Exploration Architecture Options - ECLSS, TCS, EVA Implications

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Many options for exploration of space have been identified and evaluated since the Vision for Space Exploration (VSE) was announced in 2004. The Augustine Commission evaluated human space flight for the Obama administration then the Human Exploration Framework Teams (HEFT and HEFT2) evaluated potential exploration missions and the infrastructure and technology needs for those missions. Lunar architectures have been identified and addressed by the Lunar Surface Systems team to establish options for how to get to, and then inhabit and explore, the moon. This paper will evaluate the options for exploration of space for the implications of architectures on the Environmental Control and Life Support (ECLSS), Thermal Control (TCS), and Extravehicular Activity (EVA) Systems.

I. Introduction

New architectures for conducting human exploration in space have been developed and assessed for feasibility since the Presidential Vision for Space Exploration (ref 1) was announced in 2004. In 2009 President Obama formed the Augustine commission that issued a report in the Fall of 2009 that identified 7 options for conducting human exploration. During 2010, NASA conducted a set of studies referred to as Human Exploration Framework Team (HEFT) (Ref 2) and followed the initial effort with a HEFT2 study (Ref 3) of potential exploration destinations and the technology needed for each. President Obama in his Federal Budget proposal for Fiscal Year 12 called for a plan to pursue human space exploration via development a Heavy Lift Launch Vehicle (HLLV) and Multi-Purpose Crew Vehicle (MPCV) and enabling technologies including those enabling closed loop, highly reliable life support. The HEFT2 report identifies missions to progressively more challenging destinations.

This paper is intended to provide an overview of recent exploration planning and the implications those plans have on ECLSS, TCS and EVA (referred to as a group of systems in this paper as ETE) requirements, functionality and technology options. A discussion of the exploration mission characteristics is followed by a discussion the ETE implications of each class of mission, then approaches and emphasis that make sense for ETE development. An overview of Constellation Lunar Scenarios and the ETE implications for those missions is provided to capture the important aspects of surface missions that will need to be considered iin future exploration missions.

In 2006 the Constellation Lunar Surface Systems (LSS) project was formed to develop and evaluate potential ways that the exploration of the moon could be conducted. The LSS project and recently the International Architecture Working Group (IAWG) conceived and evaluated over 16 scenarios (and many sub options) during the 2006 to 2009 period. Lunar missions are not in the current planning for exploration of deep space so Lunar exploration mission implications on ETE will be addressed in later sections on potential scenarios developed by LSS and IAWG.

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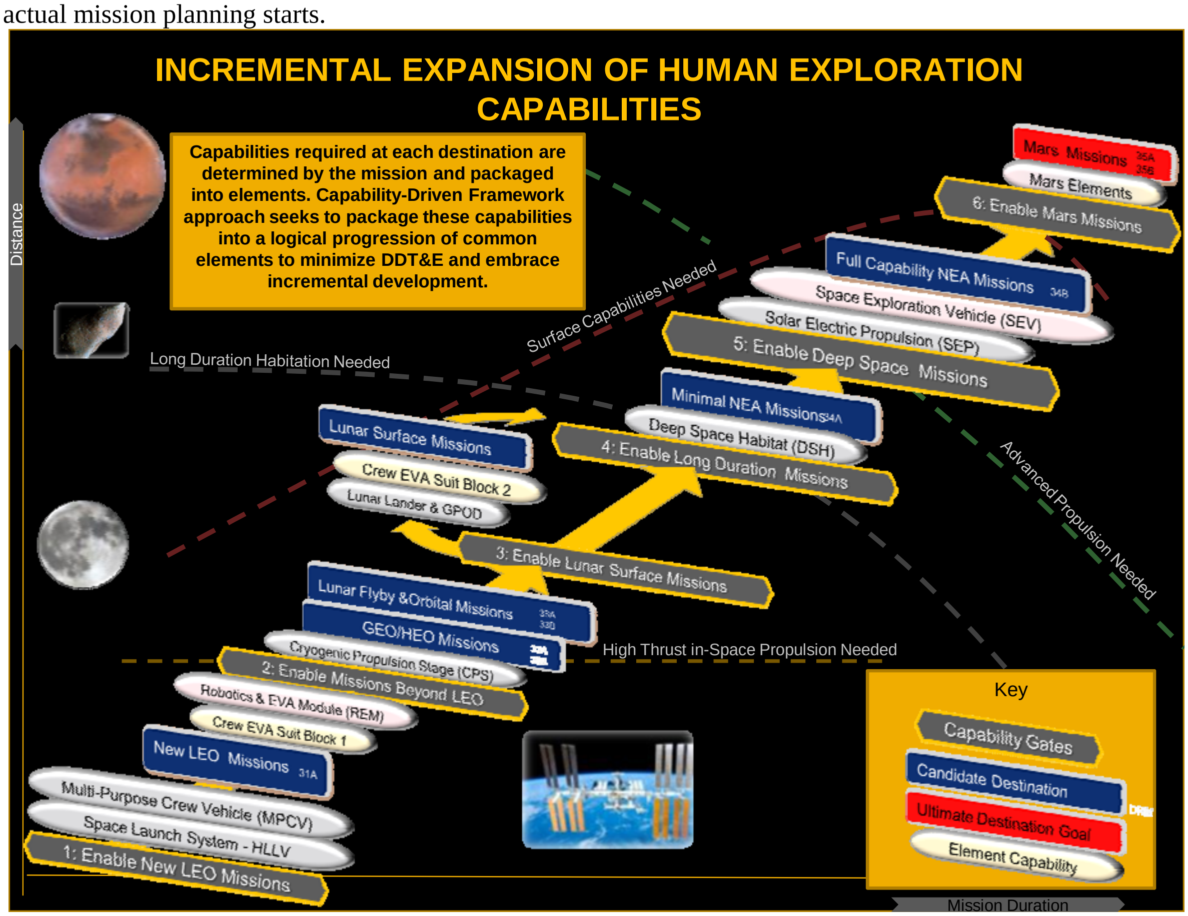
The FY12 Presidential NASA Budget Proposal and the HEFT Direction

The FY12 Budget proposal calls for development of capabilities that will enable exploration. A HLLV rocket and a MPCV are specifically called for as is technology development to enable exploration and commercially provided crew and cargo launch capabilities.

1. Human Exploration Framework Team Direction

The incremental capabilities approach is to provide technologically advanced capabilities to enable future missions to the destinations in shown in Figure 1. The HLV and the MPCV are needed to support all exploration missions. Technology developments are required to address the deep space environment, and the gravity well related mass constraints and surface operations for the long mission durations required to achieve exploration missions. The approach leads to having the technologies available and ready to apply to vehicle development when the actual mission planning starts.



2. Figure 1 – Incremental expansion of capabilities to enable successively more ambitious exploration

Notional concepts of elements that could be required to accomplish those missions are shown in Figure 2.

The focus of ETE efforts will be on the human transit vehicles (the MPCV and Landers), the Deep Space Habitat (DSH), the Multi-Mission Space Exploration Vehicle (MMSEV), the EVA suit and EVA related systems.

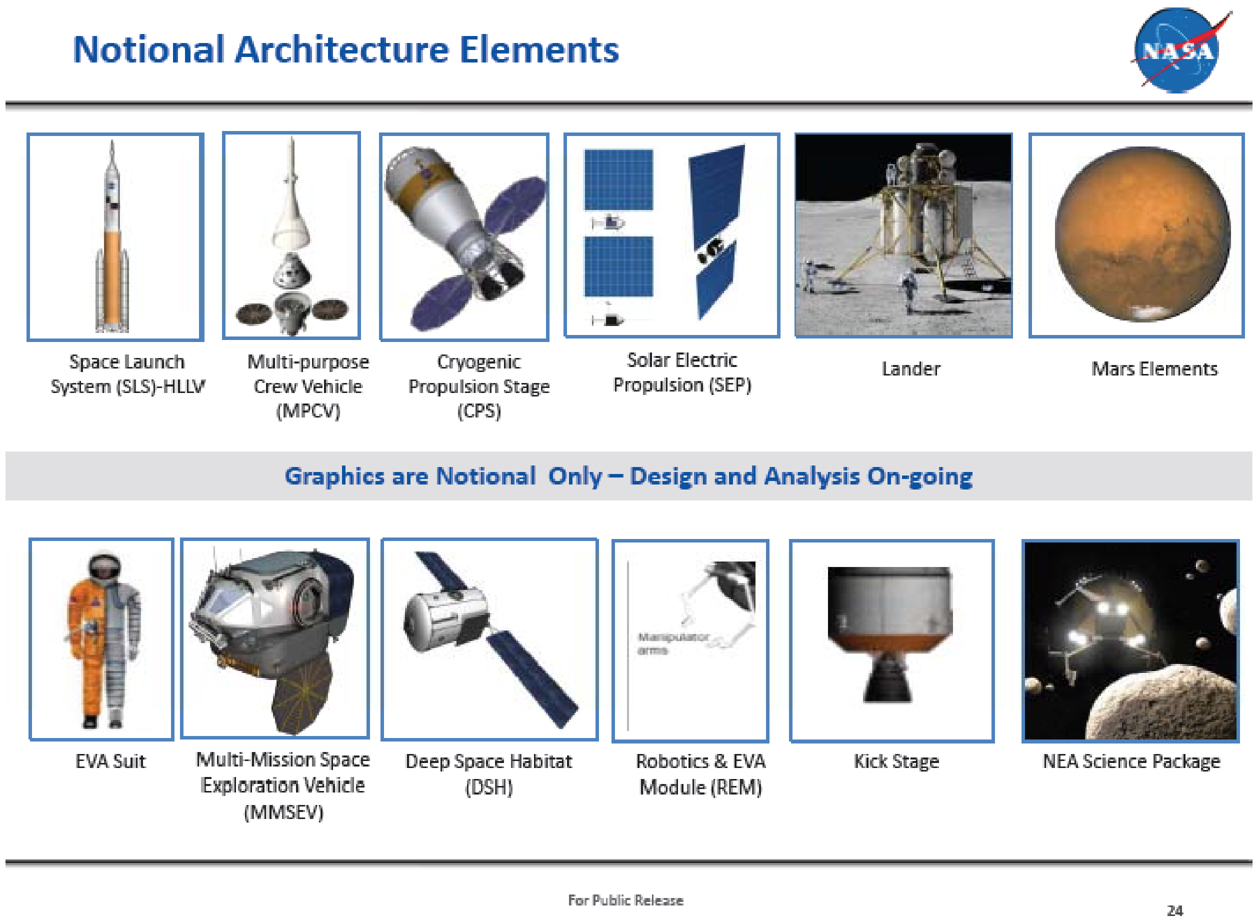


Figure 2 – Notional Architecture Elements needed for Exploration

Potential Missions Characterization

A. Human missions to Geosynchronous Earth Orbit (GEOs), High Earth Orbit (HEO), Lagrangian Points (LPs), Near Earth Asteroids (NEAs), a Mars fly-by or Martian Moons

Potential human missions to GEO, HEO, NEAs, LPs, a Mars fly-by or Martian Moons (Phobos is the currently envisioned target) will be characterized by the severe (relative to LEO) deep space environment. EVA and robotic activities for exploration missions will be similar in many ways. The potential operations on the surface of NEAs or Phobos will include the possibility of contamination from material from those objects themselves. Thus NEA and Phobos missions will be similar to GEO and LP operations except that dust and gas contamination also need to be addressed. Those missions could involve extensive robotics to accomplish mission goals as controlled by humans in close proximity to allow real time control of robotics that would otherwise be slowed by the time delay to control robotics at Mars from Earth.

All exploration scenarios (except lunar and Mars surface operations) will need to be zero gravity compatible. Weightless conditions will require processes that rely on separation of liquids and gases or liquids and solids have special provisions to accomplish such separation without the aid of a gravitational field. Concerns about crew de-conditioning during long zero gravity phases of a mission may prompt designers to include a vehicle wide countermeasure involving near continuous acceleration or centripetal force via rotation. On the other hand, operations like EVA and assembly in zero gravity can take advantage of the reduced force needed to move mass (although the momentum of masses in motion will need to be addressed in operations).

3. Lunar Missions

Missions to Earth's moon are likely to address the need to exercise capabilities before embarking on deep space missions. Those are not currently required in the HEFT2 direction. Lunar missions are addressed at the end of this paper for reference.

B. The Ultimate Destination - Mars Missions – ETE Factors

Mars missions will likely involve LEO or LP based assembly operations that require EVAs and robotic operations followed by deep space transit operations leading to a Martian Moon or surface exploration followed by deep space transit to return to Earth then operations leading to return to Earth surface. Those operational concepts are captured in the Mars Design Reference Mission (DRM) document (Ref 4).

The LEO, HEO or LP assembly operations will be similar to those of the ISS. The transit operations will be similar in environment to those of the LP station operations except that the solar irradiation will decrease during transit to Mars then increase during the return transit. The environment around Mars will be influenced by the presence of Mars but will be considerably colder than LEO and will not have the radiation protection afforded by the Earth's magnetic field.

Mars surface operations will involve robotic and EVA operations but both will be affected by the presence of the thin Martian atmosphere and Martian dust. Unlike Lunar dust, some Martian dust will be carried by the Martian atmosphere and thus will affect even stationary components of elements of a Martian base. Dust will affect the operation of equipment and will form deposits on surfaces affecting both thermal radiation characteristics and penetration of radiation to optical surfaces. The Martian atmosphere, although thin, will result in convection of heat from and to equipment of the surface operations. The composition of the Martian atmosphere allows use of the CO2 a possibility to supplement resources carried from Earth. The presence of subsurface water on Mars also makes the potential use of Martian water to supplement resources carried from Earth feasible. Martian gravity can be used to provide many potential refinements of processes that require separation of liquids and gases or liquids and solids. Martian gravity can be used to improve EVA and Robotic operations; however the Martian geography will provide both intriguing exploration and operational challenges. The radiation environment will present challenges to both equipment and humans. A combination of elements likely for a Mars mission is illustrated in Figure 3.

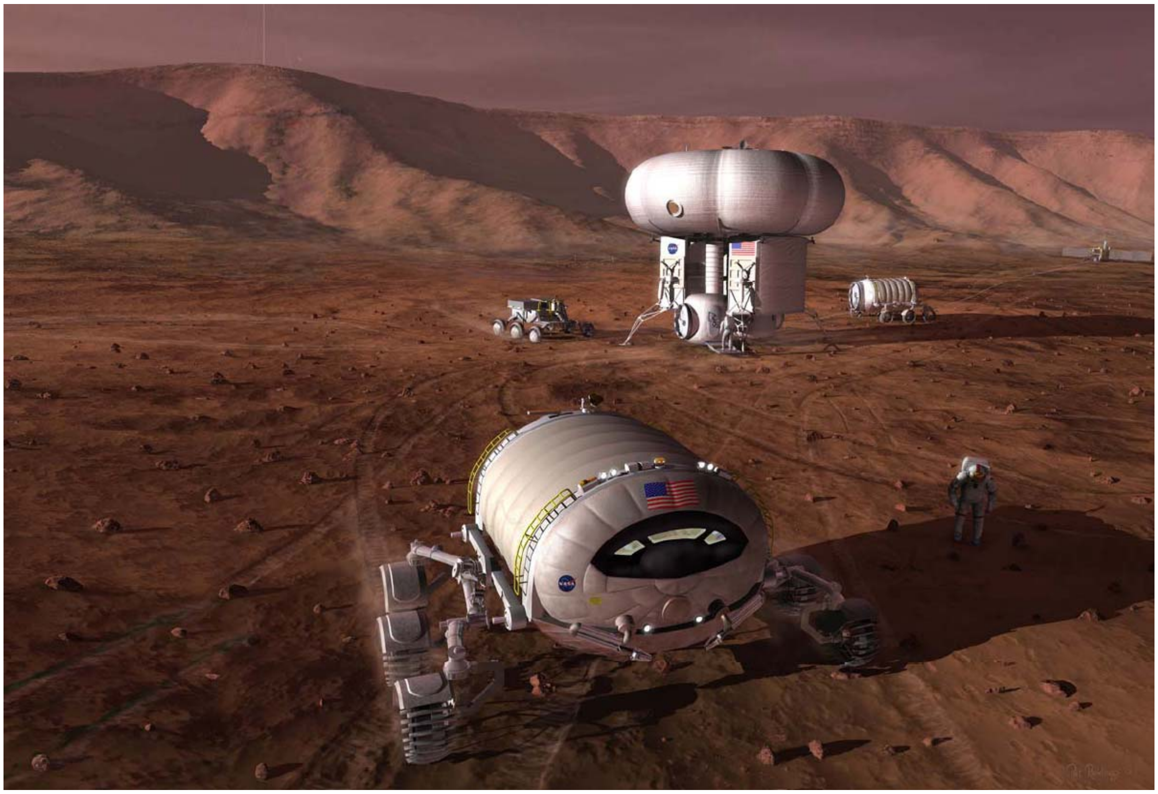


Figure 3 - Potential Mars Surface Mission Elements (from the March 2010 Mars Design Reference Mission Document)

Incremental Capabilities Approach - ETE Options and Implications

A challenge from the FY12 budget proposal is to infuse new technologies into exploration designs to improve the functionality of those vehicles. In that context, new technologies will be considered that improve the functionality and lower mass, power and thermal control resources and reduce maintenance required to operate.

The LEO activities will be similar in environment to the assembly and EVA and Robotic activities that have been conducted to assemble and operate the International Space Station (ISS).

C. Crew Transit Vehicles to and from LEO, GEO LP Bases

For crew transit vehicles to and from LEO, GEO and Lagrangian bases, the periods that those vehicles are occupied and the environment they are operated in will be similar to those of the Shuttle (LEO only) or the Orion MPCV. Thus the requirements for ETE functions will be similar to those of the Orion MPCV. Thus the Point Of Departure (POD) for transit vehicle technologies will be the Orion MPCV technologies.

The potential for a commercial LEO launch and re-entry vehicle and perhaps a different vehicle that acts as a tug to cycle back and forth between the LEO (maybe ISS) and GEO or LP bases or the moon may result in more efficient transit vehicle designs. Such a tug wouldn't see the Earth launch environments and wouldn't require the re-entry provisions such as the Thermal Protection System, life rafts, ammonia cooling after landing, snorkel fan, etc. that are required for MPCV class vehicles. If vehicle orientation is used to address thermal control fuel cells might used to provide power leading to water consumables being produced affecting ECLS requirements.

The CO_2 and Moisture Removal Amine System (CAMRAS) is baselined for the MPCV and is a game changing technology in that it provides the capability to remove CO2 and Moisture from Cabin air without requiring consumables (versus LiOH used in the shuttle). It also is game changing because the humidity removal does not require condensing water from the cabin atmosphere and thus the thermal control system can operate at higher temperatures and reject heat more efficiently. CAMRAS provides essentially unlimited CO2 and humidity removal via regeneration of the amine by vacuum desorption. CAMRAS technology development is planned to be mature for future vehicles due to integrated testing and due to a Detailed Test Objective (DTO) that is being conducted on the ISS. CAMRAS could be considered for longer term operations in vehicles but will incur penalties associated with loss of water and CO2 that could be regenerated if other technologies are employed. The version of CAMRAS that will be used on ISS will probably include a humidity removal system upstream of the CAMRAS unit so that most water in the cabin air will be recovered.

D. Operations at GEO and LPs

Operations at GEO and LP points will be similar to LEO operations but the environment will be more severe due to the near continuous solar irradiation thermal environment combined with continuous deep space and the radiation environment that will be more severe since the protection afforded by Earth's magnetic field will not be present. For refueling and assembly operations, the approach to mitigate extreme hot or cold conditions by rotating the vehicle is probably not useable since such a rotation would complicate those operations. Thus the extreme hot on the sun side and extreme cold in all other directions will have to be addressed (especially if solar power generation is employed because those could constrain vehicle attitude to a solar oriented attitude).

E. EVA for GEO and Lagrangian locations

EVA for GEO and Lagrangian locations will be done in weightless conditions as at ISS but will be in much colder environments. Use of the EMUs and Orlan suits used on ISS is feasible. However, the EMU technology is heavy, bulky, requires significant consumables and requires significant time and logistics to conduct EVAs. NASA's EVA technology project and LSS efforts have identified and started development of technologies that promise to improve the functionality of the EVA systems. Use of the CAMRAS technology will improve CO2 and humidity control. Use of a rear entry suit and potential use of a suit port and/or suit lock system technologies (envisioned for lunar bases) can dramatically improve the logistics of EVAs by reducing preparation times for EVAs to minutes versus hours and significantly reducing consumables. Modern high density batteries will reduce mass and/or volume. Operation of exploration vehicles should be done at reduced pressure to aid in conduct of EVAs using less preparation time and yet being safer by reducing the possibility of incurring bends. Reducing the pressure will also reduce leakage from exploration vehicles. Potential use of cryogenic O2 in both O2 storage for EVA and in cooling during EVAs is being investigated and may prove to be the most efficient and capable way of conducting EVAs.

F. Potential Bases for Assembly and Refueling

Bases for assembly and fueling of exploration missions may be needed to efficiently assemble elements of an exploration mission. Such bases may be occupied for more than a few weeks thus the life support requirements will be similar to those of the ISS. ETE approaches using ISS proven technologies for the crew accommodations modules will be a POD for such bases.

In addition to the POD and advanced technologies that will be considered for new base habitats; synergy with refueling operations and advances that are expected to result from cryogenic propellant storage may make new options available for sharing consumables and exchange of consumables between propulsion and ETE systems. The potential use of continuous deep space viewing may make approaches that use very low temperature thermal processes (described later) attractive when compared to POD and currently envisioned new technology options.

4. The Need to Develop Dual Barrier Heat Exchanger (HX) Technology

A persistent issue for ISS ATCS is the potential hazard of leakage across the internal water to external ammonia heat exchanger. While LEO environments will be similar to ISS, the more extreme environment of GEO or LP bases will require that external heat rejection coolants are compatible with extremely low sink temperatures. The requirement for operation at both moderate temperatures and extremely low temperatures means that external coolants will probably be similar to ammonia in toxicity. A solution that eliminates the potential for leakage of the toxic external coolant to the internal cooling loops is a dual barrier heat exchanger.

Dual barrier HXs that provide an added barrier between internal and external coolants have been developed and were almost ready for replacing those in the ISS ATCS. Funding was not available to complete the replacement of the ISS HXs but that technology option should be pursued and made ready for exploration vehicles.

The dual barrier HX technology if combined with ongoing micro-channel heat exchanger technology (that improves heat transfer via use of smaller flow passages) could provide better performing HXs with improved safety.

G. Transit to/from NEAs

Transit to NEAs will require a vehicle that supports flights of several weeks to months in the extreme environments of deep space. Due to the duration, technologies that regenerate more resources will be favored over those that use more consumables. Thus the ECLSS and ATCS technologies will probably be more like those of traditionally long duration bases. Also in order to keep NEA material from being contaminated during EVA operations, venting from the EVA suits may be limited significantly. The number of EVAs conducted during a NEA mission is not likely to be as large as those of a Moon or Mars mission. Shuttle and ISS EVA systems may have the reuse capabilities needed for NEA missions whereas they might not be compatible with Lunar or Mars surface missions. Mass constraints may force the evolution of shuttle and ISS EVA capabilities to use new technologies to reduce weight and consumables.

EVA technologies considered for NEA missions will have to address the potential contamination by material from the NEAs. Considerations will include contamination of samples to be returned from a NEA and potential contamination of the crew during return and of Earth after return. EVA processes requiring venting may not be acceptable for NEA or Mars missions.

The ATCS dual barrier HX technology will be relevant to consider because internal and external fluids will need to be separated for safety for NEA missions also.

H. Mars Mission approach for ETE

Mars missions will require advances in ECLSS and TCS technologies to address the long duration mission without resupply. Planetary protection would need to be considered for containment of samples and equipment that is used on the Martian surface, EVA interfaces would need to be robust to address the dust environment and provide the isolation needed for the crew from potential Martian contamination.

5. Fueling or Refueling at LEO or, HEO or LP

Fueling or Refueling at LEO or, HEO or LP or en route offers the possibility that propulsion may be more robust for Mars scenarios than in prior concepts. LSS Scenarios 9 and 10 (that will be addressed in the Cx Lunar section to follow) started the thinking on how refueling can impact mission strategy. They also started the thinking on how reuse of vehicles could be beneficial for mission planning.

6. VASIMR implications on ETE

The VASIMR propulsion system as envisioned could reduce Martian transit time and address issues of long duration radiation exposure and crew deconditioning. VASIMR is to be continuously operated so that the Martian vehicle is continuously accelerated then decelerated to reach Mars orbit then accelerated and decelerated to return to Earth orbit. While the Mars mission would still be a long duration mission for ECLSS and TCS requirements, the duration would be shorter (estimates are that transit times could be reduced to as little as 39 days each way) thus concerns of long term radiation exposure and weightless deconditioning that prior Mars design reference missions would be addressed. The mission consumables and thus the approach for ETE would change with the reduced mission length. The continuous acceleration and deceleration provided by VASIMR might make ETE processes that use low gravity to separate gases from liquids and solids from liquids possible solutions.

7. Single Crew Module Concept for Transit ***and*** *Surface Operations*

Fueling or Refueling and assembly of a vehicle in LEO, HEO or at a LP assembly location offers the possibility that systems concepts such as a single crew habitat vehicle could be used for both the transit to Mars, the descent to the surface and surface operations and the return to the transit vehicle and back to Earth. Such a concept could reduce overall mission mass and logistics by eliminating the need for separate ETE systems for the transit and surface vehicles and those vehicles themselves. In this concept the life support and command and habitation capabilities needed to support the crew during the entire mission would be included in a single module of the mission. Propulsion systems that must be capable of landing a long duration habitation module could return the crew and command module to low Mars orbit given enough propellant. Other mission elements such as interplanetary propulsion would connect to the crew module and be commanded via the crew module for transit to and from Mars orbit. Trade studies would be needed to evaluate the overall mission benefits of having a single crew module (with the propellant needed for ascent from Mars) versus separate transit, descent and ascent and surface habitats.

The implications on ETE for this concept are that a single ECLSS system would be needed (versus 3 for more standard approaches of Transit then LMO to surface vehicle then Habitat) thus reducing development and overall mission costs. The system would have to be robust to address all mission phases. The module would provide the capabilities needed for the duration of the mission for the crew and thus should be designed to meet the long duration mission requirements (closed loop life support is relevant for such a long duration mission).

8. Mars Surface Systems

In this section the differences between Lunar and Mars surface missions will be addressed.

Many of the activities to be conducted by astronauts while on Mars will be similar to those the LSS team has conceived of and studied for Lunar missions. Thus the discussion of surface activities will be deferred to the Cx section on LSS where a moderate level of detail will be presented.

The LSS concepts for mobility using a Space Exploration Vehicle (SEV) and very efficient EVA processes using a suit port concept will probably be implemented during Martian surface operations. However, the presence of the Martian atmosphere will change the operation of both the SEV and the suit. The Martian atmosphere will require that convection be addressed by the thermal systems for both the MER and the suit. Sophisticated approaches for the SEV and Martian suits are in work in technology developments and may take advantage of the slightly convective environment.

The gravity of Mars is twice that of the moon making mass of the EVA suit more critical than for weightless or moon EVAs. Many of the EVA technology development areas will reduce the overall mass of the EVA system as they are matured to useable technologies. Technologies that make use of Martin CO2 to aid in EVA process may make a significant difference for the Martian EVA systems.

With a diurnal cycle nearly the same as the Earth's, Martian operations will include operations during the Martian night. Lighting will have to be addressed in the SEV and in suit technology.

Cooling solutions will have to consider recycling of internal heat and insulation that performs in the presence of some atmosphere and the convection that induces.

However, the 24.6 hour day results in the night cycle being much shorter than for the moon. So the duration without sunlight will change energy storage requirements versus the moon. That energy storage difference will lead to operational changes that allow more frequent operation of equipment that requires high power (in cases where solar power is used). The use of nuclear power will be attractive because it would address the lower solar irradiation and because it would eliminate the need to schedule power use.

Martian dust will be a significant factor in surface operations and will have significant effects on EVA and Thermal systems. Martian dust will be deposited on spacecraft surfaces both due to operations on the surface and due to atmosphere borne dust.

The Martian rovers have provided a wealth of information on the nature and extent of the problems that Martian dust induces. Mechanisms including connectors will need to be developed to be dust tolerant. Thermal systems will have to be robust to tolerate the degradation of performance that the gradually thickening layer of dust will induce.

Cleaning techniques can be developed that use compressed gas to clean sensitive surfaces. The Martian rovers have provided the experience of having been cleaned during a Martian tornado. Therefore compressed gas cleaning processes should be viewed as a way to address surface property recovery during future missions on Mars. The use of compressed Martian atmosphere may provide the expendable source of gas needed for cleaning surfaces.

Solar flux will be low during Martian surface operations resulting in the Martian base and the SEV probably using nuclear power. Use of nuclear power will make the power supply continuous thus making operational constraints related to sunlit periods less of an issue. Operational scheduling of activities can be related to convenience rather than power availability.

The presence of CO2 in the Martian atmosphere makes the technologies that convert CO2 into O2 for crew or propulsion use attractive. Sabatier reactors have been developed and tested as integrated with potential CO2 removal and water electrolysis processes and show promise for regenerating the O2 used by the crew. ISS missions have integrated a Sabatier reactor with the ISS Carbon Dioxide Removal Assembly (CDRA) and Oxygen Generation System (OGS) systems. Thus, for exploration, the Sabatier technology will be viewed as a mature demonstrated technology (for crew needs).

The Sabatier reactor is so promising that Science Fiction Author Kim Stanley Robinson referred to Sabatier technology in the third of his trilogy of books on Martial exploration and human evolution "Blue Mars" (Ref 4). He referred to Sabatier reactors in a Martian museum as used in the initial Mars human settlement.

A version of the Sabatier technology imbedded in a ceramic structure and combined with Oxygen generation via electrolysis in Solid Oxide Electrolysis (SOE) technology shows promise.

9. Planetary Protection

In forums addressing contamination during Martian missions held during 2006 (Reference 5) contamination both of Mars and of Earth on return of crew and samples from Mars were addressed.

Concerns relating to the contamination of Mars during Martian exploration will need to be addressed. ECLSS functions that require venting of gases or waste products will have to consider the potential for contamination of Mars. One of the significant concerns is that gases or other waste products released during a Martian mission could affect the materials collected during the mission thus compromising the validity of results. The harsh environment of the Martian surface may mitigate some concerns since biological materials will not likely survive for long in the low pressure, cold and radiation intense environment.

Due to the forward contamination concern, ECLSS operation on the Martian surface will need to severely limit the amount of waste products generated and released. That will be another significant argument for a closed loop life support system. Especially important will be the processing of solid waste products. Processes leading to making waste products biologically stable or inert have been envisioned and low TRL development has been conducted. Those technologies will need to have more emphasis to reach the TRL needed for closed life support system use and mission readiness.

Return of the crew and samples from Mars was identified as even more of a concern than contamination of the Martian environment due to the potential to contaminate the Earth with biological elements that could negatively affect Earth ecosystems. Special handling of samples and mission items exposed to the Martian environment will require special ECLSS and thermal provisions.

Approaches for Exploration

I. Commonality and sizing of components

Given the unique requirements of the variety of exploration missions, designers usually try to develop optimal solutions for each mission and each element of each mission. That approach does result in designs that meet mission requirements and minimize resources needed to provide the functionality of each element. The optimization approach for each element usually leads to unique equipment to address functions for each element. An alternative approach is to identify functions that are common for several elements for a mission and drive each element to use common equipment designs to address a specific function is each element. If commonality is realized across several elements, it will result in significant overall program cost savings.

ECLSS, TCS and EVA commonality concepts have addressed potential use of the PLSS for both EVA and habitation ECLSS. Recognizing that the PLSS addresses nearly all life support needs for a crew during the high metabolic rates of an EVA; the commonality study evaluated use of the PLSS for EVA being operated to support the crew during nominal operations in the crew cabin. The study quantified the savings that could be achieved but also identified the penalty in infrastructure incurred in the process of connecting multiple PLSSs to a cabin ECLSS. This concept was considered relevant for MPCV and Altair missions. Another facet of the commonality identified was the difference in operational life requirements for a cabin system that runs continuously while the vehicle is operated versus the PLSS that is operated only during EVAs. The concept could not be pursued because the PLSS development lagged the need to establish the design of the Orion MPCV.

Commonality of equipment has been studied in past Shuttle and International Space Station programs and has been addressed in constellation studies. The need to design systems to meet schedules generally means that equipment designs for one vehicle must be established before the detailed requirements for the next vehicle in a mission architecture are established. Thus the potential for a common solution to a function is difficult to achieve because of schedule and optimization arguments.

Commonality has been achieved and has resulted in savings in several components of the ISS. The ISS PhotoVoltiac Radiators (PVR) intended for use only to condition power production equipment were recognized to have the functionality needed to support the United States Laboratory of the ISS. An innovative use of the PVR implemented two PVRs oriented orthogonal to each other mounted on the P6 truss to provide the heat rejection capability needed for the USL.

Common design of many ATCS and ECLSS components is used for most elements of the ISS.

J. Recommended approach to Exploration Commonality

Commonality implementation in future exploration vehicles requires that management direct system developers to consider functionality required of each vehicle and use a common approach to providing common functionality. Since a common crew size and a common deep space environment applies to many exploration mission concepts, the potential for employing common technologies is real and should be pursued.

Vehicles developed for short duration missions can usually reduce mass by employing ETE technologies that use consumables. However, it may make sense programmatically if the same technologies that are essential for long duration vehicles are also used in short duration mission vehicles. Development of one set of technologies to accomplish all exploration missions may be cost effective versus developing different technologies for short versus long duration missions. Trades should be conducted to determine the differences between regenerative versus open loop technologies for short missions so that programmatic savings can be considered.

K. Reliability Requirements and Implications

As soon as missions leave the LEO arena the capability to perform maintenance and provide logistical consumables becomes a significant factor. Thus the reliability of equipment used to perform ETE functions must be high and the need for replacement parts has to be low.

Programs conducted in LEO for the past several decades have had the advantage of both frequent missions to their LEO locations or the possibility of abandoning the mission and returning to Earth in a short period of time. Exploration missions will have decreasing capabilities to address unexpected maintenance and resupply as the destination becomes farther from Earth.

Technology selection for ETE systems must consider maintenance and reliability as key parameters for technology selection.

The ISS can be viewed as having capabilities that make the approach of flying equipment and systems that have not been thoroughly tested on the ground because the capability of testing the component or system at ISS can be used to verify functionality. That approach is advantageous to reduce ground testing requirements. However such verification in space approaches are acceptable only because ISS offers the infrastructure that can tolerate a component or system failure and the capability to troubleshoot a problem and if needed the capability to return components to the ground for investigation and problem resolution.

Exploration missions will require that equipment be functional and reliable because a failure will compromise the success of the mission and/or endanger the crew.

Integrated testing on the ground can be effectively used to verify that components and systems are ready to perform their functions before launch. Since functionality during a mission is much more important during exploration missions versus ISS; integrated testing should be used to minimize the possibility of failures of exploration equipment.

L. Synergistic technology options

This section provides an overview of technology options and which make sense for the missions that are to be undertaken and decisions that will be made and their influence on technology solutions

10. Factors that influence ETE technology selection

Mass, power and volume dominate considerations for all spacecraft technology selections. If taken on an individual component basis, a minimum solution may not be compatible with the minimum solution for other spacecraft components. Thus a system approach is usually implemented. Occasionally selection of technology is based on the overall benefit to an entire spacecraft and that will lead to a more integrated and compatible design. Future exploration missions should consider technology selection based on the entire compliment of elements needed in a mission.

LSS missions have considered use of cryogenic storage of consumables and connection between propellant and ECLSS fluid needs. Those studies show that significant efficiencies can be realized by use of cryogenic storage approaches. HEFT2 direction calls for study of propellant depots which will require long term storage of propellants in cryogenic state. The technologies developed for propellant storage should be considered for storage of consumables for ECLSS and EVA.

EVA technologies using cryogenically stored O2 may take advantage of the thermal conditioning needed to provide cryogenic O2 to the crew to provide heat rejection for the suit and PLSS.

Studies are showing that cryogenically stored O2 can be used to provide the pressure increase needed to achieve the EVA needs for high pressure O2. The thermal conditioning needed in that approach should be integrated into the SEV and/or habitat ATCS system.

Water stored in water walls for radiation protection could be viewed as a source of water for crew consumption in contingencies thereby reducing the inventory of potable water required. Processing of water wall water would probably be required to ensure it is acceptable for crew use. Thermal conditioning will be required to ensure the water wall is maintained within limits and the water wall could be used to address transient heat loads by using its thermal capacitance.

ETE Emphasis for Development

Technologies currently under development in the Enabling Technology Development and Demonstration (ETDD) program Life Support and Habitation Systems (LSHS) project will support and improve the functionality of vehicles that will be needed in future missions. New technologies that are either identified via new technology requests or that have been identified but are not currently adequately funded may also become candidates to consider for future missions.

M. Transit Vehicles

For transit vehicles, the CAMRAS technology makes sense to address the need for CO2 and Humidity removal with the caveat that programmatic considerations could lead to a more regenerative solution if that solution results in a lower overall programmatic cost. Deferring all but contingency EVA capabilities to bases continues to make sense for transit vehicles.

The concept of a space tug to transport crew and some equipment from LEO to bases or interplanetary vehicles makes sense to eliminate the significant ascent and entry provisions from the vehicles that are used only in space. The tug concept does imply that the capability to return from space bases of missions include the capability to decelerate to enter LEO so that crew and cargo can then transfer to a vehicle that returns them to Earth. That LEO entry and rendezvous capability is consistent with the refueling approach capabilities to be developed..

N. Deep Space Bases

Deep space bases should employ concepts that use the extremely cold thermal environment to aid in both thermal control and ECLSS processes. Development of new EVA suits and infrastructure should consider ISS requirements for performing assembly and the improved technology that minimizes consumables required for each EVA. Synergistic EVA and ECLSS approaches will improve the overall mission efficiency by minimizing consumables needs via regenerating resources. The next generation of space suits probably needs to have an evaporative heat rejection capability to address potential surface uses but should baseline heat rejection via radiative heat rejection and synergistic use of cryogenic O2. Cryogenic O2 can be used to provide the high pressure O2 needed for EVAs and should be considered for deep space bases. The link between propellant cryogenic storage and ECLSS O2 needs should be considered to minimize O2 storage requirements. The dual barrier HX concept should be implemented to address safety by keeping the potential hazard of toxic coolant from entering the habitat. The development of bases to assemble and outfit mission vehicles should be pursued probably at GEO but possibly at a LP.

O. Potential Lunar Mission for Verification of Mars Capabilities

The lunar scenario that is likely to be implemented will probably be a combination of the NC-5 international concept with a focus on Mars forward concepts. Closed loop life support will be employed to minimize the mass needed for consumables. It is likely that the rear entry suit concept will be implemented with a suit port of suit lock concept. Mobility via electric rovers is likely since that approach is consistent with Mars mission needs. Designs that address the polar environment should be pursued to take advantage of the moderation that environment provides (versus the extreme hot and cold of equatorial regions). If missions to lunar equatorial regions are conducted those should include kits and consumables to address the extreme environment of those locations and the mission length may have to be constrained. Use of nuclear power should be considered but the lack of mobility for significant nuclear power concepts would have to be traded against mission objectives.

P. Mars Mission

Q. The probable capability for fueling and/or refueling at an assembly bases should be fully considered in developing the Martian mission architecture. Having adequate propellant resources could result in a single crew and command module to address the crew life support needs during the entire mission to and from Mars including surface operations. Taking advantage of the deep space environment could lead to more integrated life support and thermal systems. Many of the concepts for habitation and mobility developed by the LSS will probably be used for the Martian mission. The SEV and closed loop life support will be used. However, the presence of the Martian atmosphere will need to be addressed in ETE systems. The CO2 content of the atmosphere will lead to using technologies such as for a Sabatier reactor important for life support and potentially for propulsion. Compressed CO2 should be used for cleaning (to a level) of sensitive surfaces. Planetary protection will need to be addressed in ECLSS systems specifically to minimize venting and to make waste products biologically inert. Mars sample handling and contamination of EVA infrastructure will need to address the need to keep Martian samples from contaminating life support systems. Shortening the transit time via development of nuclear propulsion systems (maybe via the VASIMR concept) will reduce concerns for radiation exposure and crew deconditioning and would reduce overall mission length that ECLSS has to address.

Summary of the ETE implications related to HEFT2 Directions

MPCV designs for ETE are relevant for transit vehicles specifically use of the CAMRAS technology for CO2 and humidity control. The concept of a space tug for both crew and cargo transport from LEO to assembly bases at LEO, GEO or LPs is consistent with the direction that includes commercial transport of crew and cargo to LEO and bases for propellant transfer in space.

Dual barrier heat exchanger technology should restart development so that it will be ready for deep space missions to provide a safer ATCS for virtually all exploration elements.

Technology development efforts in EVA will lead to rear entry suits that when combined with lower cabin pressures will address provisions for frequent EVAs (required to support fueling and vehicle assembly). EVA technology developments will improve efficiency specifically for bases and surface operations on NEOs, Mars and Phobos.

Concepts that should be investigated further are:

1) Use of the extremely cold heat sink of deep space for heat rejection and possibly a better way to revitalize the cabin air
2) The concept of a single crew module for an entire NEO or Lunar or Mars mission. This concept could result in significant overall mission mass savings by eliminating duplicative systems and entire elements of the exploration architecture. It could also substantially reduce overall cost of exploration missions by eliminating the need to develop several versions of ECLSS and habitation and control systems.

The Martian 1/3 gravity will make it essential to pursue EVA technology improvements to reduce the weight of the EVA system to be used on the Martian missions. Mars forward approaches should consider the weight of the EVA system for Lunar EVA systems to ensure the technology demonstrated on the Moon is compatible with Mars mission needs.

Technologies that can take advantage of Martian CO2 should be developed further to use that natural resource for a source of O2 and as a compressed gas for cleaning surfaces as they accumulate Martian dust.

Planetary protection should be considered important for Mars missions and technologies that close the life support loop will minimize the need for venting and thus accomplish a level of planetary protection. Waste management technologies that sterilize waste will be essential for Mars ETE.

Integrated testing should be viewed as essential to improve reliability of ETE equipment.

II. Overview of the Constellation Lunar Scenarios

The Lunar scenarios considered during the Cx Program included LEO operations to rendezvous and assemble elements that then proceed to the moon; Low Lunar Orbit (LLO) operations to separate elements used for transport to and from LLO from those that go to the lunar surface; then operations on the lunar surface. Cargo elements operate in the LEO briefly before the transit to LLO then descent to the Lunar surface and then operate on the surface.

Two of over 14 scenarios addressed by the Lunar Surface Systems (LSS) team considered the possibility of refueling elements of the lunar missions and potential reuse of transport equipment to deliver elements and crew to the lunar surface then return to LLO to be reused again after refueling. Those scenarios might have applications to the new human exploration program because those also take advantage of refueling processes.

The 2004 VSE [1] included a concept for delivering crews and equipment to the lunar surface and human return. That concept was evaluated in much more detail by the LSS team and the feasibility of the concept was established in the Lunar Capability Concept Review (LCCR) [Reference 7] conducted in 2007. The LCCR established that the entire lunar architecture (starting with the Ares 1 rocket and the Orion Crew Exploration Vehicle (CEV), the Altair Lunar vehicle combined with the Ares V Heavy Lift Vehicle (HLV), cargo elements, and EVA systems needed to conduct lunar surface operations) was feasible based on engineering assessments and analysis. The LCCR assessments and analysis included Master Equipment Lists (MEL) of equipment required to conduct the mission and weight estimates of the entire compliment of equipment needed to conduct the operations. It also included evaluation of the lift capabilities of each stage of the mission and even a financial assessment based on budget estimates for the total content of the missions. The mission assessments started with a Design Reference Mission (DRM) and documented assumptions and the architecture needed to accomplish the scenarios in Surface Architecture Reference Documents (SARDs) for each scenario. This paper will address the features of the variety of LSS scenarios that affect the content and operation of the ETE of the elements to be used in the mission architecture (Section M herein).

R. Constellation (and potential new) Lunar Mission approach ETE options and implications

ECLSS, TCS and EVA are addressed in the Orion MPCV, the Altair lunar lander, Lunar surface habitats and LERs. ECLSS and EVA provisions are also included in Power and Utility Platforms (PUPs) and TCS provisions are required in all elements of the Cx fleet of vehicles.

11. The Orion ETE approach

The Orion vehicle must address crew support for launch, the duration of NEA, lunar or Mars missions, then during entry and postlanding operations on Earth. Since Orion is required to be the primary support for crew operations for 21 days of the mission consumables are sized for that length of time. Consumables sizing for life support and for thermal control specifically address the 21 day manned operations. However, it must also address potential unoccupied periods of up to 6 months while at ISS or in Low Lunar Orbit (LLO) during long duration lunar missions. Unoccupied periods during NEA andf Mars missions would be even longer. To address the long unmanned periods of operation; life limits for unmanned operations are established that primarily address the thermal environment the vehicle will experience.

The Orion ECLSS, TCS and EVA design provides vehicle solutions that meet the relatively short crewed period of operations with minimum mass.

Storage of consumables is generally the minimum mass solution for ECLSS functions for short missions and that solution is used for crew required gases and food and water.

To address removal of human (Humidity and CO2) and vehicle contaminants from the cabin atmosphere a partially regenerative CAMRAS system is to be employed.

TCS needs are addressed with an Active Thermal Control System (ATCS) that radiates waste heat via radiators during normal space operations and uses consumable water to supplement when needed. Entry and landing heat rejection is addressed via an ammonia boiler similar to that of the shuttle though sized for the lower Orion heat loads. Heat rejection storage of capacity may be included in the form of a Phase Change Material with a heat exchanger to interface with Orion ATCS.

EVAs are not planned to be conducted from the Orion vehicle but contingency planning requires that the crew have the capability to address contingency scenarios. The life support for the suited crew while in the Orion vehicle is provided via the core ECLSS system via umbilical attachments for each crew. The approach of deferring provisions for nominal EVA to bases or surface transit vehicles should be considered for all transit vehicles.

12. Altair ETE Approach

The Altair vehicle duration of crewed operations is even shorter than crewed times for Orion. The solutions for ECLSS, and TCS are much like those of Orion. However, EVA is an essential operation from the Altair lander. The Orion ECLSS schematic shown in Figure A shows the functions addressed including those supporting EVA.

Provisions for support of EVA from the Altair vehicle significantly alter the vehicle functions. Surface EVA requires that the suits operate independent of the Altair vehicle and thus a Portable Life Support System (PLSS) is required. The surface suits with PLSS must address the lunar gravity and thus keep mass under limits that a suited crew can support and still have significant mobility. One way of controlling suit + PLSS mass is to provide O2 via high pressure storage at a target of 3000 psia. The Altair solution for providing O2 at that pressure is to use the Altair O2 at normal supply pressures and compress the O2 to 3600 psia to provide PLSS charging at the 3000 psia required.

TCS is provided via radiators on the descent stage while on the surface and via water sublimation during ascent of the ascent stage only. An ammonia boiler is not required because the Altair only operates while in the vacuum of space (water is more efficient than ammonia for evaporative heat rejection).

13. LSS ETE Approach

Lunar surface systems are required to provide a habitat for crew while on the moon and mobility aids to conduct exploration. The LSS project was established to conceive of ways to establish habitats and conduct exploration of the moon. The project used the concepts and direction established in earlier studies beginning with the ESAS (ref 8) and progressing to 2 Lunar Architecture Team studies (ref 9 and 10). The first in-depth study of the lunar architecture resulted in the LCCR (ref 7) held in 2007. After establishing the feasibility of the Lunar architecture; the LSS team opened the forum for considering alternate architectures to encourage creativity in providing for lunar habitation and improve exploration capabilities. In 2008 the LSS team initiated international communication of the aspects of the lunar program to start communication and exchange of ideas. International interactions continue in 2011 and have resulted in several approaches that have been assessed as new scenarios for conducting lunar operations. The LSS addressed over 14 scenarios for how to conduct lunar habitation and exploration have been assessed by the LSS team. Each scenario has addressed how to transport and assemble the modules and equipment needed to establish habitats and explore.

Interactions with international counterparts started with exchange of information on LSS team scenarios and have resulted in new hybrid scenarios that include contributions from international partners. The most recent of the scenarios are referred to as campaigns and involve US and international partner both providing assets to the lunar surface.

LSS activities were directed at architectures and functionality that enables habitation and exploration of the moon; however, most of those concepts apply to habitats and exploration for deep space and Mars exploration. The environment of the moon is similar in many ways to that of the surface of Mars. Thus the basic functionality addressed in lunar elements is applicable for Mars missions with adaptations that address:

1) Reduced intensity of sunlight,
2) Low pressure atmosphere,
3) Dust that is distributed via Martian atmosphere (not just via human disturbance)
4) The need to address contamination.

The LCCR established the feasibility of the Constellation program to achieve a well defined lunar program to the lunar polar region. It established that the POD for Lunar exploration infrastructure of the Ares 1 and Orion crew modules, Altair Lunar crew lander and Ares V cargo capacity all meet mission requirements to establish an initial Lunar base of operations.

Figure 4 shows many of the elements considered during the LCCR. The solar array power generation system is prominent as are the core habitation modules and the Small Pressurized Rovers (the SPR evolved into the LER then into the Surface Exploration Vehicle (SEV)). The Chariott and ATHLETE elements provide the mobility to explore a significant portion of the moon from the lunar base. A version using inflatable habitation modules was also considered.

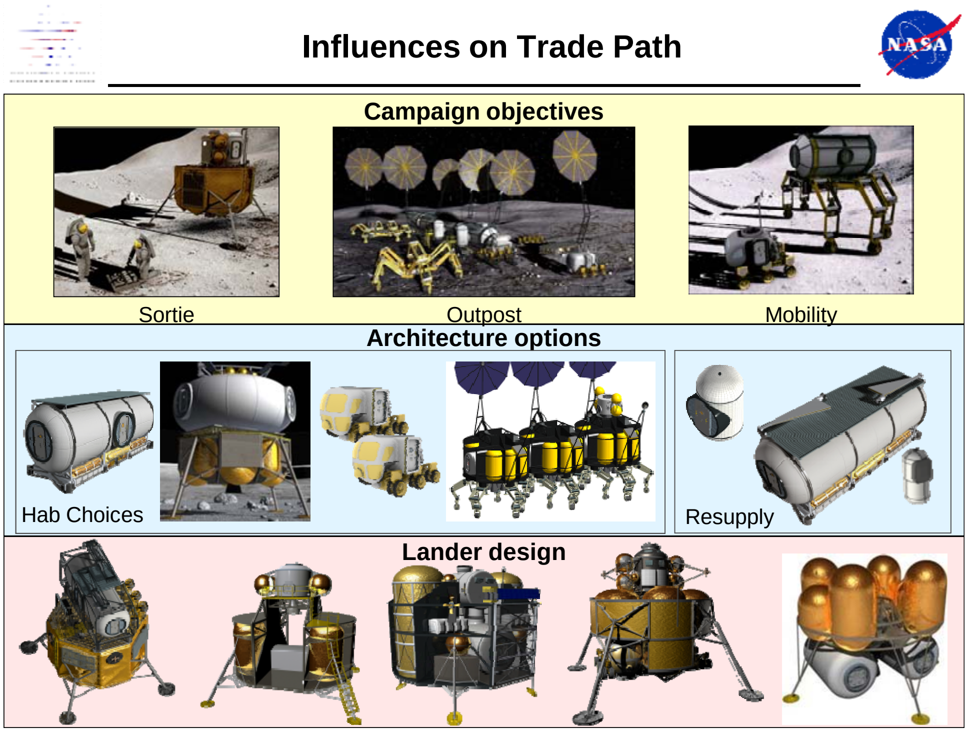


Figure 4 – Influences on Architecture Trades (From 2/1/10 Pitch on off loading options intro (good way to introduce LSS architecture and options that have been considered)

The ECLSS concept design was developed primarily using ISS technologies since information on the mass, power, thermal, volume was known for those technologies. The compliment of ECLSS and EVA and TCS equipment needed to accomplish the LCCR missions was defined and the requirements for the amount of infrastructure and resources needed were calculated. That level of fidelity established that the habitation modules could be delivered to the lunar surface by the Ares V system, the Altair cargo capabilities and the ATHLETE capabilities to remove the modules from the Altair and deliver them to the lunar surface. Most of the functionality of the ECLSS was established based on either demonstrated or planned ISS ECLSS. A challenge to reduce the infrastructure and resources required by the ECLSS and TCS by using more advanced technologies was given.

The TCS system was envisioned to be sized to address the 10 kW of power generated loads via radiators on the habitation modules and the SPRs. Details of the thermal system are in work but a set of assumptions based on ISS technologies was used to develop the compliment of equipment needed and estimate the mass, power and volume needed by the ATCS system.

EVA concepts envision using a rear entry suit that will provide faster suit donning versus the Shuttle and ISS Environmental Mobility Unit (EMU) suits. Altair operations would be conducted with resources needed provided via umbilicals connected to the crew module of Altair. The PLSS needed to go to the lunar surface would be donned in the Altair or airlock to enable surface EVAs. Operations on the surface would be conducted to complete assembly and exploration concluding with return to Altair during early operations. Once the SEV is available, crews would translate to the SEV via EVA then ingress the SEVs via suit ports to minimize consumables needed during each EVA. When habitation elements are operational EVAs would lead to the HAB and ingress into the habitat elements via an airlock or suit lock or suit port (the decision on which option to employ was not final).

Advanced PLSS concepts and the rear entry approach were conceived of and evaluated in engineering studies that addressed Airlock, Suit Lock, or Suit Port Architectures by a team of EVA experts (the ASPAT team).

EVA concepts have been conceived of in the EVA technology development project.

S. LSS Scenario Overviews for ETE

Lunar scenarios considered many ways to accomplish Lunar exploration and habitation as outlined in Table 2. Common features of all scenarios are the need to support the crew for an extended period (once early sortie missions are conducted).

Scenario

Scenario	Description
1	Full Outpost Assembly (Trade Set 1)
2	Mobility oriented Outpost (Trade Set 2)
3	Habitation oriented Outpost (Trade Set 3)
4	LCCR + Manifest Change - Rebuild of LCCR scenarios increasing crew flights to at least 2 per year
5	Nuclear power based scenarios – Use a fission reactor as the primary power source
6	Power beaming scenarios – Consider ways to beam power from orbit or surface to systems
7	Recyclable lander – Scenarios that make massive reuse of lander components to build up the Outpost an surface infrastructure
8	Extreme mobility – Scenarios that deploy Small Pressurized Rovers early and use them as primary habita
9	Improving Lander offloading – Scenarios that support a lander configured to make unloading much less complex
10	Refuelable lander – Scenarios that support a lander designed for multiple flights to and from LLO
11	Mars Centric – Scenarios that optimize Mars exploration ties
12	Horizontal or Vertical Hab with limited element mods
13	Cargo Capability Limited Architecture Study 10.5 t, 12.5 t or 17.0 t
	Noordwijk Campaigns – International Architecture Working Group
NC-1	Early Scientific Return Emphasis - A staged approach that emphasizes site diversity initially and relocatio non-polar sites then established long duration human stays later
NC-2	More Balanced Science/Mars forward approach - Earlier long duration phase, Long duration comes befo Non-polar relocatability, Polar relocatability scope is slightly reduced to increase potential re-use of previously deployed hardware for long duration phase
NC-5	Reduced Overall Level of Resources - Start with limited series of sortie mission (up to 6), Moves long duration stays earlier after initial relocation mission to Malapert, Reduces both the number of sites and length of stay for human activity

Table 2 LSS Scenarios that have been considered (Spring of 2010)

Some of the architectures and options for how to implement LSS goals are shown in Figure 4.

Scenario 4 combined features from 1, 2 and 3 and essentially documented the results of the LCCR efforts. It was the first to consider options of internationally provided elements with inclusion of ESA landers.

Scenarios 5 and 6 focused on the power production system and provided ways to provide the power needed even during periods when sunlight would be unavailable. Scenario 5 was consistent with the goal of establishing a permanent base but constrained mobility. Scenario 6 was not evaluated in detail due to lack of resources; but that scenario could support mobility and would have the potential for spinoff benefits since the power beaming concept could be used to provide power to Earth also.

The availability of power during shadowed periods adds flexibility and capability to lunar operations. Operations that would otherwise have to be scheduled to wait for power to be available can be conducted instead in ways that make sense to optimize crew timelines and for optimum equipment usage.

Many regenerative ECLSS functions require significant power resources and are thus scheduled to operate only when solar power is available. The continuously available nuclear power or beamed power would relax operational constraints.

Scenario 7 started looking into recycling of lander components that would otherwise be left unused after their missions are complete. That approach evaluated use of many parts of landers but perhaps the most important for ECLSS is the use of residual propellant left in tanks after landing to create water for surface operations use.

Scenario 8 considered making even the base of operations mobile.

Scenario 9 addressed the difficult task of removing exploration elements from the top of the two story high descent stage. This and scenario 10 considered changes to the vehicle architecture for lunar landing vehicles.

Concepts developed provided landing capabilities that resulted in much less EVA and robotic activities being required to deploy elements to the surface.

Scenario 10 addressed the reuse of both crew and cargo landers by providing enough fuel to accomplish both landing and relaunch of landers to LLO. This concept included the concept of refueling vehicles either in LEO or in LLO which enhances capabilities to deliver equipment to the surface. The reuse of sophisticated lander vehicles would dramatically reduce the cost of the overall lunar program. It also included an enhanced mode of operation affording the capability to abort either the descent to the surface or the ascent to return to LLO.

This concept led to several technology development efforts on refueling.

Reuse of landers does have the impact of not having the used lander descent stages on the surface after missions. Not having that equipment and residual supplies means that concepts (scenarios 7 and 12 particularly) that rely on those residuals for resources would have to provide those resources in some other way.

The Mars centric approach of scenario 11 is possibly the most likely scenario to be implemented under the recent HEFT2 direction. This scenario conducts Lunar missions only as needed to demonstrate capabilities that are essential to demonstrate before a Mars mission can be conducted.

Scenario 12 collected features from earlier scenarios and became the POD for international interactions. The vertical node concept of Scenario 8 then 12 could be viewed as very similar to the ISS nodes in both scale and function. That concept could lead to an arrangement similar to ISS in which ESA via Alenia could provide the structure of the lunar node that would be outfitted with equipment from both ESA and the US.

Scenario 13 considered how exploration could be conducted if the capability to deliver cargo to the lunar surface was larger or smaller than the LCCR Ares 5 infrastructure capability.

Scenarios considered in late 2009 with international organizations considered how to accomplish exploration with international contributions of elements delivered to the lunar surface. The international meetings held Noordwijk resulted in "campaigns" of robotic precursor and human missions to accomplish scientific objectives primarily in NC1 and more Mars forward approach in NC2.

The fiscal realities that were identified by the Augustine commission in mid 2009 resulted in NC5 that calls for a reduced yearly expenditure thought to be more realistic to accomplish lunar exploration. NC5 takes more time to accomplish lunar goals to address expected budget availability.

T. ETE concepts used in all LSS scenarios

14. Regenerative ECLSS

Habitation elements that support extended stays with regenerative ECLSS are a common part of nearly all scenario architectures.

Supporting the crew for extended periods combined with the limited capacity of the lunar mission infrastructure to deliver mass to the lunar surface makes recycling of any resource that can be recycled attractive. Because recycling can result in lower mass of consumables more exploration can be accomplished per mission.

ECLSS is a major user of consumables for any human mission thus the emphasis on recycling is a focus when considering ECLSS technologies to employ during lunar missions. The ECLSS schematic for lunar habitats and related SEV and airlock Figure 5 (ref 11) shows the focus on regenerating any ECLSS resource that is feasible. It also shows how interdependent ECLSS functions are with many processes depending on other processes for inlet feed streams. The connections between air and water and waste processed are well established. Closure of ECLSS functions can result in recovery of over 90% or water in waste, and most of the O2 from exhaled CO2.

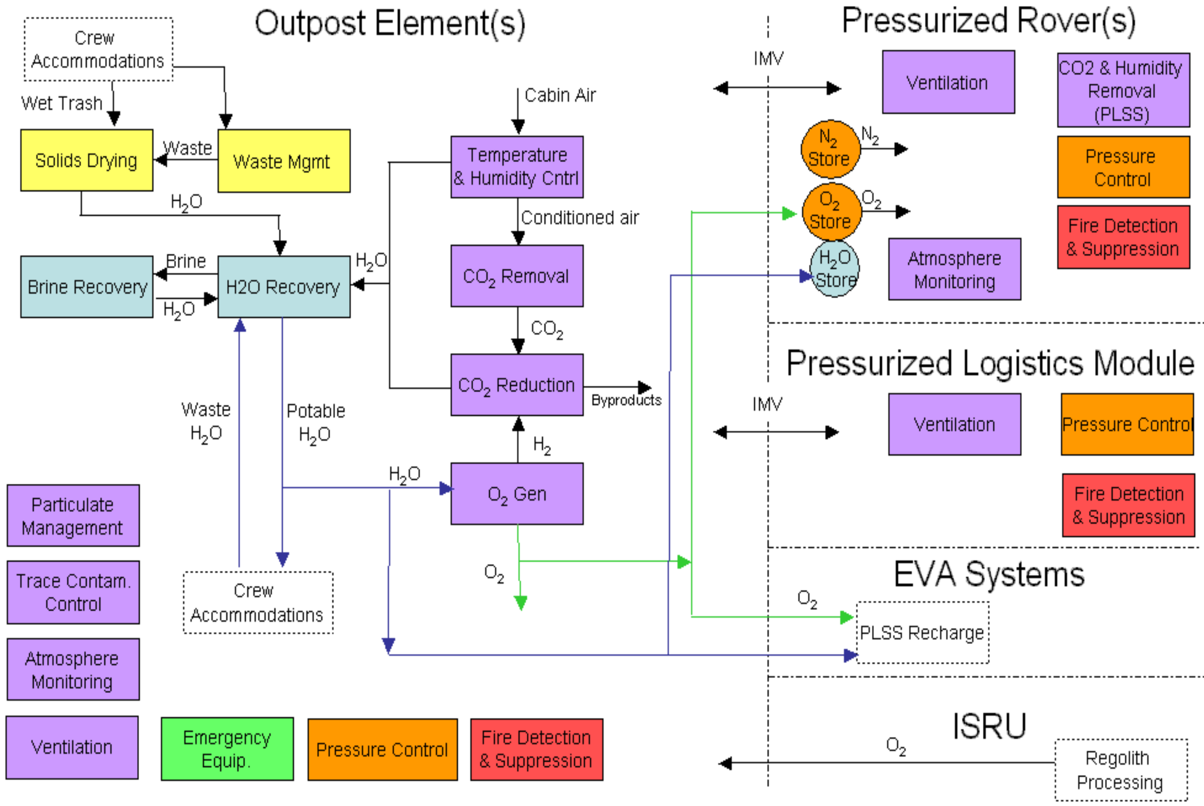


Figure 5 – Regenerative ECLSS Functions and Interactions between Envisioned LSS Elements

The interaction between TCS and ECLSS is significant because many ECLSS processes rely on thermal control to make functions efficient. To date the integration of ECLSS and TCS functions has not been addressed in LSS studies. Synergistic design of the ECLSS and TCS systems can provide benefits for both in the efficiency of the processes and the use of waste heat to benefit other processes. The integration of TCS and ECLSS functions will be addressed in future design efforts when the habitat and other elements of exploration architectures begin detailed design activities.

15. LSS TCS

Thermal control system functions must be addressed for all elements of the exploration architectures. TCS is included in all lunar missions but becomes more active and capable to address higher heat rejection requirements for the crew supporting elements.

Thermal systems operated in polar regions will have to address long periods of sunlight on one side of the vehicle while having deep space viewing on the other side with the side toward the sun slowly changing.

Heat pipe networks to transport heat from a hot side to a cold side can be used to address vehicle structural thermal conditioning.

Deep space heat sink environments will be available continuously in the up direction for polar regions. That very low temperature sink can be used to:

1. Minimize radiator area required to reject heat at nominal temperatures.
2. Support low temperatures needed for cryogenic processes
3. Support new processes of air revitalization that revitalize air via thermal instead of chemical processes

Sortie missions to the equatorial regions of the moon will have to address the hot lunar noon by either avoiding missions during those periods or use of thermal control technologies that can function in that hot environment. Since planning considered equatorial sites only for relatively short sortie missions, the potential for using heat rejection technologies using consumables is feasible.

16. EVA approach for LSS

All LSS scenarios include extensive use of EVA for assembly and exploration functions from the first Human Lunar Return (HLR) mission to the end of each scenario. EVA is required to conduct most assembly operations and can be enhanced by operation of robotic equipment.

EVA accommodations are required in Orion for contingencies and in Altair, the LER and the habitation elements for nominal operations.

Altair approached EVA via an airlock with the intent to minimize mass.

SEV approached EVA via a suit port concept to minimize consumables for the many EVAs envisioned to be required during SEV operations.

Habitat elements address the need to conduct EVAs and to maintain the EVA systems by considering a suit lock, suit port and airlock concepts. Suit ports or suit locks would be used for frequent habitat based EVA while a suit lock or airlock would be required to enable maintenance of the suits.

17. Lunar Dust Control

Dust control was identified during Apollo missions as very important in conducting Lunar missions (and likewise for future Mars Missions). To mitigate the problems that Lunar dust could cause during exploration many approaches have been considered.

1. The suit port concept allows the crew to ingress and egress EVA equipment from LERs or habitats without exposing the interior to dust that may accumulate on EVA equipment during EVAs.
2. Different exterior materials and equipment designs are being assessed to minimize the amount of dust that accumulates on EVA suits and other equipment.
3. Operational procedures and cleaning approaches are being developed and tested to keep lunar dust that has accumulated on EVA equipment from entering habitats.
4. Air filtration technologies are being developed that address dust that does enter habitats in spite of all other mitigation measures.

Equipment maintenance is acknowledged to be required for long term exploration to address the effects of dust and maintenance concepts are being developed.

18. EVA and ECLSS interdependence

EVA and ECLSS are connected due to the many EVAs envisioned as needed for lunar base assembly and exploration, each EVA has a small effect but over the course of many EVAs has a significant impact on overall ECLSS functions. Closure of an ECLSS system to well over 90% recycling of waste water means that loss of consumables during EVA can have a significant effect on the overall use of consumables. Both for the efficiency of the EVA itself and for the overall efficiency of the combined EVA and ECLSS systems, EVA technology options that conserve resources or capture consumables for ECLS recovery have benefits for long missions with many EVAs. EVA technologies that minimize the amount of water used for cooling and recover water from waste products will significantly affect the overall vehicle consumables use.

U. Lunar Architecture Factors

19. Lunar location effect on ETE

The location on the moon of exploration missions and the timing with respect to lunar diurnal cycles results in wide swings in the thermal environment.

Lunar poles have a benign overall environment relative to equatorial regions when the entire diurnal cycle is considered. For high latitudes sunlight is available for over ½ of the lunar cycle and always at angles near the horizon.

TCS systems can take advantage of having deep space viewing in the vertical direction almost continuously at polar locations. The sun angle changes slowly during the 28 day cycle which means that TCS systems could take advantage of one side being relatively hot due to sun illumination while the other side of the element would see very cold sink temperatures.

Equatorial regions experience extreme hot near solar noon due to the sun angle and the heating from the heated Lunar surface. That combination makes the lunar noon one of the hottest environments to be addressed in space system design.

Most constellation studies and LSS studies have targeted lunar polar regions for exploration and bases due to the scientific interest of those areas (geology and the potential for water ice in permanently shadowed craters). Elements of the lunar architecture operated in polar regions will have to endure significantly long periods of shadow.

20. Lunar Environment influences on ETE

The environment of Lunar Polar regions will affect primarily TCS and EVA element designs. TCS can benefit from continuous deep space viewing in the up direction near the lunar poles because a small area is required to reject heat to that extreme cold heat sink.

The extremely low heat sink temperature can also be used to achieve very low controlled temperatures from the radiative surfaces.

Those predictably low temperatures can be used to operate new technologies such as cryogenic storage of fluids and to separate gas constituents from cabin air.

A concept to condense CO2 from cabin air by lowering the air temperature has been confirmed to be feasible and will be pursued for development as an alternative to absorbent beds that have been used for CO2 removal.

The lunar surface temperature will be low due to the low solar incidence angle on the surface. That low temperature will require that parts of Lunar vehicles that contact the surface address the thermal control needed to maintain equipment temperatures within required limits.

Equipment that might be used in permanently shadowed craters will have to be designed to function in temperatures well into cryogenic temperature ranges. Even metals used will have to be assessed for brittleness when cooled to extremely low temperatures.

Access to resources of water (that have been confirmed to be present in permanently shadowed craters) will have to consider the extremely low temperatures in ISRU equipment design requirements.

EVA technologies use evaporative heat sinks in most concepts but radiative and hybrid radiative plus evaporative in other PLSS/suit approaches. Those using evaporative heat rejection technologies will not be affected significantly by the polar or equatorial environments. Those using radiative hybrid approaches will work better (consume less water) in the polar environments.

EVA systems will have to address the severe lighting of polar regions by developing viewing means to adjust filtration of light and possibly providing reflectors for use of sunlight to illuminate shadows (to reduce the need to use battery power for lighting).

Operations in Lunar equatorial regions will have to either be short duration to avoid operations during Lunar noon or have design requirements to address the extremely hot environment.

Radiative surfaces will experience the extremely hot sink environment whether viewing up (toward the sun) or horizontal (toward the hot surface). A project referred to as the Intense radiation xx is studying an approach to enable radiator surfaces to function in the lunar noon environment.

An alternative for short duration missions is to use evaporative heat sinks. Only for short missions is the use of water for heat rejection acceptable since water supplies will be limited.

Another option is to reject heat at higher temperatures by use of heat pump technology to elevate the temperature of an exterior thermal loop. Such systems will be heavy and energy expensive to operate but in a long term habitat located at the lunar equator heat pump systems may be one of few solutions to address the hot environment of solar noon.

21. The effect of use of Propellant residuals

In Situ Resource Utilization (ISRU) has considered the use of not only lunar regolith and mineral resources but equipment and residual fluids and gases in lunar landers.

By far the most reliable of those sources is the residual propellant in H2 and O2 tanks since for safety and mission flexibility there will always be some propellant left after landing. ISRU studies have evaluated propellant storage approaches to establish how much residual propellant will be left in tanks after landing then evaluated approaches for use of those either liquid cryogenic or gaseous resources. Most of those studies have considered ways to use residual O2 and H2 via fuel cell approaches to convert those resources to water. The water is then available to be transported in a compact form to elements that can use the water.

It can be used for a water resource or as the feed to electrolysis processes to convert the water into O2 of H2. The O2 can be used for many ECLSS functions. The H2 can be used in Sabatier processes to recover O2 from crew generated CO2.

The focus of many propellant scavenging studies is to use the water to address crew protection from the radiation environment with focus on protection of the crew from Solar Particle Events. Both habitat and SEV concepts use water to create water walls that intercept most radiation before it can harm the crew. Water from residual propellant resources is collected over several missions to slowly fill water walls in the SEV and/or habitats so that when crews have longer stays on the surface of the moon the radiation protection has been accrued.

22. The impact of ISRU use on ETE

Use of residual propellant or lunar regolith for water provides a significant source of water for lunar elements. Having that source of water means that closure of the water loop by recovery of waste water is not as critical as it would be without ISRU water. Studies have quantified how much water can be provided using residual propellant to provide water and have shown that the water walls can be filled early in lunar operations. Those studies assume that ECLSS closure is achieved and thus ECLSS and EVA use of water is consistent with a closed loop ECLSS system. Water from subsequent missions can be used for a variety of purposes including propellant for a concept of hoppers to enable relocation and exploration at a variety of sites or for refueling landers.

The scenarios that conserve lunar resources by reusing both the crew and cargo landers for subsequent lunar landings are not compatible with concepts to use residual propellant. Those concepts reuse the complex lander vehicles by refueling those elements in LLO with propellant transported from Earth. Reuse of those landers achieves overall program cost and complexity reduction but will not leave resources such as residual propellant on the moon.

III. Conclusion

Many aspects of exploration architectures have been addressed for the implication those missions have on life support and thermal control and EVA. The new direction of exploration emphasizes technology development and specifically closed loop life support. Technology maturation via technology demonstrations will provide the assurance that advanced life support and thermal control technologies can be considered for future exploration missions.

Several concepts have been specifically identified for consideration in future mission planning. Use of a space tug (maybe the MMSEV) could make transport of crew and cargo from LEO to potential assembly bases much more efficient by eliminating launch and entry vehicle provisions. The concept of a single crew and command module for transit and surface operations may save overall mission mass when combined with in-space fueling concepts.

To meet the needs of future exploration missions, new technologies under development (and that may be identified via the technology initiatives) will be essential for closed loop life support, efficient thermal control and efficient EVAs.

Acknowledgments

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Nomenclature

ASPAT	Airlock, Suitlock, SuitPort Assessment Team
ATCS	*Active Thermal Control System*
ATHLETE	All-Terrain Hex-Legged Extra-Terrestrial Explorer
CAMRAS	*CO2 and Moisture Removal Amine System (or Swingbed)*
CDRA	*Carbon Dioxide Removal Assembly*
CO2	*Carbon Dioxide*
CPS	*Cryogenic Propulsion Stage*
Cx	*Constellation Program*
DDT&E	*Design, Developoment, Test and Evaluation*
DRM	*Design Reference Mission*
DSH	*Deep Space Habitat*
DTO	*Developmental Test Objective*
ECLSS	*Environmental Control and Life Support System*
ELS	*Exploration Life Support*
EM LX	*Earth Moon Lagrangian Point X*
EMU	*Extravehicular Mobility Unit*

ES LX *Earth Sun Lagrangian Point X*
ESA *European Space Agency*
ESAS *Exploration Systems Architecture Study*
ETDD *Enabling Technology development and Demonstration*
ETDP *Exploration technology Development Program*
ETE *ECLSS, TCS, and EVA*
EVA *Extra-Vehicular Activity*
FYxx *US Government Fiscal Year xx*
GEO *Geosynchronous Earth Orbit*
GPOD – Global Point of Departure
H2 *Hydrogen*
HEFT *Human Exploration Framework Team (reports 1 and 2)*
HEO *High Earth Orbit*
HLR *Human Lunar Return*
HLLV *Heavy Lift Launch Vehicle*
HX *Heat Exchanger*
IAWG *International Architecture Working Group*
ISRU *In-Situ Resource Utilization*
ISS *International Space Station*
LAT *Lunar Architecture Team*
LCCR *Lunar Capability Concept Review*
LEO *Low Earth Orbit*
LER *Lunar Electric Rover*
LiOH *Lithium Hydroxide*
LLO *Low Lunar Orbit*
LP *Lagrangian Point*
LSHS *Life Support and Habitation Systems (technology development project)*
LSS *Lunar Surface Systems*
MEL *Master Equipment List*
MER *Mars Electric Rover*
MMSEV *Multi-Mission Space Exploration Vehicle*
MO *Mars Orbit*
MPCV *Multi-Purpose Crew Vehicle*
NCx *Noordwijk Campaign x*
NEAs *Near Earth Asteroids*
O2 *Oxygen*
OGS *Oxygen Generation System*
PLM *Pressurized Logistics Module*
PLSS *Portable Life Support System*
POD *Point of Departure*
PUP *Portable Utility Pallet*
PVR *Photo-voltaic Radiator*
REM *Robotics and EVA Module*
SARD *Surface Architecture Reference Document*
SEP *Solar Electric Propulsion*
SEV *Space Exploration Vehicle*
SOE *Solid Oxide Electrolysis*
SPR *Small Pressurized Rover (earlier acronym for LER)*
TCS *Thermal Control System*
TRL *Technology Readiness Level*
TSx *Trade Space x*
USL *United States Laboratory*
VASIMR Variable Specific Impulse Magnetoplasma Rocket
VSE *Vision for Space Exploration*

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