The Hudson's Bay Company for the 21st Century

Moon Base Design Competition for the Moon Society

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Abstract

This paper describes the technical design, economics, architecture, crew, and governance of a 24 person lunar base. The multiple missions include propellant production, production and sales of solar cells produced from lunar regolith, provisioning of produce and seafood for other lunar bases and asteroid mining operators and housing for visiting scientists, space tourists and a Rest & Recreation (R&R) site for crew from other lunar bases. When (if) there is a significant market demand for on-orbit construction materials such as silicon, iron and aluminum these materials will be processed from the regolith and a mass driver will be added. The base can also support construction of a far side radio telescope. Additional revenue is expected from the YouTube channel and other social media that will chronicle events on the lunar surface. The base is located on a ridge 11 km WSW of the rim of Shackleton Crater since it is expected this will be the location of numerous commercial lunar operations. Since it provides long duration sunlight for power and thermal stability as well as access to water ice deposits in the permanently shaded regions nearby. Transportation from earth to the lunar surface will be provided by the SpaceX fully reusable Starship for reasons of high capacity, low cost and moderate technical risk. Habitat structures for living and working space are inflatable, low arch structures covered by lunar regolith for radiation and micrometeorite protection. The extraction of ice and other volatiles uses microwave thermal mining techniques in the permanently shaded regions. Sublimated water vapor and other volatiles are collected for subsequent processing. Mining products include H_2O, H_2, O_2, CH_4, N_2 and S.

Introduction

The Hudson's Bay Trading Company was chartered in 1670 to operate fur trading and provisioning outposts across eastern Canada. By 1809 the company's operation had spread across the continent. The Hudson's Bay trading posts were the centers of commerce, offering standardized prices for a range of provisions and equipment needed by fur trappers and other settlers. In a similar manner, the people who prospered during the California and Klondike gold rushes were not the gold seekers but the merchants who sold them food and equipment. The moon will be the newest gold rush and the outpost described in this paper will provide goods and services to the seekers of the modern day beavers and gold. This *Hudson's Bay Company of the 21st Century* is called **Hermes** after the Greek god of commerce, wealth and travel.

Site Selection

It is likely that early commercial lunar facilities will be located in the south polar region with ready access to the Permanently Shaded Regions (PSRs) believed to hold water ice and other volatiles with commercial value. Hermes will be situated on a ridge 11 km WSW of Shackleton Crater. Originally, Leibnitz β at 6,055 m (19,800 ft) elevation (the highest in the south polar region) was attractive but its location 160 km (100 mi) NNE of the south pole results in long stretches of winter darkness. The selected Hermes site has over 95%.[1] Solar availability.

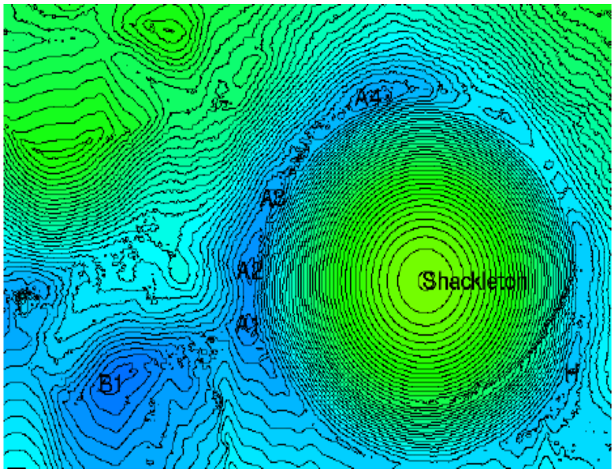

Fig. 1 South Polar Region

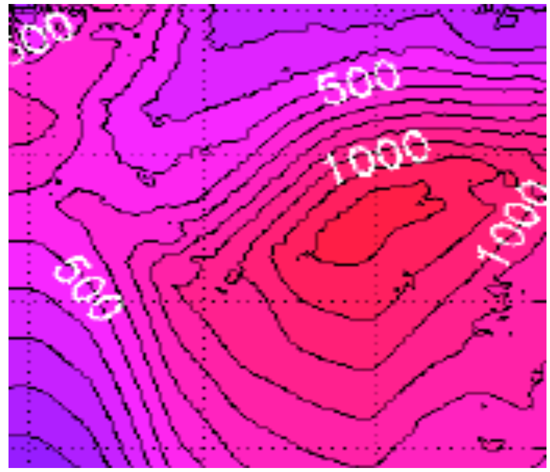

Fig. 2 Hermes Site Close Up

Curiously, most of the dark time is caused by obstruction from Leibnitz β. The site is about 2.7 X 0.6 km (1.7 x 0.4 mi), adequate for the Hermes base complex. Figure 1 shows the location of the selected site, labeled B1, relative to Shackleton Crater. Figure 2 shows an image of the 2.7 x 0.6 km site at about 1,260 m above the lunar datum.

Systems & Technologies

Transportation to Lunar Surface

There are several existing options to launch our payloads towards the moon. Unfortunately, there is no existing capability to land significant payloads on the lunar surface. NASA's Human Lander System for the Artemis Program is currently funding three contractors to study candidate landers[2]. Of these, two exist on paper and one exists, at least in part, in stainless steel. SpaceX is rapidly prototyping the upper stage of its Starship design. Furthermore the Starship payload capacity is far greater than the other two landers and it is part of a fully reusable system design which will reduce launch cost[3]. See Figure 3.

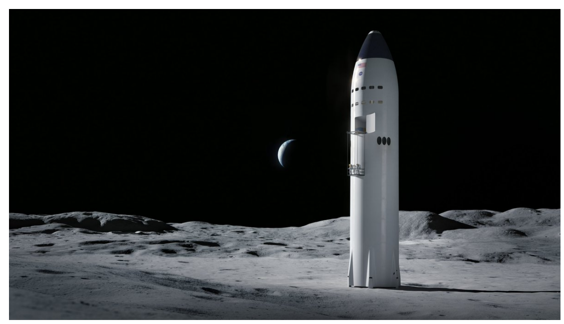

Photo Credit-SpaceX

Fig. 3 Starship Lunar Lander Variant

Habitat

The Hermes base consists of four habitat modules
-Crew and base operations (Operations)
-Hydroponics (the Garden)
-Aquaculture (the Fish Farm)
-Housing and workspace for visitors (the Hotel)

In the interests of commonality, all four modules will be the same size. The Garden will need at least 1200m2 (13,000 ft2), so the common size is set at 30M (100 ft) by 40M (130 ft). The configuration and interior design of these modules is described in the Architectural Design section.

The required square footage of pressurized habitat for living and working area plus hydroponics and aquaculture is 4,800 m^2 (52,000 ft^2). This size rules out prefabricated habitats like the Bigelow B330 or the Axiom Space modules. The large number of modules required would be too expensive, require too many launches and result in a rabbit warren of a colony. In addition, frequent transiting of the 800mm (31 in.) diameter circular hatches between modules would get old very fast. Custom construction will be required, covered with regolith for radiation and micrometeorite protection. However, once a traditional structure is built, covering it with regolith can be a difficult and time consuming process.

Habitat Technical Design

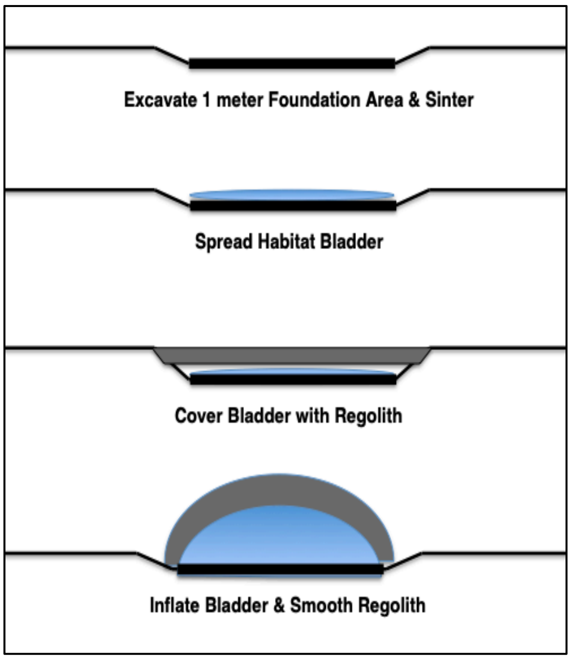

Fig. 4 Habitat Construction Sequence

The construction process selected[4] is illustrated in Figure 4. Step one is to level an area about 0.5 to 1 meter below ground level based on the local regolith density. The regolith is compacted then sintered in-situ to create a solid surface for the habitat (see In-Situ Sintering discussion below). A "Quonset hut" style inflatable bladder is then deployed across the sintered surface. The un-inflated bladder at ground level is then covered by 1.5 meters of regolith. Studies[5] of radiation and micrometeorite protection provided by lunar regolith indicate that 1.5 M is adequate protection. The bladder is then inflated, the regolith is evened as needed and the interior is reinforced with prefabricated arches. The habitat is a shallow arch design with side slopes below the 40 degree angle of repose to keep the regolith in place. The inflated habitat also has a ribbed exterior construction to help retain the regolith.

Regolith Excavation: Site preparation and regolith spreading on the bladders will require moving about 9,600 m^3 (339,000 ft^3) of regolith. Not a job for a hand shovel. Fortunately, NASA has already studied and prototyped a bulldozer blade attachment[6]. The 6m (20 ft) wide Lunar Attachment Node for Construction and Excavation (LANCE) shown in Figure 5 is just what is needed. See Rover section for details of the CHARIOT rover.

Photo Credit-NASA

Fig. 5 LANCE Bulldozer Attachment

In-Situ Regolith Sintering: The regolith below the habitat must be stabilized to prevent shifting and stresses on the floor membrane. Common terrestrial building materials such as concrete and aluminum plate, while effective in this application, are far too heavy. Solar sintering was considered but eliminated due to concerns about lunar dust coating the lens. Instead, microwave heating was selected for site sintering.

Site Preparation Rover: All of the needed site preparation functions are integrated into a single remotely controlled vehicle. This would include excavation, compacting and microwave sintering. The compacting roller will be water filled to add mass and when it is not in use it will be elevated but the water mass will improve the operation of the bulldozer in the low lunar gravity. There is little reason to make the robot autonomous, a crew member standing nearby can effectively control the rover while avoiding much of the regolith dust. When the sites for the four habitat modules are completed, a second set of foundations for an additional set of Hydroponics and Aquaculture habitats will be created to prepare for planned expansion of food sales. Assuming that the sintering has achieved adequate depth and strength, the rover will then set to work creating landing pads and adjacent berms. See Rover section for details.

The optimum power and frequency for regolith heating depends on regolith density, nano-phase metallic Fe content and volatile concentrations. Lunar regolith analogs (e.g. MSC-1) lack the fidelity necessary to determine the optimum frequency and heating rates[7]. Even the Apollo return samples exhibit considerable variability. This indicates the need for in-situ optimization of the microwave sintering and mining parameters. The Site Preparation and Mining rover will, therefore, be equipped with variable frequencies and adjustable power levels (Figure 6). The relatively low mass penalty for the extra transmitters could result in improved sintering speed and increases in volatile recovery yield

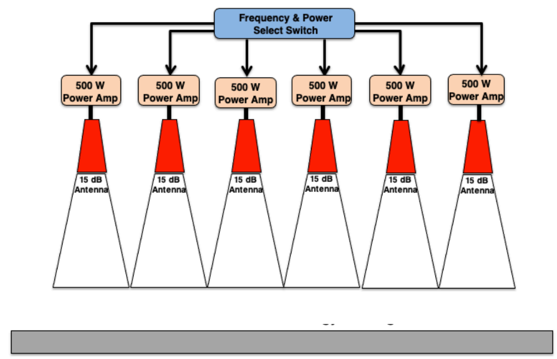

Fig. 6 Microwave Thermal Heating System

Habitat Ambient Pressure: Two factors interact in selecting the habitat ambient pressure. It should minimize the pre-breathing requirement to transition from habitat ambient to Extra Vehicular Activity (EVA) suit pressures. and be high enough to support the regolith roof loading The advantages of earth normal 1 bar (14.5 psi) pressure include lower oxygen pressures and resulting reductions in fire risks. However, the transition from habitat ambient to EVA suit pressures for normal or emergency operations poses a decompression risk. International Space Station (ISS) astronauts preparing for an EVA must pre-breath pure oxygen for 140 minutes at 1 bar and a further 30 minutes at 0.7 bar prior to switching to the .27 bar (4 psi) of the Extravehicular Maneuvering Unit (EMU). As a compromise, Hermes will operate at 0.7 bar (10 psi) with an elevated oxygen fraction of 30%. This will significantly reduce pre-breathing times and flame propagation studies indicate that fires self extinguish below 40%. Another advantage is that, at 30% O_2, less nitrogen is present to be potentially lost due to leaks or air lock venting. This is significant since little nitrogen is available on the moon.

Supporting the regolith load is easy. At an average regolith density of 1.5 g/cm^3 , the roof loading for 1.5 meter of shielding is 2250 kg/m^2 (461 psf) .For the nominal 0.7 bar (10 psi) pressure the roof support is 7135 kg/m^2 (1461 psf). Even at .27 bar habitat pressure the support would be 2,812 kg/m^2 (576 psf).

Habitat Inflation Gas: The four 30 X 40m habitats with an average height of 2.5m (8.2 ft), have a combined volume of 12,000 m^3. The inflation gas will be Nitrox with 30% Oxygen. It will be delivered to the lunar surface in composite overwrapped tanks (aluminum wrapped with carbon fiber) at 690 bar (10,000 psi). Given the desired 0.7 bar (10 psi) atmosphere, the required tank volume is 12 m^3(420 ft^3). This will be achieved in 45 standard size, 425mm x 2600 mm (1.4 ft X 8.5 ft) tanks. These tanks will subsequently be used for storage of mining products.

Temporary Radiation Shelter: Both the Hermes habitats and the Starship provide protection from solar flares and coronal mass ejection events. However, during EVAs the crew is much more vulnerable. The NASA-JPL Radiation Analysis Group or some commercial equivalent can provide advanced warning times of minutes to hours in advance of solar particle events. Prior to completion of the Operations habitat, the crew will need to return to Starship when an event is forecast. Since the Starship access is by elevator, getting as many as 44 crew to safety will take too long. Therefore, Job One on the lunar surface is construction of a small radiation shelter. Built using the same construction techniques as the main habitats, a 15 X 30 m (49 X 98 ft) shelter habitat will accommodate all 44 Operations and Construction crewmembers with food and water for a few days. Prior to completion of the Radiation Shelter, the number of crew allowed on EVA concurrently will be limited by the ability to recover them from the lunar surface in the expected minimum warning time.

Power Production

Hermes will use primarily solar power. Photovoltaic panels will power the habitats and mining operation while direct focused sunlight will be used for interior lighting and water heating. The photovoltaic power requirement is estimated at 120 kW. Recharging 145 kwh of the the Mining Rover's 200 KWH batteries within 12 hours adds 12 kw. Total solar panel generation is 132 KW. Solar incidence above the earth's atmosphere is typically 1.38 KW/m^2. For a 36% efficient multi-junction panel the required area is 264 m^2. As noted in the Site Selection section, the site has seasonally limited solar illumination. Options to mitigate this solar power shortfall include microwave or laser power transmission from sunlit areas, exotic new battery technologies like Sodium-Sulfer or thin film Magnesium-Sodium processed from lunar regolith or less risky existing Lithium batteries. A new Lithium Metal Oxide battery was described in reference 8. It offers 650 WH/KG. Rover and Gas Processor maintenance will take place over 4 days of worst case darkness. This will reduce the power draw to 85 KW requiring 8.2 MWH(12 mT) of batteries. A lot of mass but very little risk and the needed power does not depend on potentially risky in-situ processes. The capacity to recharge the backup battery system within 300 days would only add a negligible 2 KW.

At the lunar poles, although the sun is above the horizon for most of the lunar day, the sun circles low in the sky during this time, requiring rotating the panels to track the sun. A terrestrial 264 m^2 panel structure would be a lot to steer but with 1/6 gravity and no wind loading the design is straight forward.

The largest panel segment that will fit in the Starship cargo bay is about 6.3m (20') x 12m (40'). Four panels linked together provide 302m^2 (3,250 ft^2). The panels will be mounted on a rotating pedestal to provide solar tracking. The pedestal includes power conditioning equipment and DC-AC inverters.

Solar Panels are subject to both mechanical and radiation damage so replacement must be considered. Producing panels from lunar regolith can supply Hermes future needs and provide a product for sales to other lunar bases.

Solar Cell Production from in-situ Resources: One product needed by nearly all lunar base operations is solar cells, not only for initial installation but as replacements for mechanical or radiation damaged cells. Studies have evaluated techniques for lunar solar cell production via metal oxide electrolysis. The combination of the silicon rich regolith and extreme vacuum that facilitates vacuum deposition of thin film cells creates the opportunity to produce solar cells on the moon. Ignatiev et al[9] describes a possible autonomous robot that can process regolith as it traverses the lunar surface and deposit working solar cells. Figure 7 shows the cell structure. Once again the CHARIOT rover chassis can be the basis of this capability with a custom designed solar cell production payload of about 1.5 m^3 and 300kg. This has potential to be a significant income source.

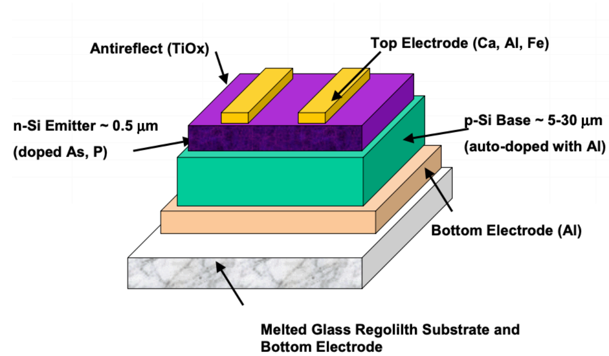

Fig. 7 Solar Cell Structure

Environmental Control and Life Support (ECLS) Systems

Hermes Life support systems will draw heavily on ISS systems and equipment[10] as well as the evolution of those capabilities for the Orion spacecraft. A highly integrated Air Revitalization system of systems generates oxygen to make up for metabolic consumption, removes carbon dioxide and water vapor from the air and captures it to recycle water and process the CO_2 with hydrogen (a byproduct of the O_2 generation) to make more water as well as Methane.

Water: ISS water consumption is about 12 liters/crew/day. All water used for hygiene is recycled. For the human consumption, 50% is returned as urine and 50% as exhaled water vapor and perspiration. The later is recovered in a condensing heat exchanger. The urine is distilled then blended with the other water recovered prior to final purification into potable water. ISS achieves 90% water recycling. A similar water processing system is used in Hermes. The ISS also has a 2,000 liter reserve tank for six crew. That suggests that Hermes should have at least 16,000 liters (4230 gal). in reserve until water extraction becomes stable and dependable. The Hotel module has the reserve water tank that also serves as a swimming pool.

Oxygen: Exhaled air is roughly 16% O_2 and 4% CO_2. Some of the daily water consumption is converted to O_2 and H_2 via electrolysis. The O_2 is used to maintain the correct partial pressure while the H_2 is stored for subsequent use in the Sabatier processor.

Carbon Dioxide*:*. The current ISS Carbon Dioxide Removal Assembly (CDRA) uses a Zeolite bed to absorb CO_2 and water vapor. When this bed is subsequently exposed to space vacuum it releases the captured gasses which are stored for reuse. NASA is currently evaluating Amine as a Zeolite replacement. Amine is the selected CO_2 absorbent on Orion[11] and will be used at Hermes.

Nitrogen: Since it is inert, Nitrogen is not consumed in any system process. Losses occur from leaks and airlock venting. The ISS resupplies Nitrogen about twice a year. However, the LCROSS data revealed about 2.5% Ammonia that could be processed to yield 21 kg of Nitrogen for every metric ton of sublimate processed (See Mining and Processing Section). This will eliminate the need for future Nitrogen resupply and is a candidate product to sell to other lunar bases.

Air Contaminants: Other gases such as carbon monoxide or hydrogen, which are generated by equipment can be removed by charcoal and "special rocks" filters. Finally, HEPA type filters are used to remove particulates, dirt and dust from the air.

Temperature Control: Heat is removed from cabin air with liquid cooling loops. The interior heat exchanger uses water while the external exchanger uses more effective but toxic Ammonia. Some of the heat will be recovered for crew hygiene and aquaponics water heating.

Food Production

Nutrition is a significant challenge for any self-contained, long duration human habitation. This section describes the long-term food production options. In the early mission stages, the crew will eat Meals Ready to Eat (MREs) or some NASA ISS equivalent. This diet over several months will create ample motivation for the expeditious establishment of locally grown food items. Also, provisioning sales to other lunar bases is part of the economic model so prompt initiation of food production is important.

Vegetables & Fruit: Growing produce without dirt is a well established industry on earth[12]. Microgravity creates some special challenges based on ISS hydroponics experiments. However, even lunar gravity should mitigate these difficulties. Table 1 lists the most easily grown fruits and vegetables with preferred temperature range and water pH.

Table 1 Candidate Hydroponic Vegetables & Fruit

ITEM	TEMP RANGE	pH RANGE
Lettuces	Cool	6.0-7.0
Tomatoes	Hot	5.5-6.5
Radishes	Cool	6.0-7.0
Kale	Cool-Warm	5.5-6.5
Cucumbers	Hot	5.5-6.0
Spinaches	Cool-Warm	6.0-7.0
Beans	Warm	6.0
Chives	Warm-Hot	6.0
Basil	Warm	5.5-6.5
Mints	Warm	5.5-6.5
Strawberries	Warm	6.0
Blueberries	Warm	4.5-6.0
Peppers	Warm-Hot	5.5-6.0

Hermes will grow a variety of perhaps 6 or 8 different fruits and vegetables, supplemented by the dwarf fruit trees in the Operations and Hotel modules (see Architectural Design section). For long-term habitation, two additional crops will be added, Cotton for production of replacement clothing and Grapes for production of wine.

Fig. 8 Vertical Stacked Hydroponics System

It is estimated that 20 m^2 (200 ft^2) is needed to feed one person continuously on hydroponics. For 24 people 480 m2 (4800 ft^2) are needed. With the expectation that food provisioning will be a significant Hermes product and the need to feed guests in the "Hotel", this design will assume 1200 m2 (13,000 ft^2) of six foot stacked hydroponic beds (Figure 8) with mirror directed sunlight supplemented with LED lighting if needed. It is hoped that provisioning business demand will be high and additional Garden and Fish Farm modules will ultimately be required. One current unknown is the need for or alternatives to pollinators (bees, hummingbirds etc.)

Protein: Although some protein will be available from crops, most will come from seafood cultivated within the habitat complex. Aquaculture, AKA Fish Farming uses a filter bed to maintain water quality and remove waste. **Aquaponics** is the combination of aquaculture and hydroponics. In these semi-closed systems, water flows between an aquaculture fish tank and the hydroponics plant growing beds. The fish waste in the water is used to supply nutrients to the plants. The plants and micro-organisms clean the water that is returned to the fish tank. This provides a mutually beneficial environment for both the fish and the plants, and results in two crops (the fish and the plants). Table 2 lists the most suitable fish and crustations for an aquaponic system along with their temperature range and growth rate.

Table 2 Aquaponics Candidates

FISH	TEMP RANGE	GROWTH RATE
Tilapia	18-30	Fast
Trout	14-20	Slow
Catfish	26-30	Moderate
Bass	24-30	Moderate
Salmon	13-18	Slow
Prawns	24-30	Fast

Initial fish stock selected is Hawaiian Gold Tilapia (Figure 9) based on hardiness and fast growth rate[13]. They can grow as big as 40 cm (16 in) with a weight of 1.2 kg (2.6 lbs)! Most importantly this fish is very tough. They can cope with temperatures between18°C and 30°C, poor water quality, pollution, and even low oxygen. They are also largely disease resistant.

Fig. 9 Hawaiian Gold Tilapia

Prawns are an interesting possibility but processing their eggs through larval stages is difficult.

Average protein consumption in the US is about 120 gm/person/day. Tilapia is about 50 % protein. Therefore about 240 gm of fish/person/day is needed to meet the protein needs Fish production requirements are: 240 gm per person per day X 24 people =5.8 kg per day.

As in the case of hydroponics, triple the 24 crew capacity will allow for Hotel guests and fish sales hence 18 kg per day or 6,600 kg year

Based on a density factor of 42 kg/m^3 (2.6 lbs/ft^3), a grow-out tank volume of 160 m^3 (5600 ft^3) is needed. The Grow-Out tank will be an oval configuration to keep fish swimming against optimal current to ensure musculature for firm flesh. This tank will be 1 m (3.3 ft) deep, 16 m (52 ft) long and 10 m (32.8 ft) wide. The Fish Farm habitat can accommodate a second grow-out tank for different species or casualties in the primary tank. The remaining module area provides space for fingerling and finishing tanks. Prior to harvest fish are isolated in finishing tanks and not fed for about a week.

These tilapia can grow to 1 kg (2.2 lbs) size in 8-10 months. They also reproduce rapidly. Terrestrial aquaculture operators need to thin the fingerling stock and/or isolate the females to prevent overpopulation that would result in deteriorating water quality.

These fish have an exceptional Food Conversion Ratio (FCR) of 1.6-1.8:1 (compared to beef cattle FCR at 20:1). Still, to raise over 6,000 kg of fish will require over 10,000 kg of food. In the long term fish food will be derived from food waste. In the short term, the mass budget must allow for 10mT of fish food.

Tilapia grow best at temperatures of 24°C and 30°C, well above the ambient habitat temperature. Water heating will be required. The heating need is exacerbated by the need to pump the water across to the cooler Garden module to nourish the plants. To reduce the electric power drain a solar water heater will be used. See the Architectural Design section for heliostat details.

Ice Mining and Processing of Volatile Products

It is believed that the upper 5-10 cm of regolith is poor in volatiles while the percentage of available volatiles increases from 4 to 10% with increasing depth below 10 cm. The Hermes mining of volatiles from the lunar regolith is done in a series of steps. First the top layer of regolith, believed to be poor in volatiles, will be removed via bulldozing a 12 km trench at 5 kph. Next the rover reverses direction and creeps along while heating the regolith to above 220K with microwaves to sublimate the frozen gases which are then captured in a “Cold Trap” tank trailered behind the rover to remain as close to local ambient temperature as possible to refreeze the volatiles. The rover will return to the starting point after 24 hours. The mining rover then transits to the gas processing facility to offload sublimate and swap the battery. Rover speed and run durations will be optimized once mining begins.

Table 3: Mining Rover Power

Mining Rover Power for 24 hr Mission				
Phase	**Watts**	**KM**	**Hrs**	**Energy (WH)**
Transit to Site X2	150	22	1.5	225
Rover Traction	150	60	24	9000
Microwave Heaters	5,500		24	132000
Rover Heaters	100		24	2400
10% Margin				14000
80% Discharge				41000
	TOTAL (KWH)			**199**

The Mining Rover is illustrated in Figure 10. It utilizes the chassis, microwave heating system and bulldozer blade from the site preparation rover. Both Site Preparation Rovers

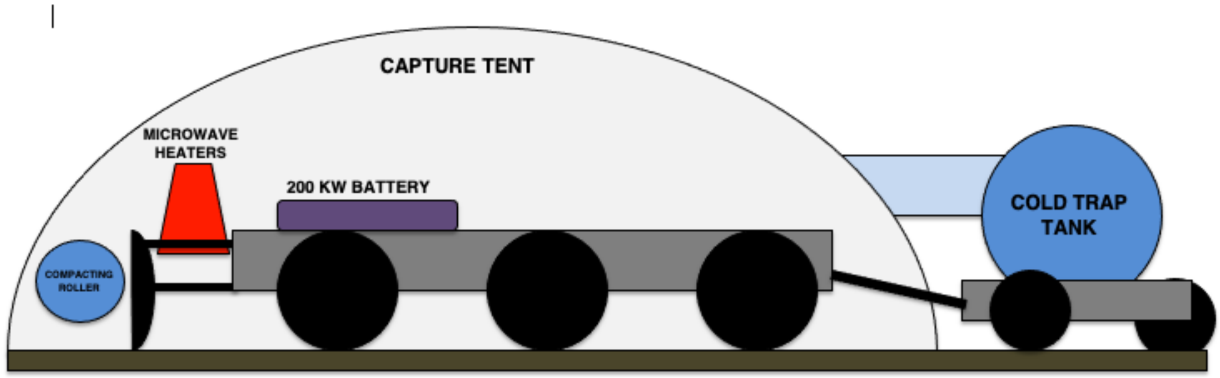

Fig. 10 Mining Rover

will be converted for Mining. A 200 KWH Lithium-Ion battery will power the rover for the 24 hours mining sequence (see Table 3). The battery will also provide additional mass to improve bulldozer effectiveness. A "tent" extending beyond the rover perimeter will be installed. The bottom edges of the tent will be fitted with steel plates to drag through the regolith and minimize sublimate leakage[14].

The microwave heating system described above can heat 900 kg of regolith to 220K in 18 minutes. At 4% water and 85% collection efficiency, the 900 kg yields 31kg of water. For a 24 hour mining run, 2480 kg of water are collected along with 3287 kg of other volatiles. With two mining rovers operating, 4960 kg of water and 6574 kg of other volatiles are collected.

Heating the regolith to free the volatiles is very energy intensive. A 2018 NASA Initiative study[15] is exploring a technique that mechanically sorts the ice grains from the other regolith particles. If effective this would result in an order of magnitude reduction in power required to harvest the ice.

The volatiles reported from the LCROSS mission are listed in Table 4.

From this "soup" of gasses, the following processes are possible:

- H_2O and O_2 for crew use and H_2 and O_2 for propellant
- CO_2, CO and H_2 to make CH_4 via the Sabatier process for propellant and water
- Combust CH_3OH, and C_2H_4 to make CO_2 and H_2O and heat the other processes.
- Electrolyze NH_3 to produce H_2 and N_2 for use as a cabin air diluent
- H_2S and SO_2 to make H_2O via Claus process
- Electrolyze the excess H_2S to produce more H_2 & S.

Table 4: LCROSS Data

Sublimate		**%**
Water	H_2O	43.1
Carbon Monoxide	CO	17.2
Hydrogen Sulfide	H_2S	13.6
Hydrogen	H_2	10.8
Sulfur Dioxide	SO_2	4.9
Ammonia	NH_3	2.5
Carbon Dioxide	CO_2	2.3
Ethylene	C_2H_4	2.1
Methanol	CH_3OH	1.2

Heating of the regolith in the cold trap tank is done in stages to create a cryogenic distillation to separate the different volatiles. This "Step Cold Trapping" is difficult and marginally effective. Another NASA research initiative[16] is evaluating filtering the sublimated volatiles through a sequence of ionic fluids tailored to bind to the expected compounds including CO, H_2S, NH_3, SO_2. This would greatly improve the effectiveness and purity of the final products. The process is illustrated in Figure 11.

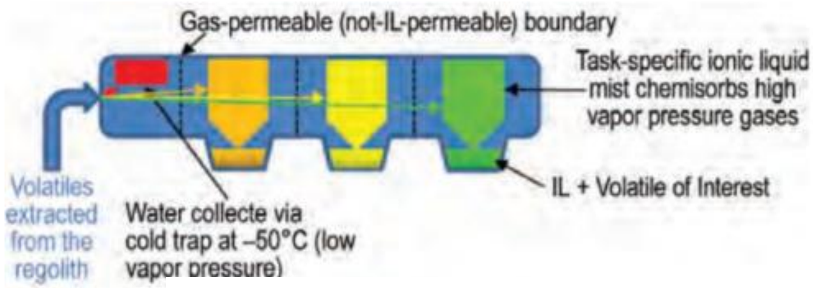

Fig. 11: Ionic Fluid Filter

Evacuated volatiles are further filtered to remove entrained regolith, and contaminants. Selected gasses are further processed and liquefied for storage and distribution (Table 5). Processing the filtered volatiles uses well understood terrestrial industrial processes (Figure 12).

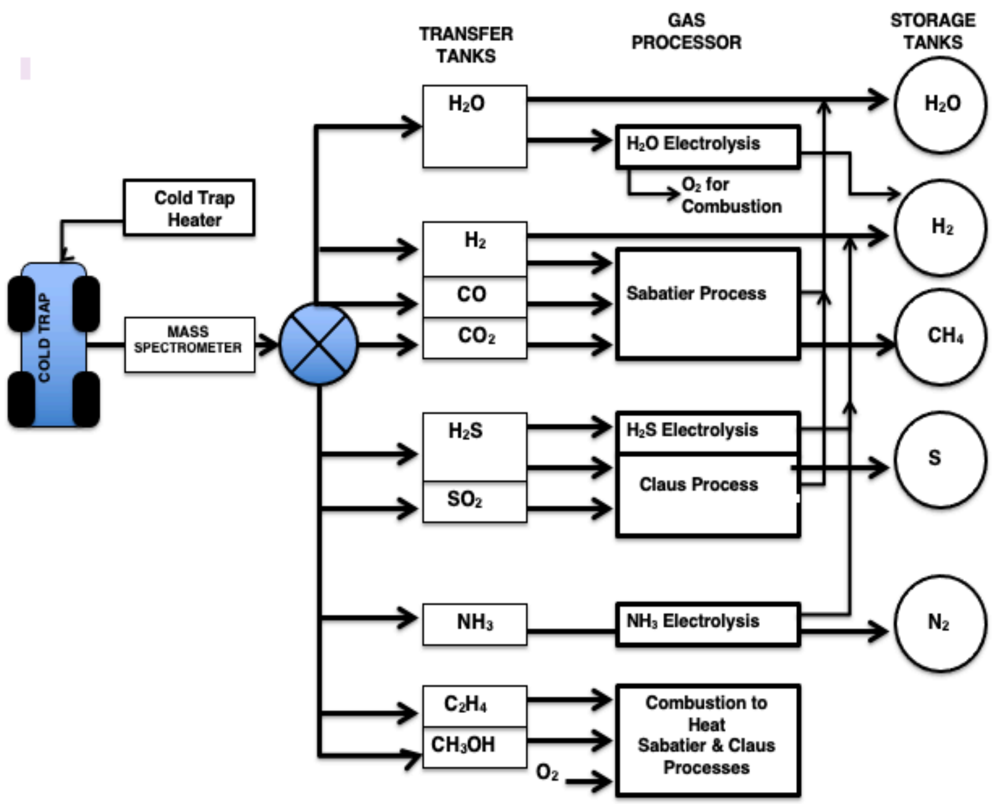

Fig. 12: Gas Processor

Sabatier Process :	$CO + 3H_2 \rightarrow CH_4 + H_2O$ or $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$
Claus Process:	$4H_2S + 2SO_2 \rightarrow 6S + 4H_2O$
Excess H2S electrolysis[17]	$H_2S \rightarrow S + H_2$
Ammonia electrolysis[18]:	$2NH_3 \rightarrow N_2 + 3$ H2

Table 5: Daily Production for One Mining Rover

Substance	Formula	LCROSS %	Input Mass	Process	Description	Output Mass
Water	H_2O	43.1	2480	Electrolysis	Of the initial 2,480 kg, 158 kg are electrolized to produce Oxygen to combust the Ethylene and Methanol and 998 kg are produced by other processes. Net Water is 3,220 kg.	**3220**
Carbon Monoxide	CO	17.2	992	Sabatier	All of the Carbon Monoxide and Carbon Dioxide are consumed in the Sabatier process, yielding 593 kg of Methane and 730 kg of Water.	**0**
Carbon Dioxide	CO_2	2.3	133	Sabatier	An additional 224 kg of Carbon Dioxide is produced in the combustion of Methanol and Ethylene.	**0**
Hydrogen	H_2	10.8	623	Sabatier	195 kg of Hydrogen is used in the Sabatier process; 51 kg are produced from Ammonia and Hydrogen Sulfide production yielding a net 479 kg of Hydrogen	**479**
Methane	CH_4	NA	NA	Sabatier	All of the Carbon Monoxide and Carbon Dioxide are consumed in the Sabatier process, yielding 593 kg of Methane and 730 kg of Water.	**593**
Sulfur Dioxide	SO_2	4.9	283	Claus	Sulfur Dioxide through the Claus process along with 294 kg of Hydrogen Sulfide produces 151 kg of water and 428 kg of Sulfur	**0**
Hydrogen Sulfide	H_2S	13.6	784	Claus	The 487 kg of Hydrogen Sulfide not used in the Claus process is electrolyzed to produce 27 kg of Hydrogen and 460 kg of Sulfur.	**0**
Sulfur	S	NA	NA	Claus	The Claus and H2S Electrolysis will yield 888 kg of S	**888**
Ammonia	NH_3	2.5	144	Electrolysis	Ammonia is electrolyzed to produce 123 kg of Nitrogen and 26 kg of additional Hydrogen	
Nitrogen	N_2	NA	NA	Electrolysis	Electrolysis of Ammonia yields 123 kg of Nitrogen	**123**
Ethylene	C_2H_4	2.1	121	Combustion	Ethylene is combusted to produce 6,436 Mj plus 64 kg of water and an additional 158 kg of Carbon Dioxide to feed into the Sabatier Process.	**0**
Methanol	CH_3OH	1.2	69	Combustion	Methanol is combusted to produce 1689 Mj plus 53 kg of water and an additional 66 kg of Carbon Dioxide to feed into the Sabatier Process.	**0**

Daily production for two rovers will be 6,440 kg of water, 958 kg of Hydrogen, 1,186 kg of Methane, 246 kg of Nitrogen and 1,776 kg of Sulfur. Prior to generating salable products from the thermal mining operation, the Fish Farm tanks will need to be filled with approximately 200 mT of water from the first 31 days of operation.

DUST ABATEMENT: Even though the Hermes System does not move a lot of regolith, the rover will almost certainly return from each thermal mining cycle coated in lunar dust. Getting rid of as much dust as possible after each cycle will minimize maintenance issues. Reference 19 describes a system that generates electrostatic and dielectrophoretic forces using intermittent currents in a spiral grid of imbedded wires. The test conducted in near vacuum conditions, deposited JSC-1 Regolith Simulant on a 10cm x 10cm solar panel and monitored the panel output as their system was energized. The remarkable result is shown in Figure 13.

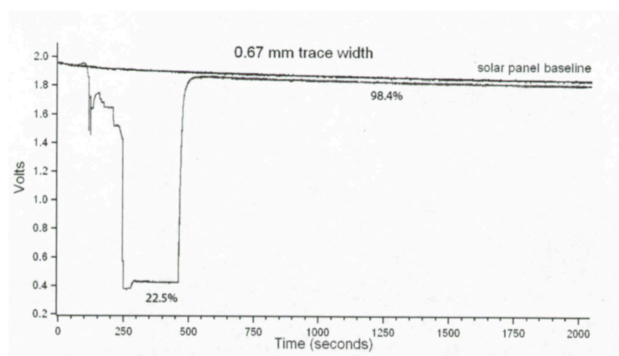

Fig. 13: Electrostatic Dust Removal

Rovers:

There are four rover functions as part of the Hermes concept; Site Preparation, Thermal Mining, Solar Panel Fabrication, and Delivery of Hermes products to other lunar bases. A flexible, adaptable "rover system" is needed. The NASA-JSC Chariot would meet this need[20] (Figure 14). The Hermes Chariot system will use four

Photo Credit-NASA

Fig. 14 NASA Chariot Rover

chassis. Initially, two will be configured for site preparation with bulldozer blades, rollers and microwave sintering equipment. This will provide redundancy and reduce the time to achieve habitat operational status. Once site preparation is complete, both chassis will be reconfigured to begin Thermal Mining from lunar regolith. The third chassis will be configured for production of solar panels from regolith. The fourth chassis will be configured as the small pressurized rover (Figure 15) for product deliveries to other lunar bases and other scientific missions. If we are successful in attracting R&R client from nearby bases, a pressurized rover with increased passenger capacity will be considered.


Photo Credit-NASA

Fig. 15 Small Pressurized Rover

Economic Analysis

Income Projections Some studies[14] of moon base economic viability are based on the United Launch Alliance (ULA) "offer" in 2016, to pay $3,000/kg for Hydrolox in Low Earth Orbit (LEO) and $500/kg on the lunar surface. As this study began it was quickly realized that these numbers were anachronistic artifacts of expendable launch systems. SpaceX has estimated that the steady state launch cost for a mature Starship system could be as low as $2 million, basically the fuel cost. Even if the cost never gets below $10 million it could deliver Hydrolox to LEO for $66/kg for a 4400% profit. (As if Elon wasn't rich enough already!). Even the existing partly reusable Falcon Heavy can deliver propellant to LEO for $1,400/kg. (64,000 kg to LEO for $90 million/launch). Therefore, basing an economic analysis on the ULA numbers is unrealistic. For the time scale of this study, it was assumed that there is not yet a market for large volumes of Helium-3.

But, what then? There are a wide variety of goods and services a moon base can provide to other lunar operations, asteroid mining operators, the scientific community and wider public. This evolved to the Hermes concept of "The Hudson Bay Colony of the 21st Century" Candidate products and services include:

- H_2/O_2 propellant sales (at greatly reduced prices)
- Methane/O_2 propellant sales. If we can refuel Starships on the moon, our net launch costs will be significantly reduced.
- N_2 for habitat and spacecraft cabin atmosphere O_2 diluent
- Sales of Solar cells fabricated in-situ from lunar regolith. Mechanical and micrometeorite damage will create a continual market for replacement solar cells. Once dependable production is demonstrated, subsequent lunar programs will buy from us rather than bringing from earth.
- Vegetables, Fruits and Protein Provisioning for other lunar operations. The value of fresh fish, fruits and vegetables increases exponentially as the appeal of MREs shrinks.
- Possibly O_2, and water plus spares of common items such as ECLS equipment for other lunar bases. We could stockpile needed consumables and critical spares in the former temporary radiation shelter.
- Rest & Recreation site for other lunar base staff. If other commercial sites are austere as expected, this could generate significant income.

- Housing for visiting scientists funded by NSF/NIH grants.
- Housing and support for lunar vacationers. Private rooms, dining room with fresh food, gardens and fruit trees, Exercise in 1/6 G, swimming pool and rover rides. $10 million to launch 24 tourists and $1,000/night is within reach for many.
- Advertising revenue from social media productions. If MKBHD can earn $1 million/year from YouTube this can be real money, though not enough to fund Mars One!
- Site surveys and construction of far side Radio and Ultra-Violet Telescopes. NASA is funding studies of robotic radio telescope construction. Much complexity and risk is eliminated with humans on site.
- Sale of regolith derived aluminum, silicon and iron to on-orbit construction sites when market evolves, delivered by mass driver. Read "High Frontier" and do the math!
- Sale of molecular Sulfur. Hermes will produce 152 kg of sulfur for every metric ton of sublimate processed. This quantity of Sulfur has no clear use. Small quantities can be used for plant nutrients. If new rocket engines are available, Sulfur is a suitable propellant offering Isp's in the 300 sec range and Sodium-Sulfur batteries are possible future energy storage solutions.

As promising as this list may be, quantifying the income potential is impossible. However, economic reality suggests that, if there is a market for these goods and services on the lunar surface, they would have to be priced such that the enterprise is economically viable.

Fortunately, the same shrinking launch costs that reduces potential HydroLox income also makes creation of the moon base far more affordable.

Program cost analysis

The major driver in controlling cost is the selection of the SpaceX Starship. Congress can force NASA to spend a billion dollars per SLS launch but our privately funded, hopefully profitable venture must reap the savings from a fully reusable launch system with an estimated cost to deliver 150 mT to the lunar surface of $10 million! Actually, as mentioned above, the SpaceX estimate is $2 million but this analysis will use the higher $10 million number.

Launch Costs: It is estimated that four Starship launches are required to deliver the necessary crew and equipment to the lunar surface. 1 crew/cargo, 2 cargo and 1 contingency mission. See Appendix A for launch mass estimates. The contingency mission may be necessary due to volumetric rather than mass constraints. Assume $10M per launch. An additional cost will be the "rental" of the crew Starship that remains on the lunar surface for the duration of the four month construction phase. Assume that represents loss of four launch opportunities and is priced accordingly so the total launch cost will be $80M.

Habitat Costs: Lacking cost data for the inflatable habitats, the B330 is used as a point of departure. The main cost element for habitats are the ECLS components. The quoted price for a six person B330 module is $125 M. However, this was for a free flying on-orbit configuration with solar panels, guidance and control avionics and maneuvering thrusters. The basic expandable structure should cost about $75M each. To support 48 people (in the Ops and Hotel Habitats) would require eight B330 modules at a cost of $600M. Interior furnishing cost is estimated at $16 M. Connecting tunnels, access and EVA hatches with associated safety equipment and regolith mitigation equipment is estimated at $40M. This includes 5,280 person days of MREs for about $45,000. The microwave system for site preparation is costed in the Mining section.

Construction Crew Salaries: This estimate is based on the most dangerous terrestrial job, saturation diving (40 times the normal occupational death rate). Deep diving offshore oil workers can earn $2,000/day. At this basic rate, a crew of 20 working on the lunar surface for four months will cost a total of $4.8M.

Operations Crew Salaries: During the construction phase, the operational crew will be working alongside the construction crew with the same risk profile. They will therefore get the same compensation, $2,000/day. Total cost for this phase is $5.8M. For the remainder of the first year the salary level will drop to $500/day with possible "hazard" pay for staff working mostly outdoors (mining, solar cell production and habitat maintenance). These eight staff will earn $1,000/day. Total salaries for first year will be $ 9.6M.

Power Generation: The 132 kW solar power system including power management and inverter electronics will be derivatives of existing products. The engineering to design and fabricate the sun tracking pedestals and packing the panels for launch will be a custom effort. The Power Generation package is estimated to cost $30M including $10M for backup battery modules based on Sion 650 wh/kg architecture.

Mining & Processing Equipment: The microwave heating system, sublimation tent and vapor extraction equipment on the mining rover and gas processing equipment will all be custom designed and fabricated. $100M is budgeted for mining equipment. This estimate will be refined based on results of the VIPER Mission.

Rovers: The prototype CHARIOT rover cost $3M. The estimated cost for four chassis plus non-recurring engineering for larger cabin, extended range and fitting different payloads is $15M.

The total cost estimate is shown in Table 6. Who would have thought one could build a 24 crew moon base for less than the price of one SLS launch!

Table 6 : Cost Summary

ITEM	COST ($M)	
Launch Costs	$	80
Habitats	$	656
Construction Crew	$	5
Ops Crew (1 year)	$	10
Power System	$	30
Mining Equipment	$	100
Rover	$	15
Total	**$**	**895**

Architectural Design

Based on the habitat technical design described above. The Hermes base will consist of four 30 x 40m inflated modules with 1.5m of regolith shielding. How do we use this space to provide an effective, safe and comfortable work environment? Crew and visitor rooms will be a common design as shown in Figure 16. Queen beds are selected to accommodate possible couples and as emergency capacity in the event of a habitat failure. The psychological benefits of house plants and pets are addressed in this design. Each housing unit will include a 4 m^2 (40 ft^2) "Garden Wall" and a 2,000

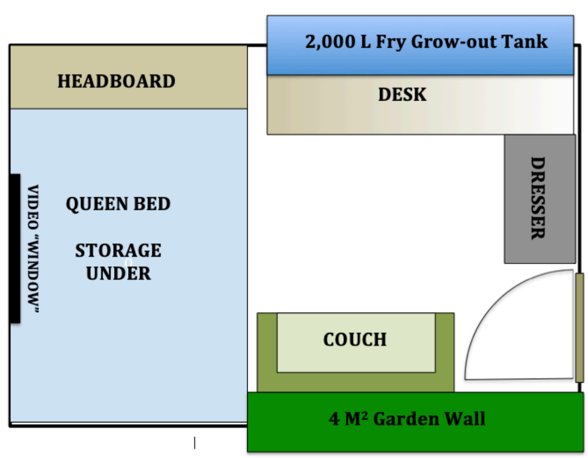

Fig. 16 Crew & Visitor Rooms

L (600 gal) fingerling grow-out tank shared between adjacent rooms with a privacy screen between. Fingerling tanks are used rather than adult grow-out tanks to avoid the problem of crew members developing attachments to large adult fish and becoming reluctant to harvest them for food. Tank filtration includes passing the water over the root beds of the garden wall plants to nourish them.

Windows are impractical given the 1.5m (5 ft) thick shielding but each room will have a 1.5m (60 in) diagonal LCD screen displaying signals from a steerable exterior mounted camera.

The notional interior layouts for the four different habitats are shown in Figures 17-20.

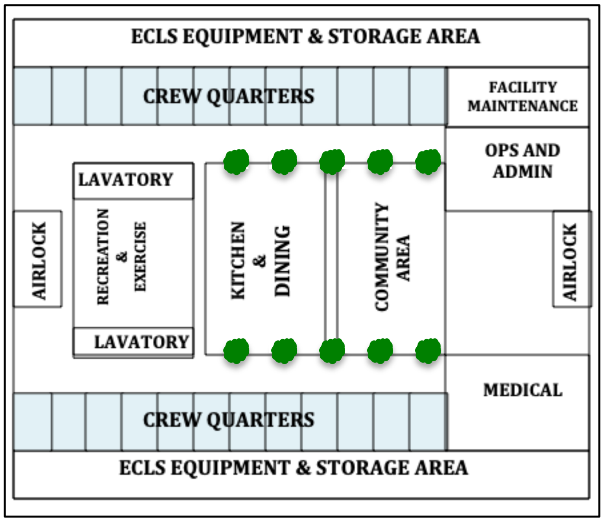

Fig. 17 Operations Habitat

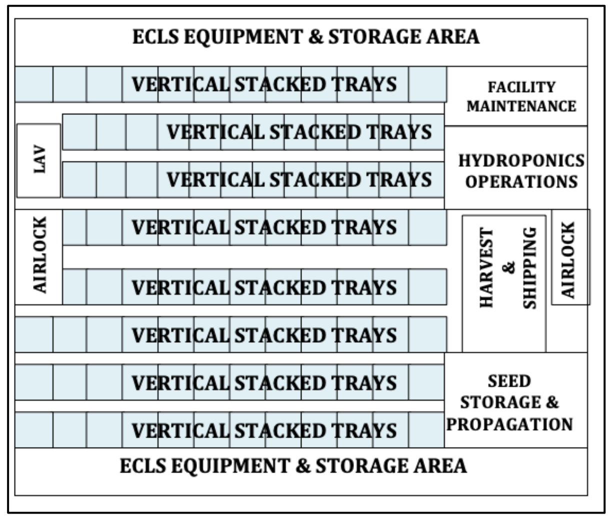

Fig. 18 The Garden

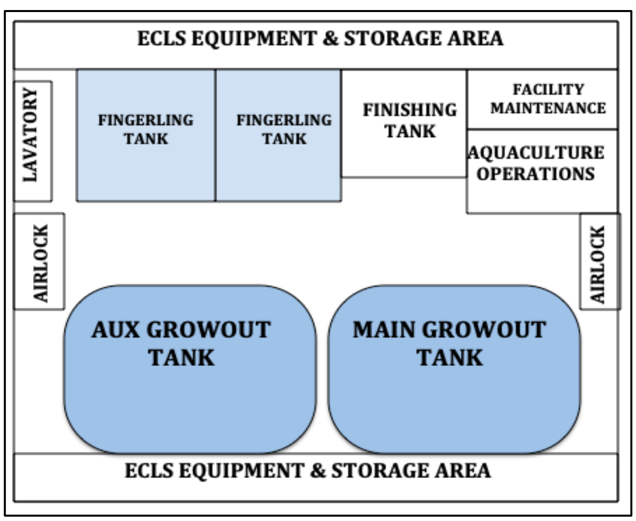

Fig. 19 The Fish Farm

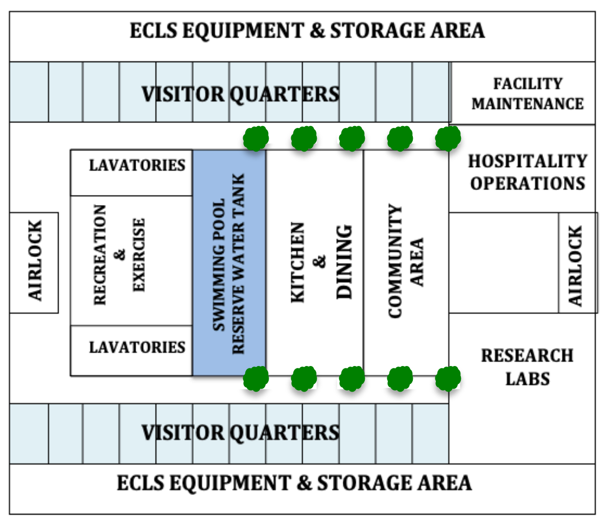

Fig. 20 The Hotel

The four modules are connected by a cross tunnel with airlocks as shown in Figure 21. The exterior airlocks will include a regolith mitigation cell to clean the suits prior to doffing. This will minimize inspiration of regolith. The Operations module has a separate airlock to directly access the small pressurized rover.

Habitat Lighting:
Interior illumination will be provided by a centrally located rotating heliostat located above the junction of the connecting tunnels, that focuses sunlight down to a stationary four facet mirror that directs light towards all four modules simultaneously. Light enters the habitat modules through clerestory windows above the main airlocks. Further internal distribution will be by additional mirrors as needed.

Sunlight above the atmosphere is 150,000 lux (lumens/m2). A well lit office illumination is 500 lux. That ratio (500/150000) allows calculation of the required collection area. Using 4,000 m2 as the area to be illuminated, the required heliostat area is 13.3 m2. An additional 6 m2 of collecting area will supply 9,000 watts for water heating. Heliostat diameter is 2.5 m

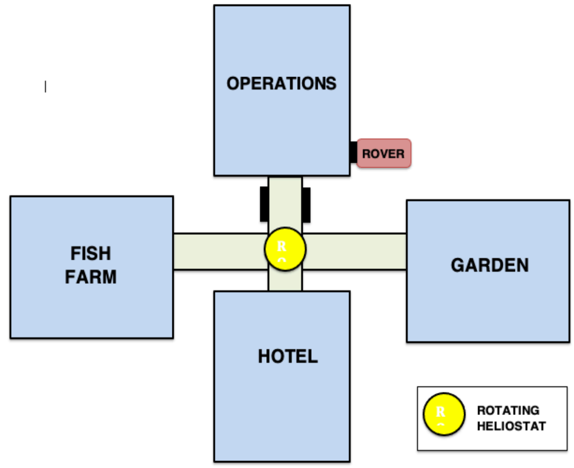

Fig. 21 Four Module Plan

The Operations and Hotel habitats have dwarf fruit trees throughout the dining and community common areas.

Moon Base Crew and Governance

Hermes focuses on developing products and services for sale to other lunar bases and asteroid mining operations as well as hosting visiting scientists and tourists. The skill distribution of the multinational crew will therefore mirror terrestrial industrial, retail and hospitality businesses. Nominal crew assignments are shown in Table 7. Given the Hermes concept of selling to and hosting crews from other lunar bases as well as international scientists and visitors, one or more crew members will be fluent in Chinese, Japanese, German, French and Russian. Hermes will also afford opportunities for rotating national crews of 6-8 members with skills consistent with staffing needs.

It is assumed that Hermes is funded by earth-based venture capitalists. The crew's contract includes provisions for the financial success of the venture to result in growing ownership stake for the crew, moving towards majority ownership and autonomy.

Table 7: Crew Assignments

Assignment	Quan	Notes
Manager	1	
Assistant Manager	1	Manages all HR Functions
Doctor	1	2 other crew members qualified Paramedics
Nurse	1	
Habitat Engineering	3	Facility maintenance & Upgrades
Hydroponics	3	Establish & Maintain vegetable & fruit
Aquaculture	3	Establish & Maintain seafood production
Volatiles Mining	4	Configure and operate thermal mining system
Social Media Specialist	1	
Sales & Marketing	1	
Research Coordinator	1	Manage visiting scientist program
Hospitality Operations	2	Manage visits of scientists and tourists
Cook	2	Assisted by Hydroponics & Aquaponics Staff

Governance Concepts

In researching governance and societal frameworks for Hermes, an amazingly large and diverse collection of corporate, academic and governmental perspectives were encountered. In the short term the following [21] seems to be the best fit.

"Safety is going to be first and foremost on everyone's mind, so a very strong safety regime will be installed so no one can accidentally or maliciously cause a system or cascade failure that will threaten the colony. The "crew" of technical staff which run the systems will be built and operated on military lines, with clear lines of authority and responsibility to ensure everything really is accounted for. In that sense you will be living aboard an aircraft carrier with a Captain who is the ultimate authority

.But not everyone will be crew, and even the crew will need to be able to express needs that are not directly related to safety. So there will be a sort of "town hall" democracy among the passengers and crew for what might be considered "non life threatening" matters, although even decisions reached by the town hall meeting will probably need to be approved by the Captain in order to ensure they don't interfere with the safety of the colony.”In the longer term, when relationships among different bases or colonies become significant, ESA’s concept[22] contains hopeful perspectives.

“ESA’s concept development of the “Moon Village” does not refer to an earthly housing and shopping development, but a “community created when groups join forces without first sorting out every detail, instead simply coming together with a view to sharing interests and capabilities,” (ESA). The association proclaims equal opportunity for robotic and astronaut activities, multi-party and nation unity, scientific and non-scientific pursuits, and the ability for nations to leave behind any differences on Earth. Its planning has also been propelled by the Moon Village Association, a non-governmental organization striving to start international discussions and formulation of plans to foster establishment of the Moon Village.”

A notional schedule for Hermes build-out is shown in Table 8

Table 8 Hermes Base Build-out

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
Cargo Starship to Moon	■																						
Crew Starship to moon		■																					24 Crew and 20 Construction Workers
Unload Cargo			■	■																			Staff live in Crew Starship during construction
Cargo Starship Returns to Earth					■																		
Site Survey					■																		Site Preparation Robot is on critical path
Build Radiation Shelter						■																	
Build Operations Hab Shell							■	■															
Build Garden Hab Shell								■	■														
Build Fish Farm Hab Shell									■	■													
Build Hotel Shell										■	■												
Install & Test ECLS									■	■	■	■	■	■	■	■							
Interior Partitions & Furnishings										■	■	■	■	■	■	■	■						
Operations Crew Moves into Habitat												■	■										
Produce Water for Fish Farm										■	■	■	■										
Production of Propellant and Nitrogen														■	■	■	■	■	■	■	■	■	
Site Prep for Add'l Garden and Fish Farm												■	■										
Build Landing Pads and Berms													■	■	■	■							
Crew Starship Returns to Earth																	■						Construction staff returns
Cargo Starship Returns to Moon																		■					Consumables plus Starter Plants & Fish

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Appendix A
Starship Payload Mass Estimates

LAUNCH	CONFIG	PAYLOAD	MASS (kg)
1	Cargo	Habitat components	
		-Bladders	9500
		-Support Arches	500
		-Interior Furnishings	15,000
		-ECLS Equipment	25,000
		-Nitrox tanks & gas for inflation (45x 0.27m3 @ 690 bar)	19,700
		Chassis 1 & 2 with Site Prep Rover Payloads	5,000
		Solar Panels & Electronics	4,000
		Backup Batteries	6,000
		Mining Rover Payload X2	3,000
		Gas Processing Equipment & Add'l Storage Tanks	12,000
		Total	**100,700**
2	Crew	24 Operational Crew & personal effects @ 400kg	9,600
		20 Construction Crew & personal effects @300kg	6,000
		44 people/day MREs (@ 700g/meal) for 4 months	11,000
		Water @ 12L/crew/day for 4 months	63,300
		Chassis 3-Small Pressurized Rover	3,000
		Backup Batteries	6,000
		Total	**98,900**
3	Cargo	Hydroponics Seed Plants	5,000
		Aquaponics Fingerlings (in water)	50,000
		Plant Nutrients	4,000
		Fish Food	10,000
		MRE supply 24 crew for 8 months	12,000
		Water for Reserve Tank/Pool in Hotel	8,000
		ECLS and other Spares	10,000
		Chassis 4-Solar Panel Production Robot	1,500
		Total	**100,500**