BUILDING AN ECONOMICAL AND SUSTAINABLE LUNAR INFRASTRUCTURE TO ENABLE HUMAN LUNAR MISSIONS

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Abstract

To enable return of human missions to the surface of the Moon sustainably, a new study was initiated to assess the feasibility of developing an evolvable, economical and sustainable lunar surface infrastructure using a public-private partnerships approach. This approach would establish partnerships between NASA and private industry to mutually develop lunar surface infrastructure capabilities to support robotic missions initially and later evolve to full-scale commercial infrastructure services in support of human missions. These infrastructure services may range from power systems, communication and navigation systems, thermal management systems, mobility systems, water and propellant production to life support systems for human habitats. The public-private partnerships approach for this study leverages best practices from NASA's Commercial Orbital Transportation Services (COTS) program which introduced an innovative and economical approach for partnering with industry to develop commercial cargo transportation services to the International Space Station (ISS). In this approach, NASA and industry partners shared cost and risk throughout the development phase which led to dramatic reduction in development and operations costs of these transportation services.

Following this approach, a Lunar COTS concept was conceived to develop cost-effective surface infrastructure capabilities in partnership with industry to provide economical, operational services for small-scale robotic missions. As a result, a self-contained lunar infrastructure system with power, thermal, communication and navigation elements was conceptually designed to increase capability, extend mission duration and reduce cost of small-scale robotic missions. To support human missions, this work has now been extended to analyze full-scale lunar infrastructure systems. This infrastructure system should have capabilities to support human missions from a few days to several months with minimal maintenance and replacement of parts. This infrastructure system should also maximize the use of existing lunar resources, such as, oxygen from regolith, water from ice deposits at the poles, and use of metals, such as iron and aluminum, from lunar regolith. The plan includes a buildup of these capabilities using a phased-development approach that will eventually lead to operational infrastructure services. By partnering with industry to develop and operate the infrastructure services using the COTS model, this plan should also result in significant cost savings and increased reliability. This paper will describe the Lunar COTS concept goals, objectives and approach for developing an evolvable, economical and sustainable human lunar infrastructure as well as the challenges and opportunities for development.

Keywords: Lunar Exploration, Lunar Outpost, Lunar Surface

1. Introduction

NASA is currently planning to send humans to the Moon by 2024 under its new Artemis Program. The Artemis program takes its name from the twin sister of Apollo and goddess of the Moon according to Greek mythology, which aptly describes the program that is planning to send the first woman and the next man to the surface of the Moon. The Artemis Program is a two-phased approach to the Moon where the first phase is focused on getting astronauts to the surface of the Moon as fast as possible, within 5 years by 2024. The second phase is focused on establishing a sustained human presence on and around the Moon by 2028. To accomplish these goals, NASA plans to launch astronauts atop the Space Launch System (SLS) and within the Orion spacecraft to a new lunar orbiting platform called the Gateway [1], in the first 3 Artemis flights as shown in figure 1. The initial configuration of SLS, for these first 3 flights, will be able to send more than 26 metric tons (mt) of crew and cargo to Gateway and a planned future upgrade, called Block 1B, will be able to send approximately 37 mt to orbits around the Moon [2].

The Gateway is planned to be a small orbiting spaceship with living quarters for astronauts and docking ports for visiting vehicles. The Gateway is currently planned to be deployed in a highly elliptical seven-day, near-rectilinear halo orbit (NRHO) around the Moon, which would bring it to within 3,000 km at its closest approach and as far away as 70,000 km at its farthest. The Gateway will provide a platform that enables global surface access on the moon, significant cislunar science and deep space technology development as well as serve as an integrator and transfer hub where spacecraft can dock, assemble and embark to the lunar surface and other destinations.

To reach the lunar surface, NASA plans to work with commercial providers to develop a Human Landing System (HLS) [3] to transfer crew and payloads from the Gateway to the lunar surface and then return crew and surface samples back to the Gateway. It is expected that the crew will be flown to the Gateway in its NRHO and back to Earth in the Orion spacecraft, where the Gateway will be used to support the transfer of crew and supplies into the HLS. The HLS should include three stages: a transfer element for the journey from the Gateway to low-lunar orbit, a descent element to carry the crew to the lunar surface, and an ascent element to return the crew to the Gateway as shown in Figure 1. In addition, at the present time, NASA is accepting alternative approaches from industry for the HLS that can accomplish the long-term goals of its Artemis program.

NASA is planning to target the lunar south pole as the first destination to land the first woman and the next man on the surface of the Moon. The lunar south pole was selected due to the recent discovery of potentially large amounts of lunar ice deposits in the permanently shadowed regions (PSRs) and surrounding areas [4]. Some studies have estimated

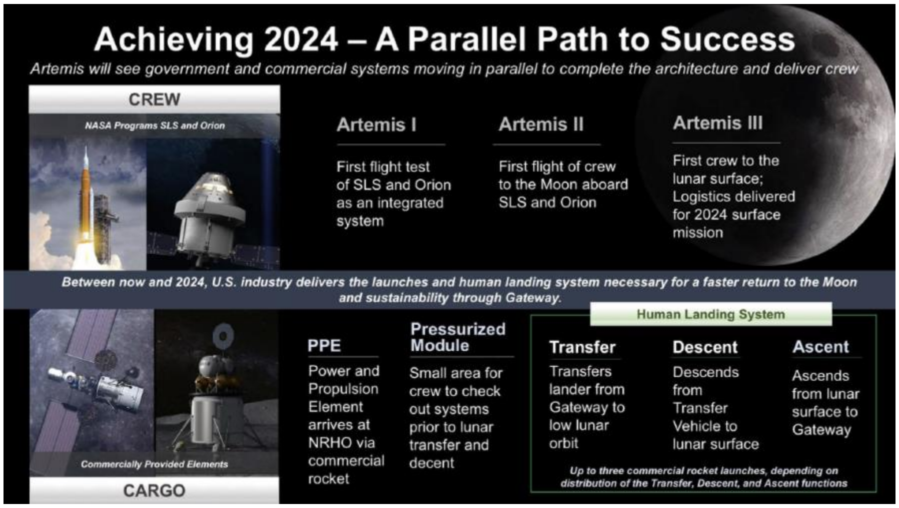

Figure 1. NASA’s Planned Architecture Elements for the Artemis Program

that the total quantity of water contained within the uppermost meter of all the PSRs could be 2.9×10^{12} kg (or 2900 million mt of water) [5], based on LCROSS mission results that also estimated concentrations of water-ice at 5.6 ± 2.9% by mass in the Cabeus crater of the south pole [6]. Water from these ice deposits is a very desirable resource for human missions as this water can be used for human consumption, life-support systems, fuel cell generators as well as for rocket propellant production, such as liquid hydrogen and liquid oxygen, that can be used for fueling ascent vehicles.

The lunar South Pole is also a highly desirable destination because of its “peaks of eternal light” which are defined as regions at high elevations and high latitudes that have extended periods of illumination. Although there are no regions on the Moon that are permanently illuminated, there are a series of closely located sites at the north and south poles that collectively receive solar illumination for approximately 93.7% of the year [7]. As an example, Shackleton crater was identified to contain three locations that are independently and collectively illuminated for a majority of the lunar year. As shown in figure 2, stations 1 and 2, which are located 1.8 km from each other, were collectively illuminated for 86.9% of the year and stations 2 and 3, which are located 2.1 km from each other, were collectively illuminated for 85.5% of the year. All three stations combined were illuminated for 92.1% of the year and the longest period that all three were in shadow was 43 hours.

The collection of nearby stations with extended periods of illumination, such as along the rim of Shackleton crater, are highly desirable areas for human exploration as they provide almost continuous solar illumination and are adjacent to large PSRs where there may be an abundance of lunar ice. These regions are also of great interest to commercial providers who are developing business plans for a commercial lunar propellant production facility [8]. Studies have shown that creating propellant from water may be a very lucrative business and may be the first step in creating a vibrant cislunar economy. Sowers [8] also cites that if such surface infrastructure can be leveraged then this may dramatically lower the cost to both public and private activities on the surface. For these reasons, development of a surface infrastructure using a public-private approach has been studied in this paper to provide economic benefits to both NASA missions and the private sector business endeavors. The following sections will describe the assumptions, approach, analysis and findings as a result of this study.

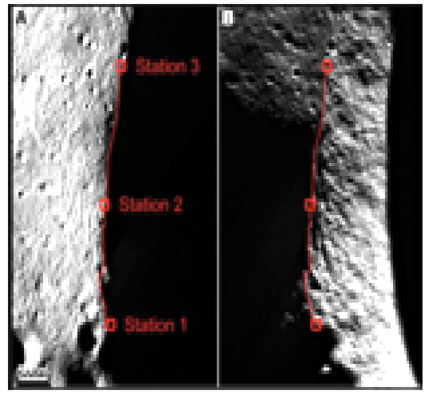

Figure 2. Rim of Shackleton crater with stations that are predominantly illuminated

2. Lunar COTS Concept

Earlier versions of the Lunar Commercial Operations and Transfer Services (LCOTS) concept was previously outlined by Zuniga et al [9,10]. This concept has been evolving as more studies and analyses are performed with the visionary goal of achieving an industrialized lunar surface and healthy space-based economy to benefit NASA, industry and the international space community. The LCOTS concept was based on the unique acquisition model from NASA Johnson Space Center’s Commercial Orbital Transportation Services (COTS) program [11]. This program was very successful in developing and demonstrating cargo delivery capabilities to the ISS in partnership with industry. It was planned together with the ISS Commercial Resupply Services (CRS) contracts which awarded SpaceX and Orbital Sciences Corp (now known as Orbital ATK) in 2008 to resupply the ISS on a regular basis with unpressurized and pressurized cargo. As a result of the COTS and CRS programs, two new launch vehicles and spacecraft were developed and have been successfully servicing the ISS program since 2012 with cargo transportation missions: 1) SpaceX’s Falcon 9 launch vehicle and Dragon spacecraft; and 2) Orbital’s Antares launch vehicle and Cygnus spacecraft. Recent studies have shown that government funding investments provided less than one half of the cost for these two commercial transportation systems (47% government funding for SpaceX and 42% government funding for Orbital) [11]. Also, it has been estimated that the final development cost for SpaceX's Falcon 9 rocket was about $400M which is approximately 10 times less than projected costs of approximately $4B for the same rocket using traditional cost-plus contracting methods [12].

The key to the huge success of the COTS program can be primarily attributed to its unique acquisition model which was developed in 2005 together with the program plan. At the time, it was desired to enter into partnership agreements with industry teams to develop new space transportation capabilities and services where both parties had 'skin in the game' in terms of both sharing cost and risk. It was also important to incentivize industry to capture new commercial markets and not solely rely on NASA as the customer. For this new acquisition method, NASA's Other Transaction Authority (OTA) through the Space Act was examined to create a mechanism to invest resources into the industry partners for development of these commercial capabilities for mutual benefit. As a result, the COTS program office elected to use Funded Space Act Agreements (FSAAs) in their acquisition strategy. The FSAAs were structured to allow much more flexibility to the industry partner with less insight and oversight from NASA, allowing for innovation without being encumbered with the full administrative and reporting requirements traditionally required by FAR contracts. However, this approach also offered more risk which has been addressed by NASA Policy directives, Space Act Agreements Guide [13] and Space Act Agreements Best Practices Guide [14].

This new acquisition approach or model was used as the basis for the Lunar COTS (or LCOTS) conceptual study. The goal for this study was to develop a plan based on the COTS model to partner with industry to develop new capabilities for the lunar surface for mutual benefit as well as to stimulate new commercial markets to grow a new space-based economy. Toward this end, development of a small-scale, lunar infrastructure system for small robotic missions was studied and analyzed to benefit both NASA and its commercial space partners. As a result of this study [15], a multi-functional, multi-purpose and self-contained lunar infrastructure system was conceptually designed to operate on the lunar surface and provide power, thermal control, communication, navigation and mobility services throughout the lunar day and night. For example as shown in figure 3, this infrastructure system or power-tower design was based solely on solar power and recently space qualified lithium-ion batteries to avoid the high costs and safety concerns of radioactive systems, such as radioisotope heating units (RHUs) or radioisotope thermo-electric generators (RTGs). The power-tower design provided a low-cost, high technology readiness level (TRL), high-reliability design that resulted in providing sufficient power to recharge and thermally hibernate small rovers and other critical equipment during the lunar night. This design was equipped with a 10-meter communication tower to provide expanded communication links between the lunar surface and Earth and local lunar communications along with navigation system to rovers for enhanced autonomous operations. Initial estimates showed that the power-tower design could extend mission duration of robotic missions from a few days to 6-8 years and increase traverse distances from a few meters to hundreds of kilometers for the same cost of a nominal mission.

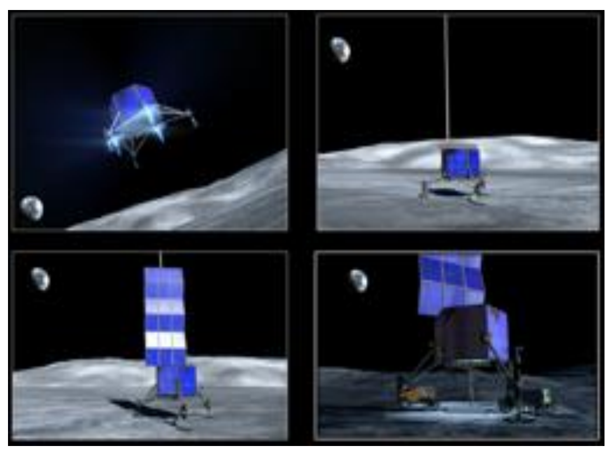

Figure 3. Power-Tower Conceptual Design

Although the power-tower design was developed to support small-scale robotic missions, it showed the feasibility of reducing cost while increasing mission performance and reliability to enable sustainable and long-term robotic missions. To determine if this concept could be applied to large-scale missions to reduce costs for human missions, the LCOTS concept was expanded to study development of large-scale infrastructure systems in support of human and other large-scale missions. This work is described in the three-phase development approach for LCOTS as outlined below.

Figure 4 shows the three-phase approach for the LCOTS concept. This approach allows for incremental development and demonstration of lunar surface capabilities and services from small-scale to human scale. As shown in Figure 4, the Phase 1 objectives were focused on developing infrastructure capabilities to support small-scale robotic missions. The power-tower concept as previously described was developed to meet these Phase 1 objectives.

Phase 2 objectives focus on developing pilot-scale feasibility missions to demonstrate infrastructure capabilities to support human habitats and large-scale commercial activities, such as lunar propellant production. The purpose of these missions would be to demonstrate these capabilities and evaluate the technical feasibility and economic viability of scaling up the infrastructure services for full-scale operations in support of the human missions.

Phase 3 of the Lunar COTS concept, as shown in Figure 4, would make long-term awards to commercial providers for infrastructure services, such as, power, communications, habitats with life support systems, etc. The decision to make these awards would be contingent on the level of success of the pilot-scale feasibility missions. This approach is very comparable to the COTS program where the technical demonstration missions informed the decision to award long-term ISS cargo delivery services.

By taking advantage of this phased development approach in partnership with industry, the benefits to NASA would be reduced development costs and risk as well as cost-effective commercial products and services to accomplish its science, robotic and human missions. The benefits to industry would be shared technical expertise as well as shared development costs to help raise private capital, implement new business plans and lower risk to capture lunar markets, such as lunar mining and lunar tourism, opening a new frontier.

3.0 ISS as an Analog for Lunar Outpost

ISS is humanity's only international orbiting platform enabling multidisciplinary scientific and technological research along with expanding our knowledge and understanding of the human body, our planet and space. It is also a habitat for 6-9 astronauts, providing suitable environmental conditions for long duration stay and necessary systems to perform research and investigations in the field of life sciences, human health and physiology along with studying the long-term effects of space travel. ISS provides multipurpose internal and external facilities which are modular and whose design specifications are publicly available for anyone around the world to perform research and experiments in space. It's this open architecture which allows the numerous international and commercial partners involved with ISS to perform a diverse set of activities, such as, enabling fundamental research in space to benefit life on earth.

Phase 1: Small-Scale Demonstration Missions	Phase 2: Pilot-Scale Feasibility Missions	Phase 3: Human Return Missions
• Demonstrate commercial multi-purpose infrastructure services (e.g. Power-Towers) to support small-scale robotic missions • Obtain ground truth data of lunar resources • Provide best targets for future missions	• Demonstrate lunar mining capabilities including propellant production on a pilot-scale • Demonstrate commercial infrastructure capabilities to support human habitats on lunar surface • Evaluate technical feasibility and economic viability of scaling up production to full scale	• NASA may award long-term contracts for infrastructure services, such as, power, communications and habitats with life support systems. • NASA may also purchase yearly allotment of lunar-produced propellant for ascent stages and other vehicles.

Figure 4. LCOTS Phased-Development Approach

ISS is a testament of successful international collaboration and cooperation to develop a modular, adaptable and open architecture platform. With the experience and expertise garnered over years of research and development with ISS, it is the perfect analog model for designing the next generation lunar infrastructure to support a long-term, human lunar outpost.

The following subsections provide description of the space environment and basic subsystems of the ISS which can be used as an analog for lunar infrastructure systems development to support a lunar outpost and enable a sustained human presence on the Moon.

3.1 Space environment in Low Earth Orbit:

Space is a very harsh environment with temperature variation from 120 deg C to -120 deg C, hard vacuum of 10^{-6} to 10^{-9} torr, 425 μSv/d ionizing radiation, micrometeoroids, orbital debris, ionospheric plasma and < 1 μg (quasi-steady level) microgravity among other effects [16,17]. In order to provide a safe and comfortable environment for astronaut habitation it is important to understand the external environmental conditions and develop appropriate mitigation strategies where necessary. The following table lists some of major environmental threats to the ISS and its mitigation strategies.

Table 1. Major threats with the corresponding mitigation strategy undertaken at the ISS.

Threat	Mitigation strategy
Micro-meteoroids and orbital debris	- Shielding critical elements to protect from <10 cm objects - Performing collision avoidance maneuvers to protect from >10 cm objects - Implementation of design features and operational procedures
Extreme tempera-tures	Thermal control on spacecrafts and spacesuits, active and passive heating and cooling systems
Radiation	Spacecraft shielding (water shelters, polyethylene), onboard radiation dosimeters

3.2 ISS Specifications

3.2.1 Mass and Volume: The ISS is 357 feet end to end, has a mass of 925,335 pounds (419,725 kilograms), habitable volume of 13,696 cubic feet (388 cubic meters) not including visiting vehicles, pressurized volume of 32,333 cubic feet (916 cubic meters). It has a living and working space which includes 6 sleeping quarters, 2 bathrooms, a gym and a 360 degrees observatory call cupola. It currently holds a permanent crew of 6 astronauts all year round. [18]

3.2.2 Power: Its 240 feet wingspan solar array provides 75 to 90 kilowatts of power. The 27,000 square feet of solar panels and their 262,400 solar cells generate power necessary to operate the station and is stored in Nickel Hydrogen batteries (currently being replaced by Lithium Ion batteries [19]) to provide uninterrupted power supply at 124V including during eclipse time. [20]

3.2.3 Communication: The Russian Orbital Segment uses a Lira high-bandwidth antenna to communicate directly with ground, while the US orbital segment uses two separate radio links in S band and Ku band. UHF radios are also used by astronauts and cosmonauts during the EVAs. In order to ensure constant communication with ISS, data is communicated to Earth using a series of ground-based antennas called the Space Network and a system of Tracking and Data Relay Satellites (TDRS). ISS also has a Ham Radio. NASA is also gearing up to test laser communication on ISS in the near future. [21]

3.2.4 Environmental Control and Life Support Systems (ECLSS): The ISS has redundant environmental control and life support systems in the US and Russian side which provide air revitalization, oxygen generation, water recycling, temperature and humidity control for the pressurized sections of the ISS. The air pressure and constituents inside ISS are similar to Earth and at about 101.3kPa (14.69 psi).

3.2.5 Water, Oxygen and Food requirements: An astronaut needs 0.84 kg of oxygen and a maximum of 2.68 kg and 25.95 kg of water for metabolic and hygienic purposes per day. [22] The water recovery system on the US segment generates 12.7 kg/day potable water providing the daily requirement equivalent for about 4.73 individuals with an overall efficiency of 88%.

Most of the oxygen on ISS is produced by electrolysis of water by the oxygen generation system in the US segment and the Elektron in the Russian segment. The Russian segment also has a solid fuel oxygen generation system called Vika. The oxygen generation system in the US segment produces oxygen at an average daily rate of 2.34 kg/ day corresponding to the daily requirement equivalent of about 2.78 individuals. The ISS also uses a Sabatier system to produce water and methane from carbon dioxide and hydrogen which are both byproducts of the life support system on ISS.

The food requirement on the ISS is 0.83 kg per meal per crew member. This paramount need is being fulfilled solely by resupply missions. [23]

4. Lunar Infrastructure Systems for Sustained Human Presence on the Lunar Surface

This section describes the infrastructure or surface systems necessary to enable a long-term outpost for sustained human presence on the lunar surface. The assumptions made in this analysis included: 1) use of the ISS subsystems as a basis for analysis; 2) a sustainable human presence for 6 astronauts; 3) mission durations of up to 30 days; and 4) use of lunar resources as much as practicable to reduce mass and cost of cargo to be delivered from Earth.

4.1 Environment: Establishing infrastructure to sustain a 6-member crew for a 30-day mission duration, raises issues related with the harsh environment of space and distinct environmental characteristics of the Moon. The following subsections outline the properties and challenges posed by these characteristics.

4.1.1 Gravity: Average gravity on the Moon is 1.62 m/s^2, about 1/6th of the Earth's gravity. Low gravity reduces the energy required to propel from the surface of the Moon. The effects of long duration partial gravity on human physiology are still to be determined.

4.1.2 Radiation: Unlike Earth, the Moon has a significantly weaker atmosphere (14 orders of magnitude lower than the Earth's atmosphere) and negligible magnetic field which does not provide enough protection from radiation. Lunar radiation is characterized by three kinds of ionizing radiation: the solar wind, the solar flare associated particles (solar energetic particles) and the galactic cosmic rays. Radiation interacts with the surface of the Moon in different ways and depending on the energy and composition result in varying penetration depths from micrometers to meters. These interactions can also generate secondary neutrons and gamma rays. The amount and type of radiation also poses a larger threat to humans than what is experienced on Earth and within the ISS.

4.1.3 Extreme Temperature: The Moon experiences approximately 14.77 days of sunlight followed by 14.77 days of darkness due to its synodic period of approximately 29.5 days. This approximate 14 day/night cycle presents unique engineering challenges as surface experiences extreme temperature changes from approximately 120 deg C in the daylight to -180 deg C at night. Surface temperatures at the poles are even colder reaching approximately -258 deg C due to the very low incidence angle of the sunlight. At these extreme temperatures, most electronics and spacecraft subsystems, such as batteries, transponders and solar panels will freeze and become inoperative.

4.1.5 Dust: Apollo missions have taught us a lot about the characteristics and properties of lunar regolith dust. It mostly has an average grain size between 45 µm to 100 µm. The grains are sharp, glassy, have extremely low electrical and dielectric losses allowing electrostatic charge to build up under UV radiation. Micrometeoroids impacting on the lunar surface are the source of a persistent tenuous clouds of dust grains. While designing systems for the Moon it is important to address the following properties of the lunar dust: 1) abrasiveness to friction bearing surfaces, EVA suits 2) pervasive nature on seals, gaskets, optical lens, windows, 3) gravitational settling on thermal and optical surfaces like solar cells and 4) physiological effects on the human lung tissue. Lunar dust can be managed/mitigated by abrasion resistant coatings; coatings that repel dust; vibration, electrostatic, magnetic, brush and vacuum cleaning systems, electrodynamic dust shield, plasma-based dust sweepers etc. [24, 25]

4.2 Infrastructure Development and Guidelines

The following subsections describe recommended guidelines for infrastructure development of an outpost for sustained human presence on the lunar surface. These subsections also describe mitigation strategies that can be implemented to overcome the challenges of the lunar environment as described in the previous subsections.

4.2.1 Power: The outpost should be capable of generating enough energy required to power the habitation modules, the scientific experimentation modules along with charging rovers and exploration equipment. Using ISS as an analog system, a goal of 75-90 kilowatts should be sufficient for a lunar outpost. There are several options for generating this power including solar power systems, regenerative fuel cells and nuclear power systems. Due to almost negligible atmosphere, efficient ground and space-based power beaming concepts could also be implemented helping connect power generation sites to exploration areas.

4.2.2 Communication: Constant and high-speed communication is a key enabler for mission operations at scale. NASA's LADEE spacecraft demonstrated 40-622 Mbit/s downlink and 10-20 Mbits/s uplink from lunar orbit to Earth and vice versa using laser communications [26]. Hybrid Optical and radio wave communication system (e.g. S, X, KU, KA and UHF) coupled with data relay satellites and mesh networks for ground communications between astronaut-astronaut, astronaut-robot/rover, between outpost and exploration crew, equipment and Moon to Earth would provide a robust and reliable communications architecture. [27]

4.2.3 Navigation: Reliable and precise navigation on Earth is an almost solved problem due to systems like the Global Positioning System satellites and ground based Differential GPS units. Having a reliable navigation solution on the Moon would be another key enabler for infrastructure development leading to a lunar outpost. Systems like star trackers, image based positioning systems, small satellite constellation and potentially using GPS on the surface of the Moon can provide the necessary foundation for a dependable navigation solution on the surface of the Moon. [28]

4.2.4 Habitation: The outpost will require pressurized modules with standard interface mechanism similar to the International Docking Adapter on the ISS for habitation and scientific exploration along with air locks at entry and exit points. The habitat should provide a radiation and micrometeorite resilient structure providing internal environment similar to ISS. The habitat air locks should also be able to remove the lunar dust particles and provide air quality similar to acceptable air quality index with particulate matter 2.5 and 10 at 35 μg/m3 and 150 μg/m3 over a 24-hour exposure period. [29]

In order to conduct operations, the ISS offers 916 meters of pressurized volume including 388 cubic meters of habitable volume. The Minimum Acceptable Net Habitable Volume defined as "the minimum volume of a habitat that is required to assure mission success during exploration-type space missions with prolonged periods of confinement and isolation in a harsh environment" is 883 cubic feet per person (i.e.25 cubic meters) [30]. Hence for a crew of 6 on the Moon the minimum pressurized habitable volume should be at least 150 cubic meters along with areas for personal hygiene and exercise.

To meet these needs and challenges, an inflatable habitation system could provide habitat units more durable with greater volume and less mass than rigid modules. Since the inflatable structure is collapsible, it can be produced in virtually any shape and can be packaged for launch more efficiently. Bigelow Aerospace is one commercial provider that has been studying the design of inflatable structures for space and the lunar surface for a number of years. Their inflatable structure concept, as shown in Figure 5, can accommodate up to 6 people for 120 days and provides an interior volume of 330 m^2 which would include 6 large crew quarters, a large amount of storage capacity, 2 toilets and 2 galleys [31]. In addition, to protect the crew from harmful radiation or micrometeorite debris, the inflatable structures could be covered with regolith or placed within a lunar cave or lava tube. Passive radiation shielding is another option that can be provided using water walls or trash recycled polyethylene while electrostatic and magnetic field can provide active shielding. [32]

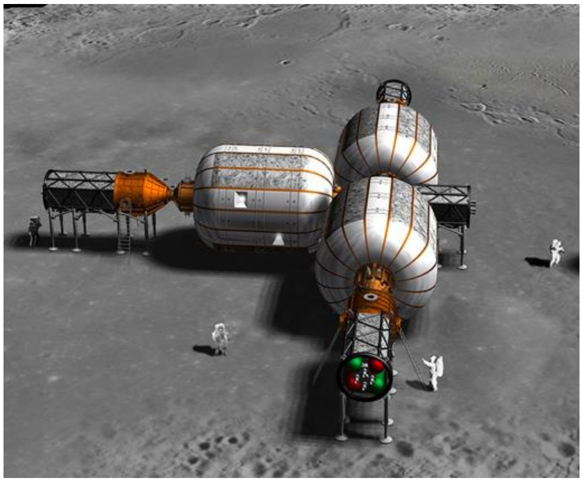

Figure 5. Example of Bigelow's Inflatable Habitat

4.2.5 Environmental Control and Life support systems, Oxygen, Water and Food requirements: The lunar outpost can commence operations using electro-mechanical life support systems from Earth similar to ISS with eventual goal of replacing it with bio-regenerative life support systems starting with local food production. Based on ISS data, the amount of resources needed per day that shall be provided for the sustainment of 6 astronauts for a 30 day mission on the Moon is approximately: 151.2 kg of oxygen, 482.4 kg of potable water, 4671 kg of water for hygiene and 448.2 kg of food for 3 meals per day. A highly efficient ECLSS system like the ISS with an oxygen generation system and water recycling system should be able to recover 70.2 kg of oxygen and 381 kg of potable water for a 30-day mission, reducing the amount of resources required from Earth. Placing the habitats near the lunar poles may also provide ease of access to the potential water-ice deposits, helping make the system more earth independent.

For bio-regenerative life support systems a crop production area of 28 m^2 to 40 m^2 would be required to generate 100 % oxygen and 50 % caloric intake per crew member. A 240 m^2 crop production area would provide all the oxygen and 50% caloric intake for a 6-member lunar crew. [33, 34]

4.2.6 In-Situ Resource Utilization (ISRU): The lunar outpost can be established using Earth-based systems with a rapid, iterative test and development plan to enable ISRU by investigating oxygen production from regolith, extracting water-ice from permanently shadowed craters and splitting water into oxygen and hydrogen for life support, energy generation and propellant production. Methane can also be produced using pyrolysis of plastic trash and crew waste with in-situ oxygen. Extreme temperature differentials close to the lunar poles also opens up possibilities to develop novel thermoelectric systems for power generation and habitat/equipment heating and cooling. Once initial investigations are complete and candidate procedures/technologies have been identified then ISRU products can replace the Earth-based systems gradually to reduce the number of re-supply missions from Earth. [35]

4.3 Outpost Site Selection: The location of the lunar outpost should be mainly driven by the availability, amount and accessibility of resources, environmental challenges, engineering development, cost, operational considerations and scientific potential. As previously discussed, the lunar poles offer sites with highly-elevated regions and extended periods of illumination or "peaks of eternal light" near permanently-shadowed regions, such as the rim of the Shackleton crater at the south pole. Such locations provide near constant access to sunlight which will enable low-cost, continuous, year- round solar power generation. The temperatures at these peaks of eternal light are also near constant which would reduce the engineering challenges of designing for extreme temperature changes at equatorial sites. Also the permanently shadowed craters at the lunar poles may contain large quantities of water-ice that can be used for human consumption, life support systems and propellant production. For all these reasons, it is recommended that these peaks of eternal light be considered as a primary option for reducing the engineering challenges, complexity and cost in development of a long-term, lunar outpost.

5.0 Potential Commercial Lunar Services

As previously discussed, the Artemis program's second phase is focused on establishing a *sustained human presence* on and around the Moon by 2028. To develop a plan that can achieve a sustained human presence, it is important to first understand the parameters necessary for sustainability. According to the United Nations Brundtland Commission, sustainability is defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [36]. According to the World Commission of Environment and

Development, sustainable development is defined as "the process of change in which the exploitation of resources, the direction of investments, the orientation of technological development and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations." To set metrics of sustainable development for the Moon, a study by the International Space University developed fifteen Lunar Sustainability Goals to ensure that proposals for future lunar missions are feasible and sustainable for the long term [37]. Through study of these references, a plan to achieve a *sustained human presence* should include: 1) an architecture or lunar outpost that provides the basic systems necessary to sustain human life and which mitigates the environmental threats that were outlined in the previous section; 2) a sustainable economic plan that yields short-term technological advantages for Earth-based and lunar-based products and long-term return-on-investments; and 3) in-situ use of lunar resources while preserving the lunar environment.

To meet these objectives, this evolution of the Lunar COTS concept aims to leverage public-private partnerships to jointly develop cost-effective, surface infrastructure capabilities that will lead to economical, commercial lunar services in support of human missions. The key to successful partnerships is finding common areas of interest that will yield mutual benefit. For partnerships with private industry, there are several potential lunar industries that have been identified that may yield substantial economic benefits for both NASA and industry. These industries range from lunar mining, manufacturing, propellant production, communication satellites, space-based solar power to lunar tourism. It is believed that these industries may lead to a multi-trillion dollar, space-based economy in the next three decades drawing interest from plenty of private companies and investors to develop business plans to capture these markets [38]. These markets, if fully or partially developed, will undoubtedly reduce the overall cost and enable sustainability for a long-term human presence on the lunar surface.

The challenge to these private companies is the size of investments needed upfront to put in place all the elements of the infrastructure needed to make their business plans successful. This is where government can help to offset this economic burden from the individual businesses and help with the development of the infrastructure. Similar to industrialization efforts of the past, government can be a catalyst to lunar industrialization by partnering with industry to build the infrastructure needed for new lunar businesses to succeed and a new space economy to emerge.

As outlined in the previous section, there are a number of infrastructure systems or utility services necessary to support a sustained human presence on the lunar surface. Most of these utility services will also be needed by industry to accelerate their business plans and lead to a positive return on investment. These utility services of common interest include power generation and storage, communication and navigation systems, water and propellant production. Therefore, it will be advantageous for NASA to partner with private industry using the COTS approach to jointly develop these capabilities. The following subsections describe some examples of these capabilities and potential partnerships for development.

5.1 Power Generation and Storage

Discussion from the previous section presented the guidelines for power generation for a lunar outpost within the range of 75-90 Kilowatt, similar to ISS. There are several options for generating this power including solar power systems, regenerative fuel cells, nuclear power systems and wireless power beaming. The key to selecting the appropriate power system depends on the environmental challenges of the lunar outpost site. For equatorial sites, there will be 14 days of sunlight followed by 14 days of darkness with large temperature changes from 120 deg C to -180 deg C. For solar power systems, these environmental conditions require long-term energy storage solutions, such as batteries. The challenge of using batteries include the addition of thermal management using heaters for cold conditions and radiators for hot conditions. The number, size and mass of the battery system will also be dependent on the overall design of the mission. For a 30-day human mission, batteries may not be a practical and cost-effective option at equatorial sites, but they may be beneficial for polar missions.

Another option to overcome the long lunar nights may be nuclear power stations but they present many other challenges such as potential radiation hazards to humans and equipment as well as safety and environmental concerns on launch. A recent NASA development effort, named Kilopower, includes a sterling-based generator that can produce 1 kilowatt of electric power with a system mass of 400 kilograms. The Kilopower concept is designed to use highly enriched uranium fuel. This design can be scaled up to 10 kilowatts with a system mass of 1500 kilograms. There are also advanced plans to explore use of a commercial low-enriched uranium fission reactor system concept that is predicted to be able to provide from 10 kilowatts to one megawatt electric power. Due to the hazardous nature of radioactive sources and amount of development time needed, nuclear options are also not the most practical and cost-effective option for 2028 timeline.

To avoid the challenge of developing a low-cost, low-mass system that can operate through the 14 days of lunar night, an attractive option is selecting a site in one of the regions that have extended periods of illumination. As described earlier, the lunar south pole has a few regions with a series of closely located sites that collectively provide solar illumination for approximately 93.7% of the year. The one region mentioned earlier was Shackleton crater in the south pole. If a lunar outpost were to be built in one of these regions, a cost-effective solution for generating power would be photovoltaic (PV) solar arrays. PV solar arrays are a space-proven technology and can provide sufficient power required for this size lunar outpost, around 75-90 kW.

In addition to the PV arrays, power beaming can be used in combination with this system to wirelessly transmit power to receivers located in the permanently shadowed regions of craters. It would be very advantageous and cost-effective to beam power into these dark regions for use in extraction of water-ice resources. Mankins [39] studied this specific option, named Lunar Surface-Based Space Solar Power, and showed very promising results. As shown in figure 6, Mankins' preferred architecture option was able to beam power in the range of 100 kW to distances in the range of 40 to 50 km. His analysis also showed hardware costs of less than $100M to deliver 100 kW which was an order of magnitude less than the cost of a nuclear power system for the same amount of power delivered. This business case offers a good example of a very practical and low-cost architecture that can be developed in partnership with industry to produce a cost-effective, long-term, commercial utility service.

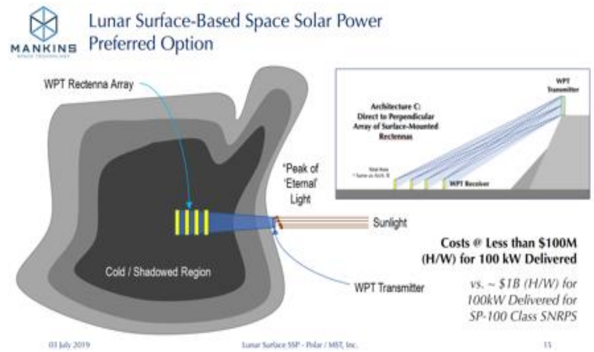

Figure 6. Lunar Surface-Based Space Solar Power Preferred Option from Mankins [39]

5.2 Water and Propellant Production

Another large market attracting interest from private industry and investors is lunar-derived propellant. A recent collaborative study [40] led by ULA and other experts from industry, government and academia examined the technical and economic feasibility of establishing a commercial lunar propellant production capability. A wide range of customers for propellant were identified including the commercial launch industry (ULA, SpaceX, Blue Origin, etc) for refueling in LEO and GEO, government space agency transportation systems (NASA, ESA, etc) for use on the lunar surface (for fueling up ascent vehicles), or cislunar space (fuel depot at Gateway or Lagrange points) or interplanetary space (missions to Mars and beyond). With the development of plans for sustained human presence on or in orbit around the Moon, additional markets can also emerge for oxygen and water to support human habitats, life support systems and other systems, such as, regenerative fuel cells for power generation, thermal management and radiation shielding systems. As a result of the potential market demand, the study identified a near-term annual demand of 450 tons of lunar-derived propellant delivered to various locations, equating to 2450 metric tons of processed lunar water.

This study also reviewed the approach, challenges and payoffs for an architecture that can harvest and process lunar ice from within the PSRs at the lunar poles to produce large amounts of water necessary to meet the demands of the propellant market. To reach these water-ice deposits, past studies have developed architectures that include large and heavy machinery to excavate, drill and haul tons of lunar regolith to obtain the water-ice. These studies resulted in excessive costs which made it very challenging to close the business case.

In contrast, a recent study focused on a revolutionary concept [41] to extract water-ice by using a lightweight capture tent and heating augers to sublimate the ice and transport the water vapor through the surface. As shown in Figure 7, the vapor is captured by a dome-shaped tent covering the heated surface and vented through openings into Cold Traps (CTs) outside the tent where it refreezes. Once the CTs are full of refrozen ice, they are removed and replaced with empty CTs. The ice-filled CTs are transported to a central processing plant for refinement into purified water, oxygen or liquid oxygen (LOX) and liquid hydrogen (LH2) propellants.

Using this concept, Sowers [42] developed a business case for mining propellant on the Moon. For this analysis, the demand side of the business case was solely specified by ULA requiring 1100 mt of propellant purchased on the lunar surface for $500/kg. The Capture Tent concept was used for the production side of the business case with an estimated cost of $2.5 billion for development, fabrication and delivery to the lunar surface. As shown in Figure 8, this business case analysis resulted in $550M of revenue per year generating a 9% return-on-investment and $2B in profit over the life of the project of 15 years.

Figure 8 also shows another business case that included an additional propellant demand and investment by NASA through a public-private partnership. In this scenario, it was assumed there would be an additional demand of 100 metric tons (mT) of propellant annually by NASA to fuel lunar landers for ascent from the Moon. The propellant price was kept at $500/kg while NASA's investment in the mining operation was assumed to be $800M. In this case, the return-on-investment increased to 16% with profits topping $3B over the life of the project. The analysis also showed that NASA's initial investment resulted in a savings of $2.45B the first year, and $3.45B each year if the propellant cost remains at $500/kg compared to delivering 100 mT of propellant from Earth at a cost of $3.5B/year.

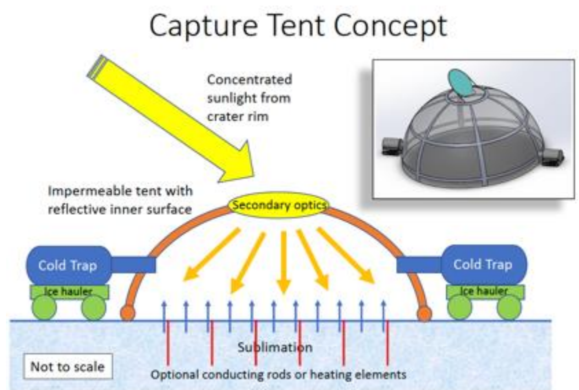

Figure 7. Capture Tent Concept for sublimating ice from lunar surface from Dreyer [41]

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Business Case Analysis

Parameter	Commercial Only	Commercial + NASA
Propellant production rate	1100 mT/yr	1200 mT/yr
Price (on Moon)	$500/kg	$500/kg
HW Development & production cost	$1.5B	$1.6B
Transportation cost	$1.0B	$1.1B
Annual ops & maintenance cost	$87M/yr	$95M/yr
Annual revenue	$550M/yr	$600M/yr
NASA cost share	$0M	$800M
IRR	9%	16%

Figure 8. Propellant Production business case analysis from Sowers [42]

5.3 Keys to Successful Partnerships Using an LCOTS Approach

As shown in the previous examples, there is a much to be gained by leveraging public-private partnerships to develop new capabilities and services for mutual benefit. These partnerships can accelerate NASA's progress in developing economical and sustainable lunar infrastructure to obtain its goal for sustained human presence on the Moon by 2028. Similarly, these partnerships can accelerate industry's progress in establishing new lunar industries to provide services to multiple customers for economic gain. However, before entering into partnership agreements using an LCOTS approach, a careful assessment should be performed to determine the likelihood of success of these partnerships to develop the specified capabilities in a certain timeframe. Some important factors to consider during this assessment are: 1) number of viable companies with enough technical and financial capability and strong interest to pursue LCOTS opportunity; 2) size of potential markets likely to emerge within 5 years to attract private investors; 3) level of affordability to fully develop capability within realistic budgets from NASA and private capital from industry; 4) strong potential for positive return on investment based on sound business plans; and 5) strong potential to reduce technical, cost or operational risk towards an economical and sustainable lunar infrastructure.

In addition to performing this assessment, another key factor, for an LCOTS approach to be successful, is committing to long-term awards of several years for commercial services. This commitment to be an anchor customer is essential for industry to raise private capital by reducing the risk to investors and setting achievable timelines in place. This approach also reduces risk to NASA by ensuring the industry partners will be able to deliver its products and services on time and on schedule. To further reduce risk to NASA, long-term awards should be made to multiple commercial providers to enable competition and withstand interrupted services. Phase 3 of the LCOTS phased-development approach (see Figure 4) sets out to meet all of these objectives.

6. Summary

A new study was initiated to examine the feasibility of developing economical and sustainable lunar surface infrastructure capabilities and services in partnership with industry to meet the goals of NASA's Artemis program for a long-term, sustained human presence on the lunar surface by 2028. This work is an extension of the Lunar COTS concept [9,10] previously developed to leverage best practices from NASA's Commercial Orbital Transportation Services (COTS) program which introduced an innovative and economical approach for partnering with industry to develop commercial cargo transportation services to the ISS. Following this COTS model, a Lunar COTS concept was conceived to develop cost-effective surface infrastructure capabilities in support of small-scale robotic missions which has now been extended to support human missions. This concept included a buildup of these capabilities using a phased-development approach as discussed that will eventually lead to operational infrastructure services. By partnering with industry to develop and operate lunar infrastructure services using the COTS model, the LCOTS plan as described shows the potential for significant cost savings and risk reduction in the development of a human lunar outpost.

In studying the needs and challenges of a lunar outpost, the ISS was examined and used as an analog for a long-term, self-sufficient habitat in a space environment. With the experience and expertise garnered over years of research and development with ISS, it was chosen as a very fitting analog model for designing the next generation lunar infrastructure to support a long-term, human lunar outpost. A review of the ISS subsystems was presented along with a description of the environmental challenges and the mitigation strategies that are in place to overcome these challenges.

A high-level analysis of the infrastructure systems needed to enable a long-term, sustainable human outpost on the lunar surface was also presented. The environmental challenges as well as the threats it may impose on the human lunar outpost were also reviewed. As a result of the analysis, guidelines for the principle infrastructure systems were recommended along with mitigation strategies to overcome the environmental threats. To reduce all the environmental threats and produce low-cost, economical infrastructure systems, it was recommended that the outpost be located at one of the highly-elevated stations with extended periods of illumination near permanently-shadowed regions, such as the rim of the Shackleton crater at the Lunar South Pole. Such locations provide near constant access to sunlight which will enable continuous, year-round solar power generation which would significantly reduce the cost of power generation and storage systems. The temperatures at these stations are also near constant which reduces the need for complex and costly thermal management systems. The nearby permanently shadowed craters may contain large quantities of water-ice deposits that can be extracted and used for human consumption, life support systems and propellant production, thus further reducing the overall cost of the human lunar outpost.

Finally, to assess the economic feasibility of the LCOTS approach, several business cases were examined for potential partnerships, common areas of interest with NASA and level of maturity to successfully develop lunar surface capabilities for mutual benefit. Several important factors were reviewed to determine the likelihood of success of these partnerships to develop specified capabilities in a certain time frame under an LCOTS approach. Two business cases were highlighted for power generation, water and propellant production as excellent examples of mature business plans where NASA can benefit by partnering together with industry to develop economical infrastructure capabilities and services to meet its objectives for a sustained, human lunar presence. Both of these business cases showed potential for a large customer base, low development costs, high revenue and return-on-investment based on projected markets. The LCOTS phased-development approach can be used to take advantage of this interest and enter into partnerships with these viable and interested industry partners to co-develop and demonstrate these capabilities at pilot-scale on the lunar surface. Once these surface missions demonstrate technical and economic viability of these capabilities, long-term awards can be made for purchase of commercial services, such as power generation, water and propellant production. Both NASA and private industry can benefit from the LCOTS approach as it is designed to reduce cost and risk to both parties as well as accelerate timelines for development which should result in large, economic gains for industry and enable a long-term, sustainable human presence on the lunar surface.

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