# ACCESS (1G-ArtifiCial gravity CEntrifuge Space Station in cis-lunar space): Concept and Operations

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**ACCESS (ArtifiCial gravity CEntrifuge Space Station) is a proposed 1G space station in lunar orbit that will operate independently without Earth resupply after the first five years of operation. The station will serve as a proving ground for human reproduction in space, a staging post for deep space missions, long duration science experiments and lunar surface exploration. The ACCESS campaign consists of a series of precursor missions to support the gradual build-up and assembly of the ACCESS space station by 2040. The station will function independently from Earth after the first 5 years of operation via lunar in-situ resource utilization (ISRU), on-board food production and in-situ fabrication of resources (ISFR). The resources are extracted from the Moon by a robitic lunar base and transported to the station using an ISRU. The Lunar Near Rectilinear Orbit (NRO) was selected for the station's operations location where it will support an initial crew size of 16 with 4 additional infants born and raised on the station. This paper presents the station and lunar base designs, key subsystem baseline designs, and programmatics and risk management strategy of the ACCESS campaign. This concept was submitted to the 2016 Revolutionary Aerospace Systems Concepts – Academic Linkage (RASC-AL) design competition.**

## Nomenclature

| | | |
|---|---|---|
| RASC-AL | = | 2016 Revolutionary Aerospace Systems Concepts – Academic Linkage |
| ACCESS | = | ArtifiCial gravity CEntrifuge Space Station |
| ISRU | = | In-Situ Resource Utilization |
| ISFR | = | In-Situ Fabrication of Resources |
| DRO | = | Distant Retrograde Orbit |
| NRO | = | Near-Rectilinear Orbit |
| ARM | = | Asteroid Retrieval Mission |
| $T$ | = | Torque, N-m |
| $\omega$ | = | Angular rate, rad/s |
| $I$ | = | Moment of inertia, kg-m$^2$ |
| $\Omega$ | = | Number of rotations per year |
| $\mu_{moon}$ | = | Gravitational parameter of the Moon, m$^3$s$^{-2}$ |

## I. Background and Motivation

The 2014 NASA Strategic Plan[1] lays out a key objective to "expand the human presence into the solar system and to the surface of Mars to advance exploration, science, innovation, benefits of humanity and international collaboration" with the goal to "expand the frontiers of knowledge, capability, and opportunity in space". To this end, NASA proposed the Evolvable Mars Campaign, which begins with Earth-reliant missions to expand the knowledge of human operations in space, transitions to missions in cislunar space which serve as a proving ground

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for demonstration and validation of required technologies for long-duration crewed missions, and ultimately results in missions to the vicinity of Mars and long duration stays on the Martian surface.

The long-term goal is for humans to work, operate and thrive independently and safely in deep space for an infinite period of time. To achieve this, an Earth-independent, variable-gravity, ISRU-enabled space station called ACCESS (ArtifiCial gravity CEntrifuge Space Station) is proposed that will accommodate new studies necessary to establish a permanent human presence in space. This paper presents the objectives, mission architecture, in-situ resource utilization (ISRU) strategy, and programmatics (cost, schedule and development plan) for the ACCESS campaign. The technologies necessary will be developed through collaboration with international, commercial and academic stakeholders and partners.

## II. Campaign Goals and Objectives

The primary goals of the ACCESS campaign are to:

1. Establish a permanent human presence in space
2. Act as a proving ground and eventually transition to a staging post for crewed missions to Mars
3. Provide a platform for crewed and robotic exploration of the solar system

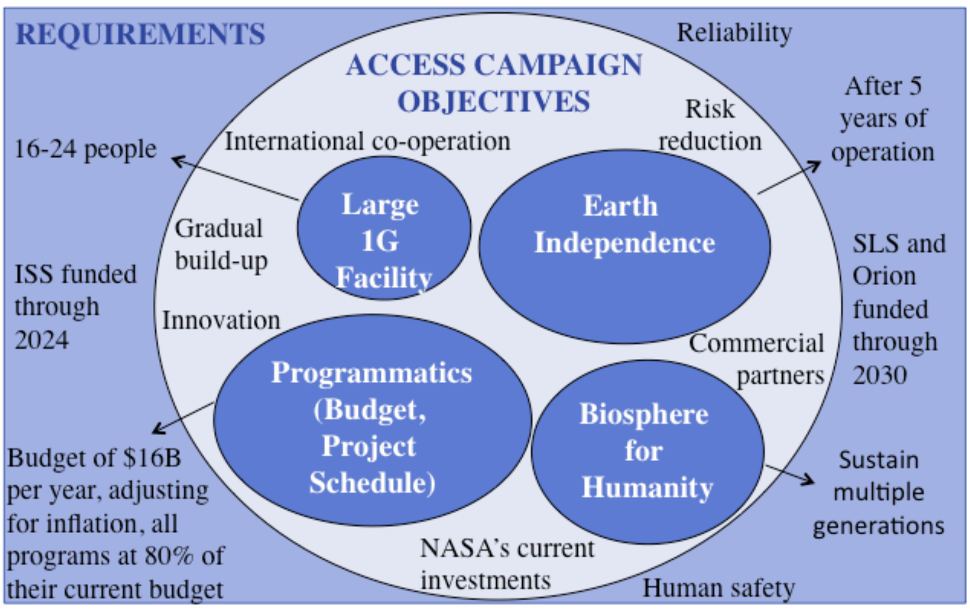



**Figure 1. Key objectives of the ACCESS campaign.**

The primary objective of the ACCESS campaign (shown in Figure 1), is to create a variable-gravity facility to enable humans to live, procreate and work independently in deep space. This modular and evolvable space infrastructure will become Earth-independent (receiving no resupplies from Earth) after the first five years of operation. Resupplies in the form of water, metal oxides, and raw material for radiation shielding are procured through in-situ resource utilization of resources from the Moon. A detailed ISRU and ISFR strategy to achieve Earth independence are presented in this paper.

The space station is designed to support a crew of 16-24 people continuously for a minimum of 20 years. The station will serve as a platform for learning about long-duration human habitation in space. Focus will be placed on understanding and enabling human reproduction, including gestation, birth, and early-childhood development in space, thus making the station an extended biosphere for humanity.

In addition to the primary objectives, the campaign will provide a platform to:

1. Study the effects of long-duration exposure to radiation and variable gravity on human health
2. Enable crewed and robotic exploration of the solar system
3. Perform in-situ resource extraction and utilization for NASA's upcoming missions like the Asteroid Redirect Mission (ARM)
4. Perform robotic on-orbit assembly of large structures for science missions
5. Enable servicing and in-situ fabrication of components

6. Encourage collaborations through commercial partnerships and international cooperation
7. Promote education and outreach activities through university partnerships

As per the RASC-AL competition rules, the ACCESS campaign will utilize 20% of the total annual budget at the FY16 funding level. A realistic budget for the ACCESS campaign, along with a project timeline and development plan are presented in this paper.

## III. Assumptions

All NASA programs are assumed to operate at 80% of the current funding level (FY16). 20% of the total budget will be directed towards the new space station design. International Space Station (ISS) funding will be redirected towards the space station assembly and expansion after 2024. Orion and SLS programs will continue to be funded until 2032, and 2 SLS launches will be available per year. The ACCESS campaign schedule is based on a gradual, staged development of capabilities and technologies spanning from initial research on ISS starting in 2018 to the beginning of nominal, full crew operations in 2040. A detailed budget with a complete development, assembly and operations schedule will be presented in this paper.

## IV. Tradespace Exploration and Feasibility Study

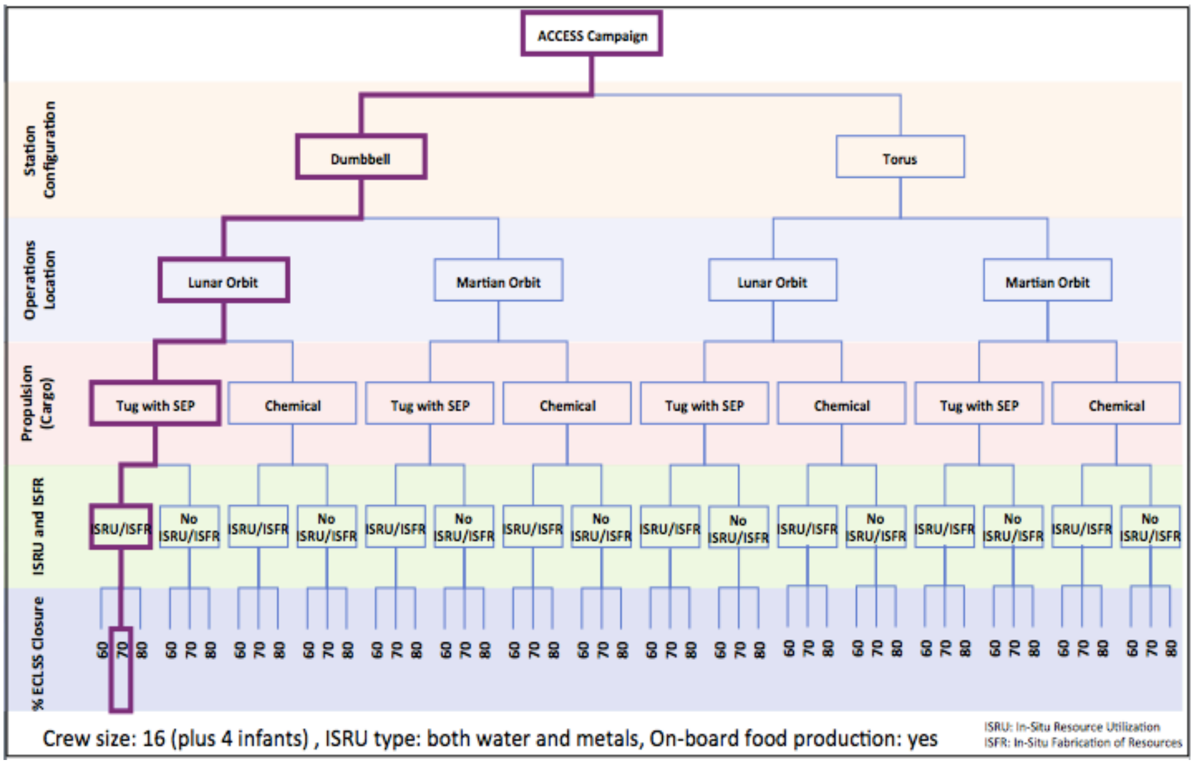



**Figure 2. Key architectural design drivers and decisions (highlighted) based on the ADG framework.**

The key architectural design drivers for the ACCESS campaign are space station configuration, operations location, maximum crew size, ISRU source and type, ECLSS (Environmental Control and Life Support System) loop closure level, propulsion (for cargo transport and station assembly), food production and in-situ fabrication strategies. In order to determine the overall system architecture that best meets the campaign requirements, 15360 unique architectures were generated based on the nine high-level key decision drivers using the Architecture Decision Graph (ADG) framework [1].

The tradespace for each of these key drivers was evaluated against constraints that included initial mass in low-Earth orbit (IMLEO), campaign cost, mission failure risk, developmental risk, and advancement of primary and secondary objectives to obtain 3409 pareto-optimal architectures, as shown in Figure 3. Specifically, we found that collecting water for propellant and metal oxides for spares manufacturing from the lunar surface and growing plant-based food provided the most benefit without increasing mission risks. ECLSS closure was found to be optimal at 70% closed level.

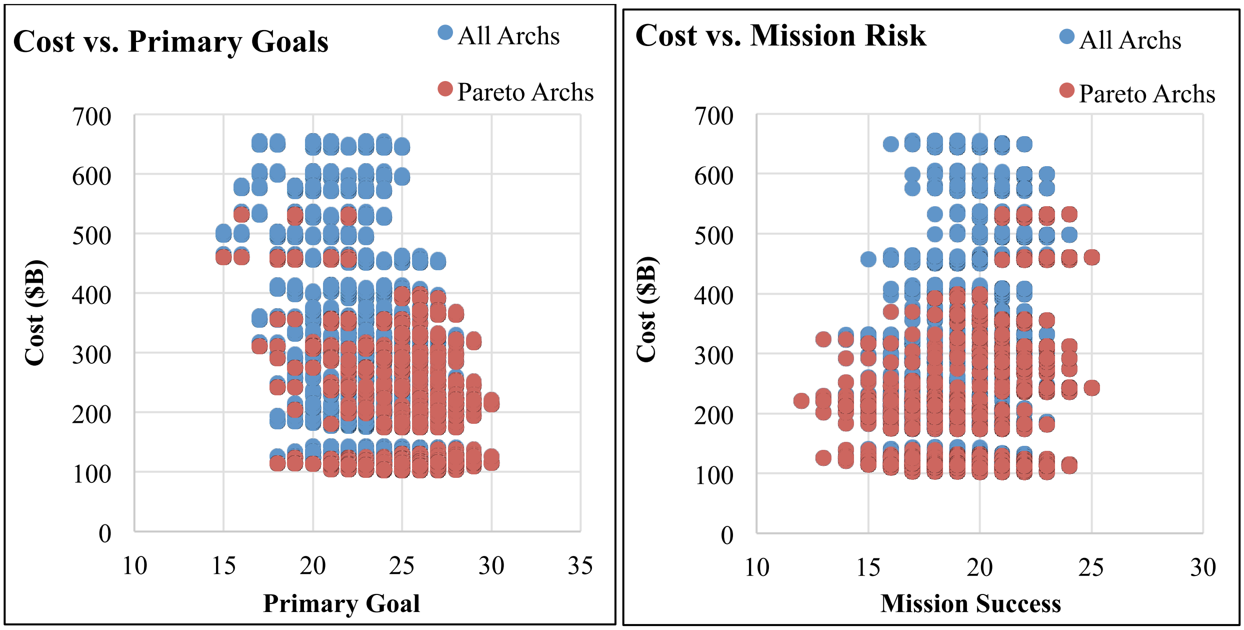



**Figure 3. Evaluation of architectures based on advancement of primary goal (left) and mission success (right) against overall campaign cost.**

The set of key decisions that satisfied all the constraints satisfactorily were 1) Station Configuration – Dumbbell, 2) Operations Location – Lunar Orbit, 3) Crew Size – 16 plus 4 infants , 4) ISRU Source - Moon, 5) ISRU Resources – Water and Metals, 6) Overall ECLSS Closure Level – 70%, 7) Propulsion – Tug with Solar Electric Propulsion (SEP), 8) On-board food production, 9) ISFR Capabilities.

## V. Campaign Design

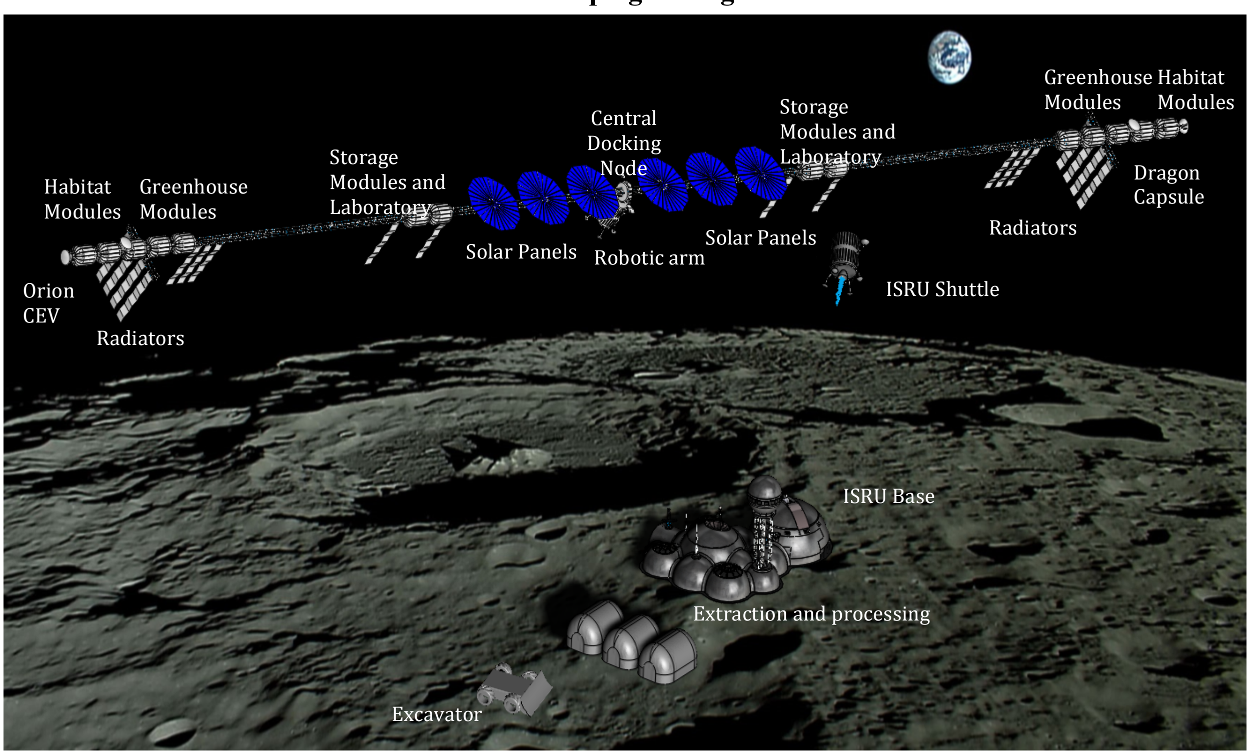



**Figure 4. ACCESS station and lunar base design.**

The ACCESS campaign will demonstrate the capability for humans to live, procreate and work independently in deep space through the creation of a large dumbbell-shaped 1G station and lunar ISRU base. Figure 4 shows the architecture of the ACCESS campaign. The 1G space station consists of three habitat modules, two greenhouse modules, two storage modules and three solar panels on either side of the central docking node. There are two crew escape vehicles, one on either end of the station to enable crew to move quickly from one end of the station to the other in case of an emergency. The escape vehicles can also be used to transfer to a safe orbit from where they can be brought back to Earth. The ISRU Base is located on the lunar South pole and consists of excavation, extraction and processing infrastructure that will produce water and metal oxides. 3 ISRU shuttles are used to transport the resources to the station.

## VI. Orbit Selection

Based on the primary objectives of the mission, several orbit types [2] were considered: LEO, Geo-stationary Earth orbit (GEO), Lunar Lagrange points, Lunar Distance Retrograde Orbit (DRO), Lunar Near Rectilinear Orbit (NRO) and Martian Orbit. Although LEO and GEO would greatly cut down trip duration and cost of launch during the initial phases of the mission due to their proximity to Earth, it would be disadvantageous to have resupply missions from Moon, Mars or near-Earth asteroids to this location in the longer term. Martian orbits would be very expensive for the initial launch and assembly of the space station. The long time duration required to abort the mission and safely return the crew back to Earth in case of an emergency, is a significant risk factor to consider. The Lagrange points EM-L4 and EM-L5 require high delta-v for injection making them unsuitable for resupply missions. The distance of EM-L3 from the Moon makes it difficult to provide frequent resupply of resources from the Moon, thus making it an unattractive choice of orbit for the space station. The Lagrange points EM-L1 and EM-L2 are unstable and require constant station keeping leading to higher propellant consumption compared to the DRO and NRO.

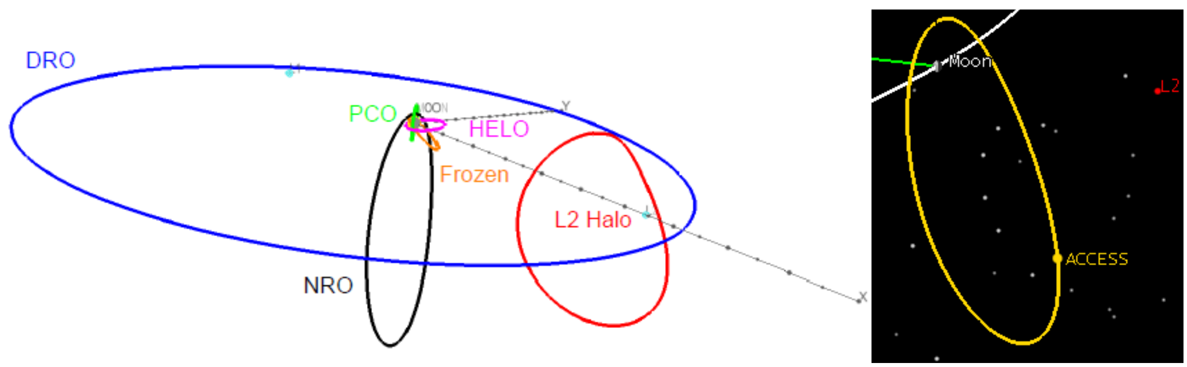



**Figure 5. Left: potential cis-lunar space orbits for ACCESS, Right: the chosen Near Rectilinear Orbit with an altitude range between 2,000 km and 75,000 km, modeled in STK.**

After having evaluated several high level architectures at different potential locations, the space station's operations location was narrowed down to cis-lunar space. Several families of orbits can be found, outlined in Figure 5 and Table 1.

| Orbit | Station keeping | Delta-v Lunar access | Communication with Earth |
|---|---|---|---|
| Low Lunar Orbit (LLO) | 50 m/s per year | 1.8 km/s | 50% occultation |
| Prograde circular orbit (PCO) | 0 m/s for 3 years | 2.57 km/s | Unknown |
| Frozen Lunar Orbit | 0 m/s | 2.85 km/s | Frequent occultation |
| Elliptical Lunar Orbit (ELO) | > 300 m/s | 3.20 km/s | Frequent occultation |
| Near rectilinear orbit (NRO) | <10m/s | 2.43 km/s | No occultation |
| L2 Halo orbit | <10m/s | 2.67 km/s | No occultation |
| Distant retrograde orbit | 0 m/s | 2.70 km/s | Infrequent occultation |

**Table 1. Orbit Comparison**

From these candidate locations, the Near Rectilinear Orbit, or NRO was chosen due to the uninterrupted view of the Earth, which would be a great advantage for the communications subsystem. It has one of the lower transfer delta-Vs to the lunar surface, key to an efficient ISRU strategy. The NRO also has large coverage of the South-pole, allowing for potential teleoperation on the ISRU base.

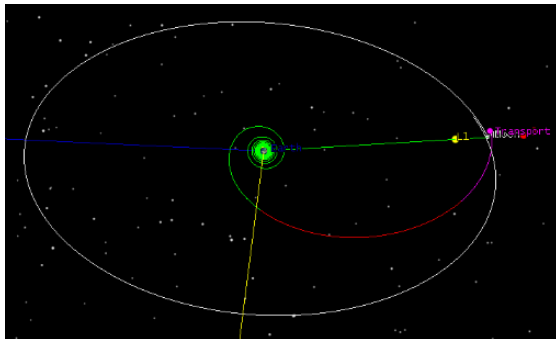



**Figure 6. ACCESS cargo/subassembly transfer with electric propulsion**

Different strategies will be adopted for cargo or subassembly transfer, and crew transfer. Whereas one would desire a short transfer time to the station for the crew, most of the station hardware used during the assembly process, can accommodate longer flights. The biggest advantage of using electric propulsion (EP) for cargo transfer is that it makes available a large mass fraction, being able to transfer more mass for less fuel. EP is an enabler for a tug strategy, which translates to launching the infrastructure that will propel any cargo or subassembly once only, and returning it to the initial orbit and refueling it for subsequent cargo trips. The delta-v required for EP transfer from GTO has been documented to be close to 3.94 km/s [3]. Crew transfers will occur with the Orion vehicle launching from the SLS, or the Dragon vehicle from the Falcon.

## VII. Station Design

### A. Space Station Architecture

The station structure is designed as a "dumbbell" configuration, composed of modules connected by a truss structure. The rotating station uses centrifugal force to create a normal 1G acceleration vector in the vicinity of the crew habitats, the magnitude of which is controlled by the station's truss length (r = 260 m) and rotation rate (2 rpm). The exact gravity levels are controlled by a closed-loop system which contains a set of CMGs at the center, thrusters and acceleration sensors in the habitat modules. This system counteracts any gravity perturbations due to dockings/un-dockings, internal mass flows as well as external perturbations. The detailed ACCESS station design is shown in Figure 7. Three shuttles, used for transporting ISRU-based materials from the lunar surface, take turns to rendezvous with the station's docking port located at the center of rotation, thus allowing for continuous station rotation while engaging and disengaging the shuttle. The overall station architecture consists of 3 habitat modules at each end of the rotating truss together with 2 greenhouse modules for food production and 2 additional storage modules located at the 3/8 G (Mars Gravity) rotation arm. The resources are transported to the habitats using an enclosed elevator system that translates inside the truss, able to support crew movement from one habitat subassembly to the other without the need for Extravehicular Activity (EVA) using space suits. The station will nominally be spinning throughout its lifetime.

Each pressurized unit of the station is an inflatable 20mT module made from flexible fabric layers including Vectran shield fabric that is compactly folded during launch to minimize volume in the SLS payload bay. Once expanded, each 330m$^3$ module will contain three levels (shown in Figure 8). This technology will be developed with a commercial partner based on the Bigelow B330 technology [4]. Each of the 4-crew habitats can house a maximum of up to 6 crew members and each side is fitted with two Orion or Dragon capsules should crew evacuation be necessary during an emergency. The inner modules on each end of the rotating assembly are connected to the rest of the station via a rigid truss structure.

Four modules of the station are located in Mars Gravity (3/8 g) to reduce loads on resource containers and allow for extended research and crew training opportunities in Mars gravity in addition to the lunar gravity of the ISRU Base at the Lunar South Pole.

Each greenhouse module also consists of 3 levels with adjustable racks on both sides of the walkway that allows the crew to gain access and tend to food producing plants. Each greenhouse module will be hermetically sealed off from the rest of the station to maintain appropriate humidity and atmospheric conditions for the plants (higher $CO_2$ levels) while not negatively impacting the crew quarter atmosphere.

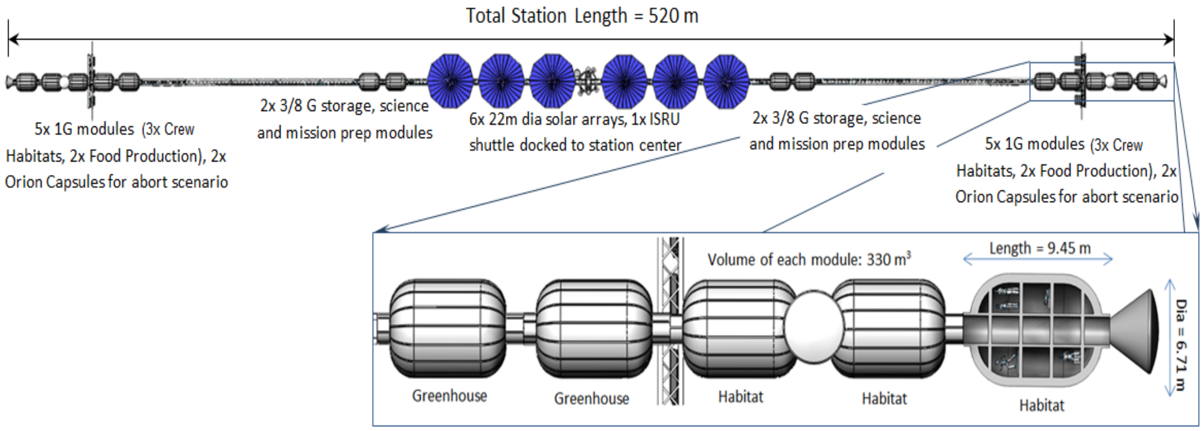



**Figure 7. ACCESS station layout (Total Length = 520m) with individual modules shown**

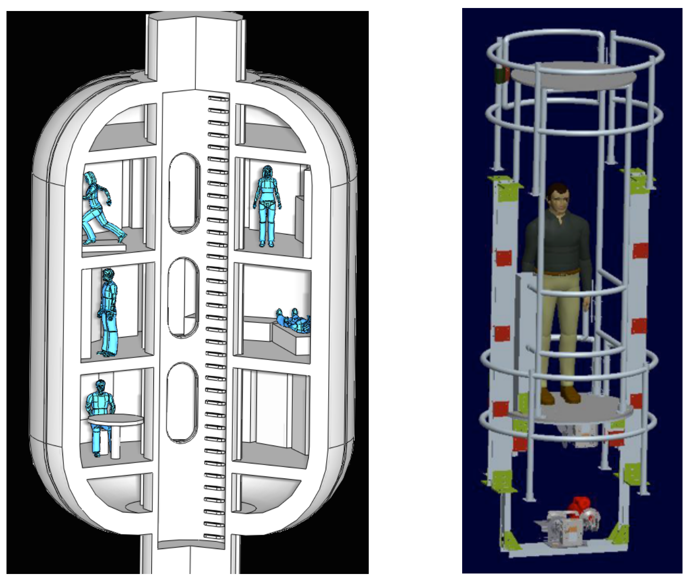


**Figure 8. (Left) Habitat design and (Right) X-HAB Elevator/Man-lift Handrail System**

Similar to the elevator concept used outside of the pressurized modules, a custom-made elevator will be used to transport crew members between levels and modules in the 1G environment, in addition to a backup ladder assembly in case of a power failure. The elevator is based off the X-Hab man-lift system developed for NASA's X-HAB in 2010 [5], shown in 8. This technology is considered to be at TRL 6 or 7.

## B. Truss Structure

The space station is built around a central truss structure that connects the modules and houses the transportation elevators. Given the design of the station, this truss structure must be sufficiently rigid to sustain structural loads, hollow to facilitate the elevators, and expandable to minimize its required launch volume. Initial design iterations considered both a rigid truss structure and a tether design that would provide tensile-only capability. While the tether design was advantageous in reducing the launch volume since it could unfold during the initial spin-up phase, the tether design lacks structural rigidity to react any out-of-plane loads. During operation, the out-of-plane loads generated from docking events, debris collisions, or any thruster firings could cause stability issues among the modules. Therefore, the truss structure was selected for its ability to rigidly separate the modules and to stabilize the entire station along its length.

Given the substantial length of station and the truss structure, the truss technology required an expandable design to minimize the required launch capacity. The concept for the truss assembly is based on the Middeck 0-Gravity Dynamics structural Experiment (MODE) Modular truss system that was flown on STS-48 [6]. The truss will be developed in collaboration with a commercial partner. The MODE project was a NASA-funded technology developed in the 1990s at the Aurora Flight Sciences Corp to test an expandable truss. The design used positive latching mechanisms to lock into place as the structure was extended from its compressed launch position. The project reached TRL stage 7-8 and was successfully tested in space. The utilization of this MODE experiment as the foundation of the truss design minimizes the truss development cost and reduces the development risk.

### C. Elevator System

Inside the truss structure are transport elevators to facilitate movement because of the station's artificial gravity. The design incorporates two different elevators: 1) a larger volume material transport elevator between the outer living module and the center docking node, and 2) a smaller elevator between the individual living modules. The primary purpose of the transport elevator will be to aid the crew in distributing resources from newly-docked ISRU shuttles to the storage modules or the living quarters. These elevators will run on a track system inside the truss structure, and the elevator cabins will be pressurized to allow for non-EVA travel to the center node and amongst the other modules.

To provide additional redundancy to the station design, ladder handles will be positioned along the truss's length to facilitate crew movements in case of elevator failure. Additionally, the emergency escape capsules located near the living modules can be used to immediately evacuate the station or relocate to the station's opposing end if one portion of the station becomes inoperable.

## VIII. Key Station Subsystems

### A. Propulsion

An efficient propulsion system is required to transport the ACCESS station modules from Earth to NRO during the assembly phase to the operations location (3.94km/s $\Delta V$ from GTO), to transport the crew to and from the station including the provision of a crew abort option for emergency situations (0.73km/s $\Delta V$ to LLO), and to transport ISRU materials from the lunar surface plant to the station (2.43km/s $\Delta V$). This resulted in the selection of a Solar Electric Propulsion (SEP) system for cargo flights as transfer duration is less of a priority than mass efficiency. This sytem reduces propellant mass for a given mission, enables longer-duration missions, allows for missions with multiple destinations, and provides mission flexibility for unforeseen in-flight anomalies. The mission concept of operations resulted in an assembly design utilizing a propulsion 'tug' module with large solar arrays and a 200kW SEP system to ferry payloads from GTO to NRO for ACCESS assembly, returning the tug vehicle to Earth for refueling between transfers. The X3 Nested Hall Thruster was chosen for the SEP system. This system was developed during 2011-2013 through a collaboration between the University of Michigan, the Air Force Research Laboratory, NASA Glenn Research Center and the Jet Propulsion Laboratory and is still undergoing ground testing. A representative prototype system demonstration has been tested up to 60kW power input in a high-fidelity laboratory environment, representing a TRL of 5-6.

| **X3 Nested Hall Thruster Properties** | **Value** |
|---|---|
| Power input | 1-200 kW (throttlable) |
| Specific impulse | 1400-4600 s |
| Thrust | 1.5 N at 30 kW (proven); 15 N at 200 kW (predicted) |
| Thruster dry mass | 170 kg |
| Thruster diameter | 0.83 m |

| | |
|---|---|
| Propellant | Xenon |

**Table 2. Properties of the X3 Nested Hall Thruster SEP System**

Based on a 3.94km/s ΔV from GTO-NRO and transporting 44mT of payload per transfer, the 200kW system would spend 5 months spiraling out to the operations location, requiring 7mT of propellant. If the payload is increased to 100mT per transfer, it would take 11 months and 15mT of xenon. Using an SEP system also correlates with NASA's goal to continue to mature higher-power Hall thrusters and ion engines for flight with the $6.5M NextSTEP (Next Space Technologies for Exploration Partnership) award made in 2016 to Aerojet Rocketdyne for the development of the XR-100 Hall Thruster, with $1M of the award going to the X3 NHT considered central to the system. NASA's 2016 budget dedicates $491M to Space Technology Research and Development with target key technology thrust areas including high-power SEP, with a mention of 30-50kW solar array and 15kW Hall Thruster technology demonstration missions. The NASA Technology Roadmap for In-Space Propulsion Technologies also predicts a minimum technology maturation time of 1-3 years for Hall Thruster systems and lists a need for the technology for 12 NASA Mission Classes through 2029. The Roadmap also emphasizes on maturing a 10 to 15 kW class [Hall] thruster for use with near-term human exploration missions, while continuing to explore and mature single thrusters in the 50 to 100 kW range, and nested Hall thrusters that exceed the 100 kW range. A 50 kW SEP system is being developed for the Asteroid Redirect Mission.

For crew transfers, a more traditional chemical propulsion systems was chosen, with the Falcon Heavy and Space Launch System being two viable candidates given the specified mission timeframe, with the option to use both launch vehicles as required by the operations timeline. SLS transfers would be limited to twice per year, but would enable a fast transfer of only 3 days. For emergency abort scenarios, the Orion Multi-Purpose Crew Vehicles would be used, with Orion Service Modules attached to supply a 1.34km/s ΔV capability that enables separation from the station and transfer into a Low Lunar Orbit (730m/s ΔV), allowing at least 4 and potentially up to 6 crew members per capsule to endure up to 21 days while a launch vehicle is dispatched from Earth for retrieval. This also meshes with NASA's current development goals, with $1.096B devoted to furthering the Orion Program crew transport in the 2016 budget.

For the ISRU shuttle, emphasis was placed on selecting a propulsion system that could be refueled using the ISRU plant. A LH2/LO2 engine was chosen as a relatively simple system with established flight heritage to allay reliability concerns, with three ISRU shuttles in use to provide redundancy. The Aerojet Rocketdyne RL10C-1 thruster was selected, requiring 23.7mT of H2 for the NRO-lunar surface transfer (ΔV of 2.43km/s): around 46% more propellant compared to the similar RL10B-2 engine used as the Delta III second stage.

| **Aerojet Rocketdyne RL10C-1 Properties** | **Value** |
|---|---|
| Specific impulse (vacuum) | 450 s |
| Thrust | 101.8 kN |
| Thruster dry mass | 190 kg |
| LH2 and LO2 tank mass | 1090 kg |
| Dimensions | Length 2.22m, diameter 1.44m |

**Table 3. Properties of the Aerojet Rocketdyne RL10C-1 LH2/LO2 Engine**

### B. ADCS

The Attitude Determination and Control System stabilizes and orients the station as it spins in order to generate artificial gravity while orbiting the moon. As the space station spins in a certain plane while operating in the NRO, it has to reject disturbances from several sources, such as radiation pressure and gravity gradient. Due to a constant solar pointing strategy, the station will need to apply a significant torque to rotate the plane of rotation of the station, as the station orbits the Sun. Due to the size of the station these perturbation and maneuvering factors are not negligible, and need to be taken into account, even at this early stage of architecture design. Although designing the ADCS system deals with sizing of both sensors and actuators, this project will only concern itself with sizing the actuators, as any sensors, such as star trackers, inertial measurement units (IMUs) or Sun sensors will compose a marginal weight of the larger structure. This sizing is achieved through an analysis on the momentum budget that the ACCESS station will need to meet. Table 4 outlines the torque that actuators will need to provide to reject disturbances, and ensure a sun-pointing station.

| Torque source | Equation | Calculation | ACCESS value |
|---|---|---|---|
| **Gravity gradient** | $T_g = \frac{3\mu_{moon}}{2R^2}\lvert I_z - I_y\rvert$ | $I_z = Mr^2, I_y = 0$<br>$R = r_{s-moon}$ | **1,140 Nm** |
| **Solar radiation pressure** | $T_{sp} = F(c_p - c_g)$<br>**Where** $F = \frac{F_s}{c} A_s(1 + q)\cos(i)$ | $i = 90°$ | **-** |
| **Torque to keep station Sun Pointing** | $T = \Omega I_z \omega$ | $\Omega = 1\text{rot/year}$ | **6,463 Nm** |

**Table 4. ACCESS Torque budget and mitigation**

In order meet these torque requirements, ACCESS will use control moment gyros (CMGs), for torque and momentum management, combined with thrusters for momentum mitigation as it builds up due to the gravity gradient. The CMGs combined with attitude thrusters are also used for ongoing artificial gravity control.

### C. Power and Thermal

The power subsystem is designed to supplement and support ACCESS's unique architecture. The key design driver behind the power subsystem is robustness. To that end, we have selected the Orbital ATK Ultraflex Solar Array as our primary panel technology. The Ultraflex panels have extensive flight heritage from the Mars Phoenix Lander to the Cygnus capsule, and are marketed as high power low mass power solutions. NASA is already working with Orbital ATK to produce larger panels for the Asteroid Redirect Mission, so continuing NASA's current investment will facilitate panel production for ACCESS [7]. The current station design has six 22m-diameter solar panels, optimally producing ~630 kW of power. The majority of this power will be used to maintain the extensive greenhouse systems on ACCESS (~320 kW), with significantly smaller portions of the power budget allocated for ISRU Processing (~75 kW), ISFR (~18 kW), ECLSS (~18 kW), and general space station bus and robotics (~50 kW). The current sizing of the panels provides for significant margin for subsystem growth and inefficiencies in the solar panels; however, the solar panels will be oriented towards the Sun at all times, which will allow for optimum incidence. The lunar ISRU plant, with its similarly high power demands of 300 to 400 kW, will be provided with a similarly sized system, with six 20m-diameter panels producing ~530 kW. The tug system is designed with three 22m-diameter panels, producing ~310 kW, meant to power high power electric propulsion thrusters with plenty of margin for inefficient pointing. Finally, each ISRU shuttle will have two 5m-diameter panels to provide several kW of power for lighting and electronics.

These energy inputs eventually have to be radiated out, and for that, ACCESS will have an established, high TRL thermal system paired with modern radiator technology. On the passive side, the station will be covered in multi-layer insulation and surface coatings to block out solar flux, the largest source of heat. To supplement that is the active ACCESS system, which is based on the ISS Active Thermal Control System, with heat exchanges placed in modules that collect heat and transfer it via ammonia lines to heat radiators outside the station [8]. The ISS Heat Rejection System radiators were built by Boeing, with Lockheed Martin as a subcontractor, and while their fundamental design is solid, the surface itself was only able to reject ~14 kW per radiator. In recent years, however, radiator technology has gotten better; a commercial group, Thermal Management Technologies, has with Air Force funding recently shown that they can develop a panel with double the heat rejection per square meter compared to the HRS radiators [9]. That technology is currently developed at a TRL 4 level, so it is important for NASA to continue investments into this upcoming radiator technology. The lunar plant is sized to have a similar system, since the Moon allows only for radiation of heat. The shuttle and tug have simpler thermal systems consisting of a heat exchanger and mounted radiator surfaces.

### D. Communications

The communication systems of ACCESS also follow this paradigm of robustness and reliability. The current specifications involve radio based systems, which have been the dominant mode of communication from, to, and in space for decades. For communication from the station to Earth, plant to Earth, and from the station to the plant, the Ku-band provides the bandwidth and pointing requirements that are desired; there are a plethora of satellites orbiting Earth as well as antennas on the ground designed for Ku-band communication. Using a pre-existing satellite system, such as NASA's tracking and data relay satellites (TDRS), ACCESS can achieve more accurate and longer communication times. Considering that from the Moon to Earth, there's a ~220 dB loss due to free space, optimized pointing is necessary. The design of ACCESS offers another unique challenge, in that the station is split into two large sections that need to communicate with each other; for this, the habitat modules are all equipped with an S-band radio system. All of these technologies are well developed; however, ACCESS will become operational decades into the future, and developing laser communication technology in the intermediate time is a major priority. After the NASA Lunar Laser Communication Demonstration showed the powerful data rates that can be achieved via laser communications, it is clear that developing this technology for use on ACCESS is a high priority.

### E. ECLSS

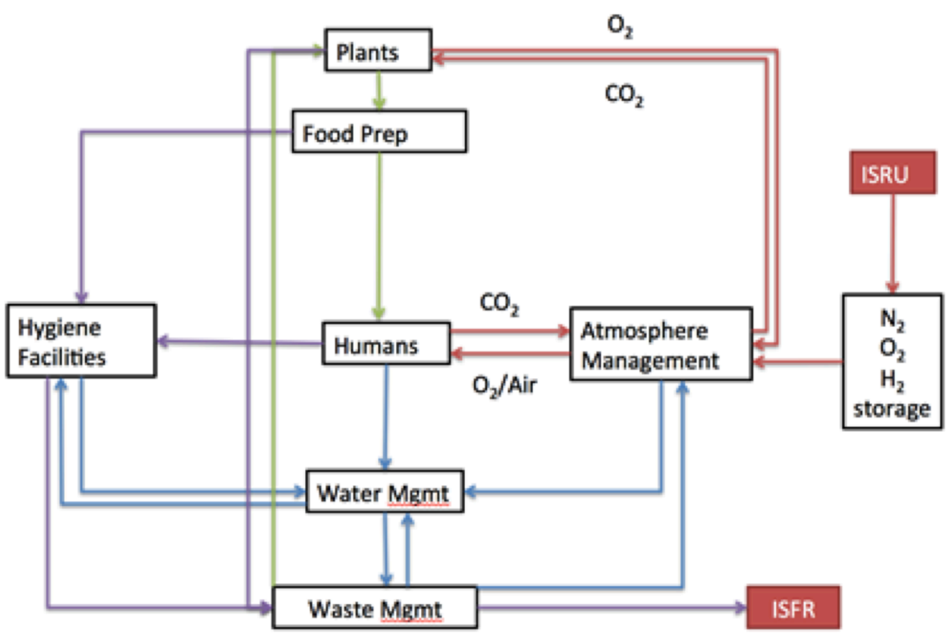



**Figure 9. ECLSS loops onboard the ACCESS Station**

For human beings to survive in space, they require water for food preparation, drinking and cleaning; food; oxygen and carbon dioxide removal. The size of crew determines the scale of the equipment required for water recycling, carbon dioxide reduction and oxygen production systems. Therefore, the smaller the crew, the lower the demand on these systems and lower is the required initial mass of the space station. ACCESS's current plan is to utilize a crew of 16 in addition to infants born on the station. Waste water recycling reduces the relative supply mass by 55% which is the largest required consumable for life support systems. Additional gains can be made by regenerative carbon dioxide absorption (15%), oxygen recycling from carbon dioxide (10%), food production by utilization of recycled waste (10%) and elimination of leakage (5%). ECLS systems for the ACCESS mission can be designed based on ISS heritage and terrestrial water recycling systems and farm use of waste. The application of 1-G will also allow for development and testing of these systems on Earth through the next 20 years. There are four major life support functions that must be managed in the ECLS system as shown in Figure 9: 1) atmosphere, which includes controlling pressure, temperature, humidity removing trace contaminants, providing makeup gases and monitoring the atmosphere's composition, 2) water, which includes providing water for drinking and hygiene, monitoring water quality, storage and distribution, and collecting and processing waste water, 3) waste, which includes collecting, processing, and storing human waste and trash, 4) and finally, food, which includes provision, storage, and preparation of foods.

For atmosphere management, the ECLSS will use a combination of physico-chemical options and bioregenerative options. The plant selection that will be grown onboard the station will provide oxygen and absorb the carbon dioxide generated onboard by humans. Temperature and humidity control as well as pressure control will be maintained by a condensing heat exchanger (CHX) and valves. There will also be Trace Contaminant Control (TCC) in order to monitor and maintain the atmosphere makeup. A Sabatier reactor will also supplement the atmosphere management loop by providing $CO_2$ reduction through a reaction process with hydrogen to create water. If necessary, the water can be broken down into hydrogen and oxygen through electrolysis. Nitrogen will be used for atmospheric makeup as well as controlling pressure due to structural leakage. Hydrogen and oxygen will be stored onboard and resupplied through ISRU, and all nitrogen necessary for the 20-year mission lifespan will be stored on the lunar surface with storage available on station as well.

For water and waste management, a month's worth of water will be stored on board for all food and hygiene functions. For water processing, water will be processed in two distinct units: waste water will be processed via multifiltration, which is relatively uncomplicated and requires little development, urine will first be sent through vapor compression distillation (VCD) before the distilled water is sent through the multifiltration unit for final processing. Solid human waste will be sent to the greenhouse as fertilizer and nutrients for plants to produce food, and any excess will be sent to ISFR for water extraction and recycling. Plants on station stored in a greenhouse will provide food for the crew.

## IX. Earth Independence

### A. Food Production – Crossover analysis between food resupply vs. local biomass production

There are three ways to provide astronauts with food on a space station: bring everything, grow everything, or a combination of the two. For this mission, the first 90 days will have pre-supplied food brought from Earth, and after that point everything will be grown on the station. Figure 10 shows the mass demands for the space station depending on the method utilized. A crossover point is reached after about 14 years.

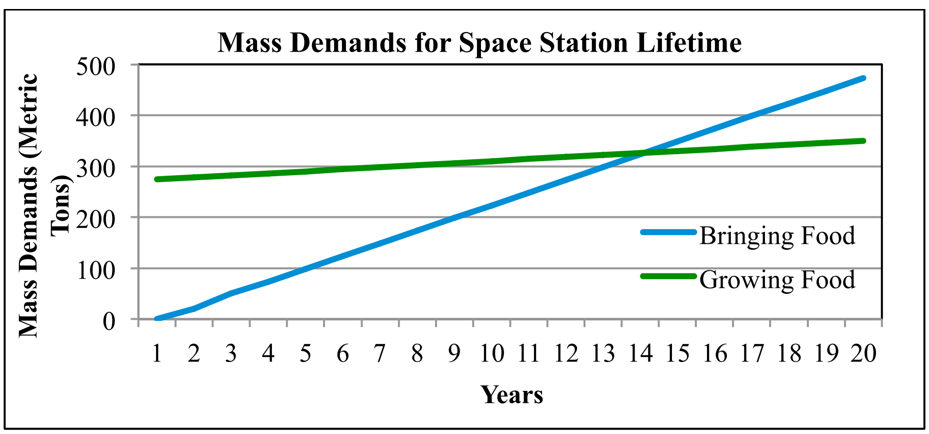



**Figure 10. Mass Demands for ACCESS Lifetime**

This provides justification for growing food for the duration of the mission. ACCESS will be fully sustained by wheat, soybeans, white potatoes, sweet potatoes and peanuts in the ratios seen in Table 5. Four of the modules will be devoted to crop production and will consist of 200 $m^2$ per module with 3 levels, each with 3 layers of hydroponic trays to grow crops as shown in Figure 11.

The shelves will be placed on racks with the ability to have variable heights. Blue and red LEDs will provide light to the crops to improve crop efficiency [10,11]. The modules will be isolated from the habitats to better control the atmosphere. Excess $O_2$ will be stored in tanks and the excess $CO_2$ from the habitat will be fed into the food production modules.

The crops will be maintained by the crew to include harvest, pollination, and regulation of stored nutrients. This will provide the crew with meaningful tasks and assist with ECLSS loop closure by processing waste and providing oxygen, while demonstrating the sustainability of the space station. The space station will be equipped to process the food, with equivalent facilities at both ends of the space station [12].

| | Percent of Growth | Type of Propagation |
|---|---|---|
| Wheat | 36.3% | Seed |
| Soybeans | 19.9% | Seed |
| White Potato | 2.5% | Plantlets |
| Sweet Potato | 5.0% | Cuttings |
| Peanuts | 36.3% | Seed |

**Table 5. Crops to be grown on ACCESS [13]**

To date, one mission has been flown to ISS to validate the capability to grow crops in the space environment. The Vegetable Production System in 2014 showed the capability to grow lettuce in a small chamber. This technology is currently TRL 6. To validate the capability and sustainability of this process future missions will be required to show a larger scale of at least 10 $m^2$ but preferably 25 $m^2$ of each crop. This will validate crop yields shown in NASA's terrestrial hydroponic studies and help determine effective logistic practices for crop growth in confined areas and atmospheres. Improvements in LEDs and agriculture could reduce the space and power requirements for food production. In addition the developments of Memphis Meats by scientist Mark Post could allow for the possibility to grow meat on the station which would provide an additional source of protein and add variety to the astronaut's diets. Vitamins will be provided to supplement the crew's diet beyond the nutrients provided by the crops.

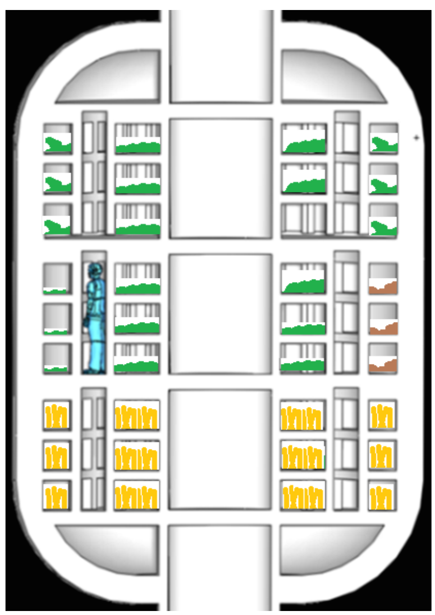


**Figure 11. Green House Module with Crew Member**

**B. Waste Management**

Two technologies that are central to the waste management strategy are the heat melt compactor (HMC) and the trash-to-supply-gas (TtSG) reactor. The HMC is a device under development by NASA as part of the Advanced

Exploration Systems (AES) Human Spaceflight Logistics Reduction and Repurposing (LRR) project, and is designed to compact trash to extract water and produce radiation shielding tiles. Figure 12 shows the inputs to and outputs from the HMC based on current technology:

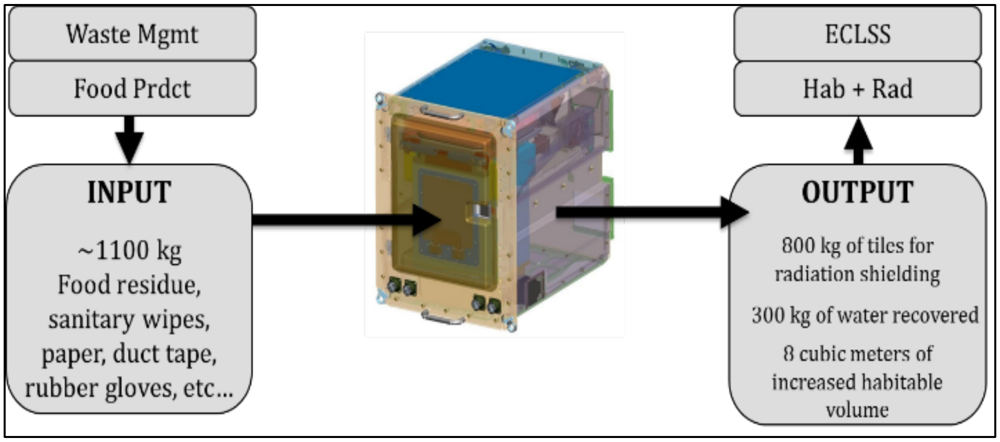



**Figure 12. Representative Technology: Heat Melt Compactor**

The TtSG reactor, also a technology being developed through NASA's AES LRR project, is designed to convert trash to propellants. Figure 13 shows the inputs to and from the TtSG reactor based on current technology.

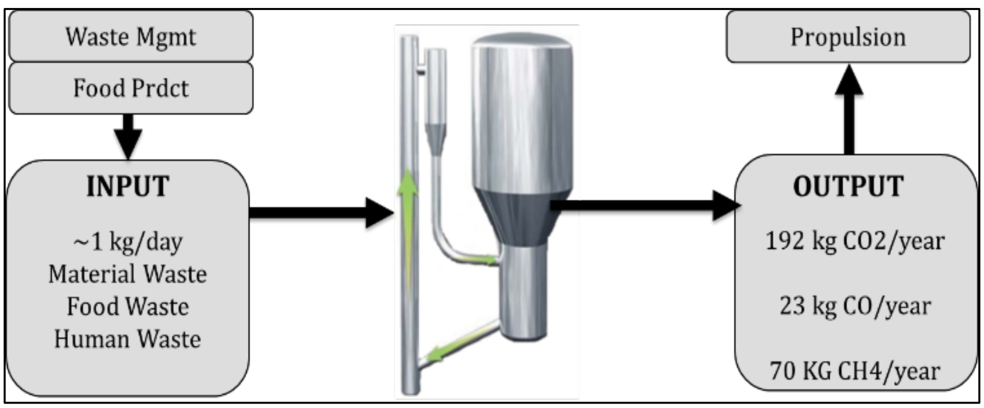



**Figure 13. Representative Technology: Trash to Supply Gas Reactor**

### C. Maintenance and Spares Manufacturing

The ISFR strategy consists of using aluminum, titanium, silicon, and iron from lunar regolith as feedstock to produce metallic spares, and recycling of used plastic components as feedstock for plastic spares. NASA also recently issues a call for proposals (STRI) in the area of biological manufacturing of biopolymers. Using currently available commercial technology and assuming sufficient research and development are undertaken to increase the manufacturing envelope, increase build speed, and expand the range of processable materials, approximately 62%, or 13,500 kg of the estimated 23,100 kg per year demand for spares can be replaced with additive manufacturing (AM) as shown in Figure 14. Figure 15 shows the subsystem-wise breakdown of replaceable spares in comparison to the total estimated spares demand.

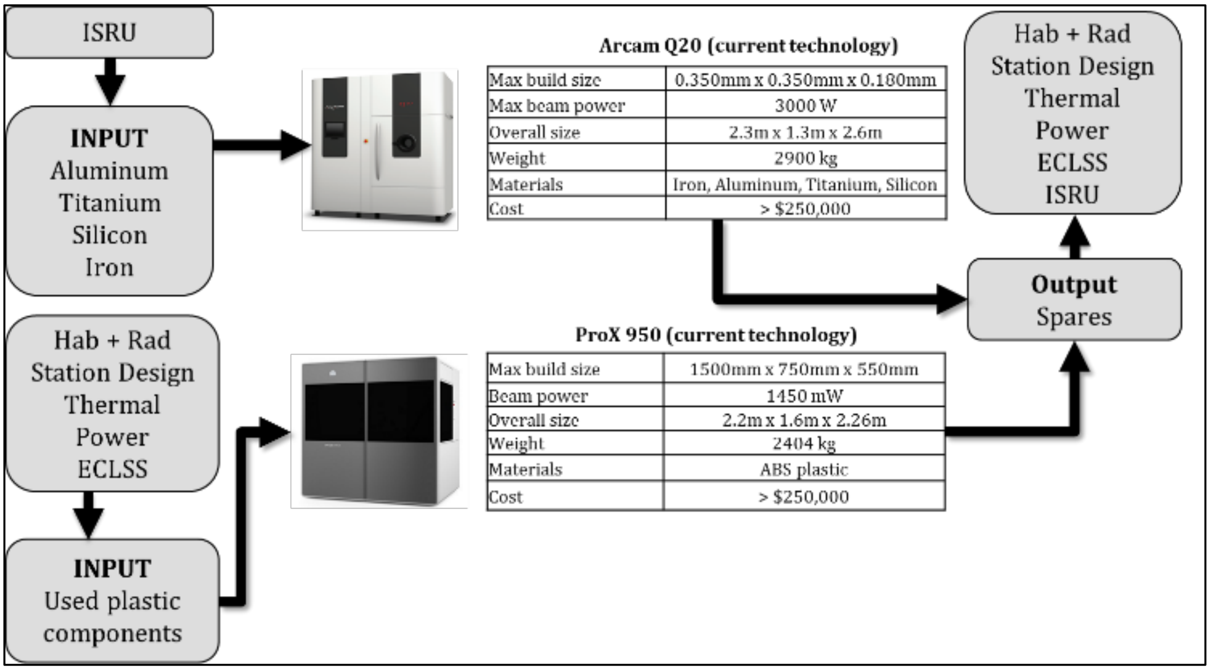



**Figure 14. Representative additive manufacturing technology**

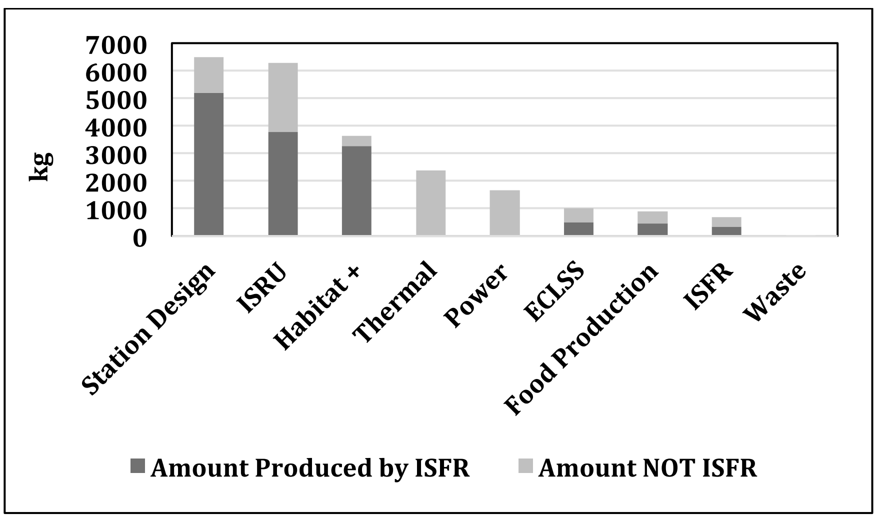



**Figure 15. Spares replaceable by additve manufacturing on station.**

### D. ISRU

**ISRU Motivation**

The ISRU subsystem will meet three needs of the station in support of Earth independence. The first, and most immediate need is to provide resources to the station. Some subsystems, such as ADCS, can be considered completely open loop, and their resources must be replenished continuously. Other subsystems, such as ECLSS or ISFR, may be able to achieve some level of closure; however, due to inefficiencies, leakage, marginal cost and complexity of achieving near-100% closure, these consumables must also be replenished. Potential resources needed by the station include water, oxygen, hydrogen, nitrogen and metals. The second, and longer term goal of the ISRU system is to provide access to the lunar surface for both humans and robotic equipment. This will build up expertise in operating tele-robotic, and automated systems on other bodies in sub-1G, dusty environments. The third goal of the ISRU system is to develop infrastructure needed for long term in-space settlements. This includes the means to resupply in-space fuel depots for deep-space missions, provide feedstock for manufacturing of components or entire spacecraft in space, and supply habitation systems with crew consumables.

**ISRU System Overview**

**a. Location**

The resources for the station will be obtained from the craters of the Lunar South Pole [14, 15], many of which are permanently shadowed, allowing materials like water ice to stay in the craters without sublimating in the vacuum of space. The water ice can provide water for the station's ECLS systems, and LOX/H2 for the ADCS system and ISRU shuttle itself. The lunar regolith in these regions can also provide oxygen, and metals such as iron, aluminum, and titanium [16, 17]. On the rim of the craters there is almost permanent solar illumination, with areas over 98%. Based on the location of the station in lunar NRO, the shuttle must only achieve 730 m/s from NRO to LLO and 1870 m/s from LLO to the surface itself.

**b. ISRU Concept of Operations and Dependencies**

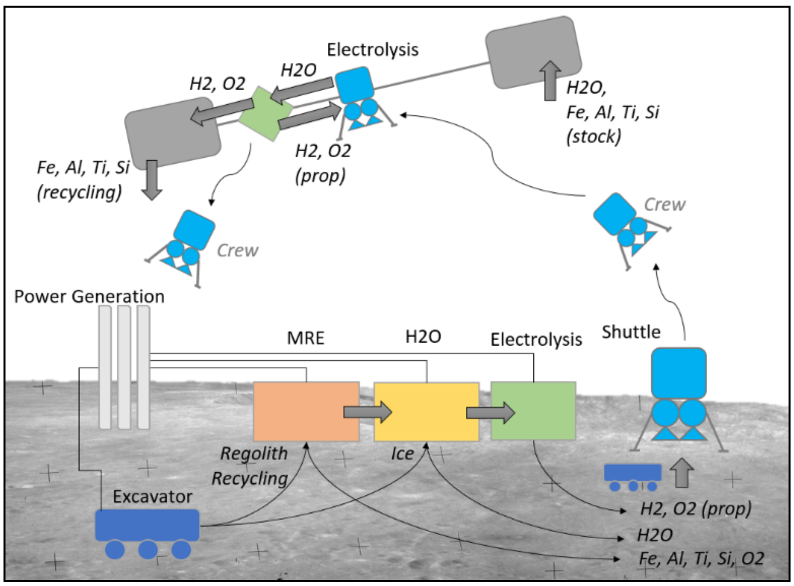



**Figure 16. ACCESS ISRU Schematic.**

| | | |
|---|---|---|
| Surface: MRE Reactor | Separates O2, Fe, Al, Ti from regolith | TRL 3-4 |
| Surface: Electrolyzer | Splits water into H2 and O2 | TRL 4-5 |
| Surface: Excavators | Collects icy regolith and ice crystals, transports material to/from shuttle | TRL 5-6 |
| Surface: Storage | Cryogenic storage for O2 and H2 ascent propellant | TRL 5-6 |
| Orbital: Electrolyzer | Splits water into H2 and O2 descent propellant | TRL 5-6 |
| Orbital: Storage | Cryogenic storage for O2 and H2 descent propellant | TRL 6-7 |
| Transportation: Shuttles | Moves refined resources, recycling, spares, and crew | TRL 4-5 |

**Table 6. ACCESS ISRU element function and TRL level**

The ISRU system for ACCESS consists of three main groups of elements decomposed based on their function: surface, orbital, and transport. The elements and their functions are shown in Figure 16 and listed in Table 6. The elements represent a minimum functional system to achieve sustainable lunar ISRU capability to the station for water, metals while also considering transportation, sparing, and boil-off. A system model was developed in order to size each element [18, 19, 20]. Given the large number of coupled variables, closed architectures were determined through numerical methods.

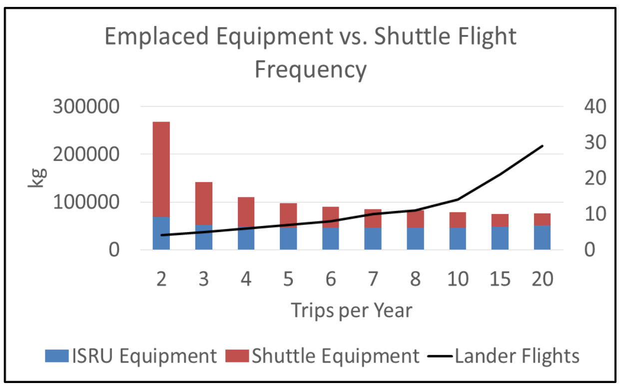
The ISRU system will be brought to the lunar surface through a bootstrapping strategy [23]. The shuttles will be used to land the ISRU system from NRO in small, modular chunks. Initial propellant production will be very small, so the rate of shuttle flights during emplacement will be low at first and increase with production as more equipment is delivered.

In the process of designing and sizing all of these elements, a number of decisions must be made which have significant effects on reliability of the system, its operational complexity, and the overall value to the station.

### c. Complexity and Reliability

The delivery frequency (trips per year) is a key variable that must be determined and significantly impacts system mass and complexity. At low frequencies, the shuttle must be very large to accommodate large payloads over a small number of flights. At high frequencies, the shuttle size decreases, however reliability must increase. This impacts our emplacement strategy because the shuttle payload capacity is fixed and scales with its size. These effects can be seen in Figure 17. The balanced solution of six trips per Earth Year, equating to shuttle deliveries to the surface, has been selected for this design.

The ISRU system is critical to the survival and success of the station's mission; the human population on the station will not be able to survive without it. For this reason, we must address the maintenance strategy and reliability of the elements. The shuttle is designed with a crew cabin for two which can stay on the surface for up to two weeks; it is based on NASA's MMSEV (Multi-Mission Space Exploration Vehicle) and will allow human maintenance when required. All of the elements will be co-designed with the ISFR system to the greatest extent possible so that replacement components can be made on-demand when time permits.



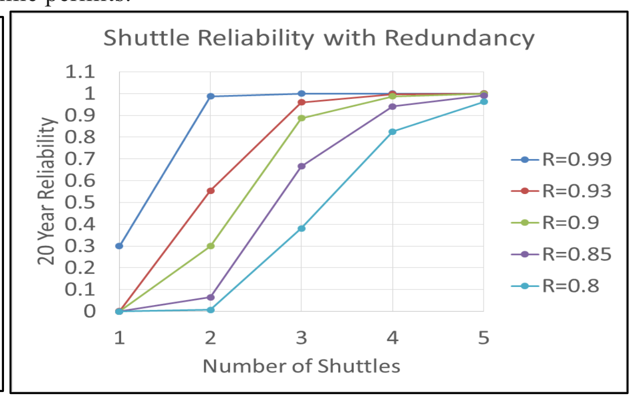



**Figure 17. (Left) Effect of flight frequency on mass and lander trips and (Right) Shuttle reliability vs. redundancy.**

Due to the large numbers of shuttle flights required over the life of the station, we present a detailed analysis of its operation. It is assumed that a single shuttle could achieve a round trip reliability of 0.93. At six trips per year, we then investigated the shuttle's reliability over time as a function of total number of redundant shuttles available. With three shuttles, our chosen design, the system achieves 96% shuttle availability of shuttles over twenty years as shown in Figure 17.

### d. Recycling

The MRE reactor can be used to recycle discarded metal components into pure feedstock by adding these components into the molten regolith melt pool (80% of the material in the reactor must be regolith for proper functioning). This reduces the amount of regolith needed to be collected and processed, just as terrestrial recycling makes the material economy more sustainable. However, the MRE system must be located on the surface for safety as it reaches temperatures over 2500 K, so any recycled components must be added to the payload of the shuttle during descent. The effects of percentage of recycling on ISRU system mass are shown in Figure 18. Using the maximum possible recycling ratio of 0.5 reduces the ISRU processing mass by approximately 25%, a substantial savings. At this level, the excavator needs only to move 1030 kg, or 0.68 $m^3$, of regolith per hour.

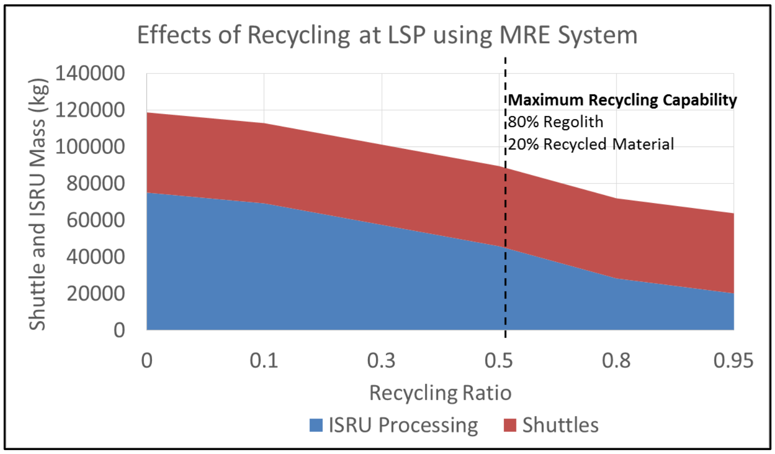


**Figure 18. Effect of recycling ratio on ISRU mass.**

**ISRU System Specifications and Value**

The final designed system mass delivered to NRO and the LSP is 82,400 kg. This includes the three shuttles of 14,600 kg wet mass, 4,100 kg un-crewed excavator, 15,000 kg MRE reactor, and 3,400 kg surface electrolyzer. Although providing an ISRU capability helps to develop a long-term in-space infrastructure, it is important to evaluate the value of the investment for ACCESS. We evaluated the system based on total mass launched from Earth over its continuous lifetime. The value of the large initial emplacement is derived from the cumulative useful mass delivered to the station. Figure 19 shows that the crossover point, where the ISRU system has essentially paid for itself (in terms of mass balance), occurs after approximately 3.5 years of operation.

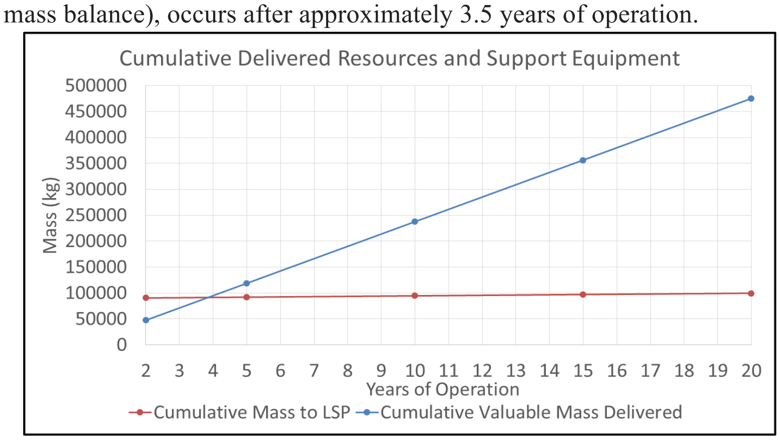


**Figure 19. Breakeven point for ISRU operations.**

**ISRU Technology Development and Current Investments**

There are many uncertainties and current technology gaps associated with the ISRU system and its development will be a significant NASA investment. However, there are projects which are currently underway or in planning which will assist in the process. Lunar mapping missions such as Lunar Flashlight, Lunar IceCube, Luna-H Map, and SkyFire are necessary to begin to evaluate candidate landing sites based on remote observation. It will also be necessary to explore the selected site directly, and so we propose two small rover missions "Sutter" and "Marshall" to characterize the regolith composition for refinement as well as civil engineering (e.g. creating landing surfaces, foundations, packed roads). NASA's Lunar CATALYST program is helping to develop the shuttle technologies needed for landing payloads during emplacement and steady-state operations. NASA's continuing work developing regolith excavators at multiple scales (i.e. Chariot and Cratos) will feed directly into the design of the ISRU element. Small scale MRE systems have been developed for use in the laboratory but are far from the level of water electrolyzers, and will require the majority of effort. It is recommended that a small scale, fully functional, ISRU system be tested prior to station assembly to mitigate risk of mission failure or even crew loss.

## X. Biosphere for Humanity

### A. Radiation Protection

Radiation is a key safety risk associated with long duration deep space missions and while certain steps can be taken to mitigate the risks, more research is needed to mitigate uncertainties associated with the carcinogenic effects of space radiation [24]. ACCESS's radiation shielding strategy involves the use of liquid hydrogen and polyethylene layers to shield the crew from harmful Solar Particle Event (SPE) and Galactic Cosmic Ray radiation along with favorable crew selection criteria and mission planning to avoid exposure during high dose periods. The literature indicates that a 20g/cm$^2$ liquid hydrogen shield halves the fatal cancer risk of 40-yr old males from 2.8 to 1.4% when compared to aluminum [25]. Given the expandable module's design, the ACCESS station can accommodate up to 100cm of liquid hydrogen inside the inner walls of the modules, with an additional water tank shelter for the crew to take refuge in during SPEs, thus effectively quadrupling the shielding afforded to date.

**Figure 20. Mutli-layer shielding strategy for the habitat modules.**

### B. Human Reproduction

While little is known about the effects of the space environment on human reproduction, we know that the two major concerns lie in radiation and microgravity. During the Apollo missions, each astronaut received an average radiation dose of between 0.18-1.14 rem for eight to twelve-day missions. Researchers have found that male exposure to radiation as low as 10 rem can lead to reduced sperm production levels and even infertility. The NCRP recommends total radiation doses for pregnant women not exceed 0.5 rem. Fetus exposures over 10 rem are associated with microcephaly and mental retardation. Additionally, while microgravity will not be an issue in a space station with artificial gravity, microgravity allows fertilization to occur normally but standard gravity is needed for embryo development. For standard medical equipment requirements, facilities comparable to facilities found onboard a traditional Navy ship or on the ISS will be maintained on the ACCESS station. In order to support normal childbirth, we will have few additional requirements such as ultrasound machines and epidurals for Caesarean sections. Personnel required will include flight surgeons (who are expected on board regardless for general medical/health requirements) as well as nurses. All women who plan to bear children on station will be limited to one child through C-section, in order to prevent the complications that arise with multiple C-sections. While the chance of childbirth complications are 4 in every 1,000, the set requirements aim to lower the chances of childbirth complications by ensuring that either the woman has already demonstrated the ability to survive vaginal childbirth, or that she is not put in danger of vaginal childbirth by opting for a C-section instead.

## XI. Programmatics

### A. Mass Budget

A first-order estimate for the total IMLEO was calculated by estimating masses for all the subsystems based on literature and previous missions. The total mass budget for ACCESS is shown in Figure 21. The mass of the station and the ISRU base added together is 1,022 mT. The total mass of the station, ISRU and all the subsystems is 1,278 mT including 25% mass margin. In addition to this, spares required add up to 200 mT while water, oxygen, nitrogen and $CO_2$ storage contribute to an additional 920 mT. Nitrogen storage is the key mass driver (since nitrogen cannot be obtained on the Moon in useful quantities), followed by the inflatable modules, food production equipment, water storage and spares storage.

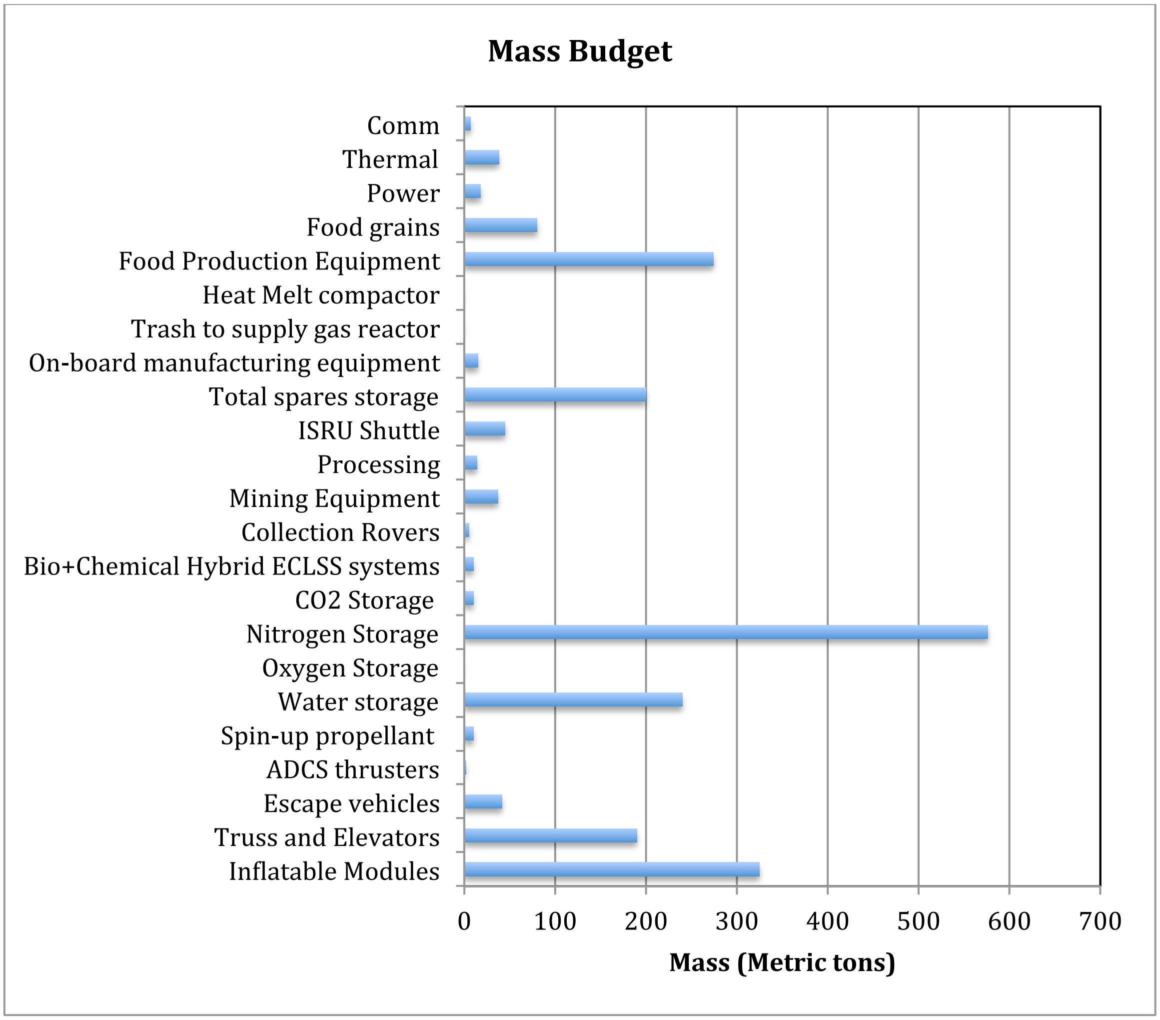



**Figure 21. ACCESS Mass Budget – Total: 1,278 mT**

The key to lower the initial mass to LEO is to establish a means for the production of nitrogen that can meet the nitrogen demands on the station, or replace nitrogen with an alternative that can be extracted and transported to the station from the Moon. This is left as future work.

### B. Campaign Cost

First-order cost estimates for the ACCESS architecture are presented in Figure 22. A rough-order-of-magnitude development cost was estimated using the Advanced Missions Cost Model [21, 22]. The launch costs were calculated using the total IMLEO assuming SLS and Falcon launches. The ISS has cost $150 Billion dollars over the last 25 years, which includes the operating costs. Given the goals of this mission, the cost estimate seems reasonable to the first order.

The total available NASA budget for the ACCESS campaign is $199 Billion, and that includes the 20% of the annual budget as per the RASC-AL competition rules, the ISS budget after it retires in 2025, the human exploration budget and that for the Orion and SLS programs after 2032. The overall ACCESS campaign cost is $168 Billion (FY16) including development, testing and launch costs for the station as well as the ISRU base. The available reserve is ~19% of the total campaign cost.

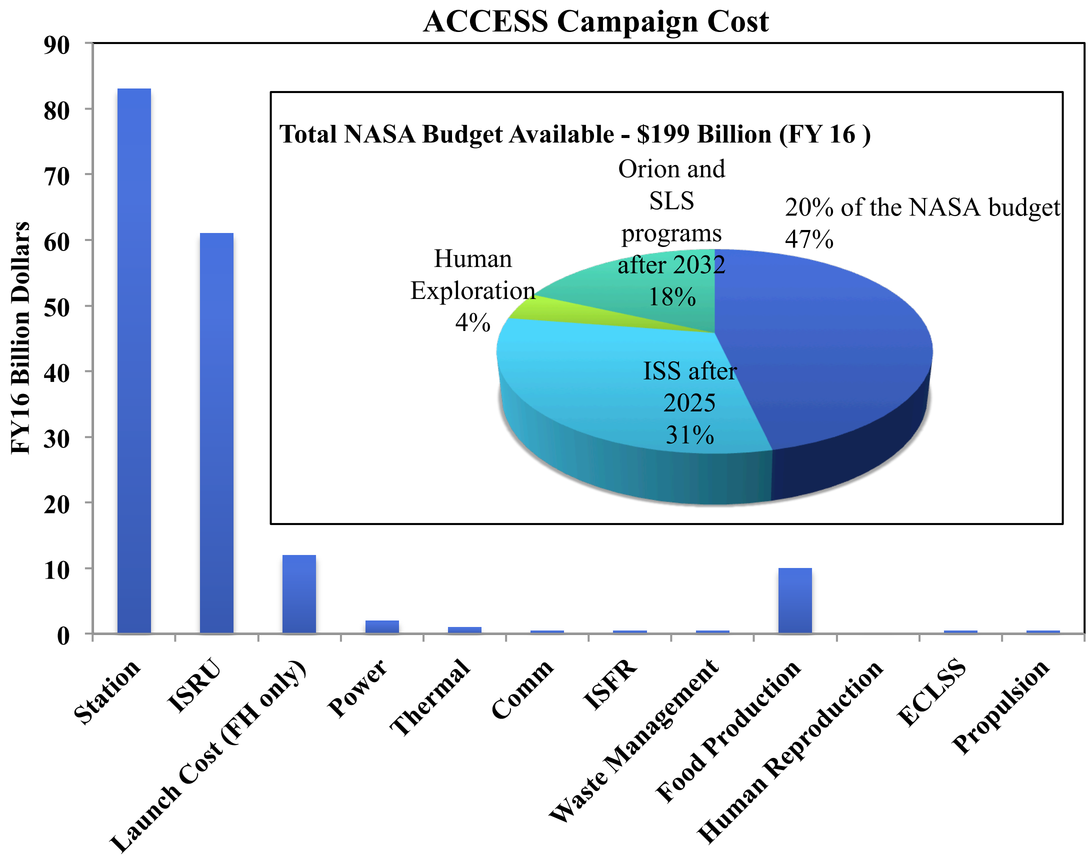



**Figure 22. ACCESS Campaign Cost Estimates. Total ACCESS station cost: $168B FY16**

The technology assumptions and precursor missions to support the ACCESS campaign are based on the 2016 NASA budget allocations. Examples of the missions with allocated budget for 2016 that we will be utilizing in our development plan are: The ARM mission to leverage development of synergistic capabilities for ISRU, and a crewed mission in the mid-2020s to mine and process the asteroid brought back into DRO. We have looked into current NASA investments in commercial launch vehicles, large-scale deployable solar array development, green propellant and high-power solar electric propulsion technology as part of the Space Technology program. Entry/descent and landing vehicles (of potential application to the ISRU shuttle for the ACCESS campaign), electrospray propulsion, microfluidic electrospray and iodine Hall thrusters, SEP including 30-50 KW solar arrays for the ARM mission (with $491M) will contribute significantly to our campaign. The Lunar Resource Prospector Mission developed under this program will be one of the key precursor missions indicating the extent of resource availability and locations for ISRU on the Moon. The Orion program (with $1,096M), crew vehicle development program ($1,085M) and SLS ($1,776M) will provide crew and cargo transfers to the operating location of the ACCESS space station. Advanced Exploration Systems (AES) develops building blocks for human space missions. This includes technology development for the ARM mission, EVA missions to collect samples from asteroids, developing Lunar Flashlight, Lunar IceCube, LunaH-Map, SkyFire and Lunar CATALYST missions that will be included in our development plan for the ACCESS station. The OSIRIS Rex mission will contribute information for other potential ISRU resources. The SBIR/STTR program (with $200M) invests in partnership with small businesses to develop key technology in areas that are directly application to the ACCESS campaign.

### C. Project Timeline and Development Plan

Figure 23 shows the concept of operations and the gradual buildup of the campaign over the next two decades. The Habitat module will be tested in GTO with 4 crewmembers on-board for 3 years before moving it to the Lunar Near Rectilinear Orbit (NRO) after the Asteroid Retrieval Mission (ARM) mission in 2026 using a propulsion tug. The lunar ISRU base is assembled between 2026 and 2032 using 4 SLS and 10 Falcon Heavy launches. The

ACCESS station is built up gradually over a period of ten years starting in 2030 with 54 Falcon Heavy launches and 10 assembly crew missions. Finally, 20 launches between 2040 and 2044 will provide resupply and spares to the station, prior to Earth-independence. The station will operate independently from the Earth starting in 2045. The detailed precursor mission, station assembly and operation and crew deployment timeline is shown in Figure 24.

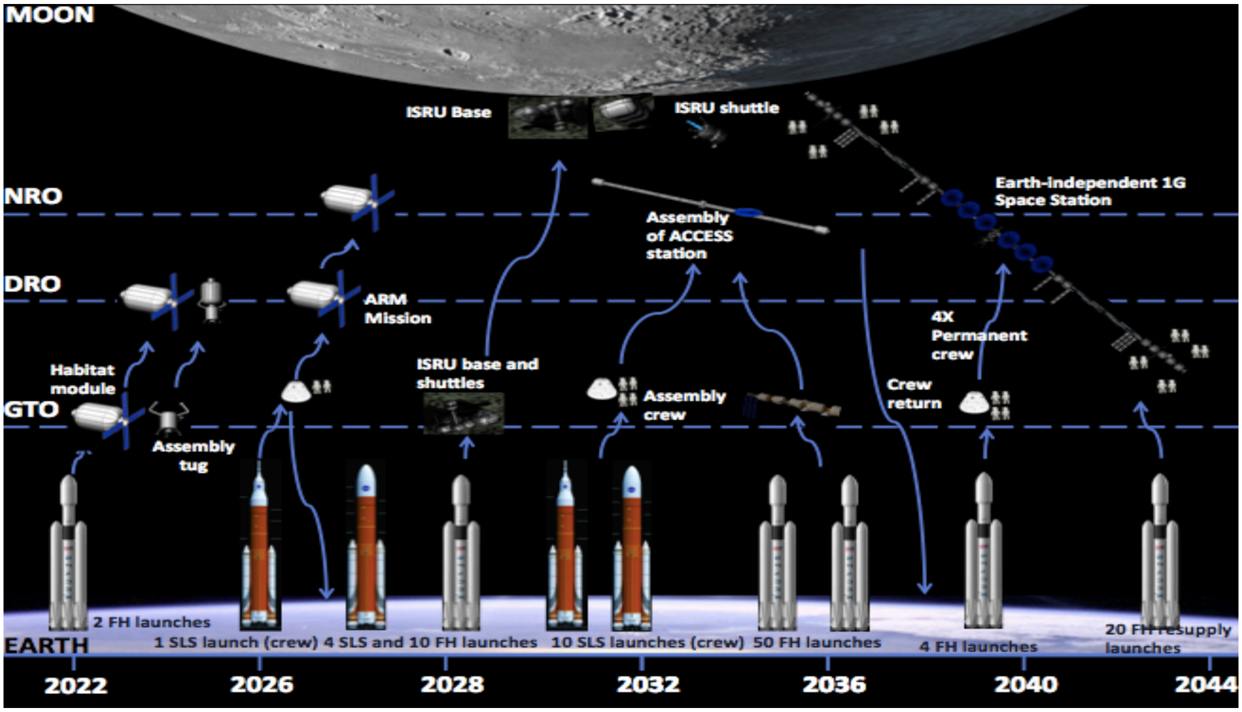


Figure 23. ACCESS station assembly plan.

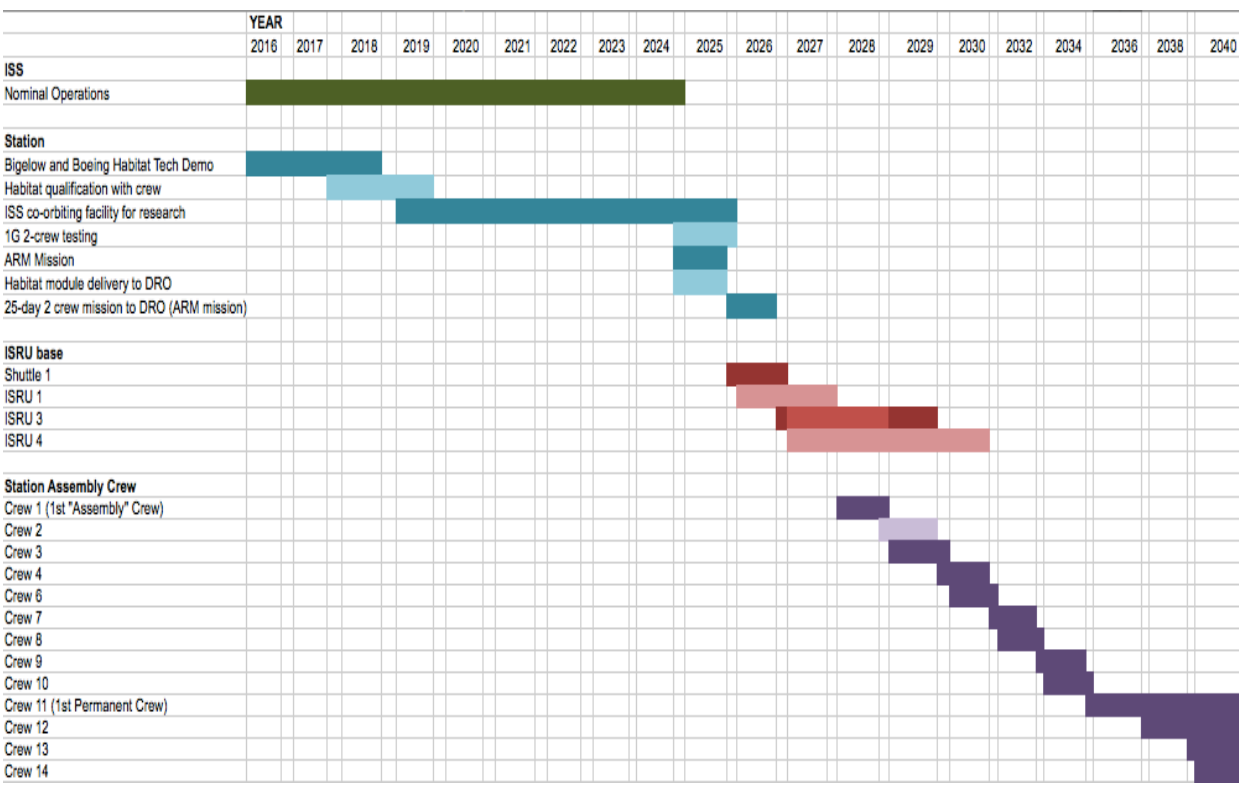
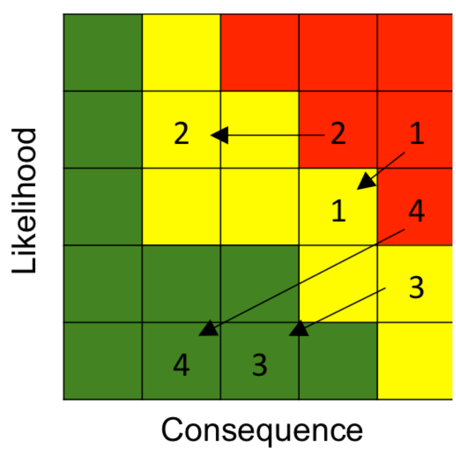


Figure 24. ACCESS Project Timeline

### D. Risk Management

Critical risks associated with the ACCESS campaign are identified along with mitigation strategies in Figure 25. Risk of failure of the mission and loss of crew arises from the possibility of space debirs impact and decompression of the habitat modules. This can be mitigated by adopting multi-layer micrometeorite debris shielding and by using modular design to section off modules with airlocks. There are also escape vehicles stationed at either end of the station in case of an emergency. The crew can use the escape vehicles to transfer to the other side of the station and also to escape into a low lunar orbit before being brought back to Earth.

Human deep-space missions come with an inherited risk associated with exposure to radiation especially to Solar Particle Events or Galactic Cosmic Rays. The effect of exposure of humans to radiation in deep-space for long durations has not been studied in detail. This could pose a major risk to the crew and also to infants born on the station. To lower the risk, a multi-layer shielding strategy is adopted. Habitat modules are lined with Polyethylene shielding and water bladders. In addition, crew will be evacuated to thick water shelters when potentially high doses are detected or anticipated. More research is required in the next two decades to understand these risks better so that appropriate measures can be taken.The third risk, although less likely, but capable of causing mission failure is not enough water ice being found on the Moon. In order to mitigate this risk, several pre-cursor missions will be undertaken to ascertain the availability and location of resources on the Moon. Lastly, to ensure that there is sufficient food to sustain the crew, four greenhouse modules with adequate redundancy are allocated for food production, and additional seeds and grains will be stored as a contingency measure.




| Risk ID | Risk Description |
|---|---|
| 1 | Decompression of habitat module caused by debris impact. |
| 2 | Excessive radiation exposure of crew during Solar Particle Events or Galactic Cosmic Rays. |
| 3 | Not enough lunar H2O available. |
| 4 | Insufficient food production. |

**Figure 25. Risk matrix showing critical ACCESS campaign risks along with mitigation strategies.**

## XII. Conclusion

The ACCESS Earth-independent-1G space station will accommodate 16 crew and up to 4 infants for a duration of 20 years in cis-lunar space. The crew will be supported by ISRU from the Moon and on-board ISFR and food production. The station and lunar base deisgn, subsystem sizing and interfaces along with the estimated campaign budget ($168B total), project timeline (2020-2045) and development plan have been presented.

Designing a 1-G Earth Independent Station is complex with numerous facets that need to interact appropriately to ensure a successful mission. Despite the need for significant infrastructure development, new and innovative technologies can be used to realize the sustained presence of humans in deep space. Collaborating with commercial and international partners drives down cost and risk, ultimately increasing the probability of successfully achieving the goal of creating an Earth Independent 1-G space colony by the year 2040. Such a colony would then be a precursor for a deeper more permanent settlement of humans on Mars and other outer solar system destinations.

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