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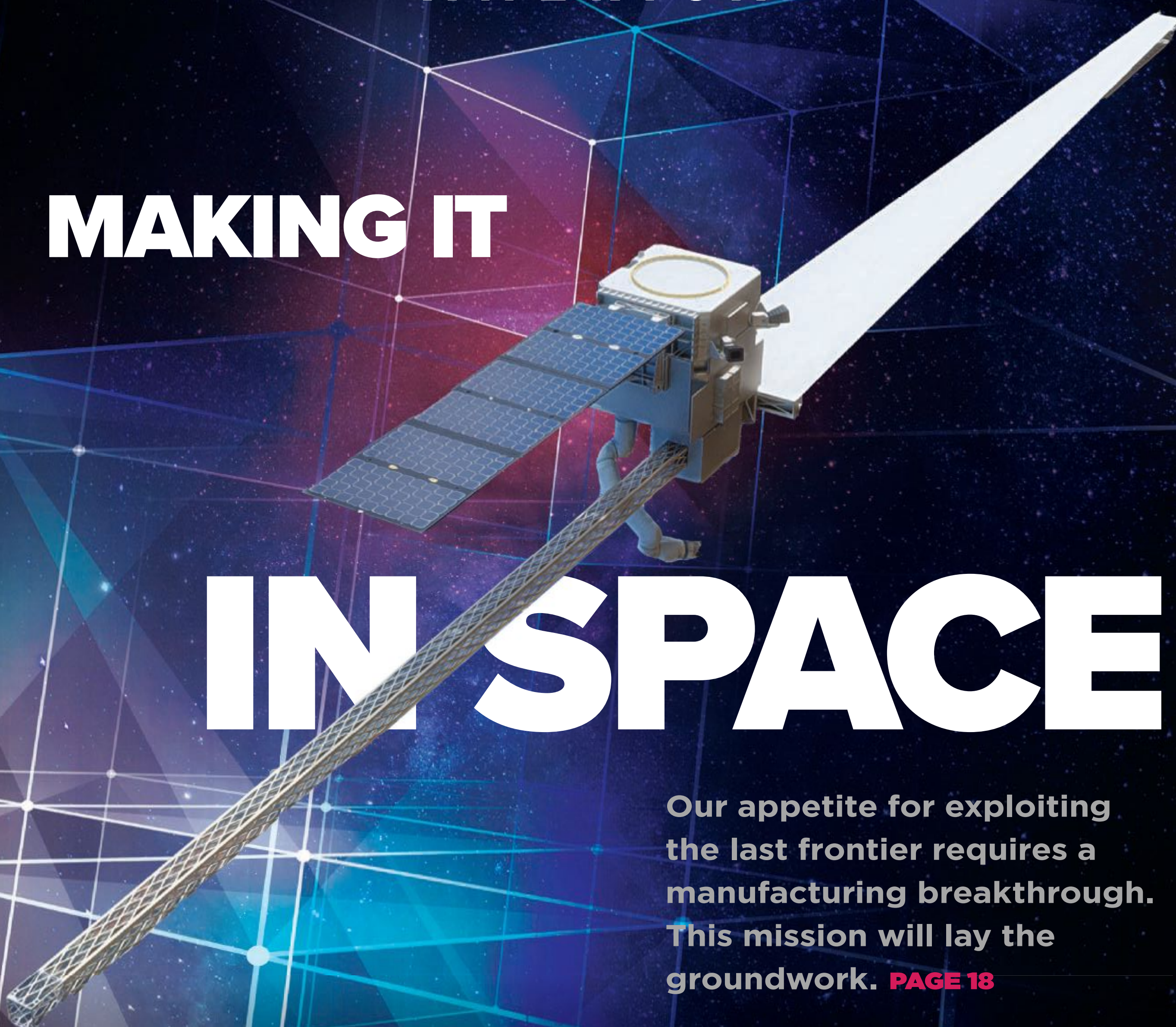

MAKING IT IN SPACE

Our appetite for exploiting the last frontier requires a manufacturing breakthrough. This mission will lay the groundwork. PAGE 18

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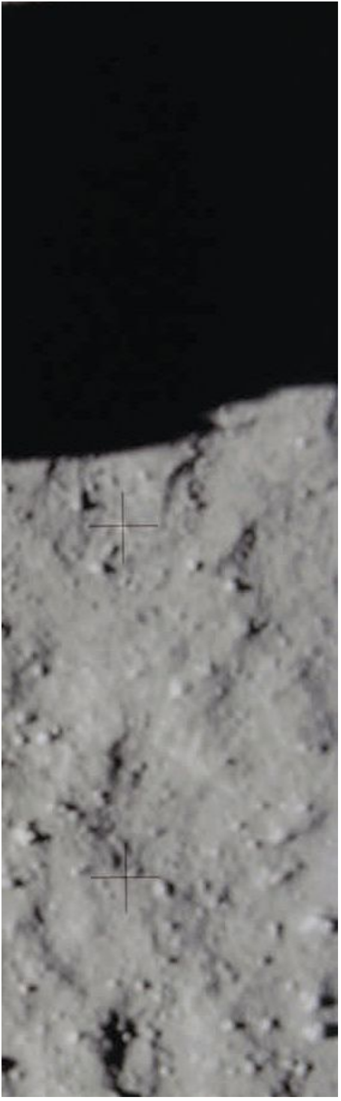
SHAPING THE FUTURE OF AEROSPACE

OPINION

Walking on rocket propellant

Returning to the moon to stay will require making rocket propellant on site, so that crews can rotate back to Earth. As it turns out, mining water ice may not be the fastest or easiest way to produce lunar rocket propellant. Michael Nord of the Lunar Surface Innovation Consortium at Johns Hopkins Applied Physics Laboratory in Maryland explains.

BY MICHAEL NORD



When the world sees America place the next man and the first woman on the moon under the Artemis program, the reaction is likely to be one of immense enthusiasm. Our 1969 landing, with an estimated TV viewership of 650 million, reportedly held the record for the single most viewed human event for 12 years, and there is every reason to expect that in a world much richer with telecommunication, the global reaction will be even greater.

Yet, unfortunately, public interest quickly dropped off after Apollo 11, and six months later the Nixon administration took the first in a series of steps that truncated the Apollo series. How do we convince the White House, Congress and the public that, this time, we will be there to stay? I argue that in-situ resource utilization, or ISRU, is the answer. By operating “gas stations” on the moon that will dispense rocket propellant made in part from lunar oxygen extracted directly from the lunar surface regolith, we will not only lower overall program costs, but also demonstrate the “live-off-the-land” ethic that is immensely popular with the American public and will, likewise, be necessary for going to Mars.

This way, Artemis will become more than Apollo 2.0. We will have shown that we are there to stay.

Our first step toward this, as space professionals, should be to demonstrate to industry and the taxpayers an early and aggressive commitment to ISRU.

So far, we have strong evidence of water at the lunar poles, and this science has increased public and congressional interest in ISRU. The potential availability of large quantities of water ice or hydrated minerals is indeed astonishingly interesting under both a scientific and an economic lens, but there remain significant gaps in our knowledge. We don’t know the exact location, distribution or form that the ice may take. Fortunately, NASA will launch a number of spacecraft in the next few years to prospect for water on the moon and narrow those knowledge gaps. Those include PRIME-1, the Polar Resources Ice Mining Experiment-1 lander, and VIPER, the Volatiles Investigating Polar Exploration Rover.

We should vigorously pursue the ISRU path in parallel with prospecting for water. An enormous resource, in fact, lies not just at the poles but on the surface where the Apollo astronauts walked. Oxygen comprises 80% of our rocket propellant needs, and this can be extracted from dry regolith anywhere on the surface of the moon. This is a technological path that will lead to a sustained human presence on the moon. We have enough knowledge to begin planning its extraction now.

Rocket propellant: main driver for ISRU

By mass, the largest consumable at the Artemis base camp will be rocket propellant. Shelters and other infrastructures can be reused. Breathable air and potable water will obviously be critical, but the local production of them is not a large concern. We have ample experience using nearly closed life support systems on the International Space Station. Water is, indeed, precious, but we know how to recycle drinking water — and even air. Rocket propellant, however, is a large resource mass that cannot be recaptured after use.

Dynetics and SpaceX — two of the three providers of human landing systems — have indicated that between 30 and 100 metric tons of propellant may be needed for every return mission from the moon. Compare this with the entire landing mass of an Apollo descent module, which was about 15 tons. Also, recall that the Tsiolkovsky rocket equation is an exponential; to land a single kilogram of propellant on the moon requires at least 80 kilograms of propellant on Earth. This provides a compelling financial and efficiency incentive to produce propellant on the moon. Such a capability will carry us a long way toward sustainability.

Liquid bipropellant rocket fuels

Cryogenic, liquid bipropellant, chemical rocket fuel is comprised of a fuel and an oxidizer. The fuel can be many things — hydrogen, methane, kerosene, even paraffin or powdered aluminum. The oxidizer is nearly always liquid oxygen, or LOX. Usually 70-80% of the mass of rocket propellant before takeoff is LOX. So, how much of these components are available for production on the moon?

We don’t expect to find the raw materials for hydrocarbon fuels on the moon. However, we know from the Apollo samples and ground-penetrating radar that the moon has oxygen distributed horizontally across its surface and also vertically to a depth of at least 10 meters. While the exact composition of this regolith is a function of location, no matter where you land on the moon, the regolith beneath you will be 40-45% oxygen, 20-25% silicon, 8-12% aluminum, 5-15% iron and 5-15% calcium, with traces of sodium, potassium, magnesium and titanium. Shortly after Neil Armstrong made his famous small step, he assembled a hand tool and scooped up a “contingency sample” of soil and rock that was stored on board in case he and Buzz Aldrin needed to leave quickly. Armstrong may not have known at the time that 40% of the rock he collected was rocket propellant!

Lunar water knowledge gaps

The craters at the north and south poles of the moon have not seen sunlight in billions of years, and they can be colder than the surface of Pluto. Various

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▲ **A bucket drum** soil excavator developed by Lockheed Martin delivers soil to the Precursor ISRU Lunar Oxygen Testbed during a NASA field test in Hawaii in 2008. NASA tested lunar rover concepts and how astronauts might make oxygen from lunar rocks and soil.
NASA

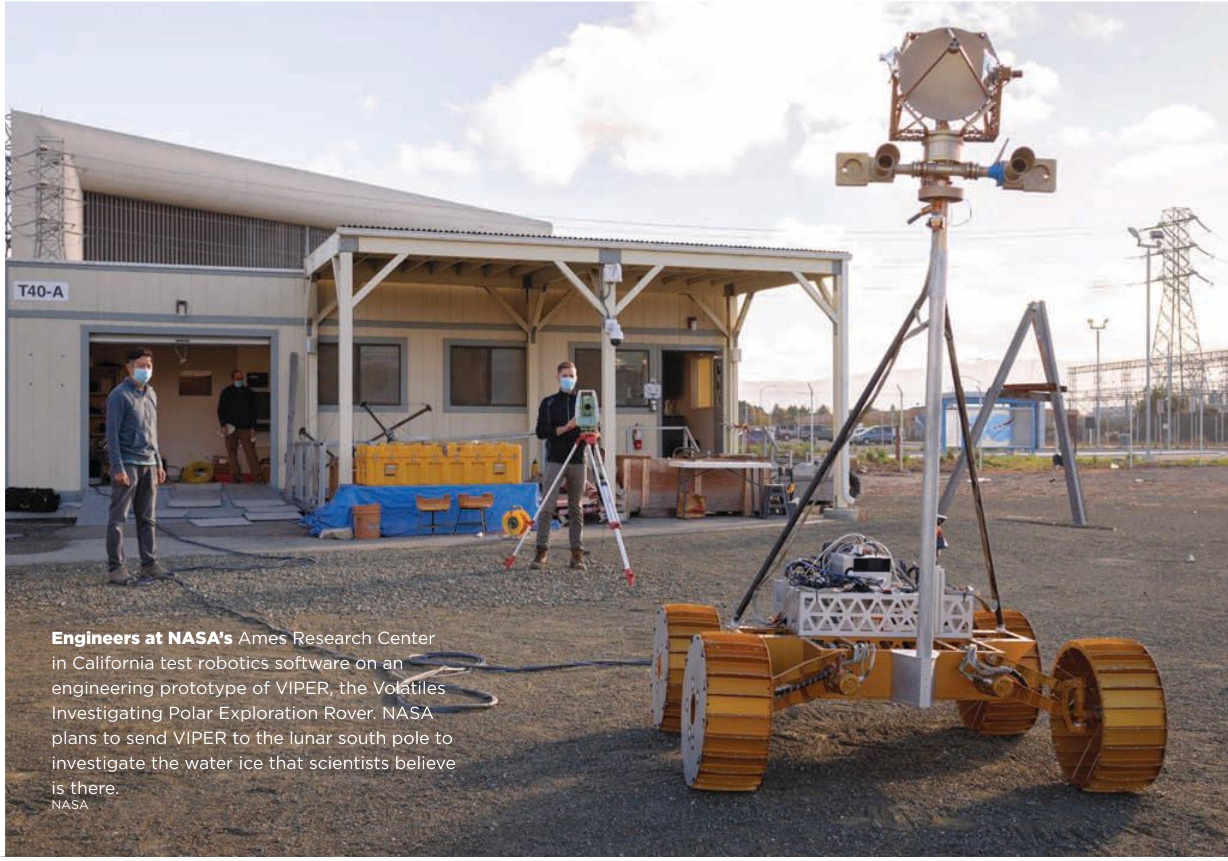
measurements of the moon in recent decades have shown that it's so cold that, even in the vacuum of space, water ice can remain stable. Water is both fuel and oxidizer together in one molecule, so it's tempting to think our problems are solved. Well, not so fast.

While the existence of water on the moon is very exciting, the story is complicated. The permanently shadowed regions on the moon equal an area of approximately 30,000 square kilometers, a little bit smaller than the state of Maryland. We know from orbital neutron spectroscopy measurements that there is hydrogen (from which we infer water ice) within a meter of the surface, and that it's likely under several centimeters of dry soil. We know from one impactor mission to the coldest, darkest and likely "wettest" spot on the moon, that there is definitely water ice, and in that location it's as much as 5% by mass of the lunar regolith. However, the observations suggest the water is not evenly distributed. We know from radar data that most of the ice cannot be in giant slabs, but we don't know how the ice is partitioned among small chunks, tiny grains and surface coatings. Most importantly, we haven't characterized the lateral and depth distribution on the meter-sized spatial scales relevant for ISRU processing. Until PRIME-1 and VIPER land in a couple of years, we will not have a widely accepted theory of its origin and evolution over time, knowledge that would improve predictive modeling of the present-day distribution. Without this information, we rely on educated assumptions for parameters that inform the design of mining equipment. Lack of exactly this type of knowledge contributed to the recent InSight mission's failure to drill into Mars.

Fortunately, preparations are underway to narrow these unknowns. NASA is scheduled to launch the PRIME-1 drill in 2022 and the VIPER mission in 2023 to conduct exploratory drilling for water in a few polar locations, and there are a slew of other small, prospecting satellite missions, either on the books or envisioned for the near future. I welcome these missions, but I am unsure if all, or any, of them will allow us to narrow down locations and develop water extraction equipment and processes inside the 2020s. Extracting oxygen and hydrogen from that water would be one way to produce propellant, but given all the unknowns, establishing the required water plant would require a decade or more of prospecting, design work and space launches.

Rocks to rocket propellant

Here's how we know that separating oxygen from regolith is a practical way of obtaining rocket propellant on the moon. Every day on Earth, silicon, iron, aluminum and other metal oxides are separated into pure metals and oxygen through various processes in refineries around the world. On Earth, the excess oxygen is considered an unwanted, but not harmful, byproduct and is released into the environment. On the moon, the oxygen would be the primary resource to be retained (and the oth-



Engineers at NASA's Ames Research Center in California test robotics software on an engineering prototype of VIPER, the Volatiles Investigating Polar Exploration Rover. NASA plans to send VIPER to the lunar south pole to investigate the water ice that scientists believe is there.
NASA

er metal products would be very useful as well). All that is needed is to capture, purify and store the oxygen. No need to go searching for "gold." No need to remove low-grade soil. No need to have machines operating in the intense cold of the permanently shadowed regions. The entire moon is covered tens to hundreds of meters deep in regolith, and any fistful of lunar regolith is rocket propellant waiting to be processed.

Since the 1960s, scientists and more lately industrialists in the U.S. and abroad have studied various processes for extracting oxygen from lunar rocks. Exactly which process is most efficient, works best with local compositions, has the best throughput and greatest mechanical simplicity and is best suited for operation on the lunar surface are all issues that can and have filled days of impassioned arguments. The bottom line remains the same: 80% of our rocket propellant needs are right there in the regolith, just waiting for us. No prospecting campaign will be necessary for that, but those prospecting missions will close the knowledge gaps and identify the most accessible locations for mining this valuable resource.

Also, there's a bonus to learning to extract oxygen from regolith. The byproducts are silicon and metals. We can expect these resources will be useful later as we start to build solar panels and other structures with material harvested from the moon. We will have to extract these resources eventually. Why not do it now?

The need for speed

There is no reason to wait until ice on the moon can be effectively extracted. System components for an oxygen-from-regolith system are at a technology readiness level of at least 4 on NASA's nine-level TRL scale, meaning multiple components have been tested in the lab and the field, in this case the volcanic soils of Hawaii. A systems integration and build will need to be completed to test these components in the lunar environment, but NASA, the European Space Agency or, indeed, a commercial entity, could conceivably have a liquid oxygen-from-regolith ISRU pilot plant already running on the moon in 2024 when plans call for the Artemis-3 crew lander to touch down.

Luckily, we can establish the oxygen-from-regolith plant near the lunar south pole, where NASA intends to establish Artemis Base Camp. The lunar poles, in addition to being the location where we think ice is, are also the regions with the maximum available solar power and regions of high scientific interest. It is going to take a lot of power to run either oxygen from regolith ISRU or ice mines. We can emplace the power, communications and oxygen extraction resources now and have it up and running in the near term, all while prospecting for water with robots and astronauts. The ice has been there for billions of years. It will be a few more years before we can find and extract it. Until that day, 80% of our propellant needs are right there in the polar regolith. Let's go get it. ★

Michael Nord is an expert in in-situ-resource utilization at the Johns Hopkins University Applied Physics Laboratory in Maryland.