Insight Moonbase

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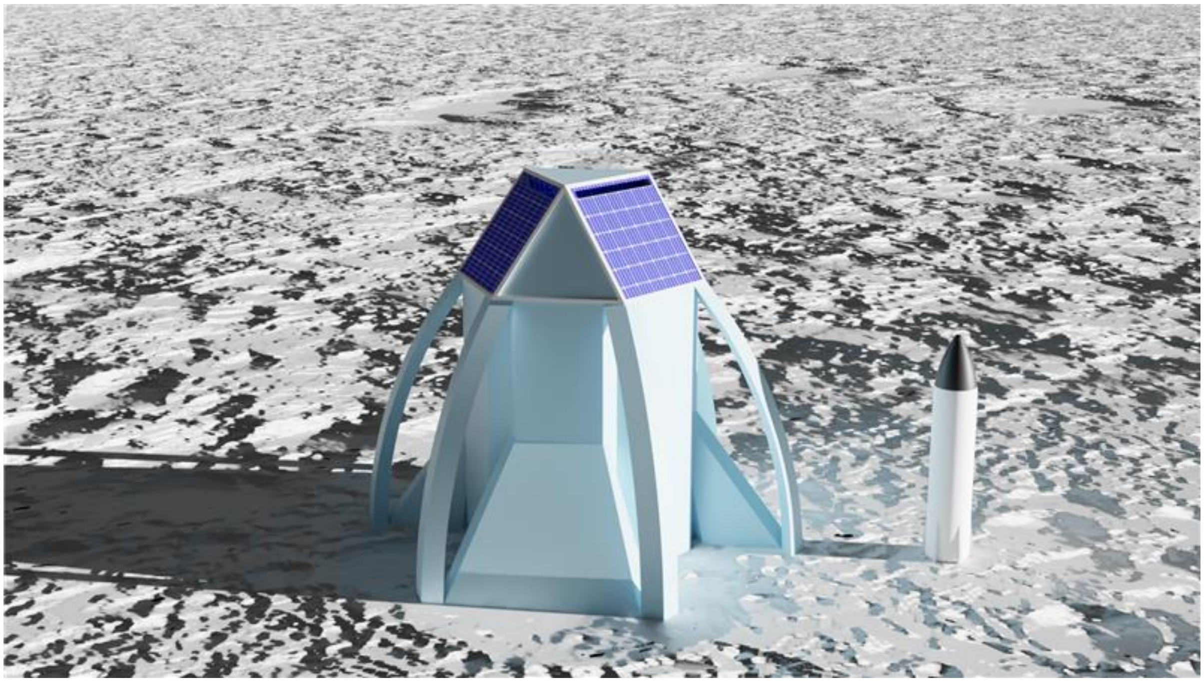

Figure 1: Insight Outpost Habitat. Lunar Starship for scale. 3D Illustration by Aarya Singh.

Abstract

Insight's primary habitat (Outpost) is a large hexagonal tower built mainly of local materials and enclosing three SpaceX Lunar Starship-derived towers. The tower provides radiation protection and additional build space. The Starship towers themselves include LED greenhouses in what were the propellant tanks, to gain roughly 80 percent food independence from Earth.

Sometime later, the crews will build a nearly identical tower as the Spaceport for Insight. It can house up to six visiting landers and provide servicing and fuel transfer between vehicles. A modular hybrid solar/LEU nuclear power plant is also part of the design.

The modular construction system for this base has the working title, "Astraea Interplanetary Modules" (AIM). This system is scalable from ten to ten thousand people. It works anywhere in the solar system with minimal modification. AIM is designed from first principles and economic realities to enable outpost construction in orbit, deep space, and on lunar and planetary surfaces. The Insight moon base design uses this modular system.

This scalability means that the thirty-person crew is transitional while a larger base is built. This paper focuses on the thirty-person stage of development, but considers the larger spaceport to show the

versatility of the system. In a still-later phase, a centrifugal track runs a Starship-derived set of rail cars to allow enhanced gravity living space. The Outpost building would then become the access terminal for the centrifuge train. Besides these construction projects, the thirty-person crew perform epigenetic food growth research and modular habitat refinements in the Insight Outpost.

General Base Design

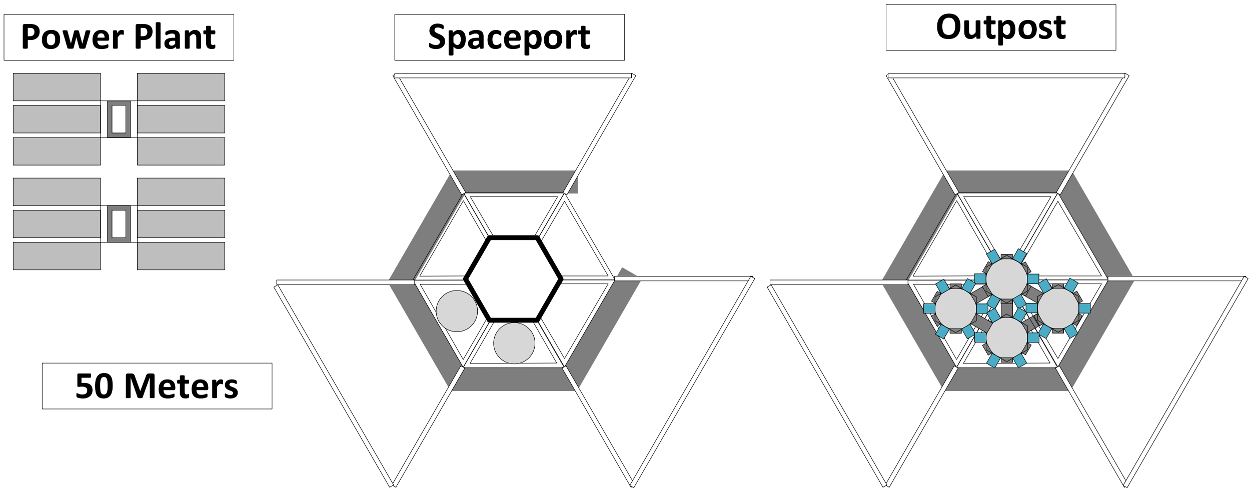

Figure 2: Insight Buildings to Scale. Power stations, the spaceport, and Outpost habitat cross sections.

The ideal site location assumes a pair of craters with the correct proportions and situated roughly 500 meters apart. Ideally, both will be 400 meters in diameter along a relatively flat base (the actual crater rim being larger), with an access “ramp” low spot along each rim in the general direction of the other crater. The crater rims should be roughly 70 meters above the bottom of each crater. One crater will house the habitat, and the other the main spaceport pad. A third crater, 30 meters in diameter, holds the power plant. The Insight base can operate at any latitude on the Lunar surface. A base design that can only operate in a polar or cave location is not adaptable to opportunities outside of those zones, whereas a universal design has no such limitation.

Outpost Habitat Building

Three Lunar Starships form the core of a large, minimally pressurized hexagonal structure used for radiation and meteor protection. The open space within the heavy shell structure allows for experimental rooms at different pressures to prototype future greenhouses and workshops. The Starship towers connect via interior tunnels and elevator shafts to a vehicle garage and airlock at ground level, and between interior airlocks at three levels within the extended tower. The roof section is mainly for radiation protection, but also houses gantry cranes, support cables, and periscopes connected to the habitat windows to give a high viewpoint of the surrounding landscape. The side of the structure getting the least sun has a large cooling radiator to offset the heat generated by LED greenhouses within the habitats.

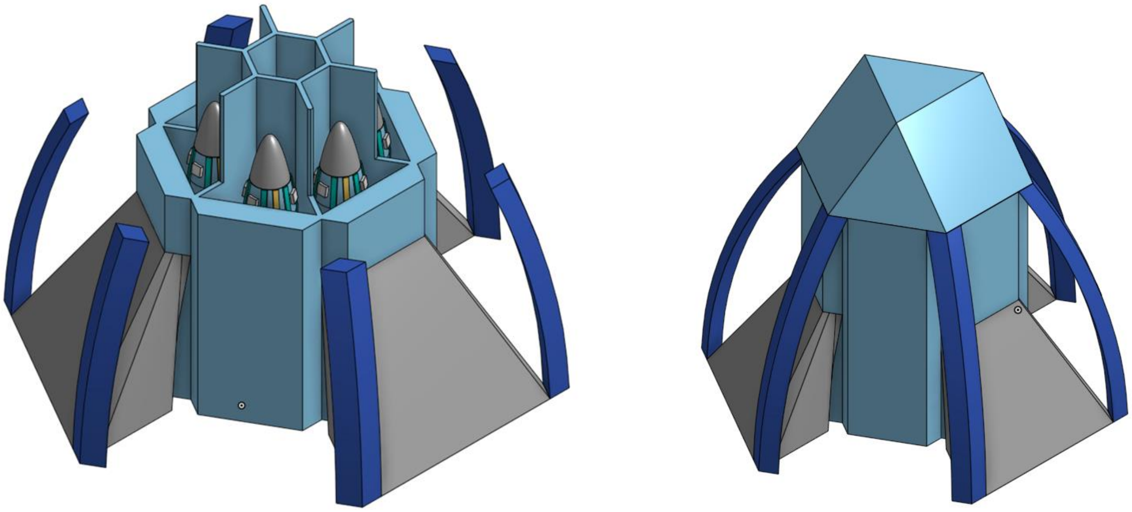

Figure 3: Insight Outpost Habitat. Cutaway reveals pressurized Star Towers within the building. 3D Illustration by Aarya Singh.

Spaceport Facility

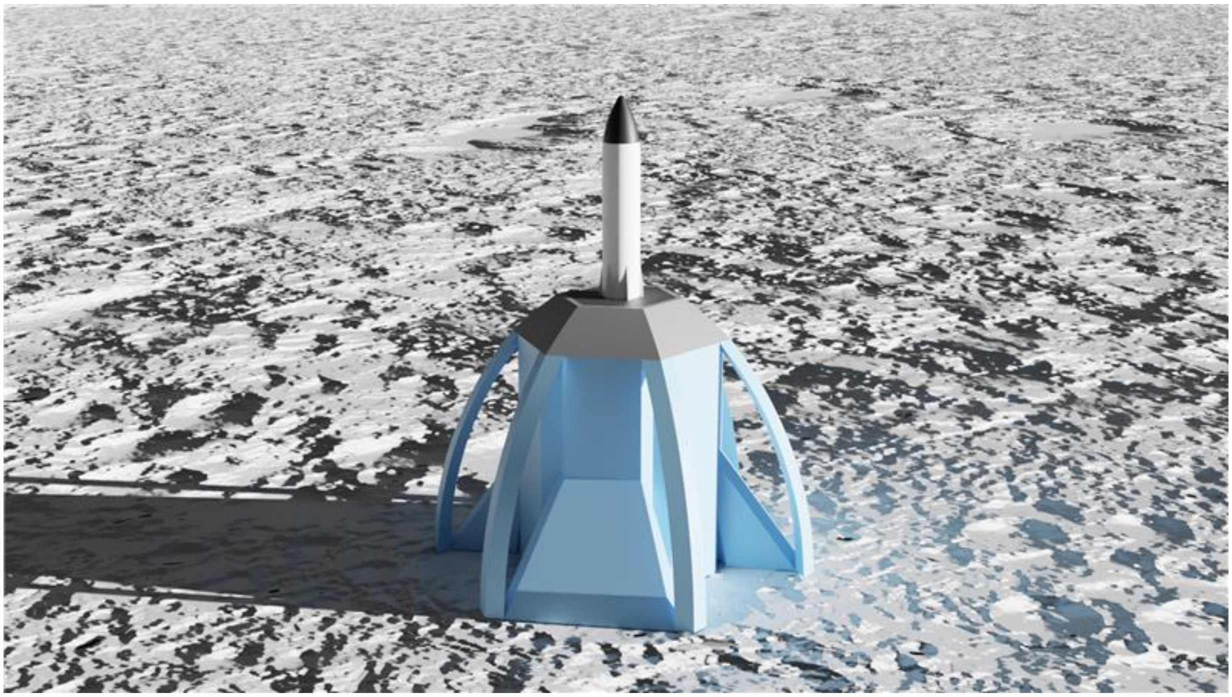

Figure 4: Insight Spaceport. 3D illustration by Aarya Singh.

The earliest landing pad is a simple, spun-basalt fabric "tarp" anchored to the surface with stakes to minimize dust and rock scattering. Crews and robots will then assemble the main spaceport as a simple skeleton of metal frames, then fill the frames with sintered bag-bricks of lunar dust. This dust collection process will also remove loose material from proximity to the base.

The spaceport itself is superficially similar to the habitat. The elevated landing pad minimizes rocket exhaust velocities near the surface. In a vacuum, the exhaust plumes expand rapidly and drop in pressure, thus transferring less kinetic energy to the regolith. The 16-meter-wide pad is 60 meters above the surface. This plus the deflector skirt around the pad ensures that direct thrust never comes less than 100 meters in a straight line from the lunar surface. The landing pad itself has a dimpled surface with curved patterns – similar to an open-front Tesla valve. This disruptive pattern passively redirects the exhaust plume against itself to minimize ablative damage and interfere with lateral flow.

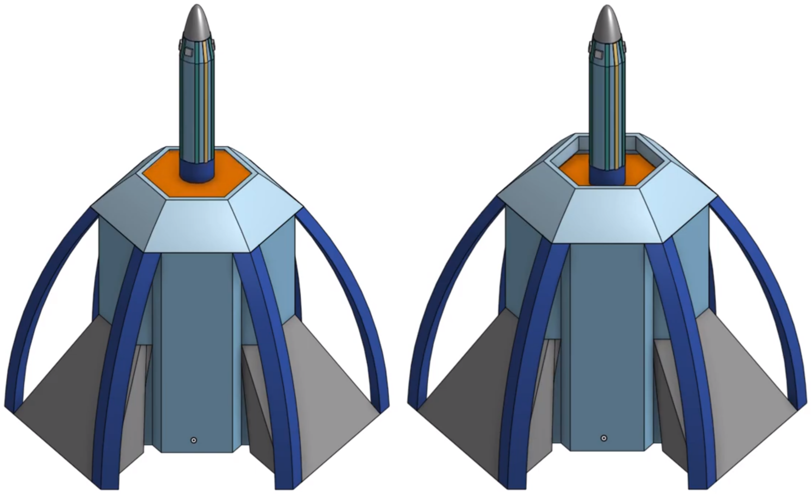

Figure 5: Insight Spaceport. Elevator in Landing position (left) and lowering recovered vehicle to hangar (right). 3D Illustration by Aarya Singh.

The pad can accommodate all three Artemis lander proposals and the atmospheric SpaceX Starship, provided the wings fold back prior to lowering it on the elevator. The tower contains hangars for up to six starship type vehicles. The side door of the tower opens to allow a crawler transporter to move the landers to off-site hangars. Fuel may transfer between landers or local tank farms within the ramp skirts. The hangar door is an inflated structure inside a metal frame to reduce weight. For relaunch, the pad has short arms that reach out from the sides of the hexagon, center the vehicle, and elevate it several meters above the landing pad itself to minimize pad ablation and heating.

Power Plant

The primary power source is a modular low-enriched uranium (LEU) system similar to Kilopower, but scaled up to match the base demands. While the Kilopower team has a “Megapower” design in planning, the reactor could be any modular concept being proposed that is both LEU and fits in a small shipping container or box truck. The core advantage of LEU is that the helium swelling of highly enriched uranium is not a factor, and LEU is less expensive, safer, less regulated, and lasts much longer than highly enriched uranium. The advantages offset the lower power output because designs can run with very low maintenance indefinitely, minimizing the cost and risk of core replacement. The load capacity for the outpost includes lighting demands for the greenhouses, which is triple that of the crew sections. With 25 percent margin for expansion in the remainder of the Outpost tower, the habitat requires 900 kilowatts continuous load.

	Volume M^3	watt/ M^3	% of day	Watts/ M^3	% of day	Load	Total kWe
Crew Space	4000	40	75%	20	25%	35	140
LED Garden	4000	250	75%	1	25%	188	751
Demand							891

Table 1: Power demand for habitat and greenhouses, leveled for 18-hour growth cycle.

When including systems such as power for electric rovers, industrial work, and so on, the peak load for Insight grows to 1200 kilowatts. A second reactor provides not only backup to the base reactor, but power for mining, factories, and resource extraction. Both reactors would provide power for microwave sintering equipment during the construction phase.

Reactor Building Design

The reactor complex itself should have space to accommodate dual reactors to allow for industrial expansion and selective shutdowns for maintenance. The reactor equipment module is 3 by 3 by 6 meters. With a shield wall enclosure one meter thick, the surface building is 5 by 4 by 8 meters.

Reactor Heat Rejection: The system requires a radiator to reject 120 MWt (at a 1:10 ratio with electricity output). In space, this requires a radiator of 50 square meters per 100 kWe. So the radiator surface area requirement for a 1200 kWe reactor is 600 square meters. (Hertzberg, 1992).

In polar regions, an array of horizontal radiators functions well in permanent shade with a crater wall or the building itself. In an equatorial region, heat rejection into space is much more difficult when the lunar surface itself is hot and we want both the reactor and radiator inside a crater for protection. This will reduce temperature differential and therefore reactor electrical output during the middle of the lunar day. That said, solar arrays can both shade the radiators and close any power shortfalls during daylight.

Hybrid Power Arrays: In either case, the reactor building sits in a small crater for natural splash damage protection of the radiators and radiation protection of astronauts. There are six radiator panels per reactor, each 19 by 6 meters, totaling 684 square meters. In equatorial regions, a solar panel hangs on a frame over each radiator to shade it, and the space around the radiator contains reflectors to minimize direct and reflected sunlight. This matches perfectly with the new Roll Out Solar Arrays planned for the ISS, which are 19 by 6 meters and generate 20 kWe each. Each radiator has an area of 114 square meters, offsetting 228 kWe of reactor power output. If the reactor drops nine percent efficiency at high noon at the equator, the solar array will offset that directly. If not, simply add more solar arrays. Infrared heat from the radiators minimizes the day/night thermal shock to the solar array, extending the lifespan of the system. (Boeing Press Release, 2021).

AIM Architecture

The Insight Lunar Base is an example of the Astraea Interplanetary Modules (AIM) space architecture concept. AIM answers all the grand challenges of space settlement at any scale with a cost effective, simple, reliable construction method. This section expands into details of the AIM base architecture.

Design Principles

Modularity: Elements are modular and field-serviceable, with the ability to bypass or reconfigure systems using tools on site. Why: Attempting to predict everything that can go wrong on a base, particularly under novel gravity conditions with a biological component, is prohibitively expensive and leads to analysis paralysis. Conversely, crews can reconfigure a modular system over time to match demands, capacity, and resources. For example, a modular water recycling system that underperforms in some area can simply stack more copies of the underperforming component into the workflow until it meets requirements. Crews then request more and better replacements, and suppliers have an incentive to build new units with higher capacity. Similarly, over-performing units may extend their design life or have smaller scale versions sent later. Field testing these systems allows for proper scaling of equipment for use beyond cislunar space.

For systems like life support, crews can cluster smaller AIM modules into the spaces designed for larger systems. For example, assume a 5 by 10 cm carbon dioxide scrubber for a spacesuit, a 50 by 10 for a rover, and a 500 by 10 for a habitat. In an emergency, the rover scrubbers can link in parallel in the habitat socket, and the spacesuit scrubbers can group into a rover socket. The clusters may be less efficient, but improvisational emergency repairs become trivially easy until the crew exhaust every lifeline available.

Raceways: Interior structures have pre-built raceways, attachment points, and cut-outs for future conduit and plumbing installation. Exterior structures also have raceways. Most raceways have unused spare pipes and conduits to allow rapid bypassing of equipment and replacement. Why: Modularity has practical limits. If every pipe connects in one-meter segments, that provides too many places for leaks to develop. Raceways exist along walls for plumbing and electrical systems. That said, hoses or cables can bypass damaged raceways in emergencies.

Open-Source Equipment: All systems are simplified to both reduce up-front costs and reduce the time and expense involved in making heavy structures from local materials. Why: Simplified systems are more independent of technology failures, captive markets from suppliers (including ones that go out of business, as during the shuttle era), and other elements that add risk and expense. Spin-off technologies using “Moon-Spec” will also be a profitable cost justification for space settlement technology development.

Maintenance Autonomy: The Right to Repair is key to all equipment where possible, and anything too technical to repair on site must be modular with spares. Any critical system must include “Right to Bypass”. This means that a crew can switch off and replace any mission critical component with a manual or simplified electronic bypass technology. Some system designs enable local sourcing of metals and so on for replacement parts. Why: A major risk with a wave of settlement is a repeat of the exploitation vectors of the mercantilist era between source nations and settlers. This may be (as it was then) at the political or commercial level. A foundational vector from Space Settlement to Space Independence will not only avoid future conflict but more rapidly unleash interplanetary civilization from logistic bottlenecks with Earth. A multi-planet species that utterly depends on Earth for some supplies is not actually multi-planetary in terms of ultimate species preservation – it simply dies more slowly from a single point of failure.

The AIM Construction System

AIM picks up with the current state of SpaceX Starship and Starlink architecture and creates a middle-ground between this foundation and interplanetary civilizations with town-scale settlements. That said, it can adapt to Blue Origin and other future start-ups. It does so with the minimal investment of time, technology, and financing possible. AIM focuses on simple, affordable systems designed for reliable life support in any environment over long time scales. AIM is intentionally pessimistic concerning the risks of space settlement to avoid setbacks when "nature gets a vote" in how safe a given living situation becomes over decades. Any structure can be scaled up, modified, and optimized to local conditions without dismantling the existing investment. This includes adding additional radiation shielding, life support capacity, or other modifications to allow for unforeseen risks.

Historic outposts that became cities used simplified building techniques that scaled and had few component types. Bricks, boards, nails, hinges and simple pipes were used to build anything from shacks to cities prior to 1900. A similar minimalist, modular, robust component family enables space settlement, rather than custom assemblies built at great expense.

Exposed AIM Modules

These are the principle building blocks for structures exposed to the space environment. The design allows astronauts or robots to bolt together structures rapidly. The scale for this system assumes the current nine-meter diameter Starship, though it allows for Elon Musk's 18-meter "Starship 2" on the same architecture to future proof the designs.

Frameworks: These are the joists and support columns used in larger structures. They are mainly simple 30-degree "angle irons" with drill holes, a bit like a large, sophisticated Erector set. Designers can use these beams to build frames, walls, columns, joists, rails, conduits, and foundational supports. Later crews can make them from locally mined metals. Along with mechanics from Earth, lunar engineers can build rudimentary transportation and construction vehicles. Specialized joints will allow for 90-degree angle wall connections between walls and ceilings, etc. Different thicknesses, lengths and materials exist within the same modular structure. Multiple frames bolt together and stack in alternating layers like bricks to make larger, more rigid structures.

The baseline of the triangular structures used throughout the base is 22 meters. The maximum length of a Starship payload with an extended bay is also 22 meters (SpaceX, 2020), but this would only be for rare, specialized equipment. Typically, these frames and panels are two meters square.

Panel Bags: These are essentially the same spacesuit material used by Bigelow Aerospace designs. The panel bags superficially resemble an air mattress glued between two tarps with grommet eyelets along the edges. Most bag designs vary in thickness from 10 to 50 cm. They may be filled with air, foam, water or reinforced ice (Pykrete) for radiation and debris protection, lunar dust (which can then be sintered internally with microwaves to make a solid structure) or a simplified concrete mix. The cells also contain spectra cable or fiberglass-like reinforcement to act as 'rebar" if used with a concrete-like material. This offers tensile and compressive strength in these applications. Conversely, panel bags walls and doors for unpressurized hangars and garages may be filled with light foam.

Brick Bags: For heavy construction, a variant called a "brick bag" allows solid wall buildings. This is a brick-shaped bag, 20 by 20 by 40 cm, and filled with fine moondust, sealed, stacked in place, then sintered with a microwave beam to become a solid structure with spectra-cable tensile support. Bricks of the above dimensions fit 10 by 5 within the 2 by 2-meter frameworks. Optional grommeted skirts on the bags can directly attach them to each other and the frame. The bricks may dovetail where structures are permanent and require sheer strength, or stack like Legos for future disassembly. Since they are "soft" when initially stacked, crews may cast them into curved arches as shown with the buttress structures above.

The foundational and outer walls of the towers are built this way. The two methods will be selected as appropriate for strength, weight, and radiation protection through each tower. The radiation shield walls around the reactors are also brick bags.

Shingle Bags: A similar sintered panel with a high-temperature bag material may interlock like shingles into roadways or landing pads. Robots would drive stakes into the regolith and anchor them like shingles on a roof.

Mechanics and Utility Modules: This is a catch-all category for the hinges, conduits, lighting systems, and other infrastructure that bolts into the frames. When set within a framed wall, the bags are entirely flush with the wall's face. This allows solar panels, radiators, hinges, and other fixtures to work with these walls without the bags pushing them out of alignment.

A simplified sizing system uses the Fibonacci sequence to determine the sizes of bolts, conduits and other equipment. This reduces the number of component sizes manufactured to meet the needs of outposts at different scales. This does not apply to units that interlock like wall panels, because they would not be compatible with each other.

Solar Panels and Radiators: These will have the same base 2 by 2-meter form factor as the structural/insulation panels, for ease of attachment to the frameworks. Longer panels are compatible with the system, but must be divisible by 2 meters to simplify construction.

Enclosed AIM Modules

StarCar: This is an original "wet lab" derivation of SpaceX Starship (Nebergall, 2020). StarCar can function as a modular space station or surface habitat unit in a horizontal floor plan. The sea level center Raptor engines mount to a removable thrust plate if needed. The nose is essentially a hollow "space tug" with the RCS and aerodynamic cone fairing as a unit surrounding the nose docking port. Hatches connect the main habitat space and each propellant tank, allowing the entire space to be habitable. It is called StarCar because they connect like passenger rail cars. This design works well for centrifuge habitats and space stations.

StarTower: While "Starcar" is horizontal, StarTower is vertical and designed for lunar and planetary surfaces. It is basically a wet-lab version of Lunar Starship and has far fewer modifications than StarCar. The upper decks are identical, as are the nose, header tanks, and downcomers for added structural strength and repurposing for oxygen and water reserve storage. The propellant tank access hatches are offset from the center to the side for internal access. An external bridge and elevator shaft set of tubes connect the towers vertically between the three pressure vessels and the surface and laterally to the other Star Towers and spaces in the shell structure. These outside access arrangements could use an expanded version of the side access maintenance door seen in Starship prototypes now. Further design simplification could make StarCar and StarTower a single hardware system with two primary configurations.

A secondary configuration option in both Starship variants is to leave the tanks intact for caching propellant and fill the payload volume with propellant management equipment to create a refueling station.

Habitat Delivery and Conversion

For launch and orbital refueling, both Starship variants use the propellant tanks as normal. The vacuum rated engines remain attached and the vehicle can self-deliver to the ultimate destination (Lunar surface, Mars, Lagrange point, cycler orbit, NEO, etc.) Either vehicle can remain in "wet" configuration and function as a deep space shuttle for a time, then permanently convert to a habitat when appropriate.

Once this transport phase is over, construction crews remove the engines and any nose fairings and RCS systems. The bulkhead hatches between the propellant tanks open and allow access both internally and via external elevator/tunnel constructions. The Lunar Starship waist engine ring is modular and removable in this redesign. The removed engines are spare parts for visiting lunar starships.

Interior Modular Systems

As with the modular life support and exterior structures, crews can adapt to new roles or unforeseen arrangements with interior spaces. This helps overcome the feeling of being trapped or stuck with a pre-defined arrangement outside of personal or group control. Architects on Earth may suggest different arrangements and have them "field tested" by the crews to find advantages or disadvantages to different layouts. Fast food kitchens use a similar modular arrangement to allow equipment reconfiguration twice daily to switch between breakfast and day menus.

Interior Surfaces: The tank interiors would use a combination of slosh baffles and stringers to provide pre-drilled attachment points for shelves, raceways, and other design elements. Those baffles minimize propellant slosh during transport and provide strength to the structures throughout their lifespan. Some raceways would have pipes and conduits pre-built into the tank walls. Slots are pre-cut in the baffles to allow both horizontal and vertical raceway configurations. They have reenforced and threaded bolt holes along the outside for light elements like insulation, and along the stronger interior edge for heavy elements like flooring.

Floor Panels: These are wedge-shaped and locked into the outside walls, with an optional support column on the core-ward side. Shorter versions function as shelves or countertops along the outside walls. Floor panels may contain built-in plumbing, ductwork, and electrical raceways. Other equipment such as lighting or fiber optic ports integrate directly into the floor/ceiling units as replaceable modules.

Work Surfaces: Flat workbench and table panels of 50 by 50 cm can lock together to form tables, desks, workbenches, shelves, cabinets, and interior walls. Custom panels may focus on strength, soundproofing, or radiation shielding.

Fixtures: A similar modular arrangement for toilets, sinks, refrigerators, life support equipment, hydroponics racks, and so on use this 50 cm square arrangement. Note that in each case, the vertical height of furniture and fixtures optimize for ergonomics rather than mathematical conformity.

Soft Furniture: In the near term, a simple camping/deck chair system of fabric and frameworks for chairs, beds, and so on is acceptable. These are easy to transport, readily repaired, and comfortable in lunar gravity. More substantial furniture may use memory foam in place of inflatable sections for couches, beds, and so on. Walls may use water-filled bags for radiation shielding in some locations and prior to the enclosure tower being completed.

Living Space Layout

This section is a walkthrough of the locations, activities, and ambience of the Insight lunar base.

Stateroom Decks: Crew members wake up in a bed much like a foam or air mattress in a small private stateroom with a basic desk, video system, and clothes storage. The computer display would wrap around and appear like a window by the desk, giving a feeling of being in nature or wherever the person chooses. The monitor would display a terrestrial or lunar sunrise as an alarm clock. Overhead lights would be full spectrum, and may be sunlight channeled in via fiber optics. These rooms are near the bottom of the structure to give the best radiation protection during sleeping hours.

Restrooms: Each set of four state rooms would share a common restroom, with at least two restrooms per Starship deck. Most surfaces are stainless steel for easy steam cleaning, and the toilet, shower, storage, and sink units. A separate laundry room will also use this form factor.

Common Areas: Most decks have air filtration (spider plants, etc.) and aromatic plants grown in the central common space. This has the practical application of helping manage trace contaminants and air quality, while also giving it a natural feel. This space could also use a Japanese motif by adding rock, fountains, and other Zen garden elements to give it a feeling of completeness with nature. The hard sharp edges of the modular construction can be softened, inset, painted flat black or wood grain, or simply left out to give a more open feel.

Connection and Isolation: Inside the starship, ladders connect the decks via the propellant tank hatches with an overhead hoist for anything heavy. Outside the starships, lateral enclosed bridges connect common ports between the clustered Starship cylinders. They also connect to airlock entries to the floor built at that level of the hexagonal tower, and common elevator/hoist shafts that extend to the surface level airlock and garage. All sections (crew, propellant tanks, and the floors of the enclosure tower) can be isolated in a few seconds if there is a fire, spill, contamination, depressurization, or other hazard. There are at least two exits from any pressurized module, and an alternate route to the airlocks for evacuation or shelter in place in another unit. Any equipment in any module must function in isolation from other units. The main habitat towers have a reserve of at least two days of internal emergency backup power.

Digital Workspaces: Scheduling, monitoring, and controlling operations require conventional screens, which double as high-definition monitors of outside cameras and stock footage from Earth. Robotic equipment is monitored and guided with HoloLens-style systems to minimize crew radiation exposure when possible. The telepresence and spacesuit helmet systems are augmented with external sensor data, which is fed to the person via sounds and lights to enhance situational awareness. Audio feedback would indicate power levels, torque stress, motor heating, radiation levels, and other ambient and relevant data.

For telepresence from Earth, local AI equipment on the moon would put the brakes on any detected hazard condition, such as driving off a cliff. These AI systems are essentially the autonomic nervous system with a faster reaction time than the teleoperator. Developing AI buffer systems like this will eventually allow remote work throughout the inner solar system. These systems can detect unexpected breaks in the work surfaces or equipment and react accordingly. Operators would share short sequences of actions with the robot which would be simulated at the workstation in real-time based on existing knowledge. Exploration situations would wait for a feedback block from the robot to arrive and fill the situational awareness gaps for the next block of actions. This would be analogous to a programmer sending code to a compiler and waiting for the results before writing the next block of code.

Windows: As noted, the conventional windows that look out from the Lunar Starship to the surface would be rigged with periscopes to look from an even higher vantage point out on the surroundings. The upper mirrors may be rotated to adjust the view from a window as desired.

The Outer Tower Workspaces: Mechanical work such as repairing equipment, assembling modular or custom hardware, and other such items will be done in a set of workshops that are fully pressurized, lower pressure with oxygen masks, or full vacuum with robotic and human tooling systems available. Note that lower pressure, oxygen mask fed systems can also be used for experimental, artificially lit greenhouses. Outer walls of the on-site construction part of the tower will use this method to create 200 to 800 millibar buffer zones between the core, 1 bar living space and the outer vacuum. A multi-layer system may have only 200 millibar pressure difference between walls, though it should be rated for at least double that in the event of a leak between zones.

Garages: The base of the non-starship side of the hexagonal tower contains at least one pressurized “Quonset hut” section for surface vehicle repair and construction, and vacuum or near vacuum storage. As with the plants, sub-pressure spaces may allow repairs in shirtsleeves with an oxygen mask, while minimizing risks due to fire on the pressure side or accidental vacuum welding on the ambient side.

Life Support

Thermal Management: Since the habitat towers are enclosed in a heavy radiation shielding structure, this buffers the typical day/night thermal shocks of the lunar surface. The hexagonal structure has a large radiator on the permanently shaded side of the habitat. If the habitat is equatorial, the panel locks under a shaded overhang. LED lighting for the plants provides ample waste heat in most conditions for offsetting low temperatures.

Air Chemistry Management: The greenhouses provide fresh greens and basic nutrition for the crew. If this is too small for a full oxygen recycling loop, the design can integrate algae tanks to offset the gap. That said, the air demands of both crew and plants will differ depending on the growing season for specific crops, crew sizes, and other factors. So early growing seasons for plants may use large algae tanks, and later growth conditions may shift to lower water levels in the tanks. Reserve tanks of nitrogen, oxygen, and carbon dioxide can keep the plants alive when crew sizes are smaller. Artificial life support systems will extract any excess gas levels and top off these tanks when appropriate.

AIM scales both natural and artificial life support systems to handle the full workload without the other. This minimizes stress on both natural and artificial loops. Much of the life support function will simply monitor levels of carbon dioxide, oxygen, and water vapor at each floor of the tower and run fans in ductwork to optimize conditions.

The artificial life support system uses recyclable carbon dioxide chemical scrubbers on a hot-swap system. When saturated, the system swaps the scrubbers and heats the saturated ones to release carbon dioxide. It then either stores the gas or routes it to the greenhouse. When working without plants, the stored gas is periodically run through a Sabatier reactor. The system can then decide to release the oxygen directly or store it for later. Note that carbon dioxide levels in the greenhouses never exceed levels safe for crew operations in those spaces.

A small industrial plant will take mined lunar material and extract oxygen and trace water for the habitats to compensate for leaks and airlock use. Note that airlocks use pure oxygen not simply to optimize pre-breathing, but to avoid releasing irreplaceable nitrogen into the vacuum. Earth resupplies and on-site bioreactors in waste management will also subsidize nitrogen supplies.

Filters will partially resolve trace gas contamination. That said, common commercial building methods of trace gas and odor control include spider plants and flowers in public spaces.

Dust Management: Within pressurized spaces, filters will first pull dust out electrostatically, then route it through washable filters. Airlocks may actually contain a form of wet shower and electrostatic systems to clear dust prior to entry. The electrostatic system works with a spacesuit skin optimized for electrostatic rejection.

Humidity Management: The greenhouse areas have cold plates for condensing and recycling water, while managing humidity before it becomes too pervasive in the habitat decks. Recirculating air from the hot/damp/oxygen-generating lower hydroponics decks to the warm/dry/carbon dioxide generating upper living decks would almost be passive with an optimized system of ductwork and cold plates. This not only adds a safety feature to the base to reduce cascade failure risks with life support, but may reduce the noise pollution of active fans and pumps.

Microbial Management: The ISS and Mir space stations had mold issues behind equipment, and that was without transpiration vapor from extensive hydroponics. After the crew harvest a planter, they will steam clean the entire shelf area and wall surfaces to remove any microbes, residue and plant debris. Crews will clean the habitat the same way where appropriate. Any fabric surface (including mattresses and couches) is washable. The only exception would be soil for perennial plants such as dwarf fruit trees. Removing soil would break up networks of fungi and root complexes that are interdependent.

Ducts include UV lighting to minimize microbial growth. Ozone generators inject into liquid waste processing, potable water maintenance, and laundry systems. Handheld ozone generators can sanitize small spaces like storage lockers, refrigerators, and bathrooms.

Liquid Waste Management: An anaerobic digester is the first stage of the sewage treatment system. The system may further clean waste by pasteurization, dehydration in hard vacuum, or long-term storage in sterilizing conditions prior to reintroduction to the composting process. A similar system distills any liquid wastes and gray water for reprocessing with reverse osmosis.

Any plant waste routes to the composting system. From here, crews may put the soil directly in plant beds or add it to a water leaching system that feeds hydroponic and soil watering systems. Crews will then optimize the nutrient stream for microbe control, acidity, mineral content, and other attributes as needed.

As a proof of concept, solid wastes from the human streams may feed non-food plants first, and then the non-food plant waste would go into the edible plant streams. This outpost is too small for this to be more than an experiment, but it may limit the “ick factor” in future large space settlements with extensive textile and wood manufacturing systems.

LED Greenhouses

Greenhouse Volume: The propellant tanks will contain 1000 cubic meters of usable volume, when allowing for other equipment. Construction crews would convert the tanks primarily into into an LED and possibly fiber optic sunlight greenhouse space. This allows roughly 100 cubic meters of plant growth volume per crew member.

Dining Spaces: Food preparation and dining spaces are in an upper greenhouse deck (top of the liquid oxygen tank) for added ambience, so that any meal would essentially be “alfresco” and surrounded by greenery. To both add a feeling of space to these areas and optimize lighting conditions for plants, the tank walls have mirrors to give the feel of a garden that extends to the horizon. The curved ceiling would be lit and projected to appear like open blue sky, possibly with an LED “artificial sun” skylight for daytime use, and a projected terrestrial sunset or sunrise cloudscape during breakfast and evening use. A core psychological need is a sense of nature and life that is lacking on the lunar surface. The garden/kitchen space would provide this environment with long mirrored sight lines and large HDTVs for displaying landscapes, seascapes, and other calming imagery. Fountains may mask the sound of pumps and fans as well.

There is also a practical matter of not hauling the plants to the living space for preparation, then hauling the stems and peels back down to the composter system.

Food Selection Criteria: There are wildly varying claims on how much land a person requires to grow enough food to be independent. There is a gradient between a dehumanizing minimalist diet of algae food pellets and a modern first-world diet, including beef and milk. Regardless of selections, there are psychological and health benefits from a more diverse diet.

Lunar logistics restrict food imports by volume and will expose them to long storage times and radiation-induced nutritional degradation (at least en route from Earth). The “hierarchy of needs” for in situ food production is first vitamins and minerals, then proteins, and finally raw caloric intake.

Green space is primarily for garden fruits such as berries, sprouts, herbs, dark vegetables, and dwarf fruit trees. Fresh ingredients are of prime importance in food quality. Even meat frozen for months can have a fresh quality if cooked with herbs from a small kitchen hydroponic planter.

When the crew have their basic nutrient needs met, the question of protein may allow for fish tanks, birds (mainly for eggs rather than meat), and so on.

Animals are chosen mainly on what they eat and what they do with it. For composted plant and animal waste, the system must account for the safe return of nutrients to the food stream without concentration of toxins or other health risks. Strong candidates for aquaponics include tilapia and catfish. Mollusks are not only filter feeders but concentrate calcium in their shells. The crew can then grind the shells to feed poultry and ducks so they make healthy eggshells.

The third tier includes grains and other annuals for caloric intake beyond that provided by the other two tiers. The need for grains and nuts will be minimal if the first two tiers produce sufficient plant and animal fats.

Epigenetic Research

The goal is to test plants and animals to determine which grow best in the lunar gravity environment and the stress of enclosed spaces. The tendency to avoid eating these animals is more because of their value as lab specimens than any vegetarian considerations. Other meats, plants, and plant products such as coffee would be easier to import from Earth but may grow experimentally to determine future adaptation of genomes to lunar gravity over several generations. A core goal of the base is determining which "heirloom" genomes of plants and animals can adapt to lunar gravity, and what epigenetic stress results appear over several generations of lunar adaptation.

The science of understanding how this epigenetic stress affects the plant's output chemistry and yields makes the study of this growth valuable from a purely biological standpoint, because it gives insights into the plant's applications on earth if the genes are turned on via modifying rather than stressing the crops. If the genes are silent, then the GMO process is simply altering the activation within a species rather than grafting in other species.

Further, this biological research of advanced species over generations cannot be accelerated past the breeding cycles of the candidate species. Therefore, advanced experiments in reduced gravity should begin as soon as possible, even if premature from a base self-sufficiency standpoint.

The Global Garden

This would be an ongoing project that has cultural value for Earth and great practical and psychological value for Lunar crews. The Global Garden project would invite crews from various culinary regions of Earth to send seeds and some animal species to the base for local growth ahead of a crew visit. When the plants and animals were mature, a chef and other nutritional scientists from that region would prepare the foods for the broader crew and examine the impact of lunar gravity, lunar dust-enriched soils and closed cycle conditions on the resulting products. The chefs would then refine localized variations on the menu. This is not only a practical source of genomic and epigenetic information, but also fun for the public and interesting for the crews. Seeds of plants grown on the moon then return to Earth. This is like the "moon tree" seeds from the Apollo era that astronauts took to the moon. They planted these seeds in many parks, and several trees still exist now.

Economics

In traditional spaceflight, two major cost drivers are over-engineering solutions to deal with unknowns and one-off production of low-volume, high complexity systems. Designing modular systems that crews can reconfigure in situ addresses both cost factors by making production volumes higher and systems more robust. A second driver is cost-plus contracting, which runs intentionally counter to being on time and on budget.

“Moon-Spec” Testing and Marketing

Mil-Spec identifies products that meet the criteria of DOD military technology– able to withstand harsh environments and still operate reliably. A similar term is “flight rated” for parts certified by the FAA for aircraft. UL listed is a privately funded test lab that certifies items for home use, though it is usually not a government regulatory requirement.

The difficulty of building a broad, simple technology base for space settlement is a problem that we can turn against itself. Setting up competitive testing of “Moon-Spec” (and “Mars-Spec”) systems needed for the habitat, even if they are as simple as bolts or countertops, can be advertised by the manufacturers to gain competitive advantage in commodity-hardware markets and spur innovation in otherwise stagnant industries. This is like a school robotics competition or car company racing teams.

The other advantage to these systems being both modular and mass produced for terrestrial markets is that the whole COTS (cheap off the shelf) procurement method. If manufacturers put Lunar-Spec products on the general market, then the lunar base can purchase these products from the general market for use on the moon. If control systems remain open source and specifications call for minimal opportunities for malware, new and better systems will continue to emerge and be simple to order for this and any future space settlement that requires those systems. Building a new crewed space system may be as simple as ordering parts from a website catalog, much as CubeSats are now.

To spur this, a large NewSpace company, NGO, university, or government could create a set of needed products for missions being launched in three years. Vendors would have time to prepare competing test prototypes of those systems to see which would be certified. The certified ones would then compete to see which is the best for flight use. The winner then gets to certify these new products for competitive advantage and has the marketing and stock prestige associated with being the winner of this competition. Field refinements, integration, and long-term stress testing of the products would then take place prior to launch. Developers would bear the development costs, though the rating organization would need to pay for testing, promotion, any prizes given, and the “shipping cost” of supplying the equipment to space outposts.

Pioneer Phase Economics

Deep space settlement will be enabled by several overlapping technology revolutions, each triggered by a social/technological wave of excitement-driven focus within the economy. As each wave is added, the economy is enriched by invention combinations. This same pattern can be repeated on Mars and other pioneering phases, and is loosely modeled on past technology revolutions throughout history. The goal here is to engineer it directly rather than simply observing it when technological convergences happen coincidentally.

The Sponsorship Wave: As noted with the spec-meeting competitions, there will be a historic collector's value in being the first space-flown items on the pioneering missions. This democratizes the responsibility, glory, and historic value to the public, as well as the cost. Owning historic collectibles will be considered an appreciating investment by those sponsors, though many will do it purely to leave a personal fingerprint on this grand historical adventure. Owning a framed certificate of sponsorship would essentially be the “St Crispin’s Day” speech from Shakespeare, where future generations would consider themselves accursed that they did not sponsor the 523rd kilogram of coffee flown to the moon.

The Collectable Wave: This wave will focus on returning lunar samples, collectable space-flown hardware, and other equivalents. This market recognizes that buying the first privately owned 1 kg sample of lunar rock will be considered a national museum grade treasure, but that the millionth 1 kg sample of returned moon rock will be a bookend in a basement bar. That said, the early lunar rock collectables are valuable in part due to democratized participation in history and exploration. This is essentially an echo of the Sponsorship Wave, based on what comes back from the moon rather than what is sent there to begin with. This may also include seed strains or worn equipment that had a service life at the Insight lunar base.

SEA Wave: The next phase will be focused on sponsored projects in Science, Engineering, and Affordability (SEA) of surface systems. Science sponsorship comes from smaller research entities (universities, NGOs, etc.) being able to afford larger and larger scale missions as the cost of travel and quality of hardware improves. Engineering research is an outgrowth of the LunarSpec project, where multiple certified systems expand their range of scale and quality within that specification of acceptability. The Affordability revolution will be the natural outgrowth of growing professional experience with these environments and specifications by larger groups of workers. This will further reduce the cost of entry for more and more participants in a virtuous circle. As is happening now with the number of CubeSats doubling every year, a similar wave will happen with lunar surface equipment.

Epigenetic Wave: Insight research will build knowledge of the acceptable ranges and stress-related reactions of plants, animals, and microbes to lunar gravity, both individually and as miniature biomes. Knowledge of “silent genes” in various species has value on Earth in adapting plants into refined crops for specific purposes, such as resource extraction, toxin processing, or material production. This will lead to refinements in biotechnology, pharmacology, nutrition, biofuels, and crop failure mitigation on a global scale.

Policies and Practices

Crew Rotations: Crews will serve four-month rotations, with a one month overlap between departing and returning crews. During that month, tourists and other visitors may stay at the base for a one-month visit. The number of visits a crew member may take part in depends on the levels of radiation exposure, reduced gravity effects, and the individual reaction of that person. At least one and probably two ascent vehicles will be on site at all times, and each should be able to sustain the full crew for either two weeks on the surface or a three day return to Earth.

Note that a single crew rotation may be extended, for either the full crew or part of it, up to eight months if the projects require it. Major construction tasks and other long operations may be determined on a case-by-case basis, provided crew members stay healthy for up to a full year. Care will be taken to minimize radiation exposure for these crews.

Continuity of Operations: The overlap allows continuity of operations and direct skill transfer with backup experienced staff on site during the acclamation period of new personnel.

Crew members are scheduled equally to all life support, food preparation, and cleaning tasks. There are two very practical reasons for this. First, a crew with only two gardeners or mechanics will enter a death spiral if either technician is incapacitated. A crew where everyone can maintain the base will remain functional at any crew size, and may split into shifts, teams, or sub-sets for extended surface expeditions without excess risk. Second, giving the entire crew gardening duties gives them an opportunity to return (at least mentally) to earth and terrestrial nature in a sensory, kinesthetic sense. These moments help keep the crew psychologically grounded in an otherwise sterile environment. Crew members may bunch this work into solid days to have time away from the routine of science/engineering and feel like they are on a farmstead vacation.

Crews and Projects: Every crew member, including tourists, have a set of projects on which they train prior to their rotation. The crew member or sub-team is the owner and expert in each of these projects. In addition to the maintenance duties mentioned above, every crew member has a block of time assigned for their projects, another block reserved for assisting others, and a third for overruns on either set of projects.

Smaller, lower priority projects will use Agile project management methods. All projects are assigned to a backlog and worked on a weekly basis. The exact mix of Kanban, Scrum, and XP methods will be worked out and tested by the crew prior to flight. Note that project queues may be started early by the previous crew or wrapped up by a following crew. Projects requiring ad-hoc teams will “bid” to either get into or out of a task as desired, often trading time or possibly resources for priority. To avoid corruption, these things will be accounted for in project management logs and meetings. It will be of interest to future historians how many laundry shifts and chocolates were expended in the construction of a lunar radio telescope.

Commander: The base commander mainly functions like a project manager. They will have disciplinary authority if needed with approval from mission support. The base operates on Pilot in Command principles, which have a basis in aviation and nautical accountability structures. Since on site commanders are closest to the situation, their orders cannot be remotely countermanded unless they are grossly negligent or dangerous. A commander may refuse an order from Mission Support that creates an undue risk, provided the refusal is stated, the reason is given, and the leader is prepared to face a board of inquiry and potentially lose their crew status. As such, the rotation commander will have the fewest personal and team projects of the group, in part to allow time for management and in part to avoid favoring their own work. During crew transitions, commanders are in charge of their own crews, and authority over the base is handed off halfway through the transition month.

Tower Engineers: At the next level, each of the three habitats will have a resident engineer who confirms all systems are working and clean, and escalates any maintenance issues if needed. Three engineers or the majority of crew can overrule the commander.

Regulation: With civil aircraft maintenance, regulation is rarely imposed in the absence of demonstrated mechanical failure. This avoids undue expenses and moving goalposts to keep systems in compliance when there is nothing wrong with them. If a system fails, it is investigated until the root cause is found, and then a solution is put out across the entire system. Where possible, other copies of the system will also implement the fixes. For example, a root cause associated with lunar gravity but not microgravity would not be imposed on space stations, and vice versa.

Tourism: Tourists must have at least one work project, either of their own or assigned by the base commander. For purely tourist efforts, these projects may be artistic or promotional. Tourist projects are not prioritized outside of normal operations–all life sustaining, engineering, construction, and science work must be done first. However, if not done in the first three weeks of the one-month tourist rotation, the visitor is free to wrap up their personal projects in the closing weeks.

A key incentive to visit the moon is to do something good with permanent and significant impact. Tourists will have a strong interest in EVA work on the lunar surface. Short-term tourists may be more inclined to do manual work on the surface than long duration or repeat crew members who are following radiation exposure guidelines. A team of highly qualified tourists may build permanent engineering and scientific assemblies such as telescopes or factories. They may also be sent on excursions to put first footprints on geologically interesting areas.

Training-Only Tourism: A more affordable option for many interested people is a tour that trains but does not fly – a bit like Space Camp. It may also provide opportunities for telepresence work on the lunar surface as virtual crew members running equipment and robotic construction systems. Free online versions would also be available for education purposes. Both options open the adventure to those who cannot medically take the flight.

The Centrifuge Track

After the base is operational, a magnetic levitation track can be built with the "StarCar" configuration of a starship to make an augmented gravity habitat lab. Initially, single cars would do brief experiments, but eventually the whole ring may contain cars in permanent or daily spin mode. The ring would have a diameter of 375 meters, a bank angle of up to 74 degrees, and a spin rate of 2 RPM, or 140 kph/88 mph. For Mars gravity, the car could spin half as fast and run with the base at a lower angle. Since the StarCar is cylindrical and the track trough is magnetically levitated, it can simply have a low center of gravity and automatically keep the floor in line with the artificial gravity downward direction at any speed. This allows thirteen cars per track, with enough internal LED greenhouse space for 130 people. If the greenhouses are outside the track at lunar gravity in new towers, the population per ring rises to two hundred. Tracks may be clustered in the hexagonal framework with a entrance/exit car used to bring crews up to speed or back to the surface. Up to five permanent rings and two transport rings can fit in this structure, which is basically the Outpost tower turned on its side. In this ultimate configuration, the small Outpost becomes the earth-like home of a thousand lunar settlers, with no dramatic technical or engineering breakthroughs required to reach full Lunar settlement.

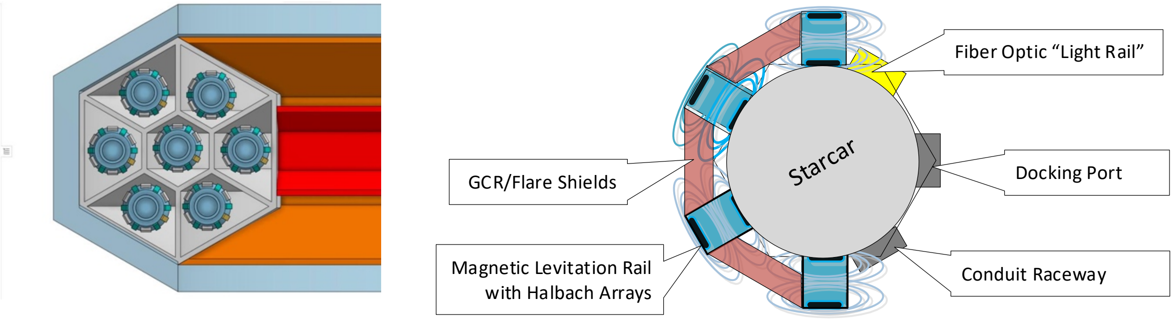

Figure 6: Full Centrifuge Habitat with seven tracks (left). Cross section of StarCar and track system (right).

Assembly and Operational Timeline

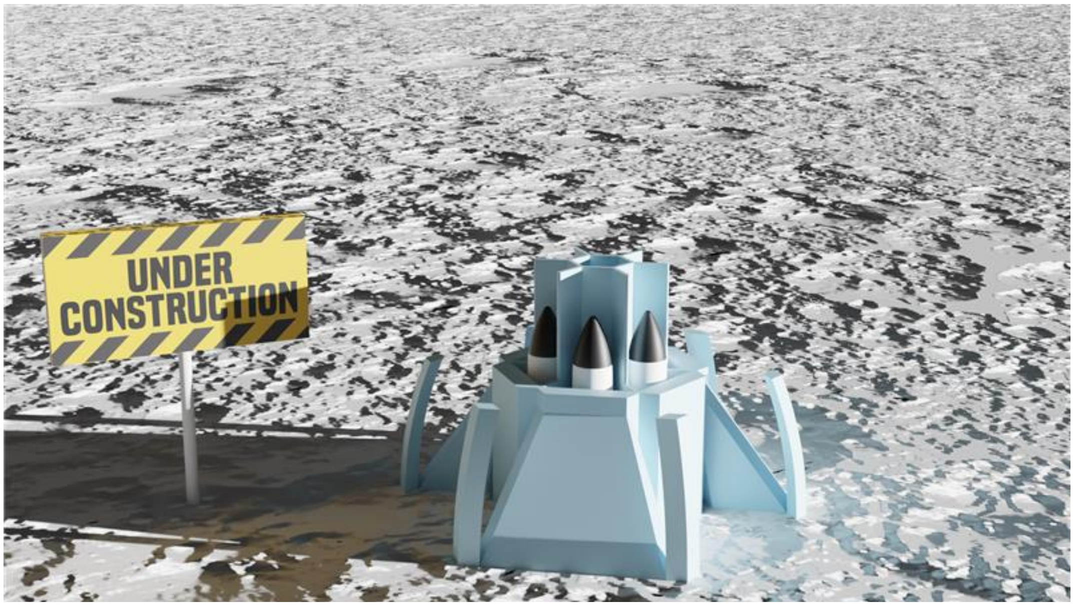

Figure 7: Outpost under construction, with shield wall being built around Lunar Starship Towers. Illustration by Aarya Singh (age15).

Phase 0: (1 Crew Lunar Starship), dust mining sweeper clears top layers, landing blanket pad for debris mitigation, small reactor, crew 10. Two-week rotations every lunar month.

Phase 1: (1 crew, 3 cargo), Basic drill/crane/excavate equipment on Cybertruck platform. Foundational blocks and permanent foundations setup for Outpost. First nuclear power plant. Crew 10. Overnight stay. Six-week rotation. Robotic Telepresence construction work continues after visit.

Phase 2: (1 Crew, 5 cargo, 1 “Star Tower”) Frame erected over Outpost and central walls started. First Star Tower lifted into place using frame. Road path cleared to permanent spaceport. Crew 20. Eight-week rotation.

Phase 3, 4, 5: (1 Crew, 6 Cargo, 1 Tower). Main Outpost built with full GCR protection walls. Base of “brickwork” half of tower started. Foundation of Spaceport started. Crew 30. Promotional breakeven.

Insight Operational. (You are here). If SpaceX were to continue on the current path, this could be done in a decade. The decade that follows this is outlined below.

Goal 2 – Spaceport complete, second reactor built. Food autonomy. Epigenetic IP financial breakeven.

Goal 3 – Industrial building on same planform built, but using single StarTower and remainder using pressurized lined brickwork structure. Net exporter of oxygen.

Goal 4 – Experimental centrifuge rail. Second spaceport. Basic extraction plants for ice, oxygen, metals.

Goal 5 – Full Centrifuge rail with cosmic ray shield. Population 200. Basic framework factory.

Goal 6 – Hexagonal centrifuge with greenhouses built with brickwork method. Population 1000.

Conclusion

Culture requires sustained excitement with steadily improving results to see a hopeful future. The excitement of Apollo and the Shuttle eras was initially great because they were long-sought breakthroughs. They became boring to the public when it seemed NASA was simply repeating the same thing for years. This is tantamount to a toddler doing the same trick over and over and expecting identical praise every time. Conversely, the computer and smart phone revolutions have been exciting not because of a single product release, but because of the constant gradient of promised future innovations.

If technology were sound, then a specific invention is a single note. It may halt like a thunderclap, repeat like a car alarm, or integrate into a historic symphony. These creative technological symphonies make history, in every sense of the word. Projects, like sounds, that repeat the same pattern endlessly are turned off or ignored. This was the fatal flaw of the first era of human spaceflight.

Insight Moonbase is simply a single measure of a long composition predating and succeeding it, using the AIM framework as the instrument. It may be stiffly conducted, improvised, or layered into an unending masterpiece. Whether Insight remains twenty forgotten pages of sheet music or swells into an anthem that moves worlds is an open question.

Like history itself, may it remain a beautiful question that is never forgotten, nor fully answered.

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