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Lunar Roadmap to Propellant Production on the Moon: A New Ocean World Proposal .

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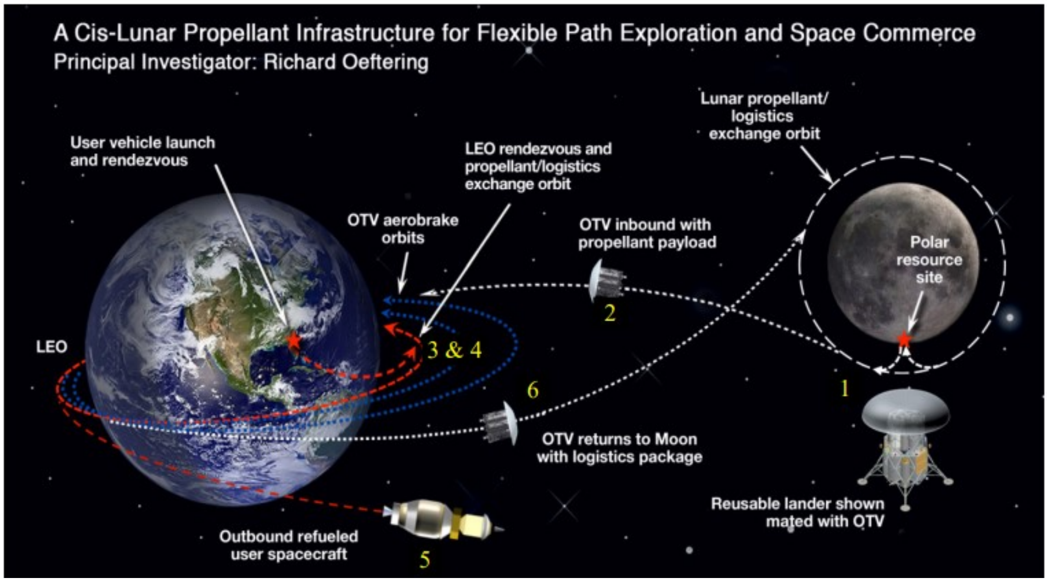


Abstract.
Identification of subsurface water reservoirs have been confirmed from near-term study missions to the Earth's moon and to Mars, from both satellite flybys as well as planetary landers. The purpose of this paper is to explore the vision of prospective in-situ resource utilization and their exploitation potential. Mission findings mapped landing sites for where ISRU will occur. The presence of extraterrestrial water suggests (1) understanding how/why of its evolution to allow for (2) characterizing ocean environments in known ocean worlds. With known ocean environments it becomes important to (3) differentiate their habitability and ultimately (4) search for extant life. Disruptive ISRU technologies can potentially be useful for future lunar space operations that include a mix of propellant production, cryopropellant management, reusable lunar landers, propellant tankers, orbital transfer vehicles, aerobraking technologies,

I. Introduction

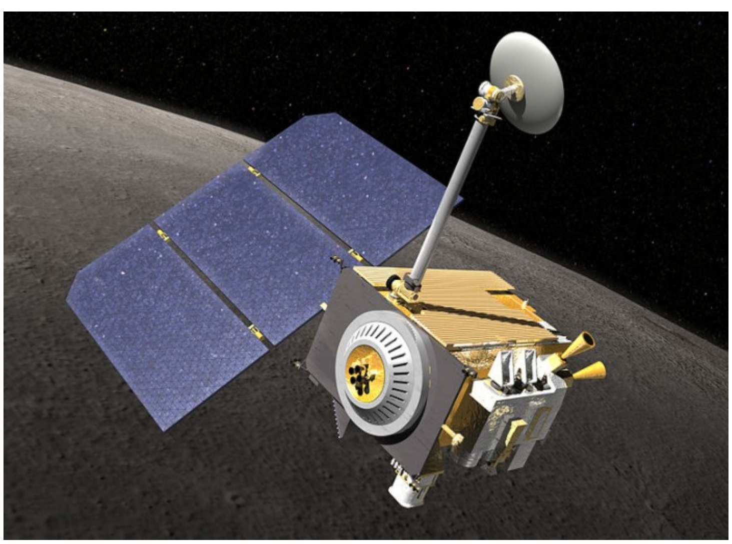
In 1959, USSR's *First Lunar Rover*, was the first spacecraft to reach the vicinity of Earth's Moon. A malfunction in the ground-based control system caused an error in the upper stage rocket's burn time, and the spacecraft missed the Moon by 5900 km (more than three times the Moon's radius). The first direct evidence of water vapor near the Moon was obtained by the Apollo 14's Suprathermal Ion Detector Experiment (SIDE) on March 7, 1971. A series of bursts of water vapor ions were observed by the instrument mass spectrometer at the lunar surface near the Apollo 14 landing site [1]. Evidence of water ice on the Moon came in 1994 from the United States military *Clementine* probe. In an investigation known as the 'bistatic radar experiment', *Clementine* used its transmitter to beam radio waves into the dark regions of the south pole of the Moon, detectable by large dish antennas of the Deep Space Network on Earth [2]. Later, the Lunar Prospector probe, launched in 1998, employed a neutron spectrometer to measure the amount of hydrogen in the lunar regolith near the polar regions [3]. It was able to determine hydrogen abundance and location to within 50 parts per million and to detect enhanced hydrogen concentrations at the lunar north and south poles. The neutron spectrometer data showed an enhancement of hydrogen concentrations at the lunar north and south poles, indicating significant amounts of water ice were trapped in permanently shadowed region (PSR) craters [4]. India's spacecraft Chandrayaan-1 released the Moon Impact Probe (MIP) that impacted Shackleton Crater of the lunar south pole, on 14 November 2008, releasing subsurface debris that was analyzed for presence of water ice [5]. On October 9, 2009, the Centaur upper stage of its Atlas V carrier rocket was directed to impact Cabeus crater, followed shortly by the NASA's Lunar Crater Observation and Sensing Satellite (LCROSS) spacecraft that flew through the ejecta plume which detected a significant amount of hydroxyl group in the material thrown up from a south polar crater. The ultraviolet visible spectrometer detected hydroxyl signatures just after impact that are consistent with a water vapor cloud in sunlight [6]. However, the Sun is always on the horizon at the poles, keeping the floors of deep craters in permanent shadow. These dark areas only receive heat from the interior of the Moon and are extremely cold. Measurements by the DIVINER instrument, an infrared radiometer on the Lunar Reconnaissance Orbiter (LRO) spacecraft indicated temperatures as cold as 25-35° C [7]. Water molecules are trapped by the cold as soon as they find their way into these craters. Over the more than 4.5 billion years of lunar history, significant amounts of water could have accumulated in many of these crater "cold traps" at the Moon's poles.

To understand where/why oceans are present, direct lunar sample analysis of moon rocks obtained during Apollo 11 space mission corroborated the spectral analysis for the presence of lunar water. In all, astronauts collected 22 kilograms of material, including 50 rocks, samples of the fine-grained lunar "soil," and two core tubes that included material from up to 13 centimeters below the Moon's surface. These samples contained no water and provided no evidence for living organisms at any time in the Moon's history [8]. However, only in the last decade have instruments become sensitive enough to analyze water in the thousands of parts per million, at most—which explains why analyses of the samples in the late 1960s and early 1970s concluded that the moon was arid [9].

During the last decade, lunar rovers like Yutu have studied the composition of the Moon's surface looking for ice, water and metals. As part of the Chinese Chang'e 3 mission to the Moon, Yutu reached the Moon's surface on 14 December 2013, marking the first soft landing on the Moon since 1976. The rover's ground penetrating radar found evidence for a minimum of 9 distinct rock layers, indicating complex geological [10]. Detailed characterization of lateral and vertical heterogeneities within the lunar deep interior, showed crystallization of the lunar magma ocean resulting from mantle stratification [11]. Seismology is the best tool for remotely investigating possible "vital signs" in ocean worlds. Detecting 30 fluid-related seismic signatures similar to those on Earth would provide key information for constraining available redox fluxes and locating possible niches for life [12].

II. Lunar Exploration for Water: From Lunar Reconnaissance Orbiter (LRO) to Lunar Polar Hydrogen Mapping Cubesat

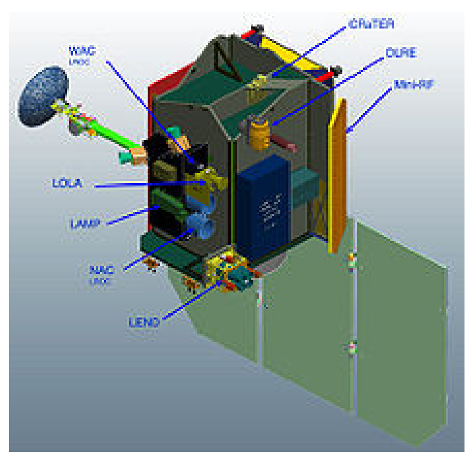
Eventually, the lunar permanently shadowed regions of water ice will expand to a lunar mining operation that extracts and processes water ice into liquid oxygen/liquid hydrogen propellant. The availability of space-sourced propellants dramatically lowers the cost of space transportation beyond low Earth orbit, enabling the development of a robust commercial economy in cislunar space.



The LRO orbiter carries a complement of six instruments and one technology demonstration:

Instrument	Mission Objective	Reference
Cosmic Ray Telescope for the Effects of Radiation (CRaTER)	To characterize the global lunar radiation environment and its biological impacts per 1. Measuring deep space radiation environment; 2. To test models of radiation effects and shielding by verifying/validating model predictions of LET spectra with LRO measurements, using high-quality GCR and SEP spectra.	"Cosmic Ray Telescope for the Effects of Radiation". Boston University.
Diviner Lunar Radiometer Experiment (a nine channel infrared filter radiometer based on the design of the Mars Reconnaissance Orbiter Mars Climate Sounder (MCS).	1.To make the first global radiometric survey of the temperature of the lunar surface; 2.To identify polar cold traps and potential polar ice deposits; and 3. To map variations in silicate mineralogy.	"Diviner Lunar Radiometer Experiment/". UCLA
Lyman-Alpha Mapping Project (LAMP)	To search for water ice into permanently shadowed craters, using ultraviolet light generated by stars as well as the hydrogen atoms that are thinly spread throughout the Solar System	Andrews, Polly "The Lyman-Alpha Mapping Project: Seeing in the Dark". Southwest Research Institute
The Lunar Exploration Neutron Detector	To measure, create maps, and detect possible near-surface water ice deposits. ("Russian neutron detector LEND for NASA Lunar Reconnaissance Orbiter space mission").	Space Research Institute of the Russian Academy of Sciences.
Lunar Orbiter Laser Altimeter	To develop a precise global lunar topographic model and geodetic grid.	
Lunar Reconnaissance Orbiter Camera	To provide measurement requirements of landing site certification and polar illumination. Comprised of a narrow-angle push-broom imaging cameras(NAC) and a single wide-angle camera (WAC).	
Miniature Radio Frequency	Radar demonstrated new lightweight SAR and communications technologies and located potential water-ice	Yan, ed. (June 19, 2009). "Backgrounder: Introduction to LRO's instruments". *Xinhua*

LRO, launched in conjunction with LCROSS on June 18, 2009, is a NASA robotic spacecraft orbiting the Moon made a 3-D map of the Moon's surface at 100-meter resolution and 98.2% coverage, excluding polar areas in deep shadow (Robinson, M. (November18, 2011) NASA Probe Beams Home Best Moon Map Ever. *Space.com*) but including 0.5-meter resolution images of Apollo landing sites (Hautaluoma, Grey; Freeberg, Andy (July 17, 2009). LRO Sees Apollo Landing Sites. www.nasa.gov).



The instruments on board the LRO spacecraft return global data, such as day-night temperature maps, a global geodetic grid, high resolution color imaging and the moon's UV albedo. However, there has been particular emphasis on the polar regions of the moon where continuous access to solar illumination may be possible and the prospect of water in the permanently shadowed regions at the poles may exist. LRO initial data sets were deposited in the Planetary Data System (PDS), a publicly accessible repository of planetary science information, within six months of primary mission completion, and thereafter, the data sets have been deposited in the PDS every three months [13].

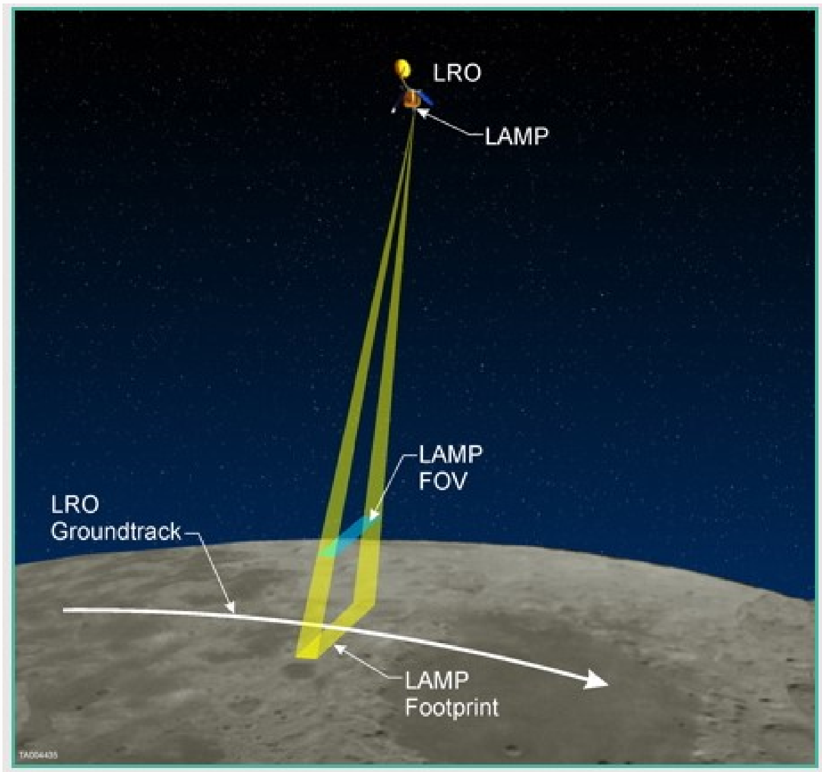


Figure. The orbiting Lunar Reconaissance Orbiter, LAMP points straight down at the Moon's surface (at "the nadir," as scientists put it), scanning a little bit at a time. As LRO progresses in its orbit, LAMP's map, assembled from these scans, becomes more and more complete. The permanently shadowed regions of the Moon don't ever see sunlight or earthshine, whose reflection off the Moon is what has allowed past "cameras" aimed at the lunar surface to take pictures and make maps.

LRO observations characterized lunar water which to date has provided most understanding of lunar polar volatile abundance, distribution, composition, and physical form is derived from remotely sensed observations of the Moon.

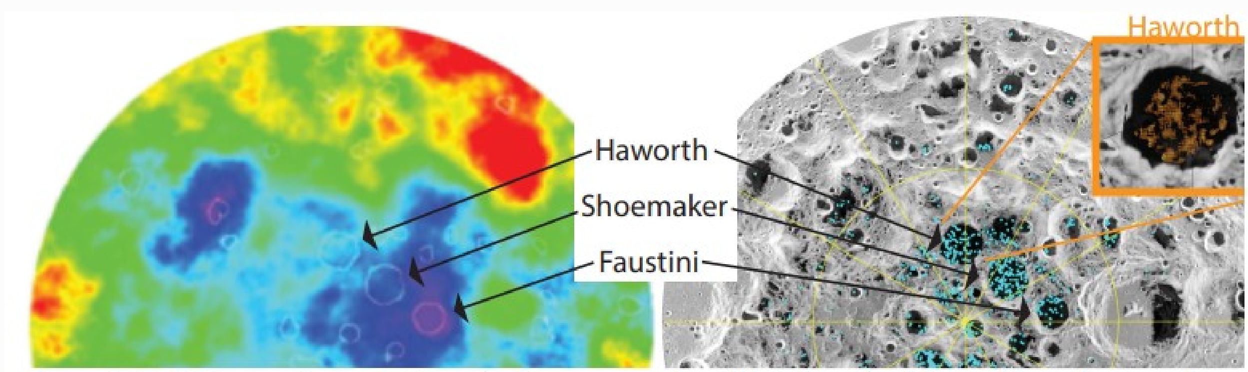


Figure. (Left) Water equivalent hydrogen in the top meter of regolith is determined from epithermal neutron flux by LEND on LRO [1] in the three large south polar PSRs: Haworth (51.4 km diameter, for scale); Shoemaker; and

Faustini with blue colors corresponding to more H. (Right) Locations of water exposures on the surface determined from LAMP, LOLA, and M3 are shown in cyan [14].The gray-scale background image indicates annual maximum temperature [15].

LAMP data indicated surface frost within Haworth crater. However, the spatial resolutions of these observations were substantially coarser than the likely scale over which lunar volatiles, deposited in the top layers of the Moon's surface by the solar wind over geologic time, varied laterally and with depth. Lacking is the fundamental knowledge regarding the age of volatiles and the processes that modulated the abundance, distribution, and retention of water at the surface [16].

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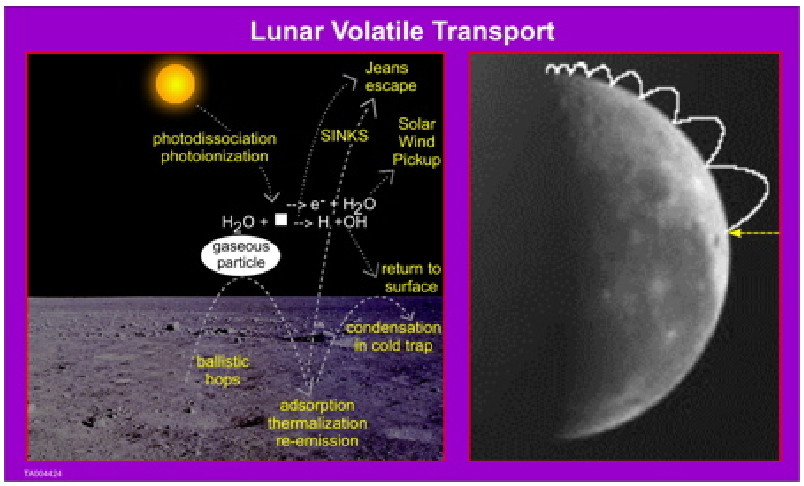


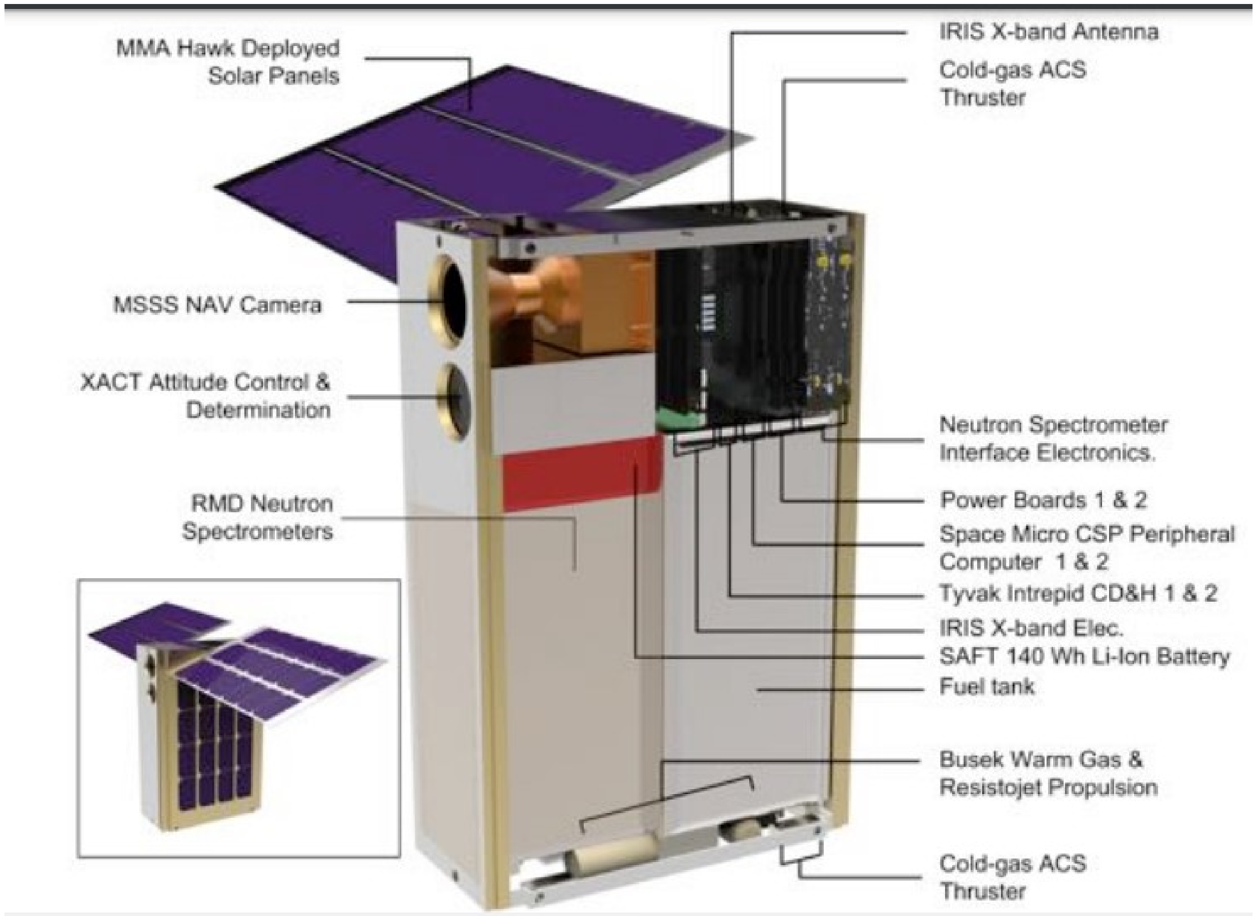
LRO exploration and science results included:

1. In polar shadowed regions found the coldest spots measured (below 30 K) in the solar system
2. Discovered significant subsurface hydrogen deposits in regions cold enough for water ice to survive, as well as in additional hydrogen deposits in warmer areas where surface water ice is not thermally stable
3. Measured surprising amounts of several volatiles (e.g.,CO_2, H_2, and Hg) in the gaseous cloud released from Cabeus by the LCROSS impact
4. New (<5 years old) impact craters and are found to be widespread across the lunar surface, with a surprising abundance of related surface changes
5. Developed an improved catalogue of lunar craters larger than 20 km in diameter, thus providing constraints on the ancient impactor population that affected the inner solar system
6. First radar measurements of the lunar farside
7. Improved the age dating of small landforms by using crater counts from the new high-resolution images
8. Discovered that the Moon is in a general state of relatively recent (<1 Ga) contraction
9. Characterized relatively young volcanic complexes, such as Ina, and revealed first direct evidence of the presence of highly silicic volcanic rocks on the Moon
10. Measured galactic cosmic ray interactions with the Moon during a period with the largest cosmic ray intensities observed during the space age
11. Mapped in detail the temperatures, UV reflectance, and near-surface hydrogen abundance of the moon's polar cold traps
12. Created the first cosmic ray albedo proton map of the Moon
13. Made high-resolution images of robotic and human exploration sites that showed hardware, the tracks of the astronauts, and surface disturbances from landing and ascent

NASA established the Lunar Discovery and Exploration Program (LDEP) in the Science Mission Directorate to establish commercial contracts for lunar landing transportation services; the development of lunar science instruments; the development of lunar smallsats; continued operations of the Lunar Reconnaissance Orbiter; and the development of long-duration lunar rovers that will utilize commercially developed landers to get to the lunar surface. Lunar Polar Hydrogen Mapper, or LunaH-Map, is one of 13 cubesats planned to be launched with Artemis 1. Along with Lunar IceCube and Lunar Flashlight, LunaH-Map will help investigate the possible presence of water-ice on the Moon. LunaH-Map will use a solid iodine ion propulsion system, X-Band radio communications through the NASA Deep Space Network, star tracker, C&DH and EPS systems from Blue Canyon Technologies, solar arrays from MMA Designs, LLC, mission design and navigation by KinetX. Spacecraft systems design, integration, qualification, test and mission operations are performed by Arizona State University [16].

Figure. LunaH-Map is a 6U CubeSat that will enter a polar orbit around the Moon with a low altitude (5-12km) perilune centered on the lunar South Pole. LunaH-Map carries two neutron spectrometers that will produce maps of near-surface hydrogen (H). LunaH-Map will map H within permanently shadowed craters to determine its spatial distribution, map H distributions with depth (< 1 meter), and map the distribution of H in other permanently shadowed regions (PSRs) throughout the South Pole.

The Lunar Polar Hydrogen Mapper Mission (LunaH-Map) will be launched on Artemis 1 in November, 2021 and spend two months mapping the abundance of hydrogen, inferring water- ice, in the lunar South Pole's deep craters. Once separated in the lunar vicinity, the Luna-H Map cubesat will use ion propulsion to conduct its own lunar flyby, then wait to be gravitationally captured into lunar orbit. The cubesat will then spiral into a very elliptical polar orbit which will take it as low as 10- to 25-km above the lunar South Pole and some 4,000-km above the lunar North Pole. And it will do so at a tiny fraction of the cost of a conventional NASA planetary science mission. Once deployed, its solar arrays unfold, the spacecraft powers on, finds the Sun, starts charging the batteries, and begins communications with Deep Space Network [17]. The cubesat spacecraft is equipped with a star tracker, an x-band radio, a command and data handling system, power control system, ion propulsion system and its primary science instrument, and a miniaturized neutron spectrometer that measures high-energy galactic cosmic ray interactions with hydrogen embedded in the lunar surface. Energy distribution of neutrons emitted from the lunar surface collisions is a good proxy for the amount of hydrogen and water ice within the top meter of the lunar surface. Detection of more high-energy neutrons indicates less water ice; while fewer high-energy neutrons indicate more water ice. The goal is to create a detailed map of the hydrogen abundance within and around these permanently shadowed regions [18]..



Previous lunar spacecraft have used neutron detectors, near-infrared spectrometers and impactors to reveal the presence of hydrogen (H) throughout the lunar surface. At the lunar poles, hydrogen abundances commonly exceed 150 ppm, and abundances could be as high as 20-40 wt.% water equivalent-hydrogen within certain permanently shadowed regions (PSRs). LunaH-Map will produce the highest spatial resolution maps of hydrogen abundance ever acquired by a neutron detector from orbit, and will demonstrate the capability of a CubeSat platform to acquire neutron spectra. This will be achieved by orbiting with a low perilune (5km altitude) above the South Pole of the Moon, centered at -89.9°S (Shackleton Crater). The implications for this measurement are significant, as it directly informs our understanding of how lunar volatile abundances are distributed within various lunar South Pole craters and regions [19].

Throughout the course of the 60-day science mission, LunaH-Map will acquire thermal and epithermal neutron counts over a total of 141 science orbits. Neutron count rates will be used to determine H abundances and distributions within Shackleton Crater on each orbit (60ppm ± 12ppm H), and can additionally be used to map H distributions within several nearby PSRs (Haworth, Shoemaker, Faustini, Shackleton, de Gerlache, Nobile, Amundsen and Sverdrup). LunaH-Map will be capable of mapping entire PSRs with an average precision of 85 ppm ± 17ppm H, and for spatial resolutions smaller than the crater diameter at an average precision of 180ppm ± 36ppm H. LunaH-Map will utilize an innovative new scintillator technology called an elpasolite, specifically $Cs_2YLiCl_6:Ce$ (CLYC), with high neutron detection efficiency across a wide energy range [20]. These detectors are easily accommodated within a CubeSat due to their small form factor, as each instrument occupies just 1U of the 6U spacecraft.

Seismology: Lunar rover verification of mapped PSRs

Seismology is the best tool for remotely investigating possible "vital signs", ground motions due to active fluid flow, in ocean worlds, yet only a handful of possible seismic sources have been considered to date. Detecting fluid-related seismic signatures similar to those on Earth would provide additional key information for constraining transport rates through the ice, and associated redox fluxes, and locating possible liquid reservoirs that may serve as habitats [21].

Lunar Geophysical Network (LGN) mission.

This lander mission concept utilizes the Advanced Stirling Radioisotope Generator (ASRG), enabling a small, reduced mass lander configuration with adequate power for the cruise and landing phases of mission operation on the lunar surface. Proposed to land on the Moon in 2030, it will deploy packages at four locations to enable geophysical measurements for 6-10 years. LGN will greatly expand Apollo-based knowledge of the deep lunar interior by identifying and characterizing mantle melt layers. To meet the mission objectives, the instrument suite provides complementary seismic, geodetic, heat flow, and electromagnetic observations [22]. A long-lived next-generation network of surface geophysical stations, the Lunar Geophysical Network (LGN), will provide simultaneous multipoint geophysical observations across four complementary disciplines: seismology, geodesy, heat flow, and electromagnetics from around the Moon. Together these observations will unlock key outstanding issues regarding the lunar interior including the existence of, size, and state of the inner core; the presence of a deep mantle partial melt layer; mantle thermal state; and composition including lateral and vertical heterogeneity. In addition to LGN, Commercial Lunar Payload Services (CLPS) missions will provide a human presence at the lunar surface [23]. Terrestrial planets all share a common structural framework (e.g., crust, mantle, core) which is developed very shortly after formation and that determines subsequent evolution [24]. The Moon is a natural target for this type of geophysical network mission as it presents an opportunity to study an internal heat engine that waned early in planetary evolution, and thereby enabled preservation of the initial magma ocean differentiation event. Such information has been lost on Earth due to crustal recycling and weathering of our most ancient rocks, and also on Mars and Venus due to their larger sizes and heat engines, producing prolonged volcanic activity and resurfacing that is thought to have continued to the present day [25].

First look into the Moon’s interior came from the Apollo Lunar Surface Experiment Packages (ALSEP) that deployed surface magnetometers, placed laser retroreflector arrays, installed seismometers that detected moonquakes and meteorite impacts and took heat flow measurements. Due in part to the relatively narrow geographical extent of the Apollo passive seismic network, understanding of the lunar interior, and especially the deep interior and core, remains incomplete. The LGN stations are situated to vastly improve our knowledge about the lunar deep mantle and core [26].

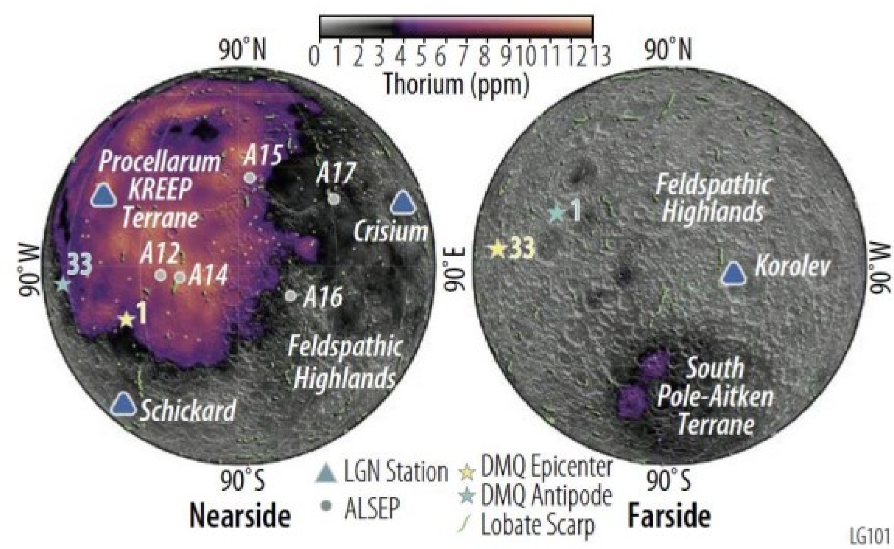
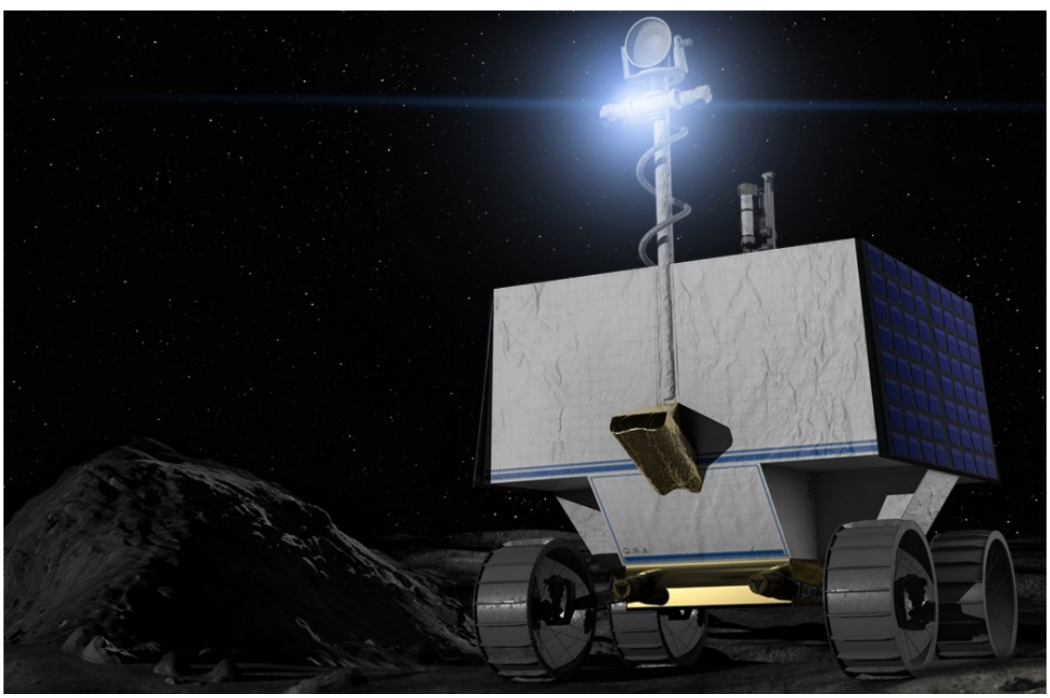


Figure . Lunar Geophysical Network station locations (blue triangles) compared to Apollo (grey circles). LGN stations will be placed across major lunar terranes and enable new interrogation of the deep lunar interior and tectonic evolution. The proposed LGN stations are positioned to take advantage of 1) possible recent lobate scarp seismicity (green lines, Watters et al., 2019) and 2) known deep moonquake (DMQ) clusters and their antipodes (yellow and cyan stars, respectively). The two most active nearside and farside deep moonquake clusters (A01 and A33) are highlighted. DMQ cluster epicenters.

The Lunar Geophysical Network mission involves the emplacement of four geophysical nodes at geographically diverse locations on the lunar surface, each with a suite of science instruments that probes the Moon's [27]. Each node should contain a minimum of a seismometer, heat flow probe, and electromagnetic sounding instrumentation as standard, plus a laser retroreflector for nearside node. The LGN seismometer will require 4+ sensors that have frequency range 0.1 to >10 Hz [28]. Subsurface temperature measurements is repeated frequently to monitor possible fluctuation of the regolith temperature distribution. A dense magnetometer network enables electromagnetic sounding (EMS) by gradiometry (geomagnetic depth sounding).The variations of pole direction, physical librations, and solid-body tidal distortions provide information about the Moon. Expansion of the network with the next generation of retroreflectors will constrain tidal librations [29]. It is critical that the LGN be established prior to extended human lunar activity because the exact locations or causes of the shallow moonquakes are not known.

1. Volatiles Investigating Polar Exploration Rover (VIPER) mission

Although orbital observations from small satellites indicated distribution of water on the sunlit and shadowed surfaces of the Moon, NASA's Commercial Lunar Payload Service promised ground verification from lunar rover experiments. The VIPER mission scheduled in November 2023 will provide in-situ investigation of multiple volatile trapping environments and about the abundance and distribution of volatiles in lunar polar regions [30]. The mission will provide the first surface-level mapping of ice and other resources on the lunar surface to further NASA's goal of establishing a sustainable human presence on the Moon under the Artemis program. The *VIPER* rover will operate at a South Pole region and rove several kilometers, collecting data on different kinds of soil environments affected by light and temperature — those in complete darkness, occasional light and in constant sunlight. Once entering a permanently shadowed location, it will operate on battery power alone until the next solar recharge. Total operation time will be 100 Earth days [31].The *VIPER* rover, equipped with a drill and three analyzers, has a Neutron Spectrometer System (NSS) that detects sub-surface water from a distance. *VIPER* will then stop and deploy a 1 m (3 ft 3 in) drill called TRIDENT to obtain samples to be analyzed by its two onboard spectrometers.



VIPER Instrument Name	**Abbr.**	**Provider**	**Function** (Tabor, A. (November, 2020). Where's the Water? Two Resource-Hunting Tools for the Moon's Surface. www.nasa.gov)
Neutron Spectrometer System	NSS	Ames, NASA	Detect sub-surface hydrogen (potentially water) from a distance, suggesting prime sites for drilling. It measures the energy released by hydrogen atoms when struck by neutrons.
The Regolith and Ice Drill for Exploring New Terrain	TRIDENT	Honeybee Robotics	1-m drill will obtain subsurface samples.
Near InfraRed Volatiles Spectrometer System	NIRVSS	Ames, NASA	Analyze mineral and volatile composition; determine if the hydrogen it encounters belong to water molecules (H_2O) or to hydroxyl (OH^-). Sub-systems: Spectrometer Context Imager (a broad-spectrum camera); Longwave Calibration Sensor (measures surface temperature at very small scales).
Mass Spectrometer Observing Lunar Operations	MSolo	Kennedy, NASA	Analyze mineral and volatile composition. Measures the mass-to-charge ratio of ions to elucidate the chemical elements contained in the sample

2. **Landers and Rovers for Lunar In-Situ Resource Utilization**
Since 2005 when NASA created the ISRU Project in Exploration Technology and Development Program (ETDP), the state of the art of lunar ISRU technologies, systems, and capabilities has significantly progressed. The benefit of incorporating ISRU into mission plans is directly related to the extent to which it is used and when it is used. Without ISRU, exploration missions must bring everything needed to sustain astronauts from the surface of the Earth. Because human exploration missions require significant amounts of oxygen, water, and fuel, incorporation of ISRU into missions has primarily focused on extracting or producing these mission critical consumables. The ISRU Project raised the technology readiness level (TRL) of lunar ISRU technologies and capabilities from a low of 1-2 for concept and laboratory feasibility evaluation to a high of 4-5 for integrated system level tests and technology operation under 1/6-g conditions during parabolic flights [32].

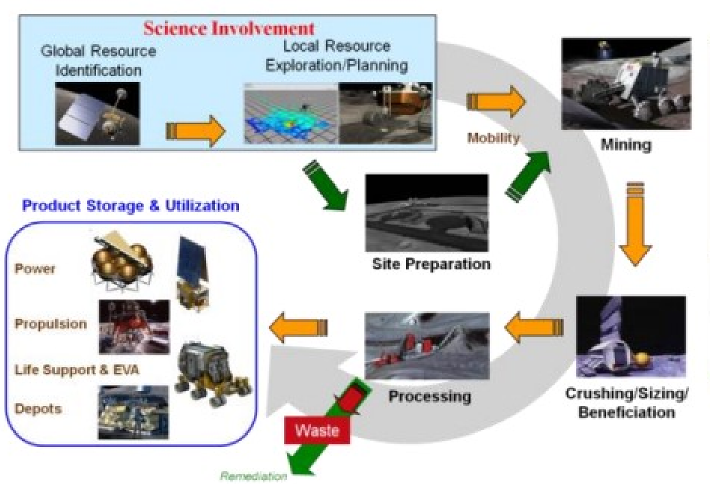


Figure. Space ISRU Mining Cycle

ISRU concepts range from producing consumables for propulsion or life support, to power generation, to mining lunar soil, to building future habitat infrastructures, in a sustainable and circular economy approach advocated by the agencies. Supplying propellants produced on the lunar surface makes the Moon an attractive space-based “refueling station”, reducing launch pad mass (and cost) for any mission beyond lower Earth orbit. ISRU derived commodities (oxidizer, fuel, metals) could be then shipped to a variety of destinations such as Mars. Moreover, recent studies claim that producing lunar propellant on the lunar surface and delivering it to cislunar space could be cost competitive with propellant launched from Earth to cislunar space if current capabilities and performance are improved [33]. Thus, supporting human missions to Mars is another reason to develop and deploy a lunar propellant production capability.

The principles of ISRU are straightforward but many of the potential technologies for resource extraction are still quite immature, with only a few examples of some possible components (e.g. Sabatier reactors, cryocoolers, etc.) having flight heritage. Most soil processing processes are similar to mining on Earth. In contrast, thermochemical or electrochemical conversion processes must be carried out in very different environments from industrial terrestrial installations with strict requirements to recycle and reuse the consumables brought from Earth if possible. Many of these technologies have barely moved out of a laboratory setting and require further systems engineering to make them a viable option for a demonstration mission. This development is required to mature these technologies to a level of reliability comparable with other space technologies [34].

Until new information is gained (e.g. ground based reconnaissance like VIPER) an ISRU lunar water reserve can’t be identified.

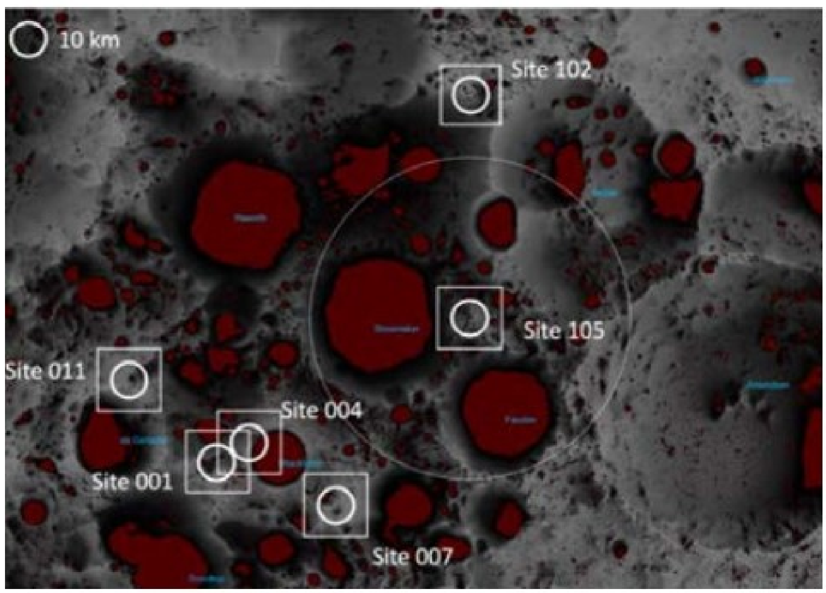


Figure. Potential Human Landing Systems landing sites as defined in the Artemis plan. This study focuses on Sites 001 and 004.

ISRU, proposed for the lunar South Pole to leverage the extended periods of solar illumination and allow for potential access to water ice in the permanently shadowed areas around the poles, is possible for producing both fuel and oxidizer to fully refuel a vehicle. The ISRU system architecture involves two sites: 1. the mine site in a shadowed crater where water ice is excavated and extracted from the regolith; and, 2. the propellant production site at an illuminated ridge to process water into liquefied O_2 and H_2 propellants. Fixed hardware would be emplaced at each site, with two alternating water tankers to transport water between them. Notional lunar sites would be identified for this baseline architecturally-specific environment parameters.

The overall concept of operations (Con-ops) involves three systems, the operations at the mine site (water excavation and extraction), operations at the ridge site (propellant production), and the water transport vehicles (tankers) that runs between them.

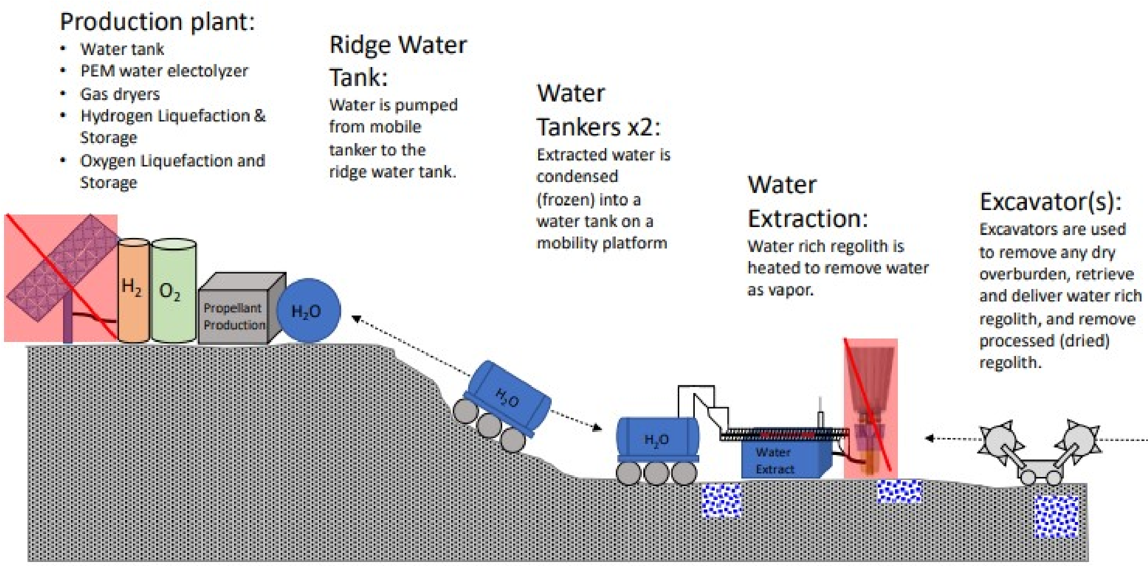


Figure. ISRU architecture. Tentative power systems are shown for completeness, but were not included in the model.

At the mine site, water-ice rich regolith is removed using excavator(s) and delivered to water extractor(s) that are located at a fixed site. A pit-mine approach was baselined for this study, where the surface excavator(s) remove a dry overburden layer to reach resource rich material. Alternative options include mobile water processors and in-situ processors. It should be noted that a mobile processor was traded early using a 12.7 cm diameter, 1 m deep heated core drill [35].

The baseline case in this proposed case study assumed that 10 mT of oxygen, along with enough hydrogen to support a propulsion mixture ratio of 6 must be produced in 225 days. Therefore 15 mT of water would need to be collected and processed. The baseline solution results in a system mass of 5 mT with the majority located at the ridge site (2.6 mT), 1.8 mT to support water transport using two tankers, and 0.5 mT for mine site hardware. The key variables that impact mass are production rate and time between water transports. While reducing the transport time decreases mass, the increased number of trips would increase a not quantified wear and risk. Total required power for the baseline case is 68 kW. Of that, 46 kW is needed at the ridge site, where solar power can be leveraged. The major drivers are the hydrogen liquefaction and electrolysis subsystems at 20 kW each. At the mine site 22 kW is needed with almost all (20 kW) dedicated to the water extractor subsystem. Both mass and power are most strongly impacted by production rate. A longer production time would reduce production rate without decreasing the amount of propellant produced. The water based ISRU system is then traded against a system that would extract only oxygen from the surface regolith. Both systems target the same production requirement over the same time. Even considering the main assumption differences between the two models, and accounting for the mass of terrestrial hydrogen that would be needed for the oxygen from regolith case, the oxygen case clearly traded better in terms of both mass and power. The use of direct solar thermal energy to process the regolith and the ease of access of the resource resulted in significantly lower values for the oxygen from regolith case: 2.7 mT and 11.8 kW. However, the mass trade, in particular, would favor the water case over successive missions where the hydrogen up-mass of over 2 mT per mission accrues against the oxygen system [36].

III. Development of Lunar In-situ Resource Utilization: Future Lunar Production of Fuel

Notional architecture of future lunar space operations will include a mix of technologies such as cryopropellant management, reusable lunar landers, propellant tankers, orbital transfer vehicles, aerobraking technologies, and electric propulsion. To minimize operational cost, the infrastructure is entirely telerobotic. Resource-intensive human flight operations are deferred until the infrastructure is operational and capable of supporting human missions.

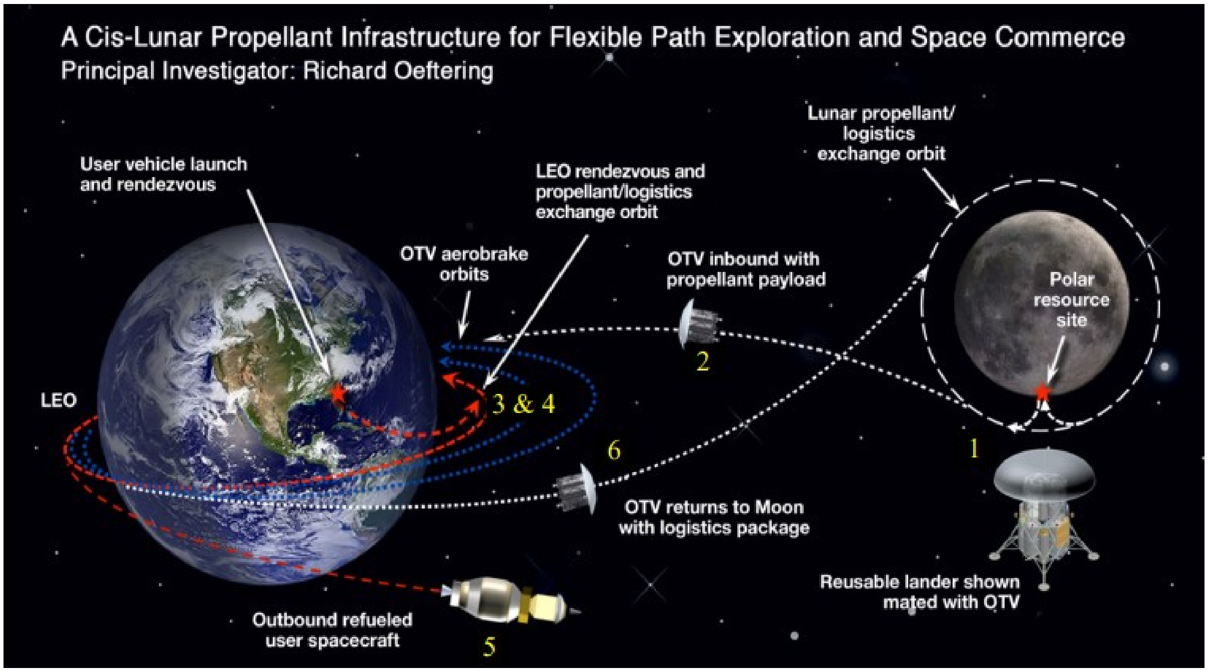


Figure .—Cis-lunar propellant infrastructure concept: (1) A reusable lunar lander launches a propellant payload into lunar orbit. (2) An orbital transfer vehicle (OTV) with aerobraking capability transfers to low Earth orbit (LEO). (3) A user spacecraft and OTV meet in LEO. (4) The OTV transfers propellants and picks up a logistics package (Log-Pak) (i.e., it exchanges propellants for logistics). (5) The refueled user spacecraft proceeds to its destination or is transferred to its destination by the OTV directly. (6) The OTV returns to the Moon with the Log-Pak. The exchange allows the cis-lunar propellant infrastructure to operate without dedicated logistics launches.

Lunar propellants serve as a commodity for trade. The availability of propulsion and propellant services extends the useful life of revenue generating spacecraft. Reusable, refuelable, and refurbishable spacecraft stimulates spacecraft servicing. The ability to refuel spacecraft provides continued revenue while the ability to refuel spent stages can launch a market for secondary applications for hardware that would otherwise be discarded. Some of these secondary applications include supporting the cis-lunar infrastructure as propellant storage elements for depots, and as assets like tugs and tankers [37]. NASA, other governments' space agencies, and some commercial entities are pursuing a long-term goal to develop process systems to produce liquefied H_2 and O_2 propellants from available lunar ice deposits. H_2 /O_2 propellant made from ice in lunar permanently-shadowed regions (PSRs) will enable missions in cislunar space and secondary cislunar launches to further destinations. System balance-of-plant optimization to minimize mass, energy requirements, and life cycle costs can facilitate designs for reliable long-term operation in the extreme environments of PSRs [38]. Producing propellant at the location of demand has been shown to enable self-sufficiency and reduce the need for propellant to be pushed through the 15+ km/s of ΔV required to reach the lunar surface from Earth [39].

Propellant produced from extracted lunar water remains the main objective. It was asserted that a refueling station would enable the use of the low lunar escape velocity to facilitate further interplanetary exploration. Although the cost of developing the technologies needed to extract space resources was seen as being as costly, as supply from Earth, the ability to produce in-situ propellant was considered a game changer for the economic viability of longer term space exploration [40]. No minimum viable product for in-situ propellant production exists for a location such as the Moon. This is primarily due to the lack of storability for typical in-situ derived propellants such as hydrolox, the cryogenic bipropellant of liquid oxygen and hydrogen. Other cryogenic fuels that have additional elements, such as methane, are difficult to create in-situ due to resource limitations. Most storable alternatives to cryogenic propellant are toxic and also require hard-to-find elements in-situ.

The ISRU plant is modularized with each module deployed separately. Each module includes both the processing plant and the supporting bus subsystems so that it can be operated independently. Later stages are deployed using propellant generated by the earlier deployed ISRU plant stages. The following stages utilize the propellant from the ISRU plant by meeting the tanker from the Moon on its way (e.g., in lunar orbit, Lagrange points, or Earth orbit) [41].

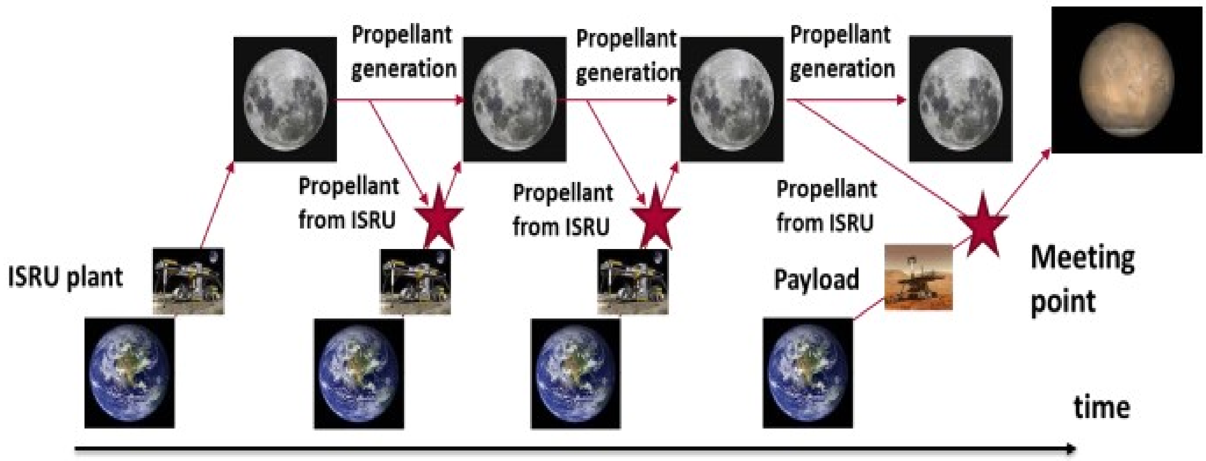


Figure. Example of Bootstrapping ISRU Deployment Method

Case 1.
Hydrazine thrusters have heritage on larger missions but have not been demonstrated on CubeSat missions. They are capable of comparatively high thrust, but the toxicity of the propellant makes them difficult to work with in a research setting and requires more mass to ensure safe handling and operation. Alternative, sometimes called "green," propulsion, is an alternative to hydrazine. Ammonium DiNitramide (ADN) and Hydroxyl Ammonium Nitrate (HAN) are the two main "alternatives." Both alternatives have a greater fuel density, higher Isp, and are less toxic, making them superior all around. The NanoAvionics Enabling Propulsion for Small Satellites system (EPSS) is a CubeSat ADN thruster that was tested to TRL 7 on a 3U CubeSat in 2017 [NanoAvionics].With the exception of cold gas thrusters, this was considered the first ever test of chemical propulsion on a CubeSat. The Hydros system from Tethers Unlimited is also considered and alternative propellant with water as fuel. It has a 4U volume, but it also has a total impulse of more than 2000 Ns and a completely safe fuel [Tethers Unlimited "Hydros" Tethers Unlimited. Retrieved from www.tethers.com/wpcontent/uploads/2019/09/2019-HYDROS.pdf].

High-test peroxide (HTP) has been identified as a propellant that shows promise for interplanetary and small-body exploration [42]. Hydrogen peroxide is nontoxic and requires only hydrogen and oxygen to produce, both of which can be collected from lunar ice. Unlike hydrolox, the cryogenic bipropellant of hydrogen and oxygen is easy to store. The specific impulse for 98% HTP monopropellant is approximately 192 s, and HTP is a high density-specific impulse fuel at 17140 lbf-s/ft3 [43]. For comparison hydrazine, which cannot be made from lunar resources, has a slightly higher specific impulse of 245 s, but a lower density-specific impulse of 15295 lbf-s/ft3 [44]. Because HTP is storable and can be manufactured from commonly available hydrogen and oxygen, HTP is one of the best candidate propellants for in-situ production on the Moon in the near future. In an Orbit Fab trade study, a comparative analysis shows advantages in a lunar HTP production capability.

A more compact alternative to the anthraquinone method is a proton-exchange membrane (PEM) fuel cell. The reactions occurring within a hydrogen peroxide PEM cell are as follows in Equations 1–3.

Anode hydrogen oxidation reaction:

$$H_2 \rightarrow 2H^+ + 2e^- \quad (1)$$

Cathode oxygen reduction reaction:

$$O_2 + H_2O + 2e^- \rightarrow H_2O^- + OH^- \quad (2)$$

Overall PEM cell reaction:

$$HO_2^- + H^+ \rightarrow H_2O_2 \qquad (3)$$

In order to facilitate ion exchange, most PEM cells require the water passing through to be conductive, which may be accomplished by the addition of an electrolyte. The electrolyte must be added to incoming water and removed from the peroxide product. Due to the added complexity, such a process is not ideal for in-situ peroxide production [45].

Table 1: In-situ propulsion system trade study shows the advantages of HTP monopropellant

Characteristic	Solar Electric	Direct Solar Thermal	Chemical	Water Solar Thermal	Cryo ISRU	Biprop HTP/ Hydrocarbon ISRU	Monoprop HTP ISRU
Complexity	low	med	low	med-high	high	med- high	low-med
Ascent Thrust	no	no	yes	no	yes	yes	yes
Solar Array / Collecting Area	high	high	low	high	high	medium	medium
ISRU	no	yes	no	yes	yes	yes	yes
Storable	yes	yes	yes	yes	no	yes	yes

Orbit Fab has undertaken a propulsion system trade study. One nontoxic, storable monopropellant stands out for near-term in-situ resource utilization (ISRU): high-test peroxide (HTP), which can be made directly from water. HTP catalytically decomposes into oxygen and water vapor and can provide high-density specific impulse to power a lunar or small body ascent vehicle. However, the Wang Group at Rice University has developed a solid electrolyte PEM cell that does not require an electrolyte to be added to the input water, instead using a stationary solid electrolyte matrix for ion conduction [46]. The PEM cell and concentrator are integrated into a system to include water and HTP tanks, a water purifier, and an electrolyzer which provides the hydrogen and oxygen gas to the PEM cell. Excess hydrogen is created, which may be vented or stored for use elsewhere. This self contained system requires only water and energy as inputs, and produces HTP on demand. This HTP production system is currently at TRL 3, and could be raised to TRL 6 in a one-year development program.

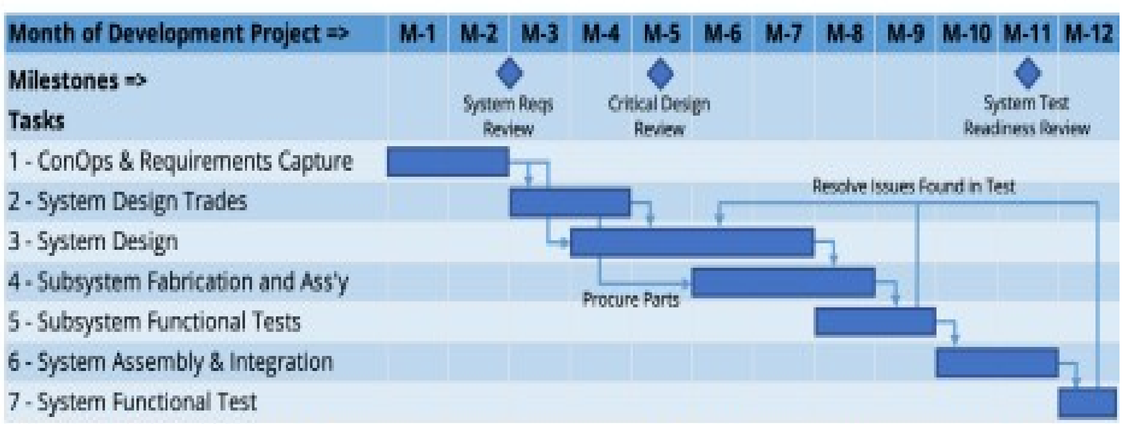


Figure 3: Milestone schedule from requirements capture to TRL 6 HTP production system MVP in a 12-month development period

The cell can produce 130 L of 1% peroxide per hour per square meter of membrane, meaning that only a 0.69 m^2 is needed to produce 1 L/hr of 90% HTP. HTP is a promising propellant for in situ production for upcoming lunar missions due to its storability, low toxicity, and ability to be produced from the readily available elements hydrogen and oxygen. However, no system yet exists to produce HTP from the water harvested on the Moon or an asteroid.

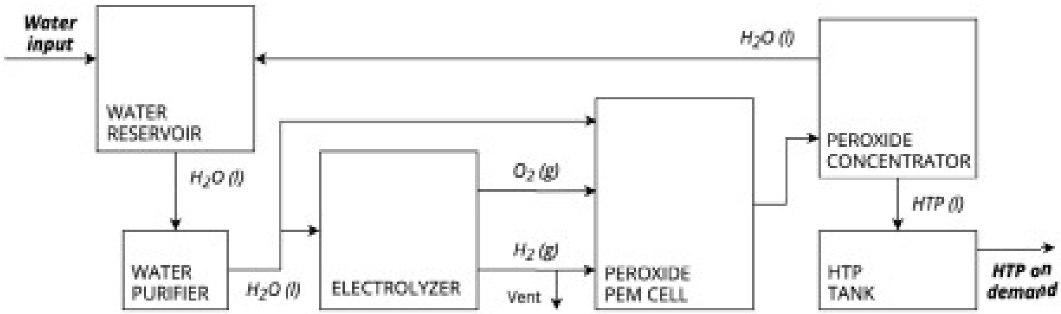


Figure 1: Notional block diagram highlighting major subsystems of water-to-HTP system

Case 2.

Resistojets have been demonstrated successfully for satellite attitude control and are the most common technology on the commercial market of water-based thrusters. Other electrothermal systems, especially microwave electrothermal thrusters are also promising, With considerable interest in electrolysis-based systems and various hybridized architectures, water's versatility lends itself to broad operational capabilities, and is likely to drive the in-situ resource utilization technology development. A performance comparison shows that water-fueled systems compare favorably with their traditional counterparts [47]. Xenon Microwave Electrothermal Thruster (XMET) uses a free-floating plasma discharge in a cylindrical resonant cavity operating at 2.45 GHz. The fundamental operating principle of METs is the use of microwave (MW) energy to create a free floating plasma discharge in a cylindrical cavity resonator, which efficiently heats gaseous propellants that are subsequently expanded through a conventional gas dynamic nozzle [48].

The MET uses an electrodeless, vortex-stabilized microwave discharge to superheat gas for propulsion. In its simplest design, the MET uses a directly driven resonant cavity empty of anything except gaseous propellant and the microwave fields that heat it. It is a robust, simple, inexpensive thruster with high efficiency, and has been scaled successfully to operate at 100 W, 1 kW, and 50 kW using 7.5, 2.45 and 0.915 GHz microwaves respectively. The 50 kW, 0.915 GHz test was perhaps the highest power demonstration of any steady state electric thruster. The MET can use a variety of gases for fuel but the use of water vapor has been shown to give superior performance, with a measured specific impulse (Isp) of greater than 800 s. When this is added to the safety, ease of storage and transfer, and wide availability of water in space, the potential exists for using a water-fueled MET as the core propulsion system for refuelable space platforms. Silicon Valley startup Momentus' is reporting success in on-orbit testing of water plasma propulsion and other key elements of its Vigoride in-space transportation vehicle.

Water is found on the poles of the Moon, Mercury, and Mars, and is abundant in the outer solar system. Water is easy to transfer between spacecraft and to store and accumulate in space. Water is also an element of all human spaceflight, where it is byproduct of fuel cell operation, a source of oxygen, and essential for human life and health functions. This means that a water handling infrastructure exists on all human flight missions in space and can thus be expanded to accommodate propellant water. All of this mean that the MET, using water as a propellant, has enormous potential for human spaceflight missions, most principally those to the Moon and Mars [49].

Momentus launched an experimental cubesat, called El Camino Real, in July 2019, that validated water plasma propulsion technology, now technologically mature enough to be baselined for operational in-space transportation mission [50].

IV. Conclusion

Lunar flybys observed potential sites of water-ice predominantly in south polar regions of the Moon. Validation of the lunar presence for water was provided from analysis of the plume ejecta resulting impactor events and from technology recently available for Apollo moon rock samples. Lunar Reconnaissance Orbiter provided closer and more accurate observation. Lunar Hydrogen Mapper and the Commercial Lunar Payload Services are planned for the mapping of Hydrogen-indicative signatures for lunar water-ice sites including those of permanently shadowed regions about polar craters. Planned CLPS deliveries include landers, rovers, and other equipment for excavation, mining, and transport. Proven technologies of propellant production from water portend a critical feature of lunar infrastructure of long-term presence for in-situ resource utilization.

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