One step from Earth

Now we know that the Moon's poles hold millions of tonnes of water ice, firms in the US as well as the Indian and Chinese space agencies are planning to mine this resource and sell it to space missions as fuel. **Richard Corfield** reports

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On 14 December 1972 a small flower of flame blossomed under a squat metal box in a valley on the south-eastern edge of our Moon's Mare Serenitatis. Within seconds, the ascent stage of Apollo 17's lunar module *Challenger* was lifting commander Gene Cernan and lunar module pilot and mission geologist Harrison "Jack" Schmitt back into lunar orbit to rendezvous with the Command Module *America*.

To Cernan and Schmitt it was a time of mixed emotions. They felt exultation at having become the 11th and 12th members of the human race to set foot on a celestial body other than the Earth. And yet their departure was also a time of mourning, for it signalled the end of NASA's Apollo programme – the only project ever to have landed humans on the Moon. Budget cuts meant that all future Apollo missions were scrapped and humanity retreated to Earth orbit.

But the scientific analysis of the rocks brought back by the Apollo programme continued and Apollo scientists showed that the lunar regolith is rich in elements that are scarce on Earth, such as helium-3 as well as lanthanum, neodymium and other rare-earth elements. Now, more than four decades since the end of the Apollo programme, nations and companies are beginning to take the prospect of lunar mining very seriously indeed. After all, when something's scarce there's money to be made.

Gas stations in the sky

Humans may not have ventured beyond low Earth orbit since Apollo 17 came home, but unmanned spaceflight has made giant strides since then. In particular, during the 1990s two robotic science missions were sent to the Moon: the joint US Department of Defense and NASA Clementine mission in 1994, followed by NASA's Lunar Prospector Mission in 1998–1999. Both used small orbiting spacecraft and the missions suggested that, contrary to all expectations, there might be water ice on the surface of the Moon.

The Clementine orbiter used ultraviolet and infrared imaging to map the Moon, and initial results suggested that water might be present in the polar regions. The Lunar Prospector Mission used a neutron spectrometer to search for the presence of hydrogen, particularly at the south pole region of the Moon. NASA's announcement in March 1998 that the Lunar Prospector had found significant quantities of water in the Moon's polar craters made headlines around the world.

Since then, several new lunar-orbiting science spacecraft have been launched, including India's Chandrayaan-1 in 2008 and America's Lunar Reconnaissance Orbiter (LRO) in 2009. The latter carried the Lunar Crater Observation and Sensing Satellite (LCROSS) booster, which was specifically designed to crash into the Moon's south pole in an attempt to confirm the presence of water.

"We want[ed] to identify whether there is hydrogen at the poles that is associated with water ice or other volatiles," recalls Richard Vondrak, project scientist for the LRO and deputy director of NASA's solar system exploration division. "Our goal [was] to locate them, measure their concentration and [answer] the question: is that material accessible in the quantities required for use?"

LCROSS impacted a permanently shadowed crater in the south polar region of the Moon on 8 October 2009. The ejecta plume, which was analysed by an instrumented probe following behind the impactor, confirmed – using infrared and visible light spectrometers and cameras – the presence of water ice in the region. Estimates currently suggest that there are approximately 1 billion tonnes of water ice at the south pole of the Moon and 600 million tonnes at its north pole.

It is this, more than anything else, that has kindled interest in mining the Moon, for where there is ice, there is fuel.

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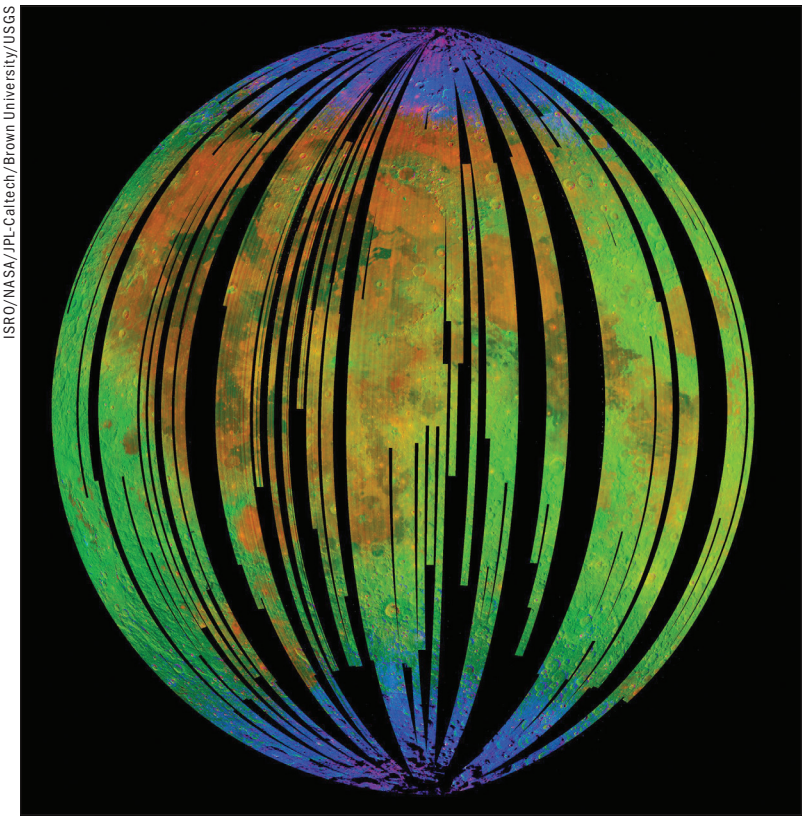
The icemen cometh

At the forefront of interest in excavating lunar ice is the Shackleton Energy Company (SEC) of Austin, Texas. The firm was founded in 2007 by explorer and space entrepreneur Bill Stone with the aim of developing the equipment and technologies necessary for mining the Moon.

Dale Tietz, the company's chief executive officer, says SEC wants to take advantage of what it believes are enormous quantities of ice at the poles of the

Victor Habbick Visions/Science Photo Library



ISRO/NASA/JPL-Caltech/Brown University/USGS

Pole position
This image of the Moon, taken by NASA's Moon Mineralogy Mapper on India's Chandrayaan-1 mission, shows the distribution of different materials across the side of the Moon that faces the Earth. Blue shows the signature of water, green shows the brightness of the surface and red shows a mineral called pyroxene.

Moon. "[This] can be mined and converted into rocket propellants and sold in low Earth orbit to all space partners at significantly lower prices than anything available today that could be launched from Earth," he explains. The savings will come because it is much cheaper to launch spacecraft from the Moon, which has one-sixth of the gravity of Earth. "If you run the numbers it comes out as a 20-fold improvement on the ability to launch something from the Moon compared to from the Earth into low Earth orbit," says Tietz.

Low Earth orbit (LEO) is SEC's preferred destination for its "gas station in space" because it is close to its customer base, namely Earth, and also because the International Space Station is in LEO. "It is simply convenient for us to put our depot there," says Tietz.

Tietz is adamant that the firm's initial goal is only to mine water ice – because of its potential as a rocket fuel – rather than other resources such as helium-3, which is in short supply on Earth. Helium-3 has several applications on Earth, such as cooling materials to less than 1 K and being used as a detection material in neutron-scattering facilities , but when it comes to the Moon, some firms think it has potential as an energy source.

SEC plans to mine water ice by sending both crewed and uncrewed (i.e. robotic) miners to the lunar poles. "We will electrolyse [the water ice] to liquid oxygen and liquid hydrogen and use some of it for our own lunar propulsion activities, for example to power mining hoppers, lunar rovers and life support," says Tietz. Predominantly though, the ice extracted there will be shipped in the form of water or ice to LEO. "LEO is where we will have monstrous electrolysers to convert the water to propellants on an on-demand basis," he says.

SEC also plans to exploit other deposits of volatiles on the Moon harvested as a by-product of its ice-mining operations. Tietz says that the firm expects to capture nitrogen and carbon dioxide, which can then be reused for growing foods or developing chemicals.

Tietz is dismissive about the economics – at least initially – of mining helium-3. This isotope of helium is produced by fusion in the core of the Sun and is fantastically rare on Earth because it cannot penetrate our atmosphere and so is only available as a by-product of man-made nuclear-fission reactions on Earth. "At the present time, we do not find the concentrations of helium-3 in our polar target areas to be of sufficient abundance to be economic," says Tietz. "If you look at the real estate that has to be mined to get to it where we will be, which is in an extremely harsh and geographically small area at the lunar poles, from a percentage point of view we do not think it will be worthwhile."

A watery tale

Moon Express is another privately funded lunar-resources company that is planning a return to the Moon. Founded by Silicon Valley entrepreneurs Naveen Jain, Bob Richards and Barney Pell, the firm unveiled its MX-1 lunar lander spacecraft in December 2013. According to the Moon Express website, the MX-1 is a "breakthrough robotic space vehicle capable of a multitude of applications including delivering scientific and commercial payloads to the fraction of the cost of conventional approaches".

Like SEC, Moon Express is interested in using water as a fuel – but in a different form. It plans to fuel its operations and spacecraft using "high-test peroxide" (HTP), which has a long and illustrious history as a propellant. First developed by the Nazis during the Second World War, it was originally named C-Storff and used to fuel missiles and the U-Boat 1407. Britain's Royal Navy then built two Explorer-class submarines, *Explorer* and *Excalibur*, using HTP as an experimental fuel. The project was, however, abandoned after several fires, which led British naval personnel to rename the two subs the "Exploder class".

While the fuel might not have been suitable for underwater work, it was used in combination with kerosene to successfully power the British Black Arrow rocket in the 1950s, which launched the UK's Prospero X-3 satellite from the Woomera Range in South Australia.

It is perhaps no surprise therefore to see HTP making a comeback in the MX-1 satellite. Moon Express has the goal of winning the Google Lunar XPRIZE and mining the Moon for resources of economic value. Its focus is rare-earth elements, which include niobium, yttrium and dysprosium.

Farouk El-Baz, the geologist behind the original site selection of the Apollo missions, is as enthusiastic as SEC and Moon Express about the return to the Moon. "There are all kinds of questions about the Moon which remain to be answered," he says. However, El-Baz is cautious about the idea of sending humans back to the Moon. "I think to answer [these questions] the best way is to send robotic missions."


NASA/David Nathan

One last step for man
Gene Cernan took this photo of Jack Schmitt packing up equipment after taking soil samples during the Apollo 17 mission to the Moon.

Another, more academic development in lunar exploration is that being spearheaded by Lunar Mission One. Sponsored by academia and industry as well as crowd funding, the project aims to enhance understanding of the Moon and the Earth by using drilling technology at the south polar region to understand where the volatiles in the crust came from and identify additional resources that will make a permanent presence on the Moon a reality.

Enter the dragon

Rare-earth elements, which are vital for everything from mobile phones to computers and car batteries, are also attracting attention from other nations. China, whose Jade Rabbit lander successfully touched down on the Moon in December 2013, is interested in mining the Moon for such elements as well as titanium, which the LRO found is up to 10 times more abundant in the lunar regolith than on Earth.

China currently has a near-monopoly on terrestrial rare-earth elements, having pursued a strategy of price control that has put all but its own mines out of business. Still, its own mines will not last forever, which is why China might try to mine the Moon. It already has plans to send a crewed mission to the Moon by 2020, and its space agency has publicly suggested establishing a "base on the Moon as we did in the South Pole and the North Pole".

This raises questions about the territorial annexation of the Moon. During the Cold War, the possibility of countries claiming territory on the Moon or other planets was considered realistic enough that the 1967 Outer Space Treaty was enacted to prevent it. But if there really is a superabundance of elements on the Moon, would this piece of paper stop nations from trying a land-grab?

China, of course, is also tantalized by the lure of helium-3. With a large and rapidly growing population and horrendous problems with pollution from its proliferating coal-fired power stations, a clean and limitless source of energy is impossible to ignore. Some believe that a fusion reactor fuelled by deuterium and helium-3 would be far cleaner than conventional fusion with deuterium and tritium because high-energy neutrons, which make fusion reactor walls radioactive, are not produced in nearly the same quantities. This argument has its flaws, not only because deuterium reacts up to 100 times more slowly with helium-3 than it does with tritium, but also because deuterium held in a reactor with helium-3 would produce neutrons anyway through various intermediary reactions. Still, this has not stopped China expressing an interest in helium-3 and it is for much the same reasons that India is also interested in the Moon. It plans to send Chandrayaan-2, which will carry a rover vehicle equipped with geological prospecting tools, to the Moon in 2016.

All interested parties agree that the Moon – one step from Earth – is the essential first toehold for humankind's diaspora to the stars. Indeed, Bill Stone of SEC sees his firm as an integral part of that first step. "Once established…Shackleton will represent the first fully off-Earth corporation with the majority of its continuing resources coming from the Moon, not the Earth," he claims. If this vision is realized, it would mean that the need for additional Earth-based launches would be limited to sending new hi-tech electronics and tools, and for personnel rotations. "Until Shackleton is successful, however," cautions Stone, "getting to the Moon will remain an extraordinary and very expensive and dangerous feat for everyone".

Chris Riley, co-producer of the award-winning film *In the Shadow of the Moon*, as well as the recent documentary *Neil Armstrong First Man on the Moon*, has no doubt about the importance of going back to the Moon because of its still hidden secrets. "Pure exploration is the most important driver for returning to the Moon," he says. "It's the size of the African continent, and yet we've only picked around with people on the surface in six places for a handful of days."

As for El-Baz, who trained the Apollo astronauts in lunar geology, there is a bigger vision. "Our objective in the long run should be an astronauts' mission to Mars. That's what we should concentrate on."

But it all starts with one step from Earth. ■