National Aeronautics and Space Administration

# TECHNOLOGY INNOVATION

PUBLICATION FOR BUSINESS AND TECHNOLOGY

V.17.01

A Message from the

**Associate Administrator,**

**Space Technology Mission Directorate**

Dear Readers,

This year we commemorated the 100th anniversary of the National Advisory Council for Aeronautics—the predecessor to NASA—and with that milestone comes the celebration of new accomplishments in many technology areas and the innovations to explore deeper into space, while at the same time benefiting humankind on our home planet.

Technology drives exploration, and as the new Associate Administrator for the Space Technology Mission Directorate, I am committed to continuing this tradition of developing the innovations and technologies for more ambitious robotic exploration missions and for safe and affordable human exploration of the solar system. Our success will in great part be measured by the impact these technologies have on enabling the broadest set of future NASA missions while contributing to advancing the goals and objectives of other government agencies and stimulating commercial space activities.

Advanced Manufacturing is an area of technology development that is critical to NASA and its missions, as well as the commercial sector. Since its inception, NASA has had a rich history of working closely with industry to push the envelope in the manufacture of its large-scale and complex hardware. With the onsite manufacturing of the Saturn V S-IC first stage at the agency's Michoud Assembly Facility (MAF) in the early 1960s, the space agency began a legacy of manufacturing excellence that sought out the best and brightest both within NASA and its commercial partners. Today, NASA is again expanding its efforts to engage industry and academia on advanced manufacturing technology central to the nation at its centers and through its National Center of Advanced Manufacturing located at MAF.

NASA is on the cutting edge of building technology both in space and for space, developing innovative solutions to overcome the challenges presented beyond low-Earth orbit. NASA's advanced manufacturing investments are vast, ranging from the complexities of the Mars Curiosity Rover to the optical mirrors on the James Webb Space Telescope. NASA has taken the concept of friction stir welding out of the laboratory and put it to work in practice on the space shuttle external tank and for major components of the Space Launch System. NASA has partnered with industry to test the next generation of liquid rocket engines fabricated via 3-D printing, and the agency has worked with American entrepreneurs to develop a thermal protection system out of multidimensional, woven materials for the Orion spacecraft.

NASA also looks to the future of manufacturing by continuing its commitment to excellence in science, technology, engineering and mathematics (STEM) education to ensure that the next generation of Americans can carry the torch of space exploration.

NASA's space technology investments are closely coordinated between mission directorates in alignment with the Agency's Strategic Plan, as well as with President Obama's National Manufacturing Initiative. Our goal is to drive exploration by building the technology and capabilities for tomorrow's space missions, today.

Sincerely,

**Steve Jurczyk**
Associate Administrator
Space Technology Mission Directorate
http://www.nasa.gov/spacetech

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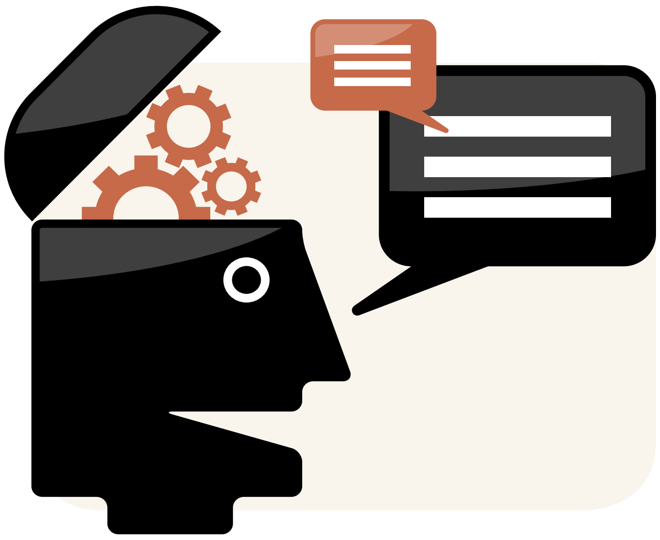


# ROCKET SHOP

## Michoud Assembly Facility

## Take a tour of the one-of-a-kind facility where NASA is manufacturing tomorrow's launch vehicles.

With ports on the Gulf of Mexico, five Class I railroads and the Mississippi River passing through, and no fewer than five interstate highways converging on it, the city of New Orleans makes a convenient location to bring in materials, assemble them into supermassive structures and float them off to their next stops. Today, an 832-acre tract of natural high ground in the Crescent City, once part of a vast sugarcane plantation, has also become a confluence of commercial, federal and state manufacturing, research and education.

“New Orleans is just a very natural place to build big things, because you’ve got this great intersection of water and rail and roadway,” says John Vickers, manager of advanced manufacturing at NASA’s Marshall Space Flight Center.

The Michoud Assembly Facility, built to support the United States’ World War II effort, became a NASA property in 1961, at the start of the Apollo missions. Over the last decade or so, advances in cutting-edge technology have made it attractive to commercial manufacturing.

The heart of Michoud is a sprawling, 43-acre facility filled with manufacturing technology new and old. Known simply as “Building 103,” this was the world’s largest building when it was constructed, and it remains one of the biggest manufacturing facilities in existence. It’s where the first stages of the Apollo missions’ Saturn I and V rockets were built, and later, the 154-foot external tanks for shuttle launches. Now, both the core stage for NASA’s Space Launch System (SLS) and the Orion capsule it will carry into space in 2018 are being built at Michoud.

Patches from the 138 missions it has supported are displayed on the facility’s walls, and workers zoom past on bicycles or electric carts to overcome the building’s vast distances.

Since 1999 the building has been home to the National Center for Advanced Manufacturing (NCAM), a partnership between NASA, the state of Louisiana, Louisiana State University (LSU) and the University of New Orleans (UNO). NCAM owns many of the facility's state-of-the-art technologies.

Among these, the one that has done the most to open up space for commercial manufacturers in the facility is self-reacting friction stir welding. During the shuttle program, parts of the external tanks were passed from one welding station to the next, with around 200 welders at work, Vickers explains. Now, all that work is done on four massive tools.

Friction stir welding was pioneered by The Welding Institute in the United Kingdom in the early 1990s. Although not actually welding in the strictest sense, in this process, two pieces of metal are joined by a spinning pin that heats them to a plastic state by friction and stirs them together as it runs along the seam. The result is an especially strong, uniform weld with no weight added by the beading of a traditional weld. The weld path can also be programmed and automated.

However, a considerable amount of joining force was required during this process, necessitating a heavy anvil behind the metal being welded and limiting the device's movements. Since the early 2000s, NASA engineers have patented improvements to friction stir welding, the most important being a design that houses the pin between two shoulders, which grip the metal like a vise and eliminate the need for an anvil. Adding a gimbal to the lower shoulder allows it to accommodate changes in thickness of the metal being welded.

## build the big stuff

"Using this self-reacting friction stir weld capability, now you can begin to do arcs and curves and shapes that weren't possible before," says Pat Whipps, who is leading the build of the SLS core stage at Michoud.

NASA also designed pins that last longer and spin faster — up to 29,000 rotations per minute — allowing friction stir welding of temperature-resistant metals like titanium.

Whipps says the more versatile tools have allowed a few machines to carry out all the welding for the SLS. In Building 103, a dome weld tool builds the domes that will cap each end of the rocket's tanks, and a segmented ring weld tool has already completed all the rocket's rings. In an adjacent building, curved panels are assembled into barrels for the tanks in the cylindrical, 30-foot-tall vertical weld center.

And in another adjacent building with 210-foot ceilings stands the colossal vertical assembly center (VAC), where the barrels will be stacked and welded together. At 170 feet tall, this bright blue tower is the world's largest welding tool.

Like the other three tools, it has its own foundation, independent of the building. “We want to make sure each of these tools is a freestanding entity,” Whipps says, adding that, for the VAC, “the foundation we put in is comparable to that of a skyscraper you would see downtown.”

Overhead, 70-ton cranes will be used to build the rocket’s two major substructures. Whipps explains the process: In the VAC, the dome that will cap the liquid hydrogen tank will be friction stir welded onto the tank’s top barrel. Then the dome and barrel will be lifted and the next barrel slid in under them and welded on, and so on, until the five barrels of the liquid hydrogen tank have been sealed at the bottom with a second dome.

The reason for this seemingly counter-intuitive construction process is to avoid what Whipps calls “FOD entrapment.” Any “foreign object debris” from welding will fall through the tank to the floor of the building, rather than landing on the bottom of the tank and hitching a ride.

The hydrogen tank will then be proof-tested, cleaned, covered in epoxy primer and thermal protection foam, and vertically attached to the engine section. The liquid oxygen tank, just two barrels long, will be built in the same fashion and attached to the rest of the rocket, which will ultimately depart the facility on a barge, floating into the Gulf of Mexico and around Florida to arrive at Cape Canaveral.

This will be the first, 70-ton version of the rocket, which is to be followed by a 130-ton version.

Additional parts of the rocket will be made at Marshall Space Flight Center and other locations, but the heavy lifting has always been done at Michoud. “When it’s time to build the big stuff, we’re NASA’s only manufacturing facility,” Vickers says. Because Marshall is where the rockets and spacecraft are designed, the manufacturing center falls under its purview.

Now, since NASA is using only about half of Building 103, the Agency has begun leasing space to commercial tenants through Space Act Agreements. “Going forward with the SLS project, we don’t need all that space, so the idea is to offset the cost of operating the facility,” says

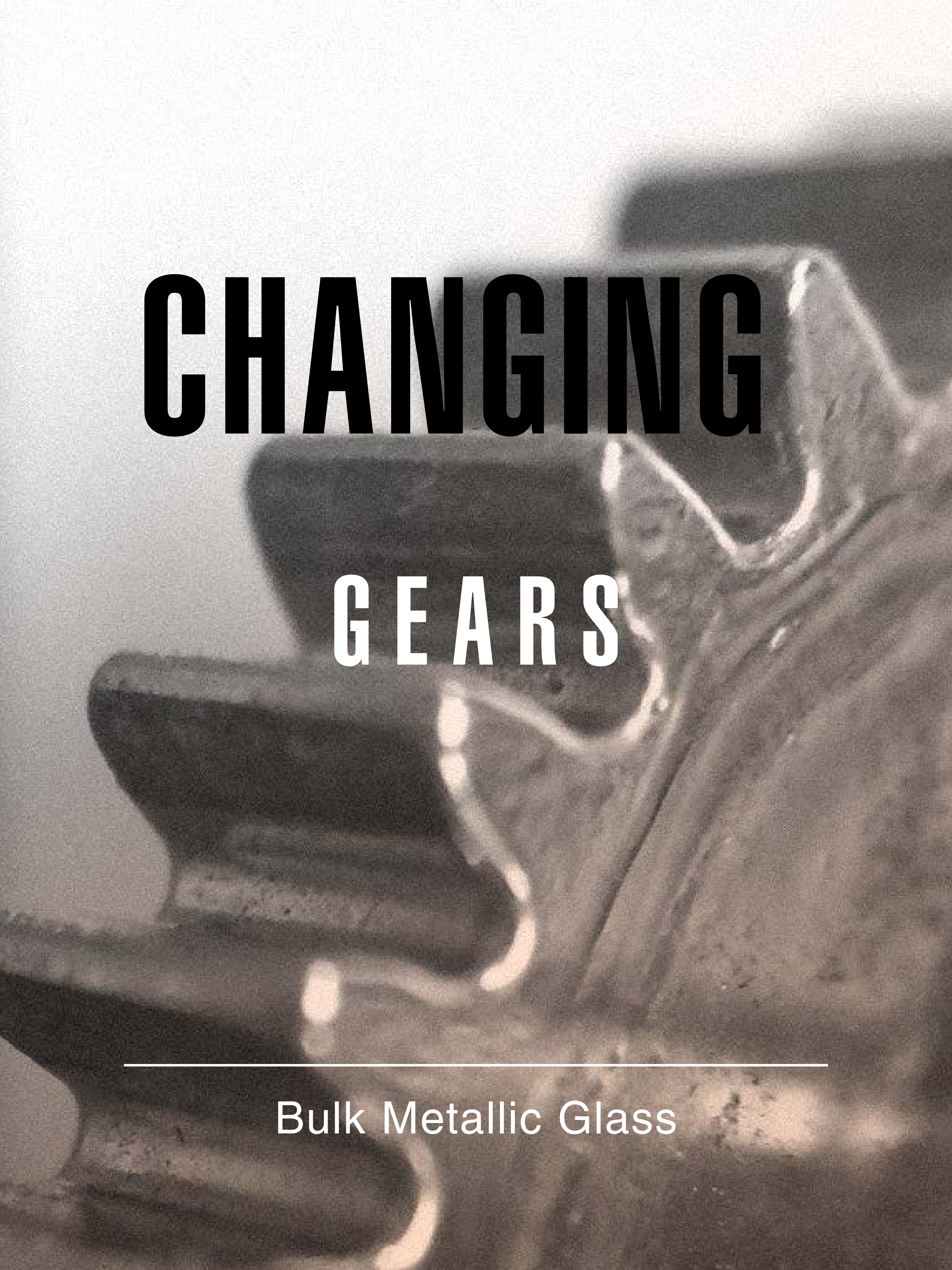
Malcolm Wood, deputy manager of the Michoud site. “Over the last 10 years or so, that’s been very successful.”

At least nine companies and six government agencies lease space at Michoud, with many others using the facilities on a temporary basis.

The machinery available is almost beyond inventory. Among NCAM’s advanced technology are two automated carbon fiber placement units that can mass-produce the sort of strong, lightweight carbon-fiber parts used in turbine blades, airplanes, speedboats and the Orion capsule. A 12-foot-tall nondestructive evaluation machine uses ultrasonic waves to check for flaws in products of all sizes and build computer models that can be used in simulations. Two automated high-speed machining centers can carry out complex operations on metal and composite parts.

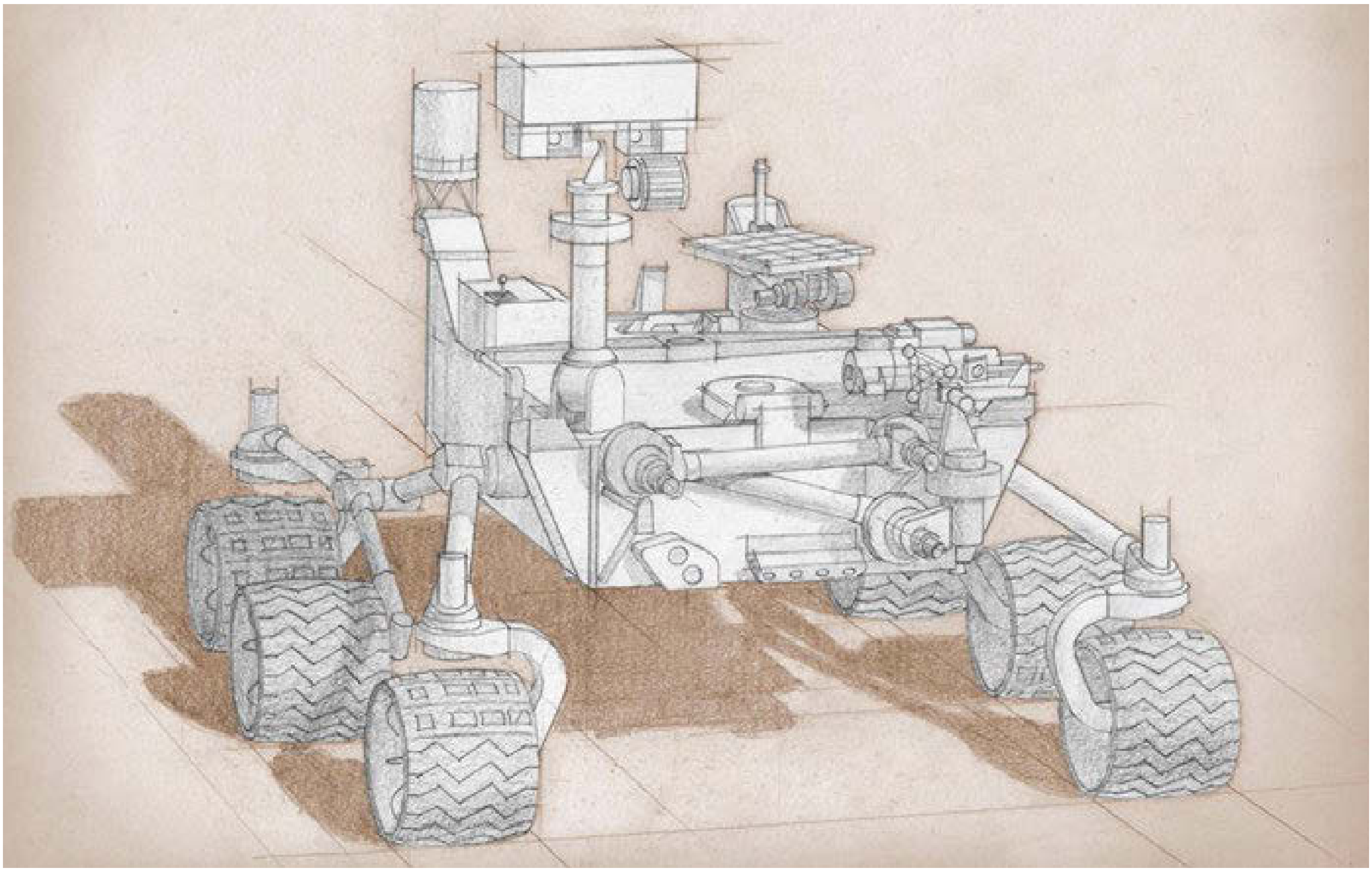
The facilities are also available to engineering departments of all of Louisiana’s colleges and universities, and the first friction stir welding classes, open to LSU and UNO students, were held in the fall of 2014. Michoud also supports workforce development programs and educational outreach to students in kindergarten through 12th grade.

“The SLS core that will one day be completed at Michoud will have greater lifting power than any rocket ever built,” Wood says. “But we and our partners are also using the extensive, state-of-the-art technology at NASA’s primary manufacturing facility to provide lift to Louisiana’s economy and the American manufacturing industries.”



# CHANGING GEARS

## Bulk Metallic Glass



## Materials created to solve a NASA challenge could transform commercial manufacturing.

What's both glass and metal, has the wear resistance of a ceramic, is twice as strong as titanium and can be injection-molded like a plastic? That's the riddle a group of researchers at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, Calif., set out to solve over 4 years ago. The answers they've come up with not only may find their way into next-generation planetary rovers but also could have profound implications for a range of manufacturing industries.

Most people still are not familiar with the idea of metallic glass — that is, glass made of metal — but that's likely to change in the coming years.

“Basically, you have the economics of plastics but mechanical properties that are beyond those of conventional, crystalline metal,” says Douglas Hofmann, principal investigator of the JPL research team.

What we all recognize as glass is primarily silicon dioxide — melted sand, usually — with some sodium carbonate, lime and other additives thrown in before it’s rapidly cooled, causing it to solidify before its atoms can arrange themselves back into crystal form. Scientifically, though, it is only this “amorphous” atomic structure, not the specific elements it’s made of, that make it a glass. Obsidian, for example, is a glass made from rapidly cooled igneous rock.

**[ What we all recognize as glass is primarily silicon dioxide. ]**

Hofmann’s team didn’t invent the idea of making glass from metal, but he began touting the potential of metallic glass alloys for gearboxes years ago. When he set about testing the varieties of alloys that were commercially available at the time, though, he was horrified. “I had professed to everybody that metallic glass was good for high-performance gears, and here the commercially available alloys were terrible,” he recalls.

Undeterred, he and his team of modern-day alchemists set about mixing their own alloys. “When we started this program, we were making hundreds of alloys,” he says. Eventually, they decided to explore combinations with the primary ingredient of copper. Glasses based on titanium also proved interesting, primarily for their low density.

The need they were trying to meet at the time was a challenge faced by virtually no one but designers of space machinery: a demand for gearboxes that could function smoothly at temperatures well below — 100 degrees Celsius, or about — 150 degrees Fahrenheit. “This is a

problem unique to NASA, particularly for Mars, which is where we have our sights set," Hofmann says.

At these temperatures, below the most frigid ever recorded on Earth, traditional liquid lubricants freeze up and become useless, so current Mars rovers have heated gearboxes, explains Andrew Kennett, a mechanical engineer at JPL who was brought onto the project to ensure the results would meet practical specifications. "The main driver for us at JPL is that we're always looking for better gear material."

**Mars rovers have heated gearboxes.**

Engineers would prefer to use dry lubricants — coatings of slippery solids like graphite or tungsten disulfide — and eliminate the need to heat gearboxes, which can eat up 20 to 30 percent of a rover's energy, Kennett says.

"When you have a limited power budget like you do in spacecraft, you have to make operational decisions on how to use this power," says Peter Dillon, who manages the bulk metallic glass element of the Space Technology Mission Directorate's Game Changing Development Program. "You can't do as much science as you could if you didn't have to heat that lubricant."

The problem is that when they rely on a dry lubricant, the steel alloys now used in gearboxes for space exploration don't last long enough to meet NASA's requirements.

Metal's weakness lies in its crystalline structure, Dillon says. The atoms arrange themselves into ordered patterns — planes that, under enough pressure, can slide against each other, resulting in permanent deformation.

"With bulk metallic glasses, the cooling rate is sufficient to not allow those atoms to organize themselves," Dillon explains. The result is a metal alloy about as different from its atomic constituents as window glass is from sand.

**[ Metal's weakness lies in its crystalline structure. ]**

Early metallic glasses, known as "amorphous metals," could only be made in small thicknesses by depositing a molten alloy onto a cold surface to create items like ribbons and foils. What scientists at the California Institute of Technology discovered in the 1990s was that by incorporating a number of different elements, particularly combining those with large atoms with those made of small atoms, they could slow the speed at which an alloy crystallized, Dillon says. It simply takes longer for the atoms to move around each other and arrange themselves, buying time for the alloy to cool as a glass and allowing thicker parts to be produced. Hence the term "bulk" metallic glass.

"You now have 30 seconds, 45 seconds, maybe a minute to cool the alloy, which is now in the realm of commercial manufacturing," Dillon says.

At the right temperatures, the substances also have glass's characteristic rubbery transition state, which allows additional possibilities for manipulation, termed "thermoplastic processing."

What make them ideal for gearboxes, though, are their physical properties in solid form, Hofmann says, noting that they have tensile strengths of up to 145,000 pounds per square inch, twice that of the best titanium alloys. And while metals tend to exhibit surface wear more quickly than some other materials, JPL's new metallic glasses have surfaces as durable as ceramics — some of the most wear-resistant materials in existence.

Significantly, Dillon adds, "There are some particularly good alloys within that family that have phenomenal performance with dry lubrication."

They also happen to have remarkably low melting points. "Most metals that have low melting points are soft, and most metals with high melting points are hard, so metallic glass is a unique case," Hofmann says.

This is where the solution to a NASA-specific problem explodes into the realm of commercial manufacturing. Metal parts, especially hard metals, are typically produced by machining, meaning they are cut, milled, rolled, drilled or forged into shape. They are difficult to cast because their high melting points — for example, 1,700 degrees Celsius (almost 3,100 degrees Fahrenheit) for titanium — mean they would destroy most molds in their molten form. Either way, it's a costly process.

But with melting points of 700–800 degrees Celsius (about 1,300–1,450 degrees Fahrenheit), JPL's metallic glasses can be cheaply manufactured into parts by injection molding, just like plastics. "A high-performance gear can cost $100," says Kennett. "We can make one for maybe $10."

As part of the experimentation, researchers also had 30 small components known as bistable springs made commercially out of a metallic glass alloy, demonstrating another property of this new family of materials: their elasticity. Some elasticity in traditional metals is what allows clothespins, paper clips and other springs to be momentarily deformed and then bounce back to their original shape.

NASA engineers like to use “flexures,” such as bistable springs, to move parts like telescope lenses and mirrors, which must be precisely positioned, Dillon says, explaining that gears can’t offer this exactitude because there’s always a slight turn necessary before their teeth catch. Flexures are also efficient, needing only a nudge to unleash a much larger amount of kinetic energy.

**[Most metals that have low melting points are soft, and most metals with high melting points are hard.]**

Titanium alloys are often used for this purpose, but the right metallic glass can offer twice the flexibility of such alloys. “With bulk metallic glass, the amount of deformation or displacement you can get, the amount of energy you can put into the system and have it recoverable, is much higher than in the same metal in its crystalline form,” Dillon says. “You can make much better springs out of the same material.”

While researchers at JPL have been inventing, testing and optimizing these alloys, others at Langley Research Center in Hampton, Va., have been working to evaluate them and characterize their properties so that standards can be developed for this new class of materials in preparation for the inevitable transfer to industry.

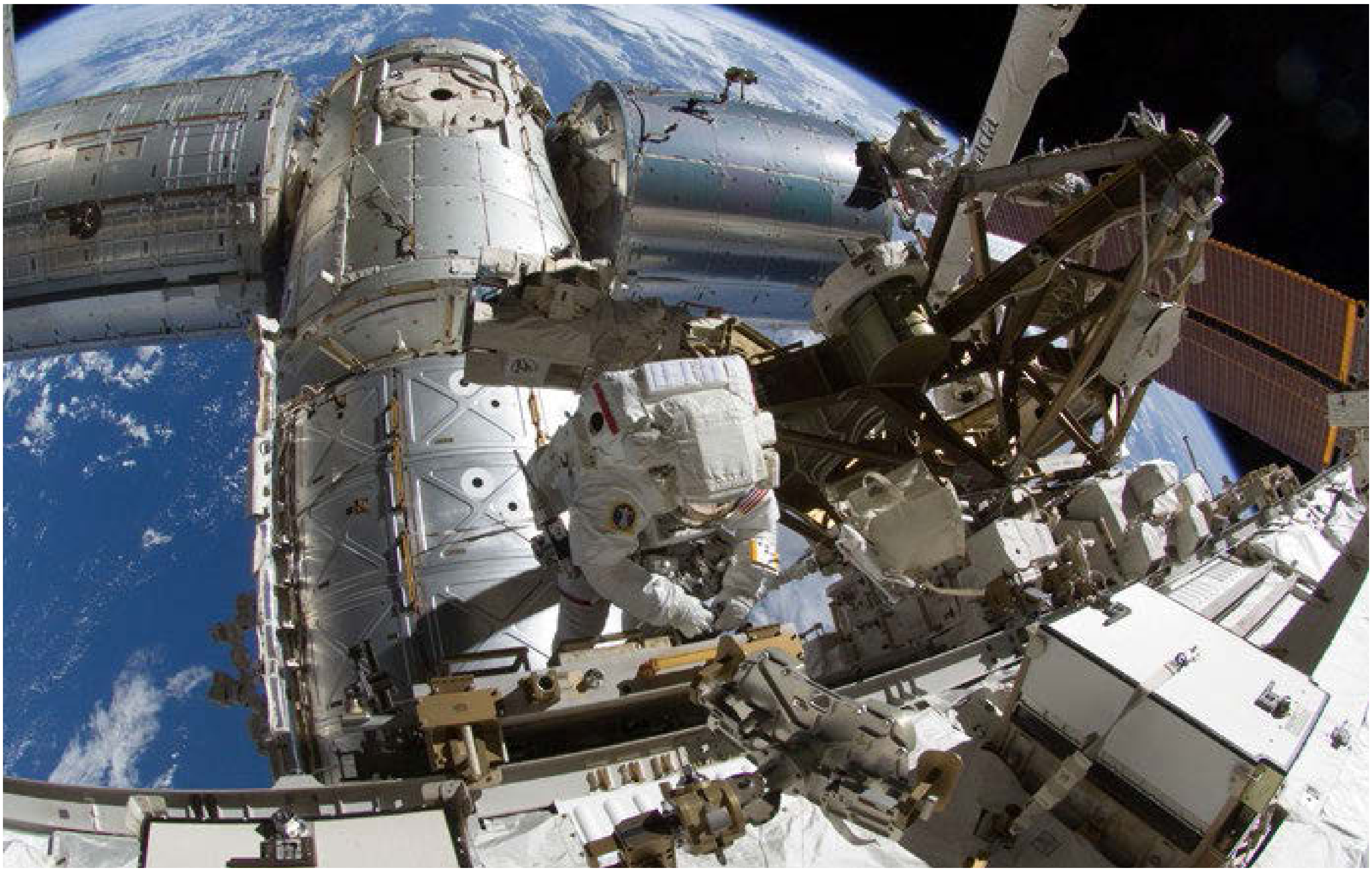
Hofmann, whose team has already filed more than 15 nonprovisional patent applications, sees any number of potential uses for them beyond NASA's needs. Ease of making parts would be attractive to manufacturers of everything from cellphones to automobile components. Their elasticity makes them ideal for golf clubs, prosthetics and medical devices, among other applications. And the sporting goods and defense industries might be interested in their strength.

"Anytime you have a material with properties that don't exist in other materials, there are applications where you can make huge strides in other industries," Hofmann says. "We're trying to identify those applications where we believe metallic glasses are the best option."

Tallying all these potential uses might just be a bigger job than creating the alloys in the first place.

# BUILDING BLOCKS IN SPACE

## Digital Materials and Robotic Assembly



## An innovative approach to construction may one day revolutionize space exploration.

Assembling large structures in space is an enormous undertaking, and the International Space Station, or ISS, which is longer in length than a football field, is the prime case in point. Its construction was challenging. First, the modules, or compartments, had to be built on Earth, where engineers have access to tools for piecing together an agglomeration of parts. Then, apart from being of suitable size to fit within the rocket fairing, each module had to be structurally reinforced to withstand the violent turbulence of launch. Once in space, a tricky rendezvous-and-docking sequence was employed to join them all together.

The ISS is no doubt an out-of-this-world wonder of ingenuity, but NASA is exploring another technology that could turn the current paradigm of giant spacecraft and aircraft manufacturing on its head.

As a graduate student at the Massachusetts Institute of Technology (MIT), Kenny C. Cheung, now a structural materials research scientist at Ames Research Center in Moffett Field, Calif., was looking for a new approach to constructing intricate things such as spacecraft and airplanes, which require many specialized parts that must be put together like an insanely complicated jigsaw puzzle. "Take a Boeing 747," Cheung says. "It requires 6 million parts to build one of them, and about a million of them are unique parts. Spacecraft are made the same way, with a lot of specialized pieces that cost a lot of time and money to make."

With goals of simplifying and reducing the costs of the manufacturing process while maintaining flexibility of use, Cheung and his advisor developed flat, geometric carbon-fiber composites that can be linked together into a three-dimensional lattice, forming any kind of object on any scale. They're also lightweight, strong (10 times stiffer than other ultralight materials), and can be disassembled and reassembled in order to repair damage or to take on new contours and shapes. What's more, these components can be affordably mass-produced and, because of their simplicity, are cheaper to simulate because only a single analytical model is needed, whereas traditional methods use thousands or more.

**[ Spacecraft are made the same way, with a lot of specialized pieces that cost a lot of time and money to make. ]**

"You can build the hull of an entire aircraft using these kinds of parts," Cheung says, adding that when these composites fail, they fail incrementally rather than suddenly, making them safer and more easily repairable than their conventional counterparts.

With funding from NASA's Aeronautics Research Institute, Cheung and collaborators at Ames and NASA's Langley Research Center in Hampton, Va., have already tested a prototype 4-foot wing using only eight different

composite types. Wind tunnel tests show that the prototypes hold up well to aerodynamic forces, so much so that the model wouldn't break even when the team purposefully tried risky dynamics tests that could tear them apart. The next step, besides automating the process, will be applying shape-morphing technology to the wing, which by itself is an entirely up-and-coming technology that aims to increase maneuverability and fuel efficiency while also reducing noise pollution.

> **You can basically flat-pack all the parts like furniture stores do and send them into space.**

As if that concept isn't innovative enough, Cheung's current work under the Space Technology Mission Directorate's Game Changing Development

Program has an even more ambitious end goal: to design a self-assembling and -repairing spacecraft using what are called digital materials.

Imagine a crewed spacecraft, a huge one, built with the same composite components, only each panel is computerized, possessing a processor chip, sensors and its own power source. The panels are able to pass along information, whether it's payload data for a research mission or damage taken by radiation or space debris, to antennas and other nerve centers that store information and give marching orders to other computers. In case of structural damage, robots are sent to replace panels and heat shields and anything else that's needed to repair the spacecraft, which means that astronaut extravehicular activities are not necessary. But the robots do much more than repair the spacecraft; they build it, reconfigure it and do nearly everything else in the way of manufacturing and upkeep.

**[ The idea isn't at all far-fetched. ]**

"You can basically flat-pack all the parts like furniture stores do and send them into space," Cheung explains, adding that such a method removes the constraints imposed by having to launch fully built structures into space, as had been done with the ISS modules. By his reckoning, robots, sent along with the materials, would first build other robots, forming a small army that would then be able to work together in constructing whatever the blueprint dictates. Cheung says, "They can snap these panels together like LEGOs into an effectively infinite number of structures."

While the concept sounds ahead of its time, Cheung says the technology for all of the pieces of the system are readily available, and to demonstrate that, he has built a proof-of-concept prototype called the Modular Rapidly Manufactured Small Spacecraft, or MRMSS. It's a nanosatellite assembled with a collection of panels that can talk to each other and distribute power. One panel has a research payload attached to it: a science experiment out of MIT that will test functional electronic components. The spacecraft is expected to launch on a sounding rocket this year to show that all the equipment works in space. “We also want to show that such a spacecraft can survive launch, even though in the long term, the idea is that these things would be manufactured in orbit, because many of the manufacturing benefits still apply to premade spacecraft,” Cheung says.

In the more distant future, he envisions robots mining for raw minerals, which would then be used to manufacture components in order to build more spacecraft or even a spaceport. Cheung notes, “We’ve seen that we’re capable of landing on a comet, so the idea isn’t at all far-fetched.”

LaNetra Tate, principal technologist for the Space Technology Mission Directorate, is equally excited by the prospect. “These digital materials have the potential to revolutionize not only how we get to space, but also what we’ll be able to do once we get there,” she says, “and that’s why NASA is investing in this technology.”

# METAL SCULPTING

## REDUX

3D Printing

## 3D-printed rocket engine parts stand to make space travel more efficient and cost-effective.

In order for humans to make that next leap beyond Earth's orbit into the reaches of deep space, to Mars and beyond, NASA is currently constructing what will be the most powerful rocket ever built, the Space Launch System, or SLS. Its initial 70-metric-ton configuration will stand taller than the Empire State Building, provide 10 percent more thrust than the moon-trekking Saturn V and carry three times the payload of the space shuttle.

But not only is NASA aiming to take us yet again where no person has gone before, it's also aiming to do that through the most efficient, cost-effective means possible. Toward that end, the agency is looking to break the mold of conventional rocket engine fabrication by introducing additive manufacturing — popularly known as 3D printing — to the process. The way rocket engine manufacturing works now, says NASA engineer Samuel Stephens, who's stationed in the SLS Advanced Development Office at Marshall Space Flight Center in Huntsville, Ala., is by assembling a great majority of the parts piecemeal.

"There are specialized components such as turbo pumps, combustion devices and valves, and each of those has multiple parts such as inlet and outlet flanges, center bodies, actuators and so on that are specially made with traditional manufacturing techniques," he says. "Then we have to assemble all those thousands of parts. There's a lot of tough labor involved, a lot of man-hours dedicated."

But additive manufacturing, particularly through a relatively new method called powder bed fusion, stands to rewrite the way a lot of those parts are made and assembled.

Marshall has maintained an additive manufacturing lab since 1991, when 3D printing for plastic parts first arrived on the scene. Powder bed fusion, on the other hand, prints metals. The laser technology that makes it possible to "sculpt" metal from powder matured about 4 years ago, says Ken Cooper, who leads the advanced manufacturing team at Marshall. "When the industry went away from pump lasers to using solid-state lasers, it gave us the wattage and precision needed to print metal."

In describing how powder bed fusion works, it helps to make a comparison to skyscrapers, which are built layer by layer from the ground up. The powder bed fusion process begins with an empty steel plate that's lowered into the machine. Next, a large windshield wiper–like device sweeps a layer of powdered metal a thousandth of an inch thick across the plate. The solid-state laser, following computerized directions, etches a shape into the bed, melting the powder together in precise patterns and creating a solid object.

The plate then indexes down another thousandth of an inch, and the next layer of powder is applied and melted on top of the previous one. "The part gets continuously buried," Cooper points out. "All you ever see is the very top layer as it gets built from the bottom up."

**NASA's Game Changing Development Program in the Space Technology and Mission Directorate has been actively funding research in 3D printing, including testing Aerojet Rocketdyne's thrust chamber assembly, made from copper alloy, in October 2014. This was the first time a series of rigorous tests confirmed that 3D-manufactured copper parts could withstand the heat and pressure required of combustion engines used in space launches.**

The technique offers several advantages. Larger parts that are usually made by combining smaller ones can instead be printed as one piece, reducing the time and cost involved in making components. And a technology that can make virtually any component obviates the need for purchasing custom tools that might only be used to make a few different parts. There's also less waste, because you print only what you need.

> **You print only what you need.**

Before the technology can be used for SLS and other rockets, NASA is conducting full-scale material analyses of a range of printed metals. The results have been promising. Last year Cooper and his team tested their most complex pieces yet: rocket engine injectors responsible for sending propellant into the engine through 40 individual spray elements. Their

**Engineers successfully complete hot-fire testing on two 3D-printed rocket injectors at NASA's Marshall Space Flight Center in August 2014. A highly complex part — traditionally fabricated from 163 components — the injector mixes liquid oxygen and gaseous hydrogen together, which combusts to produce more than 20,000 pounds of thrust. Using 3D printing technology, NASA only needed to join two parts to create each injector.**

design was similar to ones that would power the RS-25 engine that will be used to propel SLS.

Using the old method, 163 pieces would first have to be made individually and then assembled, whereas 3D printing meant that only two parts needed putting together. "This method allows us to save time and money while enhancing performance and reliability," Cooper says, adding that the pair of injectors performed very well, producing 20,000 pounds of thrust at temperatures of 6,000 degrees Fahrenheit. Solid Concepts in Valencia, Calif., and Directed Manufacturing in Austin, Texas, fabricated the two prototypes.

Collaboration with industry is critical for making these advancements happen. In another joint effort through a Space Act Agreement, Pratt & Whitney Rocketdyne — now Aerojet Rocketdyne — partnered with NASA's Space Technology Mission Directorate Game Changing Development

Program and Glenn Research Center in Cleveland, Ohio, to complete a series of hot-fire tests on a copper alloy–based thrust chamber assembly the company had created through the Selective Laser Melting method. It's an important milestone because while copper plays an important role in dissipating heat and maintaining integrity in rocket engines, it's also more difficult to melt and meld with lasers due to its high reflectivity compared to other metals such as steel and nickel.

**[ NASA wins when the whole industry succeeds. ]**

"NASA has been instrumental in helping us to understand the material and the design as well as the whole process up to getting that part successfully tested," says Jay Littles, the company's director of advanced launch programs.

Aerojet Rocketdyne has long contributed to American space exploration. The company provided the liquid rocket boosters for NASA's Titan vehicle, which delivered the first crewed Project Gemini flight into orbit in 1965. More recently, in December, the firm provided propulsion technology in all stages of NASA's successful test flight of the Orion spacecraft, which is slated to carry humans on the SLS. The goal for Aerojet eventually is to implement the technology into legacy products such as the RL10 upper stage engine, while also applying it to next-generation propulsion systems, including the Bantam engine family, as well as its new large, high-performance booster engine, the AR1.

Kristin Morgan, a strategic analyst at Marshall who is involved in the SLS development, says working with industry is critical to the agency's success. "Ultimately, the more people we have who are working in these areas, the more knowledge will be generated and the faster we can adopt these techniques," she explains. "NASA wins when the whole industry succeeds, because the better the quality, the better the part."

SPINOFF HIGHLIGHT

# SPACESUIT STRUCTURES BIRDAIR

## MATERIALS DEVELOPED BY NASA TO PROTECT ASTRONAUTS ARE NOW THE CENTERPIECE OF MANY MODERN ARCHITECTURAL MARVELS.

One spinoff from NASA technology is so ubiquitous that, if you’re a sports fan, you’ve seen it — though probably without knowing it.

More than a half-dozen stadiums used in the last two World Cup tournaments in Brazil and South Africa featured it. Professional and collegiate sports teams in the United States, including the NFL's Dallas Cowboys, Houston Texans and Atlanta Falcons, benefit from the technology.

But it can also be seen around the world in all kinds of public spaces and buildings, in settings as diverse as Denver International Airport, a Formula One racetrack in Shanghai, and the grandiose welcome pavilion of one of Dubai's artificial islands. These and many other facilities of all sizes enjoy strong, lightweight tensile fabric roof structures that have their origins in the Apollo Program.

More than 40 years ago, NASA's efforts to send humans to the moon were nearly derailed when a fire broke out on the Apollo 1 command module during a test exercise, resulting in the deaths of the three astronauts on board. In the wake of the tragedy, NASA engineers set out to design safer spacesuits, with an emphasis on material that would be durable, strong, lightweight, flexible, and noncombustible. They settled on a fiberglass fabric coated with polytetrafluoroethylene (PTFE), more commonly known as Teflon.

**[ Fabric is not something architects usually think of offhand. ]**

Around the same time, aeronautical engineer Walter Bird founded Birdair Structures in the kitchen of his home in Buffalo, N.Y. Soon after, Birdair collaborated with the companies who had partnered with NASA and developed a modified, stronger version of the spacesuit material.

The resulting product allowed Birdair to create a new market for lightweight tensile membrane structures for roofs, skylights, and canopies.

"When there are so many architectural materials out there, fabric is not something architects usually think of offhand," says William Barden, Birdair's director of architectural development. "Walter Bird's pioneering

role in the tensile structure industry was to take a technology that was perceived by people as ‘pie in the sky’ and create a market for it.”

The same qualities that made the PTFE fiberglass fabric appealing to NASA also make it ideal for large-scale, permanent tensile membrane roofs. The material is pound-for-pound stronger than steel while weighing less than 5 ounces per square foot. It offers up to 24 percent solar translucency, letting in lots of natural light. At the same time, it provides as much as 75 percent solar reflectance, keeping out heat and making it an energy-efficient roofing alternative. It is also cost-effective due to its durability and low-maintenance characteristics.

**[ Pound-for-pound stronger than steel. ]**

Birdair’s roof fabrics have received numerous awards and recognitions, including an ENERGY STAR rating by the U.S. Environmental Protection Agency, as well as recognition from the Cool Roof Rating Council based on the fabric’s high solar reflectance and thermal emittance.

The technology’s fingerprint on large structures will likely pass the test of time, too: On a Friday night in March 2008, fans at a college basketball game at Atlanta’s Georgia Dome noticed that the scoreboard was beginning to sway. Unknown to those in the stadium, a tornado was ripping through downtown. The safety of the more than 18,000 people in attendance would depend in large part on the integrity of the stadium’s domed roof.

The arena came out of the event with only slight damage to its roof, and not a single injury to its occupants, even though 135 mile per hour winds caused significant destruction across the rest of the city. The roof’s fiberglass membrane, the same material that once protected astronauts in the harsh environs of the moon, required only minor repairs.


# MOLECULAR TINKERING
# PIONEER ENERGY

## TECHNIQUES FOR TURNING MARTIAN WATER AND AIR INTO RESOURCES HAVE BECOME TECHNOLOGIES FOR EXTRACTING OIL AND HARNESSING NATURAL GAS.

A human trip to Mars will require astronauts to use resources on the Red Planet to generate oxygen and fuel for the ride home, among other things. This can be accomplished through any number of chemical conversions, and Robert Zubrin, president of the Mars Society and founder and president of Pioneer Astronautics, among other companies, has spent much of his career devising methods for turning Martian water and air into useable products.

In the course of its work, Pioneer Astronautics has won about 60 Small Business Innovation Research (SBIR) contracts, most of them with NASA, totaling more than $12.5 million. Some of the earliest, dating to the mid- to late 1990s, were with Johnson Space Center in Houston, Texas, and focused on creating rocket fuel on the surface of Mars by taking apart and building molecules, as if their atoms were Tinkertoys.

**A lot of his work, like the name of his company, was very pioneering.**

For example, the company devised methods by which hydrogen transported from Earth could be combined with carbon dioxide from the Martian atmosphere to produce methane and water. The water could then be electrolyzed to make oxygen for crew use while recycling the hydrogen; the methane and oxygen make a good combination for rocket fuel. The confirmation of water on Mars only expands the possibilities.

“He helped build one of the first prototypes for how to collect carbon dioxide from the Mars atmosphere and turn it into oxygen and methane,” says Gerald Sanders, In Situ Resource Utilization (ISRU) chief engineer with the Propulsion and Power Division at Johnson, noting that much of the work was in the areas of life support and power systems, the backbone of any space exploration mission.

“A lot of his work, like the name of his company, was very pioneering, trying different things out that may be interesting to NASA for exploration,” Sanders says.

“Some of these SBIRs made me realize that we could take a form of this technology, run it backwards, and we would have something we could use on Earth for oil recovery,” Zubrin says. In 2008, he created Pioneer Energy to put the theory to work.

“On Earth, we’ve got methane in the form of natural gas, which right now is very cheap, and you can react it with water, which we also have a lot of, and produce carbon dioxide and hydrogen and then split them,” he explains. The hydrogen can be used to create carbon-free electricity, and the carbon dioxide can be used to pull oil out of defunct oil wells.

Depending on its geology, only about 30 percent of the oil in a well is captured by the initial pumping. Flooding the well with water yields another 20 percent of the original oil store. Another 20 percent or so can be extracted by pumping carbon dioxide into the well, but this usually requires carbon dioxide to be carried to the site by pipeline or truck, which is enormously expensive.

The Pioneer Portable Enhanced Recovery Technology (PERT), on the other hand, can produce that carbon dioxide on site.

The company started testing its first full-scale model of the PERT in the spring of 2014. By then, though, the company was also testing the first field unit of another related system.

While working on the carbon dioxide–producing system, Zubrin got an idea for another technology — a sort of spinoff of a spinoff — that uses many of the same subsystems. During drilling, large amounts of natural gases may be released. Being byproducts released in isolated locations that lack plants and pipelines for processing them, they're often simply burned on site in gas flares.

"They're flaring it so much that North Dakota seen from space is now almost as bright as New York City," Zubrin says. "It's incredible. And it's a massive waste of energy."

**[ They're flaring it so much that North Dakota seen from space is now almost as bright as New York City. ]**

Pioneer's Mobile Alkane Gas Separator (MAGS) system separates these gases into three streams. One consists of propane, butane and pentane, which can be captured and shipped off for sale. Methane can be used to run a generator that would replace the diesel generators powering the oil-drilling rig. And ethane is used to power the MAGS system itself.

"We greatly reduce the flaring and the need for diesel fuel, and we produce liquid propane and butane for sale," Zubrin says, adding that the system is also self-sufficient.

The PERT system promises to significantly expand the world's oil supply.

"There are huge numbers — thousands — of defunct oil wells all over the country. But more than half of all the oil that was ever in U.S. wells is still there," Zubrin says. He estimates the technology would allow access to an amount of oil equal to more than 10 percent of all the oil ever drilled in the country. And that's just in the United States.

# INSIGHT with

## LaNetra C. Tate, Ph.D.

Principal Technologist,
Space Technology Mission Directorate

*The end of the Space Shuttle Program did not indicate the end of NASA's work. If anything, the agency is busier than ever as it prepares to kick off new efforts aimed at Mars and further exploration, says LaNetra Tate, advanced manufacturing and nanotechnology principal technologist with the Space Technology Mission Directorate. Tate's background is in nanotechnology, polymer carbon nanotube systems and carbon fiber systems. She joined NASA's Kennedy Space Center in Cape Canaveral, Fla., in 2005 as a researcher in the polymer group and now works at NASA Headquarters. She represents the agency on the president's National Manufacturing Initiative that includes the National Network for Manufacturing Innovation, and she was detailed to the Advanced Manufacturing National Program Office located at the National Institute of Standards and Technology, of which NASA is a founding member.*

*NASA's future will include human spaceflight beyond low-Earth orbit, but before that's possible, the agency and its industry partners need to refine and reimagine the vehicles that will take astronauts to Mars and beyond. In this article, Tate examines the future of manufacturing and the importance of inspiring the next generation of explorers and scientists.*

- **There are many big ideas at NASA,** but one of the bigger ideas that has taken off exponentially is additive manufacturing, or 3D printing. 3D printing did not just come about 5 years ago; it's been around for over 20 years as what we call rapid prototyping. **Most NASA centers have a rapid prototyping lab.** What has changed is the range of things additive manufacturing can potentially do in a quick time frame and the opportunity to create complex hardware and systems using 3D printing.


- When you think of manufacturing, you think of old steel plants or old-school car manufacturing hubs. **So how do we inspire the younger generation** to really appreciate manufacturing, broaden that knowledge and enhance that skill here in the United States? With today's great electronic and technological gadgets — my 4-year-old knows how to use an iPad better than I do — how do you make the manufacturing of our parents' generation attractive to the younger generation, so we can invigorate their minds to want to be the next engineers, to want to be the next scientists?

- **One component of that is the maker movement.** I think that's an awesome area to explore further. When I was in high school, we had shop classes. Those start that maker mindset of, "I can do this in my garage; I can do it at school." **Those are the early manufacturers, the early engineers, the early scientists.**

> **When I was in high school, we had shop classes. Those start that maker mindset.**

- There's a common misconception that NASA doesn't do manufacturing, or that we only make one of something. **NASA does so much for manufacturing.** Even if we're just doing one part, that part is very specific, very complex. **It makes someone else push the envelope.** Many times, it hasn't been done before, or it was sitting in a lab somewhere without a destination or previously identified use. For example, NASA starts looking at friction stir welding and realizes we need it because it looks like a technique we can use on our external tanks. NASA employed that technology, which was sitting in a lab in England, and applied it to the external tank of the SLS. **And now even Apple uses it for the iMac.**

- Then you move to space exploration: NASA just launched a 3D printer. Although it may not be NASA's flagship manufacturing depot in space, it's a platform to continue to develop needed capabilities. We look at that 3D printer as a sign of what we may need to move deeper and deeper into space exploration. **At the end of the day, everything has to be made for us to get somewhere.** From NASA's point of view, from our space-exploration point of view, manufacturing is an enabler.

- **One of the many things NASA does very well is partner.** We may do a pathfinder internally and then we go out and say to industry, “We need a 3D printer with these specific capabilities; can you make this happen?” Some of the engineers at NASA’s Marshall Space Flight Center did some of our initial testing and said we need to really grow this area. We need to see what’s out there. Through a Small Business Innovation Research (SBIR) program contract with Made In Space, Inc., now ***we actually have this printer on the International Space Station.***

- NASA really pushes itself and industry to be very sophisticated with how we manufacture hardware. We, as NASA, have to understand the complexity so we can tell the vendors what we need.

- Understanding manufacturing as an industrial model is very important to U.S. competitiveness. How do we make sure we're educating our younger generations to be able to understand and know what, for example, the laminated plate theory is, or how to make a good composite structure for the next launch vehicle? How do you do that? **The maker movement has to inspire minds at a young age, in schools!**

- There's a conversation within the manufacturing community: let's make it more automated, let's use more robots. There's a common concern that if you do that, people are going to lose their jobs. That is not the case! You need a person to be able to design the automation, the algorithm that the robot needs. You need men and women to develop, design and test it, to make sure it's operating correctly.

## [ Manufacturing is an enabler. ]

- **We are still making things.** We still have the competitive nature to continue where we left off. How are we educating our society to be more sophisticated in some of these new manufacturing technologies? For example, you may have a technician with a solid skillset that has always worked in metals or in traditional welding. Maybe we take this welder and provide training on new additive equipment and encourage him or her to branch out.

- **We need to adapt to the new technology** and move at the same pace with — or even think ahead of — the changes and make sure our workforce and our younger generation have the skills to adapt.

- **We have so much more work that we’re doing.** We retired the space shuttle, but **we’re working on another vehicle: the space launch system, SLS. We’re still doing what NASA does.** We’re still in business. We have Curiosity on Mars and we’re planning on ***launching another rover in 2020***. We’re doing a rover prospector mission on the moon and we’re building the next big space launch system. If you talk to NASA technologists and engineers, they’re busier than ever. People are still innovating, we still love our jobs and we’re still doing what we need to do to get missions done.

# TECHNOLOGY INNOVATION

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