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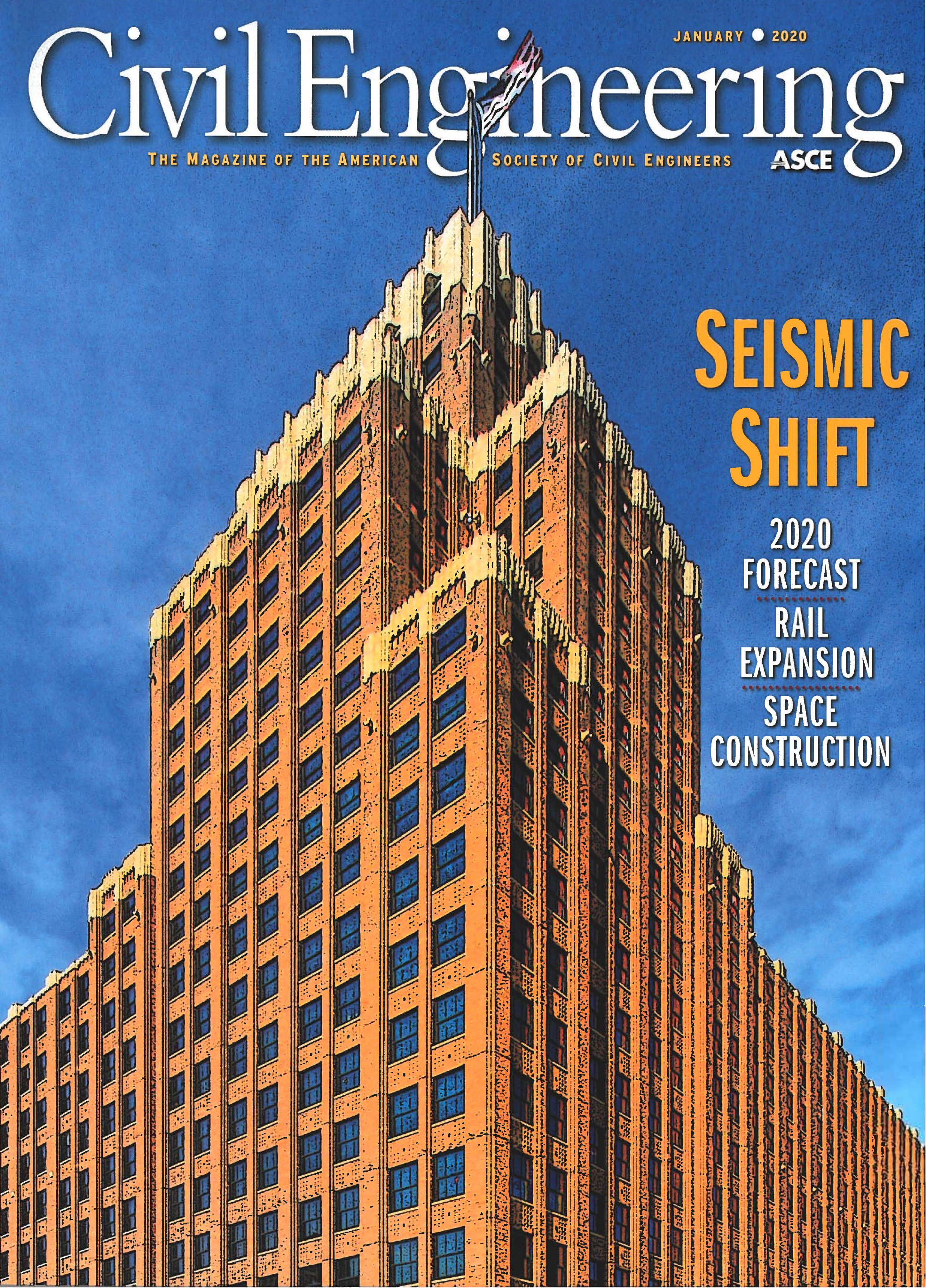


SEISMIC SHIFT

2020 FORECAST

RAIL EXPANSION

SPACE CONSTRUCTION

SPACE PLACE

To help design and construct human habitats for Earth orbit, the moon, and Mars, NASA is turning to teams of experts in academia and private industry, including civil and structural engineers. The ideas being discussed will, in some cases, take terrestrial engineering concepts into extraterrestrial settings and, in return, apply some of the space-based solutions back here on Earth.

BY ROBERT L. REID

JAMES BRIDENSTINE, the administrator of the National Aeronautics and Space Administration (NASA), has repeatedly said that humanity is going back to the moon—this time "to stay." In order to do that, though, the people sent to the moon will need a place to stay. So will the people sent into Earth or lunar orbit for extended periods as a precursor to new moon missions, or to Mars as the logical next step after reestablishing humanity's presence on the moon.

The design and construction of such space habitats will involve challenges familiar to Earthbound engineers and architects, including issues of site selection, structural integrity, resilience, seismicity, foundations, building materials, and other concerns. Of course, given the habitats' extraterrestrial settings, the teams must also contend with challenges and conditions not generally found on Earth, including low gravity and the need to seal and pressurize the structures, provide breathable atmospheres, accommodate extreme daily temperature shifts of more than 200°F, and protect against potentially deadly levels of radiation or micrometeorite impacts.

The expected use of autonomous robots to 3-D-print much of these structures would—at least for the present—also distinguish the space habitats from their terrestrial counterparts.

To design these facilities, NASA is turning to teams of scientific and engineering experts in academia and private industry. Other organizations and government bodies around the globe are also exploring how people can live in space, leading to what can almost be called an extraterrestrial housing boom.

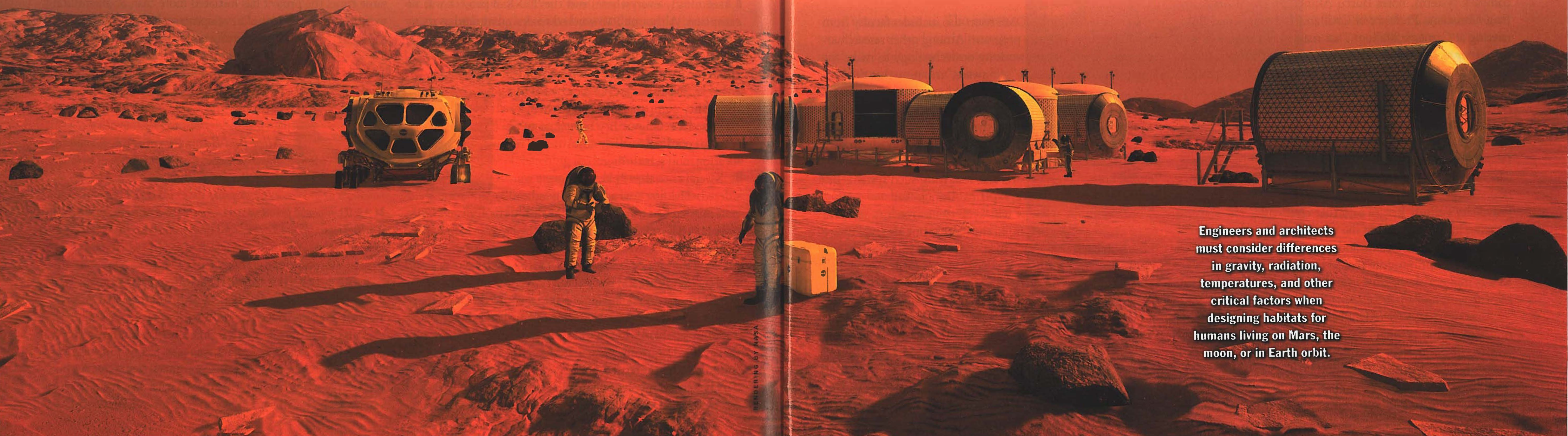
For example, NASA has sponsored various competitions since 2014 that explore how to construct habitats on Mars. A design team that included structural engineers from Leslie E. Robertson Associates (LERA), of New York City, took first place in the 3-D Printed Habitat Challenge in 2015 (read "Red Planet Plans," *Civil Engineering*, June 2016, pages 74–83, and 87). More recently, the international engineering firm Thornton Tomasetti worked with the architecture firm AI SpaceFactory, of New York City, to win the latest phase of NASA's habitat challenge in May 2019 by designing and constructing a scale-model protype of a 3-D-printed shelter for Mars that could be made autonomously by robots using recycled and indigenous materials on the red planet.

In spring 2019, NASA established two new research institutes that will focus for the next five years on space habitats and spacecraft that will feature autonomous and resilient systems, robotic maintenance, and other approaches to enable the human crews to better concentrate on their scientific missions. One institute—named the Habitats Optimized for Missions of Exploration (HOME)—is led by the University of California, Davis in partnership with civil engineers and other engineers and scientists from Carnegie Mellon University, the University of Colorado Boulder, Georgia Institute of Technology, Howard University, the University of Southern California, and Texas A&M University, along with industry partners.

The second new institute—the Resilient ExtraTerrestrial Habitats institute (RETHi)—is led by a team of civil engineers at Purdue University, working with researchers at the University of Connecticut, Harvard University, and the University of Texas at San Antonio.

NASA has also been testing full-size habitat protypes for the Gateway project, a lunar orbital platform that the agency hopes to construct sometime in the 2020s. The tests took place at sites in Florida, Alabama, Texas, and Nevada, evaluating mock-ups from such major aerospace firms as Lockheed Martin, Northrop Grumman, and Boeing as well as Sierra Nevada Corp. and Bigelow Aerospace, the latter two involving inflatable structures.

Engineers and architects in the New York City office of Skidmore, Owings & Merrill (SOM) are working with the European Space Agency (ESA) and faculty at the Massachusetts Institute of Technology (MIT) to design a proposed permanent human settlement on the moon known as the Moon Village. The ESA also worked with the Swiss Space Center on a simulated lunar habitat, called IGLUNA, that was constructed recently under the ice of a glacier in Zermatt, Switzerland. International teams of university students participated in the IGLUNA project, testing various technologies for living in the extreme environments of space. The ESA also plans to construct a 1,000 sq m simulated lunar surface at its Astronaut Centre in Cologne, Germany, to



RENDERING BY NASA

Engineers and architects must consider differences in gravity, radiation, temperatures, and other critical factors when designing habitats for humans living on Mars, the moon, or in Earth orbit.

test moon habitats, energy systems, and other aspects of a future lunar base.

Engineers and architects at Denmark's Bjarke Ingels Group (BIG) are working with the government of the United Arab Emirates to design and construct a prototype habitat for Mars—dubbed Mars Science City—that will feature a series of interlinked, domed structures in Dubai's Mushrif Park. The site will combine exhibition and learning spaces with research facilities on the robotic building methods and other technologies that could be used for an actual Mars base.

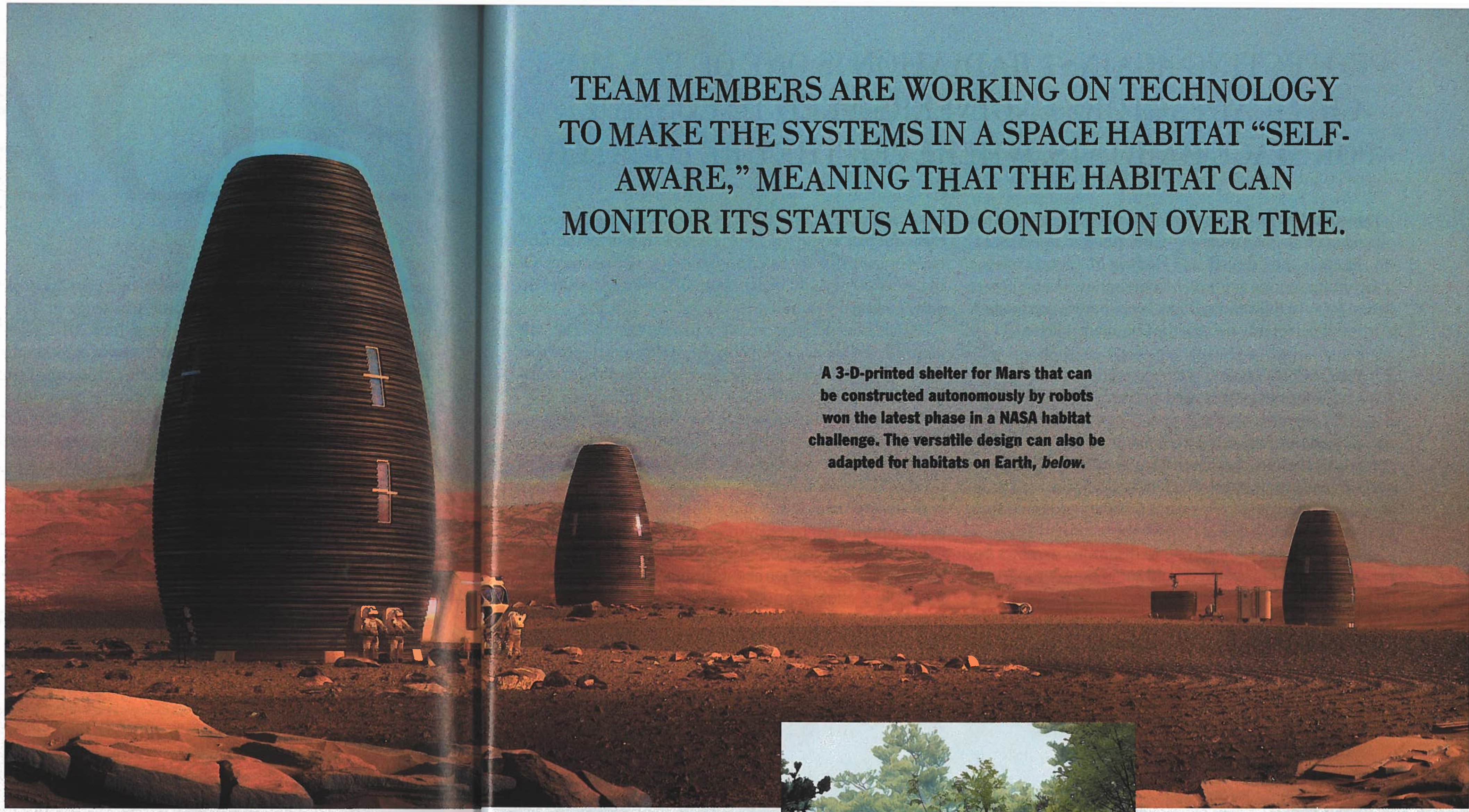
Various groups are also working on designs for hotels in Earth orbit that would cater to space tourists and include inflatable habitats in the seeming weightlessness of microgravity and wheel-shaped space stations that would rotate to create a form of artificial gravity. And ASCE's Future World Vision initiative also includes one off-world scenario. (See futureworldvision.org.)

Civil engineers will play a key role in designing space habitats because, in some respects, it's the same work they've been doing "since human civilization began," notes Ramesh Malla, Ph.D., F.ASCE, a professor of civil and environmental engineering at the University of Connecticut. Malla, who has been designing and analyzing space habitats for more than 30 years, is leading his university's multidisciplinary team of researchers on the RETHi project. Civil engineers are ideally suited to address the challenges of projects in space, he believes, because designing structures for challenging environments—whether deserts, mountains, or elsewhere—is exactly what civil engineers do. So, whether considering the geotechnical conditions at the site of a lunar habitat, designing the foundations for that facility, or considering other structural issues, "civil engineers can contribute quite a bit and even take the lead," Malla says.

Space habitats are essentially buildings that are part of complex systems, notes Burcu Akinci, Ph.D., M.ASCE, the Paul Christiano Professor of Civil and Environmental Engineering at Carnegie Mellon. That makes civil engineers well suited for such work because they "deal with complex systems, with systems of systems that interact with each other," explains Akinci. "We deal with humans in these systems and how humans impact the systems and how the systems impact the humans."

Akinci is working on Carnegie Mellon's portion of the HOME institute effort for NASA, along with her colleague, Mario Bergés, Ph.D., A.M.ASCE, a Carnegie Mellon professor of civil and environmental engineering who is leading the university's effort. Bergés says that civil engineers working on space habitats are doing the work they normally do—just "under harsher conditions and constraints, such as limited and delayed communication and limited energy budgets, as well as higher risks because everything in space is potentially life-threatening."

Although space-related infrastructure often involves more mechanical and aeronautical engineering than traditional civil engineering, Bergés believes civil engineers will be critical in such projects because they are master integrators who "pull together all the different pieces of the puzzle" to help the various engineering disciplines work together.



TEAM MEMBERS ARE WORKING ON TECHNOLOGY TO MAKE THE SYSTEMS IN A SPACE HABITAT "SELF-AWARE," MEANING THAT THE HABITAT CAN MONITOR ITS STATUS AND CONDITION OVER TIME.

A 3-D-printed shelter for Mars that can be constructed autonomously by robots won the latest phase in a NASA habitat challenge. The versatile design can also be adapted for habitats on Earth, *below*.

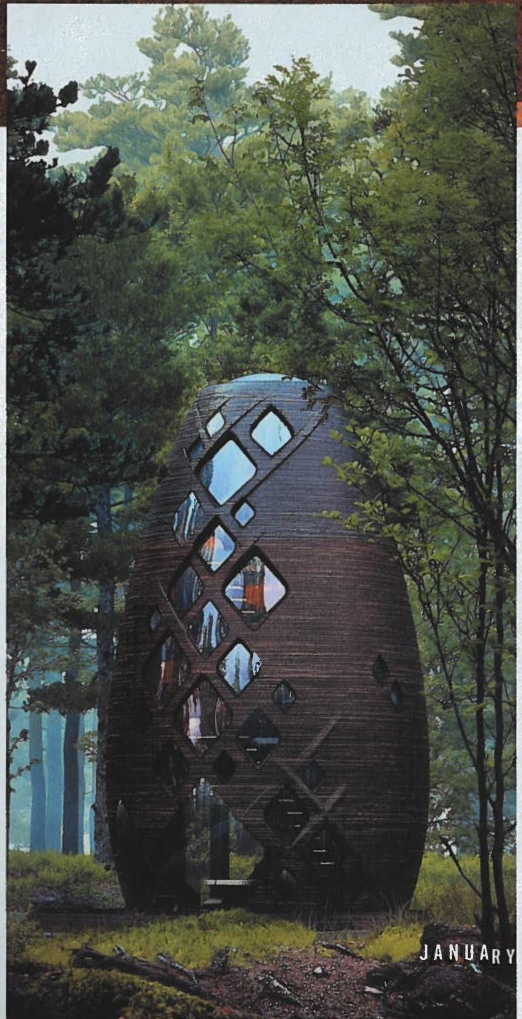
RENDERINGS BY AI SPACEFACTORY

Carnegie Mellon's HOME team also includes faculty from the university's robotics program. Among other research areas, team members are working on technology to make the systems in a space habitat "self-aware," meaning that the habitat can monitor its status and condition over time, identifying and diagnosing potential faults and even predicting faults before they occur. In addition, the habitat—which might not be occupied continuously—will act autonomously to save energy, for example, by shutting down certain operations after one human crew departs and restarting such systems before new astronauts arrive, explains Akinci.

Autonomous systems will keep the astronauts safe and comfortable while they are in the habitat but also make sure that the crew doesn't have to spend a lot of its valuable, scientific time fixing things that could more easily be handled by sensors, robots, or other self-aware systems, Akinci says.

This approach could involve robots operated remotely by humans, robots that interact with humans, or fully autonomous systems that interact with other robots, notes Mohammad Jahanshahi, Ph.D., an assistant professor of civil engineering at Purdue. As part of the RETHi project, Jahanshahi is developing new autonomous and decision-making systems that "involve having robots observe humans and learn from those observations. ... The robots would have to work with humans inside the habitat, but when something happens outside the habitat, the robots might also go outside and autonomously navigate and perform certain tasks."

Regardless of whether a space habitat is designed for the moon, Mars, or orbit, "when you think about what human beings need for space exploration, there's a lot of overlap—they're going to need potable water, protection from radiation, et cetera—no matter where the mission is," notes Dawn Whitaker, Ph.D., an investigator on the Purdue habitat project and an associate director of the Indiana Space Grant Consortium, which manages NASA-funded education, research, and outreach programs in Indiana. "That's one of the focuses from NASA, that they want things that are versatile and can be utilized for multiple types of mission scenarios," Whitaker says.



For Purdue and its research partners, the RETHi effort is designed to "bring the lessons civil engineering has learned over the last thousand years or so ... here on Earth and bring them to extraterrestrial bodies," says Shirley Dyke, Ph.D., a Purdue professor of civil engineering and mechanical engineering who is leading the RETHi program. "When we design structures here on Earth, we look at performance under realistic earthquake loads," including the duration of that loading and the life cycle of the structure, Dyke notes. "But when we talk about space structures, that takes a different perspective."

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PROTECTING AGAINST RADIATION IS ONE OF THE MOST CRITICAL FACTORS ENGINEERS NEED TO CONSIDER FOR SPACE HABITATS, WHEREVER THEY'RE LOCATED.

Moonquakes, for example, are often more frequent and last much longer than earthquakes, notes Antonio Bobet, Sc.D., P.E., M.ASCE, the Edgar B. and Hedwig M. Olson Professor in Civil Engineering at Purdue. Civil engineers know how to design for such differences, Bobet says, "but we need to look at it in a different way because the inputs are different."

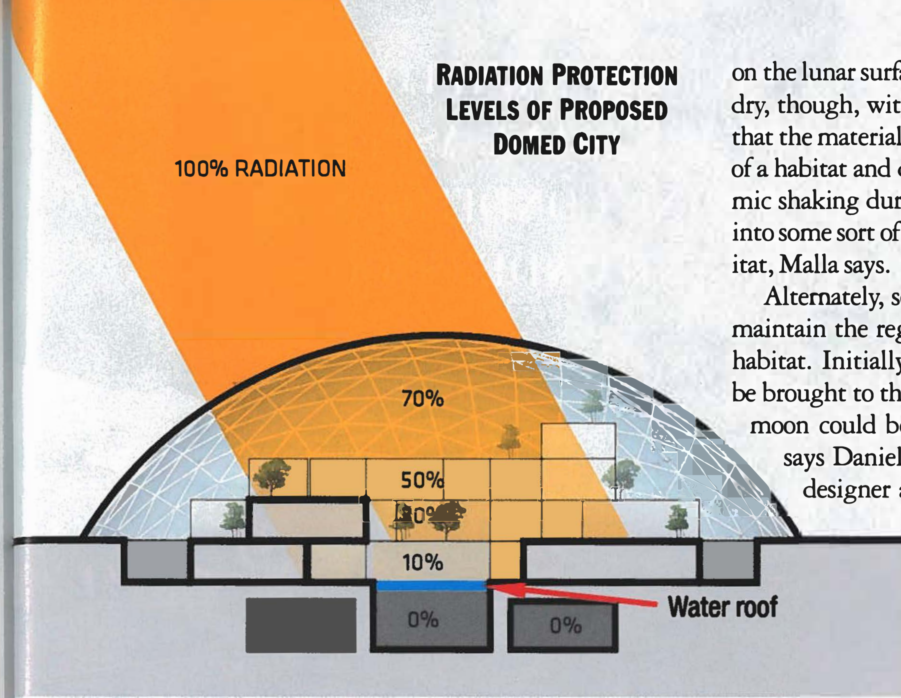
PROTECTING against radiation is one of the most critical factors engineers need to consider for space habitats, wherever they're located. These measures include shielding the habitat with thick layers of metal—lead, for instance—or concrete or other materials, such as water, ice, or the indigenous soils (regolith). Alternatively, the facility can be located underground or within naturally protected sites, such as lava tubes that exist on both the moon and Mars.

Cost and convenience are crucial determinants, notes Bobet. To use lead or concrete would mean transporting large quantities of heavy materials from Earth to the moon or Mars, which would be tremendously expensive and challenging. The use of ice or water would be easier, as both are believed to be available in large quantities at certain locations on the moon and the red planet—especially at the polar regions of each. But that would limit the possible locations of the habitat, requiring that the base be located close to the sources. Or the water or ice could be transported to the habitat site, another potentially daunting task.

An alternate solution would be to construct a special "safe room" in the habitat—a smaller, heavily shielded space that the crew could shelter in during periods of maximum radiation danger, such as when solar flares occur, Bobet notes.

Constructing the habitat either partially or completely underground or in an existing lava tube could also work. BIG's proposed Mars facility would protect against radiation with a combination of an inflatable dome at the surface with underground spaces and a layer of "water roof" above one section of the base. But going underground could be challenging, especially because NASA does not have detailed geotechnical information about the moon or Mars except for relatively shallow portions of the subsurface—only about 3 m in depth on the moon, for instance. For Mars, at least, that could be changing: A NASA probe called Radar Imager for Mars' Subsurface Experiment (RIMFAX) is expected to launch this summer and reach Mars in 2021. RIMFAX will include ground-penetrating radar that could provide geologic information on the red planet to depths of 10 m or greater.

RENDERING AND ILLUSTRATION BY BJARKE INGELS GROUP



RADIATION PROTECTION LEVELS OF PROPOSED DOMED CITY

Perhaps the best radiation protection solution, at least for surface habitats, is to use a thick layer of regolith. In addition to good radiation protection properties, lunar regolith also provides excellent thermal insulation and is widely available on the lunar surface, notes Malla. Lunar regolith is extremely dry, though, with no cohesiveness, he adds. Thus, to ensure that the material holds together on the structural framework of a habitat and doesn't lose its required thickness from seismic shaking during moonquakes, the regolith could be put into some sort of sandbag-like sack and stacked atop the habitat, Malla says.

Alternately, some sort of binding agent could be used to maintain the regolith's structural integrity as it covers the habitat. Initially, the chemicals for a binding agent could be brought to the moon from Earth, or volcanic glass on the moon could be melted and used to harden the regolith, says Daniel Inocente, LEED AP, a senior architectural designer at SOM who is working on the Moon Village project.

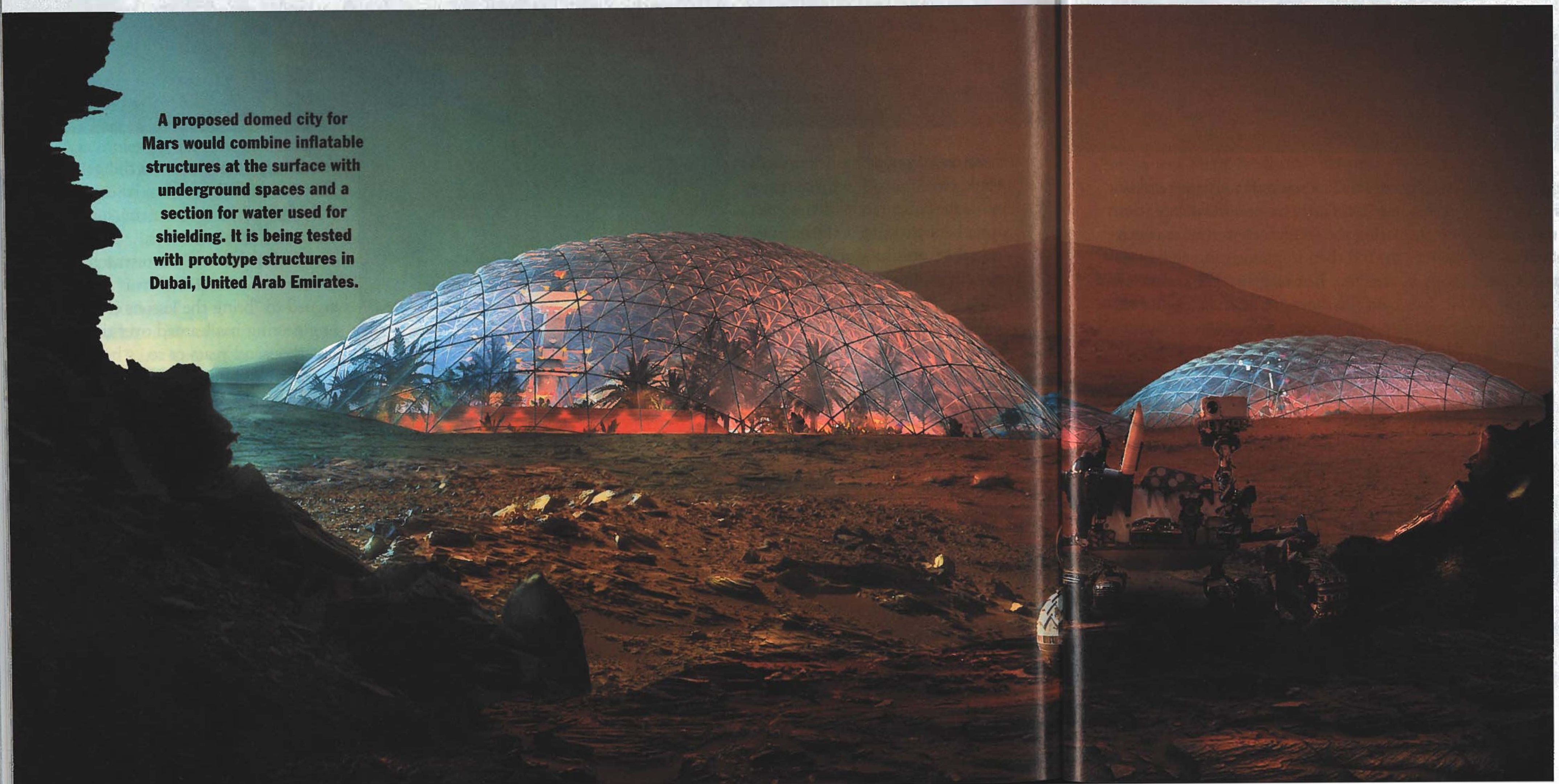
The use of Martian soil would face similar issues and require equally creative solutions. The habitat that Thornton Tomasetti designed—dubbed MARSHA—with AI Space Factory would be 3-D-printed using basalt fibers found in Martian soil combined with a biopolymer composite material that can be made from vegetable starch, explains Dennis Poon, P.E., M.ASCE, a Thornton Tomasetti vice chairman. The source of that vegetable starch would most likely be waste from the food that the earliest settlers on Mars consumed on the way or started growing in the spacecraft that they used to reach the planet, notes James Earle, AI SpaceFactory's chief engineer. Although they would initially have to live in their spacecraft, the Martian settlers would, over time, generate enough of the organic waste to recycle it as a building material for the MARSHA structure, Earle explains.

The scale-model version of the MARSHA habitat that won NASA's 3-D-printing challenge was roughly one-third the size of the actual, egg-shaped habitat. On Mars, the structure would rise 15 m tall and measure 7.5 m in diameter at its midpoint but 6.3 m in diameter at its base and just 3 m in diameter at its top, says Poon. The tapered form creates a very efficient structure that distributes stresses well and offers a high strength-to-weight ratio, he adds.

For Poon, who has designed numerous supertall towers here on Earth, the MARSHA habitat would continue a trend: At 15 m, "it will be the tallest building on Mars," he jokes.

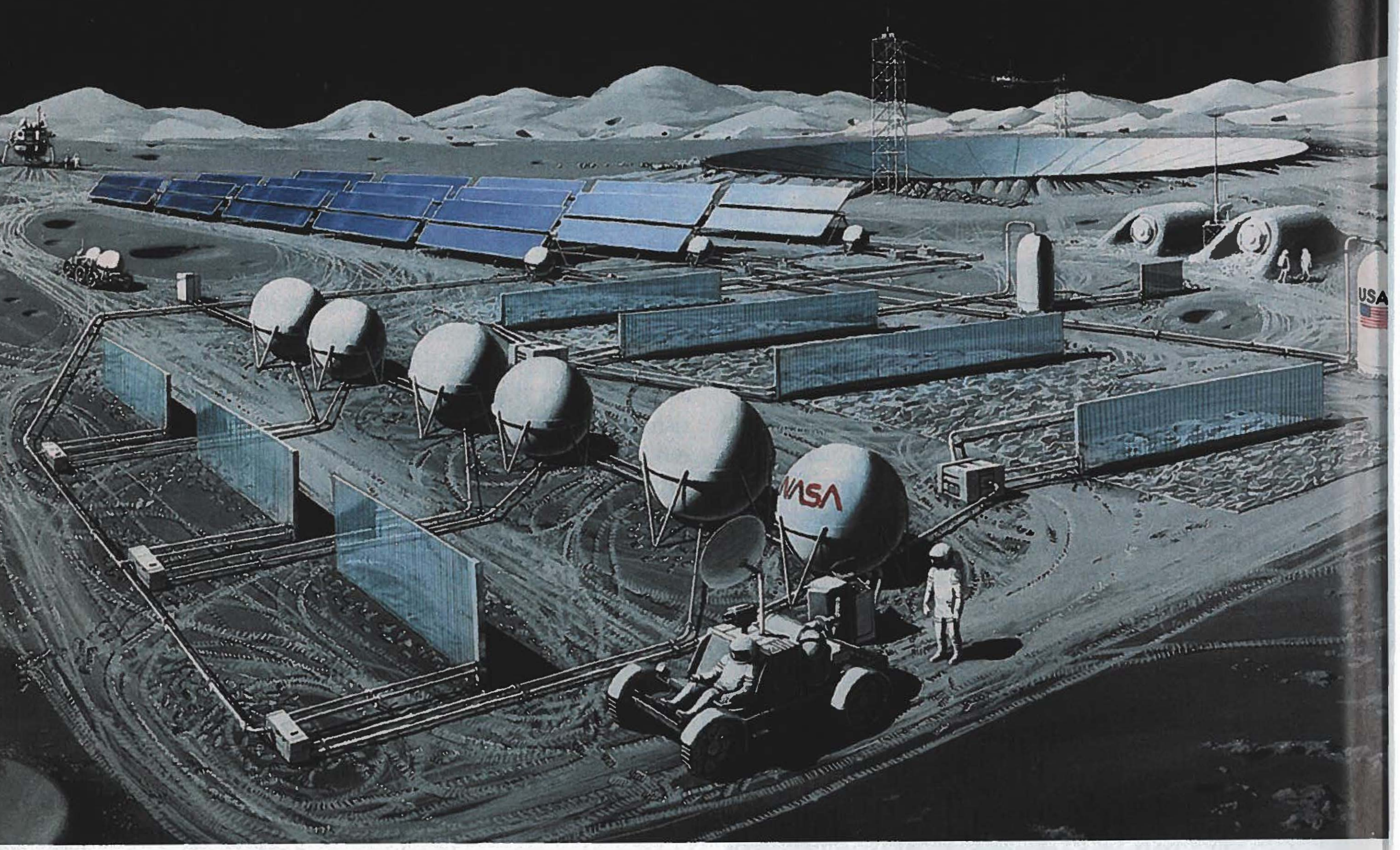
TO HELP DESIGN HABITATS for the harsh conditions in space, various engineers and architects are studying terrestrial structures that must endure extreme environments. NASA even has a *Human Integration Design Handbook*, written in 2010 and revised in 2014, that references "undersea habitats, submarines, [and] Antarctic stations," among other analogous settings for space habitats.

A key difference in terms of the loads that must be accommodated, however, is that a submarine is designed to withstand the crushing forces of the outside water pressure, whereas on Mars, at least, the opposite would apply. The gravity on Mars is one-third of Earth's gravity, and the atmospheric pressure is just 0.6 percent of the atmospheric pressure on Earth. Thus, "the main problem with designing



A proposed domed city for Mars would combine inflatable structures at the surface with underground spaces and a section for water used for shielding. It is being tested with prototype structures in Dubai, United Arab Emirates.

BECAUSE HUMANS HAVE BEEN EXPLORING SPACE FOR NEARLY 60 YEARS, MANY ASPECTS OF EXTRATERRESTRIAL LIVING CONDITIONS ARE WELL DOCUMENTED AND UNDERSTOOD.



RENDERING BY NASA

MARSHA was the uplift created by internal pressure required for human habitation," Poon explains.

To compensate for that uplift, the foundations designed for MARSHA feature tie-down anchors and a keeper-plate assembly to prevent the superstructure from lifting up, Poon says. In addition, a system of slide bearings at the base allow the structure to accommodate the extreme changes in temperature throughout a Martian day.

Lunar and other space habitats must be designed to withstand multiple challenges—from micrometeorite impacts to seismic movement—that will happen simultaneously.

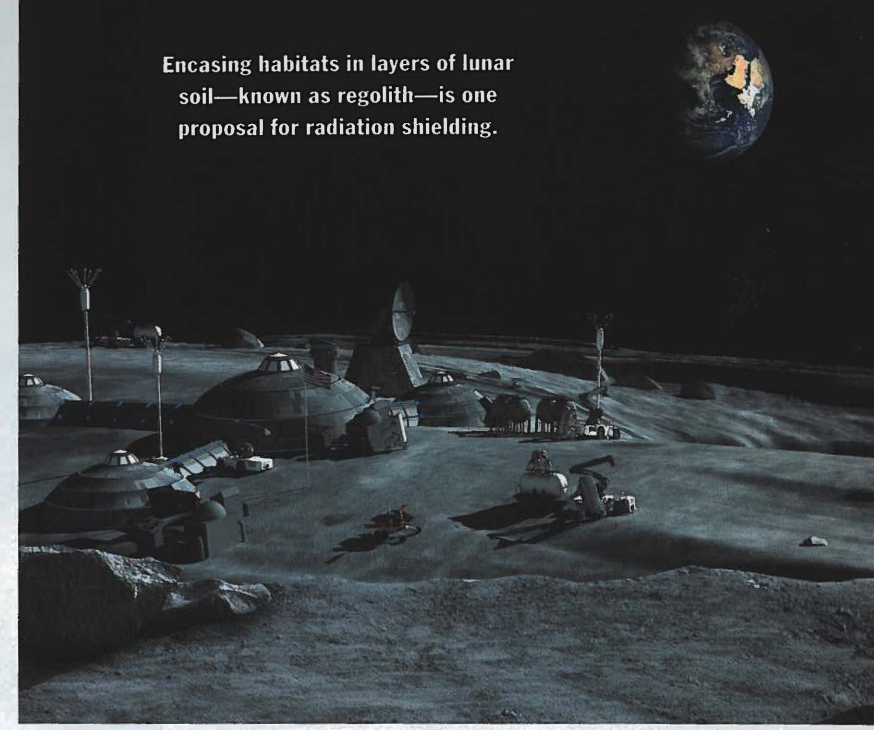
Because humans have been exploring space for nearly 60 years—and even living there for extended periods on the International Space Station—many aspects of extraterrestrial living conditions are well documented and understood. Both NASA and private industry have even developed simulated materials designed to replicate the properties of lunar and Martian regolith. But other conditions in space are more difficult to simulate and might be testable only computationally.

Space habitats "will experience a suite of anticipated and unanticipated extreme conditions, which makes them very different from their terrestrial counterparts," says Amin Maghareh, Ph.D., a research assistant professor at Purdue. "On Earth, we design for conditions by emulating the conditions in the lab, studying them, and then implementing those findings in designs. But creating the conditions in space, on the moon, or Mars is kind of impossible for us because we're dealing with radiation and other conditions we can't re-create here on Earth," Maghareh explains. "Because of these various factors we decided to take a different approach ... cyber-physical testing that we currently do for structural engineering, we decided to do for the design of extraterrestrial systems."

As Dyke explains, the approach combines computer models with physical experiments. "We can actually create a test bed where we can simulate all those different environments," she notes. "We can't exactly get rid of gravity. That's one of our challenges! And it's probably going to be difficult to create a vacuum. But we can look into all the different types of habitats by changing the computational components for the test beds [and] changing the arrangement of how we put things together."

Dyke compares the approach to "a sort of plug-and-play or jigsaw-puzzle-type test bed arrangement, where we can plug things in and take things out and make things into computer models and use physical specimens, and we can mix it in the way that allows us to study what we want to study."

Malla says he considers additional challenges, including the fact that in space, all the potential conditions or concerns may "hit you at the same time." So, how can they all be tested together? Even if engineers put a scale model of a habitat on a shake table inside a vacuum chamber and bombarded it with high-velocity objects under extreme temperature ranges, he says, there would still be challenges in scaling up from a prototype. "Would the effects be the same on a bigger scale?" Malla asks. "That's the challenge."



Encasing habitats in layers of lunar soil—known as regolith—is one proposal for radiation shielding.

Scaling up will also affect the constructability of space habitats because once engineers and architects determine what humans will need to live on the moon or elsewhere in space, "then we think about how technology can help that, and then we figure out how to fit it all into a rocket," says Georgi Petrov, P.E., AIA, LEED, an SOM associate director who worked on the Moon Village project. (When Petrov was a project architect at Laguarda.Low Architects in Dallas, he and John Ochsendorf, Ph.D., an assistant professor in MIT's Building Technology Program, authored, "Building on Mars," *Civil Engineering*, October 2005, pages 46–53.)

While space habitats might seem highly futuristic and speculative, SOM based its designs on existing technologies that are known and tested as well as technologies under development but which might not yet have flown in space. The goal has been habitats that could be constructed on the moon within the next five or so years. So, while some of the designs—such as a hybrid structure with an inflatable shell—would involve a more advanced version of current technology, "we absolutely are trying to create something that is constructible and realizable," says Colin Koop, AIA, an SOM design partner.

VERTICAL LUNAR HABITAT MODEL

RENDERING BY AMIN MAGHAREH, TOP; ILLUSTRATION BY © SOM, BOTTOM

The focus on using only current or nearly current technology may have imposed constraints on what SOM could design, but it has also "unlocked a tremendous amount of creativity," Koop adds, noting that such constraints "have been very, very helpful to the advancement of the design because they've forced us to resolve the engineering in a manner which is actually realizable."

At the same time, SOM's team also understands that the design of a space habitat must include elements of good design itself, including aesthetics. "We've found that aesthetics has an enormous role to play in the viability of a settlement because you're creating habitats for long-term stays," Koop says. Thus, the habitat design must consider both the physical and mental health of the people living within. "Aspects of aesthetics aren't just about beauty but also about positive well-being," Koop explains. "A human being's wellness is highly impacted by the quality of the environment in which they're living—the quality of the natural light and the artificial light, the ability to exercise, to sleep comfortably."

Petrov adds that because "we're working on designing and engineering what could be the first of the habitats where people would live" on the moon or elsewhere beyond Earth, the initial design of such settlements is critical. "Any time humans have started a new settlement on Earth," Petrov notes, "the first way the settlement was laid out has had an effect hundreds of years later on the type of city or society that develops."

Designing buildings for space might seem especially daunting to engineers and architects accustomed to following building codes because such codes simply don't exist for extraterrestrial structures. But help might be on the way, notes Malla, who leads the ASCE Aerospace Division's Space Engineering & Construction Committee. The committee is "looking into preliminary guidelines" that might someday help establish space-related building codes, Malla says. The committee is also offering short courses on various aspects of lunar engineering and construction at ASCE's Earth & Space Conference, to be held April 20–23, 2020, at the Renaissance Seattle Hotel in Seattle. (See earthspaceconference.org.)

ALTHOUGH THE FOCUS of all these space habitat efforts is, obviously, helping humans live in space, "any developments that come from this research can also be applied to problems here on Earth—which is one of the things that civil engineers bring to the table," notes Whitaker. Having worked on environmental controls and life support for space systems, Whitaker points to water treatment and water revitalization—as well as air revitalization—technologies that were developed by NASA and are already in use around the world. "Every year, more and more NASA things are used here on Earth to solve problems," she says.

One of the most recent and direct technology transfers involves another version of AI SpaceFactory's MARSHA habitat that was designed specifically for construction on Earth, notes Earle. Dubbed TERA, a full-scale prototype was being erected at press time at a test site in Upstate New York. AI SpaceFactory's team is "working through the equipment [and] considering the implications of 3-D-printing a structure of this size," Earle says. This includes such issues as the wind loads and how to make the building suitable for people to stay overnight or for a period of time.

"Everything we're doing is designed to make construction more 'intelligent,' and that would have huge impacts for building here on Earth or other planets," Earle adds.

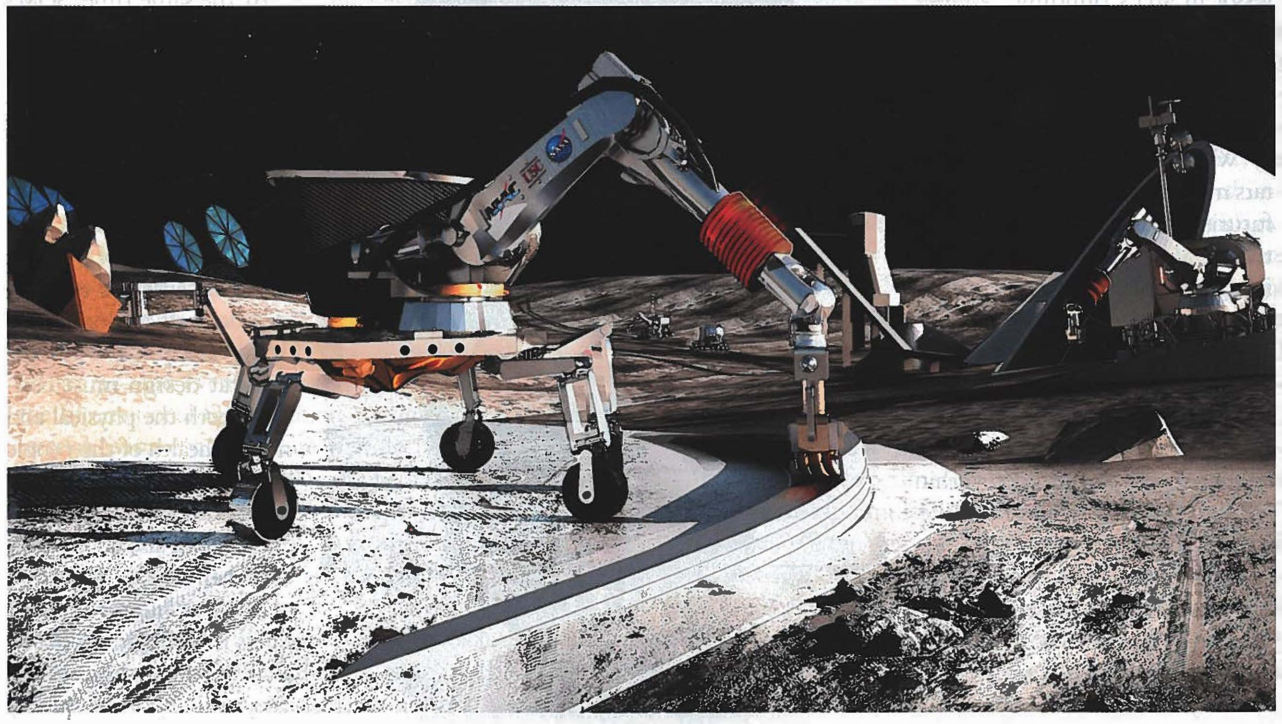
For civil engineers, the habitat work ties nicely into efforts to "improve the resilience of our communities by reducing the vulnerabilities of our civil infrastructure," notes Julio Ramirez, Ph.D., P.E., the Karl H. Kettelhut Professor in Civil Engineering at Purdue and the director of the university's Network Coordination Office for the Natural Hazards Engineering Research Infrastructure These projects also foster interdisciplinary cooperation, at both the professional and collegiate levels.

"What we're trying to do is bring the systems engineering community's and the aerospace engineering community's views of uncertainty, risk, and reliability together with the civil engineering perspective and merge those so we can have a holistic view of resilience," notes Dyke. The next generation of engineering students and researchers will have to be able to solve interdisciplinary problems, adds Jahanshahi. "So, this project provides unique opportunities for many civil engineering students to work with other disciplines, such as industrial, mechanical, and electrical engineering, to work together on a very big project, a stepping-stone for improving resiliency not only beyond Earth but also for projects here on Earth," he explains.

Ramirez notes that this work on space habitats can literally open up new worlds for civil engineering as a profession. "People perceive civil engineering as a 'mature' field" that has long been using the same materials and methods, he explains. "But this is a moment when a totally new area of inquiry for civil engineering is opening." **CE**

Reid

Robert L. Reid is senior editor and features manager of Civil Engineering.



The European Space Agency, NASA, other government organizations, private industry, and academia are all developing proposed habitats for the moon, Mars, and Earth orbit, *above*. Many proposals call for robots to 3-D-print the shelters using local material, *below*.

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WORK ON SPACE HABITATS CAN LITERALLY OPEN UP NEW WORLDS FOR CIVIL ENGINEERING AS A PROFESSION.