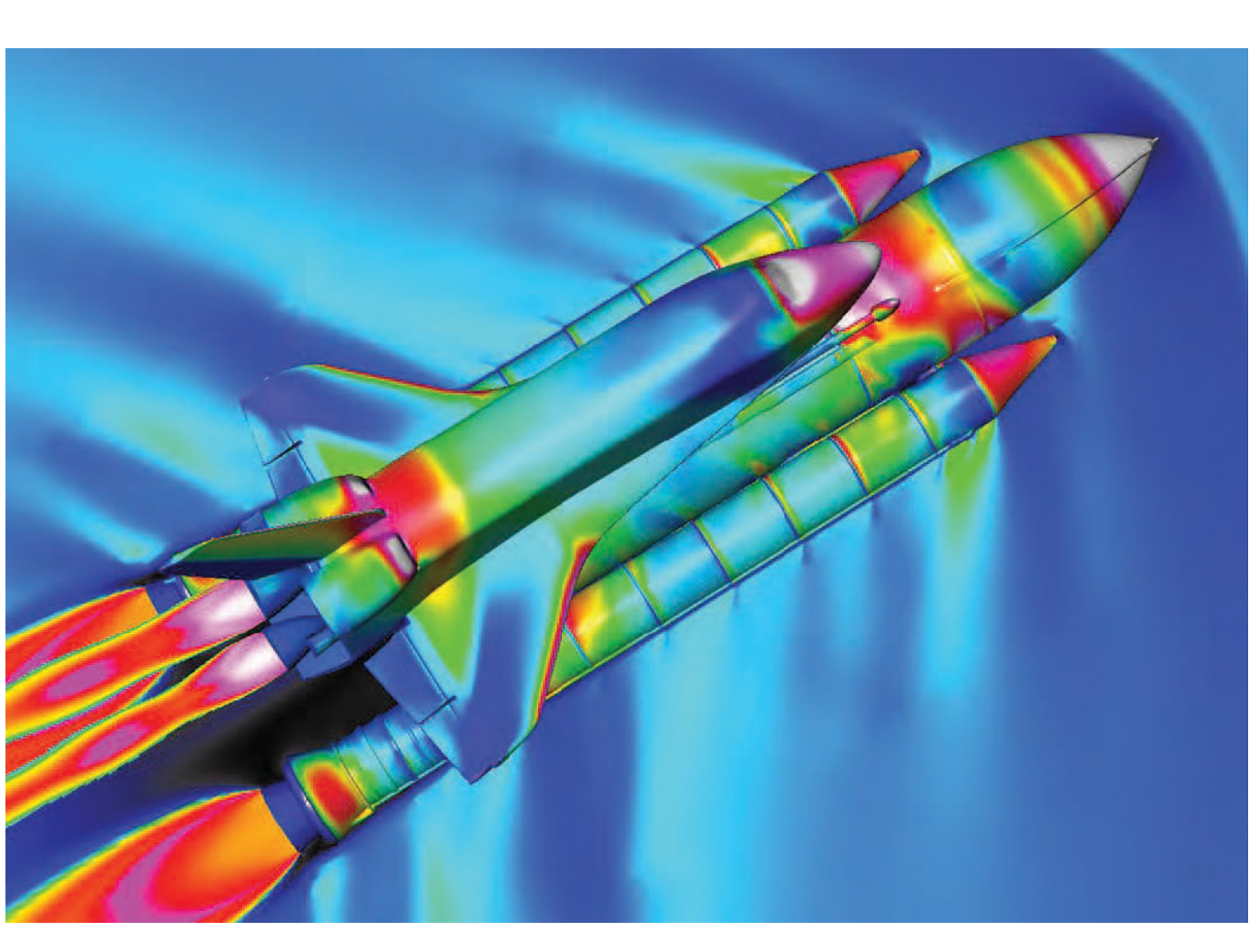
Following the Challenger disaster of 1986, NASA wanted to explore the possibility of dropping the Space Shuttle's solid rocket boosters before they burned out in case of a malfunction. To better model the aerodynamics of multiple bodies in flight, Pieter Buning and other members of a team at Ames Research Center proposed using an improvement to computational fluid dynamics (CFD) software that is now used by most air- and spacecraft designers in the United States: the overset-grid method.



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).

All CFD software breaks down complex geometries into grids of simple shapes, including breaking the air around the vehicle model into tiny bins. Early CFD work generated these grids around each major component and patched them together. Instead, overset grids overlap and interact with each other, as real air flows would, yielding more realistic simulations.

NASA developed a suite of software that enables overset grids and is now widely used: The Chimera Grid Tools program generates the grids. Pegasus preprocessing software integrates them with each other and with all the surfaces being modeled. Buning and colleagues created the OVERFLOW solver that actually runs the simulations.



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.

In the 1990s, Buning transferred to Langley Research Center, where he has continued to update OVERFLOW. The program became available through software usage agreements with Langley and was widely acquired throughout the industry and the military.

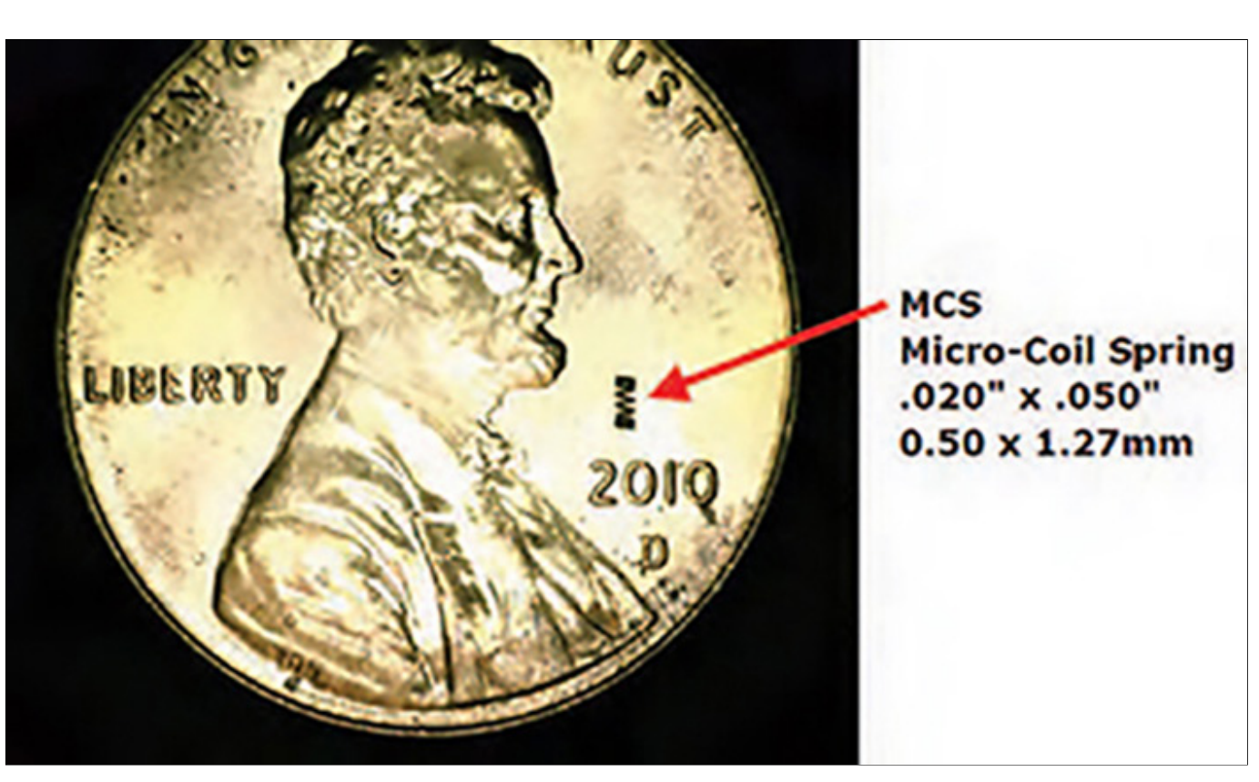
One early adopter of OVERFLOW and the rest of the Chimera Grid Tools suite was Boeing. Robb Gregg, chief aerodynamicist at Seattle-based Boeing Commercial Airplanes, says the code provides "exceptionally efficient and accurate flow solutions supporting virtually every product in the company." Beyond commercial planes, Gregg says, that includes helicopter, military, and research and development operations.

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, and aircraft manufacturers, as well as computer giants that use it to benchmark their CFD software. The latest version, released in 2017, went out to about 200 users.

Tiny Springs Improve Electronic Reliability

Space exploration comes with many giant challenges, but some 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.

Printed circuit boards are layered with copper lines and pads that connect electronic components together. 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.



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.

"We wanted something that might be a little more robust from a handling perspective, with higher reliability from a thermal perspective," says Mark Strickland, an engineer at Marshall Space Flight Center. He and fellow Marshall engineer Jim Hester developed a micro-coil spring connector that lasted up five times longer and could withstand vibrations at forces of up to 10 Gs.

The biggest challenge, the two explain, is how to connect the spring securely on both ends. "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 says.

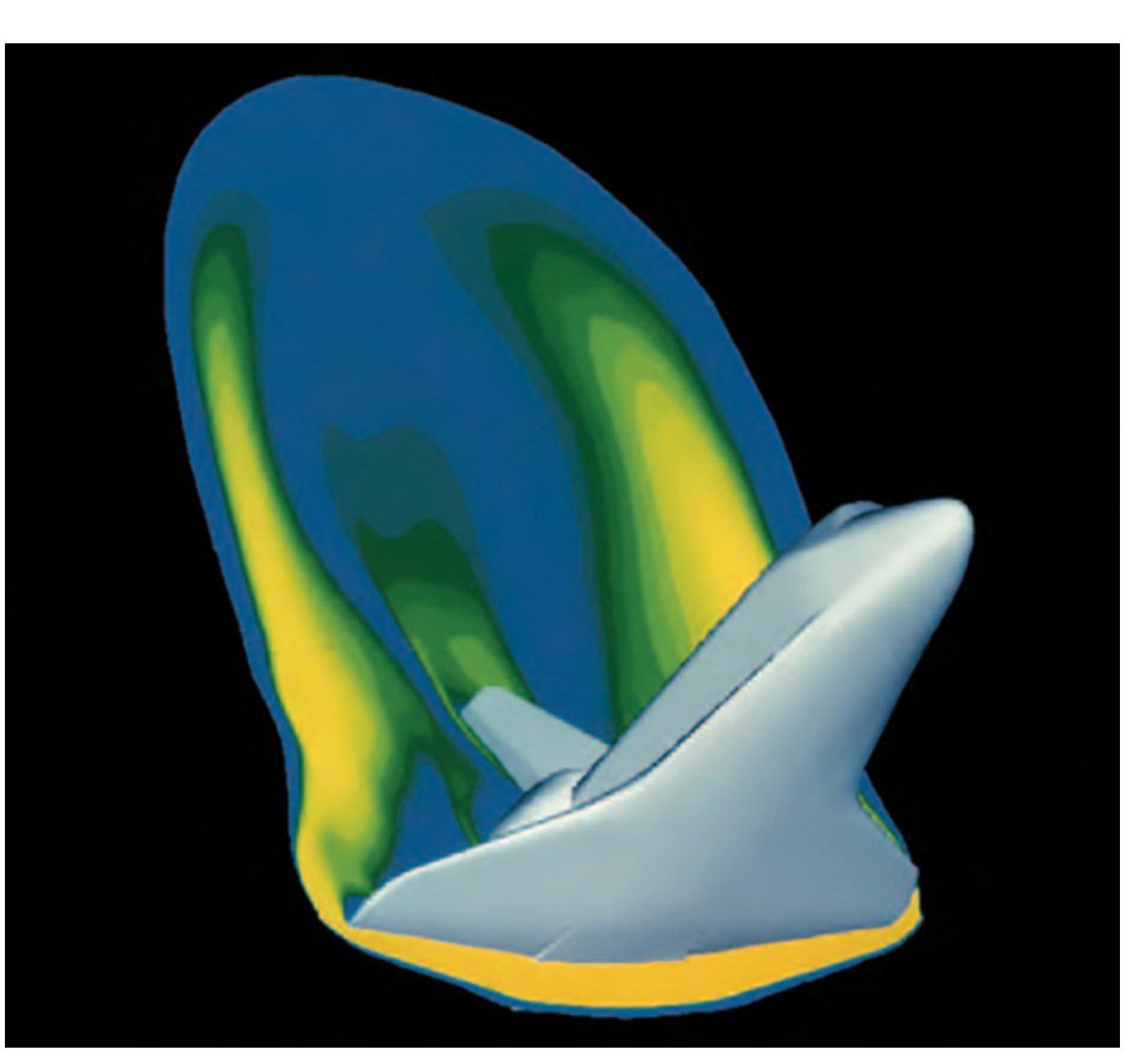
The pair worked out a system, and in 2014, their innovation won the top prize in the electronics category of *Tech Briefs'* Design the Future challenge. Now Milledgeville, Georgia-based Topline Corporation has taken it to market. However, company CEO Martin Hart emphasizes that the process first had to be streamlined and scaled up for mass production.

"NASA does a great job at figuring out a better way to do things, but it's not a blueprint," Hart says, noting that to attach even a single component would typically take an array of some 1,000 to 2,000 springs.

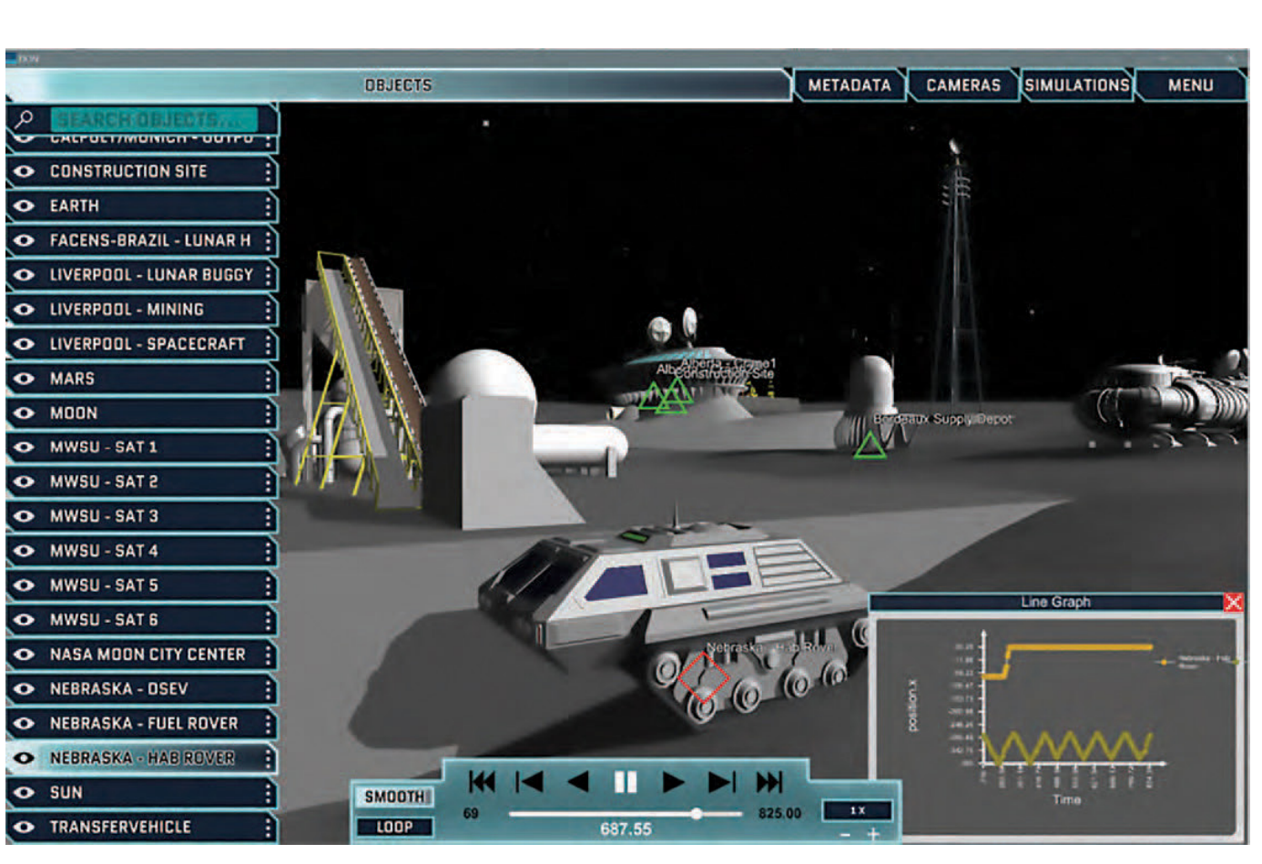
Applications include anywhere with large temperature swings, from downhole drilling to car components slotted into the engine compartment, or even a desktop computer with large ceramic parts. Hart also sees potential in medical devices, like hearing aids, and adds, "We're still at the beginning of discovering the market."

Collaborative Platform Trains Students in Simulation and Modeling

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.



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.



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.

Of course, this wouldn't be possible without NASA technology.

Moon City exists in a simulation and is visible through the Distributed Observer Network (DON), a simulation viewer created at Kennedy Space Center. 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. Sixty to 80 students participate each year.

NASA created DON to capture data from simulations created in various formats and make them portable, making it easier for them to be preserved and shared. A game engine—currently Unity 5—enables the simulation visualization.

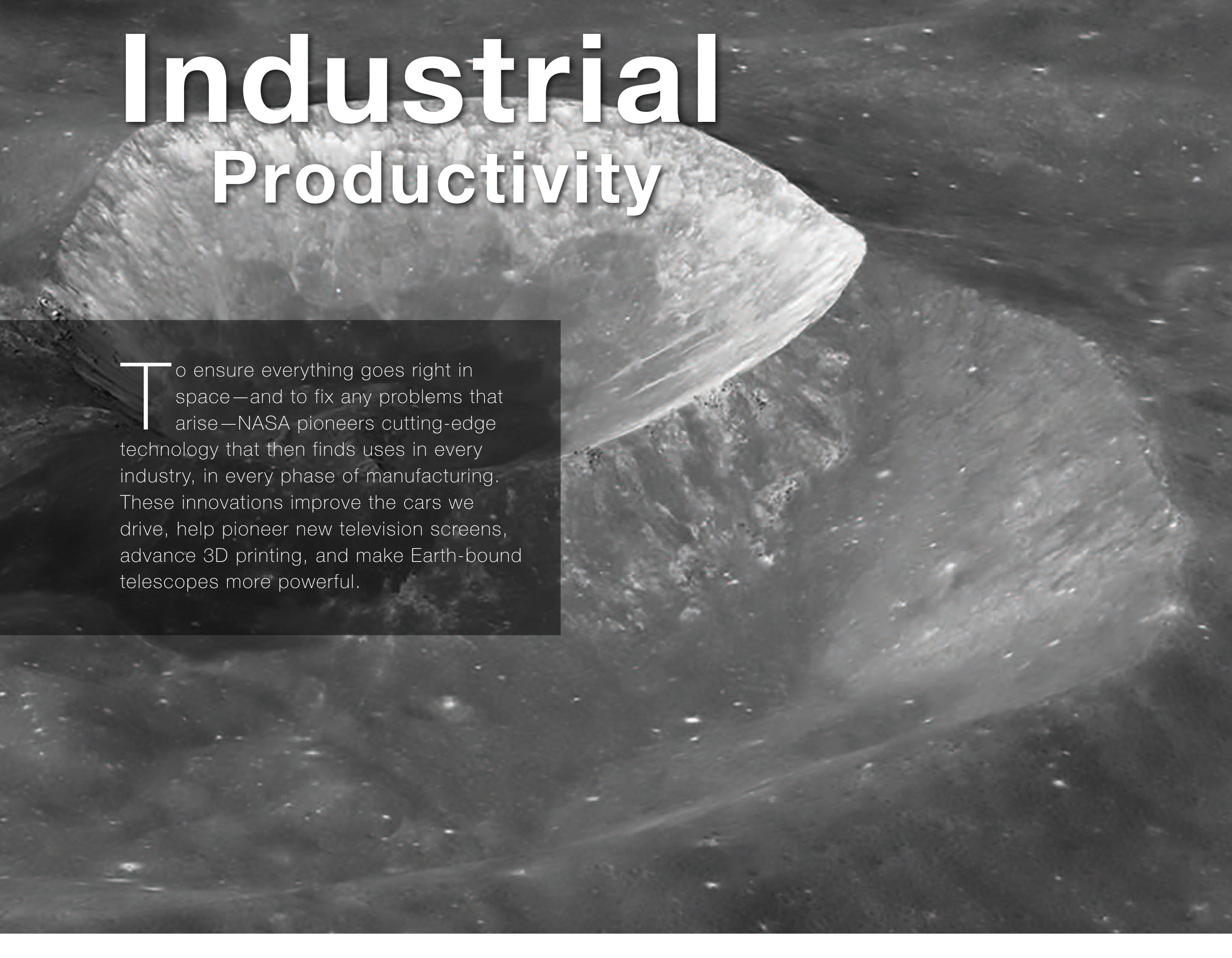
Employees from Kennedy and Johnson Space Center came up with SEE after realizing that, while modeling and simulation are widely used across many industries, few people applying for those jobs know much about it. Almost no universities offer modeling and simulation degrees.

In addition to DON, NASA supplies the teams with High-Level Architecture-based software that ensures the accurate trajectories and positioning of the planetary bodies. And the detailed model of the lunar Aitken Basin that provides the challenge's virtual setting was created at NASA's Jet Propulsion Laboratory.

SEE's overarching goal is to enhance students' employability, but faculty at participating schools can tailor activities to fit their own programs and curricula. The results are already promising: not only are participants finding jobs, but four people who participated in the program as students are now teaching simulation in colleges and participate in SEE as faculty.

Meanwhile, other organizations are building their own software similar to DON—possibly following NASA's example. DON was the first such program to use a game engine, a practice that is now common.

Industrial Productivity



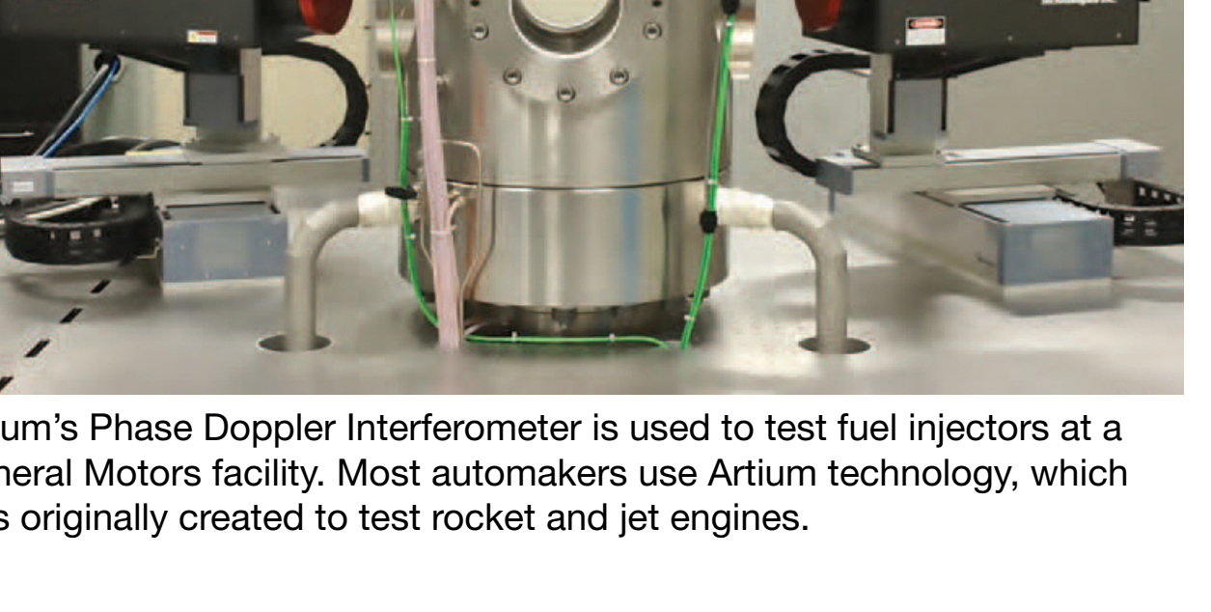
To ensure everything goes right in space—and to fix any problems that arise—NASA pioneers cutting-edge technology that then finds uses in every industry, in every phase of manufacturing. These innovations improve the cars we drive, help pioneer new television screens, advance 3D printing, and make Earth-bound telescopes more powerful.

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

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.

At first, NASA just wanted a way to analyze 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.

After founding Aerometrics Inc., Bachalo and his partner developed the Phase Doppler Particle Analyzer (PDPA) under Small Business Innovation Research contracts with Lewis Research Center, now Glenn Research Center. The device characterizes the interaction of atomized fuel and air in terms of droplet sizes, velocity distribution, turbulence intensity, and fluctuations. It remains the standard for spray characterization to this day and, along with work on using lasers to characterize soot emissions, also funded by Glenn, forms the basis for the products offered by his current company, Sunnyvale, California-based Artium Technologies Inc.



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.

The PDPA technology has been used to test and validate advanced models for fuel-efficient combustors and to design or monitor spray nozzles for paint, agricultural products, and fire sprinklers. An adapted version can characterize sprays of nebulizers, aerosols, and mists.

In 1995, Aerometrics merged with a competitor, and in 1998, Bachalo cofounded Artium, continuing to produce the technology.

Most automobile manufacturers use Artium spray-characterization devices to develop and test fuel injectors, among other applications. Others use them in spray-coating pharmaceuticals, developing and testing inkjet printers, and certifying aircraft parts.

PDPA technology recently found a new—and lucrative—market in the organic LED, or OLED, display business. These new screens, with their deep blacks and rich colors, are used in smartphones and televisions. Initially, the pixels were created through a lithographic process, but manufacturers are now working to print the screens with inkjet technology, with Artium devices providing quality control.

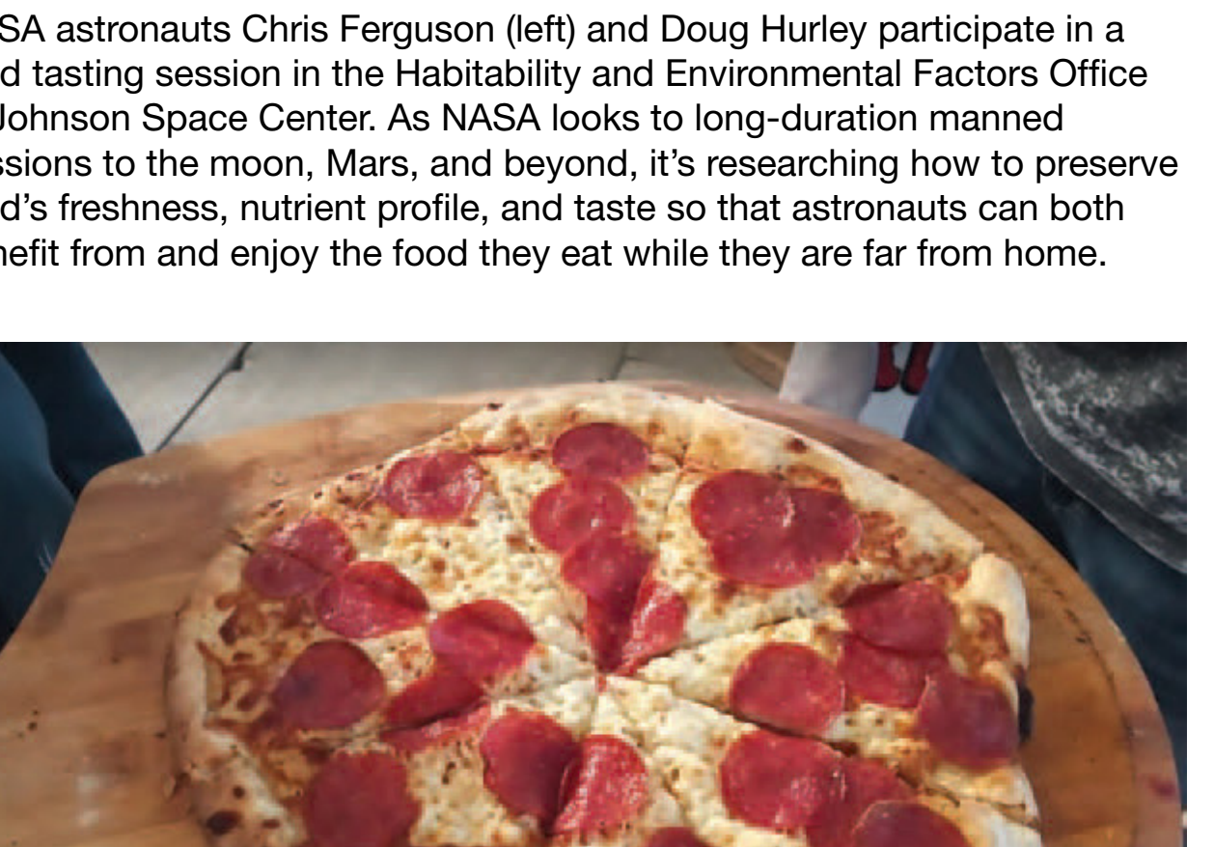
Printed screens should significantly lower the prices of OLED displays. Meanwhile, Artium's revenues have doubled in the last year.

Deep-Space Food Science Research Improves 3D-Printing Capabilities

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.

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.

In its search for new ways to provide nutrients and variety to astronauts, NASA in 2013 awarded a Small Business Innovation Research (SBIR) contract to a company with a novel idea. Systems and Materials Research Corporation (SMRC) proposed building a device capable of 3D-printing food.



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

Anjan Contractor, then a senior engineer at SMRC, was behind the company's proposal. When Phase II SBIR funds didn't immediately follow, Contractor started to think about other applications for 3D food printing. He began working on a 3D printer that could put together customized pizzas, with dough, sauce, cheese, and toppings, one at a time.

"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, now based in Columbus, Ohio, and adapted the device to decorate cookies and cakes. The 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.

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.

Image courtesy of the U.S. Navy

BeeHex is trying a variety of business models. One route is a stand-alone machine that bakers can use to design on-demand confections. "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.

Simulated Space Dirt Supports Future Asteroid Mining

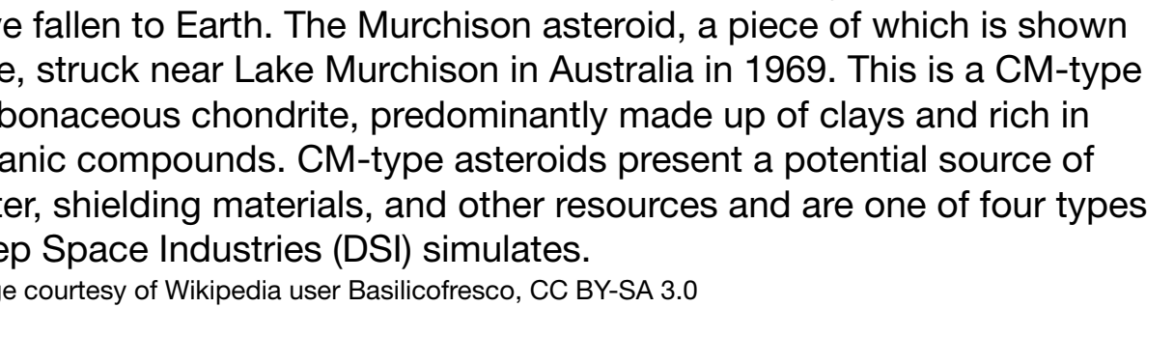
Researchers know a lot about asteroids from studying the ones that have fallen to Earth. The Murchison asteroid, a piece of which is shown here, struck near Lake Murchison in Australia in 1969. This is a CM-type carbonaceous chondrite, predominantly made up of clays and rich in organic compounds. CM-type 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

When companies begin mining asteroids, they probably won't be seeking precious metals. Some space rocks contain such materials, but in space, another substance is far more valuable: water.

Water is not only necessary for life, but it contains that other necessity, oxygen, which along with water's other ingredient, hydrogen, can be turned into NASA's favorite rocket fuel: liquid hydrogen oxidized with liquid oxygen.

But building the tools to harvest these materials from an asteroid will first require testing here on Earth. That's why San Jose, California-based Deep Space Industries (DSI), one of a few businesses working toward space mining, leapt at NASA's 2015 Small Business Innovation Research solicitation to develop soil and crust that simulate the surface composition of four types of asteroids.



DSI customers can buy raw asteroid simulant powders or mixes of a range of grain sizes.

For NASA's now-cancelled Asteroid Redirect Mission, researchers wanted to test new tools and train astronauts for challenges like anchoring to an asteroid. With very little gravity, operating on asteroids requires reliable anchoring, and even sample collection becomes tricky. The Space Agency wanted simulations of the surfaces of four varieties of carbonaceous chondrite, a class of asteroids containing abundant carbon, water, and organic compounds, all useful for space travel.

DSI delivered a total of more than 11,000 pounds of asteroid simulants to Kennedy Space Center by the spring of 2018.

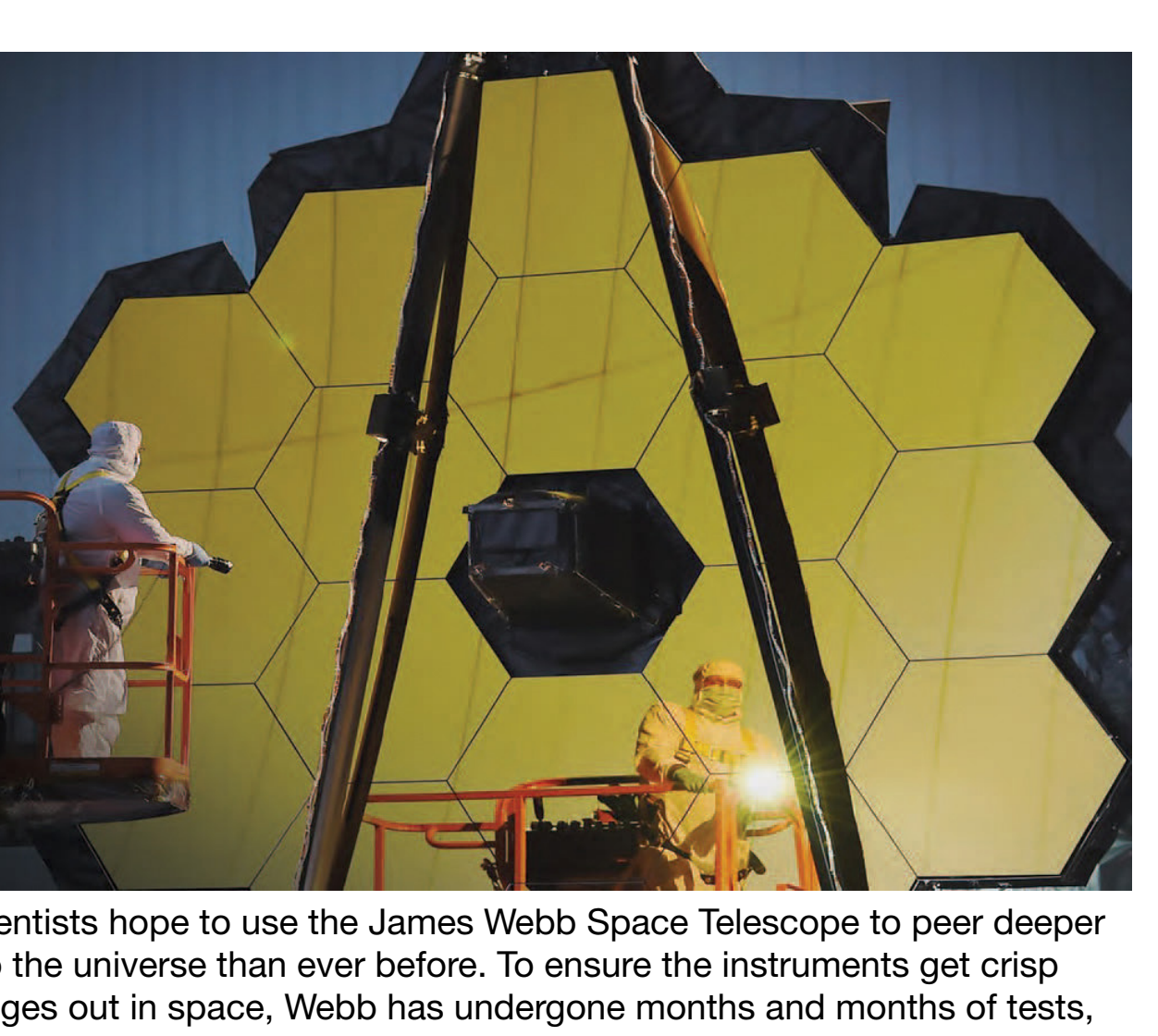
DSI ultimately wants to set up asteroid mining operations with spacecraft like this harvester concept. Any machinery bound for an asteroid, though, first needs to be tested in asteroid simulant to see how it will perform.

Several universities have also purchased the materials, as have other space agencies and companies interested in space mining.

Because it's so expensive to put water or anything else into space—about $11,000 per pound— 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.

The water could also fuel a space tug lifting a satellite from low-Earth orbit. And DSI wants to eventually use elements harvested from asteroids to manufacture parts in space, further saving on launch costs.

Vibration Isolator Steadies Optics for Telescopes

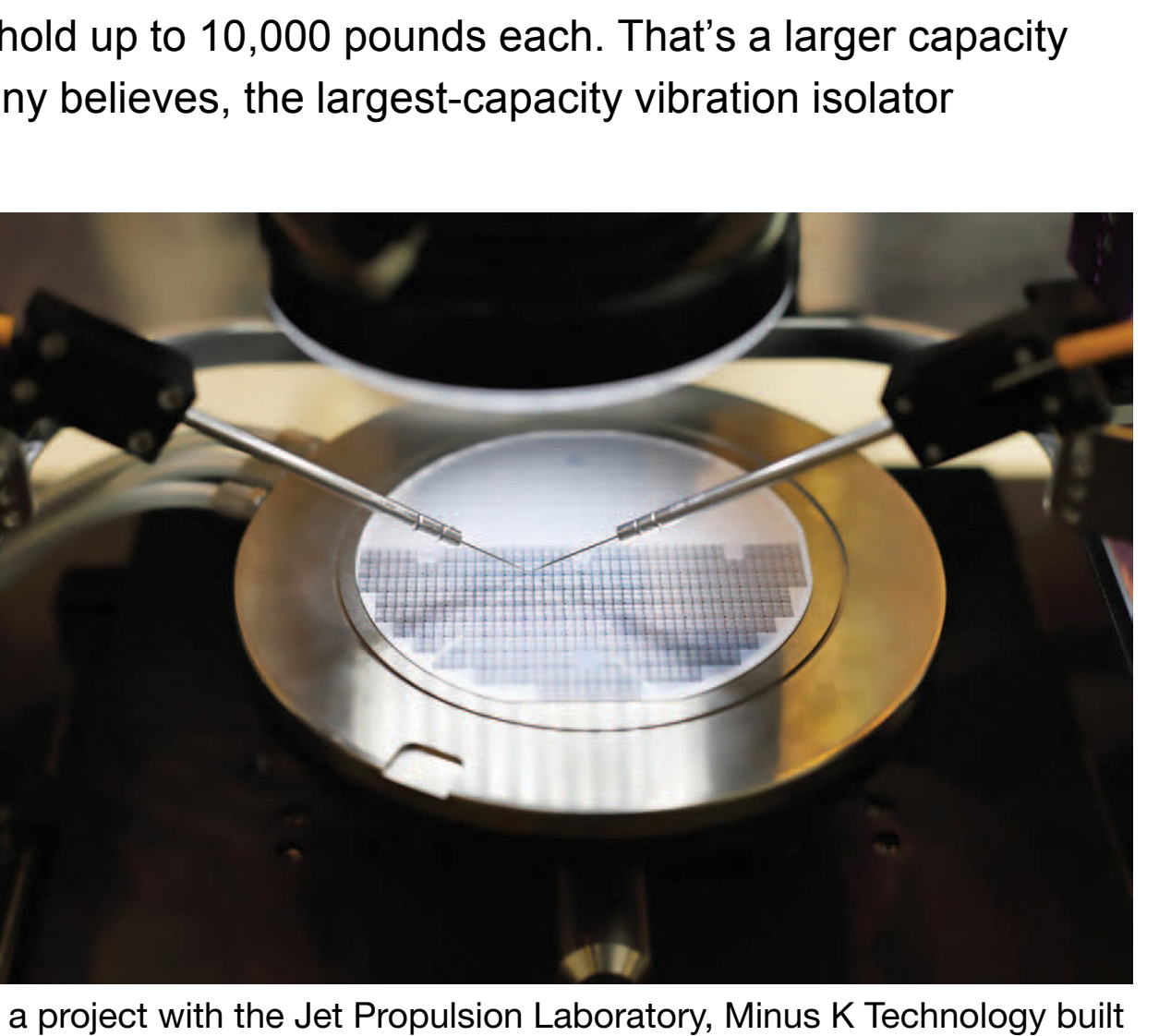


Scientists hope to use the James Webb Space Telescope to peer deeper into the universe than ever before. To ensure the instruments get crisp images out in space, Webb has undergone months and months of tests, some of which required a "vibration isolator" to hold it extremely steady.

Anybody who has ever tried to hold a camera steady for a long exposure in low light knows what happens: the camera shakes, and the image blurs. The same can happen with images from telescopes and any kind of 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 they create a more stable platform where external vibrations won't interfere with sensitive measurements.

NASA has bought several vibration isolators from Los Angeles-based Minus K Technology 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.



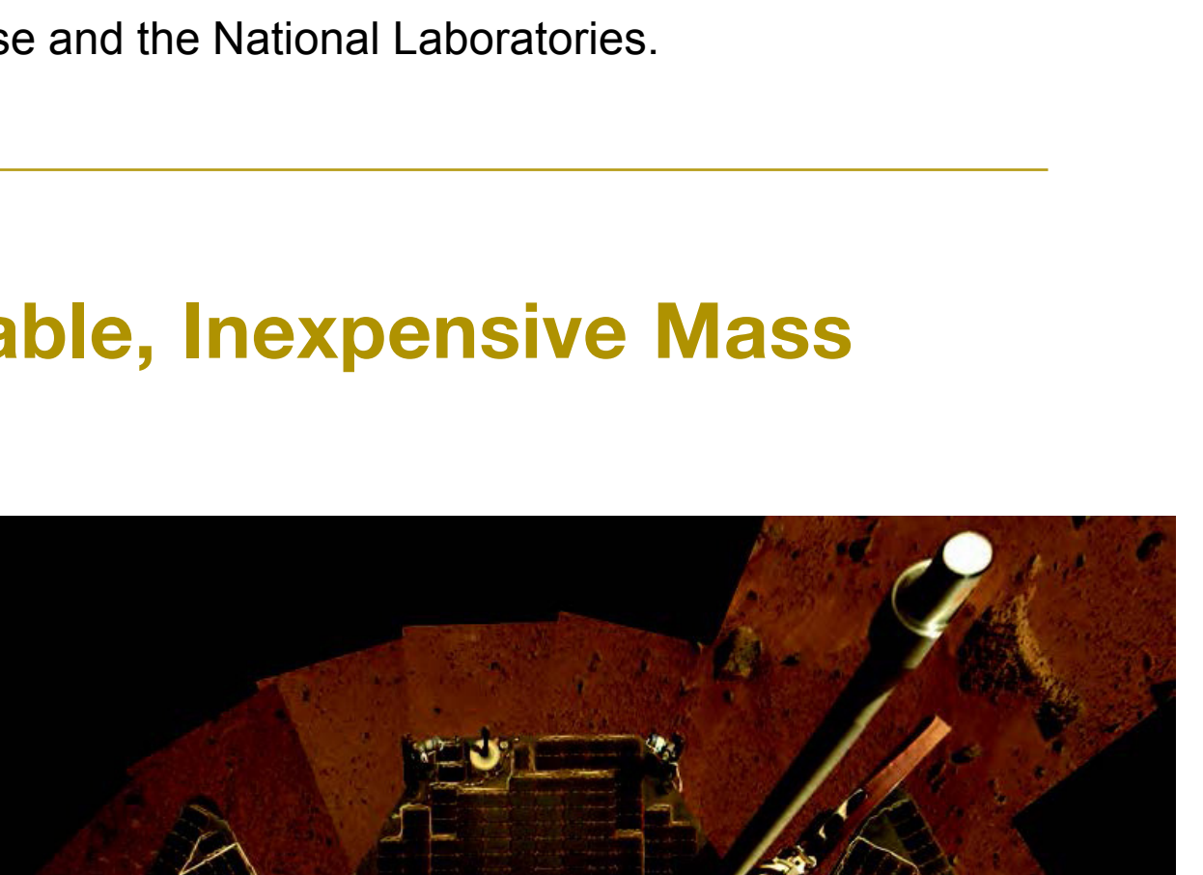
For a project with the Jet Propulsion Laboratory, Minus K Technology built a vibration isolator that worked well in a hard vacuum. The company now sells similar models to other customers, including to run quality control testing on silicon chips.

JPL also recently turned to Minus K to build it an isolator for testing space-ready optics, which requires a fairly high degree of vacuum compared to typical industry standards.

Although the company has a good deal of experience building vibration isolators for vacuum, Minus K engineering director Erik Runge says the JPL project required innovation. "There are different requirements for materials that can be used, types of coatings that are okay, and so on. We learned about what special requirements were needed at high vacuum levels."

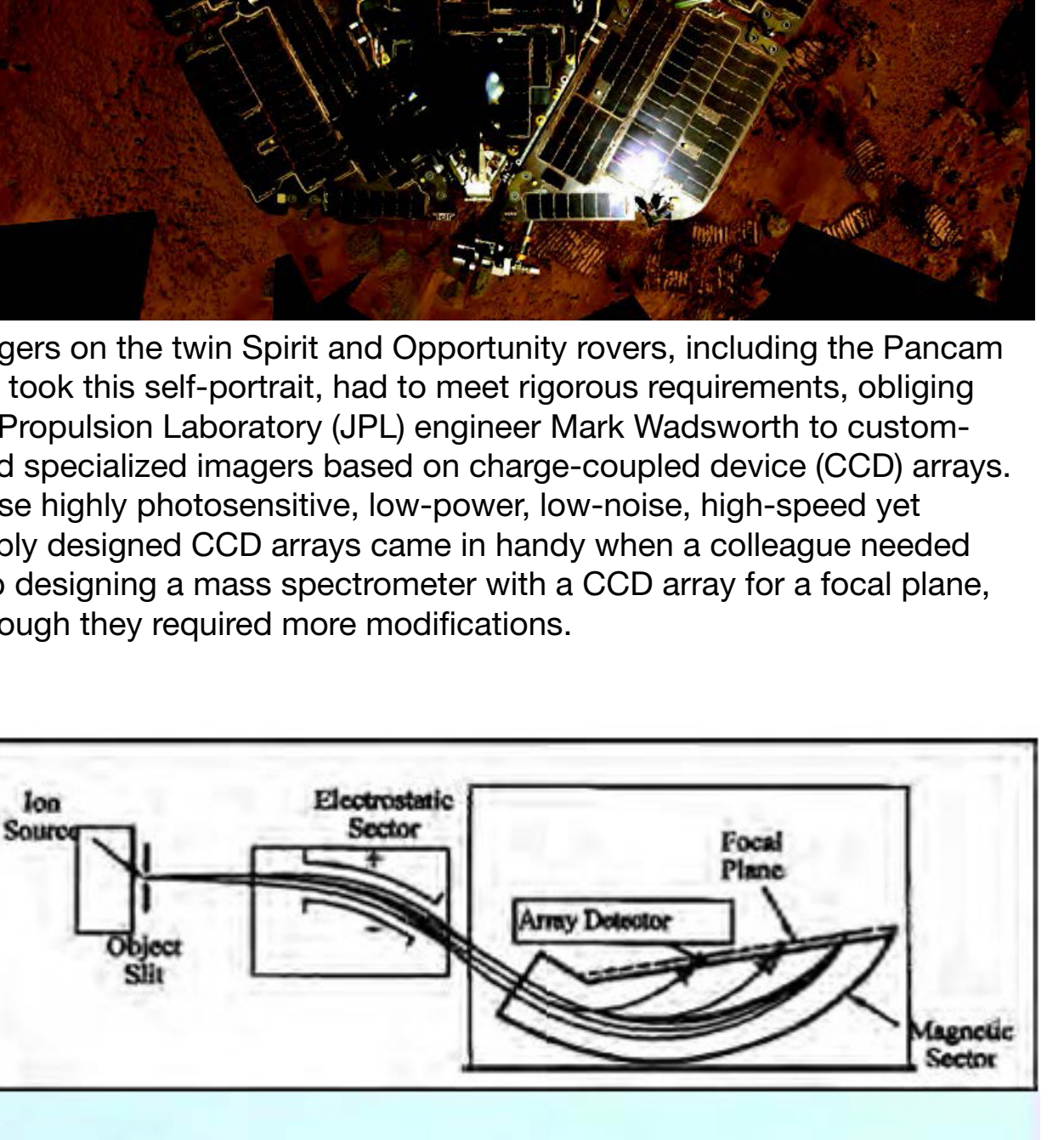
Today, the company has taken this experience and translated it into new vibration isolators for clients that make semiconductors and optics. "When building chips and measuring chips, they need to have as close to no vibration as possible," he notes. Other customers include the Department of Defense and the National Laboratories.

IonCCD Enables Fast, Reliable, Inexpensive Mass Spectrometry



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.

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. In the mid-1990s, about 20 years after taking the first digital astronomical photo, JPL engineers identified a way to replace traditional film with CCDs in a totally different application—mass spectrometers.

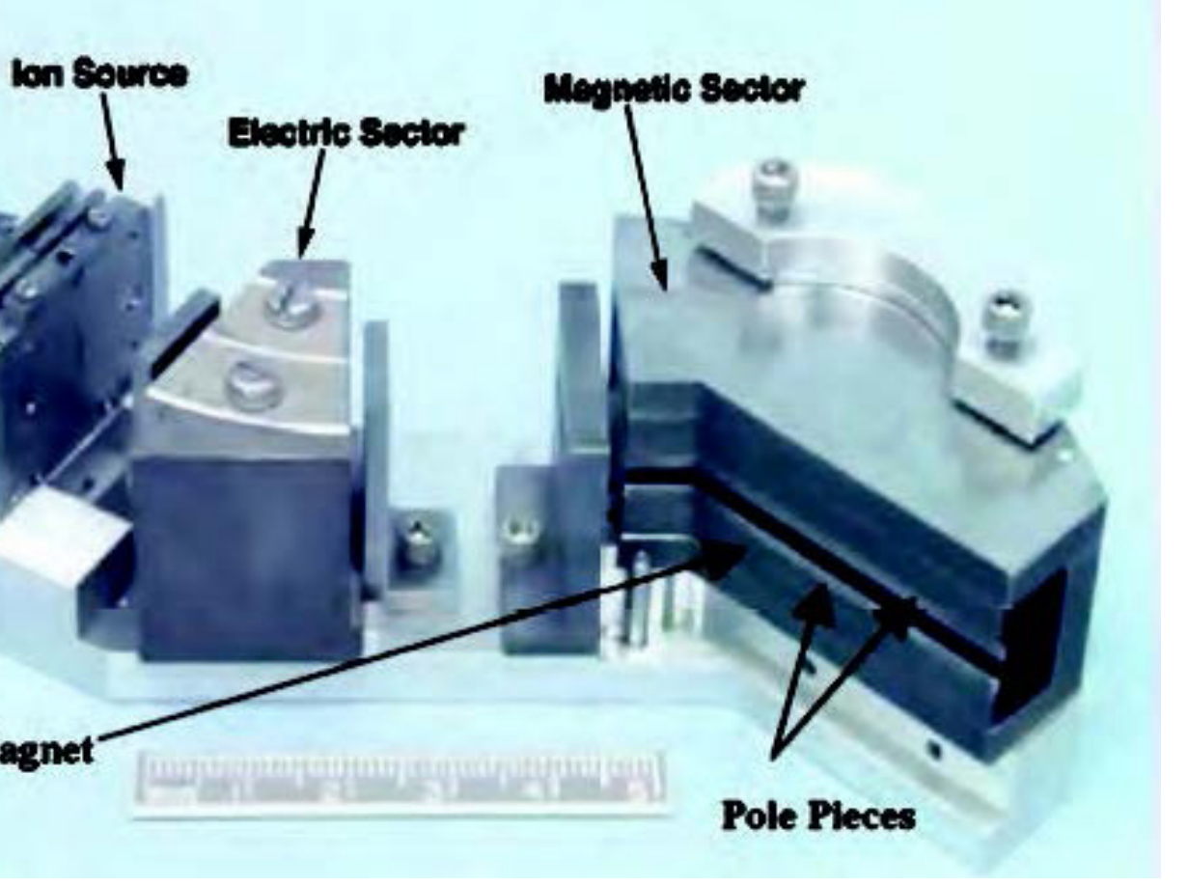


In the Mattauch-Herzog mass spectrometer configuration, ions are deflected first by an electrical field and then by a magnetic field to sort them by weight before they strike a focal plane that detects all the ions simultaneously. The CCD-based prototype created at JPL accomplished this within a small, rugged, inexpensive, energy-efficient device.

Mass spectrometers identify the ratios of various isotopes in a material, which can reveal information about its age, how it was formed, and more. The type of mass spectrometer one JPL engineer wanted to use for comet analysis—the Mattauch-Herzog configuration—discerns the masses of various isotopes according to where they hit a focal plane, traditionally made with camera film. He and a colleague devised a version with a CCD array as its focal plane, which was much easier to use and far more energy efficient.

But they didn't have the funding to build it. Instead, they helped a start-up company license the intellectual property and build the device.

In the mid-2000s, the company built and sold several mass spectrometers based on the CCD focal plane, which it named IonCCD. Then OI Analytical, based in College Station, Texas, purchased the company and launched the first official commercial line based on the technology. In 2011, when water technology company Xylem bought OI, it stopped developing mass spectrometers and started offering IonCCD as a standalone product. The company also packaged it with a camera controller and power supply to create the first series of the IDS 2030 Charged Particle Detector.



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.

Mattauch-Herzog devices deliver accurate results much more quickly than other mass spectrometers by counting all isotopes simultaneously. But IonCCD allows them to be smaller, cheaper, more rugged, and far more energy-efficient.

Customers include analytical chemists, the pharmaceutical industry, and the military's threat detection applications. The IDS 2030 also has customers in spatially resolving ion-mobility spectrometry, often used for drug and explosive detection.

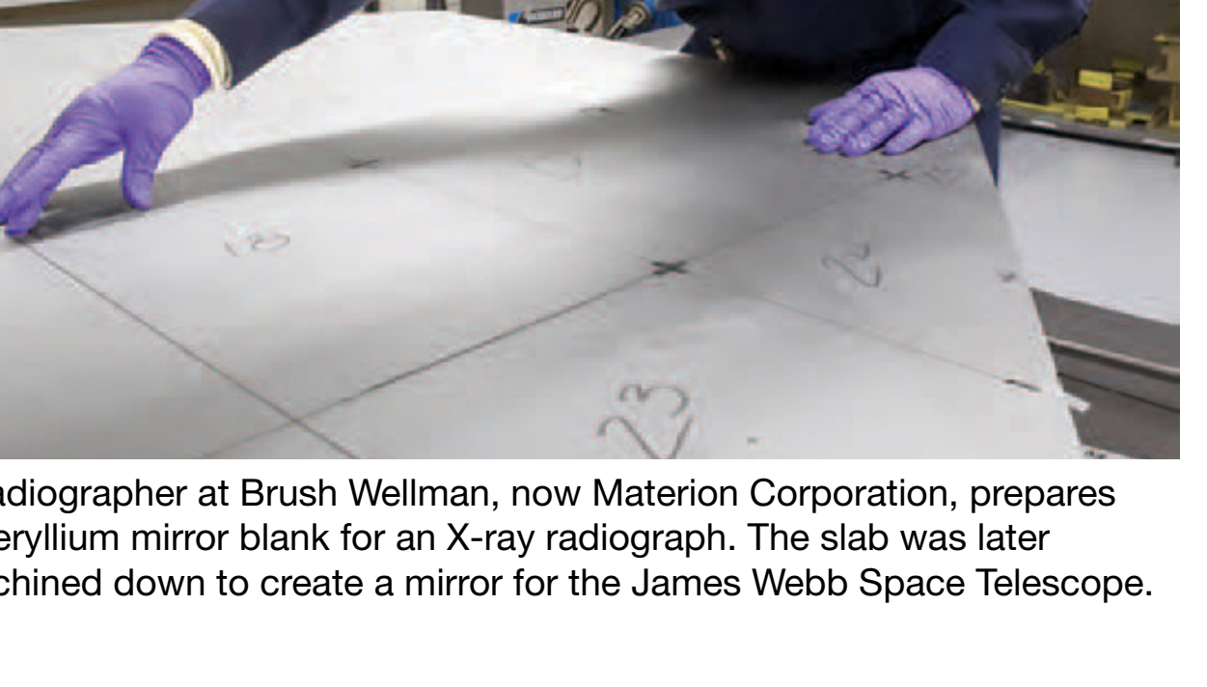
Beryllium Blazes New Trail for Telescopes

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.

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.

For the mirrors, NASA needed a material that would maintain a stable shape at temperatures approaching absolute zero and that could withstand the hazardous journey into space. The agency settled on beryllium, which stops shrinking at about -300 °F and is stiffer than other options, allowing for lighter mirrors.

When NASA was planning the telescope, Mayfield Heights, Ohio-based Brush Wellman, now known as Materion Corporation, was one of the world's top beryllium producers, and Goddard Space Flight Center selected the company to provide the raw blanks that would become Webb's mirrors.



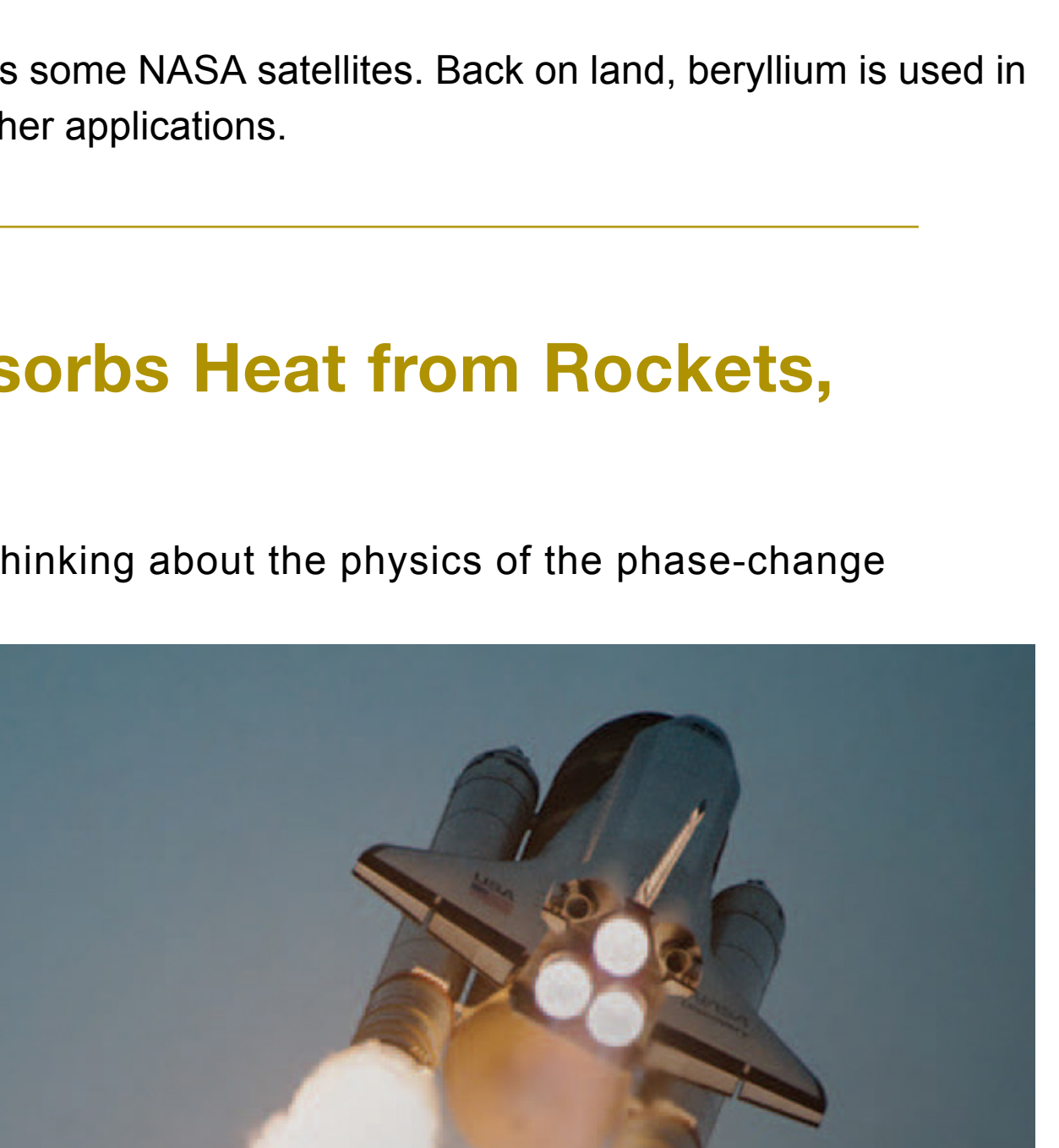
The James Webb Space Telescope mirrors are removed from Marshall Space Flight Center's X-Ray and Cryogenic Facility following testing. The mirrors are made of beryllium in part because the material will deform predictably when taken from room temperature to near absolute zero.

The mirrors began as a powder. Unlike other beryllium powders, which are made up of block-like grains, Materion's is gas atomized to be spherical, allowing for uniformity in all directions. The powder was poured into a large pressure vessel and pressed in all directions at high temperatures, fusing it together, a process known as hot isostatic pressing (HIP). This produces mirror blanks with a homogeneous microstructure, resulting in repeatable and predictable shape change.

It was the first time the company had manufactured the spherical powder in very large quantities, and Materion won several awards for the HIP tools it created to make the mirrors. As a result of the Webb work, Materion developed an industrial aerospace standard for the gas-atomized spherical beryllium powder and now makes all its materials with this high-quality, space-certified method.

Beryllium is used in military satellites and other Department of Defense equipment, as well as some NASA satellites. Back on land, beryllium is used in most X-ray and mammogram machines, among other applications.

Phase-Change Coating Absorbs Heat from Rockets, Pipes, Beer



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.

Most people enjoy an icy drink without thinking about the physics of the phase-change reaction inside the glass. But the reaction—in this case, as ice absorbs heat and melts—is powerful. It's something NASA has harnessed for far more extreme environments, and now a NASA-invented phase-change coating could keep the chill in passenger planes—or be the key to an ice-free cooler.

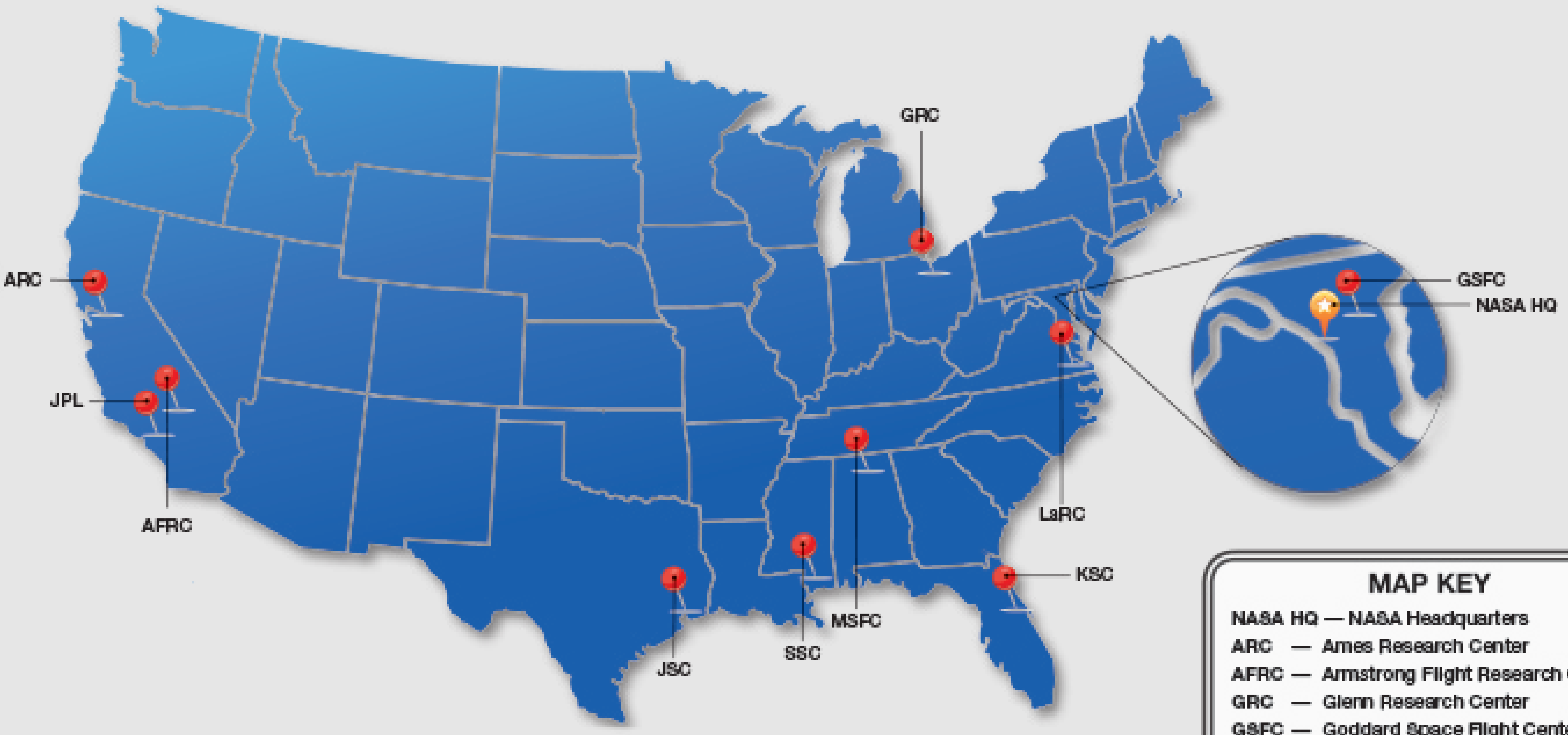
In the early 2000s, Marshall Space Flight Center materials scientist Raj Kaul encapsulated phase-change materials in a plastic that could be applied like paint, aiming to better protect the Space Shuttle's solid rocket boosters. Previously, NASA had used a material called MCC-1 (for Marshall Convergent 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. Kaul's new phase-change coating was more reliable, he says, and effective with a much thinner layer. "Another advantage," he adds, is that "it could be reused."

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.

A commercial license was quickly snapped up by entrepreneur Chris Bilec, who founded Austin-based PrimeBilec to sell the coating. For airplanes, Bilec explains, the idea would be to coat the back end of the plane, to prevent heat damage from the jet engines. He has also seen interest from a company that makes heat traps for Veterans Affairs hospitals.

Bilec has another idea in development as well—to create an "iceless cooler" along with smaller containers for lunches and leftovers. PrimeBilec embeds the phase-chase material in food-grade polyester to coat the container, and the food—or beer—inside "will stay colder for about two to four hours longer," Bilec says, depending on the temperature outside.



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

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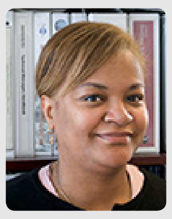

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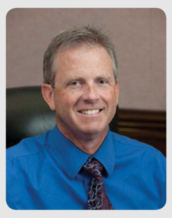

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