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Lunar Surface Habitats as a Development Opportunity for Mars Surface Life Support Systems

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The development of Mars surface systems will require extensive development testing to make a first-time human mission to Mars successful and cost-effective. As our nearest surface destination, the Moon provides excellent surface systems analogs and learning opportunities to develop Mars mission equipment, systems, processes and procedures. Among other systems and technologies capable of being tested on the Moon, a lunar habitat is ideal to test many ECLSS technologies and development sensitive architectural features. This paper will outline the path Mars ECLSS surface systems development must take to successfully establish and utilize a lunar habitat test bed by identifying the major steps and capabilities required, when these capabilities must be implemented to meet an achievable timeline for a mission to Mars and what other development must happen in parallel. Any long-term-stay surface habitat ECLSS will have many commonalities but also many major differences with the International Space Station, Space Shuttle and the Apollo Program ECLS Systems. These commonalities and differences will be discussed. The benefits of this approach to achieving a successful Mars mission will be summarized.

Nomenclature

AAA = *Avionics Air Assembly*
ACS = *Atmosphere Control & Supply*
AR = *Atmosphere Revitalization*
BVAD = *Baseline Values and Assumptions Document*
CAMRAS = *CO2 and Moisture Removal Assembly*
CCAA = *Common Cabin Air Assembly*
CDRA = *Carbon Dioxide Removal Assembly*
CHX = *Condensing Heat Exchanger*
COTS = *Commercial Off The Shelf*
CRD = *Cascade Rotary Distillation*
ECLSS = *Environmental Control and Life Support Systems*
EMU = *Extra-vehicular Mobility Unit*
EVA = *Extravehicular Activity*
FWM = *Fine Water Mist*
FDS = *Fire Detection and Suppression*
HEPA = *High Efficiency Particle Air*
HPGT = *High Pressure Gas Tank*
HPOGA = *High Pressure Oxygen Generator Assembly*
HTCO = *High Temperature Catalytic Oxidation*
HTV = *H-II Transfer Vehicle*
I/F = *Interface*

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IMV = *Inter-Module Ventilation*
ISRU = *In Situ Resource Utilization*
ISS = *International Space Station*
MCA = *Major Constituent Analyzer*
MCCD = *Modified COTS Commercial Distillation*
MPAM = *Multi-Platform Air Monitor*
OGA = *Oxygen Generation Assembly*
NORS = *Nitrogen Oxygen Recharge System*
PCA = *Pressure Control Assembly*
PEV = *Pressure Equalization Valve*
PFE = *Portable Fire Extinguisher*
PPR = *Positive Pressure Relief*
PSE = *Pedestrian Surface Excursion*
PWD = *Potable Water Dispenser*
RTCCS = *Regenerative Trace Contaminant Control System*
RSE = *Rover Surface Excursion*
TCs = *Trace Contaminants*
THC = *Temperature & Humidity Control*
TRL = *Technology Readiness Level*
UPA = *Urine Processing Assembly*
USOS = *United States Operational Segment*
UWMS = *Universal Waste Management System*
VCD = *Vapor Compression Distillation*
VRA = *Volatiles Removal Assembly*
VRV = *Vent & Relief Valve*
VS = *vacuum System*
WM = *Waste Management*
WP = *Water Processor*
WPA = *Water Processing Assembly*
WRM = *Water Recovery & Management*

I. Introduction

MARS surface exploration presents a significant challenge in the development of robust surface systems that keep the crew alive and healthy and enable a wide variety of exploration objectives. Challenges of the Mars surface environment include: 1) partial gravity systems operation versus 1G earth normal or µG ISS, 2) unknown dust environment, 3) unknown ISRU availability, 4) high-rate surface excursion expectations, 5) lack of quick escape, 6) cost and difficulty of logistics resupply, 7) potential for long dormancy periods between visiting crews, and 8) large communication lag with Earth.

Given these challenges, the benefits of an extensive development and test program using the lunar surface start becoming clear. Such a development program would allow for next generation systems designed to take advantage of partial gravity and ISS heritage systems with design improvements for radiation, dust, reliability and maintainability to be demonstrated and issues worked out before sending equivalent systems to Mars, thus significantly improving the potential for reliable and robust systems to be deployed. Experience with high-frequency surface excursions, while also battling extremely challenging surface dust, would teach designers how to build systems that are dust tolerant and reliable in such an environment. Development of ISRU technology and experience actually producing useable ECLSS resources would inform program planners on what would be required to send ISRU systems to Mars, how to plan crew interaction and what the potential paybacks would be. Finally, whether planned or not, long dormancy periods may occur with a lunar surface habitat, and precautions used to prepare potential sensitive systems could be tested for efficacy and dependability, informing program planners how to manage a Mars outpost for gaps between crew visits.

As our nearest surface destination away from earth, the Moon provides excellent surface systems analogs and learning opportunities to develop Mars mission equipment, systems, processes and procedures. The local proximity, partial surface gravity, dust environment, ISRU potential and anticipated dormancy periods all become powerful informants to build experience and knowledge that all work to make a Mars mission more successful.

To more clearly define this development opportunity, this paper will outline the path Mars ECLSS surface systems development must take to successfully establish and utilize a lunar habitat test bed by identifying the major steps and capabilities required, when these capabilities must be implemented to meet an achievable timeline for a mission to Mars and what other development must happen in parallel. This paper will also discuss EVA and its impact on the habitat ECLS system. This path shows where testing on the lunar surface provides clear advantages over ground or ISS testing.

The results of this study will better inform technology development planners on the challenges and timelines required for the successful development of Mars surface life support systems and the advantages of a large scale technology testing program on the lunar surface.

II. Challenges and Benefits of a Lunar Habitat as a Test Bed for Mars ECLS Systems

The next generation of life sustaining systems used for space exploration will need to be more reliable and serviceable at a deeper level as compared to the systems that are in use on the International Space Station (ISS). The ISS was designed as an outpost for performing science in a micro gravity environment and the thought of having the astronauts spending time servicing equipment while on board was considered unacceptable when the ISS was conceived. The concept was to utilize Orbital Replacement Units (ORUs) so that if a system went down the astronaut would simply pull out the failed ORU, replace it with another ORU and send the failed ORU back to earth for refurbishment or replacement. This approach works if there is a convenient way to transport equipment back and forth and an ample supply of spare hardware exist.

Lessons learned from 16 years of experience on the ISS have shown that having some degree of sub-component serviceability is highly desirable. The amount of ECLSS cargo that is shipped to the ISS averages 1052 kilograms per year (see Table 3) and requires multiple cargo vehicles launched from Earth. This is something that is not practical when going beyond LEO. Systems need to be designed that can be easily repaired and thoroughly tested before going to Mars.

<u>CHALLENGE</u>: Several of the challenges that will be faced on Mars will be similar on the moon. These challenges include the use of in-situ resources, temperature extremes, dust mitigation, working in a partial gravity environment, robotic operations, communication protocols, remote medical treatments, physiological effects, radiation effects, performing science experiments, building habitats, and performing routine EVA's. One of the biggest challenges will be the development of life support systems that will be extremely reliable but can be easily serviced when required. These systems include water processing, oxygen generation, air revitalization, and waste management. Although all of these systems exist in some form on the ISS their transition to a surface habitat will require extensive development.

<u>BENEFIT</u>: In order to thoroughly test the required systems for a Mars habitat an analog to Mars must be considered. A habitat on the lunar surface would have significant benefits for understanding what would be required for sustained life on another planet. The moon has several attributes that make it a desirable first step. First is its proximity to Earth. The estimated travel time to the moon is less than 3 day versus a trip to Mars that could take up to 10 months depending on the position of the planets. Even with optimal alignment of the planets a trip would still take more than 39 days with the fastest propulsion currently in existence.[i] If an emergency requires someone to be evacuated for medical reasons their chance of survival is greatly increased the closer they are to medical facilities. In addition supplies can be sent if the program planner's estimates do not work out as originally planned.

Dust mitigation systems and dust-tolerant mechanisms will be needed for both lunar and Mars surface systems. These will include: 1) devices to remove dust from crew members EMUs and equipment before coming into the habitat through airlocks or suit ports; 2) devices inside the habitat to collect dust that gets in and remove it from the atmosphere and interior habitat surfaces such as electrostatics, cyclones and HEPAs; 3) ventilation architecture design; 4) structure design, including multiple living levels, open grid work, automated sweepers, etc.; 5) hatch and valve mechanisms and seals that are easily replaceable; 6) windows radiator panels and solar arrays; 7) devices that function outside the habitat (e.g., camera or antenna pointing mechanisms etc.).

Surface habitats are envisioned to host multiple EVAs per week over months of time per increment crew visit, therefore new and clever ways to egress/ingress habitats, don/doff EMUs and control dust migration will be needed along with a host of other related features/equipment not conceived of today (in addition to dust mitigation features noted above) that are not needed on ISS today or were not employed for Apollo excursions due to their extremely low quantity and duration compared to current plans (or lack of awareness for need), but will become obvious once humans begin living and working on the Moon.

Surface systems deployment tackles the job of transporting large structures from landing sites to specific desired locations and positioning them in useful relative positions to each other. This is a totally new challenge for space systems architecture, but one that must be developed since relying on pin-point landing and never having to move these large elements is not realistic.

ISRU (extracting and processing water from lunar regolith) has a strong potential to reduce logistics burdens[ii] but requires new technology development to safely capitalize on the local resources. Chiefly envisioned are robotic devices designed to seek out, gather and return ice and/or liquid water to the habitat to be fed into a processor specifically designed to pre-process lunar water/ice to make it compatible with interior habitat water processing equipment and crew consumption. While this new equipment might seem heavy and complicated it will no doubt offset logistics water delivery mass (and cost) in a very short time and as first generation systems are built and tested, improvements will become obvious for second generations (Mars) systems, making them more robust and reliable.

By diving head-first into these new challenges on the moon a generation of engineers will reap the benefits of climbing the learning curve, reducing cost of development and dramatically reducing the risk of failure at Mars by increasing reliability and developing a better understanding of the resources needed (spares, consumables, etc.).

Table 1 shows a comparison of a Lunar Base to Mars/Lunar Orbit/ISS/Ground Analogs for ECLS system testing, highlighting advantages of using the Moon to reduce risk related to a first habitat deployment on Mars.

	Earth	ISS	Cislunar	Moon	Mars
Dust Mitigation	X			X	X
Temperature Extremes		X	X	X	X
Partial Gravity				X	X
EVA Frequency				X	X
ISRU				X	X
Radiation Mitigation			X	X	X
Tele-robotic Surface Operation	X			X	X
Communication Protocols	X		X	X	X
Building Habitats	X			X	X
Physiological Effects		X	X	X	X
Science Experiments		X	X	X	X

Table 1: Relevant Environments for Testing

III. Lunar Habitat: Technology Trades and Benefits

A. Lunar Habitat Considerations:

Habitat design: Based on the NASA Baseline Values and Assumptions Document (BVAD), and in keeping with last year's paper [ii], a crew of four astronauts is expected to inhabit the lunar habitat. It provides living space and all the basic life support functions typically expected of a deep space habitat such as is found on ISS today, like Atmosphere Control & Supply (ACS), Temperature & Humidity Control (THC), Fire Detection & Suppression (FDS), Atmosphere Revitalization (AR), Water Recovery Management (WRM), and Waste Management (WM). In addition, microbial sterilization will be an important new system and/or addition to existing fluid processing systems to manage planetary protection protocols, long term trash storage, and anticipated fluid system dormancy periods between visiting expedition crews.

Habitat structure: A surface habitat could be rigid or inflatable and in either case will likely be cylindrical. Inflatables are expected to weigh somewhat less and be more compact at launch than rigid structures. That does not make them a slam-dunk choice. Certain features cannot be installed in advance or positioned structurally for launch from earth and landing on the moon or Mars in inflatables like they can in rigid structures, so astronauts would have to do a substantial amount of "activation assembly" upon arrival. This situation may allow the inflatable habitat to take more landing G's than a rigid structure, thus allowing for a lower mass (& cost) landing system. By designing a habitat that has the crew install the systems after inflation, those systems would have to be more flexible in their installation design and be easily fitted into a number of different size habitat structures. Conversely, systems cannot be completely "checked out" prior to launch/delivery and issues could result during installation that may risk early crew occupancy. Rigid structures also have the ability to carry the atmosphere with them and not need compressed gas in tanks to inflate them after arrival.

The advantages in size, shape and overall lower weight make an inflatable habitat the most beneficial choice for an early lunar base test bed and more likely for an early Mars habitat as well. Experience with deploying an inflatable habitat (either by humans or robotic pre-cursors) on the moon may provide extremely valuable insights for Mars mission designers.

Habitat location: As determining a specific lunar habitat location has its own challenges worthy of whole separate papers, it is assumed that the lunar South Pole will be favorable to both sunlight and ISRU materials, as defined in the current NASA Design Reference Mission (DRM). ISRU sourcing will need precursor robotic prospectors to inform program management, and must be funded and scheduled in time to allow for results to be factored into the habitat location selection. This may, in turn affect the detailed design of a habitat and ISRU equipment. Finally, it must be decided if a habitat will reside above ground or below ground (e.g. lava tube).

Power/Thermal: A lunar South Pole location potentially supports near continuous sunlight, which would be optimal for a habitat test bed. Given the potential for habitat sites to be anywhere on the lunar surface with night periods of up to 2 weeks long and unknown dust issues on solar panels and radiators, an RTG thermal nuclear power source for the habitat as an alternative to large dust sensitive solar arrays should be considered. This also allows designers and operators to get experience with transporting, installing and using them safely, should they be considered for a Mars mission.

Thermal radiators will be assumed to *not* be body mounted to the habitat since an inflatable structure has been chosen for this study and the habitat may be covered with regolith or located underground for radiation protection. A radiative thermal surface structure near the habitat with fluid line connections to the habitat will be needed. Articulation of the thermal radiators may be required to achieve efficient thermal radiation performance over the course of the lunar year.

B. Lunar Habitat ECLSS Systems:

Since humans are the same everywhere, lunar surface ECLS systems will be designed as close to Mars requirements as possible, while operating on the Moon. All subsystem controllers will need to be radiaiton hardened and gravity should be exploited to the fullest extent possible to simplify components and reduce weight.

For subsystem technologies Table 2 captures the authors' thoughts on useful ISS designs and where departures from ISS may be beneficial to a lunar/Mars habitat, thus creating a basis for development test plans.

Atmosphere Control & Supply (ACS): Key ISS ACS technologies include the PCA, HPGTs, NORS, and various regulators and valves. They are not generally gravity sensitive and have proven to be very robust and dependable components on Apollo, Shuttle and ISS. An ISS ACS system could easily be envisioned for a lunar base. That said, HPGTs are relatively large and less efficient (weight and volume of HPGT per pound of useable gas) compared to NORS tanks. Therefore it is expected that NORS will be the gas transport standard for the foreseeable future. Given advances in computer technology it is possible the PCP firmware controller could be reduced in size or separated from the gas introduction valve assembly.

The biggest concern for ACS will be damage to any/all valve and regulator seats exposed to dust. This is a new concern compared to ISS and dust-damage-tolerant seals need to be developed and demonstrated. This would be considered a high priority and might even warrant a precursor tech demo on the lunar surface. At a minimum vacuum vent valves, relief valves, etc. will have to be designed for easy seal replacement, something not currently possible with ISS hardware, and redundancy will be important to allow for continued system operation while maintaining a contaminated and leaky valve.

Oxygen Generation: With EVA suit designers desire to go to 3000 psia suit oxygen tanks and with no Shuttle to refill gas storage tanks, a High Pressure Oxygen Generation Assembly (HPOGA) is an attractive option for surface based operations. Reducing the cell stack size to support 4 crew while maintaining some margin to fill tanks when needed, the stack should still be smaller than the ISS's ~ 11 person equivalent maximum output, especially considering continuous sun or nuclear power, which will also allow for reduction in the size and weight of the power supply. Removing requirements for a dome and eliminating the hydrogen sensor ORU and nitrogen purge ORU, based on ISS operational experience and with Safety concurrence, will add to the size reduction, simplification, robustness and maintainability of an exploration-class HPOGA.

Temperature & Humidity Control (THC): Key THC technologies include fans, CHX coatings, filters, etc. ISS USOS fans have not required a single change out in 15+ years of continuous operation due to a failure, therefore one would feel safe in using these designs for a lunar base. ISS requirements drive ventilation to be almost uniform throughout the habitable volumes to avoid "pockets" of CO_2, etc. A gravity based habitat may not need as stringent ventilation requirements since free convection will be at work.

Function	Component or ORU	ISS record	Gravity sensitivity	Total Pressure sensitivity	Lunar Hab candidate	Dust sensitivity	Dormant Sensitive	Mods for Lunar Hab	Mars Δs from Lunar design	Comments
ACS	PCA	Excellent	None	None	Yes	No	No	1, 4	No	10.2 psia
	VRV	Excellent	None	None	Yes	Yes	No	6	No	Seal R&R
	HPGT	Excellent	None	None	No	No	No	N/A	N/A	Use NORS
	NORS	TBD	None	None	Yes	No	No	None	None	Use as is
	Valves & Regulators	Excellent	None	None	Yes	No	No	None	None	Use as is
	OGA	Excellent	None	None	No	No	Yes	1,2,3,4,5,10		HPOGA
THC	Inlet ORU	Excellent	None	Yes	Yes	Unknown	No	None	None	Use as is
	CHX	Contam	Yes	No	Yes	Unknown	No	7, 8	None	No coating
	AAA	Good	None	Yes	Yes	None	No	9	None	Use as is
	Water Sep	Good	None	None	N/A	Low	No	2	None	Use gravity
FDS	Smoke detectors	Excellent	Yes	None	No	Yes	No	N/A	N/A	Try COTS
	PFE	N/A	None	None	Yes	None	No	2, 3	None	CO2 & WM
AR	CDRA	Marginal	None	Yes	No	Yes	No	10	None	Next gen needed
	TCCS	Excellent	None	Yes	Yes	None	No	2, 3, 10	None	Regen Charcoal?
	MCA	Good	None	None	No	None	No	N/A	N/A	Use MPAM
	Sabatier	Good	None	None	Yes	Yes	Yes	2,3,8	None	I/F control
WRM	WPA	Good	None	None	Yes	None	Yes	1, 2,3, 4, 5, 6, 8, 10	None	Elim seals, reduce reactor temp,
	UPA	Good	None	None	No	N/A	Yes	8	None	Try COTS
	W&HC	Good	Yes	None	Maybe	None	Yes	8	None	UWMS?
VS	PPT	Excellent	None	None	Yes	Unknown	No	N/A	None	Use as is
	PGT	Good	None	None	Yes	Unknown	No	N/A	None	Use as is
	CCT	Good	None	None	Yes	Unknown	No	N/A	None	Use as is
	Vent Valve	Excellent	None	None	Yes	Yes	No	6	None	Seal R&R

Table 2 - ECLSS Functions from ISS to Mars

Mod legend: 1: radiation harden, 2: size reduction, 3: weight reduction, 4: CPU reduction, 5: crew size capacity reduction, 6: seal re-redesign, 7: coating removal, 8: Take advantage of gravity, 9: in-line cleanable filter added, 10: re-design or new technology

Additionally, a lower total pressure habitat means lower mass flow for a given fan RPM. Faster fans mean higher acoustic signatures. A detailed analysis will have to be performed to determine the best balance point between good mixing, adequate filtration and crew comfort in a partial gravity environment. As the gravity on the moon is less than Mars the analog is close but not quite the same, so results would still have to be interpreted for a Mars habitat ventilation system design. CHX hydrophilic coating contamination is a known and current ISS problem that will very likely follow humans around the solar system. Note that a CHX coating was used on ISS to avoid water droplet carryover in µG. While lunar g is small it may be enough to avoid use of a coating altogether and eliminate one problem completely.

Unsealed bearings have been an issue for ISS hardware. Not so much on-board ISS (no fan failures) but for dormant spares, particularly those components stored on earth. Spares need to be rotated once a year to re-mix grease to avoid loss of oil due to separation when lunar habitat pre-positioned spares are static. Finally, HEPA filtration has been adequate on ISS. In a surface habitat gravity will help filter the air, but it will be interesting to see how things work in 1/6 g over time.

Unfortunately surface dust adds a very complicating factor that cannot be simulated on ISS and for which ISS hardware was not designed. Several new devices are envisioned for dealing with dust brought into the habitat from frequent repeated ingresses from outside. Those include cyclonic separators, electro-static concentrators, sticky mats and a habitat architecture designed with zones, features and ventilation patterns specifically intended to combat and control dust migration. This will be a huge area of emphasis and learning on the moon to ensure a demonstrated and robust design to Mars.

Fire Detection & Suppression (FDS): ISS has two types of fire extinguishers: CO_2 and water mist. They are big, heavy and fortunately have yet to be called in to service to fight a fire. These types of fire extinguishers are needed because conventional terrestrial extinguishers have chemicals not suitable for long term human exposure and use in a closed environment. Each design has its merits and issues, so for now both types are envisioned to move forward.

Smoke detectors on ISS, while robust and long lived (only one replacement in 15 years) are relatively big and bulky, and due to µG had to be placed in the ventilation stream to function. It is expected that a surface habitat will have the advantage a terrestrial home does and relatively fewer SDs can be used in strategic ceiling locations to cover the habitat. One can envision modern low cost COTS devices to be in play here.

Atmosphere Revitalization (AR):

- **CO_2 Removal**: With ISS increment crew experience growing with every year of ISS operation, it is becoming evident that carbon dioxide partial pressures for long duration crews must be lower than ISS requirements. ISS currently tries to maintain about 3.0 mm Hg $ppCO_2$ daily average (well below the ISS spec value of 5.3 mm Hg). Given the trend in CO_2 level preference on ISS, driven by crew comments related to difficulty to concentrate when CO_2 partial pressure is above 3.5 mm Hg and flight doctors concerns with long term effects of exposure to elevated (above earth normal) $ppCO_2$, it is likely that exploration vehicles and surface habitats will require lower CO_2 partial pressure levels. A recent NASA workshop determined that 2.0 mm Hg daily average exposure or less is desirable. Considering also the high maintenance experiences with the zeolite based CDRA on ISS it becomes apparent that a next-generation CO_2 removal system is needed and a lunar habitat is a good place to test it.
- **CO_2 Reduction:** When the ISS Sabatier reactor was coupled to the OGA and CDRA initial operation was good but eventually performance degraded. This was due to incomplete understanding of the interfaces between CDRA and Sabatier and the range of potential inlet conditions Sabatier would have to deal with. This real-world experience is invaluable in planning the next generation systems for ISS and exploration. For Sabatier this means designing for a wider range of inlet conditions and providing better maintenance access for recovery from internal fouling. For a next-generation CDRA, modifications would include tighter controls on CO_2 removal system effluent CO_2 constituents.
- **Trace Contaminant Control**: The ISS Trace Contaminant Control System (TCCS) was designed to use big non-regenerative charcoal filters for high molecular weight trace contaminat control. For exploration a small regenerative charcoal device, similar to the Russian BNP, is more desirable. Keeping the U.S. High Temperature Catalytic Oxidizer (HTCO) is a good idea for control of low molecular weight trace contaminants and results in a hybrid design for exploration compared to the two separate (Russian and U.S.) devices on ISS today.
- **Atmosphere Monitoring**: The Multi-Platform Air Monitor (MPAM) is the new major constituent monitoring device of choice for both ISS and Orion. It is a compact unit that is not sensitive to micro- or partial gravity and is a suitable device to carry forward for exploration habitats. Additionally, a trace contaminat monitor is needed as atmospheric grab samples will not be readily returnable to Earth for analysis.

Water Processing: A surface-based water processor must accommodate crew metabolic needs as well as any additional shower and laundry loads. This is actually how the ISS WPA was sized before the shower and laundry requirements were deleted, but the WPA was not re-sized afterward. Use on ISS provides insight into how often a surface based WPA might have to operate (scaling ISS experience and throughput up to add shower and laundry water). For ISS, microgravity drove expensive and relatively heavy bellows tanks for waste and product water management, which would not be required on a planetary surface. Even partial gravity should do well to keep liquids in containers and feed pumps, simplifying the design, reducing mass and improving maintenance access.

Urine Processing: Once again microgravity forces complex mechanical features into a process that may not have to be there in a gravity field. Urine processing may benefit from simple steam evaporation and gravity collection of condensate, and like the WPA, waste and product tanks will not have to be bellows tanks, simplifying the design, reducing moving parts, and allowing for better maintenance access. With the advent of the alternate pre-treat developed for ISS after a dramatic UPA failure, water recovery estimates are solidly at or above 90%.

Brine Water Recovery: With higher recovery in the UPA a brine processor may not be absolutely needed on ISS but it certainly has a place in exploration. A brine-dewatering system could recover up to 90% of the water in the brine that results from UPA processing, yielding an overall water recovery rate of about 99%.

Potable and Waste Water Storage: Storage of water (or any liquid) in a gravity field is far simpler than in microgravity. Simple gravity fed containers will suffice in place of expensive, heavy and difficult to maintain bellows tanks.

Dormancy: Fluid systems will need to be designed for dormancy. This may include easy ways to drain-and dry components, shock components with high levels of biocide, or irradiate systems with portable hand-held devices. Some components (e.g. OGA cell stack) cannot be dried out for long term storage, shocked with biocide or irradiated, so some means of maintaining the system during dormancy must be developed. A simple solution might be to continue to run the system periodically. However, system failures must also be considered to determine the best overall solution to avoid a truly dormant system that is subject to biofouling and loss of functionality.

Waste Management and Disposal: The Universal Waste management System (UWMS) will be tested on ISS in the near future and is baselined for Orion. This positions it as an excellent candidate for a lunar habitat commode for urine pre-treatment and handover to a urine processor, however solid waste may need additional microbial stabilization in some sort of post-use processing device prior to long term storage and eventual disposal.

C. ISRU

Water Extraction: A method to harvest water from surface regolith or ice fields should be developed and demonstrated on the moon. Having no analog on ISS makes this an imperative for learning about flaws in the first design fielded so an improved next generation system can be sent to Mars.

Processing: Depending on the method of water harvesting initially employed, either a pre-processor will be needed to extract water from regolith to be fed to a WPA or if the water is extracted in the field it may merely need to be filtered and transferred to the WPA feed stream. Return of lunar ice/water for analysis should be part of a precursor robotic water prospector mission design.

D. ECLSS Logistics and Maintenance

The closest analog for logistical resupply and maintenance for a Lunar Base is the ISS. Following retirement of the Space Shuttle in 2011, the ISS United States Operational Segment (USOS) now hosts only un-crewed cargo vehicles - JAXA HTV and the SpaceX Dragon and Orbital-ATK Cygnus vehicles under the Cargo Resupply Contract (CRS) - for resupply. Table 3 shows the total amount of hardware launched to the ISS starting in 2012 (first CRS flight) through 2016 (Note that the 2016 data is only for the first half of the year) along with what percentage of launched hardware is ECLSS-related (i.e. standard spares such as filters or replacement hardware).

Year	Total H/W Launched (kg)	Total ECLSS Launched (kg)	% ECLSS
2012	**2943.21**	**364.05**	**12%**
2013	**4453.62**	**850.47**	**19%**
2014	**8771.51**	**976.51**	**11%**
2015	**12860.23**	**1860.62**	**14.5%**
2016*	**6557.7**	**1213.76**	**18.5%**

Table 3 - ISS USOS ECLSS Hardware Launched to the ISS since 2012 by mass[iii]**.**

Prior to its retirement, the Space Shuttle pre-stocked the ISS with spares in anticipation of limited cargo capability until the CRS vehicles began to operate. Additionally the ISS is comprised of two sections, the USOS and the Russian Segment (RS), each providing dissimilar ECLSS redundancy to the other for short periods of time. Without this dissimilar redundancy the amount of ECLSS hardware launched would probably have been much higher. Now five years after retirement of the Space Shuttle, the percentage of ECLSS upmass cargo to the ISS has increased from 12% in 2012 to almost 20% of total upmass to the USOS.

Logistics and maintenance for a Mars surface mission will be a significant challenge orders of magnitude beyond the ISS. Using the ISS as a model, 20% of the pre-supply/re-supply up-mass may need to be allocated for a human Mars mission (this does not include O_2, N_2 or water consumable resupply, assuming that the regenerative life support system is not fully closed loop). One goal in the development of a Lunar base would be increased reliability and reduced sparing for the next generation ECLS systems such that upmass cargo for ECLS is no more than 10-15% of total up-mass for a Mars mission. Re-design for sub-ORU maintenance and/or increased reliability are a couple of ways to reduce the logistics estimates.

E. EVA Impacts on ECLSS

Compared to EVAs performed on orbiting platforms (ISS, facility in cis-lunar space, asteroids) lunar surface EVAs will more closely mimic Mars surface EVAs both on the types of EVAs performed (construction, maintenance and exploration), frequency and the challenges posed by the surface environment (i.e. low gravity, dust). Lessons learned with frequent EVAs on a low-gravity planetary surface with dust and the corresponding impact to ECLS systems will be invaluable in designing reliable Mars surface systems. Additionally, due to the expected increase in the frequencies of EVAs on planetary surfaces, as compared to the frequency of EVAs performed at the ISS and cis-lunar space, EVA will be a major user of the products from re-generative ECLS systems such as water and oxygen.

Assumptions - Mission duration for crews at a lunar base are assumed to be 6 months in duration. Surface EVA objectives will include in-situ resource extraction and a wider array of scientific exploration. Surface EVA capability will also take into account the use of lunar surface mobility assets.

Unlike short duration lunar surface missions, where EVA dominates the surface operations, a more balanced schedule of EVA and IVA will occur during crew missions at the Lunar base. This is primarily due to the fatiguing nature of EVA over the long term and the radiation environment the crew is constantly exposed to while performing EVAs. While every EVA conducted during lunar surface missions consisted of all crew members at the same time, more EVAs during an outpost mission will most likely consist of two-person teams, with the two different teams conducting EVAs on alternating schedules.[iv]

EVA duration is dictated by crew physiological limits. Past EVA experience indicates that EVAs within a six to eight hour range are at the extent of human capability to expect continued productive work. A day-on/day-off approach is also envisioned, where each crewmember will do a nominal 5 EVAs per 2-week period. Each EVA will consist of a minimum of 2 crewmembers and will be 6.5 hrs in duration, including egress/ingressv (standard ISS EVA planned duration, with many EVAs often exceeding this time).

Consumables - Using the current ISS EMU as a baseline, during a typical 6.5 hr EVA approximately 4.53 kgs (10 lbs) of water are used by each crewmember per EVA. This includes water used to provide cooling (which is sublimated) as well as drinking water.[vi] With 5 EVAs per week, 2 crewmembers per EVA, on the Lunar surface approximately 90.7 kg (200 lb) of water will need to be provided by the habitat ECLS system. Depending on the cooling system used, a portion of this water may not be recovered

For oxygen, the minimum usable oxygen quantity in the EMU primary O_2 system is .55 kgs (1.21 lbs). Assuming that the astronaut uses 80% of the O_2 during each EVA, for 5 EVAs per week with 2 crewmembers per EVA, approximately 4.4 kgs (9.7 lbs) of oxygen will need to be provided by the habitat ECLS system.

Dust - Lunar dust particles entrapped during EVAs and carried into the habitat can cause wear, abrasion, and contamination of ECLSS hardware. Experience from Apollo found that the micron-fine dust tends to become embedded in the fabric weave of the spacesuits Thermal Micro-meteoroid Garment (TMG) cover layer, thus inhibiting the cleaning process[vii]. It was found that the heavier dust particle concentration could be removed by simply brushing the excess dust from the outer surface of the suit. However, finer particles became embedded in the TMG.

While the use of suitports (where the spacesuits normally remain outside the pressure shell and are accessed thru a hatch in the back of spacesuit) and Airlocks will assist in mitigating dust in the habitat, inevitably dust will find its way into the habitat and procedures and techniques will have to be development to deal with the contamination.

Proposed options for dealing with the EMU dust control and collection range from wet wipes and vacuums to electrostatic precipitators and mechanical filter systems. Additionally, seals and protective covers may play an important role in the protection of sensitive hardware.

Airlocks/Suitports - The Lunar Outpost will have full airlock capability, so that the entire habitat will not have to depressurize when an EVA team egresses. This allows the flexibility of having some of the crew stay inside the vehicle in an IVA shirt-sleeve environment if needed during an EVA. An airlock capability also provides a staging area for checking out and servicing the spacesuits, as well as providing a barrier to reduce lunar dust in the habitat. A separate "scientific airlock" may be needed to allow lunar samples and small pieces of scientific equipment to be brought inside the habitat, if they do not fit inside the EVA airlocks or if needed for contamination control.

It will be desirable to recapture the atmosphere during Airlock depress and, as discussed above, to design the Airlock such that dust contamination is mitigated.

While the addition of suitports may help to reduce dust contamination into the habitat's cabin, and need to depress the larger volume of an airlock, at some point spacesuits will have to be brought into the habitat for servicing and repair.

Habitat Pressure vs Suit Pressure - Selection of the optimal operating pressure of the spacesuit is a trade-off between allowing for maximum dexterity and mobility (relative suit low pressure) and reducing the risk of decompression sickness (DCS), commonly known as the bends (high suit pressure). Historically U.S. spacecraft have operated with total cabin pressures of 34.5 kPa (5.0 PSIA) and with O_2 concentration levels between 70-100%[viii] with spacesuit pressures of 24 kPa (3.5 PSIA) and 100% O_2. This significantly reduced the time required for pre-breathe prior to the EVA.[ix]

For both the Space Shuttle and ISS Programs the total cabin pressure was kept at 1 atmosphere (101.3 kPa, 14.7 PSIA) with an O_2 concentration of 21%. This reduces the risk of a flammability event, but requires the crewmembers to perform a pre-breath protocol to reduce the risk of DCS.

Lunar Outpost EVA Rates - Attention must be paid to issues of suit durability and on-site maintenance and repair. High usage rates will drive high maintenance and repair rates. Whenever possible, common components should be used between the ECLS systems used in the spacesuits, rovers and the habitats.

Tele-robotics - While the Lunar Outpost may employ tele-robotics or AI systems to augment EVAs, it is not envisioned that this will significantly reduce the need for surface EVAs. Telerobotics will instead enable new tasks that are not currently performed by EVA due to time constraints or safety concerns. While these systems may assist EVA crewmembers, the versatility of EVA crewmembers accomplishing complex tasks within a reasonable amount of time cannot at this time be replaced by robotic systems. However the Lunar Outpost may prove to be the ideal location for testing and refining EVA and Robotic interaction prior to a journey to Mars.

IV. Approach

Hardware development and exploration approach will require a careful consideration of the goals, priorities and considerations discussed previously. While new hardware development may produce optimal solutions, budget constraints will tend to drive solutions towards new implementations of existing hardware and technology. Considering useful hardware development options that could produce useable hardware for the lunar habitats, numerous paths present themselves:

- Radiation harden existing ISS designs
- Dust-proof existing ISS designs or design from scratch new hardware
- Re-design existing ISS designs for sub-ORU maintenance
- Re-design existing ISS hardware to accommodate dormancy
- Re-design existing hardware or design from scratch new hardware to utilize gravity
- Re-design existing ISS hardware to improve reliability
- Develop new hardware unique to Lunar habitat

Furthermore, unique considerations for surface exploration will also be encountered:

- Identify what is needed to determine habitat location
- Conduct pre-curser robotic pathfinder to locate water sources
- Conduct pre-curser robotic pathfinder to locate potential underground locations for habitat
- Determine approach for power generation

These and other important surface factors will fundamentally influence habitat designs and must be decided as early in the design process as possible.

Schedule: A reasonable estimate for a first lunar habitat landing on the moon is no earlier than 2025 under current NASA and industry estimates and planning. This provides for about eight years of overall development and planning time available. Given this timeframe, ***immediate*** funding for both a robotic water prospector and geological scouting missions is needed to start informing location-specific habitat design. Assuming a three year development and launch cycle for the prospectors and another year for actual mission ops and results to feed back to the designers, a firm basis for a lunar habitat location and physical configuration (above or below ground) will not be available to designers until 2021. With flight hardware needing to be available for integrated test and launch prep about one year before launch this gives habitat providers about three years to complete the habitat design to the specific environment chosen.

Following initial funding of the robotic pre-cursors, significant development effort and funding for habitat technology should be next. Parallel work on designing and building a suite of ECLSS hardware specific to a lunar habitat must begin by 2018 to allow for a three year design effort and make ground test hardware available for integration into either a ground test habitat or the ISS with lunar flight hardware coming shortly thereafter.

Development and production of the final habitat systems will be on the critical path but will be achievable if early location-determination and systems testing is performed.

Table 2 provides insight into where and when the money should be spent to develop a lunar-class set of ECLSS hardware.

All subsystem components controlled by computers will need radiation hardened controllers. This will likely be a common design for all subsystems to save development cost and simplify sparing.

Electro-mechanical and mechanical components with seals exposed to the lunar surface dust environment (e.g. ACS vent and vacuum system valves, etc.) need to be re-designed for easy cleaning of exposed mechanical features and change out of the seals. This implies either redundant capabilities or a way to isolate the habitat atmosphere while also performing maintenance. The difficulty of implementing this concept cannot be overstated.

THC, AR and WRM subsystems have a distinct advantage in a gravity field for simplifying the designs compared to ISS and this should be exploited to the maximum extent possible.

Finally, as dust will undoubtedly make its way inside the habitat, dust mitigation hardware (non-existent on ISS today) needs to be developed for the lunar habitat. This should begin early enough that if the mitigation process needs to somehow be incorporated into the habitat architecture (likely), this information will be available to the habitat designers as soon as possible.

These kinds of considerations can apply for both in-space and surface habitats and demonstrate that development of surface hardware will also be informed by improvements and adaptations of in-space hardware that will likely precede any significant surface exploration. This points to the need for an overarching technology development plan that carefully balances strategic principles to achieve the desired result. Significant optimization and efficiency can be gained through careful coordination of development areas among all of the partners involved in exploration.

Once the above decisions on cost and approach are made, a development schedule can be created and tuned to the desired exploration architecture. These schedules will account for the differences in development time for systems adapted from previous decisions (relatively shorter development time) versus systems designed from scratch (relatively longer development time). These schedules will also be used recursively to inform development decisions on affordability.

V. Conclusion

Using the lunar surface as a testbed for Mars surface systems provide significant advantages over a testing program that only includes terrestrial and ISS or other LEO or cis-lunar orbiting platform. A lunar testbed is beneficial as it can provide testing and validation in areas such as partial gravity ops, dust tolerance, high-rate surface excursions, ISRU and long term dormancy in gravity. While these conditions will present lunar surface operations challenges, these are the same conditions that will be encountered on the surface of Mars and will provide invaluable operational experience.

Lunar surface testing will be particularly beneficial for systems such as ECLSS, mechanisms, ISRU and EVA. More specifically for ECLSS, benefits from operating on the lunar surface will help define regenerative systems such as water and urine processing and oxygen generation as well as waste and hygiene, ventilation systems and dust management features. Systems such as structures, avionics, power and non-regenerative ECLSS will see limited benefit in lunar surface testing beyond testing on Earth or at ISS, though they are all integral systems to any human habitat.

To achieve a Mars landing in the mid-2030s, the authors believe a technology development and testing program that includes lunar surface testing has clear advantages and should begin as quickly as practical for the following systems: dust mitigation, ISRU, surface mobility, partial gravity fluid management, lower partial pressure CO2 removal, regenerative trace contaminant control, trace contaminant monitoring, microbial stabilization, trash compaction, brine water recovery, radiation sensitivity and system dormancy. Many of these can be tested on ISS, including: lower partial pressure CO2 removal, regenerative TCCS, trace contaminant monitoring, microbial stabilization, trash compaction, brine water recovery, and system dormancy.

Important precursor efforts in site scouting and location selection should commence immediately to better inform habitat designers. Concurrent work on habitat ECLS systems should start within the next few years to allow for ground test hardware to be available in the early 2020s. These parallel efforts lead into flight hardware development for the lunar surface habitats and will allow habitat deployment in the mid-2020s. Testing on the moon is beneficial for all surface systems by providing valuable operational experience and history, which will reduce risk and improve performance on later Mars missions. Testing on the lunar surface provides significant benefits for Mars surface systems and the eventual human landing on Mars.

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[i] Taylor Redd, N (February 13, 2014). How Long Does It Take to Get to Mars. Retrieved from space.com. http://www.space.com/24701-how-long-does-it-take-to-get-to-mars.html

[ii] West, W., Heldmann, M., Scull, T., Samplatsky, D., Gentry, G., Duggan, M., Klaus, K., “Comparative Assessment of Delivering Consumable Resources versus In-Situ Resource Utilization for Moon and Mars Habitats Life Support Systems,” 45th International Conference on Environmental Systems ICES 2015-226, July 2015.

[iii] NASA ISS Program Office As-Flown USOS Visiting Vehicle Manifests for 2012 (HTV3, SpX1), 2013 (HTV4, SpX2), 2014 (Orbital-1, Orbital-2, Orbital-3, SpX3, SpX4), 2015 (HTV5, OA4, Spx5, SpX6, Spx7), and 2016 (HTV6, OA6, SpX8)

[iv] NASA Constellation Program EVA Operations Concepts (CxP 72177) Section 3.1.3 Lunar Out Post Mission

[v] NASA Constellation Program EVA Operations Concepts (CxP 72117) Section 5.9 Lunar Surface Operations

[vi] NASA Document JSC-19450 Rev B, EMU SYS 21002

[vii] The Lunar Base Handbook. Section 17.1.2, page 547 McGraw Hill 1999

viii The Lunar Base Handbook. Section 17: Lunar EVAs. Table 17.4, page 557. McGraw Hill 1999.

[ix] The Lunar Base Handbook Section 17., page 556 McGraw Hill 1999