Argo Base

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CANADA

Abstract — Since time immemorial, the Moon has served as an inspiration for humanity and encouraged us to venture into space with its inviting light. Despite this, lunar expeditions have been tentative, limited, temporary, and with the exception of the Apollo program, unmanned. Now as we begin a fresh new age of space exploration, the time has come to lay the foundations for a permanent and dedicated occupation of our closest celestial neighbor. In this work, we present our design for a lunar base named “Argo”, which is not only a permanent lunar settlement, but also a versatile foundation for more advanced operations to come. The design of the base places an emphasis on simple, flexible, and mature technologies to safely facilitate rapid construction with three phases in the very near future. It also serves as a critical model for the colonization of Mars, validating techniques that will strengthen humanity’s first ventures into interplanetary colonization.

1. The Project.

This paper details our submission to the Moon Society’s Moon Base Design Contest [1]. The broad strokes of the contest called for:

1) A moon base that is capable of housing less than 30 international astronauts in a comfortable environment.
2) A design that incorporates current day technology exclusively in its function.
3) A focus on such features as: adaptable technology and innovation, financial viability, architectural structure and appeal, sociological structure and relations, political legislation, and economic opportunities.
4) Last but not least, visual representations of the base.

Based on these criteria, the ethos we took with designing the base is: ‘Keep It Simple and Safe’. We researched technologies that would allow us to make our base with a minimum of fuss on the lunar surface, yet still deliver a facility that is built to last and offer comfort and utility. Simply inflating a few habitat modules with dirt over them is *not* sufficient for having a permanent presence on the Moon. A proper approach of lunar colonization is comparable to constructing a castle: a persistent and systematic build-up that yields a robust facility capable of indefinite habitation, open-ended expansion possibilities, and huge economic payoffs. Faced with the challenges of a harsh new environment, it is tempting to conjure novel techniques and technologies newly conceived or emerging in the lab, such as 3D printing with lunar regolith [2], autonomous robot construction [3], nuclear fusion power, or use of theoretical metamaterials. Yet little public attention is directed towards the realistic and effective methods of lunar development at hand. Herein, we hope to draw attention to the feasibility of occupying the Moon with the application of mundane available technology, time, persistence, and human ingenuity [4] [5]. We will consider: choosing a landing, planning the base, selecting launch systems, organizing the groundbreaking effort, and operating the working base.

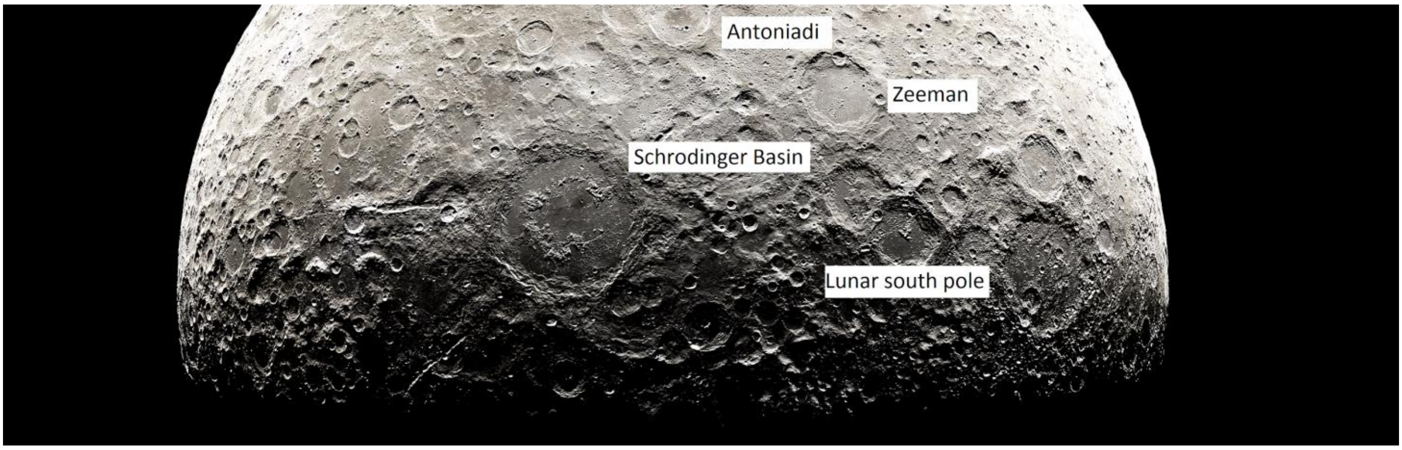


Figure 1. *A view of Schrödinger Basin from above the South Pole of the Moon.*

2. Where to go?

While there are many sites on the Moon with access to assets vital to lunar colonization, almost none have as many desirable qualities as Schrödinger Basin (SB), a large (>300km) farside impact crater centered at 75°0′0”S, 132°24′0”E [6] [7]. Some of these desirable qualities can be found elsewhere on the Moon [8] [9] [10], but others are totally unique to this basin. Most scientific and research questions the world’s space agencies hope to answer can be found in SB [11]. Choosing a site within reach of usable resources [10] [12] [13] [14] is critical to limit launch costs in resupplying the base. Furthermore, there is already ample scientific interest in SB [15] [16] [17] [18] [19]. Many questions about the South Pole-Aitken Basin can be answered within the outer rim of SB [20] [21]. Thanks to this collection of incentives, grant funding from scientific institutions, national space programs, and universities should pour in.

2.1 *Our Base Location*

There are several sites to consider in SB. Site 1 (fig. 2) is interesting for the basaltic melt sheets of the basin floor, though that geology alone does not warrant permanent inhabitation there. Site 2 has varied geology composed of basaltic flows, ghost craters, nearby rilles, and cliffs [22] [23]. But, Site 3 is best for locating Argo: it sits in the midst of several fascinating geologic features, including the pyroclastic cone Schrödinger G. This young and intriguing specimen of recent volcanic activity could sustain a scientific operation for years [24] [25]. Site 3 also offers in situ resource utilization (ISRU) opportunities, presenting minerals containing volatiles, aluminum, sulfur, iron, titanium, and oxygen. These minerals include siderophile, anorthites, FeO, microspheres alloyed with cobalt and nickel, and chlorine-rich apatites. The science related to these minerals and their uses will constitute a vital avenue of research for our base, and should lead to immense economic benefits as these resources catalyze lunar industrial operations (see pg. 12) [5] [26] [27] [28] [29]. Additionally, in this area, several deep craters are within walking distance, providing opportunity for water harvesting [30] [31] [32] and potential sites for radio telescopes [33] [34] [35] [36]. Nearby ravines and rilles may also contain interesting geology, or water ice in deeper crevices. Lava tubes might exist around the volcano, and these present stimulating prospects for exploration. To boot, Schrödinger G is a kingly position in the basin — a base near Schrödinger G is within reach of all sites of significant interest. The area is very flat at a calculated slope of 1.3 degrees N-S, and just 0.3 degrees E-W. This has obvious benefits for equipment placement. For example, the flat terrain and lack of significant peaks nearby allow us to place our solar panels without fear of them being overshadowed.

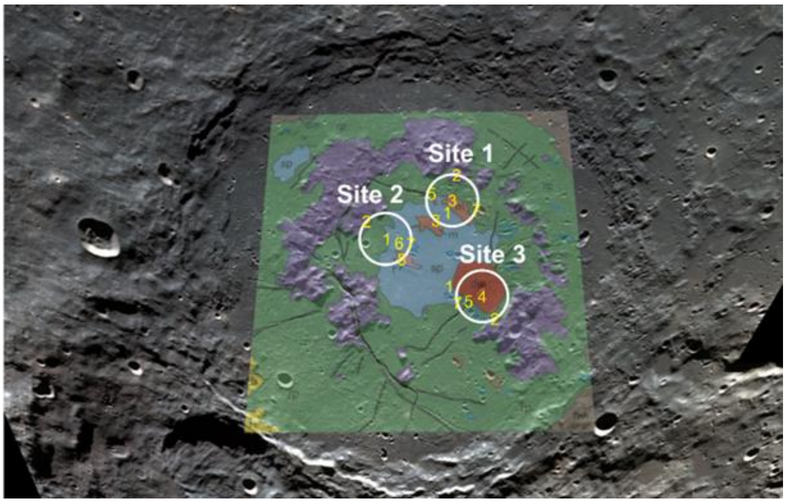


Figure 2. *A map of sites of interest in Schrödinger Basin. Argo is located at Point 5 in Site 3.*

3. Development.

Argo's construction is staged so that there is increasing complexity and comfort as the size and population increase. Rather than three different bases, Argo follows three stages of development that each facilitate the next. Astronaut teams will establish a permanent presence on the Moon, using efficient cargo delivery via an upcoming workhorse in aerospace, the Starship. The phased approach to construction avoids fuel-intensive and expensive trips to deliver construction goods en masse and prevents the abandonment of the base during the lunar night.

Phase 1 – a maximum of six days. Creates the literal groundwork for later operations so astronauts can work safely on the Moon; a quick effort with the fewest launches. This Phase verifies the techniques of base construction, and will be performed with highly trained crew and robust equipment to meet the timeline. These construction projects will clear a landing area for the Human Landing System (HLS) Starships, and establish emergency habitation in case of accidents. Astronauts will build expertise with this new construction venue and equipment. The Phase 1 habitat use extends into Phase 2, as seeking shelter in the Starships may be impossible under time constraints. The two structures that constitute Phase 1 status of the base we call "Superposition".

Phase 2 – 6+ months. The Argo Base is expanded from Phase 1 with hydroponics, significant ISRU, large scale solar power generation, and science labs, as well as extended EVA activity. Lunar construction will be industrialized and developed to enable Phase 3.

Phase 3 – 3+ years. Begin lunar exploration and start extensive usage of ISRU for building. Most operations not directly contributory to the survival of the astronauts, like prospecting, laboratories, tourism, and other economic ventures will all have their time here.

Phase 4 – expansion for larger population, greater magnitudes of power use, and generally requires technology that is not yet ready for deployment.

3.1 *Launch Vehicle Details.*

The recent development of novel systems for launches and landings and the drastic reductions in launch price they have made are the primary reasons that a moon base has become a viable proposition. Auspiciously, there are now three separate systems eligible to land modules. The systems we overview here:

The Starship/Superheavy, by Space eXploration Technologies Corp, provides many advantages as a primary vehicle for both cargo and crew deliveries to the lunar surface, with low cost being the most significant. It is the biggest vehicle capable of landing on the Moon, allowing heavy payloads (over 100 tons), and large, bulky items. Its main weakness is an inability to land on slopes. The HLS Starship cannot be used as the first landing vehicle.

The Dynetics ALPACA concept, launched on a Vulcan-Centaur rocket, is smaller and more expensive than the Starship, but with impressive capabilities handling rough terrain on landing. A high tip over angle and smaller engines that cause less high-speed regolith-eroding of the equipment during landings are desirable features. Its overall design and construction with modularity in mind simplifies cargo operations. It is ideal as a first landing vehicle.

The Blue Moon derived Integrated Lander Vehicle is appropriate for NASA’s Artemis program, but not for Argo. The lander itself is quite small, with limited cargo capacity to the surface, and its overall design limits its capability for reuse despite its hydrogen + oxygen fuel mixture being perfect for refueling using lunar ice. Its design is meant to be used in conjunction with the Space Launch System rocket causing issues with both launch cadence, and cost.

Therefore, Starship will be the main method for transporting cargo to Argo Base, with the ALPACA lander supporting the first days of base construction. Four Dynetics vehicles will be sent to the Moon by the Vulcan-Centaur launch system, with three HLS Starships following six days later which will wait in orbit if the landing site preparation is delayed.

The ALPACA landers will be modified from the original designs. Two of them must carry two small electric bulldozers to the surface, for initial levelling and flattening of regolith for the arrival of the Starship vehicles. Other modifications are:

1. Roof reinforcement capable of supporting 4 m of regolith
2. Skid plates on the lander modules, so that they can be towed by the bulldozer
3. Storage capacity for solar cells
4. Equipped with components of the life support system for Phase 1
5. Fitted with hammocks and space to use them

The amount of fuel required to take 100 tons of payload to the surface of the Moon equates to 22 launches of Starship to refuel the lander, plus the launch of the payload itself. Assuming a moderate estimate of $50 million per individual launch (though Elon Musk, CEO of SpaceX, believes that he could get the cost down to $2.5 million), the cost of this 100 ton payload is estimated to be $1,150 million, but possibly as low as $57.5 million. Estimating the cost for the ALPACA lander is more difficult because, as of January 2021, we have no cost estimates for the lander. However, we do know the cost of the rocket that would likely launch it, the Vulcan-Centaur, is $100 million for each launch. Our four ALPACA landers would have a launch cost of $800 million; 200 million per lunar landing.

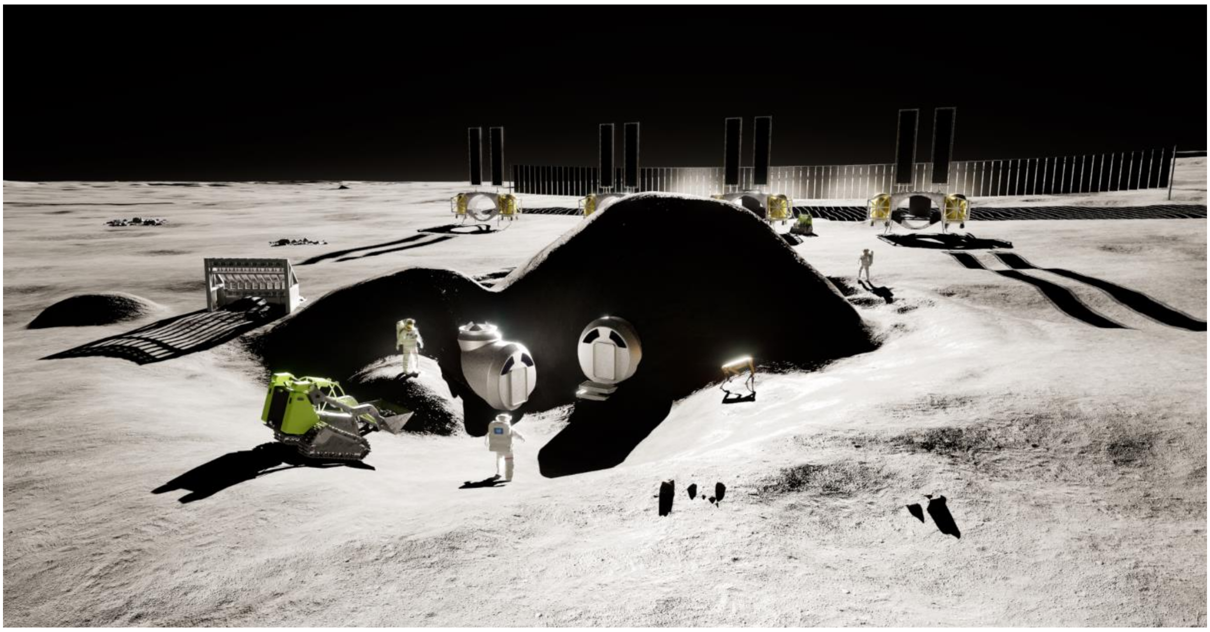


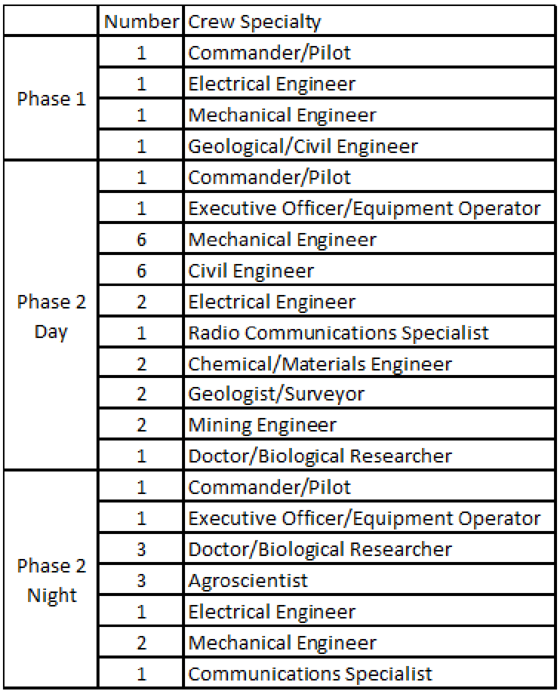
***Figure 3**. Phase 1 near completion of construction.*

3.2 *Base Construction: Phase 1 / “Superposition”.*

This section details our first landing using the four ALPACA landers. The habitation modules of ALPACA landers 3 and 4 will constitute the Phase 1 of Argo, in a mission known as “Superposition”. They will be buried by the two bulldozers remotely operated on site, which have been delivered by landers 1 and 2. Landers 1 to 3 will be guided down remotely one at a time by the commander. Then, the occupied lander 4 will be piloted to the surface. Once lander 4 has touched down, the crew will disembark and orient the solar cells, and connect all landers with power cables. Next the bulldozers are unloaded, as well as the first batch of solar cells. An area nearby is scouted for solar cell placement, with cell installation following. With the power systems secure, the crew will inspect the site of base construction for irregularities and bedrock depth with ground penetrating radar equipment (GPR). Another site about 500 m to the east is scouted as a landing area for the Starships and other future landing craft. The flatness of the landing site is an immediate concern and bulldozers are used to level this zone for imminent landings. Four radio beacons will be placed around the landing sites, allowing the navigation system of the Starships to accurately triangulate on the landing site. Data is continually sent back to Earth through satellite relays, so after the landing area is cleared, the inbound Starship crew can be confident of a smooth landing.

With power and landing area established, the ground crew advance to burying the ALPACA modules. Based on measurements gathered from the GPR and theodolites, an ideal depth for the habitats is calculated. The bulldozers excavate a trench with a sloped entryway. Some of the regolith excavated here will be reserved to cover the habitats later and some will be made into a berm between the excavation site and the Starship landing area to shield against ejecta kicked up by the Starship landings. When the trench is complete, the habitat on ALPACA lander 4 is decoupled from the lander rig and slid via skis into the trench. This lander is partially buried under 3 m of fine regolith passed through an on-site grizzly rock screen by the bulldozers and crew. This finer regolith is easier to pile, and will not damage the habitat as it is piled. Power cables from both the solar cells of the ALPACA landers and the solar array are connected to this module and the life-support is tested and run. ALPACA lander 3's habitat is not decoupled and buried until the Starships carrying cargo and the rest of the crew lands nearby. Once that happens, this habitat is buried next to #4. The Superposition mission is now complete.

All of this has been calculated by our team to take place in under six Earth days, based on how fast the bulldozers can move material and charge their batteries for the next work cycle, with a 33% safety margin (assuming the equipment is operable at 75% of rated capacity). Under this schedule both the activities of base construction for Phase 1 and critical sections of Phase 2 can take place during a lunar day. Among our team, we've called this rigorous schedule "Operation Lunatic Speed", despite the fact that it is very achievable. Tasks will be done in teams of two astronauts; one remotely manning the dozer and one spotting, working in 10-12 hour shifts, alternating with rest for 9 hours and time for meals. While a shift is "off" their bulldozer will be charging from the solar array. The mission team will have air, food and water to last about 2 weeks in the case of an abort or other eventuality.



	Number	Crew Specialty
Phase 1	1	Commander/Pilot
	1	Electrical Engineer
	1	Mechanical Engineer
	1	Geological/Civil Engineer
Phase 2 Day	1	Commander/Pilot
	1	Executive Officer/Equipment Operator
	6	Mechanical Engineer
	6	Civil Engineer
	2	Electrical Engineer
	1	Radio Communications Specialist
	2	Chemical/Materials Engineer
	2	Geologist/Surveyor
	2	Mining Engineer
	1	Doctor/Biological Researcher
Phase 2 Night	1	Commander/Pilot
	1	Executive Officer/Equipment Operator
	3	Doctor/Biological Researcher
	3	Agroscientist
	1	Electrical Engineer
	2	Mechanical Engineer
	1	Communications Specialist

Table 1. *General crew manifest. Phase 3 will have a more flexible crew composition while remaining at less than 30 crew.*

3.3 *Base Construction: Phase 2/ "Argo Ascending".*

The foothold that Superposition gives us will be used to create a permanent facility of robust function. Once Phase 1 demonstrates that a habitable pressurized module (a habitat) can be buried beneath regolith and be livable in that environment, the odyssey of Argo can begin.

Three HLS Starships land one at a time from orbit under automated navigation. Two are manned, carrying 14 astronauts in one, and 12 in the other. One of these is outfitted with a water-based radiation shielded compartment. The third vessel is a dedicated cargo Starship. While the mission needs a cargo vessel, it also needs a Starship capable of holding a crew, and an emergency back-up (though both will be manned).

After postflight system checks including equipment stored inside the onboard habitats, the astronauts disembark, check the landing site for issues, then unload their cargo starting with extra bulldozers. While all food and water is kept on board in the two passenger Starships, all of the construction equipment is unloaded from the cargo Starship by lowering the habitats one by one. Two gantry cranes are assembled and deployed and each of the habitats is hauled via the cranes, which can each be moved by a bulldozer, to the dig site. After this stage of deployment, the cargo Starship returns to LEO, to rendezvous with an Earth-standard Starship carrying more habitats, cargo, and fuel.

Back on the Moon, the astronaut crew gets to work excavating the trench that will contain the habitats for the north wing of the Phase 2 part of the base, an operation that will take under ten days.

The crew quarters, mess, bathrooms, Environmental Control and Life Support Systems (ECLSS), and water recycling habitats are placed into the trench by way of the gantry cranes. This system requires only two bulldozers, each of which is pulling or pushing the gantry crane to work position. Each habitat module may take a day or two to place in the trenches and test. This continues until all habitats are placed inside. The habitats of the north wing are not pressurized until all of them are placed. While the first habitats are being placed inside the trench, the cargo Starship will be en route to Earth to pick up 4 more habitats. It will reach LEO in 4 days, after which two habitats are likely to have been placed within the trench. After half a day of collecting its cargo and 4 more days en route back to the Moon, it will land again with its cargo the day the fourth habitat has been placed in the trench. The new habitats are unloaded and installed from the returned Starship.

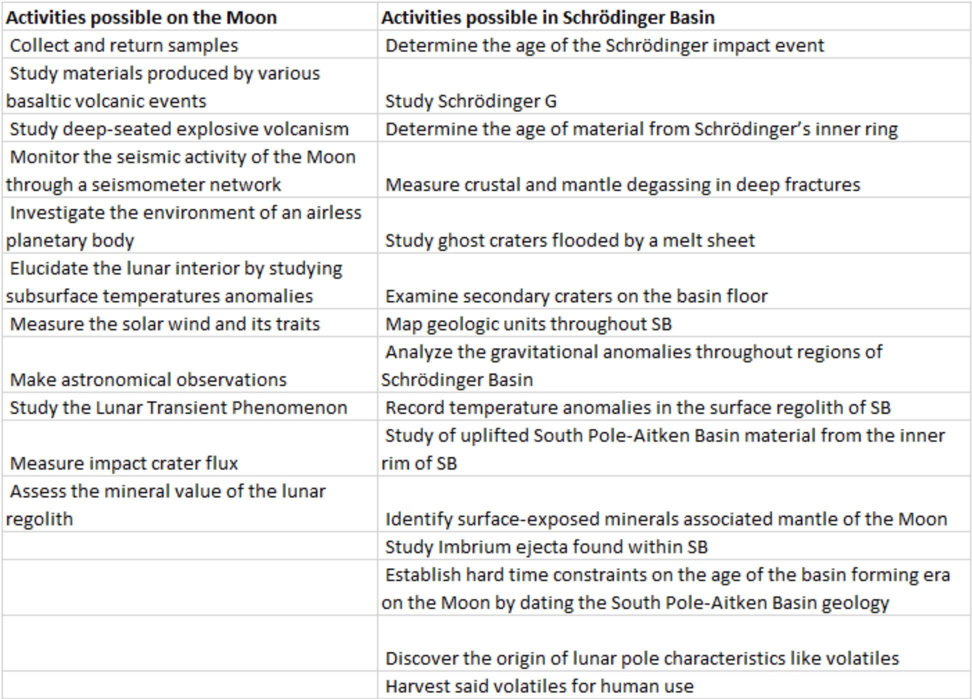
This entire operation takes the rest of the lunar day cycle. For trench excavation, two sets of crew numbering eight astronauts each will be working in overlapping 16 hour shifts, with 9 hours of sleep, a total of 1 hour of meal time, one hour of free time and one hour of prep time. For habitat placement, one team can handle that while the second team of astronauts and two bulldozers assemble extra solar panels, radiators, and communications arrays. Their housing will be the two ALPACA habitats and the two passenger Starships.

While trench excavation and habitat placement is occurring, the two geologists, two ISRU specialists, and two mining specialists will ground-truth prior orbital reconnaissance work, and seek out the sites rich with water ice.

The job of excavating and installing the northern wing of Phase 2 is completed by the end of the first lunar day. At sunset, one of the passenger HLS Starships takes flight to lunar orbit, where it takes on the night shift crew who arrived with an Earth-standard Starship (i.e, one from Earth, that can aerobrake). As the night shift crew lands, the 29 man crew of the construction will board the other passenger HLS Starship and rendezvous with the Earth standard Starship returning to Earth. The HLS Starship then returns to the lunar surface for refueling and future launches. The new crew is here to perform maintenance and interior experiments. While the 29 man crew will be the same astronauts with replacements due only to fatigue, the new skeleton crew can be made up of rotated specialists. Changeover between shifts shouldn't take longer than a day.

During lunar night, the base will switch to low power operations, limiting EVA. Four days prior to dawn, the main crew of 29 returns and lands at daybreak, with the skeleton crew returning to Earth; this crew alternation continues through Phase 2 until completion. Construction lasts at least 6 months. While the crew is inhabiting the Starships or the completed portions of Phase 2, they will be consuming imported food and water. After Phase 2 completion, water ISRU and algal photobioreactors will start to generate some local food and water.

4. Mission Objectives.



Activities possible on the Moon	Activities possible in Schrödinger Basin
Collect and return samples	Determine the age of the Schrödinger impact event
Study materials produced by various basaltic volcanic events	Study Schrödinger G
Study deep-seated explosive volcanism	Determine the age of material from Schrödinger's inner ring
Monitor the seismic activity of the Moon through a seismometer network	Measure crustal and mantle degassing in deep fractures
Investigate the environment of an airless planetary body	Study ghost craters flooded by a melt sheet
Elucidate the lunar interior by studying subsurface temperatures anomalies	Examine secondary craters on the basin floor
Measure the solar wind and its traits	Map geologic units throughout SB
Make astronomical observations	Analyze the gravitational anomalies throughout regions of Schrödinger Basin
Study the Lunar Transient Phenomenon	Record temperature anomalies in the surface regolith of SB
Measure impact crater flux	Study of uplifted South Pole-Aitken Basin material from the inner rim of SB
Assess the mineral value of the lunar regolith	Identify surface-exposed minerals associated mantle of the Moon
	Study Imbrium ejecta found within SB
	Establish hard time constraints on the age of the basin forming era on the Moon by dating the South Pole-Aitken Basin geology
	Discover the origin of lunar pole characteristics like volatiles
	Harvest said volatiles for human use

Table 2. *Scientific activities possible on the Moon and in Schrödinger Basin, some of which were key in choosing this landing site.*

Science is our top incentive. Our celestial neighbor is simultaneously the most well-known yet unknown solar system body. Geology is a major field to allay this state, but astrophysics and even biology stand to gain much from returning to the Moon. Table 2 is a selection of criteria for choosing a base.

Industry on the Moon is a second area of major interest driving lunar exploration. Such activity will sustain an interplanetary presence. According to our current knowledge, the lunar regolith is abundant with usable elements [37]. Sourcing these from the Moon will spare Earth's environment. Extracting useful minerals may be difficult on-site because veins of ore are unlikely to be present on the lunar surface. Because of this, it is prudent to anticipate that bulk collection and transportation of ore back the base will be required.

Identifying the assets for either ISRU or science-focused activities will require a multi-step process of discovering sites of interest from orbit and following up with ground observations [38]. While ISRU and field science have similar techniques to identify desirable assets, science requires only small samples to study, and has a focus on preservation, whereas ISRU is concerned within en masse extraction and processing [31]. The focus of geologic equipment in Phases 2 and 3 will be facilitating ISRU and on sample collection. With the rate of launches from Argo per month via the HLS Starships, over 20 tons of material can be sent back to Earth per Starship at a time. This could be a major source of investment for the base; mining companies, universities, and governments could all sponsor field science missions to collect material or bid on material sent back. The true major objective for the existence of Argo is as proof of concept. Achievements like cheap transport, advanced ISRU capabilities, self-sufficient power supplies, and a permanent staff of astronauts prove that humans can live in space and on other planetary bodies. It is perhaps the most important goal of this base.

Figure 4. *HLS Starships and astronauts at the landing zone.*

5. Economy.

Making space travel and exploration not only financially feasible but also profitable has been the holy grail of the aerospace industry ever since space travel was conceived. It is widely known that space development is a blackhole for money. Most countries see these operations as vanity projects: displays of a nation's wealth and prowess. However, a recent boom of various independent companies has been making space travel more affordable. With advances in rocketry and other technology, that can finally be done [39]. Still though, making access to space cheaper will not create an economy up there. Actual activity for the good of society must take place. Data markets like the ones that satellite infrastructure offers is only the beginning [40] [41] [42] – the next step is ISRU. Argo is all about that. Here are strategies to bootstrap a cislunar market using all the assets at Argo's disposal, and detail costs, payoff and incentives. Colonization has always been driven by profit, and so it is time we put this technique to work.

5.1 *Ethos.*

Our economic focus here is the establishment of a permanent moon base in a practical amount of time. This allows the greatest security for investment and opportunity for robust growth. ISRU, working to gain sponsorship for ISRU missions and field science, and facilitating tourism are the priorities. The Argo concept seeks to enable as many missions funded by outside parties as possible so that the government agencies responsible for funding the actual base are not swamped by overhead costs. Another focus is results-based investments, not lengthy R&D projects. Once sustainable industry occurs in space, space is no longer a money pit.

This may seem very pragmatic, but if pure scientific curiosity and a humanitarian desire to spread life to the stars was sufficient to get us to the Moon and beyond, then the authors would already be working in an actual lunar base. A large focus of these missions will be the commercialization and monetization of space and all its assets, and the facilitation of promoting future space activities, be they also on the Moon or on other bodies like Mars.

5.2 *Cost of Missions.*

Moon base cost estimated prices vary wildly, from a semi-manned base that NASA proposed in 2016 starting at 10 billion [43], to the first landing missions and infrastructure set up of the Artemis missions, with an approximate cost of 30 billion [44]. GOP presidential primary candidate Newt Gingrich figured he'd be able to get a lunar base operational at 35 billion [45]. Japan breaks the double-digit billions trend and stated their moon base made via autonomous robots would require only 2 billion in funds [46]. ESA's famous "Moon Village" concept has no fixed price, though most estimates peg the settlement costing more than 10 billion just based on the R&D pledges [47].

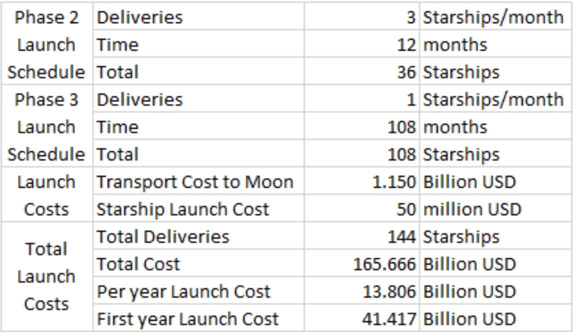
Lastly, the fabled Soviet Zvezda moon base would have had an 80 billion dollar price tag on it had it ever been built [48]. Countries have become bankrupt for less. These estimates even begin to look a bit naive compared to the total price of the Apollo program (between 156 to 175 billion in modern US dollars). Allowing for technological progress since then, the realization sinks in that it is likely a moon base cannot be made for less than 40 billion. And so, we in the modern age are at a point where we have no real concrete plans to make such a facility past a cislunar space station (which is currently under review [49]) and delayed landings [50]. All of this is not evidence of a lunar base being impossible to make. Abundant technology exists to make a permanent moon base economically feasible and serviceable both now and in the very near future.

Unity is needed to make this happen. It is only through a dedicated and coordinated effort between the nations of the world that we can hope to establish a permanent lunar presence, something that the ESA and former astronauts have called for countless times, much to deaf ears [51]. By each interested country sharing the monetary load, a moon base can be commissioned and manned. Though capitalist motivations will drive us to the stars, the international cooperative effort will instill our drive with a humanitarian creed. The construction of a lunar base will be a major diplomatic event, drawing nations closer than ever before [52] [53] [54].

Mission economics will improve with advancing technology and frequent voyaging that lower space flight costs. Our reliance on the Starship/ Superheavy combination for ferrying crew and cargo for Argo is not incidental or stylistic. SpaceX corporation is the world's premier owner of our most robust payload capacities to date. No flight system will be as economical as the Starship and its variants – not on timescales relevant here. In Section 3.1 (Launch Vehicle Details), we outline the expected costs of running missions with SpaceX. No other launch system comes close, and so we suspect that Starship will be instrumental in founding a human presence on the Moon. We are not displaying favoritism towards SpaceX and their designs though. Competition to their hegemony will only drive prices lower and encourage innovation. While Starship could sustain an interplanetary campaign for colonization as SpaceX promises it will, we see it as a catalyst for future launch systems with similar dreams.

5.3 *Cost of Argo.*

Our cost estimation takes into account the above prior estimates for lesser affairs submitted by other agencies, along with the total number of flights needed. It is lower than what may be expected of a base of this size, because of newly economical launch options and low-tech building methods via ISRU. The greatest investments are the habitats and interior technology, R&D for technology, and this is divided between nations, companies, and independent contractors. The Apollo missions proved that a decentralized, company-based network of contractors supplying technology was a superior way of development, and we should emulate that success. All considered, the total cost of the program's first operational year should be over 60 billion, depending on the final cost of launching Starships. This could drop significantly as Starships become more economical. Utilizing off the shelf technology with a minimum of modification results in an R&D cost comparatively less than the R&D costs of prior missions. A majority of the expenses will be due to testing. All this being said, returns generated with tourism and ISRU profits should partially make up for these titanic costs. Argo could be made far cheaper if we did not have permanence and comfort in mind. However, its castle-like design means that it is there for the long haul, and so stands to earn a steady income as a function of time. Argo is meant to be the foundation for an interplanetary economy, not its entirety, or its deathblow.



Phase 2 Launch Schedule	Deliveries	3	Starships/month
	Time	12	months
	Total	36	Starships
Phase 3 Launch Schedule	Deliveries	1	Starships/month
	Time	108	months
	Total	108	Starships
Launch Costs	Transport Cost to Moon	1.150	Billion USD
	Starship Launch Cost	50	million USD
Total Launch Costs	Total Deliveries	144	Starships
	Total Cost	165.666	Billion USD
	Per year Launch Cost	13.806	Billion USD
	First year Launch Cost	41.417	Billion USD

Table 3. *Launch cadence and costs.*

5.4 *The Big Payoff.*

With a 60 billion dollar price tag, it may be hard to see the benefits of colonizing the Moon over other expensive endeavors. The base constructed will have approximately 136,000 m^3, this compares favorably with the ISS, which has an internal volume of approximately 915.6 m^3 [55]. It also has a floor space of over 16,500 m^2, this is approximately half of the floor space of NASA's Vehicle Assembly Building [56]. The scope of Argo Base will allow for unprecedented access to the lunar environment. Based on the demand for lunar regolith samples from universities and scientific institutions, grant money will be a major source of income. Argo Base will also provide much of the research and experience needed to industrialize and commercialize the lunar surface. Much like Apollo, this research will also have wide ranging beneficial effects at home.

5.5 *Science & ISRU for Profit.*

Any chance to explore the Moon alone could support an entire market. As Chapter 9 (Administration) below notes, space law mandates that all data be free and open source. This does not mean that our base cannot charge a finder's fee for that data. There is also no prohibition stopping sponsors from building and paying for the launch of a scientific experiment, a base installation, an entire base habitat, or a mission. This is a vast potential market. In the case of sending a habitat at the behest of a group, Argo will allow any new module or facility to be installed onto Phase 3 if there is no cost to the base itself. If payment is handled by an interested party, it is allowed. Astronauts simply excavate the area, wait for the habitat to arrive, and integrate it into the base infrastructure free of charge. Likewise, with exterior missions, the versatility and range of our vehicles and EVA equipment allows Argo to field expeditions very quickly, to anywhere in the Schrödinger basin (and possibly beyond). Setting up experiments for measurement and observations, performing material extraction and returns, and even founding new outposts are all performed at a fee, one far less than it would cost for the sponsoring group to do it themselves. Argo is our beachhead onto the Moon. The data gained from these expeditions, findings, and research will be open source and up to the owner (the group that sponsored the missions) to decide what to do with. Via this approach and this amount of interest, Argo can expect to pull in hundreds of millions, possibly billions, of dollars in revenue.

5.6 *Advertising.*

This comes in two forms. Advertising can be obtrusive (like billboards) or unobtrusive (logos and product placements). The Outer Space Treaty bans most obtrusive ads, but unobtrusive ads have been featured in modern spaceflight [57], and will be a source of potential funding in the future. Unobtrusive ads might include logos on astronauts' apparel and equipment, as is contemporary practice. Product placement can be incorporated into media coverage of base activities – as placed products and as video headings in live stream or recorded media. The relatively spacious venue of Argo facilitates filming of commercials, and the distinctively eye-catching physics of motion in lunar gravity will be attractive to advertisers.

A concern with space advertising is that it could turn the corporate dystopias of science fiction into reality. It is not our intention to turn the lunar surface into a wasteland of billboards and corporate trash. Advertising has its small place on the Moon, but a diplomatic approach where both the dignity of the base and its monetary concerns are balanced. However, advertisers spend large sums for even small mentions or access to unique venues, and there will be nothing more emblematic of technological advancement, the explorer spirit, and new frontiers than authentic presence on the moon. Advertising revenue linked to Argo can be multi-millions of dollars.

5.7 *Tourism.*

Space tourism is a budding space market [58] [59] [60], and one of the few for which we have real-world examples. However, NASA and Russian space tourists' missions resembled special treatment more than a sustainable market. For tourism to be economic, space flight systems must become robust in safety and cost efficiency. The 2020s seem to be a time when this happens, with various companies like SpaceX and Virgin Galactic gearing up to breach this market, even if it's only just beyond the Kármán Line. Support has been astronomical. To visit the 21st century's first moon base would be a valuable objective to many people.

Tourism at Argo will have its disadvantages. To accommodate tourists is to potentially displace other occupants of the base, and to at least partially occupy the attention of the base crew that remain. Tourists must also be afforded some amenities, albeit not ones similar to attending a cruise or even climbing a mountain.

A principal advantage, however, is revenue. The cost of a visit will depend on the launch fees of the Starship vessels, and how many tourists would embark. It could cost as little as a few million or as high as $60 million, which compares favorably to the $165 million three tourists will soon pay to visit the ISS [109]. The application process would be exceedingly strict, with prospective tourists going through extensive training in astronaut facilities, much like how tourists going to Mount Everest would attend a mountaineering academy. This in of itself could be an expansive industry, with the astronaut training programs generating income for Argo, as well as associated jobs in the training and launch facilities. The cost of space tourism would drop overtime as launch costs become competitive and technology improves. Needless to say, this could be a multi-million-dollar market.

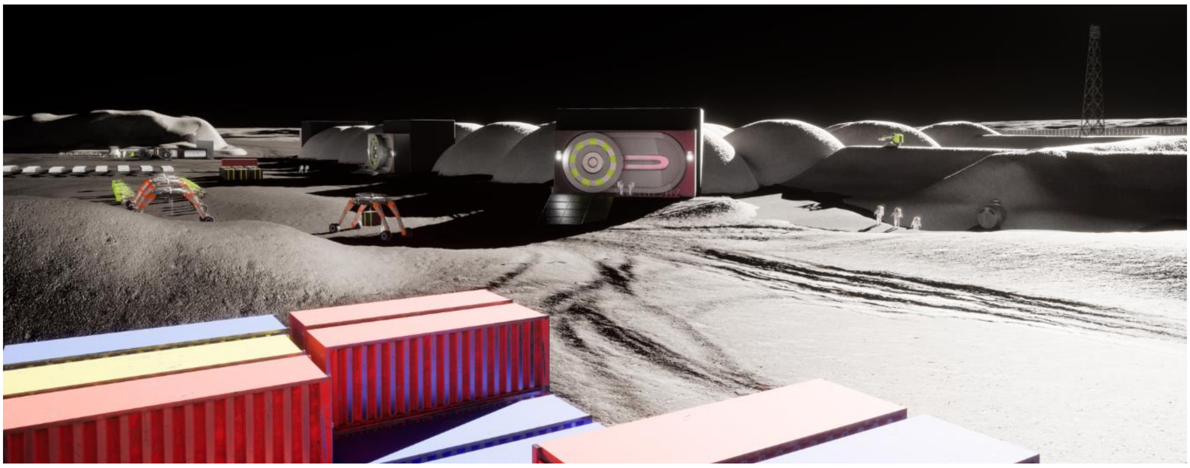


Figure 5. *Cargo for Argo waiting to be processed.*

5.8 *Associated Interests*.

Often overlooked, non-affiliated groups not directly involved with training the astronauts, manufacturing the technology, sponsoring activity, and monitoring the missions will also benefit from the existence of a moon base [61] [62] [63]. Contrary to popular opinion, space exploration has a huge impact on society. The parties involved with facilitating Argo or any space-related campaigns will spur substantial internal economic growth. If the entirety of the Apollo landings employed nearly half a million people, the number of jobs afforded by a permanent lunar base could be vast. These jobs would include humanitarian services, civil sectors, infrastructure, medical, industrial, agricultural, entertainment, and more. Putting jobs aside, groups utilizing the situation could also generate income for Argo in surprising ways. For example, movies could be made in the base, with transport fees being collected by Argo [64].

5.9 *Defense Contracts.*

In recent years, the militarization of space has gained popularity once again, with the nations of the world at odds with one another looking to the sky for any advantage it can offer [65] [66]. Some experts posit that we are beginning a new Cold War [67], or a new Space Race between nations [68]. However, Argo is a base meant to facilitate cooperation and creativity, not destruction and division – the business of war is anathema to the purpose of Argo.

However, there is no denying that the military industrial complex has plenty of cash to spend that could bring helpful financial assistance to any lunar base. Even if the Argo administrator polity discriminated here, military research details do not per se need to connect whatsoever to armaments or warfare. In any event, it seems likely that some of the intellectual property and resources developed by Argo may be of use for participant nations' national security purposes. The Moon is a highly strategic local body, and Argo will command the attention of the world's militaries. Such a facility could be instrumental in a future conflict. Depressingly, there is always the possibility that the financial prospects of Argo may falter, and military spending along with its conversion into a strategic outpost exists as its only salvation.

6. Engineering.

6.1 *Phase 2 Construction.*

Phase 2 of construction will occur in the first half year of operation, using only well understood methods, and technologies with high TRL. Due to the prohibitive mass of radiation shielding required, it must be created with ISRU. The most abundant resource is lunar regolith. Mechanically stabilized regolith is a composite material which consists of multiple horizontal layers of regolith interspersed with geotextiles, a kind of rugged fabric. The geotextiles resist the regolith's tendency to spread out into a conical shape, allowing the regolith to give vertical support, as in Figure 6.

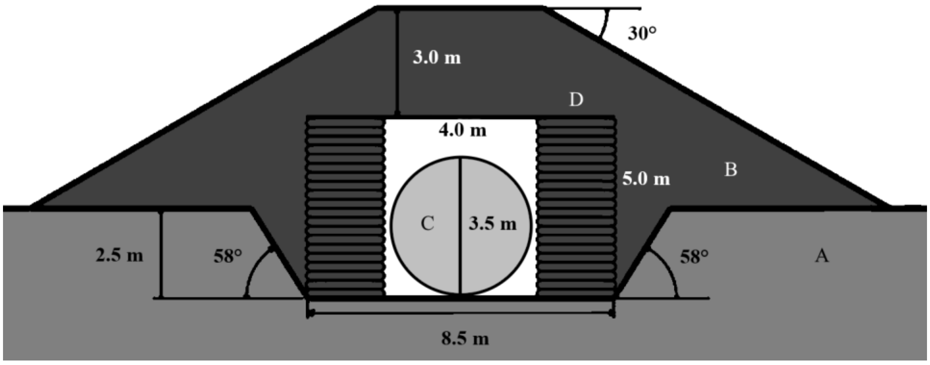


Figure 6. *Finished Phase 2 cross section. A: undisturbed regolith, B: regolith cover, C: pressurized habitat module, D: mechanically stabilized regolith wall.*

Beneath the stabilized regolith will be the pressurized habitat units. Habitats will be connected together with a version of the Common Berthing Mechanism used on the ISS, modified for a larger diameter and a temporary plastic seal to keep out lunar dust. These modules will have utilities such as water pipes, power and data cables, and air ducts routed through the circular segments above and below the interior space and the pressure vessel hull. The circular segments between the walls and the pressure hull will be used for storage. The interior space will be 2.5 m wide, 2.5 m tall, and 8 m long.

The stabilized regolith and habitats will be integrated as follows:

1) Excavate trenches 2.5 m deep x 8.5 m wide
2) Geotextiles are laid down, alternating with layers of loose regolith 25 cm thick.
3) Each layer of geotextiles will be wrapped around the layer of regolith above so the walls of the shielded corridor will resemble walls made of sandbags.
4) The stabilized regolith will be built up to an interior height of 5 m.
5) Habitats are lowered into the shielded corridor by gantry crane (on the first Starships to land after completion of Phase 1), and interconnected.
6) Aluminum honeycomb panels (delivered from Earth) will be laid atop the walls of the corridor. These panels will be 6 m long, 2 m wide, and 40 cm thick. Their maximum deflection will be less than 7 mm.
7) Panels will be covered with packed regolith 3 m deep.

6.2 *Phase 3 Construction.*

The Phase 3 architecture will take advantage of research completed during Phase 2. The enabling technology is sintering and melting raw lunar regolith into solid parts, including bricks, panels, and beams. This technology will allow for creation of more robust structures and will in turn enable larger pressurized and shielded interior volumes. Bricks will be used to create strong foundations, and beams and panels will be used to create large geodesic domes. These geodesic domes will have many triangular facets (Figure 7), and a diameter of 25 m. This will create a floor area of approximately 491 m^2 and a volume of approximately 4091 m^3. Because all of the essential requirements were met in Phase 2, Phase 3 construction can be slower, allowing for refinement of methods and enabling technologies. Domes will be constructed as follows:

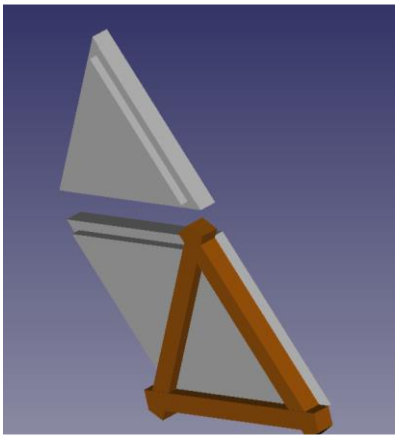


Figure 7. *Examples of the panel and frame for geodesic dome.*

1) A circular hole is dug, with a depth of 2.5 m.
2) Foundations for Phase 3 are constructed of a layer of sintered regolith bricks
3) Large cast regolith panels are placed over the foundation.
4) The frame of the geodesic dome is erected.
5) Cast regolith panels are placed with doubled cushioning and pressure-sealing silicone strips at all joints to Kevlar straps which are tightened from ground level, passing over the top of the dome to counter internal pressure.
6) 3 m of regolith is piled on top of the habitats by the electric bulldozers.
7) Leak tests are performed, and additional sealants are applied as necessary.
8) The interior is prepared: pipes, wiring and life support systems are installed on the subfloor of the dome. Then, the walking surface of the dome is installed above, leaving a crawlspace for maintenance.
9) Clean remaining dust out of the space and to run equipment tests.

6.3 *Local Geology's Usage in Construction.*

Phase 1 and 2's utilization of local resources is uncomplicated and outlined above. For Phase 3, local geology will play a much more involved role, with industrial processes and equipment utilized to render it fit for construction service. Regolith can be sieved through a grizzly to remove large rocks, poured into a form, and then cast into forms using our solar furnace design [69]. Cast regolith has excellent structural properties, even better than concrete [70]. Though it is energy intensive to produce, requiring 360 Wh/kg [71], all of this power is in the form of heat. This heat will be provided by solar thermal furnaces, which are very light weight.

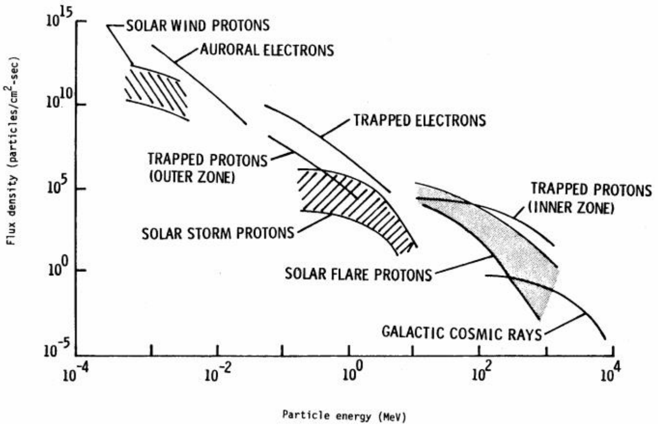


Figure 8. *Space radiation environment.*

Radiation shielding is another usage of regolith. Solar radiation is easier to block, as it mostly consists of free protons and electrons (Fig. 8). It can be blocked by thin pressure hulls, so no shielding is devoted to combating this. Solar activity protons, however, have high enough mass and energy to go through thin metal. Galactic cosmic radiation has very high particle energies, with even greater penetrative power. Due to the difference in flux density of the different types of radiation, over the course of ten years, solar particle events would cause approximately 1500 Gray of absorbed radiation to an unshielded habitat, whereas galactic cosmic rays would cause less than 50 Gray [72]. Long duration exposure of the crew and equipment to high radiation drives the requirement to eliminate radiation hazards. 3 meters of packed lunar regolith at a density of 2.3 g/cm^3 is sufficient to reduce dosage resulting from all solar radiation and galactic cosmic radiation to below 5 rem, the annual dose limit for radiation workers [73].

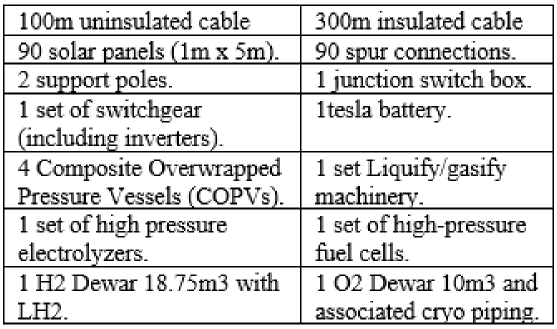
6.4 *Power Generation & Storage.*

Critical components of a moon base are the power source and storage system for that power. Complicating factors for the power system are the 14 plus days of lunar night time, micrometeorites, the need for high redundancy due to the harsh environment, and thermal management without the benefit of atmosphere. The following scheme overcomes these complications and delivers robust reliability with high TRL technology.

The electrical loads will be split into six systems: life support (oxygen and air pressure), critical systems (water circulation, airlock function, computer systems, and communications), standard base lighting (of about 200 lux), emergency lighting (control panels, critical medical care station, minimal illumination systems, all of about 10 lux), auxiliary (exterior and EVA equipment including bulldozers), and normal (all other equipment that uses electricity). Circuitry is an important component to defining the electrical system. For critical systems, a minimum of a triple circuit system will be used, while other systems will have the normal two circuit set-up of power systems. This is our safeguard. With multiple redundancies, no single critical loss of power or technical failure will disable the facility. Astronauts will have time and safety to repair the failure.

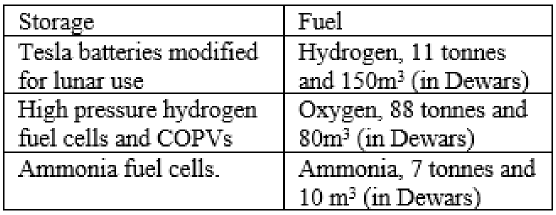
Our power system starts with a solar fence, and it remains one of our main power sources through Argo's Phase 3. Due to the amount of photovoltaic panel area, the solar panels will not track the sun because they would shadow each other for significant portions of the day. In Phase 1, panels are hung between two poles on a 7 m high cable support system, like a washing line. Panels on this cable can be added, removed, or maintained individually. The uninsulated supporting cable is one conductor, and the other conductor is an insulated cable which is buried with connections to each panel. This means that micrometeorite damage does not disable the solar panel array because it does not compromise the relatively delicate insulating layers which have been eliminated. The gains of this array are supplemented by the ALPACA lander solar cells. The establishment of this system is a top priority to Phase 1.

For Phases 2 and 3, the power system becomes much more versatile. Many Earth-standard systems can work on the Moon without modification. The solar panels are designed to match the Tesla Batteries at about 350V DC. This in turn allows for the addition of inverters for single phase power (240-260V AC) and three phase power (440-460V AC), with 50Hz chosen to minimize the cable losses, and allow the use of off-the-shelf parts. Critical components would use the DC system, while future base expansion would see the extension of the solar panel system, and possibly the use of higher voltage [74] [75] [76].



100m uninsulated cable	300m insulated cable
90 solar panels (1m x 5m).	90 spur connections.
2 support poles.	1 junction switch box.
1 set of switchgear (including inverters).	1tesla battery.
4 Composite Overwrapped Pressure Vessels (COPVs).	1 set Liquify/gasify machinery.
1 set of high pressure electrolyzers.	1 set of high-pressure fuel cells.
1 H2 Dewar 18.75m3 with LH2.	1 O2 Dewar 10m3 and associated cryo piping.

***Table 4**. A power component delivery.*



Storage	Fuel
Tesla batteries modified for lunar use	Hydrogen, 11 tonnes and 150m³ (in Dewars)
High pressure hydrogen fuel cells and COPVs	Oxygen, 88 tonnes and 80m³ (in Dewars)
Ammonia fuel cells.	Ammonia, 7 tonnes and 10 m³ (in Dewars)

***Table 5**. Energy storage.*

The initial system is based on off-the-shelf solar panels with efficiency of about 20%, but because the panels are replaceable, more efficient versions can be installed when available to increase capacity.

The equipment of Table 4, one of eight deliveries, would be placed in the respective sections of Phase 2 & 3 and in the tank farm, before it is assembled and integrated during the construction of Phase 3. On an intermittent basis, during the night shift changeover, a Starship will also bring a Dewar flask of liquid ammonia for maintaining the thermal management system and supplying ammonia fuels cells as they are expanded.

Storage is our other chief concern. The lunar night at the latitude of Schrödinger G is a long and unforgiving 14+ Earth days, and so energy storage is our only option to preserve base activity permanently, night or day.

Phase 1 only has battery storage, and is of short duration. For Phase 2 and 3, we have several battery storage units available. The basic storage system is designed for 1 MW (during day time), which equates to less than 500 KW (total of 168 MWh) for continuous use based on the efficiency conversion at night. The real-world example of a hydrogen-based fuel system is on the Toyota Mirai [77], which includes COPV's for the initial storage of H_2 at pressure. This is proven technology, at TRL 8. The above system would have multiple fuel cells and duplicated H_2 and O_2 COPV's and longer-term liquid H_2 and O_2 for a robust and multi-layered redundant system.

Hydrogen and oxygen will be generated by electrolysis of water from a devoted storage system. The water production from the H_2 fuel cells and ammonia fuel cells will send product water back to the devoted storage system. The secondary system of the ammonia fuel cells produce power, water and N_2 and are used as needed for N_2 production and power. Other rockets or exploration vehicles like the JAXA Lunar Cruiser, will require a source of high pressure and/or liquid H_2 and O_2 and this can be made available from the energy storage system [110]. Since mass will no longer be as much of a concern for Phase 4+, energy storage additions would be made from materials on the Moon using ISRU, such as sodium sulfur batteries at 150-240 Wh/kg, which would require approximately 742 tonnes of battery to be equivalent to the above hydrolox system in Phases 2 & 3 (i.e. $88[O_2]+11[H_2] = 99$ tons).

6.5 *Temperature & Humidity Control.*

Interior temperature and humidity control is provided by condensing heat exchangers. Heat is transferred from the air to a pressurized water coolant loop, then to an anhydrous ammonia system. Radiators in the shadow of the solar fence take the heat from this process. The radiator location protects them from the Sun. These are placed horizontally on the ground to prevent the radiators from radiating infrared toward each other.

Humidity is held at 50% relative humidity. This helps with particulates and static electricity. Humidity will be added to the atmosphere by plant evapotranspiration, balancing the removal by the condensing heat exchangers.

6.6 *Atmosphere Regulation.*

Atmospheric regulation is performed by mechanical ECLSS in Phase 2. In Phase 3, biological systems (see section 6.10, ISRU) will supplement, and later render redundant, some mechanical ECLSS. Carbon dioxide removal and oxygen regeneration as well as partial humidity control will be handled with biological systems.

Atmospheric pressure and temperature are Earth standard. Atmospheric composition will mimic Earth at 78% nitrogen, 22% oxygen. CO_2 levels are held at less than 5250 ppm at a daily maximum. In Phase 2, mechanical ECLSS based on systems developed for use on the International Space Station will be delivered to the Moon. These systems will be upscaled by 500% to be capable of meeting the needs of 30 occupants.

6.7 *Water Purification & Handling.*

Collecting water on the Moon will be a novel process in the history of lunar exploration. Existing data suggests potential locations for water ice [78]. A targeted search of these areas located around SB will be performed by infrared survey via cubesats in orbit [79].

Astronauts will ground-truth the survey data by first identifying concentrations via visual means (shining a light in a shadowed region, for example), and measuring the depth of ice deposits with drills to get a volumetric estimate, testing samples for purity, and verifying mining methods with pilot tests. A candidate methodology is a hotbox test, wherein a sample of icy regolith is placed in a pressurized box and exposed to enough heat for the ice to melt and separate from the regolith. The melt is tested for purity.

At full scale, water mining will be done by deploying a weighted flexible dome over an area, heating the regolith beneath, and recovering the steam that arises. The resulting steam is condensed [80], frozen, and put aside in shade for storage.

Water purification systems in Argo will be very similar to the most well-proven water reclamation system off the planet Earth: the ECLSS Water Recovery Systems (WRS) of the ISS. This system is well-tested and reclaims 90% of the water which astronauts use on the ISS [81]. We will use similar but larger engineering solutions to reclaim the water which is used in Argo, to support the larger crew and allow for greater freedom in water use like the famed toilets and showers of the Moon. Worth noting is that human consumption will not be the only use of water on-base: some water will be siphoned to other uses such as industrial processes or for use in fuel cells, and will never return to the human system.

Thanks to the healthy rate of water recycling, and the addition of more water when needed from mining operations, water and oxygen self-sufficiency will be ensured on Argo by the beginning of Phase 3.

6.8 *Food, Waste, & System Design.*

Aquaponics is a type of incredibly efficient and compact food production system that is a syncretism of aquaculture and agriculture in a biologically self-regulated setting. Aquaponics has garnered a significant amount of interest in recent years on Earth as humanity faces new challenges in the 21st century.

Unlike traditional single-loop systems, Argo will use multi-looped decoupled aquaponics for the agriculture of Phase 3. The potential of such a design is multi-faceted, namely, that fish and plants have differing requirements (in both specific nutrients and environment). Through decoupling, the system realizes improved efficiency by providing ideal conditions of both the RAS (Recirculating Aquaculture System) and the hydroponics. Since each subsystem works autonomously, in the case of failures, diagnostics and treatment are easier due to the modular nature of subsystems [82] [83]. Within the above system, nutrients present within the RAS solution, coming from excretion and excess feed, are concentrated via a desalination device (Reverse Osmosis) into the hydroponics sub-system, together with demineralized water. This process mutually alleviates the issue of solute accumulation in the RAS and concentrating it for plant utilization.

For food production, beginning in Phase 2 and expanding throughout Phase 3, we have chosen to cultivate *Spirulina platensis*, *Chlorella vulgaris*, and *Isochrysis galbana* algae [84]. Algae has a strong reputation as a nutritious, space efficient, and energy efficient food source. The nutritional profiles of various species have been shown to contain a high degree of polyunsaturated fatty acids (PUFA), omega-3, amino acids, and all vitamins in sufficient dietary contents. Additionally, algae are rich in vital minerals, including Na, P, Fe, Ca, K, Mg, Cu, Zn, and Mn. Using multiple species to balance what is otherwise an exceptional and nutritionally balanced source of food is recommended to optimize quality. Excess produce can be provided as feed to insects and aquaculture.

There are various candidate species of freshwater aquaculture stock that can give the astronauts of Phase 3 some dietary proteins. It is likely that this stock will be various species of *Tilapia*. Desirable characteristics include the following: fast maturation (5-6 months to sexual maturity and 8-9 months to maximum size of ~907g), robustness and a highly efficient feed conversion ratio (1.6-1.8:1) based on an omnivorous diet. The next animal stock, not for human consumption, perhaps; but for other uses, are crickets and mealworms. They can feed the fish with their biomass directly, and their waste can be used as fertilizer.

Plant crops are also grown in aquaponics. Their photosynthesis relies on LEDs (Red + Blue + White LEDs consuming 19 kW per 150 m^2), supplemented by piped natural sunlight during daytime. Primary crops include various species of legumes, brassicas, and sweet potatoes, which were chosen because they require a low-moderate DLI (Daily Light Integral) of ~9-21 mol per m^2 per day, as calculated by our team.

The biological systems of Phase 2 and 3 take time to mature, and will co-evolve with the base's systems. During the first six months, the astronauts will subsist on rations analogous to hiking food. After the biological ECLSS structures are implemented and mature, the dependence on rations would slowly subside as an increasing fraction of the diet comes from local produce. Combining algal supplementation with rations can effectively stretch out supplies until the main aquaponics units are constructed.

6.9 *Nutrient Cycling & Bioreactors.*

To recycle nutrients and organic material, the employment of two waste subsystems are integrated, with human excretion separately treated due to the higher strength wastewater produced. Within the aquaculture unit, biosolids and colloids are filtered and are fed into the bioreactors, breaking it down into bioavailable nutrients, which through supernatant outflow is provided to the plants [85] [86].

An Upflow Anaerobic Sludge Blanket (UASB) effluent is fed through the bottom of the unit and flows upwards through a granulated sludge blanket. The main advantages of UASB effluent treatment is the operational and design simplicity along with high (~92%) solid-removal efficiency. In ideal conditions 90% of effluent bound minerals can be remineralized in acidified UASB reactors (at pH<6 significant mineral leaching occurs, optimally at pH~4), with most organic reduction occurring between pH 6-8; thus, multi-step UASB treatment is recommended. Mineralized effluent can be provided to the hydroponics units and photobioreactors. Residual organic solids are provided as a feed component for insects and hydrothermal liquefaction as biofuel or petrochemical precursors [86].

Regarding atmospheric ECLSS, photobioreactors (PBRs) are a type of bioreactor unit that uses light to cultivate photoautotrophic microorganisms (microalgae). The selection of this unit boasts a trinity of critical features: ECLSS, water and nutrient cycling, and a source of bio-petrochemicals. They are not novel techniques for ECLSS, various experiments have proven their reliability [87] [88] [89].

As alluded to throughout, a key feature of this system is a potential to approach zero loss, meaning that it can run indefinitely, a critical feature for long term settlement which eliminates imports. This fixes the total biomass/bioavailable material, which can always increase in instances of expansion by importing additional material from Earth or in which ISRU may feature heavily.

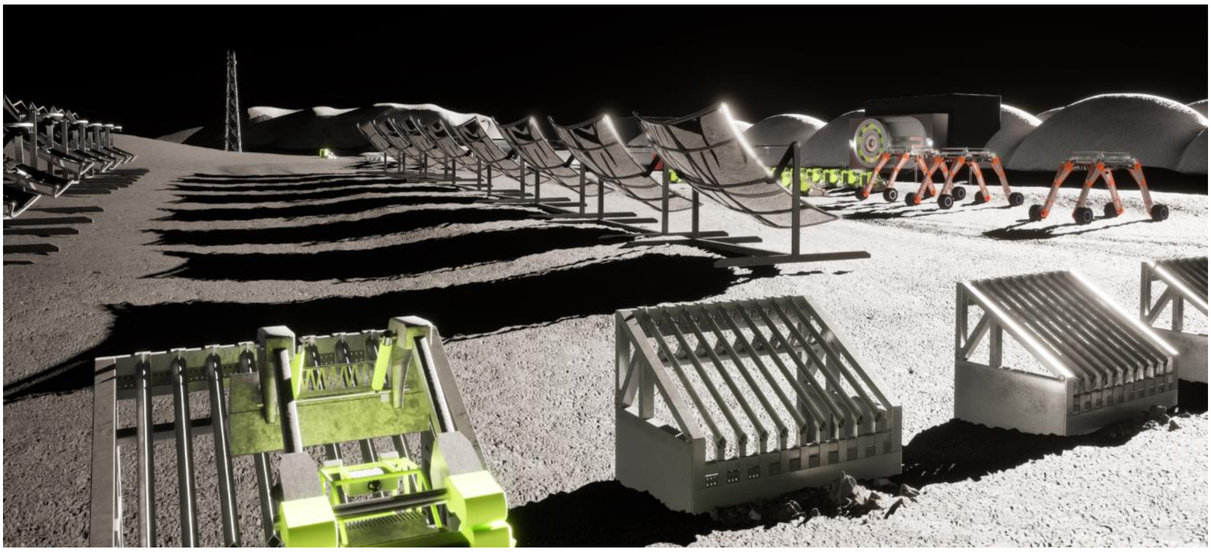


Figure 9. *External industrial area for ISRU processes.*

6.10 *In-Situ Resource Utilization (ISRU).*

One of the first methods in metal extraction may involve the utilization of magnets to extract metallic iron particles embedded within the lunar regolith, comprising ~0.5% wt. Lunar regolith is unusual in the sense that it is enriched with metallic iron, either by reduction of Fe^{2+} in silicate and oxide phases, or by the addition of metallic iron by meteoric impact. There is a strong correlation between FeO and surface exposure (r=0.98), the components regarding micrometeorites are also correlated, however with a lower coefficient. (r=0.70) [90]. Argo can extract iron via two means: refining ilmenite or with stirred tank bioleaching.

The attractive thing about using ilmenite is that it's incredibly abundant, comprising up to 8% wt of lunar regolith, 5-10% by volume of mare regolith and 10-20% of mare basalt rock. It is weakly magnetic and a process of beneficiation may help: crushing, screening, and subsequent utilization of magnetism improves the economics of processing, both in terms of energy and stoichiometry when undergoing hydrogen reduction using concentrated insolation [91]. The equation is as follows: $\mathbf{FeTiO_{3(s)} + H_{2(g)} \rightarrow Fe_{(s)} + TiO_{2(g)} + H_2O}$

This is an endothermic reaction [91] that takes place between 1,100-1,300K (837-1027ºC), which is achievable using solar furnaces. The product water can be reclaimed to regenerate hydrogen for ongoing ilmenite ore processing operations. Biomining is the process to which microorganisms are used to extract ores, usually by a form of chelation to make them water soluble. This is highly effective for extracting materials of economic importance from low-grade base materials. This has garnered interest in usage for ISRU applications on both the Moon and Mars. In the case of lunar mining, we have to deal with low ore quality base materials that cannot be easily smelted, this is where biomining, or rather bioleaching, becomes of importance in making ISRU effective. Biomining systems have been extensively utilized for over half a century [111] and have become a mature technology, featuring heavily in metal extraction where high grade ores have been exhausted. Namely, 20% of all copper is being extracted via these means [112]. Of interest, fissile elements such as uranium and thorium are extractable via these methods.

Industrially important bioleaching bacteria include *Acidithiobacillus ferrooxidans* and *Leptospirillum ferriphilum* These organisms are acidophilic, meaning that they are best suited to surviving in acidic conditions. oxidizing metal sulfides, sulfites, and related sulfur containing species. They work with sulfur-rich ores, which exist on the Moon mostly within the lunar mares with upwards of 1% by volume in any lunar rock. The most common sulfide mineral on the Moon is troilite (FeS). Other sulfide minerals exist, such as bornite, chalcopyrite, cubanite, mackinawite, pentlandite, and sphalerite. Target destination may contain such minerals due to the pyroclastic cone, though significant quantities of sulfur and other volatile materials were lost via degassing, upwards of 63%. Alternatively, recent research suggests the utilization of a fungi known as *Mucor hiemalis.* Key advantages, unlike the aforementioned acidophiles, is that they're anaerobic and multi-metal hyperaccumulators with a high-metal resistance, particularly with heavy metals. Strains EH8, EH10, EH11 are mutually tolerant and when cultured together can additionally enrich precious metal ions such as Ag/Au and Ti. Reported hyper-accumulation of metal ions are as high as 99% with Cr(III), Hg, and in excess of 90% with Al(98%), Cd(91%),Pb(97%) and are capable of hyper-accumulating well over 70% for metals such as: Zn(71%), Ni(89%), Fe, U are also noted [113]. Percentages accumulated vary between strains and strain combinations in-situ. However, the usage of heterotrophic organisms, such as *Mucor hiemalis*, is noted to, "require (as opposed to the autotrophic metal sulfide-oxidizing bacteria and archaea) the addition of organic carbon (e.g., processed waste from the agricultural or food industries)" [114].

Another consideration is using dissimilatory metal-reducing microorganisms, which involves *Geobacteraceae* spp. and facultative anaerobes such as *Shewanella* spp. which would reduce metal oxides, particularly Fe(III) oxides into Fe(II) oxides. Subsequently, from Fe(II) compounds into elemental iron nanoparticles via amino acid ligands acting as reducing agents. This process takes place under anaerobic conditions [115]. Isolation of these iron nanoparticles can be done within settling tanks, but owing to the lower gravity on the Moon isolation via centrifuges is more attractive. Since the products are pure iron nanoparticles, there is no smelting procedure and can hence be directly used in additive manufacturing (metal 3D printing) or melted and cast via concentrated solar radiation.

6.11 *Solar Furnaces & ISRU manufacturing.*

In order to melt metals, or sinter/vitrify regolith, we need a substantial heat source. Solar furnaces are ideal for usage on the Moon, requiring no fuel and easy to manufacture. Solar irradiance on the Moon is 1366 W/m^2 [116]. For the furnace itself, a parabolic mirror is ideal: reflective designs, unlike lenses, do not cause a refractive prism effect of wavelength separation, making them easier to focus. The major limiter is how much weight the mounting platform can take, and unlike a somewhat massive lens, the parabolic dish doesn't need any more thickness than foil. Mirrors are significantly easier to manufacture than lenses, with lower material costs. They can be constructed from basalt derived glass and aluminum, with approximately 90% total reflectivity. A 100 nm thick Al layer is sufficient for ideal reflective characteristics. 27 g of 99.999% purified aluminum would be sufficient to manufacture a mirror surface area of 100 m^2 on the Moon [117]. Even considering losses during this process the amount of high-grade aluminum that needs to be purified on Earth and flown to the Moon is on the order of less than 1 kg and is hence deemed a viable approach to augmenting a lunar surface mission. The first solar furnace is shipped in from Earth, all others are made via ISRU.

6.12 *Safety.*

For safety procedures of Argo, crew safety is paramount. Two sources of risk present themselves: within and without. While we will get further into detail on specific responses to safety risks in our Safety Supplement, our overall safety strategy follows.

Risks from within can include mundane accidents like normal workplace injuries, burns and cryogenic exposures, electrical shocks, the ingestion of contaminated water, inhalation of contaminated air (e.g., ammonia inhalation); ingestion of, or contact with, hazardous lunar mineral contaminants; fire, disease, decompression, and chemical exposure. The best way to keep safe from these accidents is to keep them from happening at all, so astronaut training in proper safety procedures will be paramount. Once incidents happen, medical staff will be critically important, who will serve a double purpose in collecting data on life in a lunar environment and in day-to-day light medical care. Serious cases will have to be evacuated to Earth, as medical emergencies at McMurdo base must be evacuated to New

Zealand for more advanced medical care [92].

Risks from without include meteorite impacts, moonquakes, cosmic and stellar radiation, and other dangerous natural phenomena. Equipment failures can be managed with redundancies to ensure Argo never depends on one irreplaceable machine. Fires demand a more active response, such as sealing individual modules using pressure doors which separate each module throughout the base and venting their contents after evacuation. With the sealed habitat isolated, astronauts can take their time to safely suit up and inspect the damage from inside and outside the module.

Concerning exterior threats, one method for impact mitigation involves a white coating of the ISRU-derives compound titanium oxide to the outside of Argo to visually monitor strikes, as well as triply redundant power systems. Other mitigation strategies include an early warning system for earthquakes through a seismometer network, and a thick shell of regolith around human inhabited structures of the base as proof against radiation and micrometeorite impacts. Some of the unknown dangers on the Moon include transient lunar phenomena, which have been observed but are almost entirely unknown in origin and mechanism. Careful observations of these and other currently unknown phenomena will be critical to keep Argo safe. Caution is key to operation, especially when involving any critical systems.

Extravehicular activities (EVAs) will always be the riskiest surface operations. A list of dangers includes: mundane accidents not leading to suit failure (crushes, blunt traumas, falls), punctures and other suit pressurization failures, depletion of oxygen or CO2 scrubbing capacity or other critical suit function(s), radiation exposure, and a complete loss of orientation which may lead to suit resource exhaustion. To mitigate this, EVAs will always be conducted in pairs, so help is always nearby. This will also allow astronauts to dust each other off in each of the double airlocks on entry from EVAs to prevent dust from infiltrating the station. Similarly, vehicles leaving the base will do so in pairs, sent on separate missions which lie in similar directions. If one experiences an emergency, the other will be able to quickly support it and transport the astronauts back to Argo. This kind of thinking will reduce the risks of these activities as much as possible. A gram of risk mitigation is worth a kilogram of emergency response. Proper foresight, good training, and smart procedures will be the best safety technique on the Moon, just as on Earth.

7. Architecture.

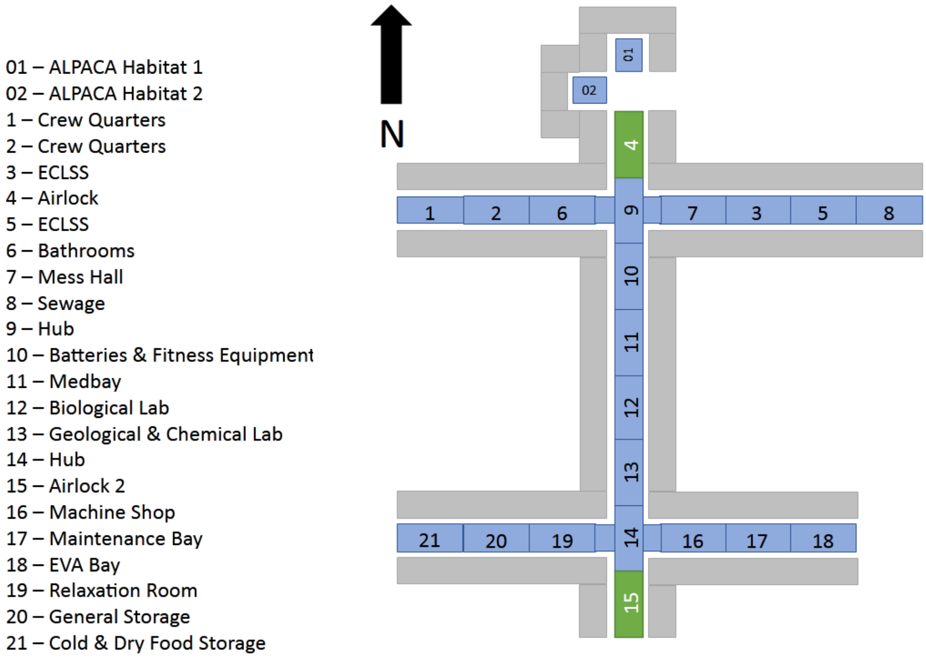


Figure 10. Layout of Phase 1 and Phase 2, as of Phase 2 completion.

While a majority of Argo's interior space is given over to science, industrial experiments, agriculture, and ECLSS, careful attention is given to affording the astronauts accommodations to live a comfortable and healthy life. All rooms utilize interior design techniques like lights in the corners, strategic mirrors, potted plants and color theory such as integrating blues, greens and earth-tones, to make them seem bigger than they are, and more inviting. These efforts make the most of the limited interior volume available in Phase 2.

In Phase 2, all habitats have a floorspace of 20 m^2 and a volume of 50 m^3. The two crew quarters habitats are split into four rooms that can host four astronauts each. The quarters have a floorspace of about 2.7 m^2 and a volume of 6.75 m^3. The lavatories and washroom are a separate habitat, with conventional Earth-style plumbing fixtures. Unlike on the ISS, where showers are replaced with dry soap rubs and wet wipes and the toilet is a vacuum suction hose, these amenities make all the difference. After a four day long haul on a Starship from Earth, this will surely be appreciated. A dedicated gym habitat also exists, with equipment and facilities. After a workout here or when returning from an EVA, taking a shower with real running water either from cargo or harvested ISRU will be heaven. Also present is a mess room, which also acts as a common room and meeting center. Food during Phase 2 is shipped in or made in the photobioreactors, so does not require much preparation. Kitchen equipment is minimal. Other habitats house the various labs and life support. All of these habitats have a one meter wide access corridor through the habitat. The rest of the floorspace is given over to the working area.

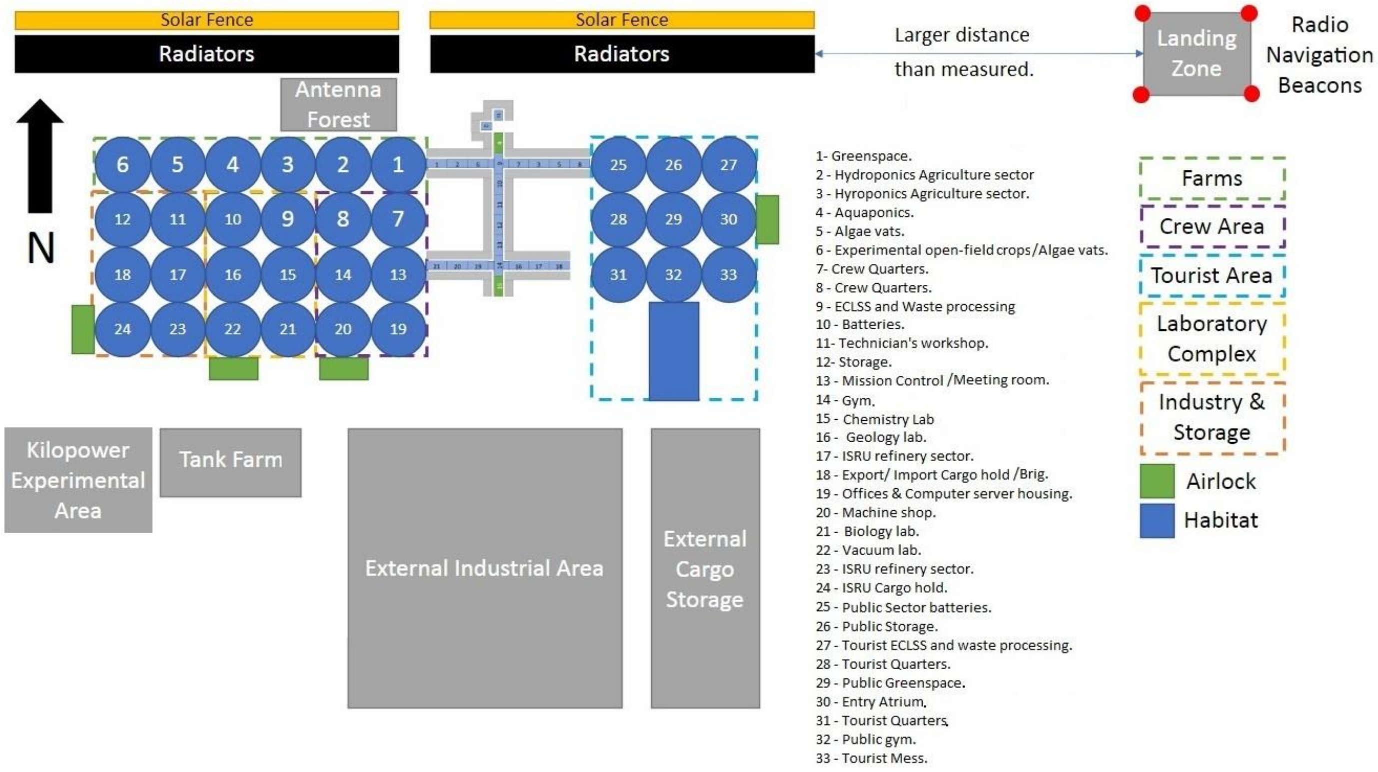


Figure 11. *Layout of Phase 3 after completion of construction.*

7.1 *Phase 3 Architecture.*

In Phase 3, all habitats are geodesic domes made from ISRU materials, with about 491 m^2 of floor space. This gives Argo over 16,500 m^2 of total base floor space, with ceilings 12 m tall. For certain habitats, multiple levels can be fitted in, for maximum space efficiency. However, a high ceiling of 3 m per level is maintained to give the base a spacious, open feeling. Within, all crew members and guests will have well-appointed personal accommodations, with a total floor space of 23 m^2. These rooms will have modern furnishings, with room for some accessories, and a personal toilet and shower. The mess, gym and relaxation facilities present in Phase 2 have been greatly supplemented in Phase 3. For example, the Phase 3 greenspace is a type of biosphere, complete with live plants, water features and artificial sunlight. With agriculture, both experimental and functional, as well as increased algae processing capabilities, the mess has a dedicated kitchen. The eating area is no longer a general common room, so executive meetings and debriefings take place in their own room, with all base control and administration taking place from a central command habitat. Admin work is done in an office area. The entire base would be serviced by a dedicated computer server room in the mission control habitat.

All crew, science, support, and industrial habitats are made first on the west side of Phase 2. Since the deployment of such facilities is priority for Argo, the tourism-centric habitats will be constructed last, connecting to the east side of Phase 2. We anticipate that tourism-centric habitats will not be constructed for at least a year after the beginning of Phase 3. Tourist habitats are the same as all Phase 3 habitats: large geodesic domes with very spacious interiors. These habitats will have the same functions as laid out for the crew (rooms, mess, common area, green space, and gym area), and be the only area tourists can freely wander. An addition to these facilities not found in the crew area is an atrium or lobby, where new visitors will be introduced to the base when they first arrive. Another interesting feature to the public sector is the low-gravity sports center. In this large (500 m^2) building, visitors and resident astronauts can have the space to engage in a variety of sports activities, enhanced by a gravity only 16.5% of Earth standard. A particularly interesting prospect would be a trampoline. We propose a trampoline chamber, wherein in one can literally bounce off the walls. We may call this the “Bouncy House” or “Battle Room”.

7.2 *Green Spaces.*

Human psychology and physical health are affected by the presence or lack of greenery and perceived natural scenery [93] [94] [95]. The inclusion of greenspaces and other natural themes throughout Argo is a critical detail. Well-appointed rooms and access to running water alone cannot alleviate the stress. Including habitats with a Zen garden-like atmosphere where inhabitants can go to relax has always been high on our list of design priorities.

Our first greenspace is the relaxation room in Phase 2 (see Figure 10). With such a limited space compared to later habitats, it is hard to properly simulate a natural environment. Like all Phase 2 habitats, we have methods to make them seem larger (see 7.2, Phase 3 Architecture). Images can be projected on the walls of nature scenes or anything else the astronauts want, and ambience played to match those scenes from speakers hidden strategically through the habitats. This with comfy chairs and potted plants makes it fit for astronauts to go and relax after a hard day of work

[96] [97] [98]. With other habitats employing similar lighting techniques to improve their visual space, the interiors of Phase 2 stand to be quite the opposite from the harsh utilitarian caves sometimes proposed for moon bases!

The greenspaces of Phase 3 are rightly more extravagant and immersive. With our robust construction techniques, we can hope to approximate nature on the Moon. Unlike most biosphere designs, the processes of photosynthesis here is not a main source of oxygen for Argo. It can be supplementary for the greenspace itself, but all life support is handled by the main ECLSS modules. While requiring significant input of materials, such as fertilizers and water, these gardens are fairly self-contained [99]. The features of the greenspaces are as follows:

1) The central point of the room is a large water fountain. It is composed of a pool with three large lunar boulders (acquired and cleaned by Argo's EVA specialists). This unpurified water is in a closed loop, with a rough volume of roughly 3500 liters.
2) Garden beds. The depth of their soils, which is purified lunar regolith mixed with fertilizers from on site and with nitrogenous enrichment from Earth [100] [101] [102], is about 2 m from the true floor on the metal paneling (see above, to above the second floor). The plants in these gardens have been specifically chosen for hardiness, ease of care and shallow root systems [103]. Photosynthesis is achieved via narrow-band LED lights on the ceiling.
3) A powerful spot light mounted at the dome apex reflecting its beam on the ceiling will constitute our artificial sunlight. The size and direction of the "sun" can be easily adjusted to simulate any time of day. Color control is also possible, so various daylights can be simulated. Having this resemble real sun is a must for us. The spotlight would be wired to a motion sensor, and turn off if no-one is in the greenspace to save power.
4) A 1.5 m wide walkway circumnavigates the dome interior at a height of 4 m, accessible via ladders, ideal for private, contemplative walks.
5) Water-proof LED projectors, much like the ones used for the Phase 2 relaxation room, can project a forest scene on the walls of the interior wall to the height of the walkway. This gives the entire dome a much larger ground level appearance at first glance.
6) Silent running, water-cooled fans in the outer wall simulate a forest breeze.
7) Strategically placed water-proof speakers intermittently (to avoid repetitiveness) play forest sounds.
8) The interior crown of the dome has a scaffold about 3 m wide mounted on it. On this, hanging plants drape high above the water feature. The spray nozzles that water them give the rest of the garden a misting. The scaffolding hides the spotlight.

Some of the plants listed here may mature in weeks, others in years. Their maintenance and care offer the astronauts a respite from industrial and mechanical work. The construction of the dome may take a few days, with the prepping and installation of all interior assets talking about a week.

Figure 12. *Phase 3 greenspace.*

7.3 *Layout.*

The sprawl of our base is such that installing new additions are as simple as excavating a new trench and laying down a habitat within. Such construction could be performed in a lunar day, with testing extending the operation to another day. Via these means, it becomes clear why we say that Phase 3 has no real end. It can be indefinitely expanded. Combining the relatively low cost of transport and ISRU utility with the monetary input of third parties, Argo represents a radically different economic model compared to modern space infrastructure [104]. Using ISRU materials and the HLS Starship to ferry cargo means that extensions of the base are not inhibited by constraints like shipping size, or building material shortages. Thus, the site of the new space can be of any dimension desired. Each new extension shares the robust durability found throughout all of Argo.

The only limitation that this overall design has is the presence of intractable bedrock that the current bulldozers simply cannot disperse. We assumed a maximum depth of 10 m of allowable depth for our facilities, though it is likely that large pieces of immobile basaltic boulders or highly compacted metallic regolith exist as obstacles at a depth as shallow as 3 m [105]. Therefore, future facilities will not homogeneously expand across the lunar landscape aimlessly, but likely capitalize on local geography to avoid obstacles and improve function.

8. Society.

Environment is the largest influencing factor to the way people live their lives, along with the place they originally came from. Since the lunar environment is the most extreme humanity will ever face, and the crew comes from a variety of backgrounds, there are the makings of a unique culture in Argo.

8.1 *The Setting.*

A crew of less than 30 is an odd number for an inhabitant of the base to handle, since while it is far too little to nudge against Dunbar’s Number, those are still too many people for the crew to know each other well. Small “clique” groups of no more than 5 to 10 astronauts will form. The theme of these groups would depend on nationality, profession, or gender. Such things happen on the ISS with far fewer folks (e.g., the Russians often stay to their side of the station), or aboard naval ships and in Antarctic bases. Regarding culture, dry humor related to space, the lunar wasteland, low gravity, access to toilets and water, and the food will all doubtless be prominent. A general attitude of “let's get this done”, echoing the Apollo program days, along with a surreal sense of actually being on the Moon and a consequent disdain for Earthly politicking will also be a feature of lunar culture. In other words, the Overview Effect will also be evident among the astronauts of Argo, perhaps more so due to their relative isolation [106] [107 [108].

8.2 *Lunar Living.*

Argo only looks rugged from the outside – the interior is as pleasant as possible. Even in the smaller spaces of Phase 2, the amount of living space allocated to each astronaut exceeds that afforded to naval crews. For any phase, the atmosphere will not suggest a lunar outpost; every habitat has its artificial windows and mood aesthetics. The windows will be either high-definition LED screens with various moving images, or LED lights behind frosted glass. For entertainment in all phases, media should be widely available; huge libraries of cinema and video games that the astronauts can pursue in their free time, alone or in groups. With the installation of a Starlink-type satellite set up, it will be possible to stream the internet on personal devices, with a healthy amount of patience for light-lag. Personal improvements to quality of life include fully functional lavatory plumbing. Access to fresh fruits and vegetables, courtesy of persistent Starship deliveries, and Phase 3 gardens, will also improve standard of life. These cargo deliveries can also bring astronauts “comfort food”. Alcohol could also be shipped in, though it is quite likely that the agriculturalists and engineers will figure out how to make crude alcohol on-site (literally “moonshine”). The greenspaces can also grow herbs, and host bees to provide honey. Simply put – astronauts will be spoiled at top dollar!

These luxuries can be enjoyed by both astronauts and visitors, but in the case of the former, hard work must be done as a consequence of living on the Moon. Monitoring an astronaut’s wellbeing is a top priority, and the best way to keep people sane is to keep them so busy they don’t have the time to contemplate their situation. Redundant upkeep and maintenance is performed so rigorously that free time is reduced to a few hours at best during the evening. This can be relaxed to an extent during Phase 3, but otherwise is a vital program to maintain sanity among the crew. Between this make-work, actual constant maintenance and the distractions offered by entertainment, it is likely that all astronauts will sleep very soundly at night. If these practices and therapy do not help, a Starship back home can easily be arranged.

Sexuality is worth mentioning here. Mix any group of 30 people together and the chances are that it may come up at least once. The attitude Argo takes on this matter is just don’t do it. In the unlikely event that a pregnancy occurs, the mother would be sent back to Earth immediately. The Moon is not a safe place to raise children, at least for now.

8.3 *Public Visits.*

Tourists would visit by way of a launch system proven to be safe by prior lunar missions. No more than six tourists at a time can be hosted in Argo. One or more astronauts either already at Argo or shipped along with the tourist(s) would chaperone these visitors. These personnel should be obeyed and be respected above all else. Their word is law in the base, and the safety of the newcomers is their primary concern. Safety regulations will include: no unsupervised EVA, no entrance to any non-public areas of the base, no base systems technology interfacing besides in emergencies or under supervision, no unruliness or disobeying crew orders, no unauthorized media capture, no altering of any critical part of the base, and no use of implements with intent to harm. Violation of any of the rules will result in placement in the base brig until a Starship is ready to take the offender(s) back to Earth – no refunds, and extra costs levied if damages occurred.

Tourism during the night cycle is out of the question, as during any construction, major projects or maintenance. Visiting durations vary, but typically would last a lunar day cycle, or around 16 Earth days. This is to take advantage of transporting the tourists in the monthly Starship trips, which haul either replacement crew or cargo to and from the Moon. A dedicated launch could be arranged though for the tourist(s) to leave whenever, provided at substantial extra cost.

The reasons to visit the Moon are many, an overview of potential visitor activities is listed here:

- The chance to actually be on the Moon and soak it in.
- A tour of the entire base and grounds.
- EVA expeditions, including further ranging moon-walks and rides on the lunar cruisers.
- EVA expeditions to sites of great interest deemed safe. Naming a cave "Tintin Cave" is required.
- EVA "nightwalks", actually taking place out of the sunlight in a crater or canyon where stars would be visible.
- EVA hopper trips to access very far locations, such as nearside to view the Earth from the surface.
- Sports activities in low gravity in the facilities provided.

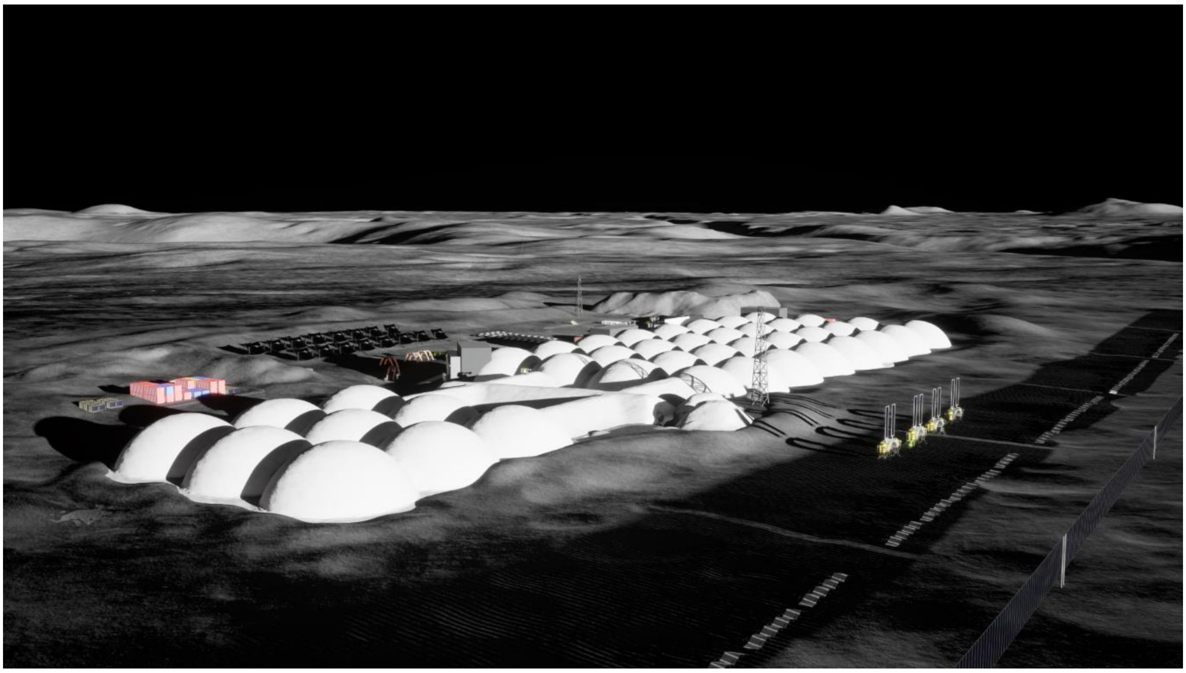


Figure 13. *Argo Base after Phase 3 completion, with the solar fence visible on bottom right.*

9. Administration.

Argo's administration, ironically, is one of the biggest issues with the concept itself. The current geopolitical situation is highly fractured along ideological lines. Consequently, the base cannot be run as a completely non-national entity, especially with the implications of modern space law. Despite this, we do intend Argo to be impartial to geopolitics. Its governing entity would not be directly under the jurisdiction of any world government. One possibility would be to mirror the current ISS organization, where the individual space agencies that are a part of the station project all administer the base jointly.

9.1 *Politics.*

American jurisdiction would take precedence over all launches and infrastructure, due to launches from USA facilities. Hence ITAR restrictions would be applicable to crew selection. Currently, the spacefaring nations of China, Russia, and India are all under these restrictions, though Roscosmos astronauts may be exempt. Canadian, Japanese, and European astronauts would have no legal restrictions however, so the base would likely be staffed by astronauts from those agencies. While ITAR restrictions would also prevent manufacturing outsourcing to certain nations, Europe, Japan, and the USA are qualified to lend support. Hence, Argo would likely be dominated by Western countries, though we hope that this future cooperation can allow more nations to get involved.

The newly christened Artemis Accord will have major implications for the design and running of the base. While their mandates concerning the preservation of heritage sites will not affect us, we will need to ensure that all scientific results, investigations and technological specifications are shared openly. This is to ensure that future missions can utilize our capabilities in case of emergency.

9.2 *Space Law.*

We do not have a very comprehensive legislative framework for space activities. While this may seem like a blessing, it is detrimental insofar as critical issues such as land ownership, mineral rights, debris mitigation, and manufacturing have not been addressed. The most important laws in need of amendment concern land rights. We obviously cannot allow it so that any nation, group, or entity can unilaterally claim territories in the solar system, or by gross extension, entire astronomical bodies. At the same time though, without an ability to make claims it will be tricky to legally mine and utilize materials from space. A literal interpretation of current space law in this regard is that manufactured goods would still be bound to the same framework as the materials they originated from, and as a result, we legally could not stop people taking equipment made from ISRU materials. Technically, the equipment belongs to no one. While security in Argo is effective enough for theft not to be a worry, there is serious future concern for true commercial lunar activity. We cannot overhaul modern law, but we can prepare our base litigation for it; any materials brought to Argo belong to the astronauts that harvested them.

9.3 *Crew Details.*

Argo will be the first time that humans permanently inhabit a low gravity body. Considering our scant prior experience with lunar inhabitation, modifying astronaut selection requirements is unwise, as nobody knows how to modify them to better suit the Moon. Simply going for physically fit and mentally stable individuals is status quo based on very limited knowledge from the Apollo criteria and training. We will need a wide variety of jobs, mostly in engineering and geology, but also in medical sciences, botany, mining, ecology, and aquaponics. This will change over time, for example, we will not be creating an aquaponics system until partway through Phase 2, so initially there will be no need for aquaponics specialists or botanists.

We envision Argo housing between 20-30 people during Phase 3, with regular crew rotations every month/Lunar day, which also allows the Starships to haul more supplies. Rotations will be more rapid during the more cramped Phase 2, on the timescale of every two weeks. This also allows us to have a day and night shift. Our plan for the lunar night focuses on power conservation being key, so we limit all EVA and industrial activities, with an energy budget reserved for low power-level scientific research. The organization of the crew is an important detail to consider, as the base will be too isolated for administration and security support. Argo will have a quasi-military naval approach with one astronaut designated as leader, who would have final say on all matters concerning crew management.

10. Phase 4 & Beyond.

It seems fitting to end where lunar colonization really begins: Phase 4, when humanity can say it is interplanetary. It’s when we are no longer just surviving on the Moon; but thriving, and planning to stay.

This future, unfortunately, will remain tantalizingly in our imagination until the foundation is laid out. Solidifying the prosperity of Argo is the aim of Phase 3 – we cannot populate the Moon until our foothold is firm in the Moon’s hostile environment. Once we are established there, beyond Phase 3, we may see our presence expand into facilities deep in the lunar crust, housing hundreds or thousands of people, and burgeoning industry and science across the lunar surface. Larger metropolises can arise. The utility and majesty of the Moon truly makes it a cosmic treasure.

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