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people sent into Earth or lunar orbit for course, given the habitats' extraterrestrial settings, the teams 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 300°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 some of the space-based solutions back here on Earth.

**BY ROBERT L. REID**

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.

James Bridenstine, the administrator of the National Aeronautics and Space Administration (NASA), has repeatedly said that humanity is going back to the moon—that 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 to 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 300°F, and protect against potentially deadly levels of radiation or micrometeorite impacts.

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NASA has also been testing full-size habitat prototypes 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
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 state 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 a human crew departs and restarting such systems before new astronauts arrive, explains Akinc.

"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," Akinc 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 Jahanhashi, Ph.D., an assistant professor of civil engineering at Purdue. As part of the RETHi project, Jahanhashi 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, etc. etc. etc.—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 distortion of those loads over the life cycle of the structure. Dyke notes. "But when we talk about space structures, that takes a different perspective."
Mohoquakes, 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 of 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 impacts are different.”

Protecting against radiation is one of the most critical factors engineers need to consider for space habitats, wherever they’re located.

“Moonquakes,” notes Thornton Toth, of the Institute for Human Integration Design, at Arizona State University, “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 of 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 impacts are different.”

To design habitats that can withstand the crushing forces of the outside water pressure, whereas on Mars, at least, the opposite would apply. The Martian settlers would, over time, generate enough organic waste to recycle it as a building material for the MARSHA structure, Earle explains.

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 comprise 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.

Launch this summer and reach Mars in 2021, RIMPaX will include ground-penetrating radar that could provide geological information on the red planet to depths of 10 m or greater. 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 cohesive tendency, 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.

“On Mars, the environment is so extreme, you can’t just use the regolith as it is and it needs to be hardened,” says Malla, 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 MarsHab—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 cowers with a high strength-to-weight ratio, he adds.

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.

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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 keep-plate assembly to prevent the superstructure from lifting up, Poon says. Both NASA and private industry have even developed superstructures for extraterrestrial living conditions are well documented and understood.

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 regoliths. 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 them 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," the 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 bed [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.

Scaling up will also affect the constructability of space habitats because once designers and architects determine what humans will need to live on the moon or elsewhere in space, "then we think about how technology can help us, 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 65-69).

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 constructable and realizable," says Colin Koop, AIA, an SOM design partner. 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 are used here on Earth to solve problems," she says.

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.)

A LTHOUGH 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 Whittaker. HaviRGW worked on environmental controls and life support for space systems, Whittaker 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 habi-

t 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 load 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., F. ASCE, 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 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.