EXPLORATION CURIOSITY EQUALITY FOR ALL OF HUMANITY SAFETY COLLABORATION

DIA

DOMI INTER ASTRA

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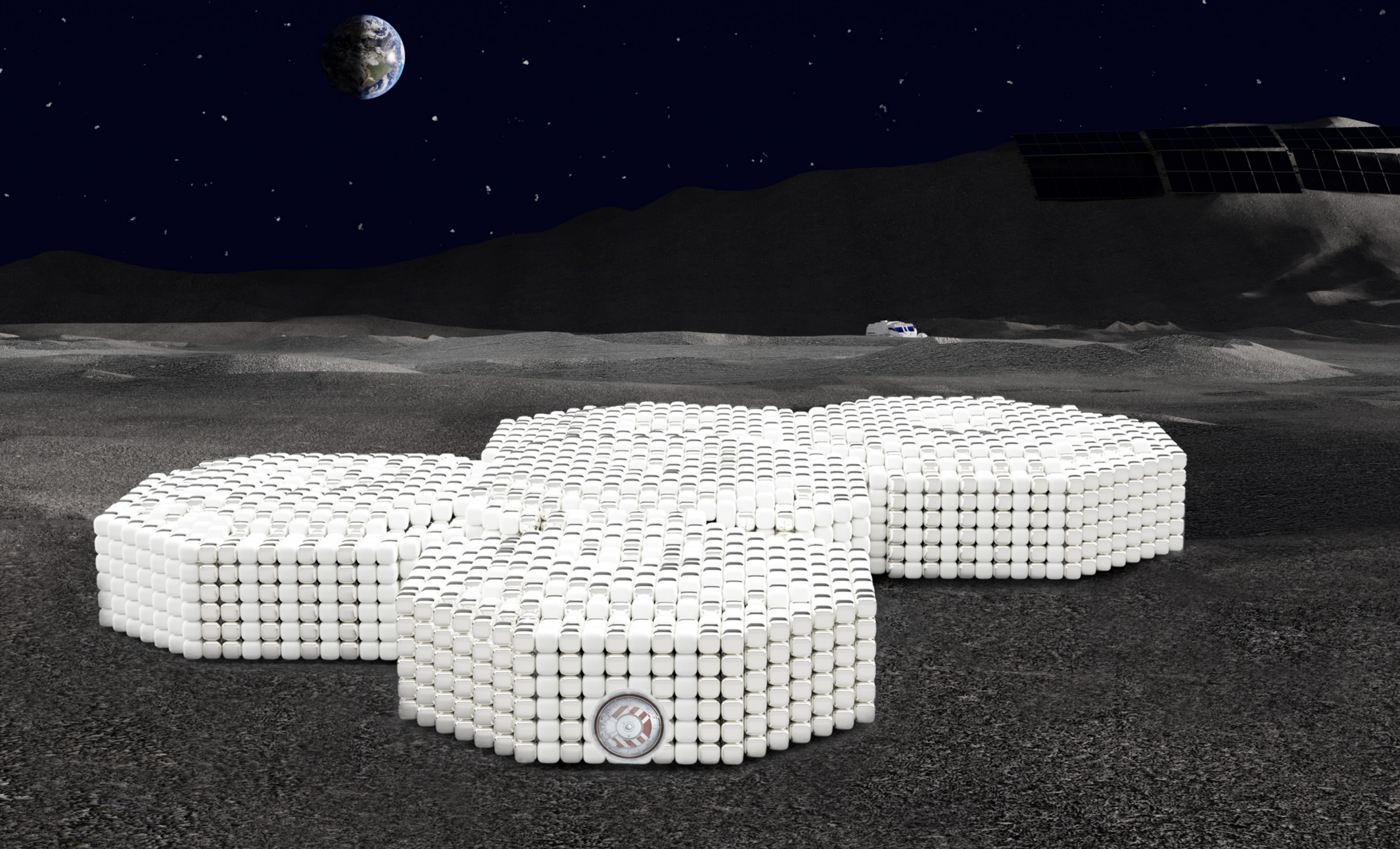


Contents

Antariksha, aptly meaning ‘the universe’ in Sanskrit, is an avid stargazer fascinated by the blanket of splurging stars she saw from her village in North East India. Today, her joy knew no bounds upon learning that she would get a chance to visit Domi Inter Astra, the lunar settlement! Perhaps what made it even more special was that she had been able to commemorate everything it stood for by winning the DIA logo making competition. She wondered how Neil Armstrong must’ve felt when he first stepped on the moon. She would soon find out. This was going to be a giant leap for all the young girls around the world, and she knew something incredible is waiting to be known.

“Each civilization must become space-faring or extinct”. Carl Sagan’s words transported her to another world, as she laid her eyes on the huge map that lay in front of her. It reminded her of home, but at the same time, it was a peek into a whole new world. She wasn’t going to be alone, she had friended the sentient AI mascot, LISA (Lunar Intelligent Support Assistant).

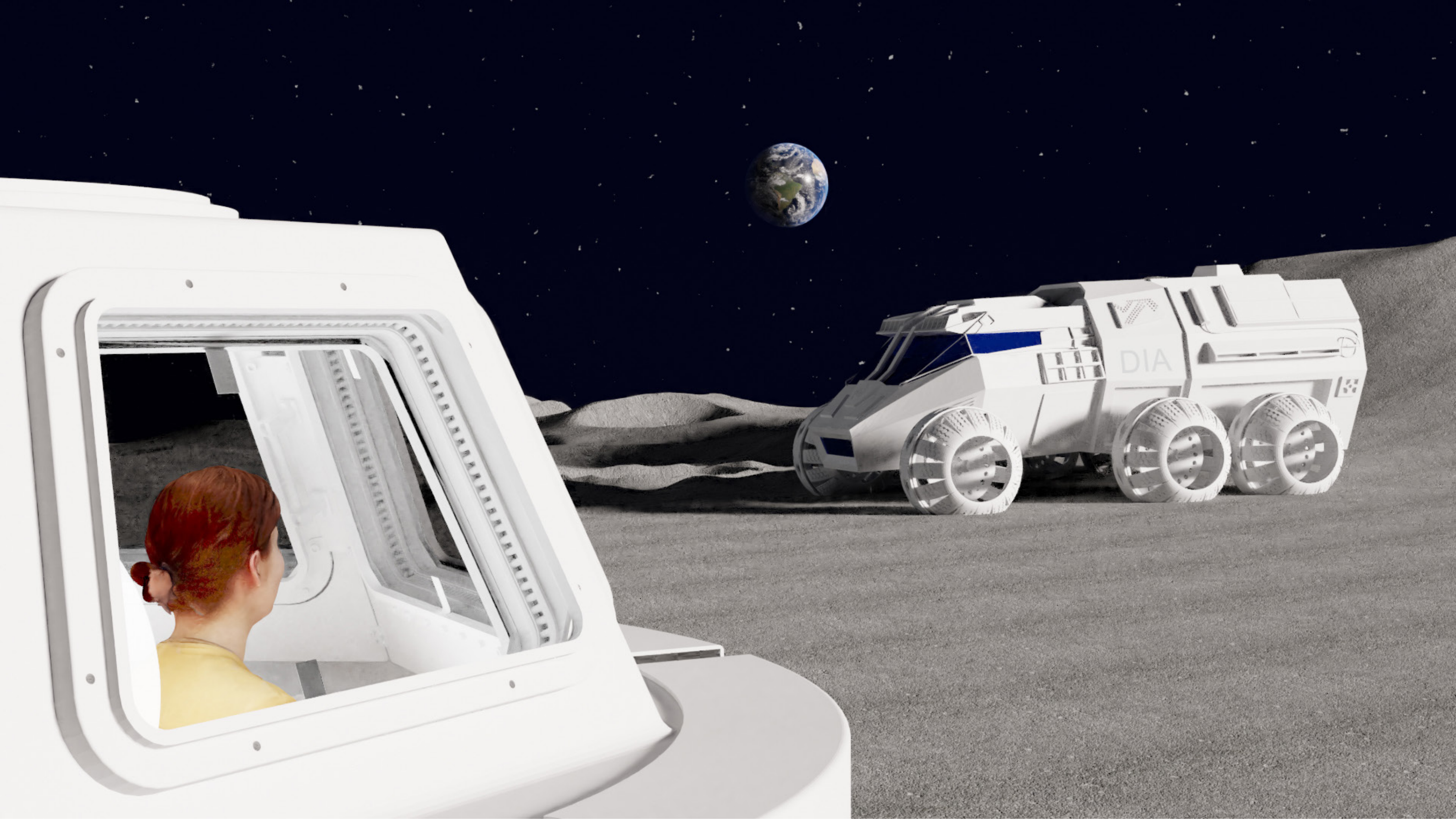


Figure 1: Artistic render of the view from the settlement cupola to the day sky and lunar landscape, showing a crewed rover model and an Earthrise in the background.

Society and Culture

***Antariksha** was intrigued about how her logo could translate into everything the DIA stood for, perhaps getting to know about the culture and society would guide.*

***LISA-** Culture resides in the heart and soul of the people and what the base stands for. It will definitely be an inspiration for generations to come.*

Domi Inter Astra (DIA) is a multinational lunar settlement, an amalgam of people from all cultures with its own multi-cultural traditions, involving those not only from Earth but also traditions unique to the settlement. The base operates for the benefit of all humankind following five core values: collaboration, exploration, equality, curiosity, and safety. The code of conduct advocates equality of financial background, education, caste, religion, creed, race, gender, color, nationality and age.

Tourist Attractions

There are a variety of tourist attractions on DIA, with the most unique being the lunar landscape (Figure 1) and opportunities for exploration and EVAs. Art and creativity is encouraged on DIA, with resident artists and the crew able to photograph the area and create other artworks to share on Earth. Tourists are also able to engage in the leisure activities available for crew, described in *§Architecture*.

Each new arrival starts their journey travelling from the landing site to the settlement - this is their first opportunity to see the lunar landscape through the crewed rover as well as the settlement as they approach. The habitat is organized as a living museum with placards describing the various aspects to the base, allowing guests to explore and experience the differences between Earth and Lunar life and see the engineering required for human exploration; as well as helping new crews learn. Tourists are welcome to follow the crew as they work with their payloads and accompany rover/EVA missions and are encouraged to document life on the lunar settlement to share as outreach, and can bring back photos, videos, and souvenirs to commemorate their experiences, as well as leave behind mementos for future guests. The uncrewed rovers are out at the different sites, including Shackleton Crater and tourists are able to look through the robotic cameras to tour the lunar surface, exploring craters and lava tubes.

Astronaut and Tourist Selection

Crew members are selected for technical and interpersonal skills needed to live long periods in an isolated environment, and for skills and passion to promote outreach and education activities that engage the public. Resident artist positions are just as valuable to the operations as core technical research and help to both enrich the lives of crews and develop tourist offerings on the settlement. All visitors to the settlement will need basic training in how to operate in microgravity and emergency response, with crews also required to be familiar with base maintenance and become familiar with the work they will be conducting[1].

Analog missions are points for preparing for life on the moon to help crew adjust to the isolated environment, as well as bond with their future crewmates.

Tourists are an integral part of the base's public outreach and offer an opportunity for non-career astronauts to experience the wonders of space. Tourists can reach the base either by purchasing a seat on existing crew changeovers, allowing them to arrive with the new crews and exit with the leaving crew; through dedicated launches allowing for more dedicated crew interaction time; or through a lottery system managed by the person's home country to open the opportunity of space travel beyond the super-rich. As launch costs decrease, the lottery system can easily scale to accommodate more frequent travelers.

Architecture

As an artist she knew how spaces could affect how one felt. She marveled at the simplicity of the structure but yet beautifully functional.

Psychological health is critical for long-duration missions[2], and is maintained by providing diverse experiences in activities, locations, and social interaction. While crew time is largely consumed by their work, time for leisure becomes more critical as length of stays grow. Entertainment such as board games, music, movies, and books are supplied, and crew may make requests for additional items to be delivered during resupplies. Spaces of varying levels of privacy allow crewmembers to have diverse activities - from large social gatherings in the social module, to smaller groups in the kitchen and crew modules, to individual activities within their rooms such as calling friends/family on Earth. Movable barriers/curtains also allow the crew to segment larger spaces for separate activities. Crew members have access to telemedical services, allowing them to monitor their mental health.

Each module was designed with psychological health in mind, providing a unique spatial experience through color, sound, and material to provide a larger sense of space and opportunities to feel like home[3][4]. Private spaces are designed to be static, providing consistency in lifestyle, while more public spaces are designed to be modular and dynamic to accommodate different activities and simulate a larger environment.

Crew and guests are provided with a digital key to control access throughout the base which maintains

Figure 2: DIA floor plan showing individual module functionality and overall base interoperability.

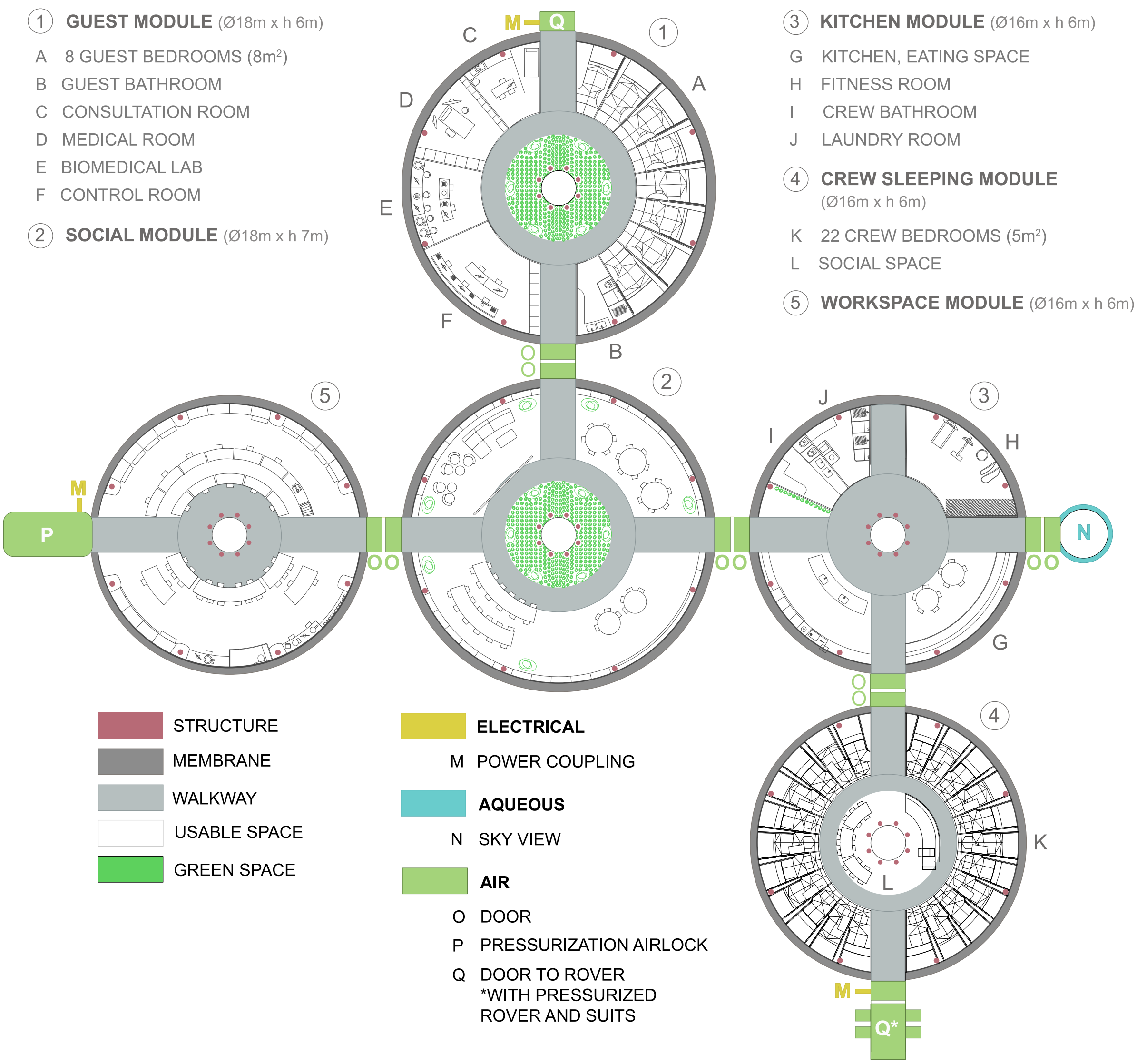


Figure 3: Artistic render of Module 2, showing crew social activities and the central greenhouse.

electronic scalability as members enter/leave. Figure 2 provides an overall floor plan of all the modules.

Furniture is designed to use lightweight composites that take advantage of the reduced gravity, be foldable to maximize habitable volume, portable to fit crew needs, and be modular to allow easy repair/replacement. Wood prints provide a warm atmosphere to help connect crew to Earth. The base uses a combination of LED lights and fiber-optic collectors to pipe in natural light when available, saving energy and adding diversity to the living environment. Lighting can be adjusted to suit the crew's needs, with LEDs in each location able to adjust color to fit the activity (darker blues for sleeping, oranges for physical activity, greens for relaxation, etc.). The ceiling, floor and wall surfaces range in texture to increase a room's apparent size or offer a more comforting atmosphere, while also minimizing equipment noise and adding to the touch experience. Fragrant herbs throughout the settlement provide greenery for crew and offer scents from home to create a continuous fresh and delicate balance of fragrance, as well as a great addition to the food.

Module 1: Greenhouse, Guest Amenities, Medicine, and Environmental Control

Module 1 is the primary entrance to the lunar settlement. When guests and new crews enter through the rover docking port, they are greeted by one of the large greenhouses which provides a familiar sight to help guests relax and acclimatize[5]. Eight guest rooms are located nearby which have a similar layout as crew rooms. This module also contains a dedicated bathroom and hygiene area for guests to have their own space separate from the permanent crew.

The medical room acts as a multipurpose space for human research, pharmacy, general practice and, if needed, emergency procedures including basic surgery with the goal to stabilize a patient for evacuation. Small-scale diagnostic equipment such as ECG, X-ray, and ultrasound are available. Crew rooms are used for nursing and any ongoing care of individual crew. Telemedicine provides the various fields of medical expertise as needed.

The control room houses the primary communications system and controllers for settlement-wide operations and acts as a backup for local controllers in each module. Crew interface with these using laptops over the WLAN, however, a crewmember may opt to work inside the room for less noise to communicate with crew out on EVAs.

Module 2: Social Space and Greenhouse

The central module (Figure 3) is where crew members and tourists can socialize together, relax, and recharge. The social space is built versatile, with furniture able to be rearranged and spaces sectioned off. Base members can share a meal together, play games, read, listen to music, or watch a movie using the ceiling projector. The large greenhouse in the center creates an ambiance of nature that helps to maintain crew mental health[6] [7]. Colors and shapes were chosen to create a modern and refreshing experience of nature, with the hex agonal blocks acting as modular units for shelves, lights, or other decorations, while referencing the collaborative strength of bees relating back to DIA's core values. Mirrors positioned throughout and an increased floor height of 4 m make the room feel larger.

Module 3: Kitchen, Fitness, Hygiene, and Social

The kitchen is the first module crew enter each day and houses the food supplies and cookware and offers a quieter space for crew to eat together. While cooking is still limited, ovens and microwaves are available for fresh baked goods and fridges for preserving fresh foods supplied or grown. To promote communal eating, the larger crew sizes (and having lunar gravity) allow foods to be shipped in bulk packaging and shared during mealtimes. The foods supplied reflect the global community at the settlement, allowing crews to share diverse experiences to support their mental health. Fresh produce and herbs from the greenhouses also serve a critical part in making crew life closer-to-home - as much as space food has improved, fresh food is still something that many astronauts miss[8].

At 1/6g, the crew still need ~2 hrs/d of exercise to retain muscle and bone mass[9]. The fitness space draws from the ISS gym for equipment including a treadmill, stationary bike, and resistance bands, as well as open warmup/cooldown areas for other activities including physiotherapy and rehabilitation. A projector in the fitness space allows astronauts to project visuals during their workouts (e.g. videos or outdoor activities).

Two bathrooms with toilets, sinks, and “showers” are here for crew use separate from guests to avoid disturbances. While crew are expected to wear clothing for multiple days, a washer[10,11] is available to minimize resupply mass (currently ~220 kg/yr/person of clothes on the ISS[12], easily justifying the mass).

Module 3: Sky-view

Viewing the Earth, the lunar landscape, and the night sky is one of the main tourist attractions on the base. The moon offers a wonderful dark sky without light pollution and a unique view to home. Tourists can participate in guided EVAs or rover exploration but can also view the sky from the Moon base at any time through the sky-view cupola (Figure 1). A telescope and camera allow guests and crew to observe and document the landscape.

Module 4: Crew Bedrooms and Private Social Space

Twenty-two crew bedrooms are placed around Module 4’s central social area which is private for the crew and ideal for quieter activities. Beds are extendable from single to double to accommodate couples and can flip upwards to reveal a small desk or simply to open more floor space. The walls have velcro to allow the crew to decorate, and the rooms are designed for sound isolation (hence minimal equipment in the module and smaller fans per room). Belongings are stored in the floor or on shelves flipped up from the walls. Temperature and lighting are adjustable within each room, making it an ideal space for private relaxation, connecting with friends/family on Earth, meditation, or prayer.

Module 5: Workspace

Module 5 houses research payloads and is where crews primarily conduct their work. Crew time is prioritized towards activities that can only be done on the moon such as EVAs, and as such most administrative tasks are transmitted to Earth. The airlock is also located on this module to allow crews to bring in larger equipment that cannot fit inside the rovers.

Figure 4: Artistic render of a crew bedroom, showing the bed, mirror, shelves, nightstand, screen and doorway out to the crew private social area

Figure 5: Artistic render of the workspace, showing the crew laptops, tables for experiments, and payload bays along the walls.

The spaces can be configured to handle a wide variety of activities including biology/biotech, earth and space sciences, physical science, educational activities, and technology demonstrations. A 3D printer is available for fabricating replacement or specialized equipment. With the large amount of equipment running, the walls and floors are designed to dampen sound and curtains used to further isolate spaces as needed to reduce transmission throughout the module[13].

Management and Politics

Governance, Ownership, and Intellectual Property

DIA does not purport to any national appropriation through claim of sovereignty or other means and recognizes that exploration and use of outer space is the province of all humankind through the freedoms enacted in the Outer Space Treaty[14]. International law is considered to apply in this region, and environmental policy follows the Artemis Accords and analogue terrestrial activities such as in Antarctica[15] .

DIA is governed by a fragmented polycentricity scheme[16] which provides efficient, adaptive accountability to mitigate financial and public interest risks associated with single-state-led projects[17]. This allows all stakeholders to retain decision making power and avoid concentration of power with any single group. The governance is divided into three layers, shown in Figure 6. States or blocs of states that contribute infrastructure to DIA represent the core decision making group and may be arranged with the support of the UNCOPUOS as a subcommittee with a rotating leadership. Private organizations that directly contribute to the settlement or states that contribute non-infrastructure pieces represent the second layer and have influence over their specific contributions. States or organizations that do not have the funds to invest in the settlement may participate in the third layer as observers. DIA's functioning is based on transparency.

To maintain operational costs, there is a minimum threshold for investments to grant access to the 1st and 2nd tiers in exchange for access to the settlement for state- or privately-sponsored crew and payloads. The power granted in decision making is proportional to the contribution but capped such that no state is able to hold over one third of votes, and no bloc of states is able to hold over one half. English is the primary language of the base due to existing ground systems' functioning language; however, all native English-speakers must learn a second language primarily dependent on the countries contributing infrastructure equipment.

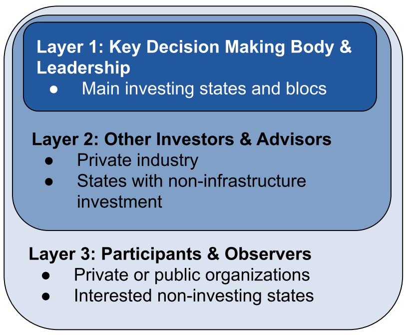


Figure 6: Polycentric governance model for DIA

As space activities have developed, innovations in outer space have outgrown existing intellectual property (IP) legal frameworks, as was shown on the ISS Columbus Module[18]. A proposed framework for IP involves creating a central patent regulation authority to treat space as a unique territory for patent rights[19], administered by a UNCOPUOS subcommittee to regulate the registration and allocation of patent rights and resolve patent disputes. This would provide more comprehensive protection for inventor rights, and a uniform approach to clarify the patenting process as a single jurisdiction. Inventions are protected using blockchain technology as it is cost-effective, fast, accurate, and can create immutable records of information to protect inventors[20].

Crew Operations

Crew operate in three rotating shifts, shown in Figure 7, to allow continuous monitoring of the settlement, limit the loading of shared areas, and provide overlap periods for members to interact with family/friends from home. To prevent fractioning, each shift overlaps with the others for 2 hrs. of leisure/meal-time and 2 hrs. of work each day. Arriving groups are trained by current groups over a 1-week overlap before the senior-most group exits (Figure 8), during which the settlement may not exceed 30 people. Stays do not need to be equal; however, only one group should be changing at a given time.

UTC	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Crew A	Sleep							M	L	W	Work		M	L	Work			M	Work		Leisure			S
Crew B	W	M	Work		Leisure			Sleep								M	L	W	Work		M	L	Work	
Crew C	Work		Work		M	L	Work		L	M	Work		Leisure			Sleep								M

Figure 7: Example schedule showing the interaction periods between each crew (bolded). Schedules align with North America, Europe, and eastern Asia landmasses

Period	1	2	3	4	5	6	7	8	9	10	11
Crew Rotations	Group 2		Exit		Entry	Group 5			Exit		Entry
	Entry	Group 3			Exit		Entry	Group 6			Exit
	Exit		Entry	Group 4			Exit		Entry	Group 7	

Figure 8: Example rotation using equal crew durations. During entry/exit, the settlement is at peak occupancy.

Base Management System

Combined with committed efforts of the crew and a strong management system, what could have been a major disaster was curbed.

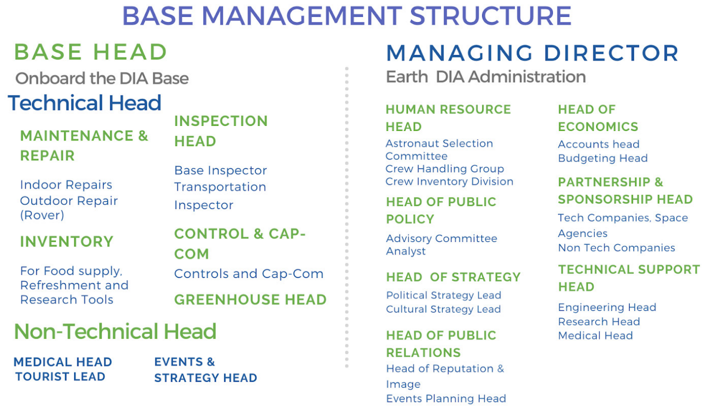


Figure 9: Management structure on DIA

The management structure is divided into a lunar and Earth segment (Figure 9). The lunar segment is responsible for day-to-day activities, relying less on Earth for guidance, while the Earth segment acts to support lunar operations with policy, budget, tourism, marketing, resupply, etc. Both are overseen by the Managing Director that rotates among the 1st tier of supporting countries. The lunar segment hosts two groups: crew and tourists. Leadership follows the US/Russian spaceflight models[21] with a commander and mission/payload specialists. The responsibility for the base operations lie with the commander and their

Technical Risk	Critical life support failure	Major crew health failure	Non-critical system failure	Reliability compromised	Functionality at reduced capacity	Increased maintenance
Human Risk	Immediate threat to life	Injury requires early base exit	Injury resulting in reduced capability	Recoverable major injury	Minor injury requiring first aid	Minor injury. No medical attention
Risk level & Example	Air system failure	Food spoilage within a module	Thermosyphon freezes	Cooling water leak	TH-AD system fouling	Lights are flickering
Redundancy	System & redundancy in each module	2 redundan- cies, with 1 being dissimilar	1 redundancy required	Selected spare parts available, & allow bypass	Allow bypass of affected system	No redundancies needed
Barriers	2 with one Dissimilar	2	1	Prominent label + instructions	Visible marking	No action required
Detection	All previous & monitoring with alarms	Prev. maint., & monitoring with alert indicator	Monitor core functionality	Routine failure mode audit	General audit	No action required
Incident Response	Evacuate area & attempt to repair	Reduce crew ops & attempt to repair	Replace affected systems & attempt to repair	Attempt repair & otherwise monitor	Attempt repair & otherwise monitor	Monitor
No. of crew responding	Full crew	Full crew	Multiple people per shift	1 person per shift	1 person	1 person
Research Priority	Eliminate failure mode	Eliminate failure mode	Eliminate or mitigate	Mitigate or simplify response	Not prioritized	Not prioritized

Table 1: Risk response matrix based on the risk level identified. Detection is additive as risks increase in severity. Physical redundancies, barriers, and detectors contribute to the launch mass.

delegates on other shifts, while mission/payload specialists work directly with specific systems. As tourism increases, a tourist head will be responsible for acting as a guide and developing tourism programs.

Power is decentralized among the crew to ensure equitable management; however, in emergencies the commander assumes control to coordinate response.

Safety & Emergency Planning

Antariksha had never seen a more peaceful and serene place, when suddenly her thoughts were interrupted by a small fire that had broken out in one of the kitchens. Deep down she knew she would be alright and her gut was right! She recalled her training on dealing with emergencies. The base was perfectly equipped to deal with them.

The isolation, complexity, and large investment into the lunar settlement supports a conservative approach to risk reduction[22, 23, 24]. While risks can be mitigated, a disaster may still occur, requiring emergency response procedures[25] that all occupants must be familiar with. Human, technical, and social hazards are identified with a failure mode effects analysis and scored using a risk matrix shown in Table 2 to assign a risk level. Appropriate engineering and policy controls are determined using Table 1. The lunar gateway is required during the early setup stages (1st to 2nd module) as an evacuation method as only one level of redundancy is in place for most systems.

	Consequence					Response Action
Probability	1 Negligible	2 Minor	4 Moderate	8 Major	16 Extreme	
5 Certain	6	7	9	13	21	Emergency
4 Likely	5	6	8	12	20	Alert
3 Possibly	4	5	7	11	19	Mitigate
2 Unlikely	3	4	6	10	18	Monitor
1 Rare	2	3	5	9	17	Record

Table 2: Risk assessment matrix for identified hazards. Consequences are non-linear to capture scale.

Engineering

Being an Arts major, her curiosity knew no bounds specifically regarding what, how, and why it worked. Everything around her was an engineering marvel. She especially wondered how this particular location was chosen for the base.

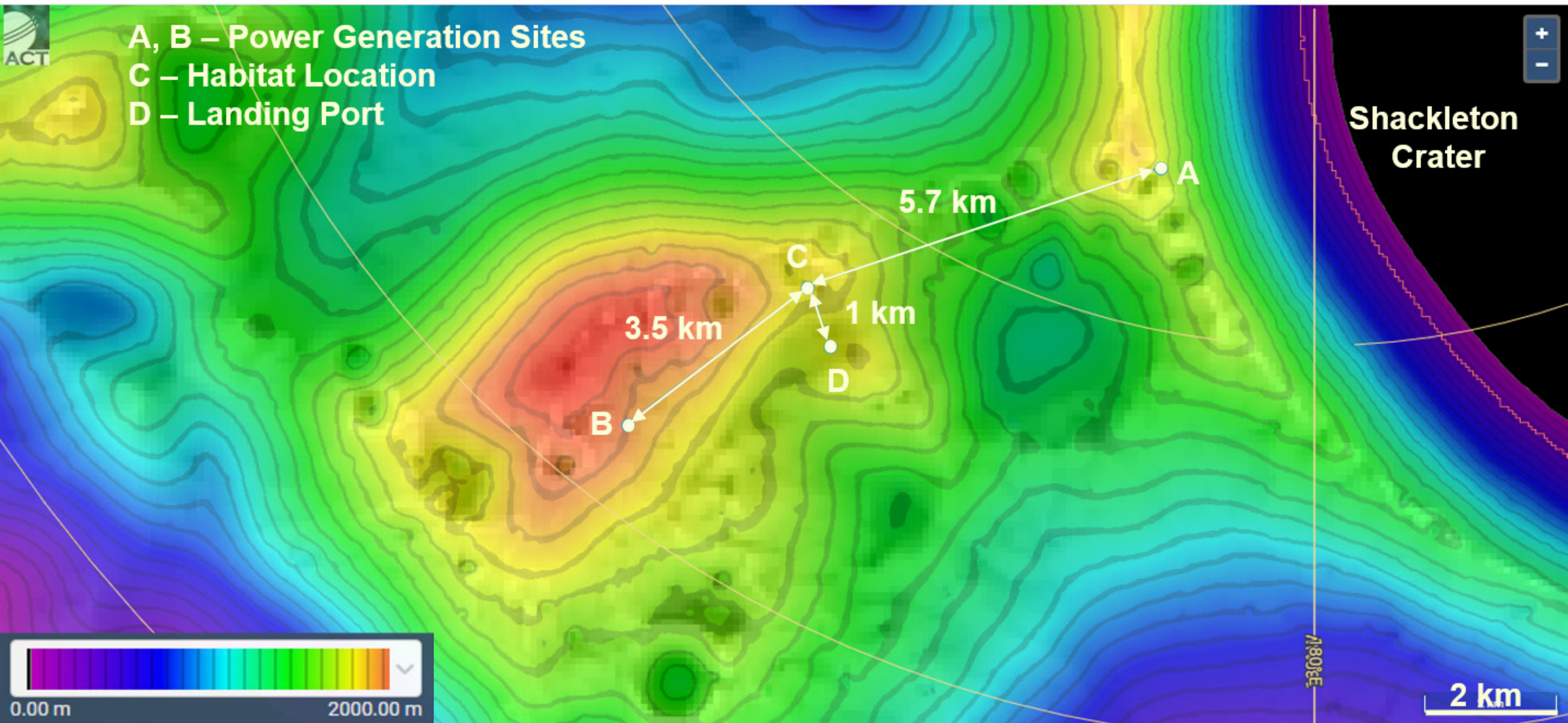
Antariksha- *I'm very curious as to how these systems would function on the moon. Is it as simple as our subsystems on Earth? How are they different?*

LISA-*You'd be surprised to know how far engineering can take us, after all it is what got us to the moon, the perfect combination of creativity, design and practicality.*

Landing & Settlement Site

The settlement site near Shackleton Crater, Aitken Basin, is chosen due to its scientific interest, proximity to resources and flat topography for landing. Shackleton Crater contains a permanently shaded region and possibly frozen water for life support and fuel[26]. Bussey et al. identified points A and B in Figure 10 that are each illuminated >80% of time[27], making them ideal solar power sites. Point C marks the habitat location in a flat (<10o) region between A and B; and point D is the landing site ~1 km downhill to provide a sufficient safety zone[28]. Speed constraints in the terrain from the settlement to Shackleton Crater limit crewed EVAs into the crater; however, teleoperated mining is conducted using Site A as a recharge/storage hub. This crater has been proposed as a site for an infrared telescope due to the low temperature inside and near-continuous solar power at the rim[29], and the regional soils are also of geological interest from the 2019 Lunar Science for Landed Missions Workshop[30].

Figure 10: Topography map (SLDEM2015(+LOLA)) built using ACT Quickmap



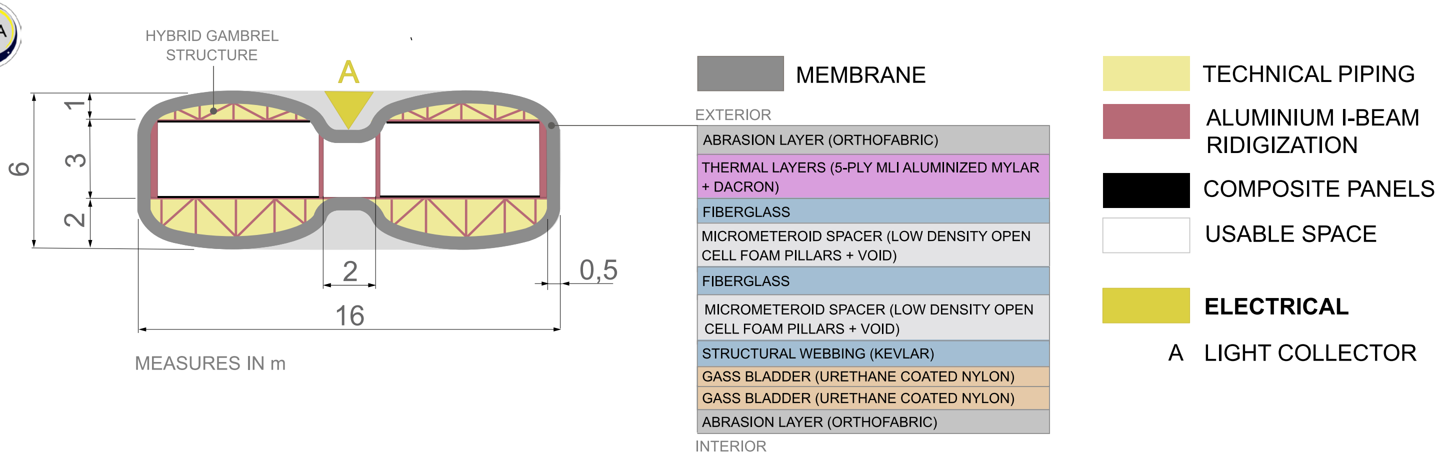


Figure 11: Cross-sectional view of floor/ceiling and internal frame structure and the membrane material layup

Launch Vehicles & Landing Infrastructure

Existing and near-term lunar launch vehicles were compared to select the most cost-effective solution, shown in Table 3. Vehicles were grouped by payload weight class (~10 mt, ~25 mt, and 40+ mt), which may be used at different construction stages. Vehicles with insufficient public data, as well as light-payload launchers (<<10 mt), were omitted. SpaceX's StarShip is the most suitable for payloads above 40 tones; however, it is still in development. For lighter payloads, the Falcon Heavy is strongly preferred due to its low cost of ~$7000/kg.

Currently there are three landers under development as part of NASA's Artemis HLS program. The National Team ILV can carry ~7.2 mt of payload mass using an extended tank[31], allowing it to transport the modules and crewed rovers which are the heaviest single items. Landers utilize optical terrain maps to navigate to the surface, with an expected accuracy of ~23m[32]. However, the ILV requires surface hydrogen refueling to return, limiting it to one-way transport until infrastructure is developed.

Weight Class	Launch Vehicles	$/kg[33]	Flight Heritage	Reusability
Super Heavy	StarShip + SuperHeavy (Orbit Refuel)[34]	0	0	0
Super Heavy	SLS Block 1B/2 Cargo[35]	-1	-1	-1
Heavy	Falcon Heavy (expendable)	0	0	0
Heavy	SLS Block 1 Cargo	-2	-1	0
Heavy	Yenisei[36]	-1	-2	-1
Heavy	Don (Yenisei variant)	-1	-2	-1
Medium	Delta IV Heavy[37]	0	0	0
Medium	Vulcan Centaur (Heavy)[38]	2	-2	1
Medium	Ariane 6 (A64)	1	-2	0
Medium	Long March 5[39]	1	-1	0

Table 3: Comparison of launch vehicles rated on a -2 to +2 scale against a baseline in each weight class. For vehicles in development, flight heritage is based on achieved TRL.

SpaceX's StarShip has a payload capacity of ~100 mt and acts as a reusable lander and temporary shelter, which can greatly shrink the launch schedule. The main risk of StarShip during early launches is in mission assurance and a large amount of idle equipment on the lunar surface which would compress the cost timeline and begin depreciation without generating revenue unless the construction timeline is shortened. To prevent regolith debris from damaging equipment during landing, the landing site is microwave sintered[40].

Settlement Structure

The settlement consists of five linked inflatable toroids, detailed in Table 4, totaling ~2200 m3 of habitable volume, allowing 10-20 people to live comfortably for long durations[41] and a maximum of 30 during peak periods (e.g. crew changeover). Fewer, larger modules were preferred over multiple smaller habitats to avoid multiple setup missions which consume crew time[42], while still distributing life support systems such that the loss of any one module would allow the crew to continue operating.

Parameters	Option 1	Option 2	Option 3	Option 4
Quantity	1-3	4-6	7-10	11+
Locations	Single	Split (two)	Split (multiple)	--
Type	Rigid	Inflatable	ISRU	--
Shape	Cylinder	Sphere	Toroid	Other
Floors	Single	1.5	Two	Multiple
Micrometeroid Shield	Solid	Whipple (ISRU)	Whipple (Integrated)	--
Radiation Shielding	Solid	Water	ISRU	Underground
Rigidization Material	Titanium	Aluminum	Composite	Steel
Load Bearing Method	Catenary Arch	Triangulation	External Cable	Shell

Table 4: Module design morphological chart. Qualitative & quantitative trade studies considered cost, safety, human factors, and flight heritage. Selected option is highlighted.

Radiation shielding is achieved with a 3m regolith layer on the sides which are most heavily exposed to the sun, and ~1.5m layer on the rooftops that are less exposed to maintain safe exposure[43] while minimizing structural load.

The module is rigidized with rings placed radially around the toroid (Figure 11) to withstand the weight of equipment and occupants inside, and the membrane and regolith weight in the event of depressurization. The top and bottom regions in the torus occupied by the rigidization are used to store equipment, which offer sound isolation.

The membrane layup (Figure 11) is based on past inflatable and spacesuit designs[44 45 46 47]. Micrometeoroid spacer whipple shielding is located on the upper sides for debris that punctures the regolith layer. The bottom surface contains additional insulation to minimize conductive heat loss. When deflated, the module can be packaged similar to the TransHAB proposal to fit within a 6m wide payload fairing [48]. The total mass is ~6.6 mt/module.

Robotics and Extravehicular Activities (EVAs)

With no standardized commercial mobile platforms for surface lunar exploration, selection was based on commercially available uncrewed ground vehicles (UGVs)[49 50]. The chassis is based on a COTS UGV (50 kg mass + 75 kg payload capacity on Earth) optimized for long-duration operations[51]. At 1/6g lunar gravity, actual payload capacity and range is likely higher; however, ruggedization such as heaters and static charge dissipation limit some of this opportunity.

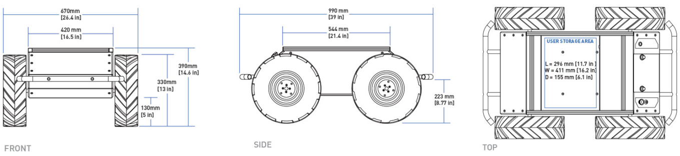


Figure 12: Schematic of a UGV used for baseline rover[52]

Each UGV has a standardized power and data interface to facilitate payload swapping[53] to maximize utilization and overall fleet reliability. Different payload types (Table 5) allow the UGV to perform specific tasks required to assemble the settlement. All mobile robots are teleoperable by the crew in-situ or from Earth, with potential autonomy added once the settlement is established to perform routine exploration.

Activity	Task	Payload Component	Comment
Recon	Localization	Visual navigation suite (Stereo camera, LIDAR, CPU)	Mass optimized to maximize rover range
	Mapping		
Ground Preparation	Obstacle Clearing	Drill attachment to arm	Breakdown of larger rocks for removal
	Levelling	Bulldozer blade attachment	--
	Excavation	Excavator & collection attachment to arm	--
	Regolith Sintering	Microwave sintering assembly	--
Assembly	Manipulation	Fine gripper attachment to arm	For finer tasks & payload swapping
Support	Loading	Heavy gripper attachment to arm	--
	Cargo Transport	Cargo bed	--

Table 5: Rover labor breakdown and associated tooling

Delivery consists of 4 rovers based on the construction requirements in Figure 14, with a 5th in a permanent manipulation configuration for payload swapping and acting as a spare. During early construction, an infrastructure base station, such as in Figure 13, containing hybrid solar/fuel cell power, docking stations for rover recharging, and communications capability to relay telemetry and commands between the fleet and Earth is used.

Crewed lunar rovers are based on the Toyota/JAXA rover (~6.5 mt[54]), with a detachable passenger cabin to allow the rover to be converted into a cargo carrier. The passenger module has a docking port on the aft to facilitate transfer of crew with the habitat and other rovers, and two suit port extensions on both the port and starboard side for spacesuit access without dust contamination. Long range crew expeditions can be performed with an extended power supply. One rover is required to tow the habitat module from the landing site to the settlement location, with a second rover available for rescues during EVAs.

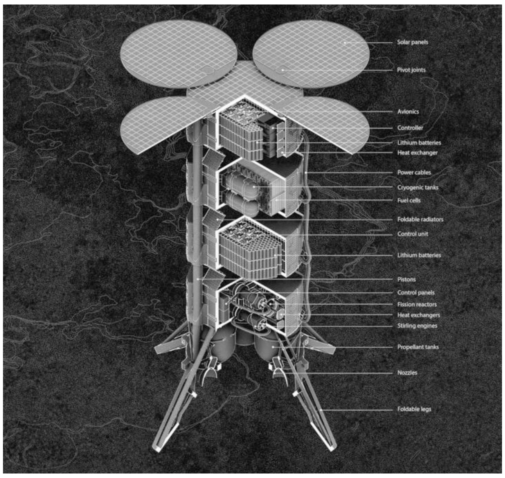


Figure 13: Example base station lander concept[55]

The spacesuits require a custom design based on the Artemis xEMU Spacesuit which can be easily adapted for suit-to-vehicle interfaces[56]. Upon arrival, the crew don their suits to transfer to the crew rover and enter the settlement through the docking port. Cargo can be towed by the rover and imported via the airlock. The exiting crew takes their suits back to the Gateway station to be left for the next arrival. ~12 spacesuits are required (4 on Gateway, 8 on surface), with unused suits stored in the airlock. Airlock use is avoided to minimize power and air losses; however, it provides flexibility to conduct EVAs in a pure O2 environment for very active missions.

Construction Timeline

The design phase is able to begin immediately as critical technologies are flight proven and new technologies are already in development. The critical path is to assemble and crew the first module to begin payload missions and test new technologies. A phased approach for expanding into the final configuration allows gradual growth of crew size, capability, and exploration into Shackleton Crater for ISRU operations. Construction duration was not estimated as funding will influence the schedule; however, Figure 14 shows the relationships between the construction activities and the resources required.

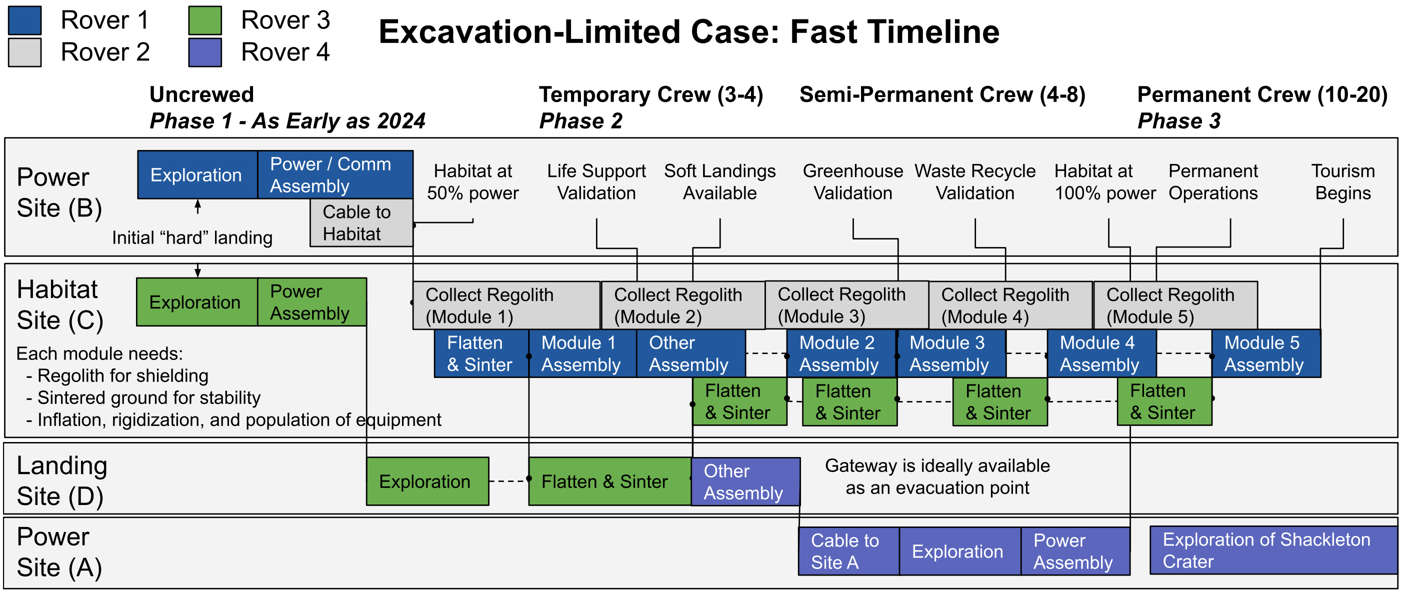


Figure 14: Timeline for the settlement construction assuming regolith collection is rate-determining but comparable to other activities and construction targets the shortest timeline with minimal uncrewed payload mass redundancy.

Three core activities are identified to prepare the site for a habitat module, described in Figure 14. To minimize the regolith and transportation required, regolith collection occurs at the habitat site to a depth of <2 m with the habitats built in the resulting pit. If these activities are relatively similar in duration per module, three rovers are able to maintain high utilization with other minor activities during gaps. If one of the activities takes significantly longer than the others, a fourth rover and 1-2 duplicate payloads become economical to improve timeline.

Communications System

A lunar south pole communications system must maintain a constant communication link with Earth, provide high data rates (hundreds of Mbps) for scientific data transfer, support multiple frequency bands (Ka, S) and service four independent surface channels for various activities, prioritize high TRL components and scalability, and minimize maintenance and/or station-keeping and maximize autonomy[57]. From Table 6, a satellite relay-based system was selected to relay data to the Deep Space Network (DSN) on Earth to provide the required visibility[58].

Model	Data Rate (Mbps)		Band		Range (km)	Scalab-ility	TRL	Cost ($M USD)
	Earth	Moon	Earth	Moon				
2 satellites in polar elliptical orbits	154 down 67 up	222 down 147 up	Ka	Ka + S	250	H	H	750
Lander on Malapert mountain	500 down 200 up		Ka	Ka	5	L-M	L	500
1 satellite + lander on Malapert summit	500 down 200 up	222 down 147 up	Ka	Ka + S	5 & 250 (63% visibility)	H	L	875

Table 6: Comparison of communication models based on existing and proposed concepts. Cost includes R&D, launch, deployment, station keeping, maintenance over 5 years.[59] [60]

The communications system (Figure 15) is divided into four short-range channels serviced by on-board RF units, and four long-range channels to communicate with Earth and one surface relay. The base and crewed rovers act as terminals containing a multiplexer to interleave information which are relayed to Earth via satellite/lander. A separate frequency channel is dedicated to high-volume data from science missions. The Ka band provides higher data rates compared to the S band at the cost of increased power, as shown in Figure 15, and is reserved for transmission to Earth.

The lunar settlement contains a WLAN network using 2.4 and 5 GHz frequencies divided into three VLANs to segregate crew computers/controllers, science payloads, and guest computers. The physical layer has a two-tier peer-to-peer network of controllers and laptops which distribute computation and data, providing high reliability.

The NASA LRS communication satellite[61] is used as the design for the relay satellites as no current missions are able to meet the orbit, data rates, and mission requirements. The payload contains 1 m diameter S- and Ka-Band antennas co-located at the bottom of the spacecraft deck pointing to the South Pole, offering 250 and 30 km circular ranges respectively. Two satellites in the Table 7 orbit with 180o phase difference provide 100% surface visibility, with future satellites at other inclinations offering expanded coverage. Since the Ka-band range is small, initial telemetry of scientific data is done from the base and exploration missions >30 km must use S-band.

Orbit Type	Semi-Major Axis	Eccentricity	Inclination	Arg of Perigee	Period
Inclined polar elliptical	6142 km	0.5999	57.7°	90°	12 Hours

Table 7: Satellite orbit design[62]

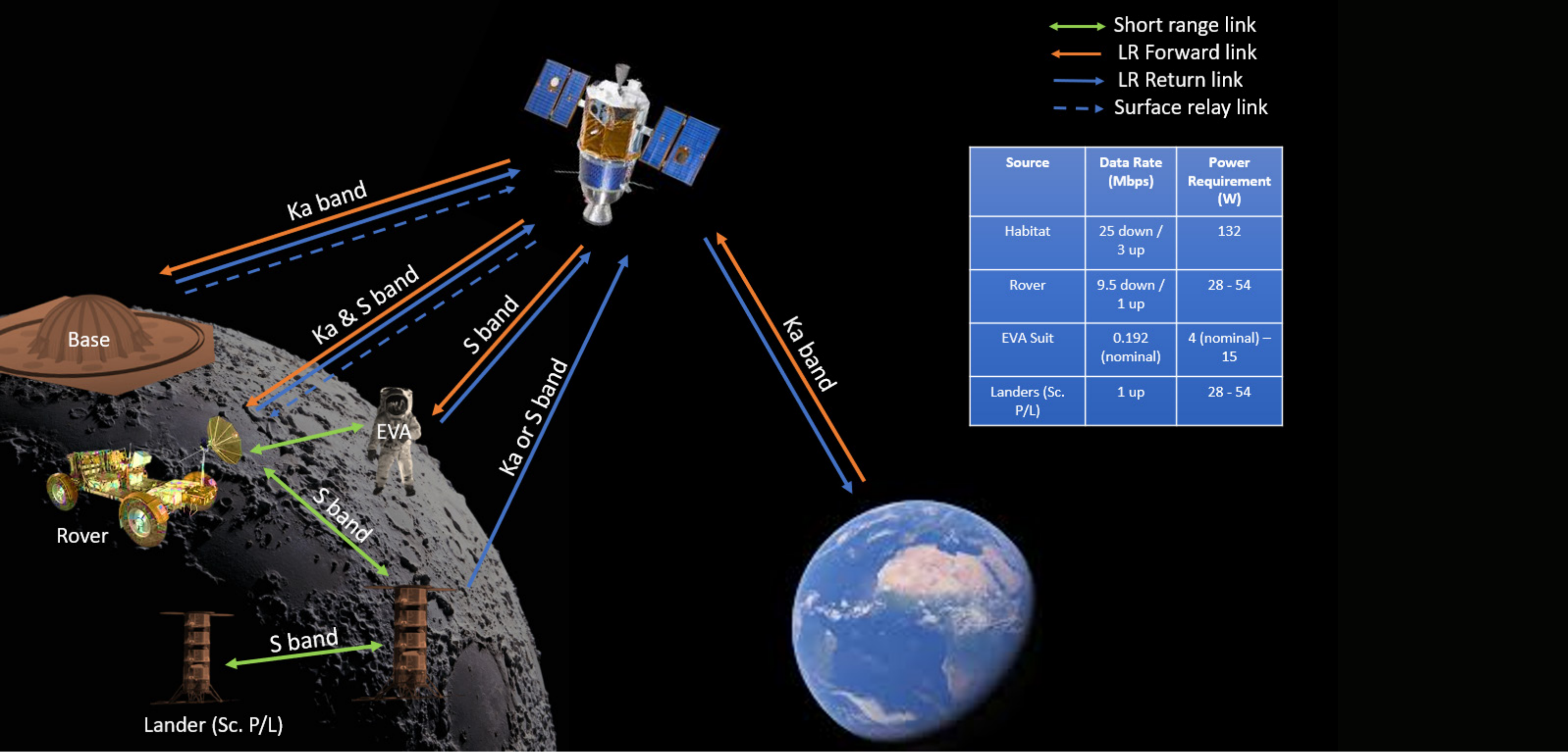


Figure 15: Communications architecture showing the connectivity of surface units and Earth

Critical Life Support (Air & Water) Systems

The settlement operates at 1 atm (79% N2, 21% O2) from high-pressure tanks[63] due to its simplicity compared to lower-pressures which have difficulties in cooling, added fire risk, and impact of contaminants. Periodic resupplies are needed to replenish losses through the airlock. Oxygen is replenished using solid-oxide electrolysis of water which has considerable flight heritage and technology developments over its lifetime on the ISS[64].

From Figure 16, carbon dioxide (CO2) is concentrated using an improved 4-bed molecular sieve[65] and sent to a Sabatier reactor to produce water and methane (CH4)[66]. Both technologies have ISS flight heritage and are mass and power-efficient over alternative processes[67]. Methane pyrolysis (a TRL 4 technology)[68] is used to close the loop, reaching >95% oxygen regeneration by splitting hydrogen from methane, which is then used by the Sabatier, leaving behind solid carbon dust which is collected and stored as waste with potential future applications (e.g. as a sorbent).

Trace contaminants are removed using UV-TiO2 photocatalysis to oxidize organics[69], followed by sorbent beds. In an emergency where air becomes contaminated (e.g. fire), rebreather gas masks are used during the immediate response. For power or equipment failures, solid-fuel oxygen generators are used as a backup oxygen supply. Sufficient air is always on-hand to repressurize one module if a depressurization event occurs.

The water system in Figure 16, leverages ISS designs and technologies developed in space[70]. Two new opportunities are explored to improve overall water recovery to >90%:

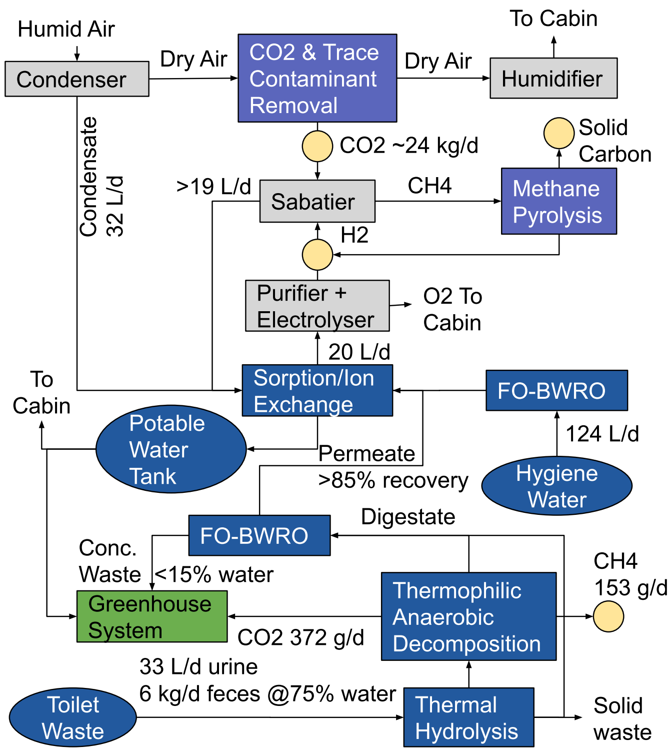


Figure 16: Air and water systems. Unlabeled streams contain water. Most separators are omitted. Flow rates estimated from ISS and Mir[71 72].

1. Converting human waste to fertilizer using thermal hydrolysis (TH) and anaerobic digestion (AD) to increase overall water recovery[73] (with losses from unused human waste until the greenhouse systems expand).
2. Using forward osmosis (FO) separation with brackish water reverse osmosis (BWRO) draw recovery due to improved weight and reliability verses filters (no moving parts and reduced clogging)[74 75 76]. Hygiene water (washing, laundry, personal cleaning) is processed separately from human waste due to different flow rates and composition.

TH-AD sanitizes the waste and releases trapped nutrients for the greenhouses and produces CO_2 and CH_4 for air revitalization. The TH process is fast (~30-min residence time[77]) while AD is slow (~4-day residence time[78]), so a train of four parallel TH-reactors with offset batch cycles are used to provide a consistent flow rate between the two systems[79]. There is opportunity to reduce the energy consumption by operating at lower pressures to boil at ~80oC for a longer time to achieve a 5-log kill[80] and sufficient conversion at the cost of increased reactor mass. Since urine is mixed into the TH-AD process, stabilization with chromium trioxide (used on the ISS)[81] cannot be used; however, the larger crews allow near time-of-use water recycling, eliminating the need for storage.

Thermal System

Beyond passive thermal protection provided by the regolith and MLI, habitat temperature is actively controlled by water-cooling air drawn from ventilation fans (Figure 17), with power-intensive equipment using dedicated water cooling. The water exchanges heat with an ammonia/N_2 thermosyphon which transports it to external radiators[82]. Thermosyphons have high heat rejection capability (~20 kW) over long distances (>5 m) using thin 40 mm wide conductors[83], making these systems energy-, mass-, and cost-effective. The N_2 acts as a non-condensable gas to prevent freezing[84]. The base of the modules contacting the lunar surface conducts heat out, so condensation must be prevented with sufficient ventilation and humidity control. Some systems may; however, take advantage of this cooling.

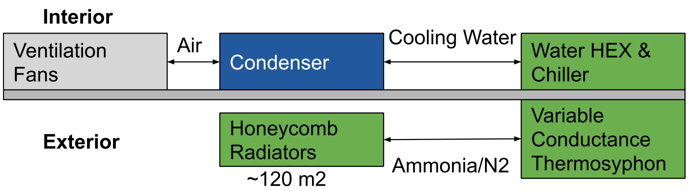


Figure 17: Diagram of the heat transfer system for each module[85]. Lunar gravity allows thermosyphons to function, eliminating exterior pumps which are less reliable.

The radiators are raised ~4m for the thermosyphon to function (10-30o angle[86]) and allow radiation to occur on both faces. Panels are positioned between modules radiating upwards (Figure 20) to minimize distance to multiple locations. Variable emissivity coatings[87] reduce the required mass when the sun is incident to maintain heat rejection capability.

Food & Human Waste Recycling

During early stages, food is resupplied from Earth, with greenhouses supplementing the diet until sufficient reliability is achieved. Plants support closing the life support loop by recycling human waste; however, the quantity of plant matter in early stages is insufficient. Fast-growing plants and increased CO_2 inside the greenhouse improve conversion rate. Organic gasses produced by plants are removed using TiO_2 photocatalysis[88].

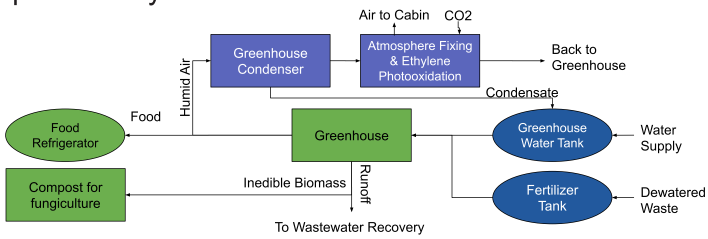


Figure 18: System diagram showing the food cycle on the lunar settlement

Two independent greenhouses are used to tailor the environment to different plants. Each greenhouse (Figure 19) has concentric tiered hydroponics and paths for crew access. Outer- and inner rings can grow larger plants that need trellises (e.g. tomatoes), while the middle rings can support shorter plants (e.g. lettuce). LED grow lights and sunlight via fiber optics are used with a large opportunity to maximize lighting efficiency using lenses/diffusers[89].

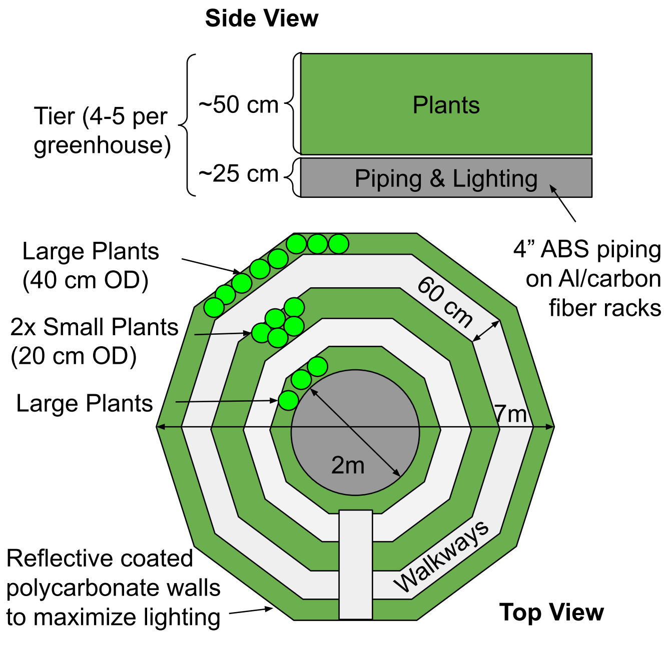
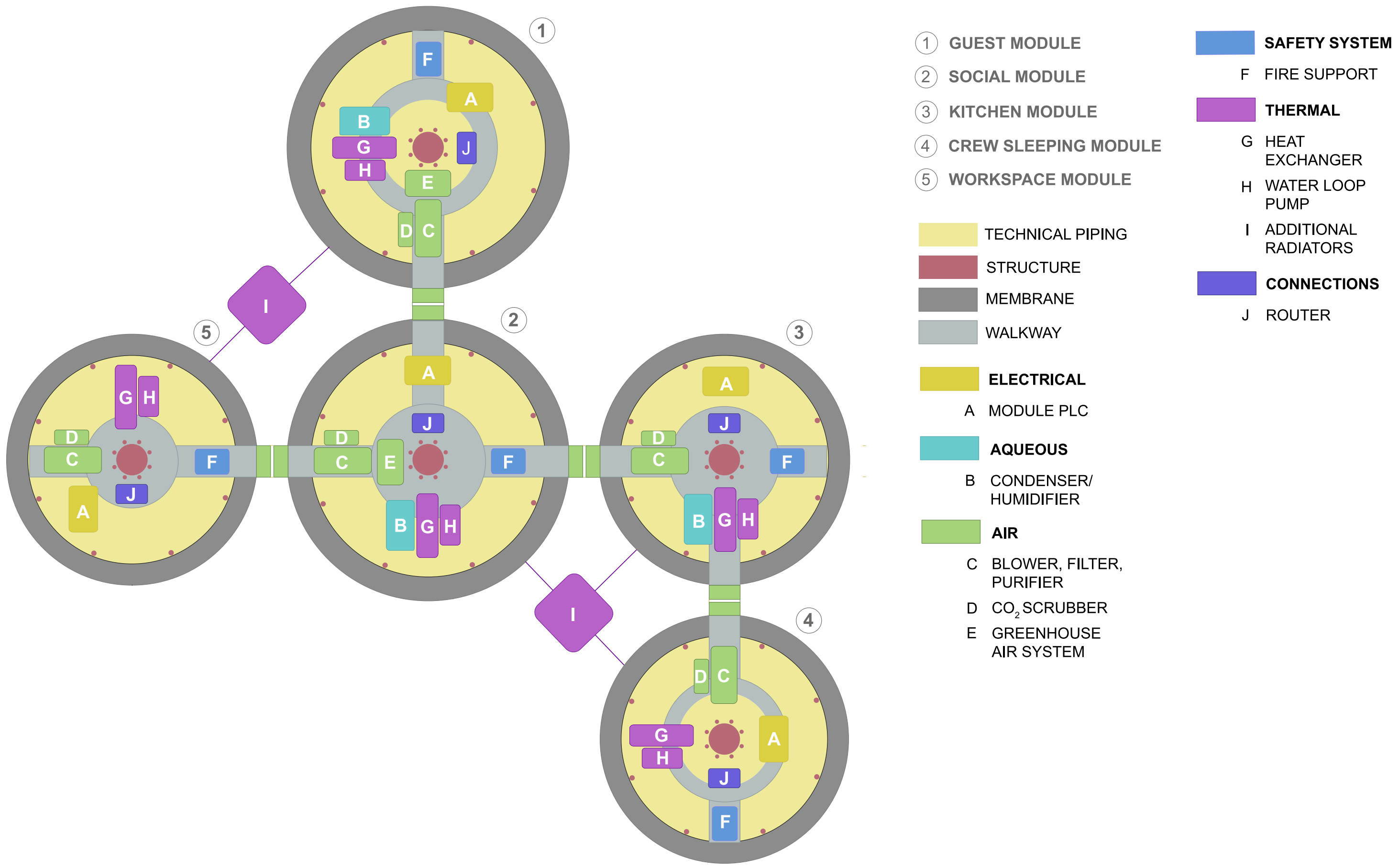


Figure 19: Diagram of the greenhouse layout.

Using lettuce as a representative[90, 91, 92, 93, 94], the greenhouses use ~1.5 kg/d of CO_2, ~0.4 (dry) kg/d of excreta and transpire ~100 kg/d of water to yield ~8 kg/d of fresh produce. Inedible biomass is recycled via composting to supply mushroom farms to release trapped carbon[95]. The greenhouses achieve mass-parity after ~2-3 years of operation, justifying expansion up to ~4-6x, before becoming fertilizer-limited and ~10x before becoming CO_2-limited for a 20-person crew. By this stage, crew diets are largely sourced here, which require careful nutrient management and improved cooking capability. Automation systems are required to support crop management. To minimize waste and food storage, planting/harvest cycles are offset to approximate a continuous flow.

MOONBASE TOP VIEW, CEILING



MOONBASE TOP VIEW, BENEATH FLOOR

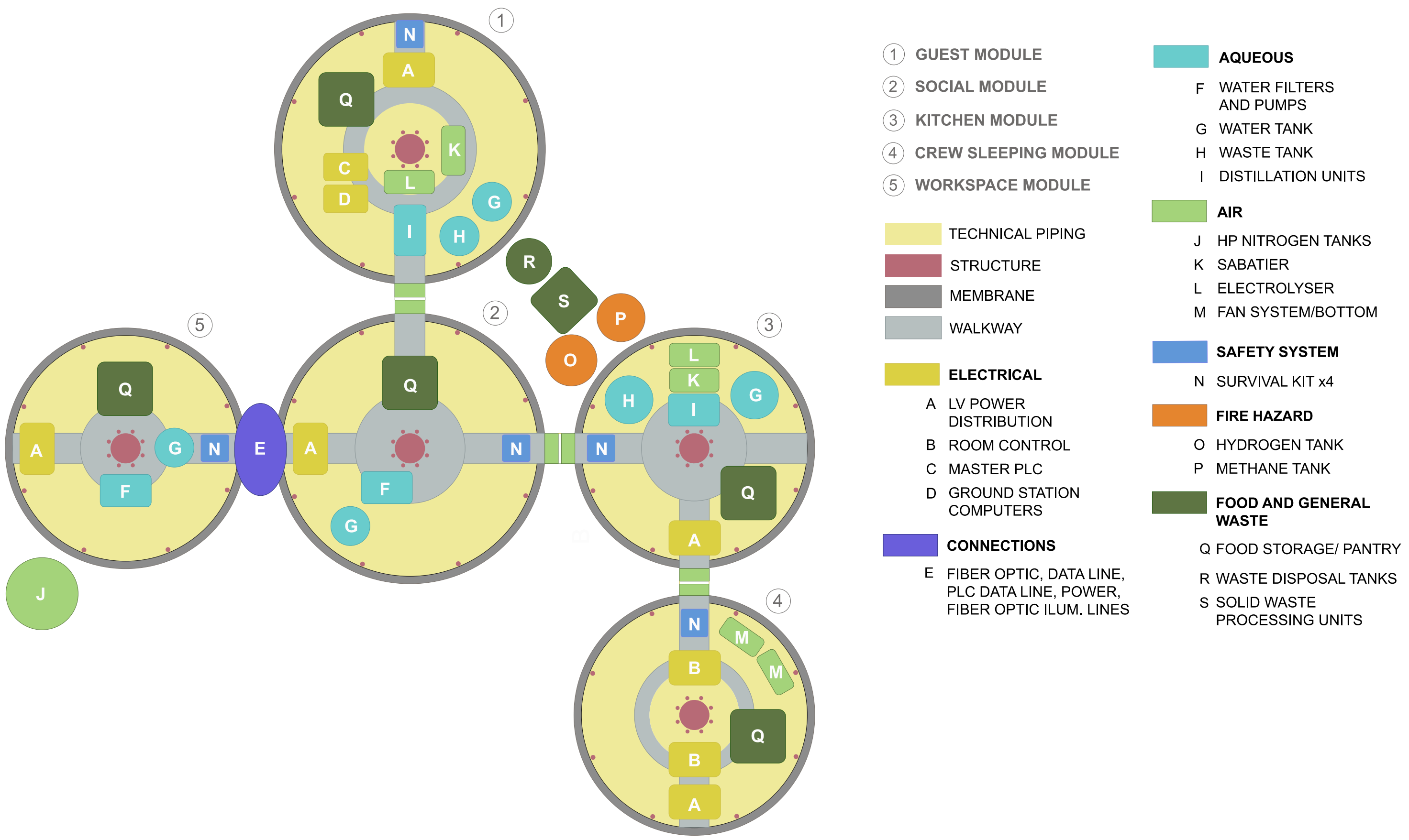


Figure 20: Utilities layout in the module floors (top) and ceiling (bottom).

Other Waste

With food being resupplied, packaging waste will accumulate or require expensive disposal. Since food must last for 9-12 months in ambient conditions, multi-material packaging is often used, however, this makes recycling difficult. The strategies adopted by the settlement to minimize waste focus on reducing packaging first:

1. Allow packages to be opened to be hydrated (eliminating the nozzle found in ISS food packets)
2. Minimize the amount of food shipped by expanding the greenhouse/fungiculture capacity
3. Package food in bulk to take advantage of larger crews
4. Design packaging to be disassembled into homogenous materials to be re-extruded as 3D printer filament

Technical Floor Plan

Equipment is installed in the ceilings and floors, concentrated above/below walkways (Figure 20) to avoid excess interfaces through the membrane and facilitate maintenance; with the exception of loud equipment, pressurized tanks, and high-voltage systems. Critical life support systems (Floor: A, G, N; Ceiling: C, D, F, G) are in each module so that crews can operate if one module fails. Recycling (Floor: I, K, L) is in Modules 1 and 3 as these contain the majority of water consumption activities which concentrates the plumbing; and sized such each is sufficient for nominal loads.

The settlement's environmental system is cascade controlled, with each module independently operating and one global controller. The WLAN allows the crew to interface with equipment via laptops and tablets from any module, simplifying cross-module communication by using a single shared physical layer to minimize data lines.

Power Generation & Storage

The two power generating sites (Figure 10) have opposing illumination profiles; collectively lit 94% of time with a maximum dark period of 50 hrs.[96] which minimizes battery needs. Deployable solar arrays[97] are sized to allow normal operations during shoulder periods when one site is lit (26% of time), and high-power activities when both sites are lit (68% of time). Lunar dust impact on panel performance is mitigated using electrostatic "wipers"[98], with future missions to raise the panels. During eclipses, ~70 Li-ion batteries[99] are used to power the base, with the crew minimizing operations. Docked rovers act as backup power.

Power is transmitted from each solar site via 5 kV bipolar high-voltage DC (HVDC), shown in Figure 21, to minimize joule heating losses and mass. Early on, battery charge/discharge units may be linked directly to DC switching units at the solar arrays for rovercharging. Grounding and switchgears for fault currents are needed to mitigate the safety risks of DC power[100], with all modules linked to facilitate inter-module grounding. The two power sites provide redundancy due to the lack of space heritage of HVDC. In Shackleton Crater, water may be electrolyzed and the gasses cryogenically stored, providing a smaller footprint and eliminating high-pressure tanks[101]. These gasses can be used in regenerative fuel cells for power[102], which provides dissimilar redundancy to the power system, improving overall reliability[103].

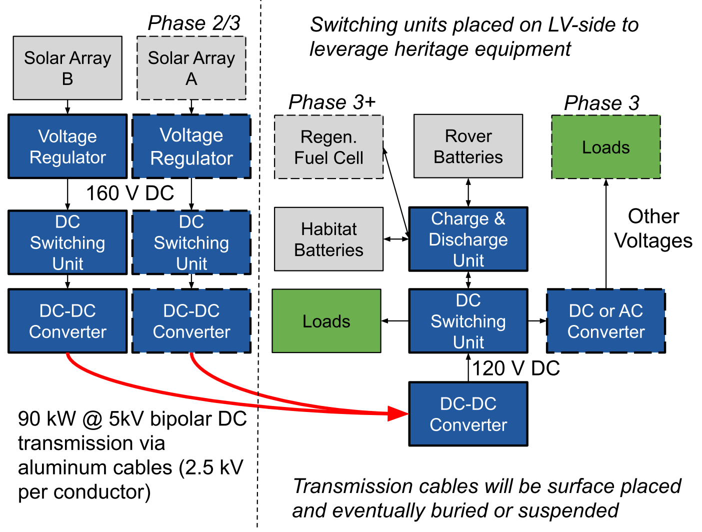


Figure 21: Lunar habitat power system

Since lunar regolith is an insulator, grounding is difficult to protect against faults, and lunar HVDC is still in early development[104]. Some technologies exist to mitigate static buildup from solar radiation and triboelectric charging[105] of rovers and astronauts. Dissipative materials on suit/rover interfaces allow controlled discharge when reconnecting.

The power requirements of the settlement are estimated in Table 8 based on past and proposed missions, and terrestrial technologies are can be supplied by ~20 arrays divided between the two generation sites based on new high-efficiency designs[106] and the expected solar irradiance and impact of dust at the lunar south pole[107]. Figure 22 paretos the nominal case, identifying the greenhouse and sensors as primary areas to reduce power use.

Mode	Uncrewed	Shoulder	Nominal (20)	Max Crew (30)	Peak
Settlement Power (kW)	3	15	17	19	49
Experiment Allocation (kW)	0	25	30	30	30
Transmission Losses (kW)	<1	11	13	14	24
Subtotal +50% Margin (kW)[108]	**<5**	**77**	**90**	**95**	**155**
Total Energy (kWh/d)	100	1200	1800	2600	3300

Table 8: Estimated habitat power budget based on settlement systems (time in Earth days)[109 - 117]

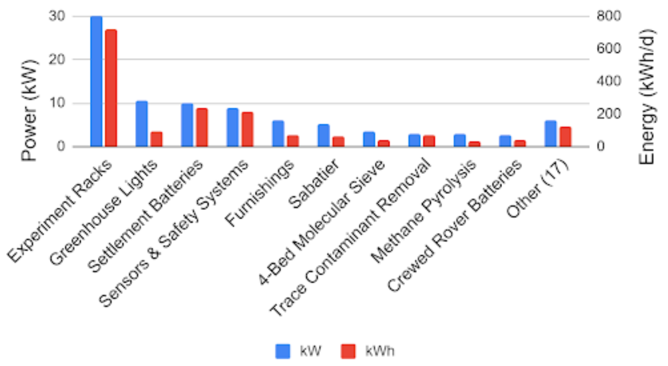


Figure 22: Pareto of settlement power and energy usage

Economy

It had been an unusual day, unlike any other she had experienced. She wondered if she could have taken back a souvenir home, something that would remind her of the moon and the wonderful things she learnt here.

Antariksha- *Can I have a souvenir that would remind me of this trip?*

LISA- *Yes! DIA has a provision for buying mementos to take back.*

She chose a locket made out of a moon rock. As she held it in her hand, it was a surreal feeling that one day this could be our future home.

Capital & Operating Costs

The cost of a lunar space program may be divided into three segments: the design/construction, launch program, and operational costs.

Depending on the geographic location and project delivery methods chosen by each investing organization, design, raw materials, labour, and indirect costs will vary considerably.

The life-cycle cost of the settlement was estimated to be $200 Bn USD +/- 50% (2020) for a 20-year operating life as a multiple linear regression[118] of 9 analog programs (Apollo[119], ISS[120], MSL[121], Gateway[122], Insight[123], MAX-C[124], GPM, GRAIL, and LADEE[125]) based on launch mass, distance, categorical complexity (1-4 based on requirements for orbit/landing and human/robotic), and categorical mission cost estimate accuracy (1-4 based on design phase at time of cost estimate) that span the parameter space. When applied to analog Mir station, this method produced a vast cost overestimation however the Mir project is an order of magnitude smaller and comparatively simpler (orbital in LEO). From the regression, launch mass is the primary cost driver (likely in lieu of complexity/scope), as such Figure 24 may be used to prioritize areas to identify simplification technologies.

To minimize cost overruns, ~10% of life-cycle costs is expected during early design to thoroughly define each mission[126].

Governments will likely represent the primary investment group due to their ability to invest in high-capital long-duration projects, contracting directly with private industry or issuing bonds. Venture capitalism is a viable option for private companies (e.g. Axiom Space, Bigelow Space, and other Commercial Lunar Payload Service (CLPS) providers[127]) to fund independent contributions, with services sold to other businesses and governments once operational[128]. Public-private partnerships are ideal to spread project risks across organizations and promote competition to identify cost-saving opportunities with the goal of improving the internal rate of return.

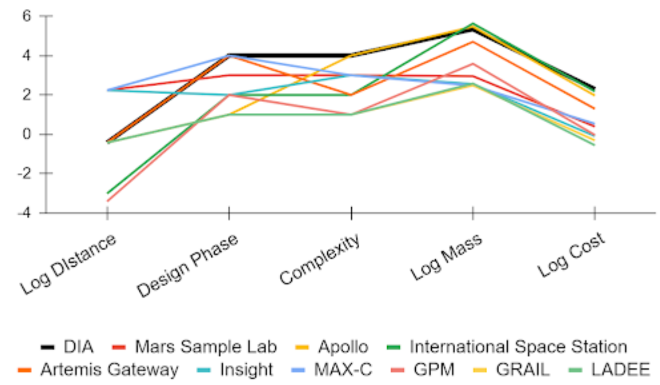


Figure 23: Analog missions used to estimate DIA life cycle costs.

Mass allocation for launches sought to minimize the launch frequency and distribute costs over the entire construction period to minimize idled equipment on the lunar surface, with spare mass sold as "ride-along" payloads to help recoup costs (Figure 25). Resupply mass includes food, water, air, and personal care packages for 20 people, plus 50% for other consumables and unplanned maintenance.

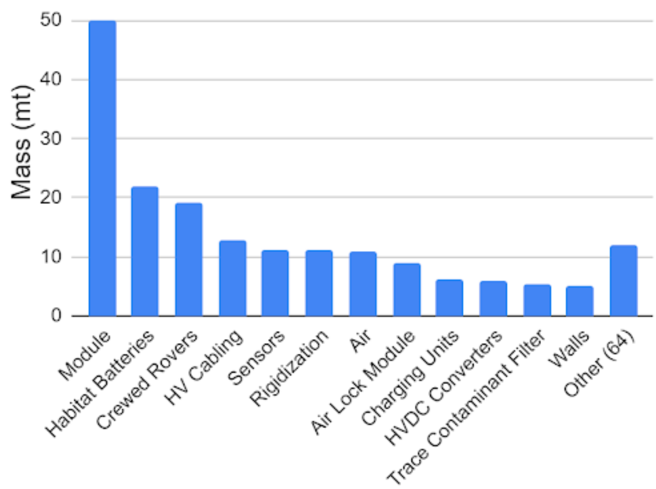


Figure 24: Pareto of system launch masses with +50% margin[128].

Cost Schedule

Based on analogs in the ISS[130], Mir, and Chinese Large Modular Space Station[131], the design, development, and Earth construction will take on the order of 5-10 years before the first launch, another 1-2

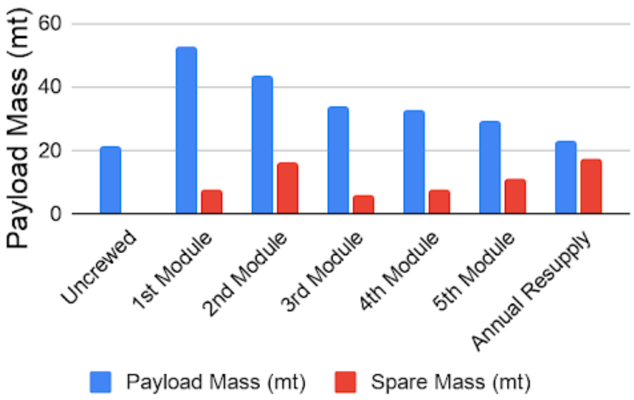


Figure 25: Settlement construction launch mass timeline. Crew/crew module mass is not included. Spare mass is available for ride-along missions based on the Falcon Heavy capacity[129].

Source	Revenue	Margin	% Readiness						
			Un-crewed	Module					On-going
				1st	2nd	3rd	4th	5th	
Rideshares	M	L	40	10	30	10	10	30	40
Commercial Payloads & IP	H	M	10	20	30	50	80	100	100
Infrastructure Sharing	M	M	20	30	30	30	50	80	100
Branding & Naming Rights	M	H	10	20	30	50	80	100	20
Crew Allocation	H	M	0	0	0	0	50	100	100
Crew Services	M	M	0	0	0	20	50	100	100
Education & Outreach	L	L	10	10	10	10	30	50	100
Tourism & Recreation	M	L	0	0	0	0	50	100	100
Material Export	L	L	0	10	10	20	30	50	100
Manufacturing	L	L	0	0	0	0	0	10	20

Table 9: Summary of identified revenue sources, their relative size, and the construction stage at which these sources are active in increments of 10%. 100% represents full revenue generating capability is achieved.

years between deployment and first crewing, and an expected 1-2 years for each subsequent expansion. The Chinese example has demonstrated the ability to perform these missions incredibly fast (4-6 years from announcement to first launch), however the cost is not yet known.

As a surface outpost, robotic construction activities must be conducted in parallel during these deployment periods. Labour cost in operating the robotics (akin to the operations of Mars rovers) will be in addition to the fabrication costs during these stages.

Revenue Generation

High launch costs and small workforces (10-30) on the lunar surface result in a service-based economy being the primary method of revenue generation. Space investments suffer from rapid depreciation of physical assets in the space environment, and obsolescence of R&D[132]. To balance between the need for rapid income generation from assets and methodical scaleup to minimize risk and spread financial investment, revenue sources have been identified throughout the construction timeline to minimize the idle time of physical assets (Table 9). This also provides robustness with de-scoping to respond to changing funding and public interest.

Estimating the revenue from space investment de pends heavily on the system boundaries and involves "knock-on" effects that benefit investing countries beyond the initial scope of work[133]. With the current fast expansion into commercial space exploration which are opening new opportunities for private industries and public organizations to become involved, an exact market size and revenue cannot be estimated. However, as the first lunar settlement, this base effectively has a monopoly on lunar research that is beyond uncrewed exploration. Revenue generated is directed towards the states and other organizations that invested in the settlement to amortize their investments. To maximize return on the initial capital investment, the DIA investors should position themselves to provide services to private organizations.

Tourism & Outreach

Lastly, outreach and tourism are an opportunity to expand directly to the public. This is particularly critical for maintaining public interest in the lunar settlement to support ongoing govern ment budgets that will fund the operations. Lottery systems open crowd-funded methods of travel to the public, and outreach activities conducted by crew members while on the settlement and after they return to Earth expands educational institutions as customers and extends the service capability of astronauts when not directly on a mission. Tourism can expand rapidly as launch costs decrease and the settlement becomes more self-sufficient; however, until then, it will likely remain a low-margin activity primarily used to mitigate funding risks.

Commercial Activities

The earliest revenue source is in CLPS which can take advantage of early infrastructure (communications, power, rovers) and excess launch capacity. This will continue to grow as infrastructure is deployed (modules, telescopes) and merge into astronaut services conducted at the settlement. While this market will largely be government, public, and privately funded payloads, other funding models may be possible to expand the market[134]. Beyond selling crew time and infrastructure resources, IP developed as a result of lunar research will stimulate terrestrial industries ("spin offs"), creating tangential benefits.

Owners are able to sell branding/advertisement space on their equipment which opens crowdfunding options (e.g. "$1 for your name on a lunar plaque") as well as direct business branding. This, however, is a finite resource without continuous new surface area (e.g. clothing).

Crew allocation is initially provided to the investing countries; however, as more space-faring nations emerge, these crew positions may be sold to other countries to participate in the settlement.

Nevertheless, margins will likely remain low until launch costs drop further.

Lunar Manufacturing

Lunar manufacturing is unlikely to be a significant revenue source due to the need for further capital expense to establish the necessary infrastructure for ISRU or import materials from Earth. However, ISRU is a cost-avoidance opportunity especially around water mining for power/life support and manufacturing of solar panels and ceramics. Lunar manufacturing is more advantageous to LEO if the processes are energy-intensive or require large quantities of materials that could otherwise be found in-situ. Exports of raw lunar regolith will likely be a steady income source, with prices dropping as supplies become readily accessible, increasing public accessibility[135].

Antriksha drifted to sleep, and she thought about the humbling experience this had been, after all we are but a speck of dust suspended in a sunbeam. She thought about how the universe reveals itself to us little by little and she wondered how far we as humans would expand our horizons, as we are explorers set to unravel the beauty of infinity and beyond.

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DIA

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