Mining on the Moon;
Yes, it's really going to happen

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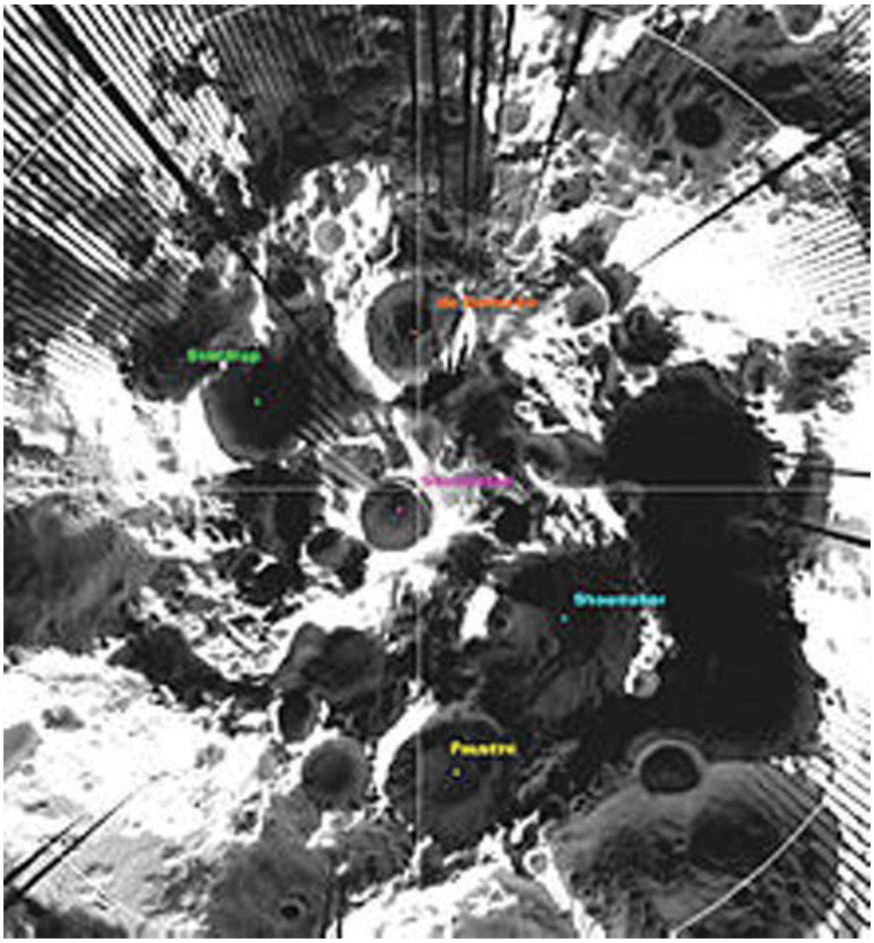
Outer space technology and exploration have reached a tipping point, so that mining and mineral processing in outer space is now a certainty and not a dream. Several competing companies worldwide are on the way to building spaceships to land on the Moon and eventually mine the Moon and asteroids for volatiles, rare earth metals and Helium-3.

The Google Lunar XPrize offers a $30 million prize[1]. China has recently landed a spacecraft on the Moon. The European Space Agency, with cooperation from the United States, has landed a spacecraft, Philae, on a comet. And, Mars One is planning a one-way trip to establish a settlement of humans on Mars.

How and why are the Moon and asteroids and their resources of interest to private space industry companies? Why are the Moon and asteroids viewed as a potential business venue?

Figure 1

Shackleton Crater as imaged by LRO.



Geology of the Moon and asteroids — Why do we want to mine there?

Space enterprises are actively working toward establishing and operating lunar and asteroid mining locations for resource extraction, resource processing, conversion to salable products and distribution of the products and services in space and to Earth and beyond[2].

Forty-five years ago, the Apollo manned missions to the Moon returned rocks and regolith to Earth, which were studied and analyzed. What they found was that the Moon contains valuable minerals and resources. These minerals are largely due to meteor and asteroid impacts, which have, over eons, created this mineral-rich regolith. These impacts have occurred on Earth as well, for billions of years, particularly early on in the history of the solar system. However, on Earth, wind, water and vegetation have erased most of these impacts. On the Moon, in contrast, the only weathering is caused by subsequent impacts and the solar wind.

The Moon regolith contains valuable rare-earth minerals, platinum-group minerals (particularly where the Moon has been impacted by asteroids), volatiles (useful for processing and habitation), Helium-3 and titanium.

Almost nonexistent on earth, Helium-3 is abundant and accessible on the Moon and can be used in nuclear fusion power plants, producing much more energy than fission reactions and with much less radioactive waste. One of the main reasons Helium-3 is sought after as a fusion fuel is because there are no neutrons

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generated as a reaction product. Governments and private companies are focused on the mining of Helium-3 on the Moon as a basis for their economic models.

Moon Express, one of the private companies that is planning on mining on the Moon, will recover moon rocks to fund its early operations[25]. Subsequently, it will recover Helium-3, platinum and rare-earth metals as it engages in surface mining operations.

Space ventures that are primarily interested in mining platinum-group minerals will mine asteroids rather than the Moon. It is estimated that a small asteroid contains $50 billion in platinum[5]. Platinum on asteroids is the focus of the private space company, Planetary Resources, co-founder Peter Diamandis, who also co-founded the XPrize Foundation. Deep Space Industries and Kepler Energy and Space Engineering are other companies focused on mining asteroids[5]. Japan and NASA also have plans to land on asteroids and collect samples.

Volatiles on the Moon are likely to be found in lunar cold traps (LCT). These are crater interiors near the north and south poles that lie in permanent shadow due to the sun's angle being constantly below the crater rim. With no sunlight reaching the surface, LCT temperatures lie in the 30-50 K range, allowing volatile compounds to permanently exist in solid states. Water can be extracted from LCTs for life support, construction materials and rocket propellant for local use or export to Earth. This mining operation for volatiles would ideally be positioned within the Shackleton Crater, 21 km (14 miles) in diameter and 4.1 km (3 miles) deep, near the lunar southern pole. This is one of the most promising locations for volatiles. The Shackleton Crater is located in the Aitken basin, which is one of the largest and oldest impact craters on the Moon, Fig. 1.

Continuous planetary, lunar and orbital habitation require supplies of oxygen and water for human life support systems. Oxygen and hydrogen can also be used for greenhouses, electrical power production with fuel cells and electrical power storage with a reversible fuel cell.

A key to reducing transport costs is reducing the requirement for launching on-orbit spacecraft propellant from Earth[12]. This is significant for a potential future lunar spaceport or surface colony. The preferred fuel/oxidizer propellant combination is hydrogen/oxygen, which is commonly used in rocket upper stages to transport communications satellites from a low earth orbit to a geosynchronous transfer orbit or geostationary transfer orbit.

Hydrogen/oxygen propellant can be processed from the Moon lunar regolith. This is a key motivation for extraction of water from the Moon's surface. It can then be electrolyzed to form the hydrogen and oxygen propellant.

In light of this, the costs associated with both space exploration and geostationary satellite launches can be significantly reduced if most of the upper stage propellant does not need to be lifted from Earth. Costs would be saved if the upper stage can be refueled with propellant already in low earth or lunar orbit.

The Apollo missions chose landing sites primarily on the basis of safety on landing and then on the basis of general scientific interest to learn about the history and composition of the Moon. Successor lunar missions have emphasized and will continue to emphasize discovering what lunar resources (e.g., water and lunar volatiles) can best support future, long-duration commercial and human operations on the Moon.

How do we mine and recover minerals and other resources from the Moon and asteroids?

The Massachusetts Institute of Technology (MIT), Department of Aeronautics and Astronautics, has developed an exemplary conceptual design for a robotic volatile mining operation[4]. This design utilizes a base/robotic rover architecture. It includes initial setup and operations for the robotic mining rovers, energy production and transmission, resource central processing, export systems, and component hibernation (wintering). The Shackleton Crater, mentioned earlier, is the lunar surface focus for this design.

The design is to have centralized mining operations from which robotic mining rovers will obtain power, and to which the rovers will transport all collected regolith material for electrolysis and processing. The mining rovers will be powered utilizing hydrogen and oxygen power generated by a central processing plant located on the floor of the Shackleton Crater. Energy will be generated by the processing plant's electrolysis module, containing a photovoltaic cell, using lasers from one or more towers located on the crater rim.

The towers will be outfitted with solar panels to collect energy, power a high-powered laser, and triangulate positions of rovers within the crater via radio receivers. The optimal placement of the towers is to maximize sunlight.

Central processing units. The central processing unit of the MIT design has two self-contained modules: 1) an electrolysis module and 2) a refinement/processing module. The electrolysis module has large storage tanks for the liquid hydrogen and oxygen for refueling the mining rovers. The refinement/processing module is used for mining operations when enough regolith material has been collected and delivered to the processing site.

By processing the regolith inside the crater, the volume of material required to be exported from the mining site drops 94-98 percent.

The primary source of energy storage in the crater is hydrogen and oxygen, which can be combined in fuel cells to generate electricity and heat. These fuels will be generated/replenished through the electrolysis of water, powered by energy transmitted from the solar panels on the crater's rim. Due to the low temperature in the crater, both the hydrogen and oxygen can be stored in liquid form. This dramatically reduces the space required to store these fuel supplies, compared to compressed gas storage.

The MIT design has a single large processing unit at the base that runs continuously and then transfers a portion of the fuel it produces to the rovers when they return to base.

Regenerative fuel cells are used for power. They are unique in that they comprise a closed loop system and are completely sealed. The hydrogen, oxygen and product water inside regenerative fuel cells are simply recycled over and over again. To operate regenerative fuel cells on the Moon, one starts with a tank of water. The solar arrays make hydrogen and oxygen during the day, then use the hydrogen and oxygen to make electricity during the night when there is no sun. Ideally, if nothing breaks or wears out, they could run forever.

Initial setup. The MIT mining project design anticipates installation in three phases[4].

In the first phase, the power towers are fully assembled with the laser transmitter and solar panels, using a maintenance robotic rover that lands outside the crater. This solar-powered maintenance rover will utilize the long summer days to place the towers in their designated positions and assist with solar array deployment.

The second stage of initialization, the payload, will land directly inside the crater. This payload will consist of a robotic rover, the electrolysis unit, and enough fuel to sustain operations through the first winter hibernation.

Once the rover has installed the electrolysis unit in the desired location, the rover will begin to gather regolith. It will bring the regolith to the central processing station, creating mounds to be processed in the final stage.

The electrolysis unit will convert water produced by the rover's fuel cells back into hydrogen and oxygen. The hydrogen and oxygen will be stored in storage tanks. These storage tanks will allow for refueling the mining rovers.

Stage two can run indefinitely before the processing unit arrives, creating flexibility in the project schedule.

In the third phase, the mining operation will be delivered. This will consist of a regolith processing unit, a volatile evacuation mechanism and any additional rovers.

The processing module will be attached to the electrolysis module and begin to process the mounds of regolith collected previously by the robotic rovers.

Volatile evacuation. Once the base has been established and volatiles are collected, it will be necessary to transport these volatiles out of the crater. There are a number of possible methods of accomplishing the evacuation.

Hypervelocity accelerators (magnetic levitation cannons) are one possibility. They have two parallel conducting rails, with a conducting projectile touching both rails. A current is then sent down one rail, across the projectile, and back up the second rail to create a magnetic field, which accelerates the projectile very quickly, until it leaves the rails and enters a ballistic trajectory [6,7,8]. A primary difficulty with hypervelocity accelerators is catching the projectile at the top of the crater. At a minimum velocity of 78 m/s (256 ft/sec), the impact could either bury the projectile deep within the regolith or destroy it on impact, which would make recovery of the volatiles difficult to impossible. A tiny error in launch velocity could cause the projectile to miss its target[4].

An alternative method for evacuating volatiles would be to use a cable-bucket system, such as a cable lift, to transport material while suspended, or a winch system, which would drag the resources along the ground[9]. Using a winch may be more viable than an elevated cable, as a winch only requires a hoisting mechanism at the top of the crater and a single length of cable, half the length of a continuous loop system[4]. Also, the space venture would need to transport heavy steel cable to the Moon, unless the cable can be

Figure 2

ATHLETE vehicle standing 4 m (13 ft) tall, shown crawling off of a half-scale lunar lander mockup. Credit: Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.

created in situ using lunar iron deposits.

The energy for this extraction method for volatiles can be supplied by solar panels, or beaming power into the crater by the laser.

Mining robotic rovers. Automated and tele-operated rovers will be used to harvest regolith from the lunar crater floor and then transport the regolith to the central processing station[4]. Ideally, these rovers will also be flexible enough to assist in setting up and relocating the base unit, as needed, rather than requiring additional specialized construction rovers for these tasks. The rovers will be designed to travel relatively long distances and carry large payloads to reduce the number of mining trips required.

Along with traverse, the other main operating mode for the rovers is robotic mining. The legs and actuators can accomplish this by lifting one of the legs, attaching a scoop, then collecting and lifting regolith to dump it into a container on top of the rover chassis[4]. Each rover will need sufficient onboard power to operate for an entire mining sortie before returning to a central base to recharge.

The Jet Propulsion Laboratory (JPL) has developed an "All-terrain, hex-legged extra-terrestrial explorer" for a mining rover[11], specifically for the establishment and operation of a lunar base. The JPL rover has six identical legs arranged around a central hexagonal body, which houses the electronics, power, and other payloads for the rover, (Fig. 2).

Fuel cells and batteries. The main energy storage options are fuel cells and batteries[14,15,16]. Fuel cells are powered by combining hydrogen and oxygen, which can be generated from the water that will be mined from the cold traps. When electricity is generated, the fuel cell's water output is stored on the rover so that it can be stored and reprocessed back at base[4]. This is essentially a regenerative fuel system, but with the energy and equipment for electrolysis located at the base.

Fuel cells have a high energy density, both in terms of mass and volume, compared to batteries. Unfortunately, fuel cells have a much lower maximum power output than batteries. The MIT rover design therefore uses a hybrid power system. The fuel cells run continuously and charge a set of high-power batteries while the rover is operating nominally. Then, whenever the rover needs to perform an energy-intensive maneuver, such as climbing, it can discharge these batteries to level the load.

Alternative lunar mining designs. Other lunar settlement and mining concepts have been designed with the goals of human and robotic mining [9,10]. As one example, The National Space Society (NSS), a nonprofit educational organization, has published "Milestones to Space Settlement: An NSS Roadmap [26]."The NSS roadmap suggests the following steps: Robotic confirmation of lunar resources, determining the nature and extent of lunar ice and volatile deposits, providing the information necessary to guide the choice of the best sites for a lunar outpost, establishing lunar research to study human habitation, testing of various equipment and techniques and conducting lunar investigations, evolving the initial research facility into a permanently occupied industrial lunar base and increasingly performing commercial functions, and evolving into a permanent lunar settlement that is increasingly self-sufficient and focused on commercial activities.

The "self-financed, self-developed and self-supporting profitable lunar colony" is another exploration and settlement strategy published by the Wisconsin Space Grant Consortium and Orbital Technologies Corp. for NASA[27]. Its strategy is to establish a low-cost lunar colony at the south pole of the Moon that is focused on in situ resource utilization. Its lunar mining concept presents three basic approaches to extracting water. The first involves the in situ heating of water from the regolith without excavation. The regolith is heated and water vapor is collected at the surface by freezing, so that it can be transported mechanically out of the shadowed area, or liquid or gaseous water is transported by heated pipeline from the cold trap. The second approach is to excavate the water/regolith mixture, but process it in a furnace situated in the cold trap and transport liquid or gaseous water from the cold trap to a collection site outside of the shadowed area. A third option is to excavate the regolith and transport it from the cold trap to a sunlit area for processing.

Government vs. private lunar mining missions

China. China has a commitment to lunar habitation and commercialization, including mining[28,29,30]. China has already landed on the moon (Dec. 14, 2013). The Chang'e-3 lander successfully soft-landed in Mare Imbrium, a very large lunar crater. A small robotic rover (Yutu) was deployed onto the lunar surface and conducted a cursory surface exploration.

With its Chang'e-3 test missions to the Moon, the Chinese have successfully completed steps needed to conduct lunar exploration. During a six-year span, China has methodically conducted a series of missions to refine the skills it needs to explore, habitate and mine the Moon. In October 2010, China launched a lunar orbiter that mapped the Moon at high resolution. Additionally, it carried a laser altimeter that produced a high-quality global topographic map of the Moon and a gamma-ray spectrometer to map surface elemental composition. The lunar phase of this orbiter was completed in nine months, with a departure from lunar orbit in June 2011. At the end of August 2011, this spacecraft was sent to Sun-Earth L-2, a stable libration point about 1.5 million km (932,000 miles) from Earth. At this point, Earth and Sun remain fixed in space (relative to the spacecraft) and minimal fuel is needed to remain here. After loitering at L-2 for about eight months, the spacecraft departed in late April 2012 for an intercept and flyby of the asteroid Toutatis in December of 2012. High-resolution images of Toutatis were obtained and the Chinese spacecraft entered solar orbit, where it remains to this day.

China's latest successful mission (Nov. 1, 2014), flew a spacecraft to and around the Moon. The capsule was returned safely to the surface of the Earth — in effect, the mission sequence required for lunar sample return.

The plan for the next Chinese mission (Chang'e-5) will be to conduct a robotic sample return mission sometime in 2017, including bringing back fusion-ready Helium-3. The mission profile calls for a soft landing on the lunar surface, the collection of soil and rock samples, the ascent of the sample-return vehicle to orbit (where it will autonomously rendezvous with the Earth return stage), and then the firing of a rocket engine to leave lunar orbit and return to Earth.

China is also at work on a manned lunar space program and anticipates a manned landing on the Moon in the mid-2020s. "In addition to manned lunar landing technology, we are also working on the construction of a lunar base, which will be used for new energy development and living space expansion," said Zhang Yuhua, deputy general director and deputy general designer of the Chang'e-3 probe system, at a recent speech at the Shanghai Science Communication Forum.

Private companies, Google Lunar XPrize and NASA. The Google XPrize Foundation1 has provided a significant catalyst and incentive for private companies to innovate and enter the recent lunar space race. The Google Lunar XPrize incentive of $30 million for the first private company to successfully land on the Moon's surface, and have a robot that travels at least 500 m (1,640 ft) transmitting images back to Earth, has attracted 16 private company teams, worldwide. Some of these companies hope to win this prize by 2017.

One of the companies, Moon Express, has received $30 million from NASA for development of its space technologies, and has

Figure 3

Portrait photo of Yutu moon rover taken by camera on the Chang'e-3 moon lander, Dec. 15, 2013. Credit: Chinese Academy of Sciences.

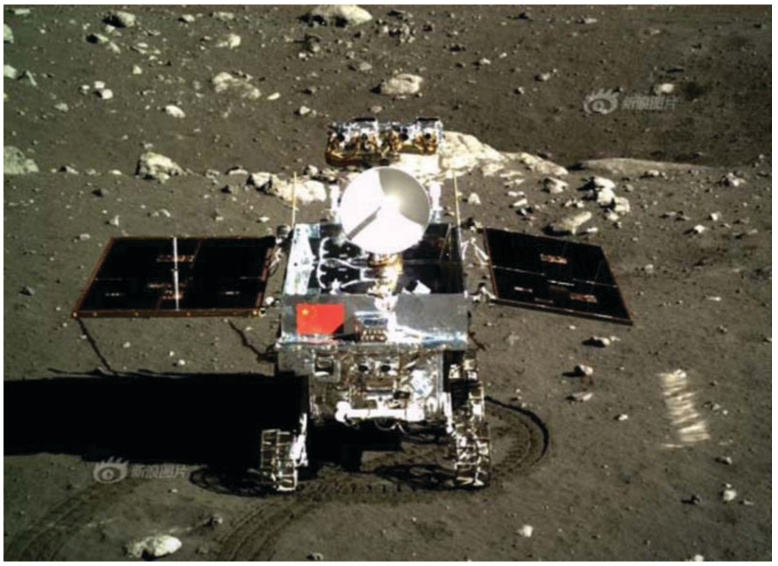
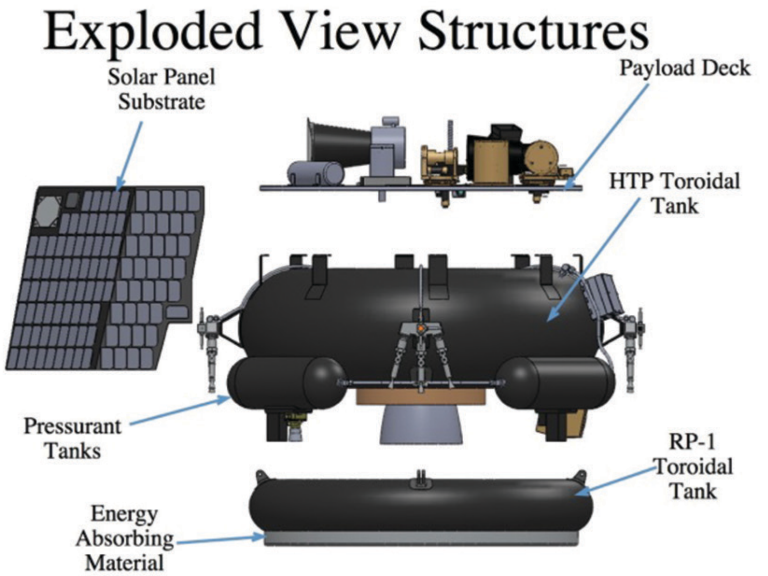


Figure 4

Moon Express Lunar Lander. Credit: Moon Express.



recently signed a contract with Rocket Lab, a rocket launch company in New Zealand[25]. Moon Express is developing its own lunar lander and robotic rover.

In November 2016, Moon Express partnered with NASA to brainstorm potential experiments that could be conducted based aboard Moon Express spacecraft. Moon Express is preparing to land its spacecraft on the moon in 2017. For this initial landing, Moon express hopes to be able to propel itself along the lunar surface using the craft's thrusters. By covering some distance on the Moon's surface, Moon Express hopes to be able to conduct a variety of experiments. This initial landing will also serve as a dress rehearsal for future landings by providing valuable experience for remote control of craft on the moon.

Historically, the enormous costs required to undertake exploration of our solar system, build satellites, create test and support facilities, and recruit, train and retain personnel was left to national governments. National exploration space programs of this era were undertaken for the advancement of science, national prestige and to prevent colonial planetary competition[17]. Today, NASA is collaborating with private companies for research and development of rocketry, moon landings, asteroid capture, and human space travel and landing on Mars[18]. Likewise, there is collaboration among private space companies and among governments to develop space technologies.

Mars One. Mars One is a not-for-profit foundation co-founded in the Netherlands with the goal of establishing a permanent human settlement on Mars[3]. The first unmanned mission is scheduled to depart in 2020. Crews will depart for their one-way journey to Mars starting in 2026. More than 200,000 people applied to be in the initial crew. Subsequent crews will depart every 26 months after the initial crew has left for Mars.

Mars landing modules will carry life support units that generate energy, water and breathable air for the settlement. Supply units will have food, solar panels, communications systems, spare parts and other components. Living units will be deployable inflatable habitats for humans. Rovers will be sent to Mars, in advance, to set up the outpost before humans arrive and to do initial exploration.

Mars has resources that can be used for a sustainable settlement. Water is present in the soil which will be used for drinking, farming and a source of oxygen (generated through electrolysis). Nitrogen and argon can be mined from the Martian atmosphere to provide the inert portion of the habitat breathable atmosphere.

Rosetta Spaceship and Philae Lander. On Nov. 12, 2014, the Philae lander made history by landing on the comet 67P/Churyumov-Gerasimenko. This space feat was accomplished by the Rosetta Plasma Consortium, led by the European Space Agency, and in cooperation with many countries, including the United States. This is considered by many to be the most difficult space mission ever accomplished, because the rocky comet was tiny and spinning. The technologies utilized and information obtained will be useful for space companies in their pursuit of mining the moon and asteroids.

What are the laws governing mining in outer space?

Outer Space Treaty. The 1967 United Nations Outer-Space Treaty (Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies) is the primary international treaty adopted and signed by the United States and other nations to govern relations and activities in outer space[19].

The limitations and principles laid out in the Outer Space Treaty are[20]:

- Exploration and use of outer space shall be carried out for the benefit and in the interests of all countries and shall be the province of all mankind, and outer space shall be free for exploration and use by all states.
- Outer space, including the Moon and other celestial bodies, is not subject to national appropriation.
- Nuclear weapons or other weapons of mass destruction shall not be placed in orbit or on celestial bodies or stationed in outer space.
- Astronauts shall be regarded as the envoys of mankind.
- States shall be responsible for national space activities, whether carried out by government or nongovernmental entities.
- States shall be liable for damage caused by their activities in outer space.
- States will retain jurisdiction over objects launched into space.
- States shall avoid harmful contamination of space and celestial bodies.

In the context of the 1960s and the Cold War era, the Outer Space Treaty is an anti-militarization treaty directed to national governments and state sponsored agencies planning and executing space and planetary exploration[21].

The United Nations negotiators in developing the Outer Space Treaty rejected outer space as res nullis, or that unclaimed territory is subject to national appropriation. The legal framework adopted in the Outer Space Treaty is that space is to be res communis that is, all entities, including individuals, corporations and nations have equal access to outer space and the resources therein[23].

Article II of the Outer Space Treaty. Article II of the Outer Space Treaty prevents nations from appropriating territory in outer space, the Moon or other celestial bodies (i.e., planets, asteroids or comets). Arguably, the treaty does not prohibit private individuals or legal entities such as corporations from making claims to develop, extract or manage celestial resources[23].

Article VI of the Outer Space Treaty. Article VI of the Outer Space Treaty obligates a state (nation) to retain jurisdiction and responsibility over the space activities it or its private citizens perform.

A state's implementation of the Outer Space Treaty's provisions include a legal jurisdiction and obligation to oversee and control the space activities of its private individuals and entities, such as private corporations.

Article VIII of The Outer Space Treaty. Article VIII of the Outer Space Treaty assigns liability and responsibility to the nation for any object or person launched by a nation or from a facility located within the nation, and the state continues to have liability and responsibility wherever there is a landing.

Need for update of the Outer Space Treaty

World affairs, the relationships between nations, and space travel and exploration have evolved, but the 1963 Outer Space Treaty has remained static. The Outer Space Treaty was created as a "Non Armament" treaty that prohibits armed militarization in space and forbids the stationing of nuclear weapons in outer space[21].

The lack of clarity, consistency and unified interpretation of the treaty and international law causes ambiguities regarding the property rights of commercial planetary explorers. These uncertainties are a barrier to financial and market access by entrepreneurs and investors.

Moon Treaty of 1979. The Moon Treaty of 197913 has been signed by only 16 countries. None of the countries who are actively involved in space (including the U.S., Russia, China and Japan) signed this treaty. The Moon Treaty is highly restrictive. Article 11 states "Neither the surface nor the subsurface of the Moon, nor any part thereof or natural resources in place, shall become property of any State, international intergovernmental or nongovernmental organization, national organization or nongovernmental entity or of any natural person. The placement of personnel, space vehicles, equipment, facilities, stations and installations on or below the surface of the Moon, including structures connected with its surface or subsurface, shall not create a right of ownership over the surface or the subsurface of the moon or any areas thereof." Other Articles of the Treaty require sharing of research and benefits, and access to facilities. This treaty is considered largely a "failed treaty" in that most nations have refused to sign it.

U.S. government regulations and agencies. U.S. government agencies and Congress have traditionally created numerous barriers for private space enterprise through layers of jurisdictional and intra- and interbureaucratic conflicts, laborious regulatory requirements and policies[17]. Private companies are fighting a decades-long struggle to remove regulatory barriers. However, the U.S. government is currently collaborating with private companies to make mining in outer space possible.

From the beginning of the space age, most U.S. policymakers assumed that governments would be actors operating in space and, thus, made no allowance for private companies. In the 1970s, when private companies wanted to sell services rather than hardware to NASA and other government agencies, NASA would not give up its bureaucratic empire. Government agencies were initially barred from using private carriers to place cargo in space.

The Challenger disaster in 1986 eventually led to the removal of the ban on government payloads from private rockets. In 1995, the Federal Aviation Administration (FAA) became the regulator for private launches. The FAA recently issued a ruling giving Bigelow Aerospace permission to launch with an inflatable living space intended for the Moon, as part of its jurisdiction over payload reviews.

The Commercial Space Act of 1998 sought to remove barriers to private space efforts. It did, for example, remove the ban on private providers bringing vehicles and payloads, including private travelers, back from space. It also requires NASA to purchase services rather than hardware whenever possible.

On Nov. 25, 2015, President Obama signed into law the landmark Space Act of 2015. The Act significantly reduces regulations for the space flight industry while establishing a new government entity entitled "Office of Space Commerce." This Office will be responsible for coordinating the interstellar mining of natural resources on all planetary bodies. The Space Act establishes a basic property rights regimen in outer space — U.S. citizens are entitled to any asteroid or space resources they may obtain. The Act decisively rejects the property rights theory found in the Moon Treaty. While the Space Act establishes a basic property regimen, a legal framework will still have to evolve to adjudicate the scope of property rights claims in space. For example, the Space Act does not speak to how one can "stake a claim" to interplanetary resources. Does merely landing on an asteroid vest one in a property right to the whole asteroid? Such issues present novel questions that will have to be addressed. The basic principles of space mining are still being formulated. Businesses can expect more developments in space law in the near future.

Securing permission to launch to outer space from the FAA still involves safety requirements, reentry licensing, financial responsibility requirements, site operations licensing and various environmental impact requirements. The FAA recently issued a ruling giving Bigelow Aerospace permission to launch with an inflatable living space intended for the Moon, as part of its jurisdiction over payload reviews[22]. In August 2016, Moon Express entered history as the first private company to obtain government approval (FAA) for landing a spacecraft on the Moon. Moon Express obtained a favorable payload review and determination of its MX-1E spacecraft scheduled to travel to the moon in 2017[31]. The FAA's determination provides a framework for future regulatory decisions. The FAA's decision found that Moon Express did not "jeopardize public health and safety, safety of property, U.S. national security or foreign policy interests, or international obligations of the United States." Under this decision, the FAA sees itself as fulfilling the provisions of the Outer Space Treaty requiring government oversight of private space initiatives. It is likely the FAA will continue to fulfill this regulatory role until the United States government creates a department specifically designed to regulate space activities.

The future of engineering education

In the future, mining and metallurgical engineers and geologists will work on project teams with aeronautical, aerospace, astrophysics, agricultural and planetary civil engineers to design, test, develop and deploy robotic and human habitats, colonies, orbital and planetary surface processing units, mining operations, and power, transportation and distribution facilities.

A transitional change in training and education for future space ventures will be required to provide specific space engineering skill sets for the following outer space environments, including: non gravity, high-radiation exposure, non atmosphere vacuum, planetary material handling and use, temperature fluctuations and periods of hibernation. For mining on the moon and asteroids, new technologies and methods are needed to provide: planetary surface and orbital bases, special mining and metallurgical methods for extraction and processing, planetary materials characterization, materials handling and transportation, drilling, blasting, construction, power and life and safety systems. ■

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