The Lunar Lab Initiative

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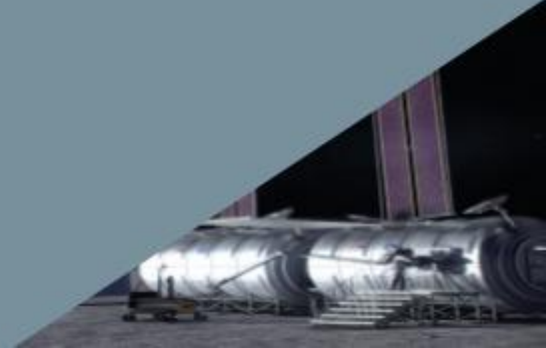
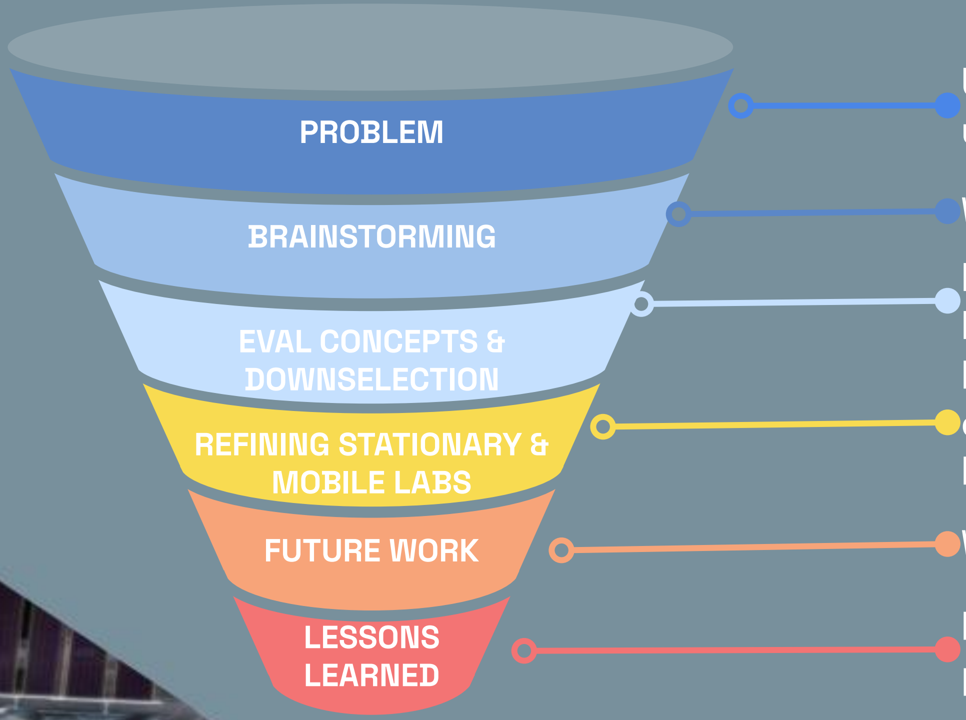


Agenda



Understanding the problem and user’s ground rules and assumptions

Wide open ideation of concepts

Ranking of Concepts and Pugh Matrix Evaluation

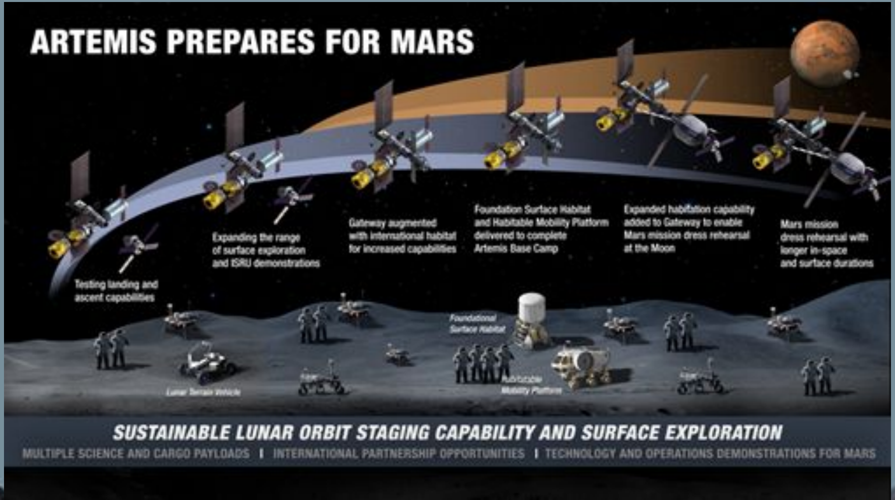
Refinement of the two selected concepts - develop the Con Ops, MEL, and layouts

Where the concepts go from here

Lessons learned from the pilot FORGE

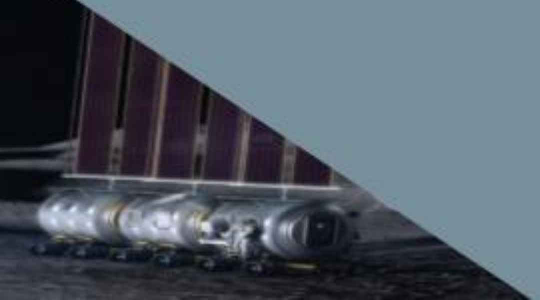
Introduction

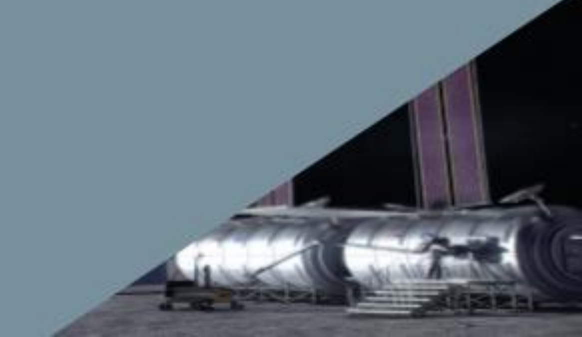
NASA is returning to the lunar surface to explore and establish a sustainable base at the South Pole of the Moon, not just to visit as was done during the Apollo Program. The current lunar surface plans include a Lunar Terrain Vehicle (LTV), Pressurized Rover (PR) and a Surface Habitat (SH), but due to lander down mass constraints, the ability to perform science in these elements is severely limited.



Pilot FORGE Study to address this science shortfall

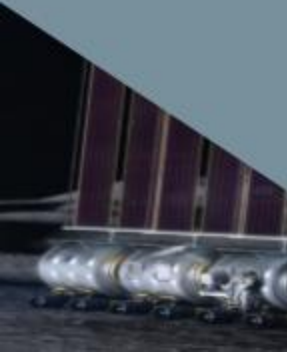
The “Forge the Lunar Lab” team included facilitators, a customer representative, subsystem experts, architects, safety experts, system engineers, human factors specialists, engineering visualization professionals, and lunar science experts. The concurrent design session was held to ideate concepts, evaluate and downselect, then refine the two chosen designs with mass, power, thermal, operations and human factors considerations. The sessions were held over five Fridays in order to accommodate the “on-call” representatives to the team with regular roles outside the study.

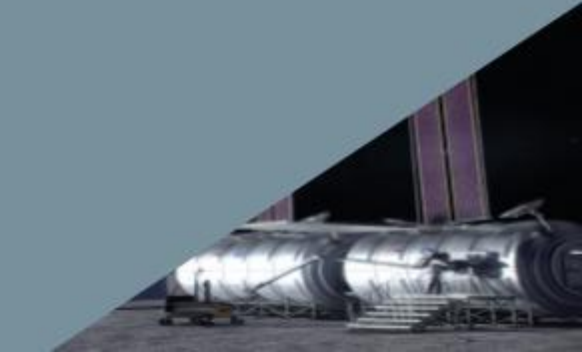




Ground Rules & Assumptions

- Programmatic Considerations
  - Annual 4 person missions to the South Pole for ~33 days of surface operations
  - 2 crew live in the Surface Habitat while the other 2 roam in the Pressurized Rover
  - Launch on existing or near term potential commercial Launch Vehicles
  - Elements are expected to be self-sufficient
- Science Objectives
  - Research can include lunar environment, biological and non-biological process in the lunar environment, research of the universe from the lunar vantage point
  - Payload grouping from Constellation Program Study:
    - Geology Lab
    - Biology Lab
    - Physics Lab
    - External Payloads
  - Missing under Constellation was Human Research Lab





Brainstorming Concepts

Several questions to flesh out the need for a science lab and different potential configurations. The team brainstormed around these questions:

1) How might we achieve science production?

2) How might we provide crew access or interface the asset to other surface elements?

3) How might we deploy the asset to its location?

4) How might we provide a pressurized volume for the crew?

5) How might we provide crew life support?

Morphology Matrix

Maximize Science Production	1. External Attached Instrument 2. External Deployable Instrument 3. External Remote Crew Operations 4. External Remote Ground Operations 5. Sample Return 6. Sample Collection/Handling 7. Lab Self-Mobile 8. External Tools & Instruments used EVA 9. Internal Tools
Asset Deployment – Delivery or Landing	1. Non-Deployed "Top-Deck" Lander 2. Non-Deployed "Underslung" Lander 3. Sky Crane 4. Davit Crane 5. Collapsible Legs 6. Multi-piece Module 7. Expandable

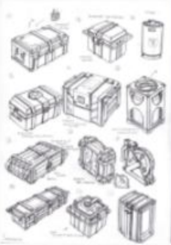
Asset Deployment – Post Landing	1. Self-propelled on wheels 2. Carried by other asset 3. Stationary 4. Towed by other asset 5. Rolling 6. Rails 7. Self-propelled on legs 8. Self-propelled on thrusters
Crew Access & Interface with other Elements	1. Airlock 2. Direct connection 3. No crew access 4. Docking system 5. Hatch 6. Suitport 7. Pressurized Tunnel 8. Pressurized Garage

Pressurized Volume	1. Lava tube 2. Repurposed asset 3. 3D-printed 4. Composite Pressure Vessel (PV) 5. Hybrid PV (metallic/expandable) 6. Metallic PV 7. Expandable PV 8. No PV 9. Multiple or segmented
Environmental Control and Life Support System (ECLSS)	1. In-situ Resource Utilization (ISRU) 2. Use Surface Habitats 3. Use Pressurized Rovers 4. Regenerative ECLSS 5. Resupplied ECLSS 6. Use spacesuit portable life support system (PLSS) 7. Hybrid of regenerative & resupply 8. Plant-based

Brainstorming Concepts

Concept 1: Minimalist, Crew Operated

necessary tools only with pallets of tools/equipment all EVA accessible. no PV volume, robotic assistants (rovers/drones)
mass driver shoots up to gateway or Earth for processing
just enough to find the interesting stuff to send back to earth/gateway which better equipment
Four 3MT pallets arrive on the lander then Davit deployed to surface for EVA access. each pallet could be themed around a science objective. Could have a pallet reduce science capacity but hop to different location.
Could be located within walking distance of surface Hab or rover drives to it for extended stay (mult EVAs living out of rover)
lander provides power to sceince pallet when in use.



- No PV/Life Support
- EVA accessible equipment
- Davit crane deployment
- Small robotic assistance
- Frequent sample return and data transfer

Concept 2: Cadillac/Pressurized Lava Tube

Underground lava tube with similar science pallets deployed from lander then drive themselves into the lava tube. requires to cargo landers - one to deploy the four 3MT science pallets and another to deploy four 3MT of equipment to provide lava tube airlock/Seal and ECLSS/habitation outfitting. will have garage area for Pressure or unpressurized rover repairs/ deployment. Greenhouse/Algae provide support for ECLSS as well as potential for ice in tube to augment as well
comm and power on surface. or nuke power deployed far away in lava tube.
unlimited expansion potential with Boring company drill

- Pressurize lava tube network
- Nuclear/Solar power plant
- Two launches
- Mobile Science Rover
- Infrastructure expansion opportunities
- Surface Comms and Power
- ISRU-augmented life support

Brainstorming Concepts

Concept 3: Top-Deck Multi-piece "Starship style" - Stationary

- airlock, walk-in/out from porches
- Suit-ports + Airlock up on porch
- Davit crane up/down
- Pre-fab pressurized volume
- Lab, Hab & airlock modules
- Inflatable section
- Reuse tank section for pressurized volume
- Fission power-source
- water-encased module for rad protection

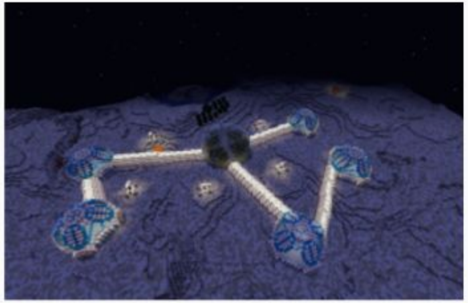
Concept 4: drop-down multi-piece, Single landing - Stationary

- 6 sections stacked on lander 3 over 3
- lower sections to ground (Devit crane) - interconnect with flexible tunnels
- Solar power systems (deploy on high mast)
- 3D printed radiation shelter
- ISRU, mine-water -> electrolysis, and carbon store LOX and CH4

Brainstorming Concepts

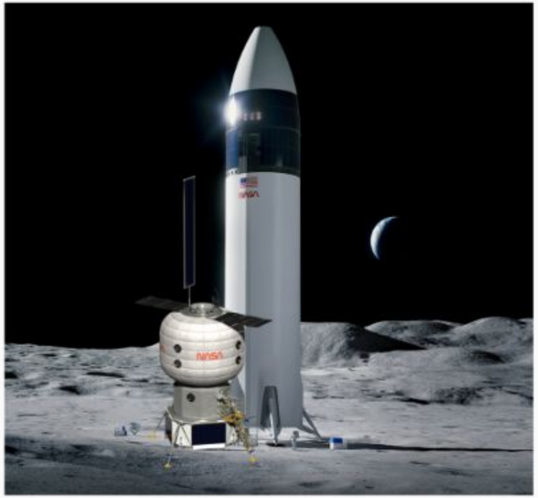
Concept 5: Interconnected Modular Science Base Camp Multi-landing, Stationary

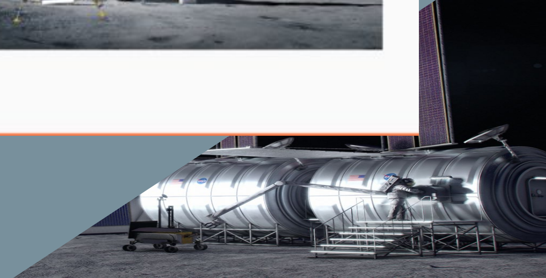
- Stationary lab
- Pre-assembled modules connected by tunnels
- Main pressurized entrance that leads to others
- Modules connected through pressurized tunnel
- Different labs for disciplines - can isolate, different temperatures, PPE, etc.
- Draw life support off the Hab - supplment if necessary
- Sample ports important
- Maximize allocated science volume
- Modularity / expandability
- Mobility system to relocate modules after landing
- Allow autonomy for science payloads - not limited to just what the crew in the room can do



Concept 6: Starship Researcher

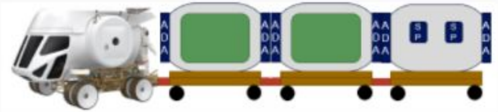
- Use an entire Starship as a science lab
- Stationary lab
- Large volume/pre assembled
- Maximize allocated science volume
- Airlock/Suitports to access
- Different labs for disciplines - can isolate, different temperatures, PPE, etc.
- Maximize allocated science volume
- TBD Mobility system to relocate Starship lab after landing
- Allow autonomy for science payloads - not limited to just what the crew in the room can do





Brainstorming Concepts

Concept 7: Mobile Multi-Module Laboratory



- Mobile
- Active Mobility
- Rover-like with a laboratory outfit
- Train Modules together via ADAs
- Mobile Platforms with same capability as rover
- Incorporate inflatables onto sides (pop-up camper)
- Reclaim consumables for inflatables deployment/retraction
- 40x60 EVA Hatch
- Open Loop/ Tanks ECLSS
- Pressurized Transfer/ Androgynous Docking Adapter
- Glovebox/ ScienceLock / Suitport
- Robotic Arm

Concept 8: 3D-Printed Stationary Laboratory

- Stationary
- Pressurized Tunnel/Docking System
- More Volume & Mass available for science
- Autonomous/ Remote Control
- 3D Printed Lab w/ Bladder on inside
- Closed Loop ECLSS
- Hybrid structure
- Airlock

Brainstorming Concepts

Concept 9: Science-focused, Pressurized Single Element Rover

- How it Landed: Underslung
- Mobility: Mobile on Wheels
- Suit Ports
- Composite, Non Expandble PV
- Regen ECLSS
- Power & data stored externally

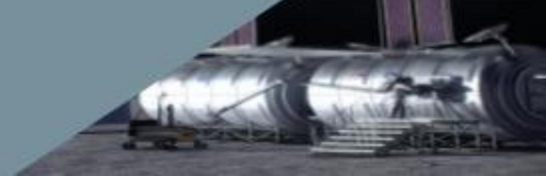
Concept 10: Non-Pressurized, Remote Operated, Stationary Lab

- How it landed: SkyCrane
- Mobility: Stationary
- Conglomeration of Science Equipment
- Remote drones
- Robotic Arms
- Robotic Sample Collectors
- Crew uses Their own Suits for Life Support & PV if they need to do maintenacee
- Power & data stored externally

Two ends of the Brainstorming spectrum

The “Lava Tube Lab” was at the low TRL end of the spectrum. This concept used a natural lava tube and underground cavern to provide the habitable volume for as large a science lab as desired. While this concept provided an unlimited expandable base infrastructure for science, the team realized that there are no known lava tubes in vicinity of the planned lunar south pole base locations. This concept could still be used if a Tunnel Boring Machine (TBM) were developed to create the underground system at the desired location.

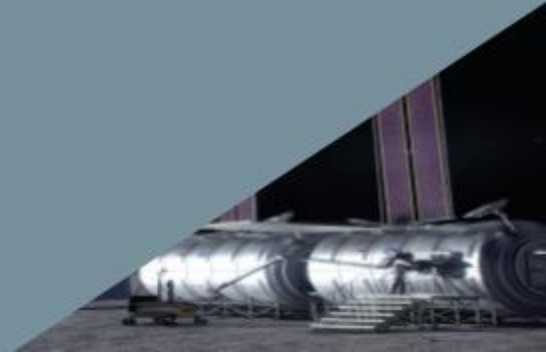
Other novel concepts utilized the SpaceX Starship as either a very large cargo delivery system or a customized Starship modified to be a habitable lab. Given the Government Accounting Office (GAO) protest at the time for the Human Landing System (HLS) selection of the Starship, the team eliminated these concepts from the trade space.



Evaluation

The team voted on the most innovative concepts, with the results showing the "Lava Tube Lab" and the "Multi-Module Mobile Lab" ranking highest.

Second, the team voted on the most feasible concepts, which resulted in the "Minimalist Lab", a single module rover, and stationary concepts ranking highly.



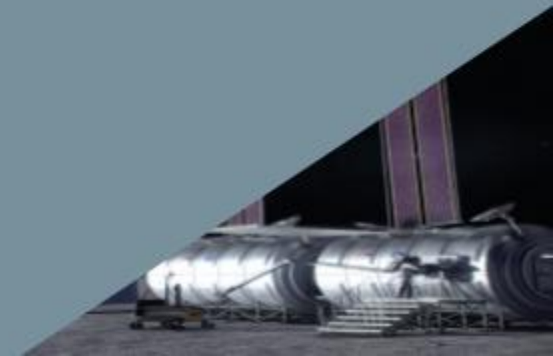
Pugh Method

The baseline (concept 5) was the multi-module stationary lab. Concepts that scored worse than the baseline (2, 4, and 8) were the “Lava Tube Lab”, the single landing stationary lab, and the 3D-printed lab. Concepts that scored better than the baseline (6, 7, and 9) were the science-focused Starship, the multi-module mobile lab, and the single element science-focused rover. The multi-module mobile lab was considered an extension of the single element rover, so the concepts were combined.

Objective	Weights	Concept 5	Concept 2	Concept 4	Concept 6	Concept 7	Concept 8	Concept 9
Completes science Objectives	25	Datum	+3	-1	+2	+5	+1	+1
Extensability to Mars	12		-1	+1	+4	+9	+8	+4
Affordability	25		-8	+3	+11	+1	0	+5
Reduced crew risk	13		0	0	+6	+1	-1	+1
Compatible w/ Artemis base camp arch.	25		-8	-2	-1	+4	-4	+5
Weighted Objective		**0**	**-3.37**	**0.12**	**4.26**	**3.71**	**0.08**	**3.36**

Multi-Module Stationary Lab

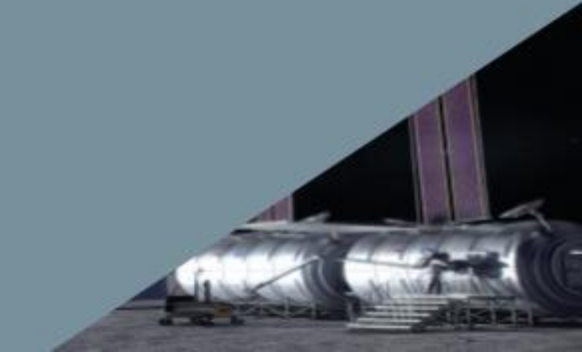
To maximize the downmass, a three-element delivery architecture was chosen with aggregation in Low Earth Orbit (LEO). This mission profile consisted of the lab element launching with a propulsion bus stage, a descent lander element, and a transfer element for performing the Translunar Injection (TLI) burn. The lab element will launch on a commercial launch vehicle, mounted vertically in the launch fairing to maximize the lab size. Once launched, the lab element and bus await the arrival of the descent lander and transfer element. The lab element will be mounted in the horizontal configuration on the descent lander to make offload and placement on the surface easier.



Multi-Module Stationary Lab Trades

Various design trades were conducted by the concurrent engineering team to fully explore the design space:

- Vertical vs **<u>Horizontal</u>** Module orientation
- **<u>Hard structure</u>** vs Inflatable
- ECLSS **<u>centralized</u>** vs distributed



Multi-Module Stationary Lab MEL and PEL

Lunar Lab MEL

Subsystem	Masses (kg)		
	Basic	MGA	Predicted
1.0 Structures	3566.8	25.0%	4458.5
2.0 Power	1294.6	20.0%	1553.5
3.0 C&DH	473.4	20.0%	568.1
4.0 C&T	0.0	0.0%	0.0
5.0 GN&C	0.0	0.0%	0.0
6.0 Thermal	302.0	18.9%	359.1
7.0 Life Support	508.7	20.0%	610.5
8.0 Crew Systems	66.5	20.0%	79.8
9.0 Robotic Systems	5967.0	26.8%	7563.8
10.0 Misc	0.0	0.0%	0.0
Total Dry Mass	**12179.0**	24.7%	**15193.2**
	Extra Systems Margin: (15% of Basic)		1826.8

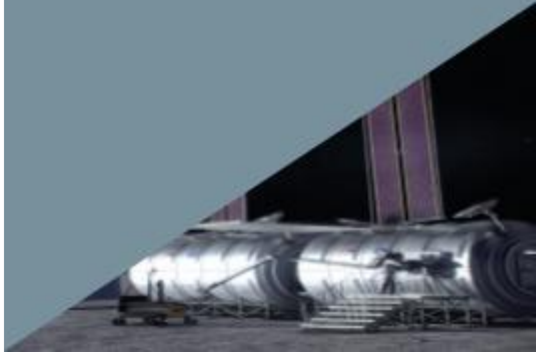
11.0 Payload, Science & Cargo	Masses (kg)		
	Basic	MGA	Predicted
Science & Cargo	7223.09	13.0%	8160.8
Non-prop Fluids (all fluids other than maneuver prop):	141.36	20.0%	169.6
	Total Wet Mass (kg):		25350.5

Lunar Lab PEL

Subsystem	Power (W)	
	Nominal	Peak
1.0 Structures	0	0
2.0 Power	450.594	548.713
3.0 C&DH	1388.2	0
4.0 C&T	0	0
5.0 GN&C	0	0
6.0 Thermal	401	0
7.0 Life Support	2046	0
8.0 Crew Systems	500	1000
9.0 Robotic Systems	8400.00	15150.00
10.0 Misc	0	0
Total Power Usage:	**13185.8**	**16698.7**
Extra Systems Margin: (15% of Basic)	1977.87	2504.81

11.0 Payload, Science & Cargo	Power (W)	
	Nominal	Peak
Science & Cargo	6794.5	8279.5
Non-prop Fluids (all fluids other than maneuver prop):	0	0
Total Power (W)*:	19980.3	24978.2

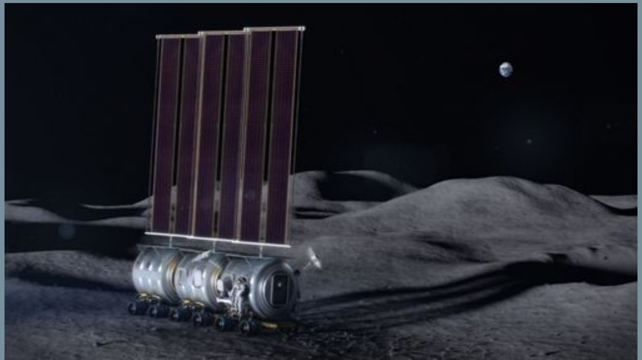
*Note does not include any margin

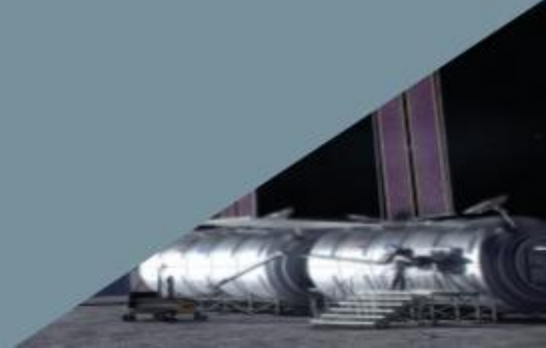


Multi-Module Mobile Lab

Each pressurized lab module will launch integrated on a descent lander and arrive at the Moon via ballistic trajectory with a coast duration of 90-120 days. Once on the surface, MCC will command the mobile lab module to deploy to the surface via either a Davit Crane or lander ramp. Once on the lunar surface, the mobile lab module will drive to the parking lot designated area to await the arrival of the other mobile lab modules.

Two crew members could use the mobile lab at the surface habitat while the other two crew members perform EVAs out of the surface habitat. Or, all four crew members could split between the mobile lab and the pressurized rover to explore an area of interest away from the surface habitat for part of the surface stay.



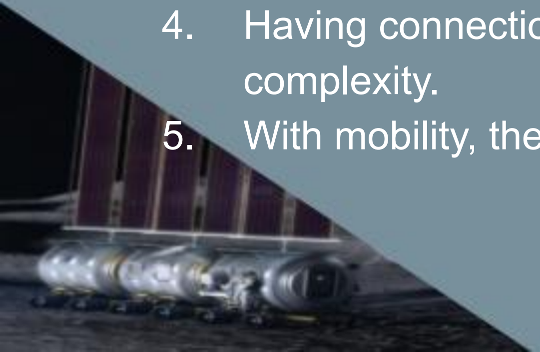


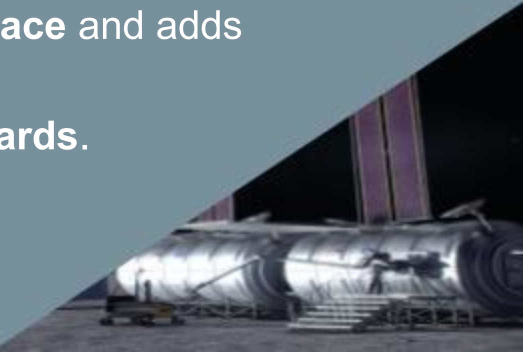
Multi-Module Mobile Lab Strengths

1. With mobility comes the ability to **provide greater area of surface exploration**, which is highly desirable by the science community.
2. With each module having its own mobility, the **assets can be pre-positioned** and do not need a separate surface transport capability.
3. This mobile lab can **share the same landing and delivery system** as the already planned Pressurized Rover.
4. If used in conjunction with the Pressurized Rover, the **overall exploration range away from the Artemis Base Camp may be increased**.
5. The mobile lab adds robustness to the overall architecture since it could **provide a safe haven** accessible from both the Habitat and the Pressurized Rover.
6. Standardized modules delivered sequentially allow for an **evolvable science capability** on the surface.


Multi Module Mobile Lab Weaknesses

1. The **science payload mass** available in each module will be **reduced** due to the mass of the mobility system.
2. While the lab was in motion, it would be hard to do any science experimentation; therefore, **crew time would be divided between science and driving**. Science equipment will have to withstand the additional loads and dynamics from the lab motion.
3. With the linear design, it is **not easy to isolate the central modules**. Additionally, driving a ‘train’ is more difficult than a single module and terrain access will be limited.
4. Having connections between modules **reduces the habitable space** and adds complexity.
5. With mobility, there is a **greater need for restraints and fall hazards**.

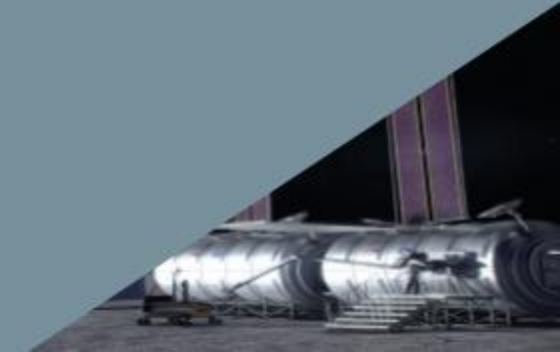




Multi-Module Mobile Lab Trades

Various design trades were conducted by the concurrent engineering team to fully explore the design space.

- Vertical vs **Horizontal** Module orientation
- **Hard structure** vs Inflatable
- ECLSS centralized vs **distributed**



Multi-Module Mobile Lab MEL and PEL

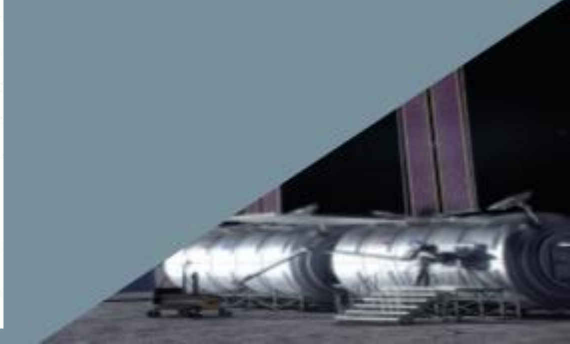
Lunar Lab MEL			
Subsystem	Masses (kg)		
	Basic	MGA	Predicted
1.0 Structures	1356.6	25.0%	1695.7
2.0 Power	1371.5	20.0%	1645.8
3.0 C&DH	444.9	20.0%	533.9
4.0 C&T	2.5	20.0%	3.0
5.0 GN&C	0.0	0.0%	0.0
6.0 Thermal	258.1	18.7%	306.4
7.0 Life Support	639.5	20.0%	767.4
8.0 Crew Systems	156.9	20.0%	188.2
9.0 Robotic Systems	4030.0	27.5%	5139.0
10.0 Misc	56.0	20.0%	67.2
Total Dry Mass	**8315.9**	24.4%	**10346.7**
	Extra Systems Margin: (15% of Basic)		1247.4

11.0 Payload, Science & Cargo	Masses (kg)		
	Basic	MGA	Predicted
Science & Cargo	4015.53	20.0%	4819.1
Non-prop Fluids (all fluids other than maneuver prop):	224.82	20.0%	269.8
Total Wet Mass (kg):			**16683.0**

Lunar Lab PEL		
Subsystem	Power (W)	
	Nominal	Peak
1.0 Structures	0	0
2.0 Power	445.266	562.319
3.0 C&DH	1737.4	362
4.0 C&T	0	0
5.0 GN&C	0	0
6.0 Thermal	401	0
7.0 Life Support	3666	0
8.0 Crew Systems	804.4	1352
9.0 Robotic Systems	9500.00	15850.00
10.0 Misc	0	0
Total Power Usage:	**16554.1**	**18126.3**
Extra Systems Margin: (15% of Basic)	2483.11	2718.95

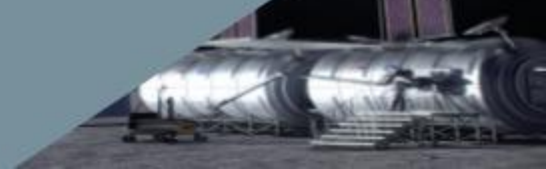
11.0 Payload, Science & Cargo	Power (W)	
	Nominal	Peak
Science & Cargo	3154.5	3749.5
Non-prop Fluids (all fluids other than maneuver prop):	0	0
Total Power (W)*:	**19708.6**	**21875.8**

*Note does not include any margin



Future Work

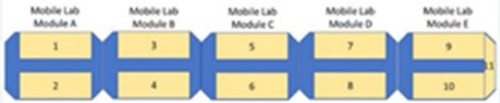
- The Study did not evaluate **development cost and schedule** for either multi-module concept.
- The **science portfolio** included was notional and mostly from the perspective of lunar science. The additional science communities should be incorporated to help refine these equipment needs.
- For both multi-module labs, the main forward work items include assessing the estimated data storage increase, evaluating antenna placement, integrating the vehicle sizing, and launch configurations to arrive at vehicle element design and **distribution on launch vehicles and mass reduction efforts** by increasing the fidelity of the models and sizing of the subsystems.
- Additional forward work items specific to the mobile lab includes assessing the mobility system's **need for six wheels**, evaluating the need for redundant C&DH systems or a transferrable C&DH, re-evaluating the solar array sizing for **peak power usage** from the drive train, **re-assessing the drive system sizing** and re-sizing the off-load ramp.



Human Factors Evaluation Needed

The purpose of the evaluation is to obtain preliminary data on human interfaces and configuration habitation layout for lunar science missions per concept.

Chose an area number for each of the internal Lunar Lab elements for Mobile Lab Modules A-E



	Biology Lab	Multi-Disciplinary Shared Equipment **(Choice 3 Areas)**	Geology Lab	Physics/Technology Testing Lab **(Choice 2 Areas)**	Human Research Lab	Habitation/Housekeeping **(Choice 2 Areas)**	EVA
Area 1	○	○	○	○	○	○	○
Area 2	○	○	○	○	○	○	○
Area 3	○	○	○	○	○	○	○
Area 4	○	○	○	○	○	○	○
Area 5	○	○	○	○	○	○	○
Area 6	○	○	○	○	○	○	○
Area 7	○	○	○	○	○	○	○
Area 8	○	○	○	○	○	○	○
Area 9	○	○	○	○	○	○	○
Area 10	○	○	○	○	○	○	○

Chose an area number for each of the internal Lunar Lab elements for Lab Modules A-B

	Biology Lab	Lab A Multi-Disciplinary Shared Equipment	Lab B Multi-Disciplinary Shared Equipment	Geology Lab	Physics Lab & Technology Lab **(Choice 2 Areas)**	Human Research Lab	Not Used
Area 1	○	○	○	○	○	○	○
Area 2	○	○	○	○	○	○	○
Area 3	○	○	○	○	○	○	○
Area 4	○	○	○	○	○	○	○
Area 5	○	○	○	○	○	○	○
Area 6	○	○	○	○	○	○	○
Area 7	○	○	○	○	○	○	○
Area 8	○	○	○	○	○	○	○
Area 9	○	○	○	○	○	○	○
Area 10	○	○	○	○	○	○	○

Lessons Learned

- Lessons learned on the process and development of the Forge are documented in a separate paper (Forging the Forge March 10 21:00 @ Lake/Canyon).
- Five days to brainstorm, evaluate, and develop 2 concepts was not enough time to fully document the trades and refine the concepts fully.
  - If future studies scope two concept designs, an additional three days will be included in the schedule and additional architects will be added to the roster.
- Sometimes it was hard to visualize current state of the concept.
  - A visual medium (visual iteration, sketching, CAD or graphics) to communicate the current state of the design, and having that displayed either in the room or virtually would have been a great benefit.
  - A better data management platform than Microsoft Office 365 and OneDrive is desired for future studies but is sufficient to meet needs at this time.
- Customer involvement in the studies is necessary, but this involvement needs to be balanced in order to allow the team the freedom to explore the solution space and make design decisions.
  - Customer involvement that is too specific can reduce the benefits of the brainstorming and concurrent design sessions.
  - The customer must also be prevented from changing the scope throughout the study.

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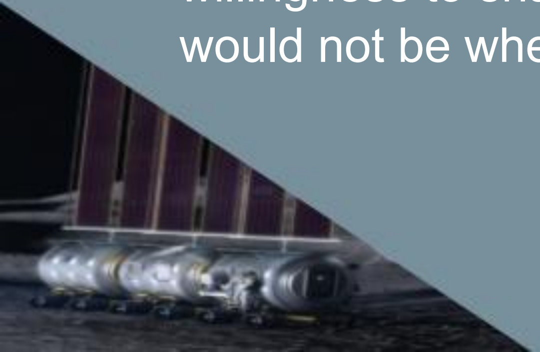

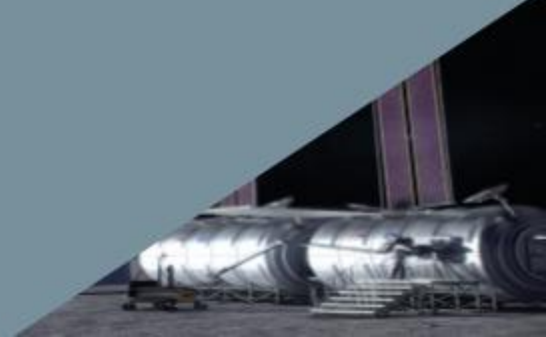

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