Artemis 2 ConOps

Part 1

Mission Objective

- Objectives
  1. Set up a lunar outpost that has a constant presence of astronauts (Similar to ISS)
  2. Explore and learn more about the Lunar Environment
  3. Learn more about deep space through experimentation and use the Lunar outpost as a testing ground for further ventures deeper into space.

Overview

Assumptions

- Gateway and initial module already established on moon pre mission (among other architecture)
- 6-month crew rotations
- Lunar Lander docked at Gateway to start the mission
- Initial crew size: 4
- Free to assume that any necessary and *reasonable* technology is available

Overview

Constraints

- Crew can be on the moon no longer than 6 months due to radiation exposure
- EVA's can last at maximum 6 hours due to radiation exposure
- Cost is not explicitly constrained but reasonable decisions having to do with anything that could increase the cost should be justified.

Overview

High Level Timeline

- 5-year mission split up into 6-month segments with crew changing out every six months
- The 5 years are broken into 3 phases
  - Construction Phase- First Two years 4 segments
  - Transition Phase- Year 3
  - Science Phase- Last Two years

Overview

Future Mars Exploration

- This 5 year mission is the perfect opportunity to learn more about the effects of deep space on astronauts and how the human body reacts to Lunar gravity
- The procedures during this mission can also help to serve as analogue to going to Mars. Mars will need the astronauts to be very independent so subsequent missions at this Lunar Outpost can test any new technologies and methods to make the astronauts even more independent

Mission Planning (PLAN) Phases

Objective: Create a detailed and conflict-free schedule of the 5-year Artemis II Mission

Phase 1: Construction (Year 1 and 2)

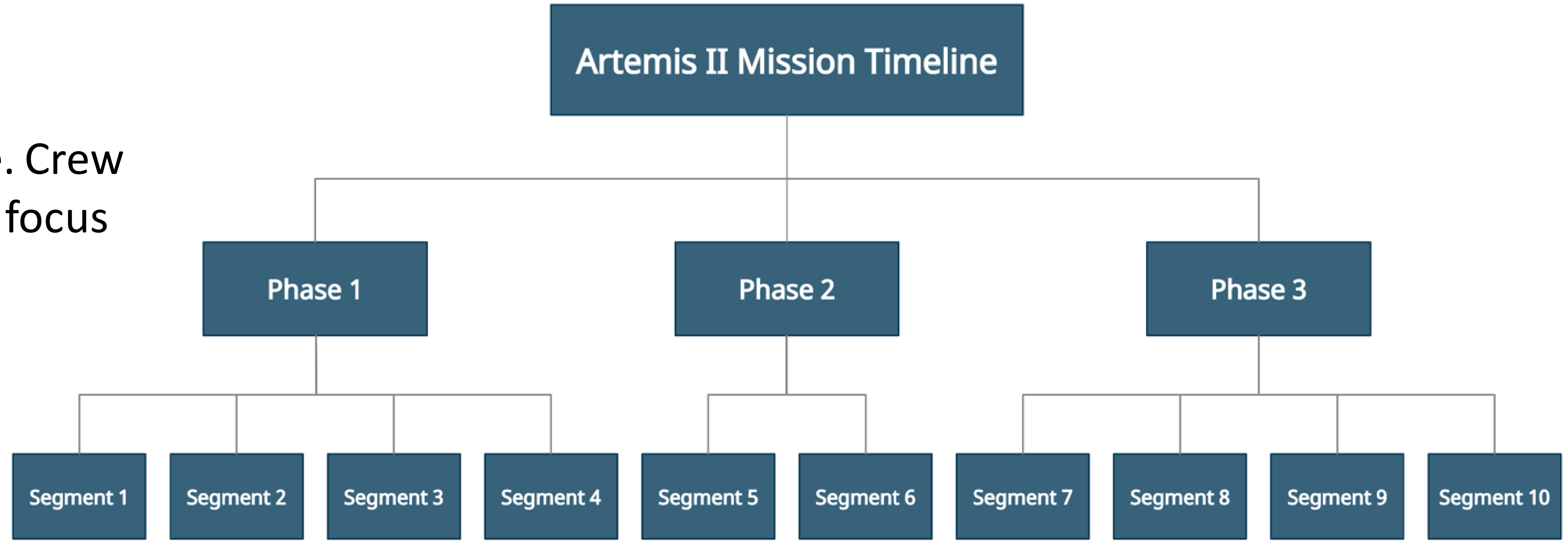
- This phase will focus on the construction of essential infrastructure for crew survival on the Moon.

Phase 2: Transition (Year 3)

- In this phase large scale construction will conclude. Crew activities and any additional construction will shift focus to scientific endeavors.

Phase 3: Science (Year 4 and 5)

- During this phase, the focus will be on conducting experiments, EVAs, and construction for scientific purposes. The essential systems should be complete by this phase and only require routine maintenance and repairs.



Assumptions

1. **Segment 1** will begin with a simple module on the lunar surface and the arrival of a 4-man crew
2. At the beginning of each new segment, a change of crew and mission resupply will be conducted.
3. During **Phase 1**, light resupply missions will occur every 45 days.
4. During **Phase 2** and **Phase 3**, light resupply missions will occur every 3 months.
5. Lunar Surface crew size will expand from 4 to 6 at the start of **Phase 2** and remain constant at 6 until mission end.
6. The Artemis II Mission will be immediately followed by another crewed mission.

Nominal Plan: Segment 1 and Segment 2

Objective: Establish required infrastructure to sustain human life on the moon.

Segment 1
- Initial expansion of power system
- Small-scale life support and medical equipment are deployed
- Begin ISRU regolith collection
- Exploration of immediate area with EVA
- Passive and active thermal control systems deployed
- LunaNet ground stations are deployed
- Construct first landing platform

Segment 2
- Expansion of power system
- Setup redundant life support systems
- Expansion of thermal and communication systems
- Lunar surface imaging and mapping with COLDarm
- Expansion of medical services beyond minimum specified for the Integrated Medical Model

Nominal Plan: Segment 3 and Segment 4

Objective: Continued initial expansion and construction.

Segment 3

- Water harvesting and utilization begins
- Large Scale storage systems now in place for various consumables
- Continued expansion and exploration
- Construction of greenhouse begins

Segment 4

- High Voltage power lines laid down
- Instillation of large-scale systems for water reclamation, CO_2 scrubbers and air filtration
- Pressurized rover now in use
- Initial LunaNet deployment concluded
- Greenhouse construction concluded

Nominal Plan: Segment 5 and Segment 6

Objective: Complete construction of habitat and expand crew size to 6.

Segment 5

- Expansion of capabilities to support larger crew complement
- Finalize construction and shift to maintenance for some systems
- Perform re-evaluation of current technology to assess current and future needs
- Begin short duration surface exploration

Segment 6

- Efficiency expansion to promote long term crew deployment
- Construction of second landing pad
- Conversion from construction to science
- Exploration of the surface expands
- Expansion of medical capabilities due to further reach of exploration
- Begin LunaNet full integration with existing systems

Nominal Plan: Segment 7 and Segment 8

Objective: Primary science missions begin, and lunar habitat construction phase concludes.

Segment 7

- Long duration EVA missions begin in the pressurized rover allowing for multiday exploration missions
- Short duration EVAs and experimentation continue around the habitat

Segment 8

- Expansion into the Shackelton crater begins
- Infrastructure supporting exploration of the crater is deployed
- Crew back at the lunar habitat will perform necessary maintenance and continue experimentation

Nominal Plan: Segment 9 and Segment 10

Objective: Science and research mission continues and concludes.

Segment 9

- Because aging infrastructure is more likely to fail, maintenance checks will now be performed monthly.
- The EVA/Robotics team will continue exploring permanently-shaded regions of the lunar surface, along with any new regions of interest.

Segment 10

- Li-S batteries installed at the beginning of the mission will be reaching the end of their lifespan, and will have to be decommissioned or replaced.
- LunaNet ground stations will offer coverage to a substantial portion of the lunar surface.
- Artemis II mission ends.

Off-Nominal Plan

Flight Computer Failure

- Due to the high redundancy of the onboard systems, one flight computer failure does not constitute and emergency
- Plans will be adapted to transfer functions over to other systems and begin repairs

Lunar Dust on Surface Habitat Radiators

- Systems are in place to attempt to remove dust with mechanical movement of the radiator
- If this is unsuccessful, then a Surface EVA will be conducted to manually remove the dust

Rover Breaks Down on EVA

- Crew on EVA will attempt to fix with a maintenance pack
- If not possible, crew members at base will come recover personnel and rover with 2nd pressurized rover

Off-Nominal Plan

Storage Systems Fail to Transfer Consumables to ECLSS Systems
- Manual hookup between systems instead of ducting methods

EVA Suit Failure
- Abort EVA, return to nearest airlock.
- Inspect and repair suit before future use.

Minor Injuries
- If near or in the habitat, the crew will return to the medical compartment and fully treat the wounds
- If far from the habitat, return to the pressurized rover immediately, clean the wounds with portable medical kits

Emergency Risk Matrix

Environmental Control and Life Support

- Oxygen Generator Failure (E-IV)
- Carbon Dioxide scrubber failure (E-IV)

Thermal Control

- Ammonia leak from radiators (E-V)

Communication

- Total loss of communication (E-V)

Lunar Environment

- Solar flare (B-III)

	Negligible (A)	Minor (B)	Moderate (C)	Significant (D)	Severe (E)
Very Likely (I)	A-I	B-I	C-I	D-I	E-I
Likely (II)	A-II	B-II	C-II	D-II	E-II
Possible (III)	A-III	B-III	C-III	D-III	E-III
Unlikely (IV)	A-IV	B-IV	C-IV	D-IV	E-IV
Very Unlikely (V)	A-V	B-V	C-V	D-V	E-V

Emergency Risk Matrix

Command and Control

- Vehicle management computers fail (E-V)

Trajectory Operations

- Debris collision (E-V)

EVA, Rovers, and Robotics

- Incapacitated crew member (E-V)

Health and Medical Operation

- Malfunction of medical devices (C-II)

	Negligible (A)	Minor (B)	Moderate (C)	Significant (D)	Severe (E)
Very Likely (I)	A-I	B-I	C-I	D-I	E-I
Likely (II)	A-II	B-II	C-II	D-II	E-II
Possible (III)	A-III	B-III	C-III	D-III	E-III
Unlikely (IV)	A-IV	B-IV	C-IV	D-IV	E-IV
Very Unlikely (V)	A-V	B-V	C-V	D-V	E-V

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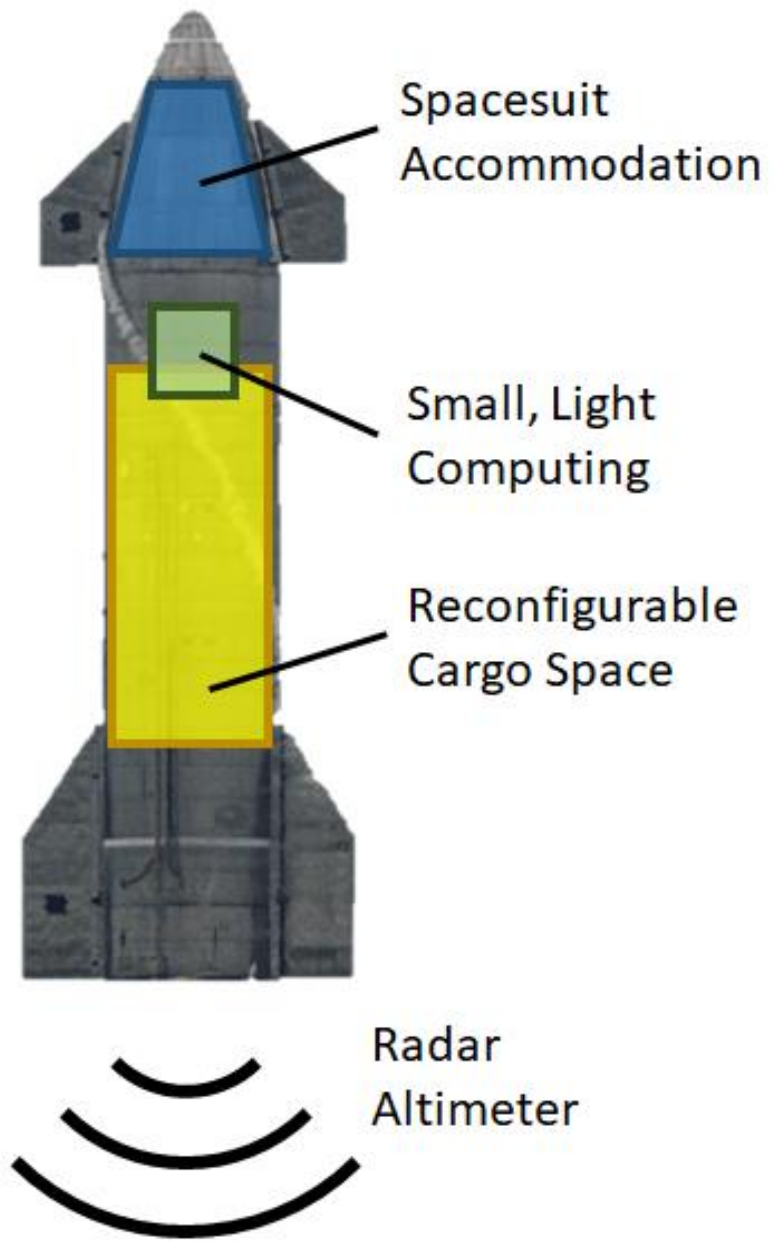
Overview

- Responsible for the transportation of crew and cargo between the surface of the moon and gateway
- Fully autonomous but has manual override capabilities
- Able to land on surface directly, later on a landing/launch pad
- Eventually will have a backup in case of emergency, but to start there will only be one

Assumptions

- Powerful computing resources are volumetrically small and of small mass
  - Complex trajectory information can be reliably solved in real-time with on-board computers
- Radar altimeters can be mounted in any orientation on the Lander
  - Enables use of altimeter for autonomous landing without prebuilt pad
- Lander payload bay is reconfigurable without need to return to Earth
  - Enables variety of payloads (e.g. rovers) to be transported to surface without specialized Landers
- Lander is not expected to support additional science operations
  - Power requirements are primarily driven by life-support, computing, and communication alone
- Human passengers will be wearing spacesuits on-board
  - Extra volume budgeted for crew compartment (bulkheads, doors, etc. will be large enough to accommodate suits)



Starship Image Credit: SpaceX

Constraints

- Must be able to produce 5.70 km/s of delta V
  - This is the minimum amount necessary for descent and ascent between Gateway and the lunar surface
- Capable of docking and interfacing with Gateway
  - Crew and cargo must embark and disembark from Gateway
- Maintain a pressurized, breathable environment
  - The vehicle will need to support the crew and control the atmosphere of the crew compartment
- Self-sufficient power generation
  - Necessary for supporting operations during descent/ascent, as well as off-nominal situations
- S & Ka band communication
  - Communication with Gateway, Ground Control, and the lunar surface is needed for efficient operation

Architecture (PWR, ECLSS, THERMAL, COMM, C&C)

- Charging station connecting to surface habitat
- Storage units aboard lander for life support consumables
- Water regenerative cycle from waste collection
- Double redundant S & KA band antennas
- Terminal supporting control and abort of lunar landing from surface habitat

LAND

Architecture (GNC/PROP, ENV, TRAJ, EVA/ROBO, MED)

- Raptor Engines as main propulsive component. Redundant Star Trackers and IMU's will be used for attitude determination.
- Landing pad established after the first mission, rovers for transportation and experimentation on the lunar surface.
- Radar altimeter, redundant computing systems with a data hardline connection.
- There will be one unpressurized and two pressurized rovers.
- Three medical kits per crewmate as well as vital sensors in the spacesuit.

Nominal Plan

- Main Goal: Transport crew and equipment from orbit to the lunar surface and back.

	Phase 1	Phase 2	Phase 3
Goals:	Crew Rotation (4 crew), Materials Transport, Resupply (~45 day interval)	Crew Rotation (6 crew), Resupply (~3 month interval)	Crew Rotation (6 crew), Resupply (~3 month interval)
Main Cargo:	Crew, Construction Materials, Construction Tools/Hardware	Crew, Construction Equipment, Scientific Hardware	Crew, Research Materials, Scientific Hardware, Experimentation Supplies
Support Role:	EVA Operations, Crew Evacuation, Rover Transport	Crew Evacuation	Crew Evacuation
Pertinent Infrastructure:	Landing Pad (to be established during this phase), Luna-net Comms System	Landing Pad, Luna-net Comms System (w/ ground stations & relays), Refueling Systems	Landing Pad, Luna-net Comms System (w/ ground stations & relays), Refueling Systems

Nominal Plan

- Autonomous, computational algorithm will navigate and control between gateway and the Moon.
- Preliminary and onboard trajectory calculation for Ascent Orbit to rendezvous at Gateway's perilune.
- Main goal is landing safely on landing pad.
- The crew is expected to be wearing their EVA during the trip.
- The lander would operate as a cargo carrier for moon rover.
- Monitor of crews vital throughout the lunar travel.
- Pressurized Cabin for 4 crew in Phase I, and 6 crew in Phase II and III
- Working communication and power network on the Lander

Off Nominal Plan

- Switch to pure battery-power in case of insufficient sunlight to power photovoltaic cells or in case of a short circuit
  - Have extra oxygen available to crew in case of insufficient CO2 removal, or wear suits in the lander if problem is known before launch
  - Have second thermal loop route to cool fuel/crew cabin in case of a shutoff due to a minor leak
  - Have redundant antennas carried and operated in case of antenna failure due to radiation
  - Have backup computers take on main processes in the event of a system reboot

Off Nominal Plan

- Have a manual pilot control system in case autonomous attitude control system fails.
  - Crew will be educated on how to maneuver all guidance and control systems
- Option to land somewhere else on lunar surface in case there are issues with landing pad.
  - Uneven surface due to loose regolith, hills and craters
- If insufficient Δv for rendezvous, preferred abort is abort-to-orbit. For sub-orbital aborts, return to landing site due to limited rescue capabilities
  - Boosts the orbiter to a safe orbital attitude
- If issues with spacesuits, return to pressurized rover to stabilize conditions
  - Ensure that astronauts are nearby other equipment with life-support at all times
- Use resupply missions to rid of/replace expired medications; have spare medical equipment in case of a break

Hazards and Risk Assessment

- **PWR:** Lunar lander power shortage (D-III)
  - **Mitigation:** Equip the lunar lander with equipment that could harness its own energy.
- **MED:** Not enough radiation protection within the lander (D-III)
  - **Mitigation:** Test effectiveness of radiation-protectant lander walls and have astronauts wear space-suits while in the lander.
- **THERMAL:** Improper fuel storage temperatures (D-II)
  - **Mitigation:** Redundant fuel temperature sensors and cooling loops.
- **C&C and COMM:** Loss of communication (D-IIII)
  - **Mitigation:** Build redundancies into communication systems and instill dependence on autonomous procedures/functions.

	Negligible (1) A	Minor (2) B	Moderate (3) C	Significant(4) D	Severe (5) E
Very Likely (5) I	A-I	B-I	C-I	D-I	E-I
Likely (4) II	A-II	B-II	C-II	D-II	E-II
Possible (3) III	A-III	B-III	C-III	D-III	E-III
Unlikely (2) IIII	A-IIII	B-IIII	C-IIII	D-IIII	E-IIII
Very Unlikely (1) V	A-V	B-V	C-V	D-V	E-V

Hazards and Risk Assessment

- **ECLSS:** Carbon dioxide scrubber system fails (E-IIII)
  - **Mitigation:** Redundant systems, venting of air, addition of more oxygen.
- **ENV:** Solar radiation exposure (C-I)
  - **Mitigation:** Materials used will be able to withstand expected radiation
- **EVA/ROBO:** Lunar dust accumulation on EVA suits (B-III)
  - **Mitigation:** Procedure to remove lunar dust before entry to vehicle cabin.
- **GNC/Prop:** Loss of automated vehicle control (E-IIII)
  - **Mitigation:** Vehicle will be switched to manual control.
- **TRAJ:** Insufficient Delta-V to Attain Desired Orbit (D-III)
  - **Mitigation:** Sufficient RCS fuel reserves will be budgeted. Incorporation of several abort paths

	Negligible (1) A	Minor (2) B	Moderate (3) C	Significant(4) D	Severe (5) E
Very Likely (5) I	A-I	B-I	C-I	D-I	E-I
Likely (4) II	A-II	B-II	C-II	D-II	E-II
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Very Unlikely (1) V	A-V	B-V	C-V	D-V	E-V

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ISRU

Mission Statement:

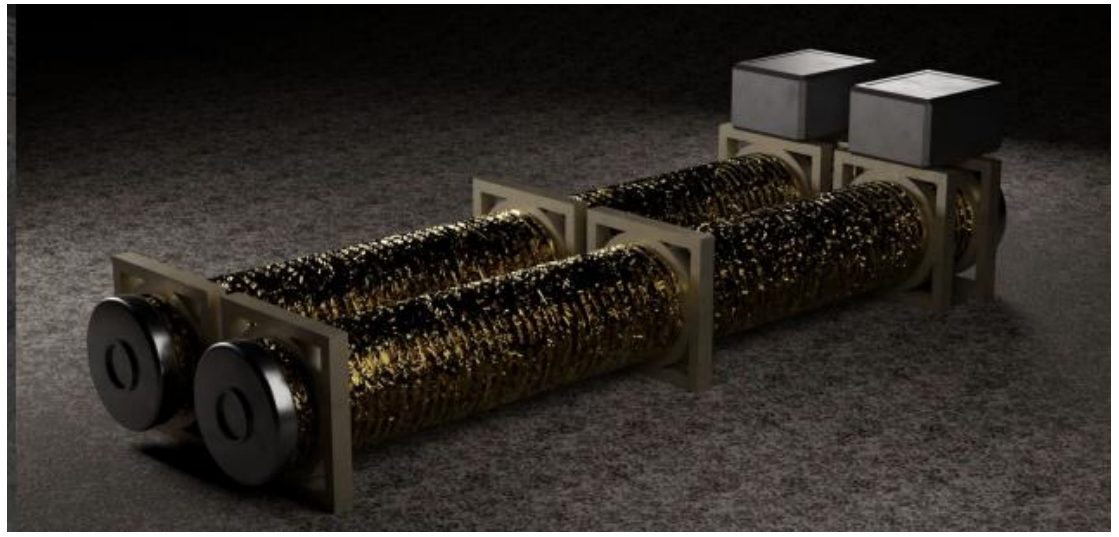
Utilize available resources on the lunar surface to support the Artemis Program

Assumptions & Constraints

- Resupply missions from Earth will help avoid resource scarcity while ISRU infrastructure is developed
- Mission control on Earth will help control and track positions of rovers and satellites
- Resource management data will be tracked on Earth as well as the lunar surface
- Nominal goal of 10,000 kg of water will be acquired within Segment 3 and 4 (12-24 months) of the mission

Architecture

- NASA’s VIPER (Volatiles Investigating Polar Exploration Rover)
- 3 of NASA's CubeSats: Lunar IceCube , LunaH-Map , and Lunar Flashlight
- 2 of TransAstra's Sun Flowers
- 10 of the University of Arizona's regolith collection rovers
- 6 radiant gas dynamic mining rovers
- Blue Origin's "Blue Moon" mining vehicle
- Resource Storage/Processing Facility near the Hab
- Rover mapping and resource management software



Nominal Plan

- Segment 0:
  - NASA's VIPER will search Shackleton Crater for water ice
  - Use CubeSat devices to locate materials of interest
    - Lunar IceCube: map water ice
    - LunaH-Map: map hydrogen enrichments
    - Lunar Flashlight: map water ice
  - All CubeSats will launch as secondary payload on Artemis I

	Lunar IceCube	LunaH-Map	Lunar Flashlight
Periapsis Altitude (km)	100	12	20
Apoapsis Altitude (km)	10,000	2,000	5,000
Inclination (i)	90°	90°	90°
RAAN	0°	60°	120°
Argument of Periapsis (ω)	90°	90°	90°

Nominal Plan

- Segment 1 (0-6 Months):
  - Mission critical infrastructure built
  - Deploy 10 regolith collecting rovers (limited to 2 km radius from habitat) to meet 2000 cubic meters of regolith required to meet HAB construction needs and construction of a landing pad
  - Regolith will be consumed rapidly
- Segment 2 (6-12 Months):
  - Begin Construction of resource storage/processing facility, continue collecting regolith

Nominal Plan

- Segment 3 (12-18 Months):
  - Reducing dependency on resources from Earth becomes a priority for self-sustainment
  - Water collecting infrastructure begins
  - 6 radiant gas dynamic mining rovers and the Sun Flower are deployed to begin mining ice rich regolith
  - Regolith is still being utilized heavily by HAB

Nominal Plan

- Segment 4 (18-24 Months): Completion of infrastructure for collecting and processing ice and regolith. Regolith consumption from HAB will begin to slow.
- Segment 5 & 6 (24-36 Months): Focus shifts to long-term maintenance of ISRU infrastructure. Rate of use for regolith and water will become established and maintained. Radius of resources acquisition will begin to increase as needed. Begin utilizing metallic alloys and other regolith products to help construction needs and to produce propellant.
- Segment 7+ (36-60 Months): Scaling ISRU operations to meet increasing power, water, oxygen and propellant demands as the Artemis Mission grows.

Off Nominal Plan

- CubeSats will rendezvous with Gateway for any maintenance
- Resource mining will be reduced to those critical to maintaining crew health.
- Refer to physical logs in event of data corruption or power loss

Off Nominal Plan

- 14 days of backup power available in the case of prolonged loss of power generation
- Rovers will have a 2km radius so astronauts can help stuck rovers resume normal pathing
- Rovers will use machine learning to avoid and mark spots that could potentially damage them
- If autonomous robotic systems fail, human control is available

Off Nominal Plan

- In the event of the drill overheating, the drill will stop and go through a "cool off" period until the temperatures are at nominal levels

- In the event of a leak, the excess will be dispersed into the atmosphere. Refueling will commence at the base.

Hazards and Risk Assessment

	Negligible	Minor	Moderate	Significant	Severe
Very Likely		Rover pathing difficulties	Lunar dust entering critical components of rovers	Damage due to lunar dust accumulation	Rover inoperable
Likely				Electrical component failure	Rover Stranded
Possible				Micrometeoroids strike a satellite	Rover fails to properly offload materials
Unlikely			Micrometeoroids strike a rover	Resource storage failure	Communications black out
Very Unlikely				Software error causes all rovers to fail congruently	EVA failure repairing rover

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Assumptions and Constraints

- **Partial resupplying should occur every 45 days and more extensive (complete) resupplying will occur every six months**
    - **In the case of an emergency, supplies could arrive at the moon in about 3-4 days**
- A buffer for essential items (such as oxygen, air, water, and food) will need to last at least 6 months without delivery
- **We have sunlight 81% of the lunar day. Therefore, there are 5.61 Earth days without light out of a complete cycle of 29.531 Earth days**

Assumptions and Constraints

- In the case of the loss of a commercial resupply vehicle or lunar lander, backups exist and are ready to be used
- **After the installation of LunaNet infrastructure, it will be possible to notify mission control of supply concerns from almost anywhere on the lunar surface instantaneously**
- Our system will require at least three different categories of storage: standard internal, special internal, and external
- **By the end of the second phase of the mission, the lunar greenhouses will supplement the food supply, provide air revitalization, water recycling, and waste recycling**

Consumables and Storage

Types of Storage

- Standard Internal Storage: This includes all non-perishable supplies needed regularly by the crew
  - Food, water, hygiene products, filters, medicines, mission equipment, misc. supplies
- Special Internal Storage: This includes items with specific humidity conditions or requiring refrigeration
  - Some food and perishable medical equipment
- External Storage:
  - Large spare equipment, solar panels, rover parts, large tanks of fluid (nitrogen/oxygen/propellant)

Consumables and Storage

Storage Plans

- Oxygen will be stored in cryogenic and high-pressure tanks. There will be a buffer of 6 months' worth of oxygen.
- Normal shelf food items will be stored in internal storage – water is included in this category. A buffer of 6 months of non-perishable supplies will be kept here. Special internal storage will be utilized for food items that require refrigeration.
- Fuel will be stored in tanks housed at the Lagrange points in orbit as well as in tanks on the surface.
- Power will be stored in flywheels, fuel cells, and batteries, but will transition to fuel cells.

Consumables and Storage

- Extensive resupplying every six months will be accompanied by a change of crew due to radiation limits.
- The first months of the program will depend more heavily on bringing consumables from Earth.
- Some of these consumables should be produced outside of Earth as the program evolves, however, there will not be complete self-sufficiency and resupply missions will always be necessary.
  - Using oxygen generator systems and growing food are examples of development in self-sufficiency.
- Oxygen, food, and water are the consumables that will take priority during storage and extraction.

Nominal Plan – Consumption and Replenishment

- Consumables that are rapidly consumed are displayed.
- Other key consumables include tools, components prone to failure, replacement parts, etc.
- Many systems are reliant on the power consumable, which supports recharging the rovers, ISRU equipment, life support equipment, refrigerators, lights, life support instrumentation, miscellaneous instrumentation, etc.
- Other important consumables include those to support the life of personnel, thermal systems, and rocket fuel.

Consumable	Rate of Consumption	Replenishment
Power	S1: 30 kW to S10: 100 kW	Passive - Photovoltaic cells
Ammonia - Cooling	Determined by observed leaking rate	Every resupply
Water - Cooling	Determined by observed leaking rate	Every resupply
Freon - Cooling	Determined by observed leaking rate	Every resupply
Supercooled liquid hydrogen and liquid oxygen	730,000 gal/launch	N/A (Fail safe: Fuel tanks at Lagrange points)
Food	2000 cal/day/Astronaut	Every resupply, grown in base greenhouse
Oxygen - ECLSS	0.85 kg/day/Astronaut	Passive - Oxygen Regeneration Assembly
Water - ECLSS	2.4 L/day/Astronaut	Passive - Water Processor Assembly, Potable Water Distributor, Waste and Hygiene Compartment
Medical Kits	9 Medical Kits/ Astronaut	Every segment

Nominal Plan

- Buffer begins in Phase 1 as architecture is being laid
- Smaller buffer for non-essential items (i.e. office supplies, various tools, etc.)
- At least double fluid necessary for cooling loops in surface habitat
- Storage for non-perishable food items, water, and batteries at room temperature in research module of lunar habitat
- Excess fuel conserved via EVA from SLS and Lander

Off Nominal Plan

- There are many cases where a lack of consumables could be considered off-nominal rather than an emergency situation. This would be whenever the habitats lack supplies which are not necessary for survival but are instead primarily used for scientific research:
  - Tools
  - Equipment needed for exploration
  - Office supplies
- In cases like this, the astronauts would be in no immediate danger, but they would also be hindered in their ability to complete scientific work, which is the primary reason for their presence at the lunar habitat.

Off Nominal Plan

- It is unlikely that there will ever be serious shortages of non-essential supplies in the lunar habitats.

  If this does occur, it will most likely be due to one of two things:
  - Underestimating the rate of consumable consumption.
  - A miscommunication in the amount of a given consumable needed before a resupply occurs.
- These can be addressed in the following ways.
  - Have a built-in buffer for supplies by estimating the consumption rate and then adding ~10% on top of this estimate.
  - Double check with astronauts which non-essential consumables are in greatest demand for the research they are performing.
  - Request that astronauts report whenever a tool breaks or begins functioning abnormally so it can be replaced in the next resupply shipment.

Off Nominal Plan

- There will be adequate backup in the case of unexpected resupply delays or accidents
  - For the food system, there will be a 6-month Safe Haven food system, offering 2000 daily calories
  - For medical supplies, resupply shipments will be completed 3 months prior to the expiration date for each individual medicine
    - Food and medicine will not rely on the refrigeration system, in the case of its failure
  - Oxygen tanks will be stored externally and away from critical systems to minimize damages in case of unforeseen failure
  - Water will have a 6-month buffer, as well as several recovery systems to aid in keeping water availability high
    - All crew will be trained in the maintenance and repair of these systems

Hazards and Risk Assessment

- Six groups of hazards have been identified:
  - Resupply delays and shortages
  - Loss of consumables (food spoilage, oxygen tank rupture, etc.)
  - Equipment broken or damaged
  - Equipment not operating correctly due to environment (lunar dust)
  - Communication issues
  - Emergencies (toxic leaks)
- Mitigation strategies described in the off-nominal plan

Failure Modes

- Resupply delays can occur as a result of launch delays (weather, supply shortages, etc.)
- Loss of consumables can occur as a result of machinery failure (refrigeration system for consumables, ammonia tank integrity for power)
- Broken or damaged equipment can occur as a result of overuse or misuse
- Equipment malfunction due to lunar environment will arise based on normal use (lunar dust settling in radiators for thermal)
- Communications issues can arise from hardware failure (EVA suit microphone fails for communications)

Risk Matrix

LOG	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)
Very Likely (5)	Limited suit mobility	Disorganization/ Mis-labeling of supplies	Lunar dust clinging to radiators		
Likely (4)	Unexpected spoilage of food	Minor resupply delays	Suppliers discontinuing parts	Loss of communication for extended periods	
Possible (3)		Tools breaking or lost	Leaks in cooling system	Oxygen tank rupture	Toxic spill or leak
Unlikely (2)	Shortage of hygiene products	Missing non-crucial spare parts	Unexpected spoilage of some medical supplies	Insufficient or inadequate medical supplies	Loss of crucial safety equipment (suits)
Very Unlikely (1)			Substantial and unexpected resupply delay	Loss of resupply vehicle	Loss of resupply vehicle during emergency resupply

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Overview

- To identify potential risks and hazards
  - Only considered one failure depth
  - Develop safety requirements to avoid or mitigate these hazards
- Determine the hierarchy of risks via risk matrices

EVA/ROBO

- Major Risks and Mitigations
  - Critical failure of robotics before habitat construction is complete
    - Preventative maintenance of rovers near the end-of-life cycle
    - Monitor record of robotics wear and tear
  - Robotics damaging other lunar infrastructure (Habitat, Rovers, etc.)
    - Increased planning of rover pathing, accounting for robotics activities in EVA planning

	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)
Very Likely (5)					
Likely (4)		Replacement of robotics parts with expected spare parts			
Possible (3)	Fatigue on repairs of robotics		Robotics failure on top of habitat or other sub-optimal location	Robotics require maintenance before habitat completion	Critical failure of robotics before habitat completion
Unlikely (2)			Robotics part failure without replacement part on hand		Robotics puncturing habitat pressure vessel
Very Unlikely (1)				Failure of airlock during EVA preparation	

PWR

- Major Risk and Mitigation
  - Loss of power
    - On spacecraft, critical systems must be able to operate off a single solar panel.
    - On the lunar surface, batteries will supply the habitat with power
  - Electrocution
    - All crew must be certified to work on any electrical systems exceeding 50V

	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)
Very Likely (5)		Lunar dust on solar array			
Likely (4)			Micro-meteoroid damage to solar array		
Possible (3)		Short circuit			
Unlikely (2)				Electrocution	
Very Unlikely (1)	Poor cable management				Power loss

ECLSS

- Major Risks and Mitigation
- Fire
  - Extremely dangerous to crew and equipment
  - Have readily available methods to extinguish and cut off all potential types
- Ammonia or Toxic Material in Atmosphere
  - Deadly to crew
  - Mitigate by good detection and ways to cut off and vent
- Rapid Decompression
  - Deadly to any unprepared crew members
  - Mitigate by a quick escape plan and closing off the compromised section

	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)
Very Likely (5)					
Likely (4)					Fire, High Radiation Exposure
Possible (3)		Failure of atmospheric sensor	Loss of food for crew, Off-nominal atmospheric pressure	Loss of water For crew	Loss of oxygen for crew, Ammonia Leak
Unlikely (2)	Failure of climate control	Oxygen filtration failure	Exposed wire	Psychological support failure	Rapid decompression, Toxic Gas Leak
Very Unlikely (1)					

THERMAL

- Major risks and Mitigation
- Micro meteors
  - Could cause leaks and part failure
  - Mitigated through shielding
- Ammonia Leak
  - As small as 300ppm is life threatening
  - Constant monitoring and quick repairs will be needed within the habitat
- Part Failure
  - Can cause total shutdown of TCSs
  - Redundant systems along with backups with different operation schemes will be needed

	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)
Very Likely (5)	Off-Nominal readings	Lunar dust buildup		Micro-meteor impact	
Likely (4)					
Possible (3)					
Unlikely (2)	Fluid loop rupture	Thermal paint/coat stripping		Part Failure	Ammonia Leak
Very Unlikely (1)					No system readings

COMM

- Major Risks and Mitigation
- Loss of communication
  - Redundancy of communication components is vital to maintain contact
- Breach of communication link
  - Standard NASA encryption and protocol will be used to ensure the safety of crew

	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)
Very Likely (5)					
Likely (4)		Atmospheric interference			
Possible (3)	RF frequency disruption		Component Failure		
Unlikely (2)	Optical frequency disruption		Overheating of components	Loss of Communication	
Very Unlikely (1)				Link Breach	

C&C

- Major Risks and Mitigation
- Loss of Communication between Earth and Lunar Hab
  - Hardware failure
  - Interference
  - Power disruption
  - Mitigated by use of redundant systems for C&C operations, Crew training and ability to troubleshoot systems, rigorous testing before launch,
- Limited Crew Capability due to C&C Operation
  - Signal interference due to overuse of comms systems
  - Physical interference from robotics etc.
  - Mitigated by crew confirmation prior to operation, training on signal capacity

	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)
Very Likely (5)	C2 operation limits access or operability of hab section	Minor interference in C2 signals	Initial setup of C2 hardware partially incorrect – limiting function	Initial setup of C2 hardware largely incorrect – limiting function for and extended duration	Network traffic issues lead to initial infeasibility of Lunanet system
Likely (4)	C2 operation requires some (minimal) training for lunar crew to execute	Weather conditions on Earth lead to decreased ability to transmit to lunar surface	Crew required to assist C2 maneuver w/o prior training – repairs etc.	Reboot of C2 hardware causes momentary lapse in connection between Earth and lunar surface	Reboot of C2 hardware causes significant lapse in connection between Earth and lunar surface
Possible (3)	Expansion of Lunanet system delayed – limited network bandwidth upon landing	Mechanical upgrade needed to robotic system prior to operation	Minor damage from lunar regolith to Lunanet hardware	Significant damage from lunar regolith to Lunanet hardware	Damage to Lunanet hardware upon landing or impact
Unlikely (2)	C2 communications impacted by language barrier, decreasing efficiency of operation	Power failure at Earth C2 suite leads to lapse in communication during C2 execution	Electrical surge damages C2 hardware	Use of redundant C2 system limits C2 operations	Hardware flaws in Lunanet hardware lead to system failure
Very Unlikely (1)	C2 operation occurs without crew notification – impacting operations	C2 operation occurs without crew notification – negatively impacting operations	C2 operation occurs without crew notification – strong negative impact on operations	Operator error leads to loss of communication with crew on EVA	Total loss of C2 capability on lunar surface

GNC/PROP

- Major Risks and Mitigation
- Sensor errors or failures
  - Power cycle sensor; redundant sensors
- Loss of engine
  - Vehicle dependent; addressed with redundant systems and performing occasional checks on engines
- Loss of attitude control (LoAC)
  - Impacts are time variant and vehicle dependent but tend to worsen as time spent in LoAC increases
  - Orbital maneuvers cannot and required attitude holds will not be possible
  - Mitigated with many redundant systems, sensors, and error filtering

	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)
Very Likely (5)	Errors in IMUs in vehicles.	Errors in GPS unit functions in vehicle.			
Likely (4)	Failure of Optical Navigation sensor on vehicle.	Errors in attitude sensor (Star tracker, sun sensor, etc.).			
Possible (3)	GPS failure on vehicle.	RCS thruster failure.	Visiting vehicle's control algorithm conflicts with the Gateway's after docking.	Loss of translational control with a predicted debris or vehicle collision.	
Unlikely (2)	Failure of attitude sensor	Orion auxiliary engine failure.	CMG or Reaction wheel failure on Gateway. Thrust vector control on Orion fails.	Loss of BHT-600 (xenon) thrusters RCS thruster-on failure. Thrust vector control of Starship fails.	Leak in propellant line or propellant tank. Thrust vector control of the Lunar lander fails.
Very Unlikely (1)		DSN is unable to provide positioning and velocity updates to vehicles	Failure of all of Orion's auxiliary engines.	Loss of Orion's Orbital Maneuvering System Engine (OMS-E).	Loss of attitude control. Failure of lunar lander main engine.

ENV

- Regolith
  - Causes damage to equipment and can affect crew health.
  - Visual/functional inspections of equipment shall be complete prior to use.
- Visibility
  - The angle of the sun (low phase angle) can reduce visibility.
    - May increase difficulty navigating and reduce depth perception.
    - EVAs should be avoided during these periods.
- Terrain
  - Uneven terrain will increase difficulty during EVA's
    - Crew members shall use extreme caution during EVA.

	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)
Very Likely (5)	Uneven terrain	Loss of depth perception due to low phase angle. No shadows	Lunar dust entering Lunar habitat/Vehicle	health effects due to the introduction of lunar dust.	Lunar dust blast during takeoff/landing damages equipment
Likely (4)	Communication issues	Difficulty operating in spacesuit & reduced gravity	Navigation Difficulties due to poor visibility	Damage due to lunar dust accumulation	Failure in Spacesuit ECLSS
Possible (3)	Falls During EVA's	Difficult extracting resources from lunar surface	Rips/tears in spacesuit during EVA	Oxygen deprivation	Medical Emergency during EVA
Unlikely (2)	Lunar habitat shifts on loose regolith	Resource storage malfunction	Micro-meteoroid impacts	Rover Mechanical system failure during EVA	Failure of radiation protection
Very Unlikely (1)	Moonquakes (Seismic activity)	Necessary equipment not prepositioned	Rover stranded	Rover unable to handle lunar terrain	Lunar Habitat Failure

TRAJ

- Major Risks & Mitigation
- Collision Avoidance
  - Debris Avoidance Maneuver
  - Flight Guidance System to remain in desired trajectory path
- Rescue Mission
  - Highly variable on issue at hand
    - Surface habitat fails to sustain life
      - Lunar module can support life for one week
    - Launch preparation timeline (4-6 weeks)
      - Feasibility of complete rescue?
    - Rescue mission is near impossible

	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)
Very Likely (5)		Fatigue on parts			
Likely (4)	Loss of Communication to Ground Station		Fall off intended trajectory path	Medical Emergency	Environmental Hazard
Possible (3)			Loss of Power	Failure in Airlock support	Loss of Air Pressure
Unlikely (2)		Failure of the Active Thermal Control system	Failure of the Water Collection System	Thruster Failure	Failure of the Oxygen Generators
Very Unlikely (1)		Loss of Food Supply	Failure of Water Generator	Flight Guidance System Failure	Debris Avoidance Maneuver Failure

MED

- Major Risks and Mitigation Rules
  - Adverse Behavior
    - Private 2-way comms between crew and family/friends once per week
    - Private sleeping quarters
    - Max of 12 working hours per day
  - Radiation Exposure
    - EVA hours should total no more than 875 hours/year/individual
  - Spaceflight Associated Neuro-ocular Syndrome (SANS)
    - Eyesight must be carefully monitored
    - At least one crew member is trained physician

	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)
Very Likely (5)					
Likely (4)		Motion Sickness	Human-System Injuries	Limited Medical Capability, EVA Injury, Renal Stone Formation	Adverse Behavior, Radiation, SANS
Possible (3)		Altered Immune Response, Orthostatic Intolerance, Space Adaptation Back Pain	CO2 Poisoning, Muscle Atrophy, Sensorimotor Alterations, Sleep Loss	Osteoporosis, Lunar Dust, Viral/Bacterial Illness, Inadequate Team Performance, Cardiovascular Deconditioning, Toxic Exposure	
Unlikely (2)		Urinary Retention	Hypobaric Hypoxia, Hearing Loss, Occupant Injury, Sunlight Exposure, Unexpected Medication Effects	Cardiac Arrhythmia, DCS, Inadequate Nutrition, IVD Damage	Exposure to Vacuum
Very Unlikely (1)				Electrical Shock	

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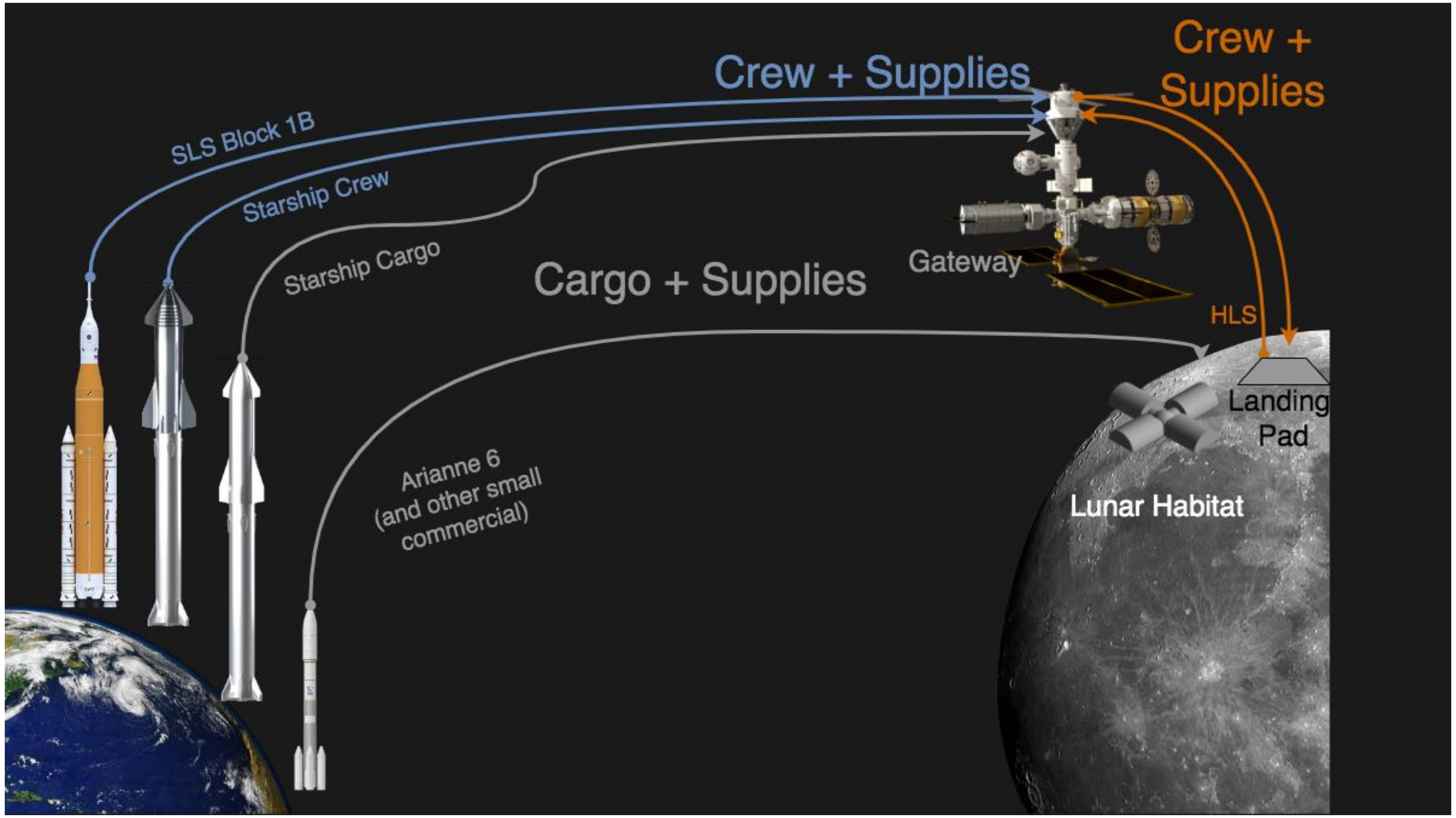
Artemis 2 ConOps

Part 2

Operations Concept Diagram



Assumptions & Constraints

- **Launch Vehicles**
  - **SLS** can launch an **Orion** spacecraft once every _6 months_
  - **Cargo Starship** can be launched once every _3 months_
    - Includes time for refueling launches
    - Cargo Starship has a robotic crane that allows it to unload itself
    - Requires landing pad. Otherwise, it needs to land _10 km_ away
  - **Smaller resupply missions** can be launched once every _45 days_
    - Expendable
    - Lands _2 km_ from the habitat
  - **Crew Starship** will replace the **Orion** spacecraft for Earth-Gateway transit once the crew needs to expand to _6_

Architecture

- **Gateway**
  - Staging point for all crewed lunar landings
    - Docks with crew vehicle (Orion/Starship) and HLS
    - Docks with Cargo Starship to refuel and resupply
- **Orion**: Crew of *4*
- **Starship**
  - Crewed: Crew of *6*, allows for significant return of experiments
  - Cargo: Up to *100t* to Gateway or Lunar Surface
- **Small commercial resupply vehicles** (Arianne 6, New Glenn, Vulcan, etc.)
- **Landing Pads**
  - Allows all craft to land closer to habitat

Nominal Plan

- **Orion/Crew Starship**: Launches toward Gateway, docks, crew departs on HLS
  - After HLS returns to Gateway, Orion/Crew Starship undocks and returns to Earth
- **Cargo Starship**: Launches toward Gateway, refuels with Tanker Starship, descends to surface, lands on landing pad or 10 km away from habitat
  - Payload is unloaded, Starship returns to Earth
- **Small commercial resupply vehicle**: Launches directly toward the habitat, descends to surface, is scrapped by ISRU
- **Crew**: Pre-Train for routine and emergency medical procedures [1, 2]
- **Supplies**: Provide medical kits, air supply, diagnostics, etc.
- **Power generation**: Solar arrays for Orion, Starship, and Gateway

Nominal Plan

- Solar panels, batteries, and cables for power distribution will need to be delivered to the surface.
- Maintain a supply of clean air and water for crew, filter CO_2 and trace contaminants, and regulate humidity and temperature within crewed cabins
- Monitor for fires in all vehicles, hull leaks in pressurized cabins, and chemical leaks in crewed cabins
- Consumable food, water, and oxygen will be delivered to the lunar surface every three months on regular resupply missions
- Equipment necessary to construct a more robust life support system on the lunar surface will be delivered over the first 6 segments of the mission.
- EVA consumable such as oxygen tanks, water, filters, and batteries will be sent frequently initially and less frequently as lunar habitat capabilities for EVA increase

Nominal Plan

- Robotic hardware such as the Lunar Transport Vehicle, 6 radiant gas dynamic mining rovers, 2 long distance pressurized rovers, and Cold Operable Lunar Deployable Arm (COLDArm) will be delivered to the lunar surface
- Communication to ground stations will be done by using the Deep Space Network (DSN) or by using the Artemis II Optical Communication (O2O) system
- LunaNet nodes will be delivered to the lunar surface
- Maintain livable temperature conditions using heat exchangers, pumps, and radiators
- Provide equipment with heating/cooling using cold plates and Multi-Layer Insulation
- Perform a barbeque roll to prevent the vehicle from being baked on one side
- Orion, Starship, and Gateway will make use of Global Navigation Satellite System (GNSS) signals to provide accurate position, navigation, and timing (PNT) services

Nominal Plan

- Spacecraft will include optical navigation (OpNav) sensors as a means of parallel position/navigation redundancy
- Rendezvous radars and laser sensors will provide a means of relative navigation during docking and flight rules have been constructed to limit firings to ensure the safety of equipment and crew
- The launched spacecraft enter Earth parking orbit as performing the perigee raise maneuver
- Trans Lunar Injection(TLI) burn is performed for approximately 20 min to transfer to the Lunar orbit
- Gateway orbit insertion burn is performed and rendezvous to dock to the Gateway
- Two Vehicle Management Computers (VMC) are used to control spacecraft during transit to lunar orbit
- Vision Processing Unit (VPU) used as a hot backup during mission critical maneuvers
- ERSA monitors radiation levels and solar activity
- HERMES conducts experiments and observations in the lunar environment

Nominal Plan

Segment 1: Observation module delivered and unloaded

- Cargo Starship lands at least 10 km from the habitat on unimproved lunar surface
- Habitat modules and rovers are moved to the final habitat location

Segment 2: EVA module delivered and unloaded, secondary small-scale ECLSS systems delivered

Segment 3: Research module, greenhouse, large ECLSS storage tanks delivered, and water rovers delivered and unloaded

Segment 4: Power equipment, LunaNet antennas, large-scale regenerative ECLSS systems, and pressurized rover delivered

- Pressurized Rover now required to ferry cargo to the habitat

Segment 5: Remaining ECLSS hardware delivered and unloaded

- Crewed launch and lunar transit will be performed by Starship

Nominal Plan

Segment 6: End of Phase 2: Transition (Construction --> Science)

- Construction of the 2nd landing pad allows cargo Starship to land closer to the HAB
- Delivery of the remaining hardware for power and thermal systems which supports the end of the construction phase
- Science hardware begins to be delivered and unloaded to stage for Phase 3: Science

Segment 7: Primary science missions begin, and habitat construction concludes

- Additional science hardware delivered and unloaded
- Support of long duration EVA missions in pressurized rover
  - Resupply of rover parts, Deep Space Network (DSN), increased solar flare & meteoroid detection

Segment 8: Expansion into Shackelton crater

- Infrastructure to support expansion delivered and unloaded

Segment 9: Continued exploration of regions of interest

- Additional experiments are delivered, and long duration EVA support continues

Segment 10: Conclusion of Science and research missions

- Final long-term experimentation is staged onboard the Gateway and the crew is transported back home

SpaceX Cargo Starship Unloading

Credits: SpaceX

Segment	Experiment	Delivered Architecture
6	Reconfigurable, Radiation Tolerant Computer System	RadPC single board computer Montana State University payload
7	Thermal Energy for Lunar ISRU	Hydrogen Reduction Reactor Carbothermal Reduction Reactor Lens/Mirror Concentrator
8	Electrostatic Thrusters	Safety area Test bench
9	Microwave Power Transmission	Commerical Lunar Orbiter Ground rectenna

Off Nominal Plan

- Cargo Starship is only needed every 6 months (once per Segment), so if there is a failure, another one can be sent up in time to prevent an effect on operation
- On hand consumables should last the crew until the next resupply if there is an issue with the resupply vehicle
- At least 50 days of spare oxygen will be kept on board at all times
- Emergency medical procedures will be conducting according to NASA's Medical Emergency Manual [2]
- Manual attitude control is accomplished with the use of translation pulses while yaw, pitch, and roll are controlled automatically. This ensures the crew is able to perform any necessary midcourse correction burns while the GNC system is down.
- All spacecraft must be able to operate critical systems off a single solar panel in case of any failures.
- Procedures have been created for dealing with high concentrations of toxic chemicals because of a leak, fire or a combustion event, and a hull leak resulting in depressurization of the cabin.

Off Nominal Plan

- Redundancy is built into the CO_2 filtration systems, the temperature and humidity control systems, and the fans used to ventilate the cabins
- Redundancy in ground stations and communication components will be implemented to avoid loss of communication
- Delay/Disruption Tolerant Network (DTN) and standard NASA protocol will be followed to ensure that the most important data is being transmitted first
- A delay in delivery of EVA or robotic hardware will result in a delay of the mission as rovers and EVA equipment are crucial to construction of the lunar habitat infrastructure. There will be multiple extra EVA and Robotic equipment to minimize any schedule delays.
- If EVA or robotic hardware gets damaged, there equipment will have to be repaired with extra hardware at the lunar habitat. If repair is not possible, the crew will have to wait for a replacement delivery, thus delaying the mission.

Off Nominal Plan

- Reroute coolant and utilize removable cold plates in the event of a failed barbecue roll
- Heat shields will be deployed in the event of a MMOD shield becoming damaged
- Replaceable pumps and radiators will be available on the outside of the vehicle
- For collision avoidance, burn for determining debris avoidance maneuver (DAM) will be required during flight
- Vision Processing Unit (VPU) will take over all mission operations with dissimilar redundant features if Vehicle Management Computers (VMCs) fail
  - Powered by independent batteries in case there is an ECLSS failure
- Alert lunar crew in the event of increased radiation from solar or cosmic anomaly
- Crew returns to Orion vehicle during anomaly

Hazards and Risk Assessment

	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)
Very Likely (5)		• Heightened Solar Activity			
Likely (4)		• Failed barbecue roll			
Possible 3)	• A ventilation fan fails • A problem occurs that delays the C argo Starship	• Thruster fails while firing • A problem occurs that delays the re supply vehicle	• Small toxic chemical spill or leak		
Unlikely (2)	• One CO2 scrubber fails	• GNC system is down during transit	• MMOD Shield damage	• Loss of communication • Humidity or temperature control failure	• Coolant Leak
Very Unlikely (1)		• Small, patchable leak in pressurized hull	• Damage to rover or other robotic hard ware in transit	• Vehicle Management Computer fails • Fire damages equipment • Hypoxia or other medical emergency	• Loss of power • Large leak in pressurized hull • CO2 scrubbing system fails • Spacecraft runs out of oxygen

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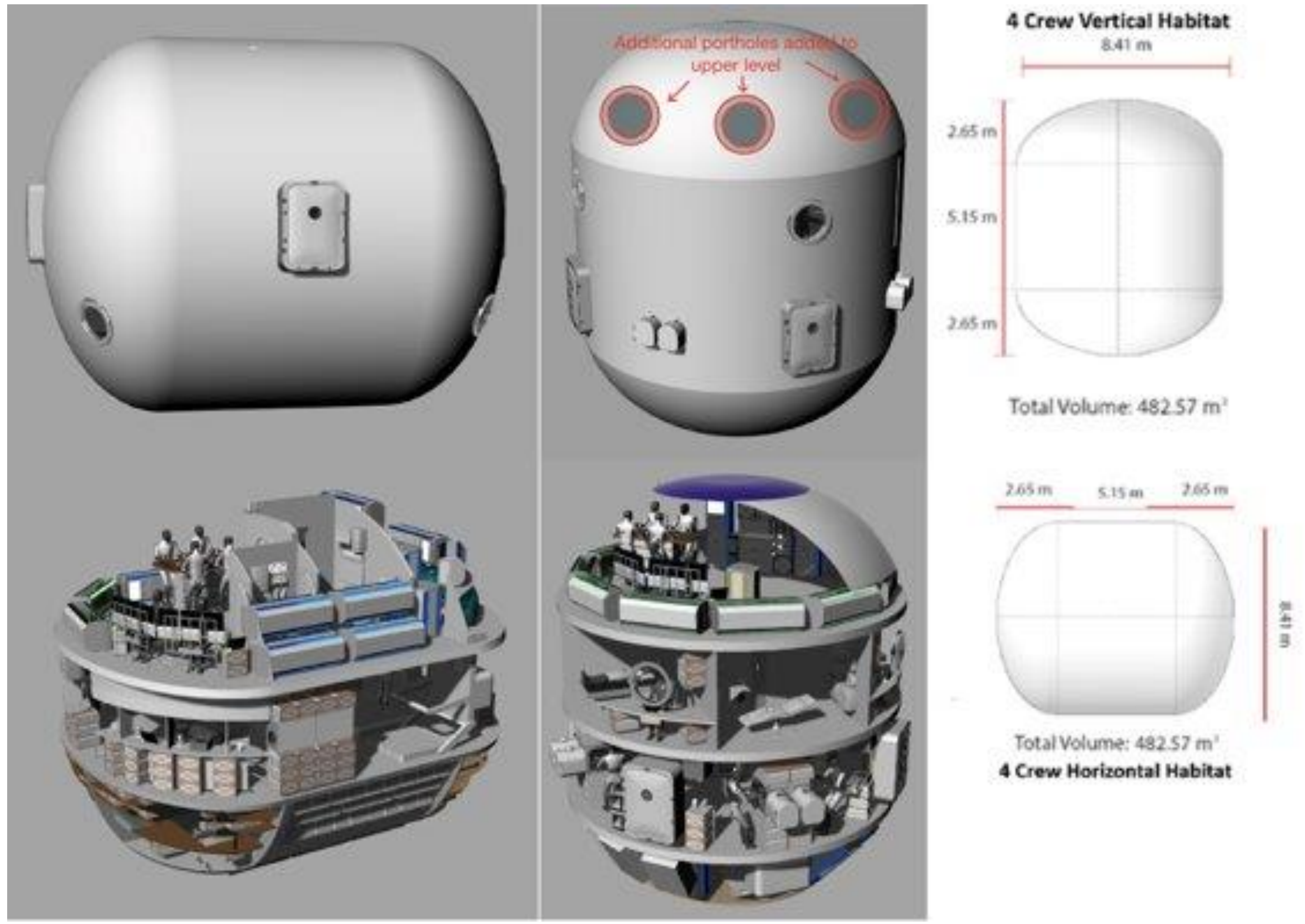
Assumptions & Constraints

- The Independent Module will be in place and functional before the arrival of the 1st long stay crew.
- Landed modules can be remotely driven from the landing site to the construction site.
- Regolith will depress evenly under the habitat.
- One meter of regolith depth will be needed to cover the Habitat to provide adequate radiation protection for the crew.
- Astronauts will have tools available that help to sufficiently remove regolith from themselves, their clothes, and some of their equipment.

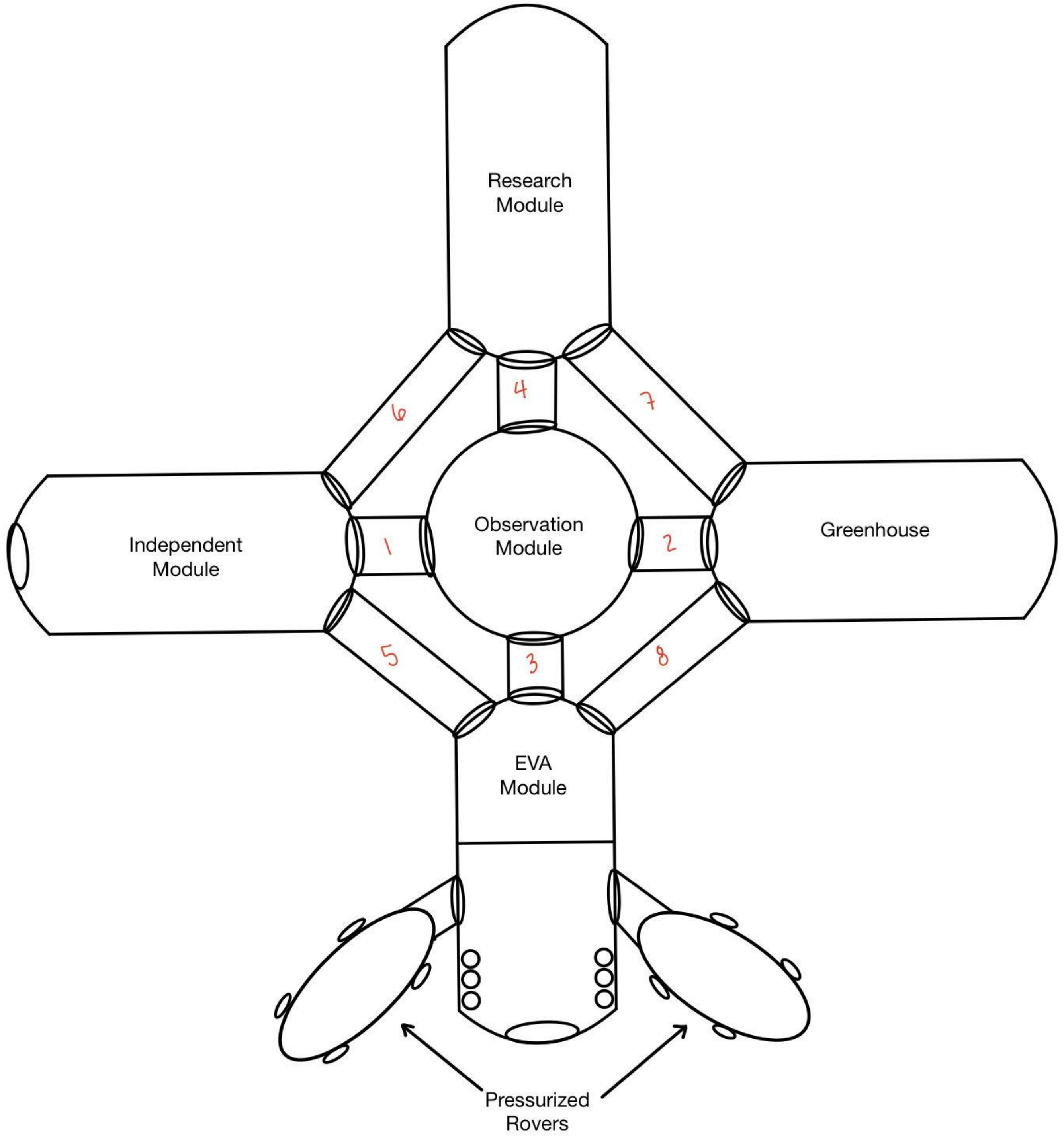


Habitat Module Concept
Obtained from "Design Variants of a Common Habitat for Moon and Mars Exploration" - Robert L. Howard Jr. , NASA Johnson Space Center

Architecture

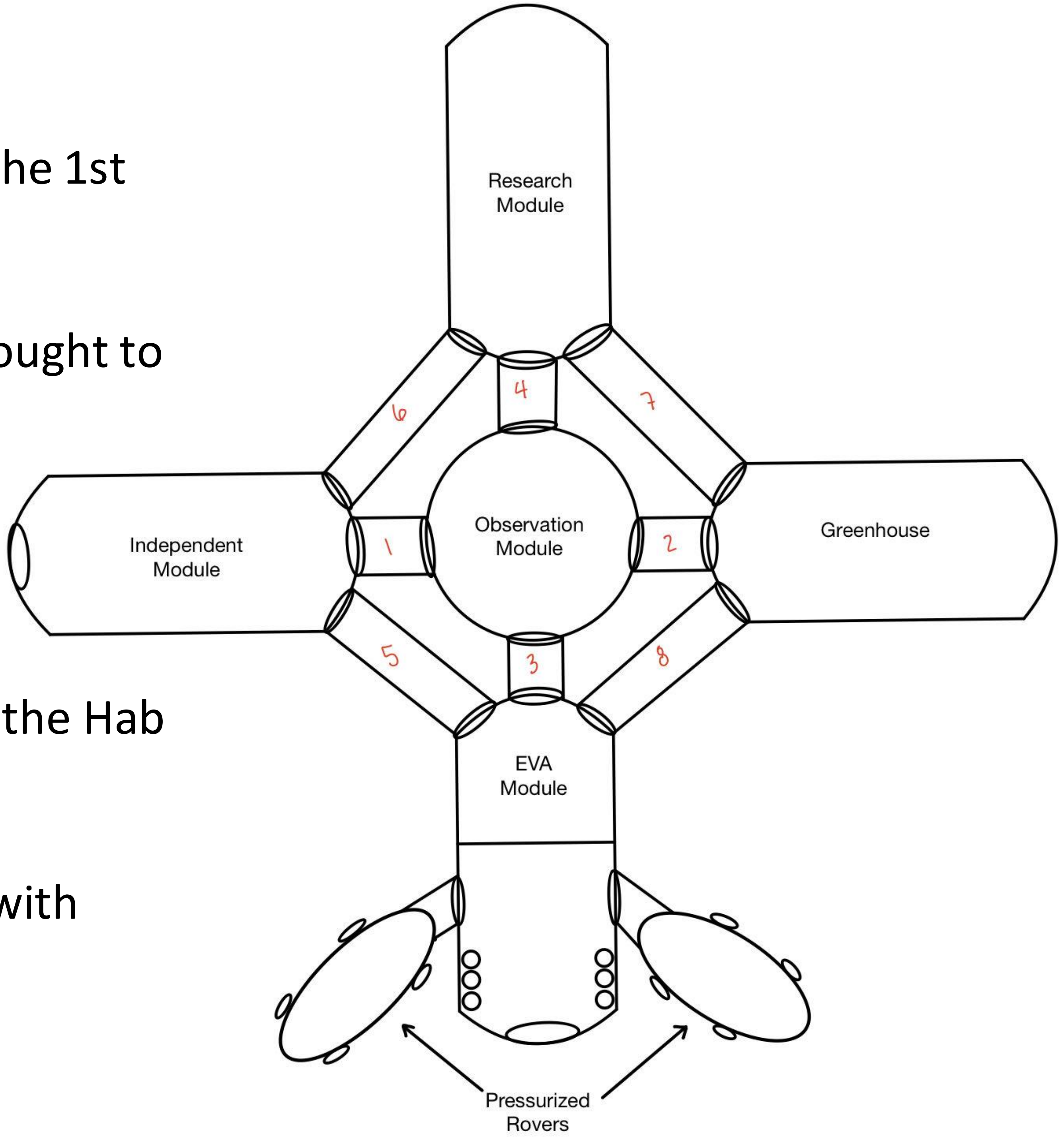
- The finished habitat will be comprised of:
  - Independent Module, Research Module, Observation Module, EVA Module, Greenhouse, and connective hallways.

Lunar Greenhouse Chamber
Credits: University of Arizona



Phase 1 Construction

- **Pre-Mission:** The Independent Module is brought into operation before the arrival of the 1st long term crew.
- **Segment 1 (months 1-6)**: The observation Module and hallways 1-4 are landed and brought to the construction site. Regolith is being collected by rovers and used in construction.
- **Segment 2 (months 7-12):** The EVA Module is integrated into the HAB, connected to the Observation module by hallway 3.
- **Segment 3 (months 13-18):** the Research Module and Greenhouse are integrated into the Hab and connected to the Observation Module.
- **Segment 4 (months 19-24):** Hallways 5-8 connect the modules and covering modules with regolith continues.



Phase 2 Transition

- **Segment 5 (months 25-30):** Covering the modules with regolith continues through segment 5, as modules are fully covered, the crew will prepare the modules for their planned operations (I.e., move EVA suits to the EVA module, transition research equipment to the research module, establish greenhouse with initial growth)
- **Segment 6 (months 31-36):** All modules should be fully integrated into the Hab by this point, larger scale experiments and sustainable plant growth in the greenhouse should be established in this segment.

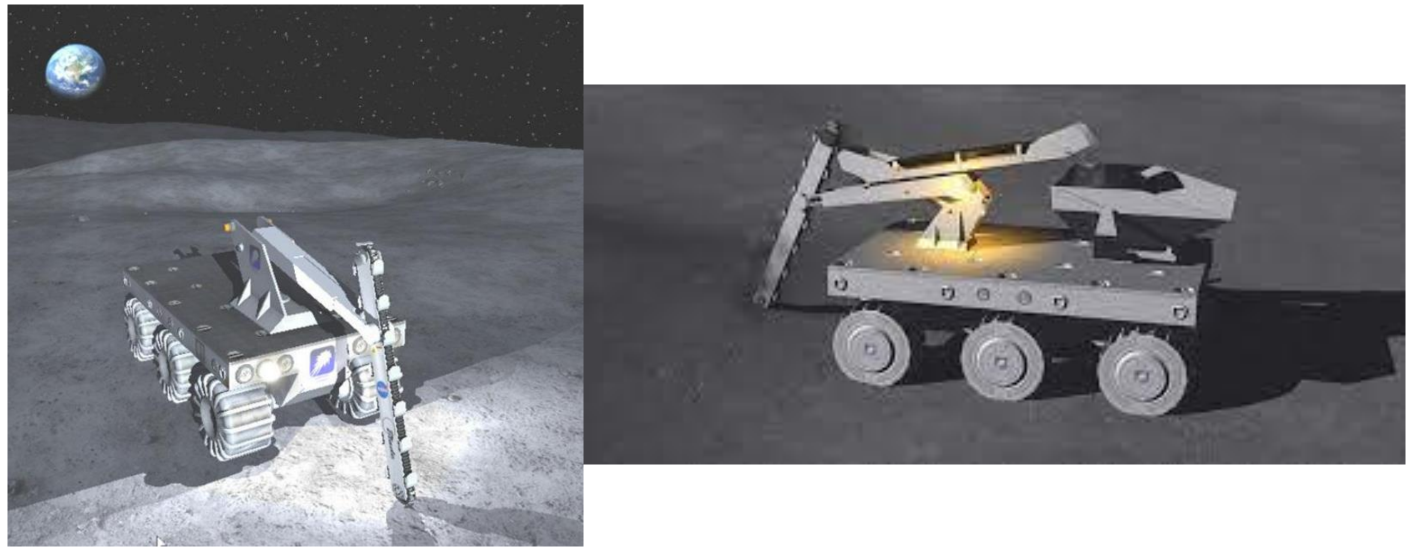
Phase 3 Science

- **Segments 7-10 (months 37-60):** The Habitat is fully complete; plant growth is established the crews primary focus is shifted to research. Hab operations shift from construction to upkeep.

HAB - Nominal Plan

Construction and Power

- Covering the Habitat
  - Approximately 2000m^3 of regolith will be required to cover the Habitat in a regolith layer of 1m thick. Each module and hallway will be covered with regolith to provide protection against radiation and meteorite impacts.
  - 10 rovers can hold 50 kg each, about 0.033 m^3 per trip. During Hab construction, regolith will be gathered by rovers to cover the modules.
- Power plan
  - Solar panel array supported by Li-S batteries
  - Fuel cells manufactured by ISRU will assist batteries in power storage
  - 100 kW available at end of mission for all systems
    - 30 kW needed for 6-person crew life-critical systems



SysRand NASA SBIR Multi-Purpose Excavation Demonstrator (MPED)
Credits: SysRand / NASA Images

ECLSS, Crew Arrival/Departure, and Resources

Arrival/Departure Procedure:

- Transport from landing site to habitat achieved through rover, first the unpressurized, then the pressurized once the pressurized rover is delivered. EVA suits required
- Enter/exit habitat through the EVA module
- Lunar regolith containment and health screening

Resupply Procedure:

- Resupply every three months
- After 1 year, supply intervals can decrease as greenhouse capabilities increase

ECLSS Delivery Timeline:

Phase 0:

- Pre-supply life sustainment goods and small-scale storage

Phase 1:

- Delivery of small-scale habitation regulators, establishment of small-scale life sustainment systems
- Delivery of secondary systems and large-scale storage systems
- Delivery of large-scale life sustainment systems

Phase 2:

- Delivery of large-scale habitation regulators, small-scale systems to act in support of large-scale

Phase 3:

- Routine inspection and maintenance of life support systems

HAB - Nominal Plan

Hygiene and Medical

Medical - Possible health concerns and adaptation in habitat

- Radiation – shielding and regolith
- Decrease in bone/muscle mass and vascular functions – Exercise devices
- Nutrition
  - Prepackaged food with dedicated nutrition plan assessed before the mission
  - Self-grow food after construction of greenhouse

Hygiene

- Low-suctioning toilets/personal urination systems (adapted for low gravity)
- Low-water system/items for hand washing and showers
- Disposable items and reusable electronics for shaving/trimming/cutting hair

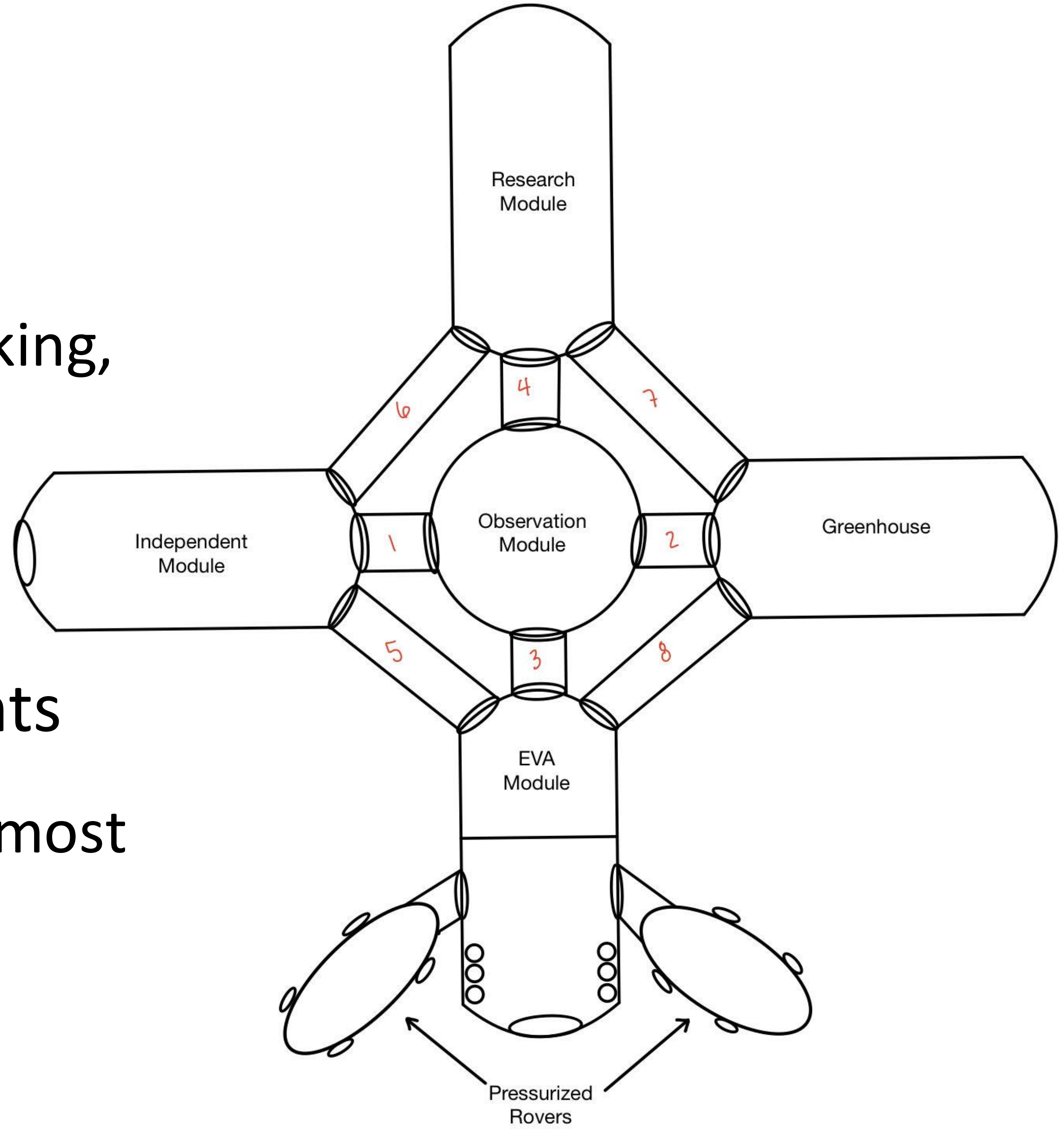
HAB – Nominal Plan

Communications, GNC, and Propulsion

- Communication hub located in the Independent Module
    - Includes command and control, navigation capabilities
    - Ability to act as a secondary command center behind Mission Control
    - Displays for all critical information – sensor data (battery levels, pressure, CO_2, etc.), EVA status/location, experiment data/status
- Ka-band frequency within habitat
    - Allows for high transmission rates, ~130 Mbps

Off Nominal Situations

- Pressurized rover docking failure
  - Mitigation: Remove rover from docking area, re-attempt docking, attempt docking at redundant port
  - Mitigation: keep docking area clean and regolith-free
- Higher than expected concentrations of trace contaminants
  - Mitigation: Change filters in affected habitat modules, isolate most concentrated modules, use redundant transit directions



Hazards and Risk Assessment

Risk	Likelihood	Consequence	Mitigation/Plan
Habitat Puncture / Damage	1	5	Crew will be able to evacuate to an adjacent module
Severe Crew Injury	2	4	Rigorous training and carefully designed procedures
Tank Explosion	1	4	Prevent pressure of tank from rising beyond 80% of maximum pressure
Module Transport Failure	2	5	Well designing and carefully planning module transport
Extended Power Outage	1	3	Emergency low power configurations (life support only)

	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)
Very Likely (5)					
Likely (4)					
Possible (3)					
Unlikely (2)				Severe Crew Injury	Module Transport Failure
Very Unlikely (1)			Extended Power Outage	Tank Explosion	Habitat Damage

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Assumptions & Constraints

- Max travel distances
  - Single unpressurized rover: 10 km
  - Single pressurized rover: 12km
  - Two pressurized rovers: 100 km
- Pressurized rovers will be able to support 2 crew members on mission and 4 for rescue operations.
- Pressurized rover can support long range missions and crew for up to 45 days.
- The Deep Space Network (DSN) will be used to establish communication between astronauts and earth.
- Lunar dust and regolith will collect inside the vehicles and will need to be regularly cleaned.
- Pressurized vehicle allows extended transport time and therefore requires additional resources.

Assumptions & Constraints

- Gateway will provide positioning capabilities for rovers.
- Long Range Rover and VIPER – data transfer via S-band frequencies, allows for 10 Mbps transmission for voice, telemetry, video, etc. [1]
- The only frequencies used will be S – band and Ku-band to avoid signal disturbance.
- Initial pathing and mission planning of surface transport missions will be done by ground control using known lunar data.
- Navigational data will be provided to the rover by Gateway or a Lunar Relay Satellite at all times
- Unpressurized requires the Health and Medical aspects to closely follow EVA flight rules
  - Can stay out for a limit of 6 (± 2) hours due to EVA suit constraints
  - Must have a mitigation system for dust buildup on vehicle and astronaut

Architecture

- VIPER Scout Vehicle – solar powered [4]
- Short Range Rover – 10km range [5]
- 2x Long Range Rover – solar energy collection capacity, fuel cells [5]
- Batteries, electric motors, fuel cells/solar cells for applicable vehicles
- Power management systems for safe generation and distribution of power, fault detection system
- Storage for consumables, oxygen generator, Sabatier reactor, water and urine processor assembly systems, humidifier, ACS, TCCS, intra modular ventilation, etc.
- Deployable radiators, thermal fluid loop, MLI blankets, thermal control coatings, heat pipes, heaters
- Phased array antenna used for primary transmission; omnidirectional antenna used for receiving, can be used for transmitting (low data rates)
- Redundant omnidirectional and phased array (smaller in size) antennas
- Redundant terminals, bus controllers, and enhanced MDMs interlinked

Architecture

- Star trackers, Rangefinders, Gateway positioning for determining position and attitude
- Navigational data via GPS, NASA Deep Space Network, Gateway, and Lunar Relay Satellites
- Display inside rover detailing mission pathing for manned rovers.
- Docking station to facilitate Astronauts moving between controlled and uncontrolled environments.
- Biomedical Team/Expert on transport or on standby at station during entirety of transport
    - Provide basic medical support, psychological support, and use astronaut medical equipment
        - Psychological support due to isolation, confinement, and distance from Earth/Base
        - Medical support due to radiation and thermal conditions
    - Pressurized Vehicle will require Trace Contaminant Control System (TCCS) to ensure dust mitigation

Nominal Plan Phase 1

- Ensure that not every crew member is aboard a transport at the same time – keep some crew members at base
- Surface vehicles will go on excursions to map out lunar terrain and gather critical resources, such as regolith, needed to fully establish the habitat.
- Develop routes of travel that are trustworthy and consistently safe.
- Pressurized surface transport vehicle will be equipped with all necessary life support and safety equipment
- Ensure that basic medical supplies are delivered
- Establish plan to service all rovers on a regular basis for the rest of the mission

Nominal Plan Phase 2

- Longer excursions are now being taken to fully utilize the capabilities of all three rovers, both independently and in conjunction with one another.
- The lunar surface will continue to be mapped, and in-depth studies will be conducted on the environment itself.
- Pressurized vehicle used for transporting shipments during segments 4 and 5
- ECLSS has large scale systems sent in during this phase to replace the small scale systems.
- Resupply of rover parts to last throughout phase two
  - Spare Oxygen, EVA repair kits, dust brushes, CO2 scrubber, food, thermal fluid, and water

Nominal Plan Phase 3

- Continue long distance/duration excursions to benefit lunar research and exploration. The transports will be used to allow the crew to fully interact with the environment while conducting research by providing mobile laboratories, equipment transport, cargo capacity, and lodging.
- Maintain systems and sensors on the pressurized vehicles through visual checks and sensors. Receive shipments of consumables as planned.
- Resupply of rover parts to last throughout phase three
- Continue all regularly scheduled maintenances on mechanical and life support systems

Off Nominal Plan

- Malfunctioning battery/power generation systems
  - **Mitigation:** Crews should perform routine tests and inspections. Range limitations and multiple long-range rovers allow for repair or crew rescue operations. Power system redundancies allow for operation of critical systems during such scenarios.
- Malfunctioning sensor data, malfunctioning rover control
  - **Mitigation:** Communication with basecamp to determine when the last valid data was obtained and if anything has changed in terms of the position or attitude. From there appropriate decisions will be made in terms of rescue team, manually returning to base etc.
- Fluid leaking from the thermal fluid loop
  - **Mitigation:** Crew should be trained to close emergency shutoff valves and quickly repair or replace components when fluid pressure is off nominal
- Rover becomes stranded far from basecamp
  - **Mitigation**: Having two pressurized rovers on the lunar surface allows for one to be used as a rescue vehicle. Long distance missions can be carried out with both pressurized rovers to reduce chances of being stranded for long periods of time.

Off Nominal Plan

- Depressurization
  - **Mitigation:** Automatic detection will set off alarms, crew dawn EVA suits, ensure overboard valves are shut, airflow sensors detect leak and patch. Given automatic detection systems are not working, use of manual system will replace (ears popping).
- Unexpected obstacles
  - **Mitigation:** The crew will decide on alternate routes to avoid obstacles and injury or damage to the crew or equipment. Crew will elevate trajectory altering decisions to ground crew depending on severity of the situation.
- Loss of Communication (intermittent), Antenna Failures
  - **Mitigation:** Install redundancies and fail-safe mechanisms into communication systems, follow flight rules/procedures for repairing/rebooting comms systems

Off Nominal Plan

- Unfavorable terrain: The transport is unable to follow the assigned route due to conditions of the environment such as elevation, lunar dust, and radiation events.
  - **Mitigation:** The excursion will either be scrubbed/delayed, or an alternative route will be chosen.
- Dust build-up: The transport(s) have accumulated too much lunar dust to allow for nominal performance.
  - **Mitigation:** The crew will have to take time cleaning the transports and ensuring peak operational capabilities.

- Injury/Medical Situation
  - **Mitigation:** Use best judgement hard to set a “standard” or hard rule
    - If able to address and fix, do so
    - If need to come back to base, do so

Hazards and Risk Assessment

- **Major Risks and Mitigation:**
  - Breakdown of Habitable Mobility Platform outside of LTV range
    - Mechanical failure
    - Stuck in a small crater
    - Mitigated by having a second HMP for rescue mission
  - Loss of power generation capability
    - Solar panel failure
    - Dust covered panels
    - Mitigated by cleaning and inspecting panels at the end of each mission

	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)
Very Likely (5)	• General servicing of rovers • Unexpected obsta cle in planned path				
Likely (4)		• HMP breakdown within LTV range	• Lunar dust interfering with sensors		• HMP breakdown outside LTV range
Possible (3)		• LTV rover stranded	• Fuel cell failure • Failure of positional data	• Loss of Communication	• Loss of power generation capability
Unlikely (2)		• Transmitter Failure		• Accumulation of dust inside vehicle	• Loss of oxygen • Failure of all antennas
Very Unlikely (1)			• Premature battery degradation	• Sensor malfunction due to exposure	• Fire • Toxic leak

Hazards and Risk Assessment

- **Major Risks and Mitigation:**
  - Loss of Oxygen
    - Depressurization of HMP
    - Slow valve leak
    - Mitigated by attempting to close any leaks and preparing EVA suits for use
  - Failure of Communication equipment
    - Loss of communication
    - Failure of antennas
    - Mitigated by having printed flight rules and returning to base immediately

	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)
Very Likely (5)	• General servicing of rovers • Unexpected obsta cle in planned path				
Likely (4)		• HMP breakdown within LTV range	• Lunar dust interfering with sensors		• HMP breakdown outside LTV range
Possible (3)		• LTV rover stranded	• Fuel cell failure • Failure of positional data	• Loss of Communication	• Loss of power generation capability
Unlikely (2)		• Transmitter Failure		• Accumulation of dust inside vehicle	• Loss of oxygen • Failure of all antennas
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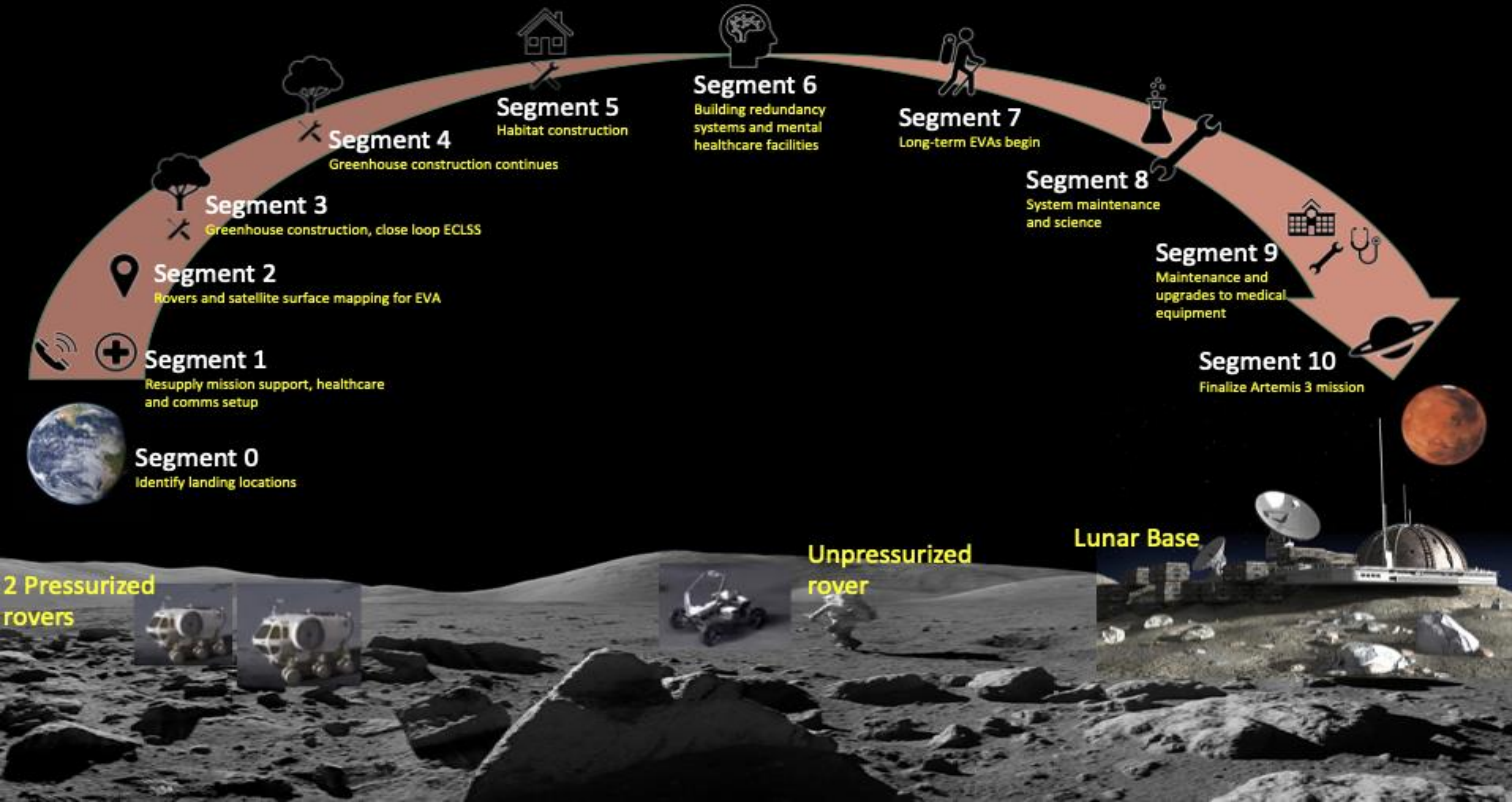
SURFACE OPERATIONS CONOPS



SURFACE OPERATIONS

Assumptions & Constraints

- 1 unpressurized rover for transport up to 10km away from habitat [1]
- 2 pressurized rovers for transport and exploration up to 100km [1]
- EVAs are limited to 6hrs a day due to radiation concerns [2]
- 3D printing of regolith acquired during ISRU will be possible for construction
- Solar Power should produce a min 10 kW for life critical equipment [3]

SURFACE OPERATIONS

Architecture

- Pre-supply includes small scale operations and storage systems.
- 3D printed landing pads to be used for resupply missions
- Rovers will be used to aid in EVAs and exploration
- Satellites will be used to aid in exploration and experimentation
- Areas of base will have 3D printed layer for lunar dust mitigation
- Solar Panel Array Grid Establishment

Nominal Plan

Segment 0 (Pre-mission):

- Pre-flight physicals and quarantine of crew
- Identification of landing locations around Shackleton where ice and regolith is harvested
- Exact measurements of Solar location

SURFACE OPERATIONS

Nominal Plan

Segment 1 (0 – 6 months):

- Construction of vital healthcare and medical facilities
- Solar panels and communications network set up
- Begin collection of lunar regolith
- Rovers and satellites will be used to survey the lunar surface
- Landing pad 1 built for resupply mission support
- Retrieve resupply and bring to habitat

SURFACE OPERATIONS

Nominal Plan

Segment 2 (6 – 12 months):

- Expansion of medical supplies beyond Integrated Medical Model of segment 1 [4]
- Solar panels and power storage withstand 7-day eclipse period
- Rover and satellite map out surface to find paths for crew and EVA

Segment 3 (12 – 18 months):

- Identify and begin collection of ice from crater
- Begin to close loop supply 1/3 water and food consumption
- Greenhouse construction begins

SURFACE OPERATIONS

Nominal Plan

Segment 4 (18 – 24 months):

- Continue Greenhouse construction

Segment 5 (24 – 30 months):

- Habitat construction concludes as the final modules are brought to accommodate increased crew size of 6.
- Ramp up collection of lunar regolith for 3D printing.

Segment 6 (30 – 36 months):

- Modification of small scale to large scale redundancy systems.
- Development of mental health systems.
- Begin growing vegetation to support the crew's dietary requirements.
- Landing pad 2 built for resupply mission support

SURFACE OPERATIONS

Nominal Plan

Segment 7 (36 – 42 months):

- Perform Long-term EVAs in pressurized rovers
- Increased monitoring for Solar events and meteor showers
- All systems are checked, at three-month intervals, through sensors and visual checks to ensure adequate operations

Segment 8 (42 – 48 months):

- Continuing system maintenance within three-month intervals.
- Continuing research and experimentation at the habitat and on long duration EVAs
- Begin expansion into Shackelton Crater

SURFACE OPERATIONS

Nominal Plan

Segment 9 (48 – 54 months):

- All systems are checked at one-month intervals to ensure adequate operations.
- Maintenance and upgrades to medical equipment
- Continue exploration of permanently shaded regions

Segment 10 (54 – 60 months):

- Maintenance will continue to be checked at a one-month interval.
- Finalize research and prepare habitat for end of mission

Off Nominal Plan

- Inoperable Rover – Rover breaks down, gets stuck, or tips over.
- Loss of Communication – Rover/Spacesuit hardware/software malfunction, issue with satellite
- Damaged Tools – Lost tools or damaged beyond use
- Latency Issues – Connection error, unable to connect to servers or computers.
- Power shortage – Blown fuse, Short circuit, Solar panel degradation due to radiation.
- Overheating and Overcooling of Systems – Lunar vehicles, radiators, coolants, EVA suits, etc.
- Adverse Behavior – Private communication with crew physician, on-earth therapist, or finally early mission termination

Hazards and Risk Assessment

	Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)
Very Likely (5)		• Dust			
Likely (4)		• Motion Sickness	• Uneven terrain		
Possible (3)			• Muscle Atrophy • Carbon Dioxide Poisoning	• Viral/Bacterial Infection • Cardiovascular Deconditioning • Osteoporosis	• Dangerous exposure to radiation • SANS • Adverse Behavior
Unlikely (2)		• Damaged tools	• Overcooling • Overheating	• Damaged rover	• Loss of communications
Very Unlikely (1)			• Pointing/tracking, and heading inaccuracy	• Software failure/malfunction	• Loss of power

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Assumptions

- The initial lunar habitat modules have been established
- Gateway has been established
- SCI/UTIL required architecture is readily available as needed on the lunar surface
- The necessary communication infrastructure is established

Constraints

- Any required construction is completed, this will determine the onset of experimentation
- Astronaut work/rest balance and scheduling
- Lunar/Space environmental effects
- Nominal vs. off-nominal operations

SCI/UTIL

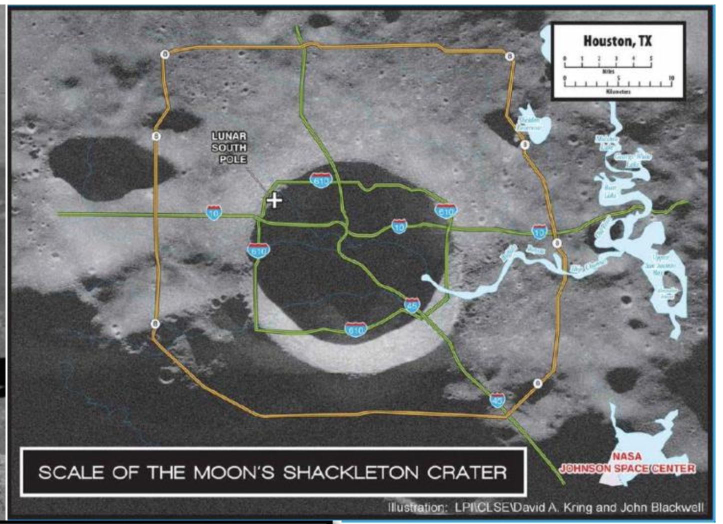
Phase(s)	Segments	Experiment	Required Architecture
1 2 3	1 – 10	Geological Sampling	EVA suit Collection tools Unpressurized & Pressurized rover
1 2 3	1 – 10	Calcium Excretion	Dexa scanner Urine sample storage Urine analysis equipment
1 2 3	1 – 10	Cell Growth Kinetics	UV sterilization Shielded environment Microscope
2 3	5 – 10	Lunar Greenhouse	Regolith Advanced Surface Systems Operations Robot Cylindrical deployable plant growth unit
2 3	5 – 7	Effect of Lunar Regolith on Antenna Systems	Commerical Payload Lander Lunar antenna system

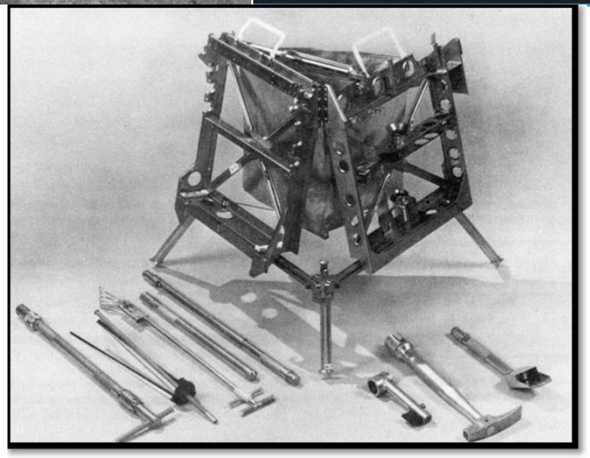
SCI/UTIL

Phase(s)	Segments	Experiment	Required Architecture
2 3	6 – 7	Reconfigurable, Radiation Tolerant Computer System	RadPC single board computer Montana State University payload
3	7 – 10	Thermal Energy for Lunar ISRU	Hydrogen Reduction Reactor Carbothermal Reduction Reactor Lens/Mirror Concentrator
3	8 – 9	Electrostatic Thrusters	Safety area Test bench
3	9 – 10	Microwave Power Transmission	Commerical Lunar Orbiter Ground rectenna

Nominal Plan [All Phases]

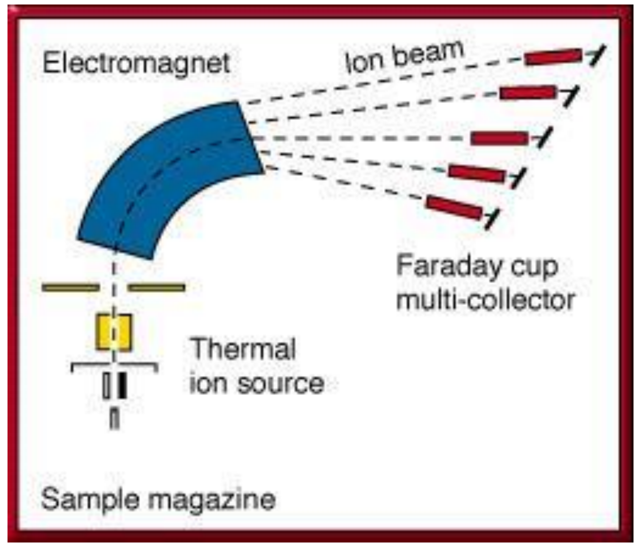
- Experiment: Geological Sampling
  - Purpose: Collect geological samples for further analysis/testing.
  - Procedure:
    - Selection of equipment.
    - Travel to designated sample collection location.
    - Collection of samples.
    - Storage of samples for return to earth or analysis in Lunar Habitat.
  - Results/Benefit to Future Missions:
    - Improved sample collection techniques
    - Potential for finding resources such as Hydrogen and Oxygen that will allow the lunar habitat to become sustainable.
  - **Off-Nominal Plan:** In the event that a pressurized rover breaks down during a collection excursion, the secondary rover will be utilized to resume the astronauts leading the EVA.



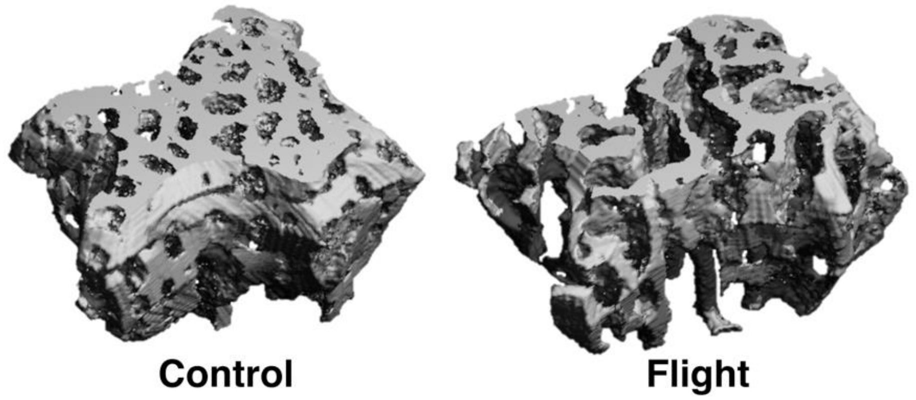


Apollo EVA Tools and Carrier

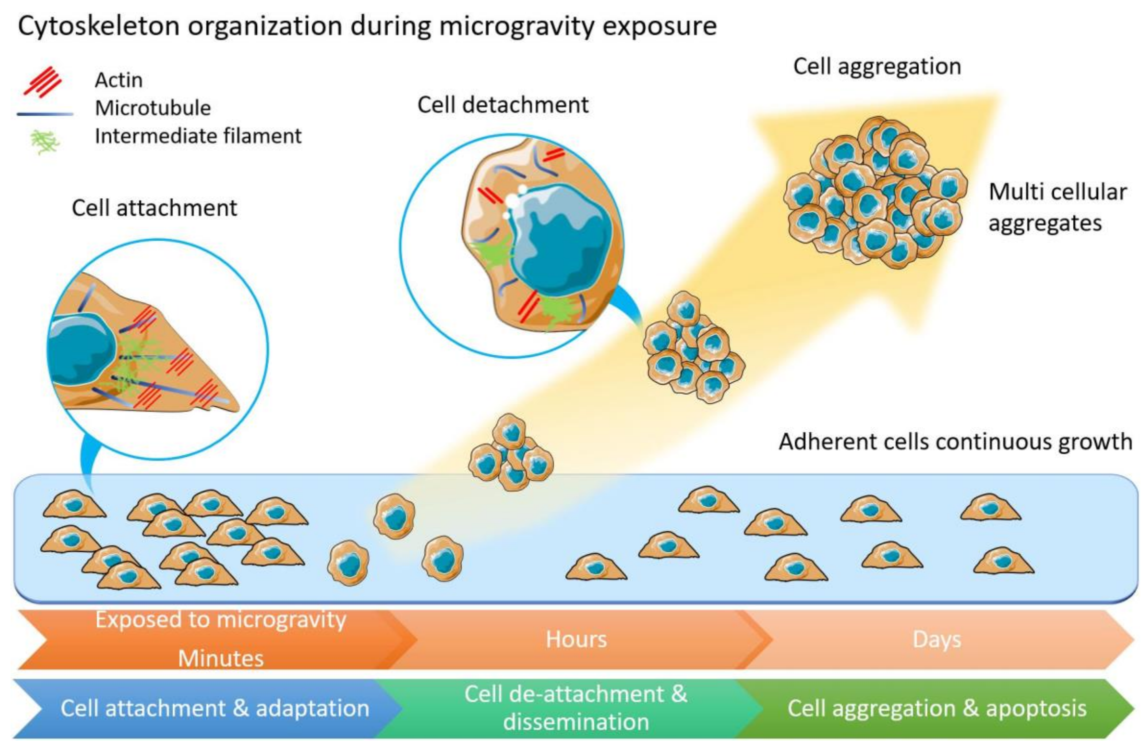
Nominal Plan [All Phases]



- Experiment: Calcium Excretion Experiment
  - Purpose: Measure calcium excretion by urination and correlate to bone mass density loss
  - Procedure
    - DEXA scans before and after mission
    - Collect daily urine samples from each crewmate
    - Measure for ratio of naturally occurring Calcium isotopes using thermal ionization mass spectrometry (TIMS) [1]
  - Result/Benefit to Future Missions
    - Determine a baseline of bone mass density loss solely using TIMS and urine samples
    - End goal: easily regulate and monitor bone loss in crewmates
  - **Off-Nominal Plan (Contingency)**
    - If TIMS stops functioning properly, urine samples can be frozen for up to 1 year



Nominal Plan [All Phases]



- Experiment:
  - Purpose: Observe long term effects of microgravity on cell biology (on gateway)
  - Procedure:
    - Grow cultures in sterile and shielded environment
    - Observe parameters such as proliferation, gene expression, immune response etc.
  - Results/Benefit to Future Missions: Understanding the effects of extended periods of microgravity on cell biology will pave the way for preventive medical care to ensure the safety of astronauts on long journeys (such as mars transits).
  - **Off-Nominal Plan:** It is vital that the culture growth environment remains clear of contaminants. If contaminants are introduced to the environment, ultra-violet sterilization methods will be employed. Extra culture samples will also be housed for redundancy.

Nominal Plan [Segments 5-10+]

- Experiment: Lunar Greenhouse (LGH)
  - Purpose: This experiment will utilize hydroponics to supplement or support the lunar food supply. Additionally, this bioregenerative life support system (BLSS) will utilize plants and crop production for air revitalization and waste recycling. [3]
  - Procedure:
    - Subterranean, cylindrical, inflatable greenhouse excavated using Regolith Advanced Surface Systems Operations Robot Excavator
    - Utilizing an irrigation and nutrient delivery system (NDS) and electric LED (light emitting diode) lighting [4]
  - Results/Benefit to Future Missions: Addressing hydroponic cultivation challenges before potential long-term, large-scale production. Can also be utilized to scrub carbon dioxide and produce oxygen.
  - **Off-Nominal Plan:** If it was relied on to provide most of the food supply and there was a failure event, it would starve the crew. The same could be said if the carbon dioxide scrubbing functionality was depended on.

Nominal Plan [Segments 5-7]

- Experiment: Effect of Lunar Regolith on Antenna Systems
  - Purpose: Determine the effects of lunar regolith on the effectiveness and efficiency of communications systems on the surface.
  - Procedure:
    - Identically configured static antenna stations present on surface
    - Antenna functionality/baseline tests performed
    - Measure performance for a period of time, recording all EVA, Lander, etc. activities
    - Repeat cycle with varying degrees/methods of cleaning
  - Results/Benefit to Future Missions: Determine the effects of contamination on communication systems, allowable cleaning interval, transmission power losses/antenna performance.
  - **Off-Nominal Plan:** In the event of a failure or emergency, power will be shut off to all systems to reduce impact of RF radiation on crew health and electrical equipment health.

Nominal Plan [Segments 6-7]

- Experiment: Reconfigurable, Radiation Tolerant Computer System (RadPC)
    - Purpose: Determine and demonstrate the effectiveness of a radiation tolerant computing system.
        - RadPC systems will be implemented across the mission.
        - Systems will be tested for functionality and baseline measurements will be taken.
        - C2 systems will be exposed to varying amounts of radiation.
        - Performance degradation will be monitored closely to determine effectiveness of system.
    - Results/Benefit to Future Missions: The results of this experiment will be used to characterize the effects of solar radiation on electronic systems. Results can also be applied to the electronic components of other ops teams.
    - **Off-Nominal Plan:** In the event of a failure or emergency, power will be shut off to all systems to reduce impact of RF radiation on crew health and electrical equipment health.

Nominal Plan [Segments 7-10]

- **Experiment:** Thermal Energy for Lunar In Situ Resource Utilization
  - **Purpose:** Obtaining oxygen from lunar raw materials is critical for sustaining a lunar habitat, using Solar concentrators.
  - **Procedure:**
    - To obtain oxygen the regolith must be heated using various processing methods
    - Hydrogen reduction and carbothermal reduction processes will be used for all the different concentrators, to extract oxygen.
    - The best method will then be determined for heating regolith.
  - **Results/Benefit to Future Missions:** To produce 1000 kg/year of oxygen, 15,241 W of thermal power will be required. Successfully obtaining oxygen from regolith would help extend human habitation on the Moon, for fuel cells and rocket propellant.
  - **Off-Nominal Plan:** Efficiency losses due to light absorption, geometry inaccuracies, and scattering. can be improved by using highly reflective mirrors, short ray lengths and highly transmissible lenses.

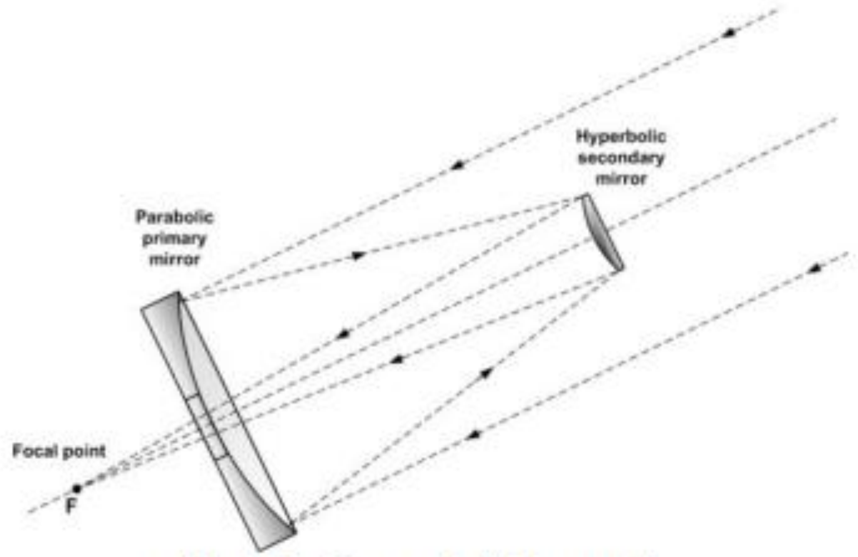
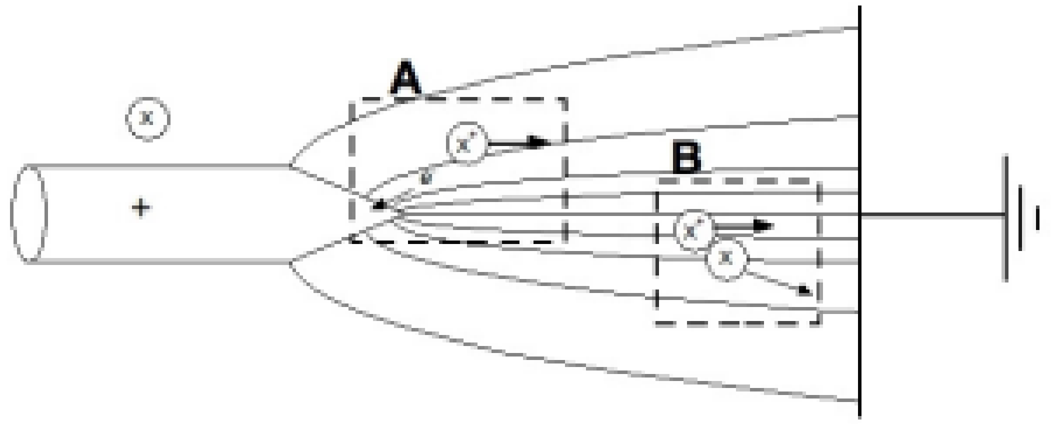


Figure 3.—Cassegrain light-ray path.

Nominal Plan [Segments 8-9]

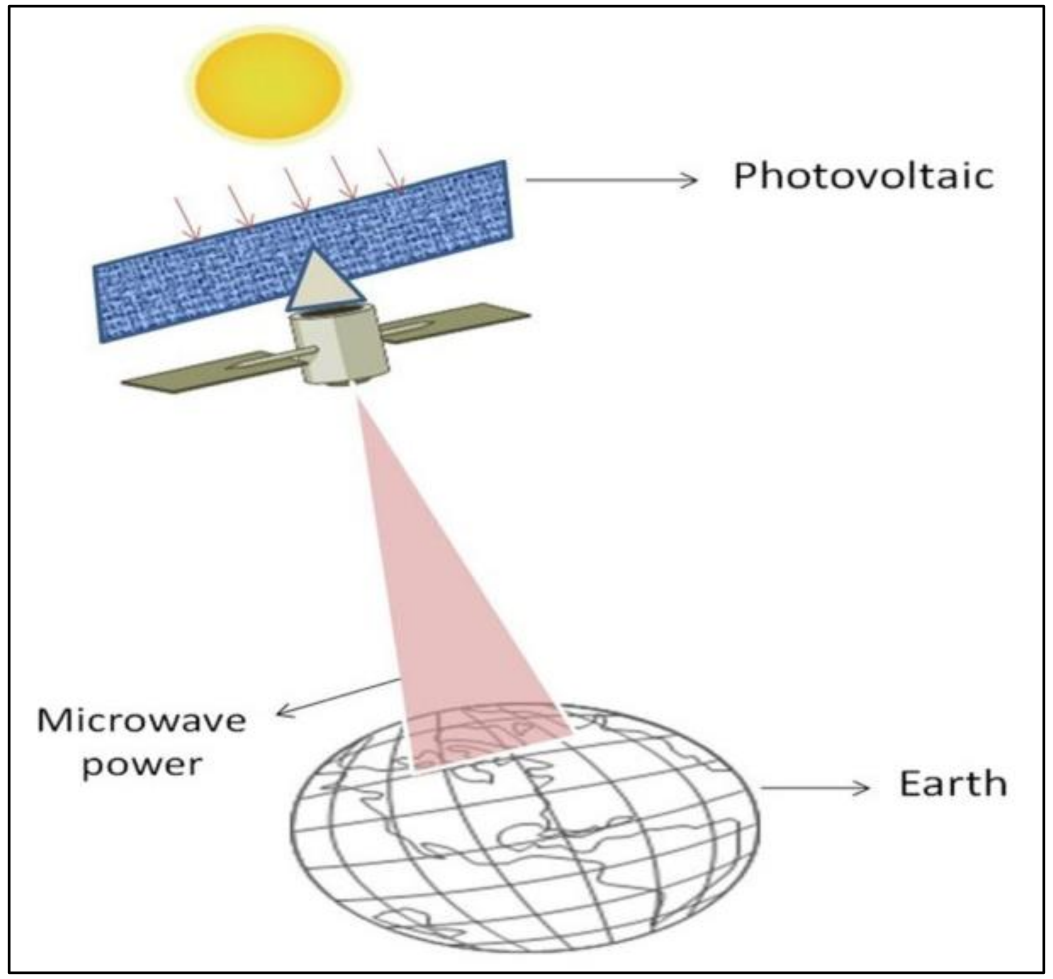
- **Experiment:** Electrostatic Thrusters for Microgravity Propulsion in a Pressurized Environment [7]
  - **Purpose:** Motivated by long-term human exploration missions which could benefit from robotic assistants. A prototype thruster based on an Ion-Drag Pump was developed.
  - **Procedure:**
    1. Run propulsion readiness
    2. Perform static tests
    3. If static tests is successful: Perform dynamic test
    4. Measure and log current, voltage, and thrust periodically
    5. Evaluate data to determine outcome
  - **Results/Benefit to Future Missions:**
    - Future engines to support astronauts on activities during their stay at the surface habitat
  - **Off-Nominal Plan:**
    - System serviceability/stability is critical – The system to be testes will need to be designed to be serviceable and come with the appropriate replacement pieces, manuals, and tools, to perform maintenance/repairs of the most delicate/important components to keep it operational. All thrusters will need to have a safety remote shutdown in case of emergencies while testing.



Ion Drag Pump Thruster Concept [7]

Nominal Plan [Segments 9-10]

- Experiment: Microwave Power Transmission
  - Purpose: Testing of long-range microwave power transmission systems.
  - Procedure:
    - Solar -> DC power -> microwaves transmitted -> microwaves receives by rectenna -> DC power -> measure efficiency of the conversion and transmission process [2]
  - Results/Benefits to Future Missions:
    - Demonstrate microwave power transmission across long distances in the lunar environment
    - Provide power to remote locations where ground resources are unavailable
  - **Off-Nominal Plan (Contingency):**
    - Antenna alignment is critical – any ground components can be designed to be serviceable while orbital assets will need to have built in redundancies for attitude alignment.
    - Depending on the satellite's orbit, many timeframes for the experiment will be available.



A high-level graphic for microwave power transmission from space. [2]

Hazards and Risk Assessment

		Consequence				
		Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)
Likelihood	Almost Certain (5)	- Radiation from DEXA scan - Solar Radiation	- Regolith (dust clinging, abrasiveness, and clogging)			
	Likely (4)	- RF Radiation				
	Possible (3)		- LTV getting stuck	- Astronaut getting stuck during EVA	- Vacuum Cementing	
	Unlikely (2)			- Medical injury during EVA - LTV Breaking down		
	Rare (1)		- Greenhouse Failure		- Thruster malfunction	- Exposure to toxic materials - Regolith Ingestion

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