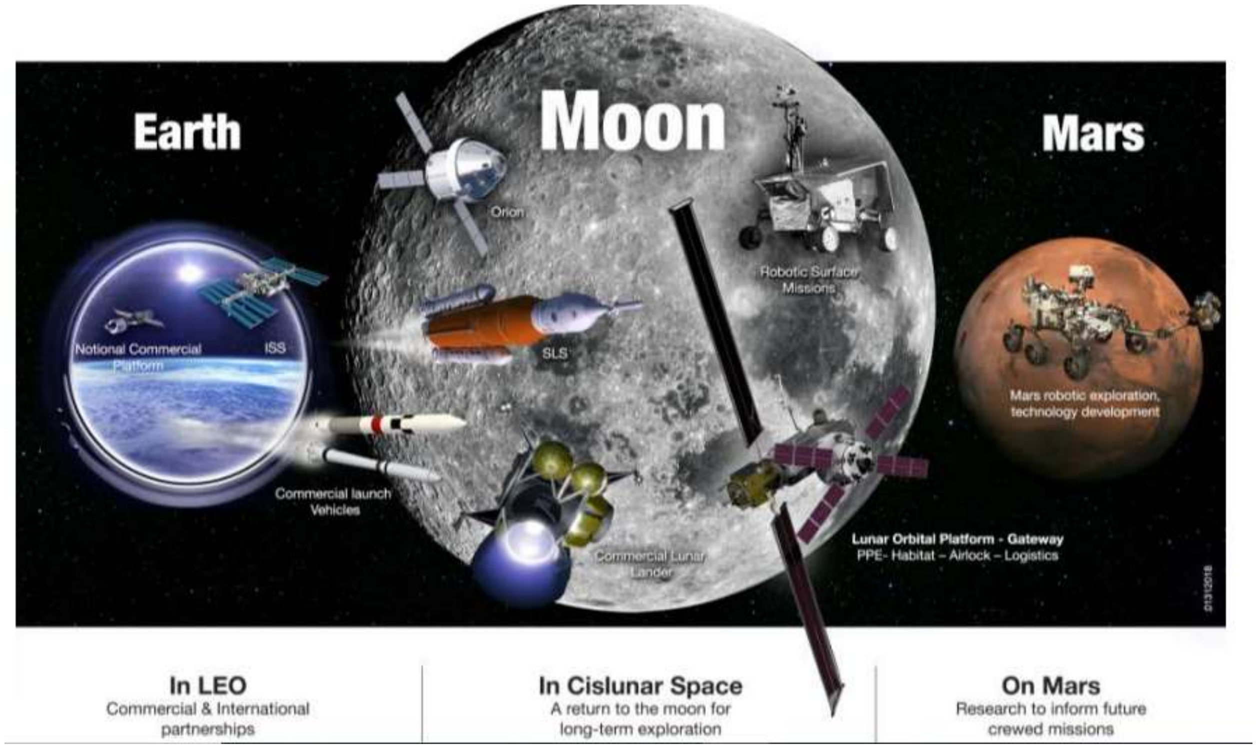


STEM: Teaching Space Science of Extraterrestrial Development and Defense

Ronald H. Freeman, PhD
Editor-in-Chief, Journal of Space Operations & Communicator

Abstract. The 2013 Next Generation Science Standards required core science curricula to include for all K-12 grades, the subject area space science. Students learning space science contributes to a science literacy that will correlate in real time to the evolving human-crewed exploration and human-robotic extraterrestrial space development. In contrast to learning space science ideas first, students will discover relevancy in a context learning approach of space. World-wide use of space systems is broken down into three user communities: Military, Civil, and Commercial. This paper describes the operations of each user community's mission in which space science ideas are embedded. The paper further outlines the needed activities (and progress) for developing notional architectures user communities will extend to the lunar surface and Mars planet in-situ resource utilization and communications.
Keywords: Space Science, Context-based Teaching, Lunar in-situ resource utilization, Space Situational Awareness.

INTRODUCTION

Context-based approaches in science teaching employ contexts and applications of science as the starting point for the development of scientific ideas. This contrasts with more traditional approaches that cover scientific ideas first, before looking at applications. Aikenhead (1994) emphasized links between science, technology and society (STS) by first introducing students to a technological artifact, process or expertise as they co-relate technology and society [1]. Both context-based and STS approaches frequently refer to scientific literacy that young people need for intelligent awareness of the world community they are a part. Space science and respective spin-off innovations grow their world future of space science literacy [2].

Space science is a new field of science begun only with the first flights into space in the 1940s and 1950s. As a course, it has not been a classic subject for K-12 education in most schools. There are related fields such as Earth science and astronomy, though neither has been a principal focus in pre-college education in the US for a century [3]. National learning standards recognize the importance of the new knowledge about space, the universe, and the Earth, and acknowledged the excitement and motivation such study creates [4]. The National Research Council, the National Science Teachers Association, the American Association for the Advancement of Science, and Achieve worked together to developed The Next Generation Science Standards (NGSS), establishing national standards for K-12 science education. The 2013 Standards require core science curricula for all K-12 grades, in all schools, in three subject areas: physical sciences, life sciences, and earth and space sciences [5]. Curriculum establishment has been a state and local governmental function. A default national curriculum is effectively established through textbook adoption in the larger states, like California and Texas, where some 30 percent of the textbook market is controlled [6].

The broad range of activities comprising space science allows a view into the activities of scientific research and engineering. Coskie and Davis [7] proposed that students learn the skills of visual literacy to understand complex and abstract information both in and out of science. Teachers are encouraged to teach students the skills on how to use different models in science, as well as discuss how to choose which model to use and the limitations and benefits of each model. All areas of science rely on data to learn about the natural world. Scientists design and conduct experiments, collect data, and then perform analyses to address relevant questions in science. To successfully learn about science, students must understand how empirically visual data relates to scientific facts and theories. Interpretation of visual data is enabled when contextualized in events or activities currently undertaken and reported for national programs. Therefore, showing context in science is important.

Understanding science, whether in the form of visual data or as written analysis is a vital skill for students [8]. The following user studies for space systems and space-industrial base development provide the contemporary context in which space scientists actively operate and/ or build. Their progress is regularly reported in the media wherein the public is informed. Beyond sourcing the media for how science is advanced, students can project vicariously their personal engagement in the visuals and envision a future role for themselves in further development of space science.

Space System User Studies

Generally, world-wide use of space systems is broken down into three user communities: Military, Civil, and Commercial. Each of these communities share common needs, interests, and uses of space systems and services. The commercial space user community is primarily interested in broadcast communications, point-to-point communications, position and navigation services, and imagery. However, the commercial futuristic exploratory space community would be focused on mining natural resources discovered on the moon and on planets. Developing a lunar or planetary economy requires an infrastructure which will rely heavily on In Situ Resource Utilization (ISRU) and the technologies needed for their exploitation. Primary requirements include construction materials to build habitats, storage bins, landing pads, roads and other infrastructure [9]. The civil space community is composed of non-military and non-intelligence government agencies that develop and employ space assets for orbital or planetary utilization. In the U.S., the largest civil organizations engaged in space are NASA and NOAA. NASA is charged with exploring space, doing science missions focusing on the earth and our solar system, and developing technology for use in space. The military space community is composed of the armed forces and the intelligence agencies that use space as a medium from which to gather information or as an environment in which to execute operations. Intelligence users are interested in employing satellites to monitor activities in denied areas. Additionally, military users gather intelligence to support specific military engagements. For space architectures with multiple satellites, the launch segment plays an important role in mission risk reduction and constellation replenishment and maintenance strategies.

The commercial user community includes startups which dominate the smallsats market. When compared to traditional satellites, smallsats typically have shorter development cycles, smaller development teams, and consequently, lower cost, both for the development and for the launch of the satellites. Constellations of hundreds smallsats perform in the aggregate space missions similar to those of traditional satellites. They display expendability, faster refresh, and simultaneous deployment in large numbers. Demand and subsequent investment in on-orbit servicing, assembly, and manufacturing (OSAM) is needed for long-term functions of communications, Earth observation, space exploration, data analytics, etc. [10].

With on-orbit servicing (OOS) support, Defense Advanced Research Projects Agency (DARPA) has pioneered the concept of using robots in space. Active Debris Removal (ADR) technology demonstrated the best way to capture the estimated 40,000 pieces of space debris orbiting Earth. In a public-partnership with Space Infrastructure Services (SIS), sophisticated satellite servicing was commercialized, including that of refueling. Moreover, content connectivity provider SES Networks operated more than 50 geosynchronous satellites and 12 mid-Earth orbit satellites. Governments and commercial interests appear to be pivoting GEO-based capabilities to low earth orbit. In comparison to reduced station-keeping propellant, geostationary orbits afford mission planners a fixed sub-satellite point with the advantage for broader end-to-end mission. For example, mission designs indicate nearly continuous coverage. Still, GEO constellations fail to provide access to the planet's polar regions, a driving requirement for some mission [11].

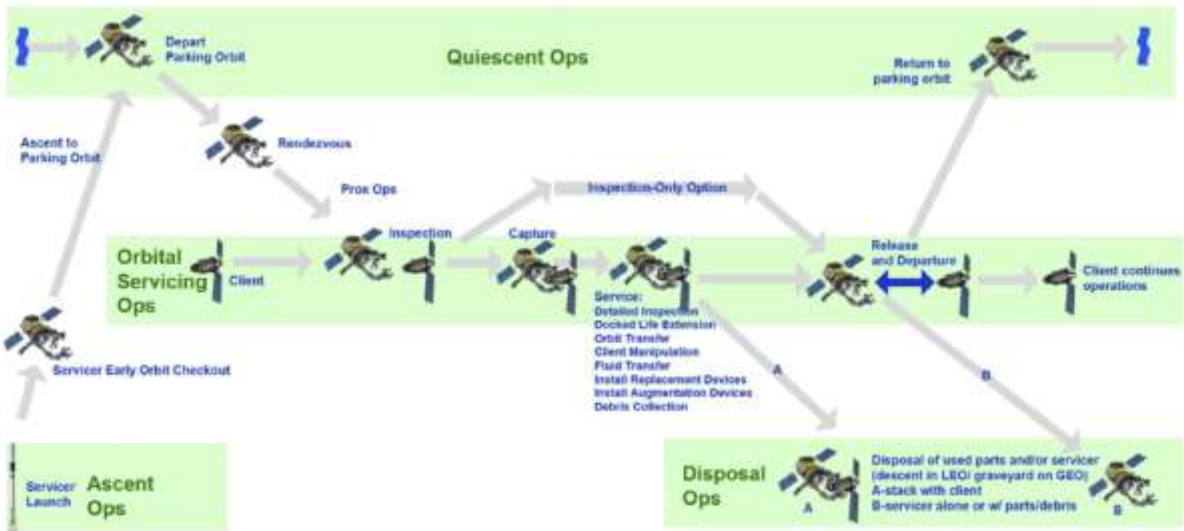


Figure. System Analysis Diagram for On-Orbit Servicing LEO-GEO in-situ resource utilization (ISRU)

NASA's efforts to explore space have also been the driving factor for OOS development. Commercial resupply missions to ISS indicate a consistent need to perform rendezvous and proximity operations (RPO). If these missions are successful, the space industry will likely see a rapid growth of OOS capabilities resulting in reduced operating cost, including servicer use in satellite insurance contracts to mitigate or repair failures in lieu of replacing spacecraft. The Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) is an industry-led initiative with initial seed funding provided by the DARPA to leverage best practices from government and industry to research, develop, and publish non-binding, consensus- derived technical and operational, OOS- and RPO-standards [12].

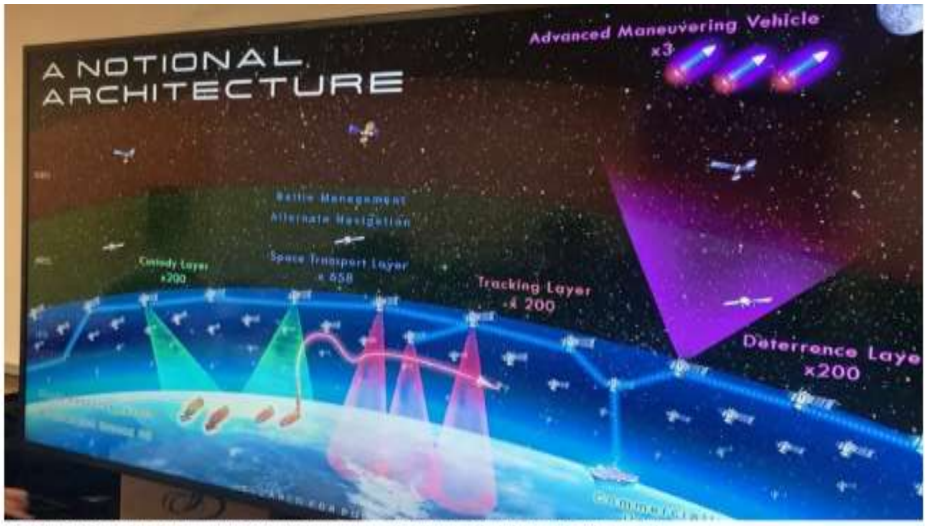
Military User Community: Space Situational Awareness Architecture

Nations are also developing, and in some cases demonstrating , destructive space capabilities. Consequently, space situational awareness (SSA) functions as a defense strategy that relies on integrating space surveillance, collection, and processing data on imminent threats. Since space assets provide combatant commanders (CCDRs) with near-worldwide coverage and access to otherwise denied areas, the advantages using space for operational purposes include freedom of action, overflight, and global perspective and responsiveness. Missile warning mission, uses a mix of space-based and terrestrial sensors. Satellite communications (SATCOM) systems facilitate beyond line of sight connectivity. Terrestrial and space environmental monitoring gives the joint force commander (JFC) awareness of the operational environment (OE). Functions common to joint CCDR operations at all levels of warfare consist of seven basic groups: command and control (C2), intelligence, fires, movement and maneuver, protection, sustainment, and information. SSA assists C2 by characterizing the space environment. SSA also provides insight into an adversary's employment of space systems [13].

The Space Development Agency (SDA)

A limited war strategy is to protect and defend US and Allied interests in space. Secondary objectives include (1) the ability to negate especially critical adversary space systems that place joint and coalition forces at extreme risk during terrestrial operations; (2) the ability to reconstitute or build resiliency into space architecture; and (3) to continue supporting the joint terrestrial force with war-winning, space-based enabling capabilities such as the Global Positioning System, missile warning, and satellite communications [14]. The chief of the Pentagon's Space Development Agency (SDA) Fred Kennedy advocates, "As commercial activities (such as resource extraction) expand outward from Earth to the Moon, there will be a need for the equivalent to a Navy or Air Force to protect that region of space." Specifically, notional space architecture for the future envisions a "deterrence layer" of some 200 satellites based in high LEO or low MEO equipped with optical sensors looking out toward the Moon to provide real-time custody of objects in cislunar space. This sensor layer will provide space traffic management (STM) functions for operators in the region and relay data for Advanced Maneuvering Vehicles (AMVs). The notional architecture envisions the U.S. military with access to and rapid transit between the Earth and the Moon for various national security tasks threat [15]. SDA proposes a future National Defense Space Architecture (NDSA) to feature multiple layers in low Earth orbit (LEO), each with a unique mission and a potentially large number of satellites. While these systems may be required to provide a particular military capability at all times, there will likely be periods when a constellation of certain satellites and sensors are not needed. These redundant space assets can perform a secondary mission such as observing Resident Space Objects (RSOs) at or near geosynchronous earth orbit (GEO), effectively augmenting the Space Surveillance Network (SSN) and enhancing space domain awareness. Leveraging these efficiencies enhance the utility of resilient space architecture and also reduce costs for the government to develop and field separate SSA capabilities. The NDSA includes a Tracking Layer with a primary mission to track and target advanced missile threats and provide critical indications and warning.The backbone transport layer of hundreds of satellites in LEO will all be optically connected to form a mesh network in space. SDA will fly about 20 transport satellites to form the network and enable communications to legacy tactical datalinks. The data transport layer will talk directly via existing tactical datalinks, down to weapons systems that are already fielded and already have such capability (e.g., Army's TITAN ground system).Three sensing layers will feed data to transport layers: (1) a tracking layer made up of overhead persistent infrared (OPIR) sensors to detect and track adversarial advanced missiles; (2) a custody layer that would allow military users to send target location information in real time directly to weapons systems; and (3) a deterrence layer for space situational awareness. The sensing satellites will detect the missile; send the track to the transport layer where that data could be fused with other data and then sent down to the ground to the actual weapon systems that would engage the threat [16]. Although current space domain awareness assets are primarily focused on lower orbital regimes, there is a growing interest in regimes beyond GEO, extending to the lunar regime [17].

A notional tracking layer is equipped with visible and/or infrared optical sensors used for Earth-pointing observations produce observations of space objects when pointed away from Earth and into deep space. Maintenance and update of an existing space catalog of resident space objects (RSOs) reveal the intent and characteristics of spacecraft based on their positioning and movement over time. Actual cataloged information of RSOs, including publicly available object size parameters, enable simulations of RSO detections, yielding the quantity of space objects observed and revisit rates. The quality of orbits determined from the aggregated RSO observations helps to identify concepts of operations (CONOPS) that represent the different duty cycles [18].

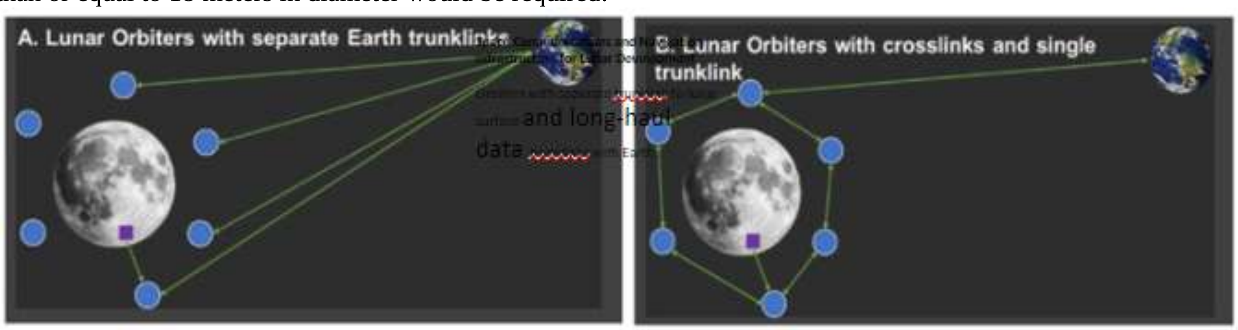


Space Defense Agency "Notional" Space Architecture Reaches For The Moon

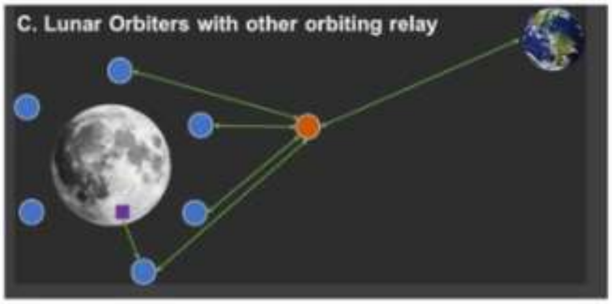
Civil User Community: Human Spaceflight Architecture

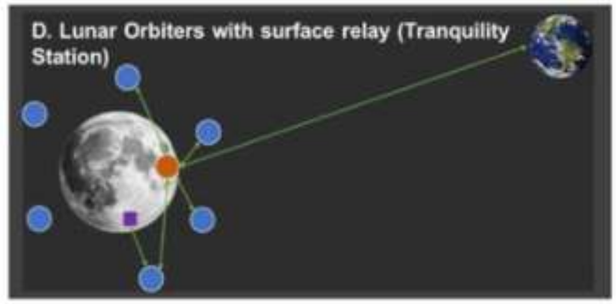
The LunaNet architecture implements bundled (data) packages (BP) to achieve networked communications. NASA will continue its membership in standards setting organizations such as the Interagency Operations Advisory Group (IOAG) to maximize international interoperability. Networked communications, supported by timing and navigation services, facilitate the collaboration and innovation seen in terrestrial mobile wireless network service providers and enable data-driven internet application platforms, ultimately contributing to the buildup of the solar system internet.

Lunar development will serve as a critical proving ground for deeper exploration into the solar system. Space communications and navigation infrastructure will play an integral part in realizing this goal. Just as LEO smallsats communicate with ground control centers on Earth, lunar orbiters will communicate with relay stations on the lunar surface as the industrial base develops on the Moon. And, there will be a direct lunar-Earth direct link for communications. In the first case (Figure A), each orbiter has a separate communication trunklink with Earth. Though this limits the number of links before the data gets to Earth, orbiter supports both the communication with the lunar surface and the longhaul links with Earth. For significant data rates, radio frequency (RF) antennas greater than or equal to 18 meters in diameter would be required.



In Figure B, the orbiters have crosslinks such that only a single orbiter communicates with Earth. This requires crosslinks at the full aggregate data rates. The remaining two examples have each orbiter first relaying data with another relay in lunar vicinity, either in a higher lunar orbit or on the lunar surface. The relay in higher lunar orbit in Figure C could be a larger spacecraft able to receive multiple links from lunar orbiters, which themselves have aggregated user data, and connect each orbiter to Earth over the larger relay's links with Earth. The Moon provides an interesting possibility because the same part of its surface always faces Earth.





In Figure D, a relay on the lunar surface (perhaps a "Tranquility Station" located at Tranquility Base, for example) would provide links with Earth for the aggregated data connections. The lunar surface relay however would not provide the same amount of contact time for each low lunar orbit relay as the relay in a higher lunar orbit. The higher orbit relay may also act as cloud service providers and provide trunklinks to route data to multiple simultaneous lunar destinations. Lower orbit relays could provide service to lunar users not capable of closing the link with the higher orbit relays. All relays would carry space weather or other science instruments and have the capability of providing space weather alerts.

Through the use of Delay/Disruption Tolerant Networking (DTN), LunaNet adapts and extends the fundamental and application-enabling attributes of Earth's internet. LunaNet architecture can be assembled through multiple infrastructure systems. For example, a relay supports IP networking over commercial link layer standards, but tunnels DTN bundles over IP to a neighboring node that supports the commercial standards and forwards the bundles over a fully Consultative Committee for Space Data Systems (CCSDS) compatible trunklink back to Earth. DTN-based network architecture will fully translate for use at Mars and other destinations when the speed of light delays to Earth is much greater than those between the Moon and Earth.

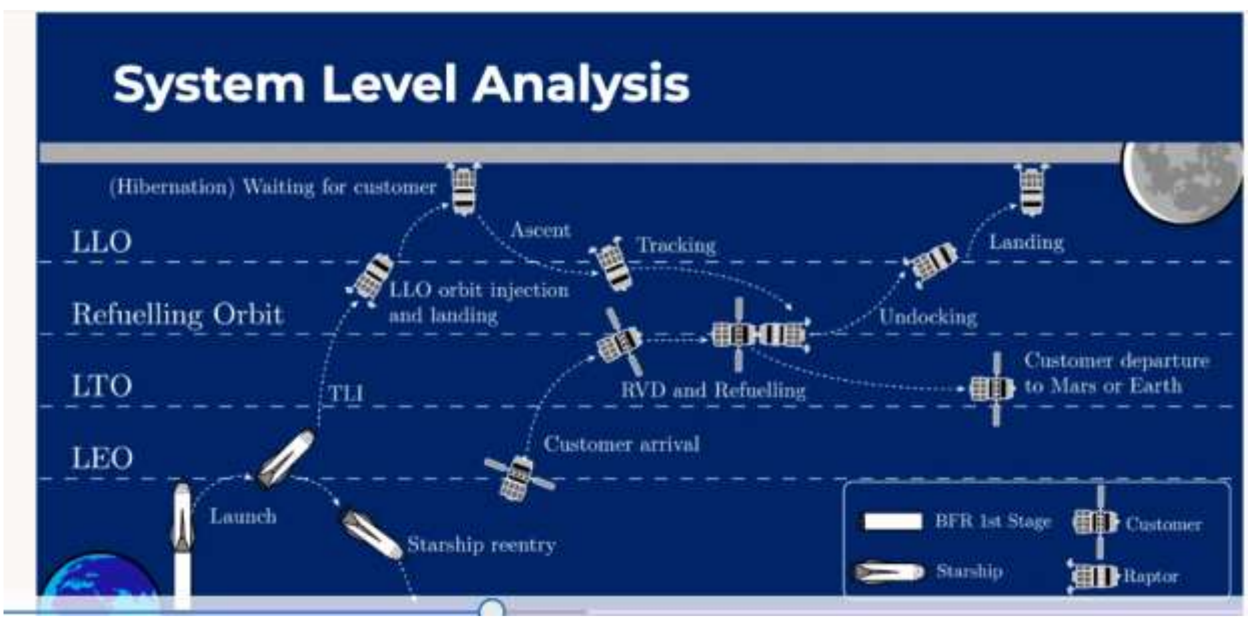


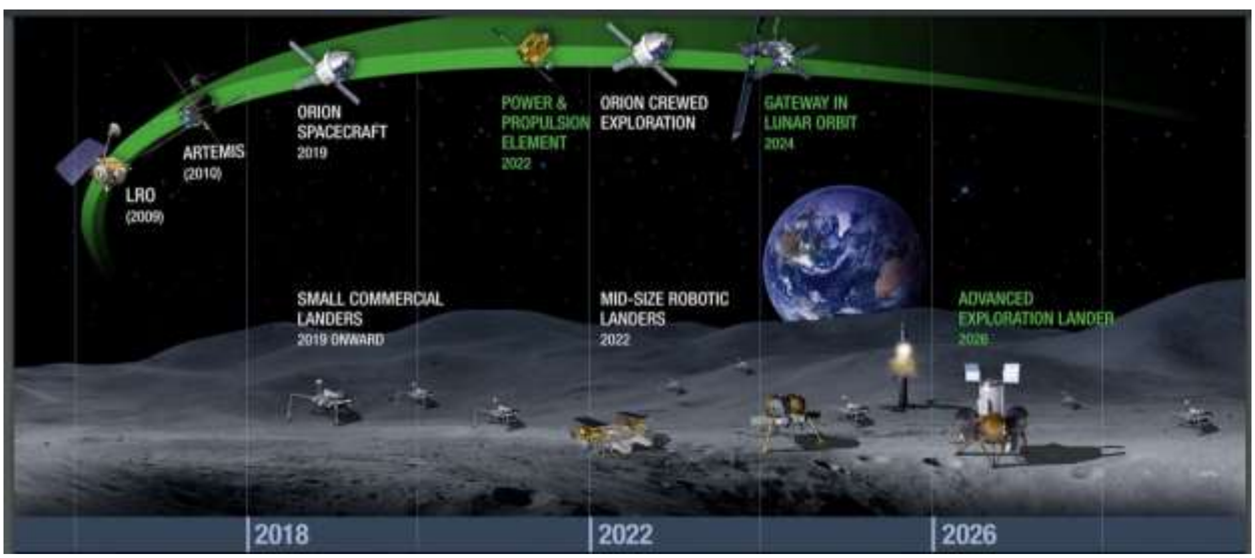
Figure. System Analysis Diagram for lunar in-situ resource utilization (ISRU)

A proposed architecture for lunar in-situ resource utilization (ISRU) will provide propellant, typically cryogenic hydrogen and oxygen, to a cislunar aggregation point in support of future space missions to the Moon, Mars, and beyond at a price competitive with commercial delivery from Earth. The establishment of sustained human presence on the Moon for science and exploration builds on the integrated design and operation challenges experienced from build-up and crew operations of previous Apollo lunar missions and International Space Station (ISS). The ability to make propellants, life support consumables, and radiation shielding, reduce the cost, mass, and risk of sustained human habitation beyond Earth. Because ISRU hardware and systems have never been demonstrated, the ISRU Project within NASA's `Exploration Technology Development Program has started development and testing of the hardware and systems in three areas: 1. Regolith Excavation, Handling and Material Transportation; 2. Oxygen Extraction from Regolith; and 3. ISRU precursor activities [19]. Exploration Mission-1 (EM-1) was to be launched without crew in 2020, in a Distant Retrograde Orbit (DRO). For EM-2 in 2022, the Orion spacecraft will take first astronauts on a lunar flyby. The SLS Block 1 cargo variant will deliver Orion beyond LEO in a Trans-Lunar Injection (TLI). The evolved Block 1B will deliver 9-10 metric tons to TLI, co-manifested with Orion. Human lunar missions will be used to build an outpost at a polar site. The ability to fly human sorties and cargo missions with the human lander will be preserved. Initial power architecture will be solar with the potential augmentation of nuclear power at a later time. Robotic missions will be used to:

- Characterize critical environmental parameters and lunar resources
- Test technical capabilities as needed (Build-up approach).

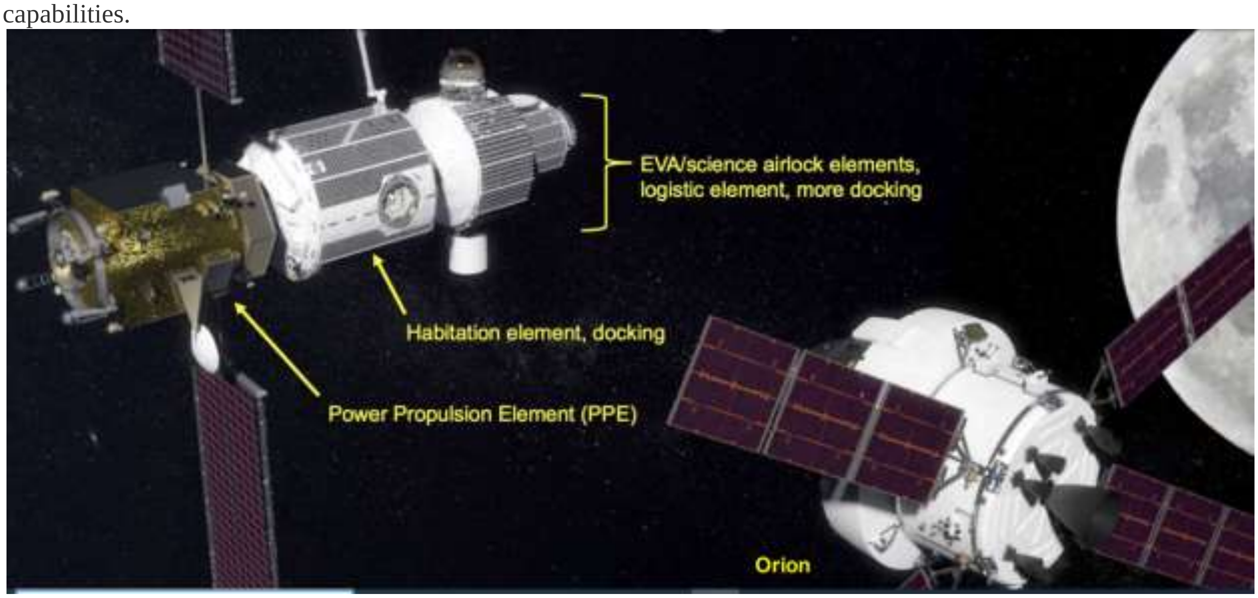
Civil User Commmunity: Lunar Orbital Platform-Gateway

An updated NASA plan describes a human lunar landing in 2024, annual sorties to the lunar surface thereafter, and the beginning of a Moon base by 2028 [20]. Human lunar missions will be used to build an outpost at a polar site. The ability to fly human sorties and cargo missions with the human lander will be initially solar- powered with the potential augmentation of nuclear power at a later time. Robotic missions will assess critical environmental parameters and lunar resources and test technical capabilities as needed (Build-up approach). In NASA's Exploration Campaign, the operations and the deployment of a U.S.-led lunar orbital platform, "gateway" will be established. Together with the Space Launch System (SLS) and Orion, the gateway is central to lunar surface access and missions to Mars. NASA's gateway concept distributes necessary functions across high-level capabilities: a power and propulsion (and communication) element (PPE), habitation/utilization, logistics resupply, airlock, and robotics. An effective habitation/utilization capability comprises pressurized volume containing integrated habitation systems and components, docking ports, environmental control and life support systems (ECLSS), avionics and control systems, radiation mitigation and monitoring, fire safety systems, autonomous capabilities, utilization, and crew health capabilities, including exercise equipment.



Lunar Reconnaisance Orbiter employed six individual instruments to produce accurate maps and high-resolution images of future landing sites, to assess potential lunar resources, and to characterize the radiation environment. The LRO payload includes: Lunar Orbiter Laser Altimeter (LOLA) to determine the global topography of the lunar surface at high resolution, measure landing site slopes, surface roughness, and search for possible polar surface ice in shadowed regions; LRO Camera to identify potential resources; Lunar Exploration Neutron Detector (LEND) to search for evidence of water ice; Diviner Lunar Radiometer Experiment (DLRE) to identify cold-traps and potential ice deposits; and, Lyman-Alpha Mapping Project (LAMP) to search for surface ice and frost in the polar regions [21]. The Acceleration, Reconnection, Turbulence, and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) mission address key lunar planetary science objectives: the evolution of lunar exospheric and sputtered ions, the origin of electric fields contributing to dust charging and circulation, the structure of the lunar interior as inferred by electromagnetic sounding, and the lunar surface properties as revealed by studies of crustal magnetism. Being the first mission to use prolonged residence in lunar libration orbits, which are important for communications and as staging grounds for lunar landings, ARTEMIS represents a pathfinder for future lunar exploration missions [22].

The Lunar Orbital Platform-Gateway has included such objectives as developing Power and Propulsion (PPE), the Habitat, the Airlock to enable Docking and Extra-Vehicular Activities (EVA), and the Logistics for cargo delivery, science utilization, exploration technology demonstrations, and potential commercial utilization. The first element of the gateway, a PPE (Power and Propulsion Element), will be launched as early as 2022 [23]. The Gateway will be constructed in orbit, incrementally, with the uses of the American-built Orion spacecraft and the Space Launch System (SLS), as well as commercial launch vehicles. In fact, NASA plans to build the Gateway with just five or six rocket launches, compared to the 34 launches it took to build the space station. Large parts will be set up by automatic assembly, mean robotically [24]. The Gateway is intended as a destination for astronaut expeditions and science investigations, as well as a port for deep space transportation such as landers en route to the lunar surface or spacecraft embarking to destinations beyond the Moon. NASA has focused Gateway development on the initial critical elements required to support the 2024 landing – the Power and Propulsion Element, the Habitation and Logistics Outpost (HALO) and logistics capabilities.

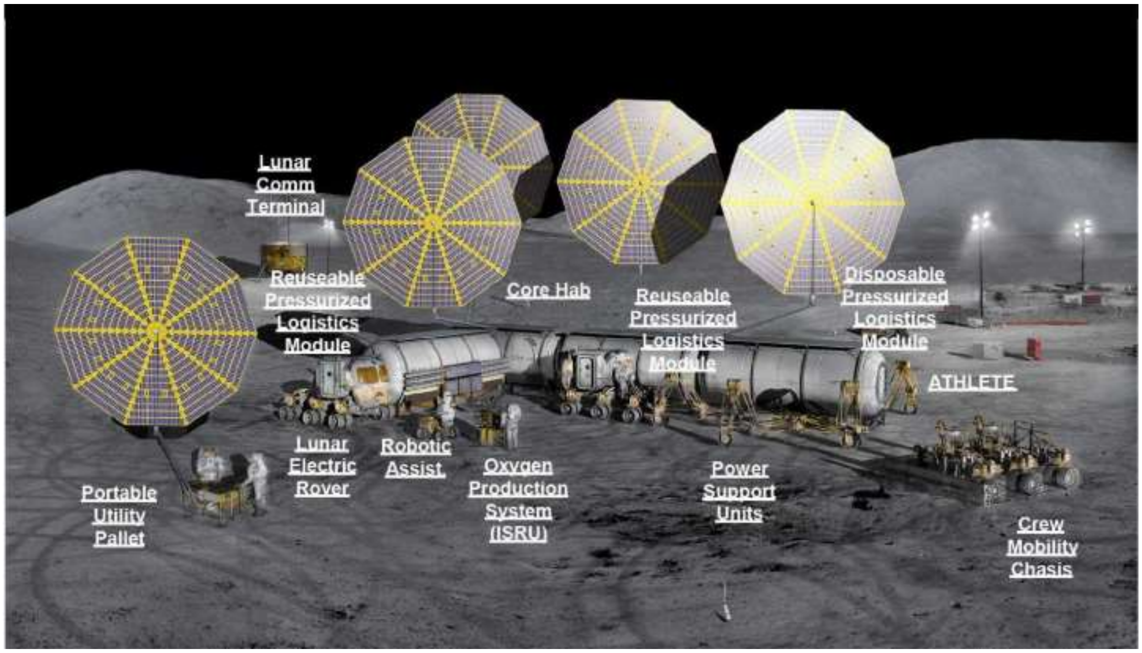


Although development of advanced technologies and capabilities allow for sustainability on the lunar surface, planned are the eventual human missions to Mars. As charged in Space Policy Directive-1, NASA's Artemis program will advance and develop technologies on the lunar surface that can be leveraged towards a safe and successful human round-trip mission to Mars [25]

NASA and partner contributions include:

- -Transportation Elements (Orion, SLS, and commercial launch vehicles).
- -Gateway Capabilities (PPE, integrated habitation systems, science experiments, docking, robotic maneuver arm) ,
- -Mission Control Center
- - Launch facilities
- - Payload and experiments operations centers

By the end of this year, the Gateway requirements will be base-lined, which will enable the acquisition and partnership activities leading to Gateway hardware development and deployment [26].



NASA's exploration architecture concept envisions a combination of relatively short duration lunar sortie missions, with surface stay durations of up to 7 days, and longer surface missions of up to 180 days per crew rotation. Sortie missions will be conducted from crewed landers without dependence on any prepositioned surface assets, thereby enabling limited exploration of widely dispersed lunar locations of scientific interest. Additional exploration objectives can be met through the utilization of surface assets that can be incrementally deployed and integrated at a fixed location to create a more operationally-capable lunar outpost. Such a lunar outpost is expected to include habitats, logistics carriers, power generation and energy storage systems, surface mobility assets, science payloads, and in-situ resource utilization systems that enable the crewmembers to live, work, and explore the lunar surface in ways that would be unsupportable on lunar sortie missions [27]. Lunar campaign scenarios studied to date share a common attribute in that the capability to support continuous human presence requires the accumulation of a variety of assets and supplies that are collectively beyond the means of a single cargo lander to deliver. As a result, the early years of a campaign may be marked by prolonged periods of unoccupied dormancy during which emplaced elements will be required to be maintained in a safe, quiescent state without an attending crew. In fact, prior to launch, much of the equipment within a surface habitat can be expected to be in an unpowered, non-operational state while vehicle integration and launch preparations are completed. Once landed on the lunar surface, integrated habitats may remain mostly idle, with nothing other than a minimum set of "keep alive" functions operable until a visiting crew arrives, perhaps months later [28].

Visions of lunar outposts often depict a collection of fixed elements such as pressurized habitats, in and around which human inhabitants spend the large majority of their surface stay time. In such an outpost, an efficient deployment of environmental control and life support equipment can be achieved by centralizing certain functions within one or a minimum number of habitable elements and relying on the exchange of gases and liquids between elements via atmosphere ventilation and plumbed interfaces. NASA's exploration architecture concept envisions a combination of relatively short duration lunar sortie missions [29]. A lunar outpost on the other hand will differ from the ISS in an important way. Most lunar exploration and science objectives will require the crew to spend a much larger percentage of their time outside the confines of the outpost habitats performing EVAs both in close proximity to the habitats as well as at relatively distant locations while on excursions in pressurized rovers. While a single 14-day excursion could be effectively conducted simply by carrying supplies of consumable gases and liquids and by discarding wastes along the way, such an open-loop approach would, over the course of repeated excursions over the operational life of an outpost, impose large logistics penalties on the lunar architecture as a whole. Yet the small confines within a rover and the need to keep the rover lightweight maximize its translational energy efficiency that conspires against burdening the rover with a full complement of water or oxygen recovery equipment. So the challenge becomes one of enabling efficient, frequent, and long rover excursions into an overall lunar architecture in a manner that is conducive to minimizing outpost logistics burdens through water and oxygen recovery [30].

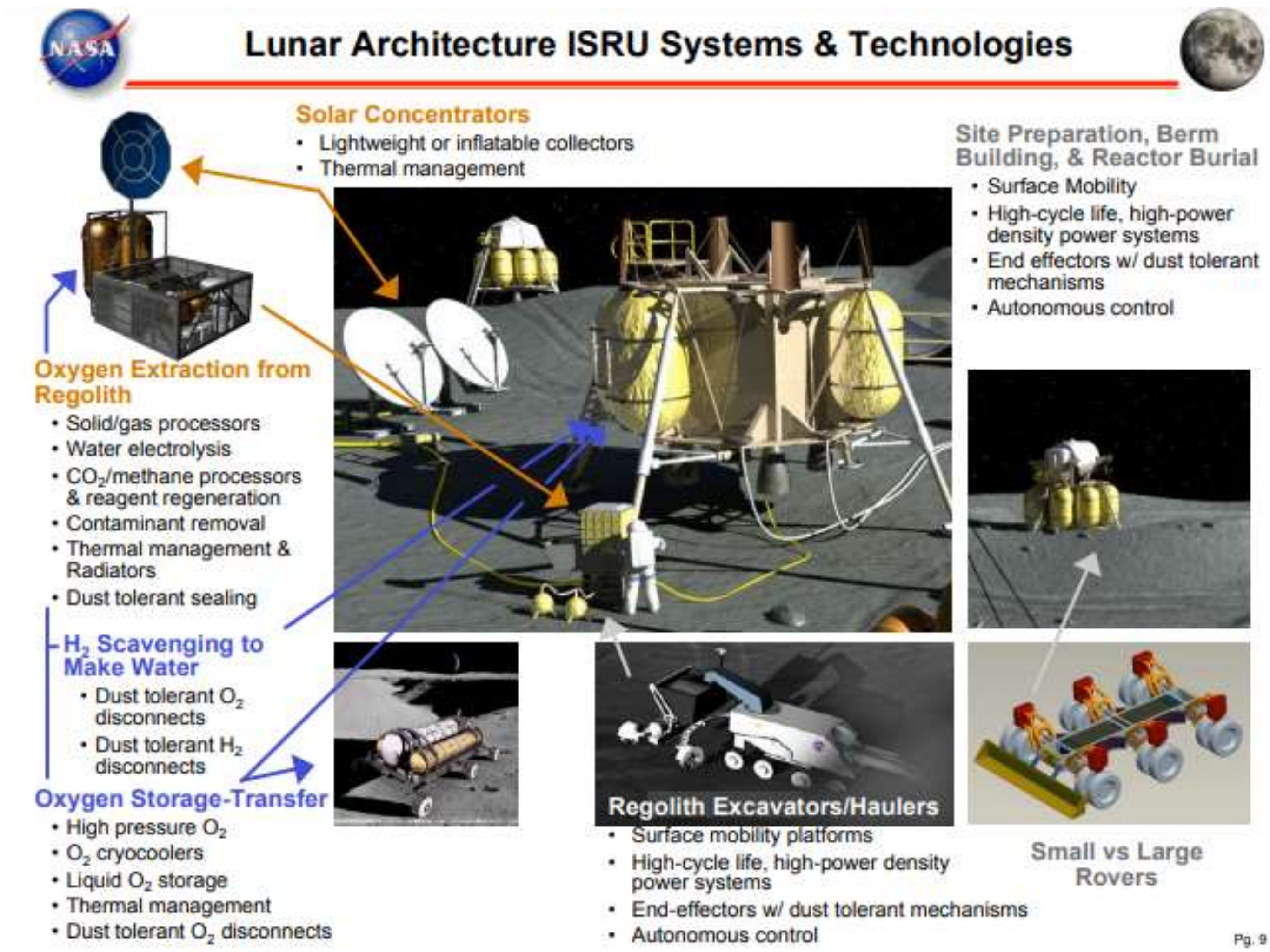
In-Situ Lunar Resources Lunar Platform

In-situ resources utilization (ISRU) on the Moon is an unproven capability for human lunar exploration and cannot be put in the critical path of architecture until proven. ISRU should fit into the planned lunar architecture for sustained human presence by demonstrating evolutionary growth in technical capability, integration with ties to Mars, and display of ties to Space Commercialization. ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources to create products and services from robotic and human exploration In-Situ Lunar Resources constitute the 'natural' lunar resources of regolith, minerals, metals, volatiles, and water/ice [31]. Working Group on Extraterrestrial Resources (1963–1969) was an informal organization of researchers and engineers assembled to evaluate the feasibility and usefulness of the employment of extraterrestrial resources with the objective of reducing dependence of lunar and planetary exploration on terrestrial supplies; to advise cognizant agencies on requirements pertinent to these objectives, and to point out the implications affecting these goals [32]. Propellant produced from extracted lunar water remained 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. Different mission architectures with crewed and robotic activities were reported, presenting the pros and cons of involving no, partial, or total use of extraterrestrial resources. 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 [33]. Although the success and results of the Apollo missions could have contributed to the creation of a vision for lunar settlement using space resources, budget cuts Post-Apollo era (1969–1981) reduced the ambition for activities on the Moon. Some space resource activities remained but the momentum was gone. A permanent lunar outpost became a long term vision [34]. A multiyear study into the utilization of extraterrestrial resources was organized by NASA in 1981 and lasted over ten years. This followed an improvement in economic conditions in the USA, the launch of the first Space Shuttle, the initiation of the design of a space station, and a new public interest in space activities, which seemed to have increased the prospects for lunar and Martian projects. In addition to the scientific and political interests, on-orbit construction was meant to acquire experience in building large structures that require several launches, a prerequisite to any permanent presence of humans at the Moon or Mars. Space Station Freedom would then be the first piece of this long-term plan [35]. Space Exploration Initiative (SEI) discussed early robotic exploration of the Moon and Mars for characterization of the environment, human exploration of the two planetary bodies, and the settlement of an outpost at the lunar surface as a preparation for one on Mars [36]. In 1995, a revisited strategy for a lunar exploration program acknowledged the failure of the SEI and of the overall idea to send humans beyond LEO. International collaboration proposed a lunar program consistent with previous USA strategies:

Phase I: Lunar resource explorer
Phase II: Permanent robotic presence
Phase III: First use of lunar resources and environment
Phase IV: First human outpost.

The reduction of activities on lunar resources was quickly compensated in the late 90s with the development of Mars ISRU, to support the foreseen Mars Sample Return (MSR) mission. The focus of Mars ISRU was also for propellant and consumable production. The proposed oxygen production process was based on a solid oxide electrochemical cell which separates oxygen from CO2 in the Mar [37].

ESA is also planning to perform ISRU experiments at the lunar surface including an end-to-end demonstrator tailored to produce in-situ oxygen or water. China successfully landed Chang'e 4, the first rover at the far-side of the Moon in early 2019. The USA is now actively preparing the Artemis Program to return humans to the Moon in 2024 and prepare a sustainable presence there to prepare for Mars. Both NASA and SpaceX have announced their exploration plans to Mars by the 2030s. To build an affordable and sustainable interplanetary space transportation system to Mars, ISRU systems and propellant depots are two critical space infrastructures. They can produce and store space resources in space, especially spacecraft propellant, to support space transportation and reduce mission costs. Some ISRU processes share the same subsystems which makes their infrastructure design and deployment more efficient. For example, the reverse water gas shift reaction (RWGS) and Sabatier reaction (SR) processes have the same reactant (i.e., CO_2 and H_2), both capable to produce H_2O. The Martian atmosphere acquisition subsystem and H_2O storage subsystem can be designed and deployed together. On the other hand, several testbeds have been built by NASA and Lockheed Martin to evaluate the performance of the hydrogen reduction reaction plant in oxygen production [39].



Lunar ambitions emerged in China during 2004–2010 with a new momentum for Space Exploration. The preparation of the orbiter Chang'e1, the first mission of the Chinese Lunar Exploration Program (CLEP), continued with a goal of eventual human presence at the lunar surface. Europe also had its first lunar orbiter SMART-1 and Japan placed SELENE (KAGUYA) in lunar orbit, none of which had ambitions beyond scientific measurements requiring ISRU. Public-private partnerships (PPP) were considered as a way to mitigate the current risk existing on the return on investment (ROI) of infrastructure development on the Moon. As before, some technologies were still developed in the US, and in 2012 the first demonstration of 3D printing of lunar soil simulant with a laser was presented. From 2012 onwards, some activities were on-going at KSC's Swamp Works facility regarding granular mechanics, electrostatics, regolith excavation, and civil structure 3D-printing [38]. Developing ISRU technologies at various TRL have emerged since 2015. The "Spaceship EAC", at the European Astronaut Centre in Cologne, Germany for example focuses on low-TRL technology development in sintering and oxygen extraction (Cowley et al., 2017). As for raising the TRL of more mature technologies, activities in lunar construction have already been carried out (Cesaretti et al., 2014; Meurisse et al., 2018; Buchner et al., 2017. Overall, the following chart highlights the slow rise of TRL of the main ISRU processes.

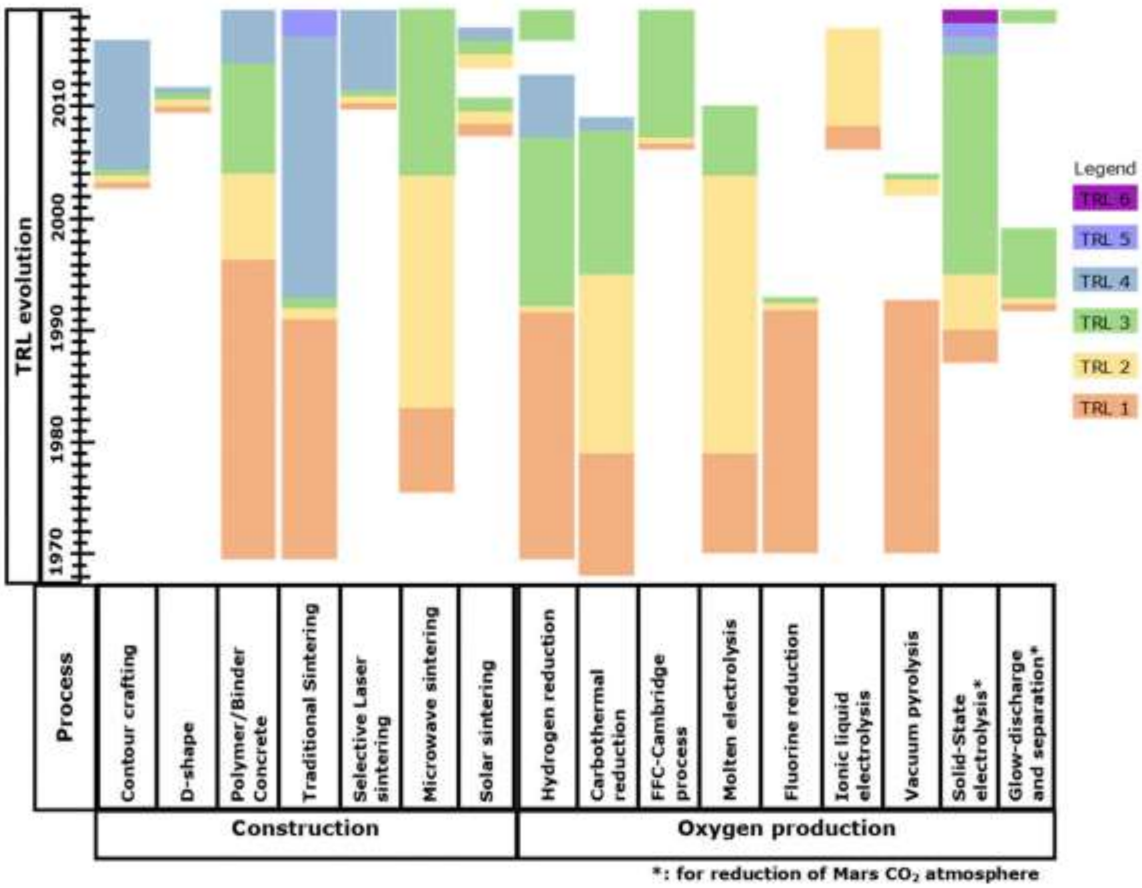


Figure. Technology Readiness Level (TRL) evolution of main ISRU processes

For construction, solely traditional sintering has been proven under vacuum (Meurisse et al., 2017; Songet al., 2018) and has therefore reached TRL 5. The fact that this process is simple to implement and does not require expensive hardware development is the main reason for being ahead of the other listed processes. Most of the other processes seem stuck at TRL 4. The lack of large thermal vacuum chambers with pumps able to deal with Martian or lunar soil simulants (also called Dirty Vacuum Chambers) delays the research progression. Consequently, it is still difficult to be sure about which process would be viable on the Moon or Mars for large scale space resources operations. Regarding oxygen extraction, the TRL of solid-state electrolysis of Mars CO_2 atmosphere has recently significantly evolved as MOXIE payload will be on board the Mars 2020 rover (Hecht et al., 2016). The interest in Mars ISRU triggered new research work on glow discharge and separation of Mars' atmosphere (Premathilake et al., 2019), which is potentially more efficient than the solid-state electrolysis.

A large menu of human Mars architecture choices organize into three distinct segments

– End State: Describing long-term architecture goals and objectives
– Transportation: Getting crew and cargo to Mars and back
– Surface: Working effectively on the surface of Mars.

A single surface site lends itself to a "field station" approach for development of a centralized habitation zone / landing site. The first mission to this site would deploy habitation, power, and other infrastructure that would be used by at least two subsequent surface missions:

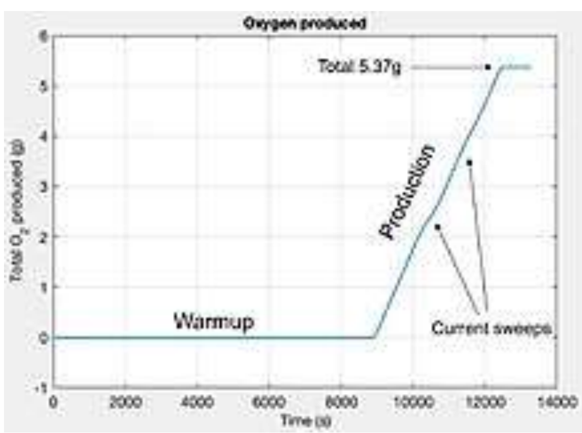
• Reusable surface elements (first 3 landed missions) – Provides some infrastructure for missions to follow
• Reusable in-space transportation and habitation (at least 3 missions) – Based in cislunar space

Cost can be spread via gradual buildup ◊of transportation/orbital capability per short surface stay -→ long surface stay.

Modular robotic concepts are identified and evaluated over the design and operations/maintenance lifecycle for autonomous Lunar, Mars, and partial gravity planetary surface excavation and in-situ earthworks equipment for the exploitation of available resources at surface of the extra-planetary site of a landed spacecraft. Material extraction from native regolith will be able to operate in a variety of planetary surface environments after initial shakedown on the moon. Using heritage from highly multi-functional, reconfigurable robotic systems like the All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE), Regolith Advanced Surface Systems Operations Robot (RASSOR), and Mars exploration rovers, a flexible maintenance-optimized mobility platform concept is designed with quick-connect/disconnect features for robotically swappable excavation implements [40].

The Mars Science Laboratory (i.e. Curiosity rover) had 10 main scientific instruments, requiring a large team of people to control, cost over $2.5 billion to build and fly. Curiosity had 4 main science goals, achieving significantly more than originally intended, and has furthered knowledge of Mars surface. The Perseverance rover was planned to copy Curiosity's design to schedule and cost, but was not as easily reused as initially planned. Generally, robotic probes and rovers achieve far less science value for the cost and time when compared to human explorers. On Mars there is a strong argument for further use of large traditional science rovers, as human travel to the surface is not expected to be feasible in the near future [41].

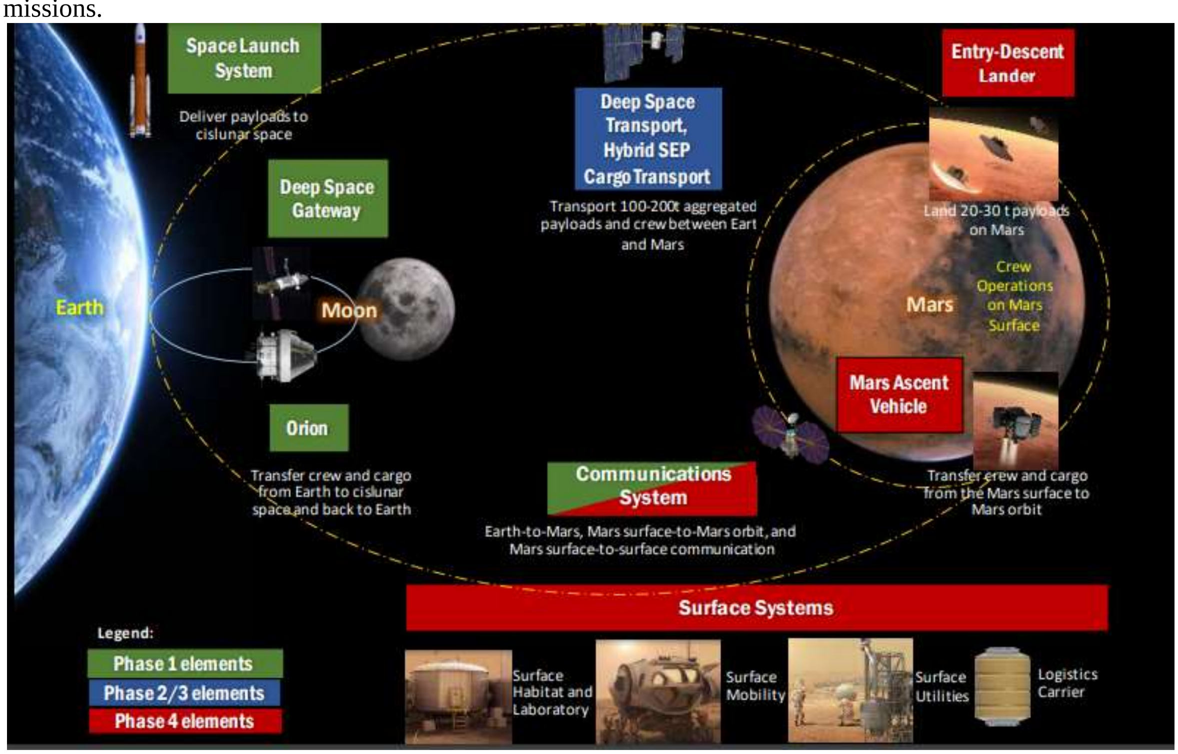
NASA scientists advance technologies to prepare for a human-crewed mission to Mars. With an atmosphere lacking oxygen and composed predominantly carbon dioxide, MOXIE scientists want to demonstrate the in situ production of oxygen on the planet's surface. The Martian atmosphere can be processed to extract valuable oxygen to support the crew's breathing needs, a commodity that can also be used as the fuel oxidizer for a Mars ascent vehicle [42]. Mars Oxygen ISRU Experiment (MOXIE) is a technology demonstration on the Mars 2020 Lander (M2020) to demonstrate In Situ Resource Utilization (ISRU) in the form of converting atmospheric CO2 into O2 On a future human mission, such a process will be used to autonomously provide up to 30 metric tons of liquid oxygen (LOx) for ascent vehicle propellant in the 16 months preceding launch of a human crew to [43]. MOXIE acquires, compresses, and heats Martian atmospheric gases using a HEPA filter, scroll compressor, and heaters alongside insulation, then splits the carbon dioxide (CO_2) molecules into oxygen (O) and carbon monoxide (CO) using solid oxide electrolysis, where the O atoms combine to form gaseous oxygen O_2 [44]. ("Game Changing Development The Mars Oxygen ISRU Experiment (MOXIE)"). In addition, a detailed assessment was made of the technologies, processes, subsystems, and systems required to make oxygen, oxygen and methane, and extract water from extraterrestrial soils to understand the state-of-the-art, options, and scope of the development effort to achieve TRL 6 for one or more ISRU systems.



MOXIE builds upon an earlier experiment, the Mars In-situ propellant production Precursor (MIP), which was designed and built to fly on the Mars Surveyor 2001 Lander mission.[5] MIP was intended to demonstrate In-Situ Propellant Production (ISPP) on a laboratory scale using electrolysis of carbon dioxide to produce oxygen.[6] The MIP flight demonstration was postponed when the Mars Surveyor 2001 lander mission was cancelled after the Mars Polar Lander mission failed [45].

Mission Architecture / End State					
Primary Program Focus	Mission Class	Level of Human Activity	Earth Based Mission Support	Cost Emphasis	Reusability
Flags & Footprints / Lewis & Clark	Opposition Class - Short Stay (1-60 sols)	Robotic / Telerobotic	Continual Control	Low Cost / Gradual Build-Up	None
Research Base / Antarctic Field Analog	Conjunction Class Long Stay (300+ sols)	Expeditions	Moderate Intervention	High Cost / Gradual Build-Up	In-Space Habitation
Primary Activity: Science & Research	All-Up vs. Split Mission	Human-Tended	No Daily Intervention	Low Cost / Fast Build-Up	In-Space Transportation
Primary Activity: Resource Utilization		Continuous Presence	Minimal	High Cost / Fast Build-Up	EDL and Ascent
Primary Activity: Human Expansion		Human Settlements			Surface Systems
		Human Colonization			Infrastructure for Permanent Habitation

The most fundamental impact on Mars mission architecture is whether a human Mars mission is intended as an Apollo-type sortie, an expedition to establish a scientific field station, or the beginning of a permanent human settlement. Field stations create a bridge between natural environments and (Earth-based) research laboratories. Research laboratories offer considerable power to conduct analyses in a predictable environment and to infer cause and effect from manipulative experiments, but they may miss factors that turn out to be critical in a natural environment. Field studies can encompass the full range of relevant interactions and scales, but they are not as tightly controlled. By offering access to both laboratories and field environments, Field Stations combine the best of both worlds [46]. A single surface site lends itself to a "field station" approach for developing a centralized habitation zone/ land site. The first mission would deploy habitation, power, and other infrastructure expected for use by at least two subsequent surface missions. Included would be reusable surface elements from the first three missions, reusable in-space transportation and habitation from earlier cislunar space stations entailing at least three missions.

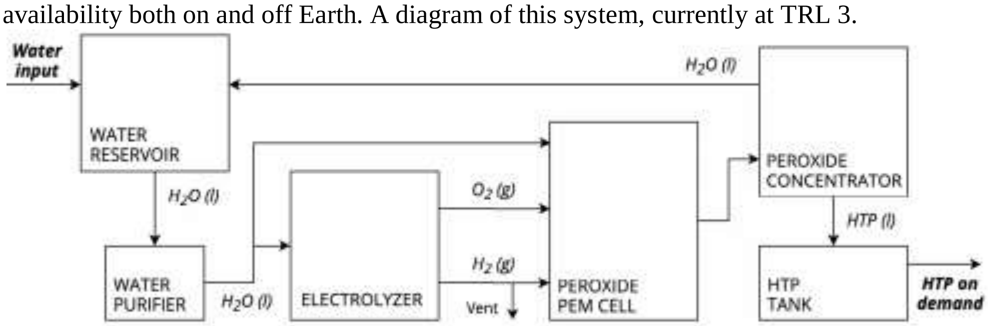


Commercial User Community: Case Study.
Three major technical challenges have been identified for the development of a lunar outpost in 2040: developing high power energy infrastructure, lander and vehicle ascent capacity, and mission architectures and technical approaches [47].
Systems which can produce propellant on the surface of the Moon or an asteroid will be integral to the development of the space economy. This fact is evidenced by the increasing number of companies developing technologies for in-situ resource utilization, and by NASA's focus on establishing a permanent presence on the Moon. Extraterrestrial propellant production will enable exploration throughout the solar system at a lower cost [48]. Off-planet manufacture of propellants is critical to the sustainability of space exploration. But 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. Orbit Fab has undertaken a propulsion system trade study$_2$. 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 [49]. The HTP used for this mission's lunar ascent and return to LEO can be made on the lunar surface from water using the Orbit Fab system. Potential lunar mission with sample return and HTP production system-enabled ascent vehicle refueling could be ready to fly as early as 2023.

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

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

Orbit Fab is developing a system that radically simplifies the production of hydrogen peroxide while increasing its availability both on and off Earth. A diagram of this system, currently at TRL 3.



Peroxide is continuously produced from purified water using a proton exchange membrane (PEM) cell developed by the Wang Group at Rice University and licensed to Orbit Fab.The peroxide is concentrated to 90–98% HTP and stored. This HTP production system could enable in-situ HTP use within a few years. A potential lunar ISRU sample return mission demonstrating the capability of Orbit Fab's HTP production system includes a 250 kg dry mass lunar ascent vehicle returning from the lunar surface to low-Earth orbit rendezvous requiring 1359 kg of HTP monopropellant (specific impulse (I sp) of 150 s and Δv of 2.74 km/s).

Since the cancellation of the Constellation Program, NASA officially has been focused on Mars as the next step for human exploration. Yet many in the space community believe that returning humans to the moon is more logical.

Often-cited reasons for this include: (1) should Nature prove to be favorable, the moon could be the basis for expanding the space economy through Off-Earth Mining (OEM) and other commercial endeavors; (2) the moon is scientifically interesting and could serve as a platform for scientific facilities; and (3) useful experience could be gained there for the human journey to Mars.

CONCLUSION

This paper was organized about three space-user communities which detailed their respective occupational missions. The military-user community was tasked with national defense of space-borne assets to grow in component number, complexity of their assembly, and the functionality of their aggregated operations. The civil-user community advanced extraterrestrial and planetary exploration and infrastructural development and sustainment of space-borne asset operations. And commercial-user community provided constellations of hundreds smallsats with specialized functions, requiring on-orbit servicing for sustained long-term performance. Describing a satellite-engineered landscape and reporting on a progressive development of the extraterrestrial landscape produce a narrative elaborating an overarching purpose for what the future extraterrestrial future would look like. By sequencing resource-dependent phases of development according to a timeline, students may envision their own timeline of what they envision as a future personal evolution. An imagined future of the world relates to an imagined future self, actively engages student motivation and interest in the subject [50].

This paper visually elaborates the system-level analysis of on-orbit servicing of smallsat constellations dependent on Rendezvous and Proximity robotics for pre-functional couplings. Inter-orbital transfers have also system-level robotic assembly of cargo payloaded and delivered to assemble orbital-space stations. This paper diagrams how smallsat constellations organize into distinctive functionalities and coordinate with other sub-mission layers of specialized functionalities providing the overall military protection of national assets whether earth-borne or space-borne. More pictorial are the design visions of Lunar- and Martian- base settlements in development. There was a 10+ year survey of the Moon for critical resources from LRO mission to the start of Gateway build-up. NASA now expects to launch the first two Gateway modules, the Power and Propulsion Element (PPE) and the Habitation and Logistics Outpost (HALO),on a Space X Falcon Heavy in 2024. The soonest astronauts would visit the Gateway would be the Artemis 3 mission, launching no earlier than 2024.

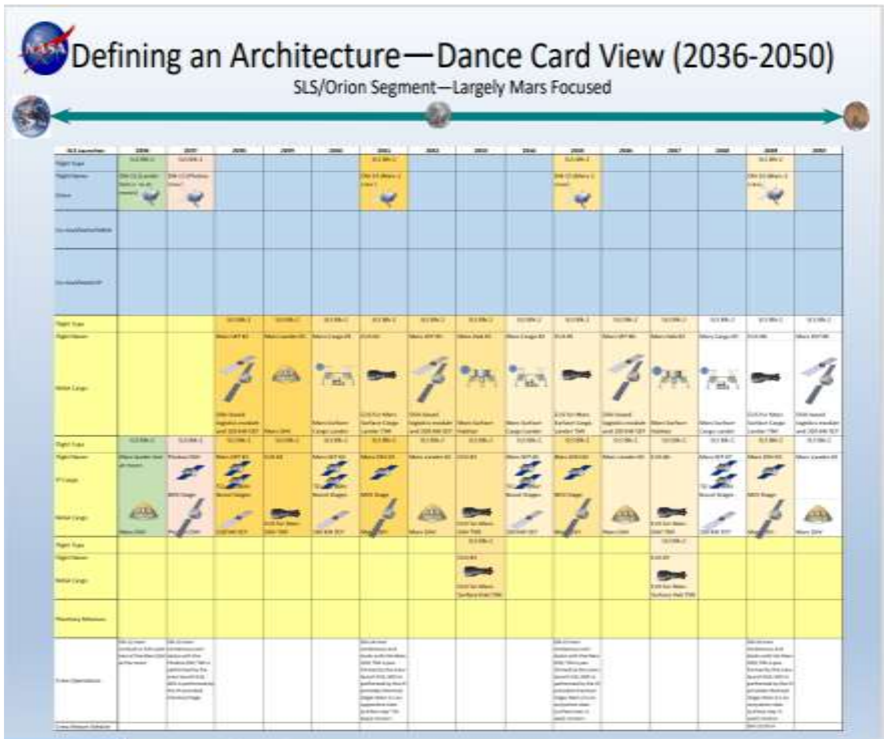
The individual phases of the required staging of space stations and base settlements are sequentially time-lined in their construction. Communications throughout all these processes and operations are relayed in a solar system internet also under development.

Although in-situ resource utilization involves hardware or operation that create products after the robotic and human exploration and extraction of 'natural' lunar resources of regolith, minerals, metals, volatiles, and water/ice, the technologies employed may not have matured enough to be employed with performance reliability. Technological readiness levels (TRL) assess the maturity of the technologies needed. Students understand the decisions and the time needed for greater technological development as well as the time needed for multiple launches carrying cargo payloads to advance space missions. To successfully learn about science, students must understand how empirically visual data relates to scientific facts and theories. Interpretation of visual data is enabled when contextualized in events or activities currently undertaken and reported for national programs. Facts and theories are embedded in the real-world work domain operations of space programs. Students learn facts and theories for decisions made and selected options decided on from the rationale explained for their respective choices. Additionally, students engaged in cross-disciplinary academics learn that costs, budgets, politics, though critical concerns, will augment greater understanding of how space missions are programmed.

Students also learn that innovations develop incrementally. How ISS was constructed may be improved on the construction of Gateway which may further be improved in the construction of outpost base on lunar surface, and eventually on the planet surface of Mars. What separates each of these milestones is distance and local resources which would preempt a more costly payload being launched from Earth.

Students need to know national programs like Small Business Innovation Research (SBIR) award grants for novel ideas and proposals when developed may be used for technological applications that contribute to mission completions. OrbitFab developed such a novel technology that converted water into a non-toxic, storable high-test peroxide (HTP), which decomposes into Oxygen and water vapor and provides high-density specific impulse to power a lunar or small body ascent vehicle.

Following a period (nominally ten years) of lunar exploration and infrastructure emplacement, JPL's Architecture Team shifts to a Mars focus by exploring mission-level architecture tradespaces, generating innovative ideas, and forging creative solutions using a concurrent engineering process at the earliest stages of formulation. The Mars mission architecture is based on high TRL systems. A proto-flight Deep Space Habitat launched in the 2030s to LEO serves to test life support technologies as well as a long-term in-space training facility for Mars astronauts. After launch, commercial spacecraft would then resupply the facility and ferry astronauts there for simulated Mars missions. The facility could be a wholly separate freeflyer or attached to a commercial LEO space station [51].



Secondary school students may anticipate that by the time they reach the age between 45-50 years old, they would have a glimpse of human-crewed launch to Mars and even a Martian outpost. For the journey to such a glimpse, students would have the references to chronicle and plot each milestone of space operations. To think that such a journey begins at beginning awareness of science and how it unravels into the future, experientially showcases the holistic life of a scientist. Understanding context that integrates science, technology and society, marks a true learner of science.

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