Concepts for Phased Development of a Lunar Surface Base

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Several design concepts were studied in 2019 and 2020 to explore a range of possibilities for development of a base on the surface of the Moon in preparation for ongoing missions to Mars. The studies included phasing approaches for life support systems to accommodate initial short-term missions under 60 days with eventual ongoing missions with crew rotations every 180 days. The approach presented is not currently in the NASA plans but is one of many approaches that could be considered as a reference for future development by government, commercial, and international partners. Included in the paper are conceptual layouts, life support phasing approaches, and mass properties for a variety of modules leading toward a permanent base on the surface of the Moon that is also applicable to a base development on the surface of Mars.

I. Nomenclature

ARS	=	Air Revitalization System
A or Av	=	Avionics
BP	=	Brine Processor
CBM	=	Common Berthing Mechanism
CCA	=	Common Cabin Air
CTB	=	Crew Transfer Bag
E	=	Exercise
ECLS	=	Environmental Control and Life Support
ECLSS	=	Environmental Control and Life Support System
EVA	=	Extra-Vehicular Activity
F	=	Food
G	=	Galley
ISRU	=	In-Situ Resource Utilization
ISPR	=	International Standard Payload Rack
ISS	=	International Space Station
IVA	=	Intra-Vehicular Activity
JSC	=	Johnson Space Center
kg	=	kilograms
kPa	=	kilopascals
kW	=	kilowatts
LS	=	Life Sciences
m	=	meters
Md	=	Medical
MSFC	=	Marshall Space Flight Center
N or Nit	=	Nitrogen
OG	=	Oxygen Generator
O2 or Oxy	=	Oxygen
P	=	Plant Growth Chamber
PS	=	Physical Sciences
S	=	Stowage
SA	=	Sabatier
Sc	=	Science
t	=	metric ton
TRL	=	Technology Readiness Level
UP	=	Urine Processor
UWMS	=	Universal Waste Management System
WMC	=	Waste Management Compartment
WP	=	Water Processor

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II. Introduction

Two recent studies in the Advanced Concepts Office at the NASA Marshall Space Flight Center explored several concepts for the buildup of habitation systems on the surface of the moon, the "Modular Lunar Surface Habitat Study" completed in 2019 and the "Habitation Life Support Phasing Study" completed in 2020. The results of these studies provide a reference for future concepts that could lead to the development of a base of operations on the surface of the Moon in the late 2020's and eventually Mars in the 2030's. Several module sizes were explored, but for the purposes of this paper one standard module about 3 meters in diameter and currently utilized in the International Space Station (ISS) commercial cargo program [1] is utilized to illustrate the possibilities of a complete system. Figure 1 presents a vision of what the habitable elements of a surface base might become.

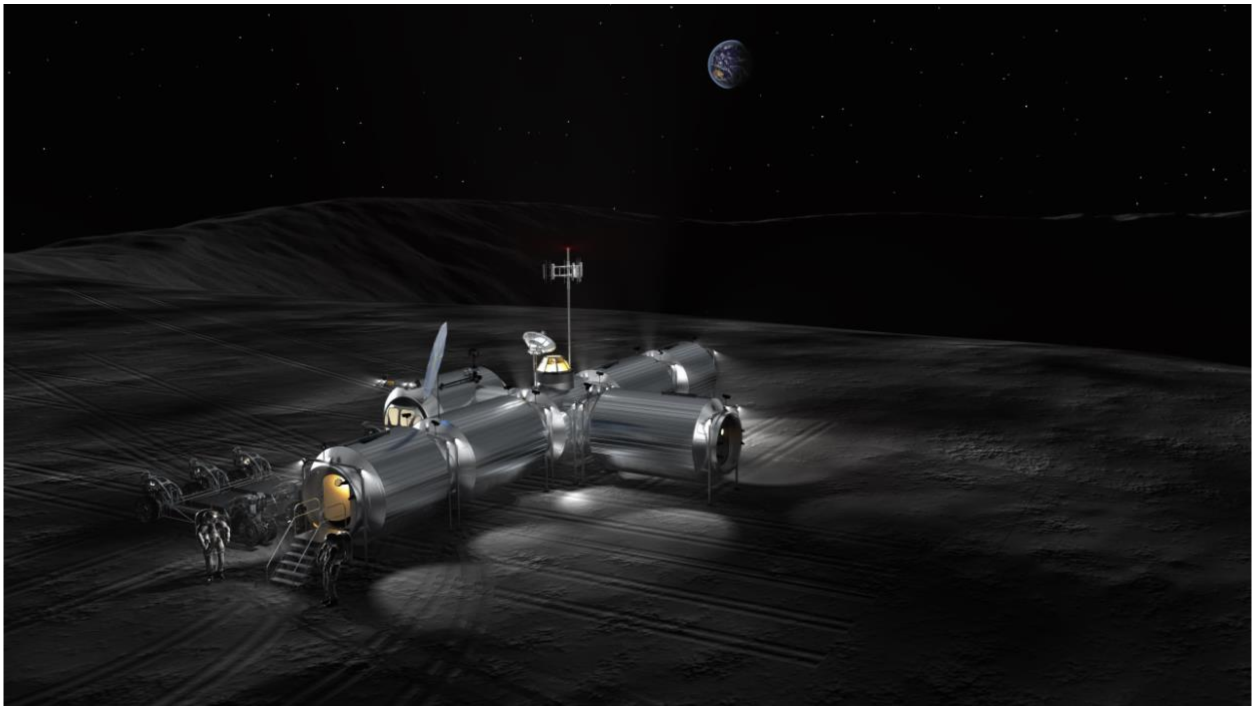


Fig. 1 Concept for a lunar surface base.[2]

The concept illustration above envisions a base at the lunar south pole where the Earth can be seen low on the horizon above the rim of Shackleton crater. On the surface are two astronauts and an unpressurized rover used to transport and connect the grouping of six modules that forms a base of operations. Behind the node module is a pressurized rover that can transport a crew of four to their ascent vehicle and a crew of two on field trips for exploration of resources and servicing of science and support systems. Not shown but required are the landers that deliver the crew and modules, the power systems for base power, and the in-situ resource utilization (ISRU) equipment for testing of new exploration and materials processing systems.

III. Mission Assumptions

The mission timeline for the buildup of this base is assumed to be in the mid to late 2020s when a human return to the surface will have been accomplished. Infrastructure already in place includes crew and payload launch capabilities to the Gateway outpost in lunar orbit, landing systems to the lunar south pole, payload off-loading systems, an unpressurized rover platform to transport these modules from the lander to the base camp, power systems for hook up to the base modules, and a pressurized rover for transport of crew across the surface.

Module delivery begins with launch from Earth on SLS or any of several commercial launch vehicles.[3,4] An attached in-space propulsion stage transfers the module to the Gateway outpost in lunar orbit.[5] At the Gateway each module is detached from its propulsion bus and then reattached to a landing system for delivery to the lunar surface providing opportunities for reuse of stages and landing elements.[6]

On the surface, the payload is off-loaded from the lander onto an unpressurized rover that can transport the module to the base camp and berth it to an adjacent module to build up the base configuration. For platform landers, the off-loading system could consist of a crane attached to the lander, or a separate mobile crane on the surface.[7] For dual and horizontal landers, the payload could be dropped directly onto an unpressurized rover without a separate crane element.

The unpressurized rover is designed to transport each module from the lander to the base location and dock it to the adjacent module for buildup of the base configuration. Each module has a set of leveling legs that deploy after docking so the unpressurized rover can release and roll out from underneath the module it was carrying. This approach makes it possible for the entire base to be mobile such that it can be relocated in the future if needed. In addition, the combination of a pressurized module and a rover platform could become the basis for a permanent pressurized rover designed for crew transport and a variety of exploration vehicles for extracting resources from the surrounding terrain.[8]

IV. Habitation Elements

An approach using a 3m diameter module from the ISS commercial cargo program was selected because of its low mass, current manufacturing capabilities, and an interior volume similar in size to a conventional camper or recreational vehicle. In addition, it is one of the modules that was explored during the Constellation Program for lunar surface habitation.[9] It is tight for a crew of four because the center corridors must be narrow to accommodate all of the required functions along the exterior walls, and the height provides little room for overhead systems and the needed open volume for crew comfort. The larger 4.5m diameter module from the ISS program would be better from overall systems and habitable volume capabilities, but the outfitted mass and handling requirements for large modules drives the mass growth of all of the supporting systems too. A size in between these two modules in the 3.5 to 4m range was not considered, but probably should be in future studies. In addition, it was found that a variety of module sizes might be possible for different functions if the right handling systems are provided for setup and berthing on the surface. In the scenario that follows a standard 3m diameter module is utilized with each presented in the assumed order of delivery to the surface so that the operations can be discussed in conjunction with the module design.

A. Operations Module

In this scenario the operations module shown in Fig. 2 is the first habitable element on the surface providing living and mission operations accommodations for two crew when attached to a pressurized rover. Included are two foldup bunks providing work volume when stowed, a waste management compartment (WMC), medical (Md) and life sciences (LS) equipment to maintain crew health and safety, avionics (A) for communications and control of external systems, and a galley (G) with food (F) stowage. In the center of the module is a place for exercise (E) volume to accommodate both resistive and stretching type activities. Fig. 3 provides sectional views that illustrate the volume for the WMC, workspaces at the bunks, and the resistive exercise volume in the center of the module. The WMC is enclosed with a privacy curtain as are the bunks, and the overall volume in the center between the bunks is divided by another privacy curtain. As mentioned, the module shown in Fig. 2 is designed to provide living accommodations for two crew, but the first mission using this module could include up to 4 crew if the other two live out of the pressurized rover. Since there is no airlock built into this module a pressurized rover would be required for any utilization. The mass properties for this module are summarized in Appendix A, Fig. 23, showing the manufacture's mass without logistics and some portable systems to meet a 5t goal for payload mass, and then a fully outfitted module in Fig. 24 with a mass approaching 9t including logistics to support 4 crew for 15 days or possibly 2 crew for 30 days.

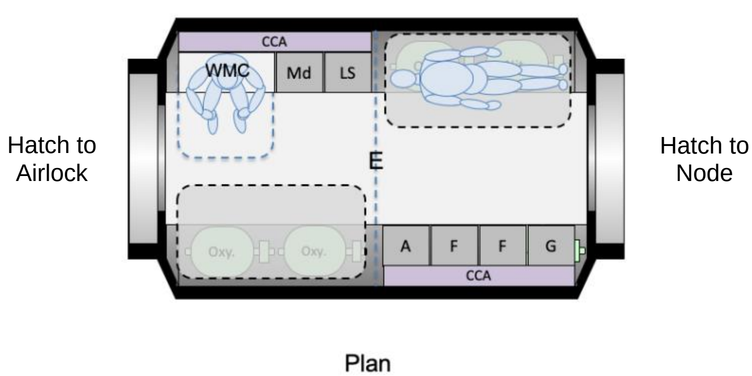


Fig. 2 Ops module plan supporting two crew members.

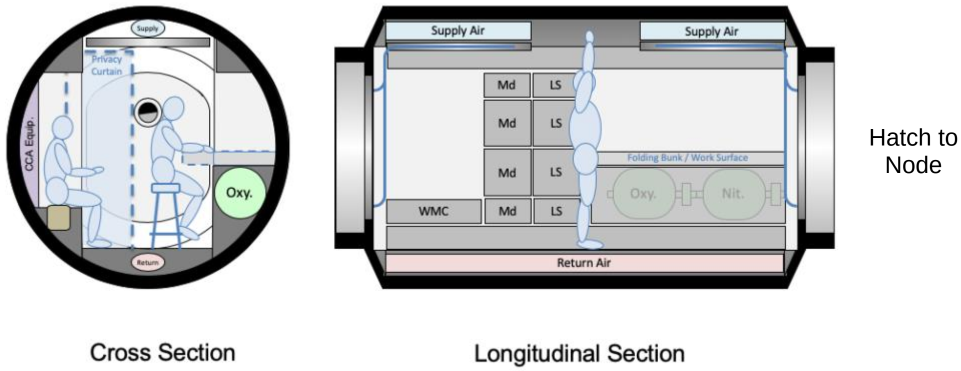


Fig. 3 Ops module sections.

A longer operations module option is shown in Fig. 4 to demonstrate how more exercise volume could be provided. In this layout it would be possible to provide the exercise volume needed for a treadmill device to accommodate better aerobic health for longer mission durations. The extended length module shown below in Fig. 4 to accommodate the exercise volume was not calculated in detail but would likely be about 1t more for the additional cylinder length with external protection and the internal supporting systems including exercise equipment.

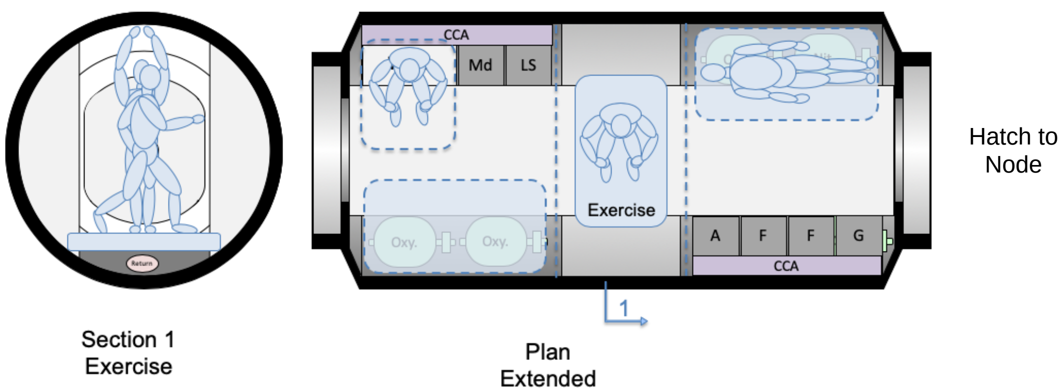


Fig. 4 Ops module with exercise volume.

All of the modules in Section IV utilize an open loop environmental control and life support system (ECLSS) designed to support mission durations for four crew in up to 60-day intervals. Longer mission durations using closed loop systems are discussed in Section V. The open loop system requires replacement of air and water supplies which can be seen in their operational position below the bunk / work surface volumes for each module. In addition, the common cabin air (CCA) can be seen along the outer wall with supply air provided from the top of the module and return air below the floor.

Another standard feature for all of the modules is the use of a common berthing mechanism (CBM) from the ISS program for attaching all elements together on the surface.[10] This size mechanism is needed for overall structural rigidity and to accommodate a step-through sized submarine style hatch for access between modules. The modules shown in Section IV are from the “Modular Lunar Surface Habitat Study” and utilize a 50” wide by 62” tall hatch derived from the standard 50” square hatch on ISS. The diagonal dimension from the ISS 50” hatch with its rounded corners is about 62 inches. The modules shown in Section V are from the “Habitation Life Support Phasing Study” and use the same berthing mechanism and hatch, but with a reduced hatch width of 40” to provide more equipment volume along the exterior walls. Hatch stowage varies and can be seen in both overhead and sidewall locations depending on the individual layouts.

B. Logistics / Airlock Module

An airlock is the second element needed on the surface so that access can be provided to the habitable volume directly from the lunar surface. Two approaches are shown for the airlock that provides for different operational assumptions. Figures 5 & 6 represent a relatively simple airlock that provides an open volume to clean, and don and doff suits with minimal maintenance and assumed low usage. This scenario could work if a pressurized rover were available with a suit port system where most of the extra-vehicular activity (EVA) is done from the rover and the airlock is used only as needed to bring the suits in for servicing. [11] In this scenario the airlock could be delivered with an initial load of logistics as shown in Fig. 5 that could be redistributed inside the operations module and pressurized rover before first use as an airlock.

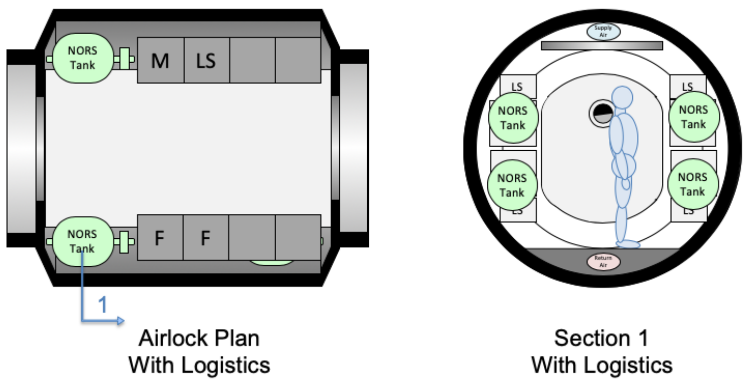


Fig. 5 Airlock with initial logistics delivery.

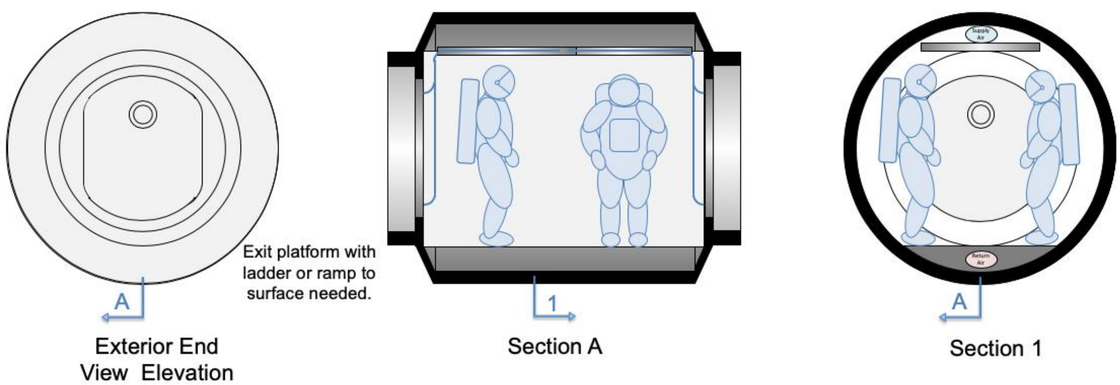


Fig. 6 Airlock in operational configuration.

A more functional airlock is shown in Fig. 7, which provides additional capabilities for suit cleaning and servicing in an attempt to keep dust out of the primary habitable volumes and to maximize serviceability of the spacesuit system. It begins on the exterior where (1) an electrostatic discharge system is proposed to help remove dust from spacesuits custom-designed with that capability. Working as a pair, the astronauts would begin the initial brushing of dust off each other's suits prior to entry into the airlock. Once inside the airlock each astronaut would use a vacuum and air shower system (2) to continue cleaning each other's suits while the air pressure is brought up to habitable levels. Once habitable air pressure and cleanliness is reached, they may begin to doff their suits either helping each other or using assistance from additional crew in the operations module. Once the suits are disassembled, they can be moved to area (3) for detail cleaning and maintenance as needed. Two air tanks are provided where one is utilized with a pump to collect the air in the module as it is brought down to vacuum, and the other is used as a backup air supply in the event the air inside the module is released to vacuum and additional air is needed to re-pressurize the airlock. This area is part of the airlock but is separated by a dust barrier to help minimize dust on the servicing tools and work surfaces. Theoretically, the overall dust removal system needs to be >99.3% effective (dust barrier efficiency) to minimize impacts to the environmental control and life support (ECLS) cabin filtration system operations and logistics management. [12]

There are other configurations and approaches for the EVA system and the airlock that were not explored. This includes the suit lock concept where an airlock like the ones above includes an interior bulkhead with an intra-vehicular activity (IVA) door and suit ports mounted.[13] That design would permit bringing the suits into the airlock for servicing and conducting EVAs frequently from the habitat either with or without a pressurized rover. Another approach using conventional Apollo or ISS program-derived suits could use an airlock like this with a pressurized rover designed with its own airlock that is capable of docking directly to one of the airlocks above. All of these approaches indicate a need for an airlock at the habitat but the approaches to the complete EVA system have many trades to consider.

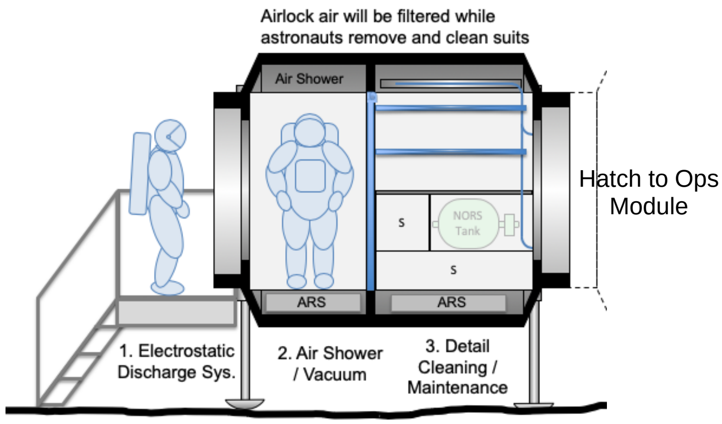


Fig. 7 Airlock in operational configuration.

C. Node Module

The third element in this build scenario is a node module, which provides a means to connect four modules together forming an intersecting cluster of elements as is done on the ISS. For surface habitats this greatly improves internal circulation and keeps the overall footprint on the surface compact. Given that the terrain is not level in most areas at the south pole it is important to keep the overall configuration as compact as possible to avoid extensive site preparations. For this build scenario the node will act as a contingency airlock in the event the primary airlock fails. It will connect to the operations module to the first laboratory module shown in Fig. 8, with the other two ports remaining open for the docking of logistics modules, additional laboratory elements, and a pressurized rover.

Fig. 9 provides a section view of the Node with a cupola option. The cupola is attached in the same manner as on the ISS, but in this case, it is put in place at the Gateway as part of the assembly of the payload and lander prior to delivery to the surface. Mass properties for the Node configurations are not provided in the appendix, however, parametric estimates indicated that a Node without the cupola element could be provided in the 5t range and that a fully outfitted Node with cupola should be possible in the 7t to 9t range.

D. Laboratory 1 Module

The fourth element provides accommodations for two crew outfitted with physical sciences laboratory equipment designed to complement surface exploration. Fig. 8 provides a layout which includes two foldup bunks providing work volume when stowed, stowage (S), physical science (PS) workstations, avionics, galley, and food stowage. The combination of these four modules provide a complete base configuration to support four crew on the surface for extended periods of time either with or without a pressurized rover.

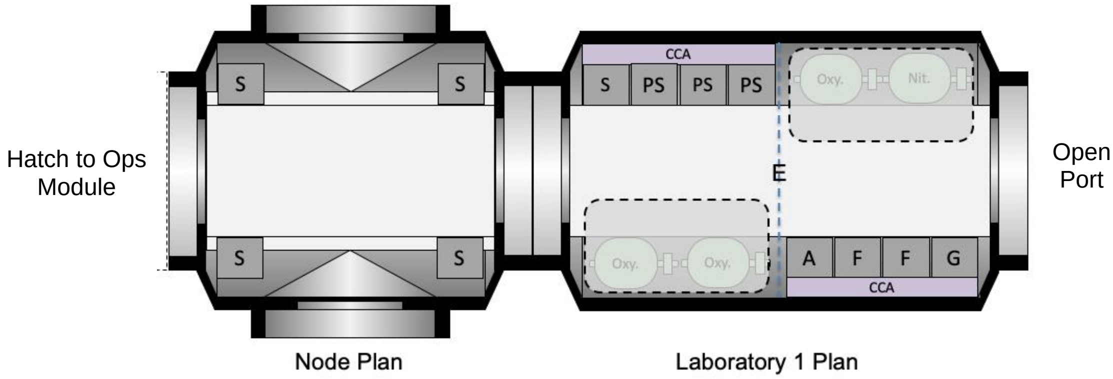


Fig. 8 . Node and Laboratory 1 supporting two additional crew members.

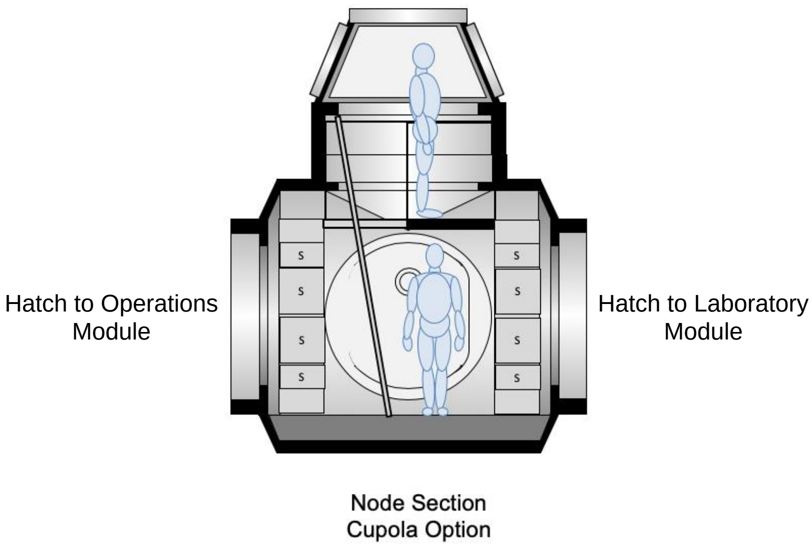


Fig. 9 Node with a cupola option.

E. Laboratory 2 Module

Laboratory 2 provides volume for additional scientific equipment and more open volume for the crew. Depicted in Fig. 10, it shows physical science equipment and workstations at one end, stowage and more extensive galley equipment at the other, and open volume in the center for crew activities.

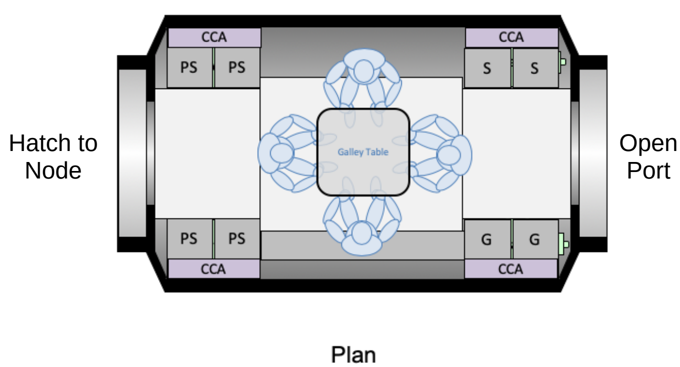


Fig. 10 Laboratory 2 or possible International element.

F. Logistics

Initial logistics requirements will vary depending on mission duration and lander capabilities. For 30 to 60-day missions, a module about the size of the airlock shown in Fig. 5 should be sufficient except that it would be fully packed including most of the corridor volume. With the Node in place it could be docked to one of its open ports or to the end of one of the laboratory modules. Of particular interest in these studies were the amount of logistics required to transition from the initial assembly missions to ongoing operations.

Ongoing operations for four crew are assumed to include crew rotations every 6 months. The 180-day limit is the planned frequency for SLS launches during the build timeframe and the current maximum duration for crew safety until more is understood about the deep space environment. A logistics mass of about 9,099kg will be required, which revealed a potential mass and volume issue. Current modules of the size planned in this scenario are used for logistics delivery to the ISS and carry less than half this mass. This indicates that at least two logistics flights will be required as illustrated in Fig. 11 and in Appendix A, Fig. 25. Additional analysis found that a closed loop ECLS system could reduce the logistics mass significantly to about 3,757kg as shown in Fig. 12 and in Appendix A, Fig. 26, which is more in line with current logistics delivery to ISS using a single module. Given that eventual ongoing operations on the lunar surface is a goal and that surface missions on Mars could extend beyond 180 days, the question became more focused as to how a transition could be made from an initial open loop ECLS system to an efficient closed loop ECLS system.

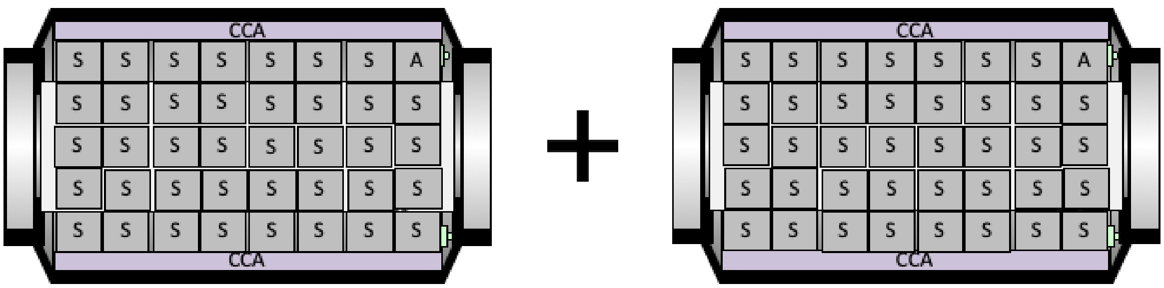


Fig. 11 Logistics with open loop ECLSS.

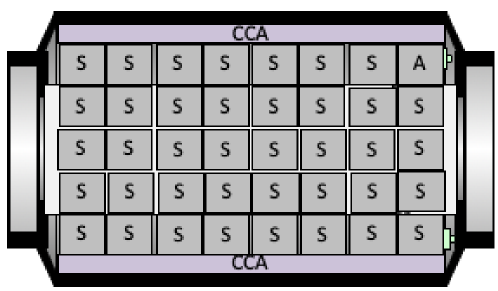


Fig. 12 Logistics with closed loop ECLSS.

V. Options for Closed Loop Life Support Systems

Three basic approaches were examined for moving from the initial open loop ECLS system to a closed loop ECLS system. These were (A) beginning the build with an ECLSS module that could be utilized as an operations module initially and then converted over time through phased growth; (B) adding an ECLSS module to the completed surface base configuration shown in Fig. 1; and (C) dividing the ECLS system into two modules for air and water regeneration respectively to help reduce payload mass.

A. ECLSS Module Phasing

One approach to transitioning from an open loop ECLS system to a closed loop system during the initial buildup of the base was to begin with an ECLSS module that could be utilized as the initial operations module and then converted over time as additional elements are added to the base configuration. This approach is illustrated in Fig. 13 where Phase 1 begins with the ECLSS module that includes an initial air revitalization system (ARS) and then as each additional element is added to the base, additional phases of the ECLS system are completed to convert the system from open loop to closed loop.

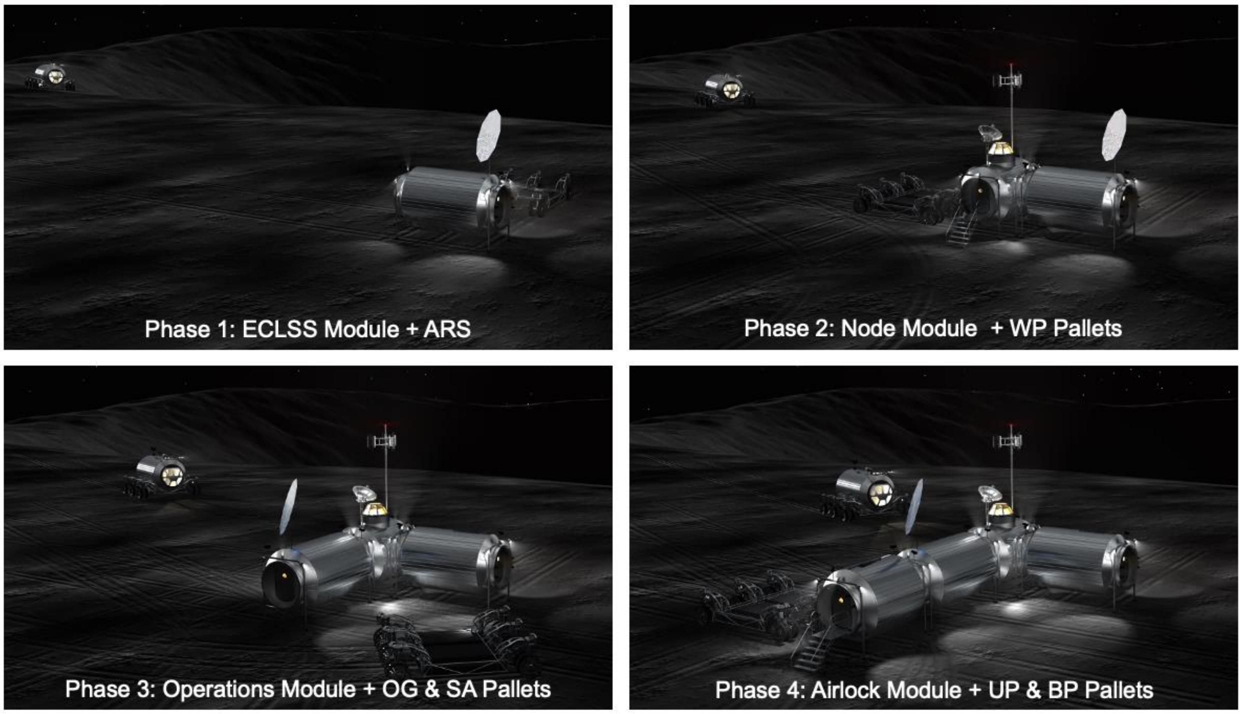


Fig. 13 ECLSS phasing summary. [2]

The ECLSS conversion from open loop to closed loop is made possible by recent work to break the system down into pallets that are more manageable in size for handling in space and on the lunar surface.[14] Fig. 14 provides a summary of the pallet system used for this study to determine a possible phasing approach. These pallets are about half the size of the International Standard Payload Racks (ISPR) [15] and can be moved through the smaller hatch size currently planned for deep space systems. Detailed schematics were not prepared for the phasing, but the systems were examined to determine the appropriate order for installation and which pallets would likely need to be built into the modules as opposed to being delivered and installed by the crew. The built-in elements include two of the ARS pallets, which contain primarily air cooling, distribution, and filtration systems that are common to all modules. The other built-in item is the universal waste management system (UWMS) due to its assumed complexity. The primary purpose was to determine a possible phasing approach and the mass impacts that approach would have for each mission during the base build up phase.

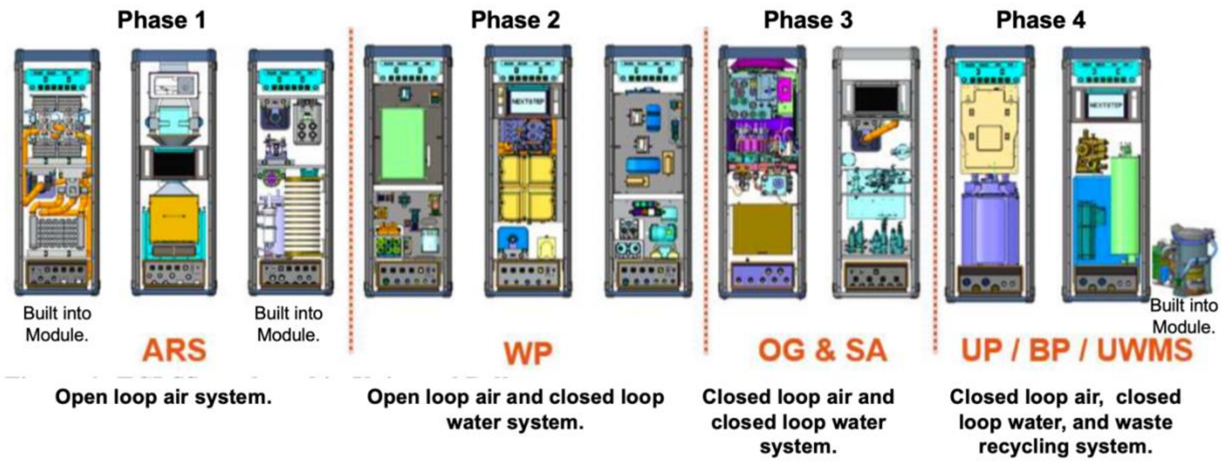


Fig. 14 ECLSS pallet summary.[14]

1) Phase 1: ECLSS Module + ARS. The first module in the surface base buildup could be an ECLSS module that is utilized as the initial operations module and then converted with the addition of ECLS system pallets from each succeeding element to provide a complete ECLS system. This approach is illustrated in Fig. 15 with a module that includes an open loop ARS pallet designed for integration with a closed loop system, a galley, two bunks, and a waste management system designed for integration with a waste recycling system. A module configured in this way could support two crew and an attached pressurized rover, with up to two additional crew members living out of the rover depending on the logistics available with these flights. The intent is to provide a near equivalent to the operations module discussed in section IV-A and illustrated in Fig. 2 above. The mass of this module was assumed to be about 7,248kg as shown in Appendix A, Fig. 27 as compared with the original Operations Module designed in the 5t to 9t range as estimated in Figs. 23 and 24.

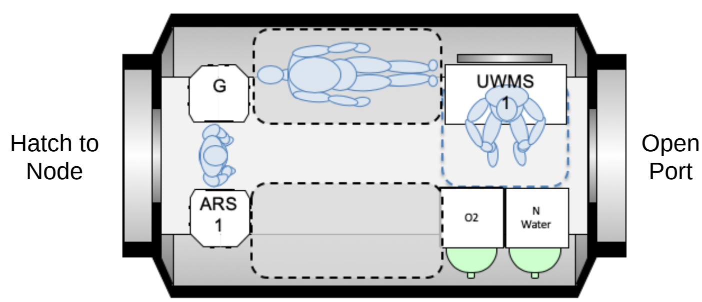


Fig. 15 Phase 1 ECLSS module with open loop system.

2) Phase 2: Node Module + WP Pallets. Phase 2 shown in Fig. 13 above adds a Node module and the delivery of three Water Processing pallets to begin the development of a closed loop water processing system. The ECLSS module is reconfigured as shown in Fig. 16 by relocating one of the bunks to a temporary location in the Node module and installing the three Water Processing pallets. In this configuration, the base could support one crew member in the ECLSS module, one in the Node module and up to two additional crew if a pressurized rover is available. If a pressurized rover is not available, then the Node could be designed to act as an airlock and support two crew for its first operational mission.

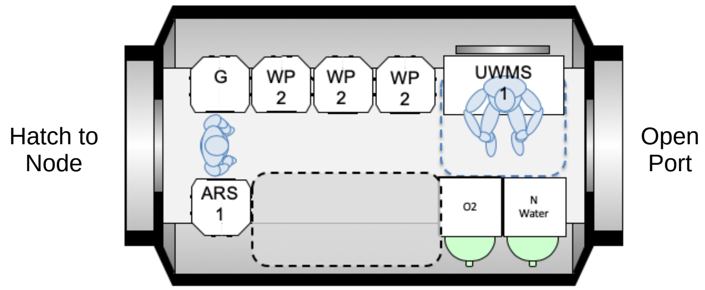


Fig. 16 Phase 2 ECLSS module with water processing pallets added.

3) Phase 3: Operations Module + OG & SA Pallets. Phase 3 adds an Operations Module and the delivery of air revitalization pallets for oxygen generation and carbon dioxide removal. When configured in the ECLSS module, the pallets will close the air system and partially close the water system. Fig. 17 illustrates the reconfigurations required, which includes moving the galley pallet and bunk to the operations module to open up the pallet slots for installation of the Oxygen Generator pallet and the Sabatier pallet.

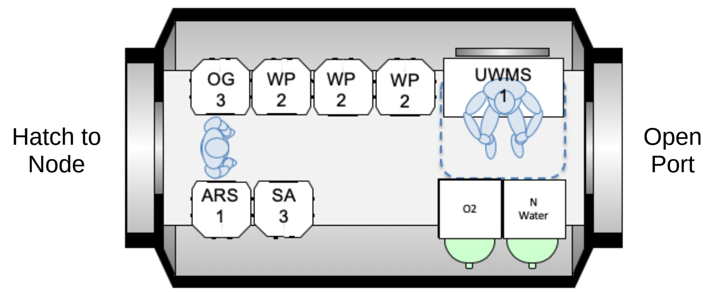


Fig. 17 Phase 3 ECLSS module with oxygen generation pallets added.

4) Airlock Module + UP & BP Pallets. Phase 4 completes the closed loop life support system by adding waste processing. The Airlock Module is added to the configuration and provides the Urine Processing pallet and Brine Processing pallet for the open slots in the ECLSS module, Fig. 18. With the airlock in place, additional laboratory modules can be added to the Node to complete the overall base configuration as originally planned in Section IV. With an operational regenerative ECLS system in place, the growth can now support four crew for ongoing 6-month missions with only one logistics flight per mission.

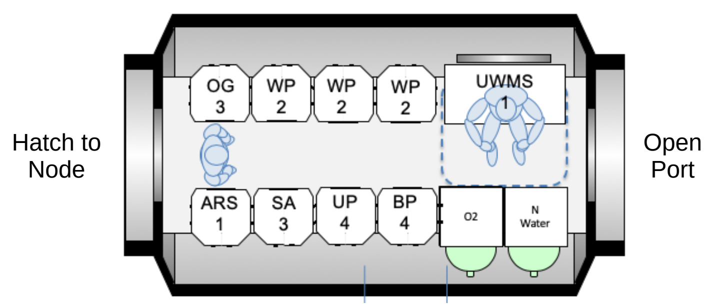


Fig. 18 Phase 4 ECLSS module with waste recycling system added.

The ECLSS consumables vary by number of crew and mission duration throughout this buildup from Phases 1 through 4. Table 1 provides a summary for the buildup scenario envisioned beginning with two crew for the initial mission and then 4 crew with varying mission durations for the remainder of the build. For the first mission it seemed mass prohibitive to use 4 crew for 30 to 60-day missions so the crew size was reduced to 2 crew for 30 days or 4 crew for 15 days with an ECLSS consumables mass of about 561kg. After the phase 2 through 4 pallet installations the consumables mass drops significantly until only some nitrogen is required with no oxygen or water requirements.

Table 1. ECLSS Consumables for Phased Buildup

Phase	Crew	Days	O2 (kg)	N2 (kg)	H2O (kg)	Total (kg)
1	2	30 60	131 230	5 10	425 849	561 1089
2	4	30 60	131 239	21 42	77 154	229 435
3	4	30 60	0 0	28 56	128 206	156 262
4	4	30 60	0 0	33 67	0 0	33 67

B. ECLSS Module

Another approach to providing regenerative ECLSS to the surface base is through the addition of a complete system in one module. Fig. 18 above is a good representation of that module and the mass was found to be about 8,853kg as shown in Appendix A, Fig. 28. This indicates that a lander with a payload capability in the 9t range might be sufficient to provide a complete system thus avoiding the crew time expenditure on the lunar surface just to set up equipment.

C. Air and Water Modules

Another approach explored to provide completed ECLS systems was to split the life support system into separate air and water modules for delivery to the surface. The goal was to reduce the payload size and mass and minimize the crew time required for internal systems assembly.

1) Air Module. The air module provides equipment for a closed loop air supply system to support the entire surface outpost, Fig. 19. It includes one ARS pallet with built in air distribution systems, one WP pallet, the oxygen generator and Sabatier system for removing oxygen from carbon dioxide with additional volume available for some stowage. This system provided in a single module has a mass of about 5,557kg, Appendix A, Fig. 29, indicating the possibilities if smaller landers are utilized for payload delivery.

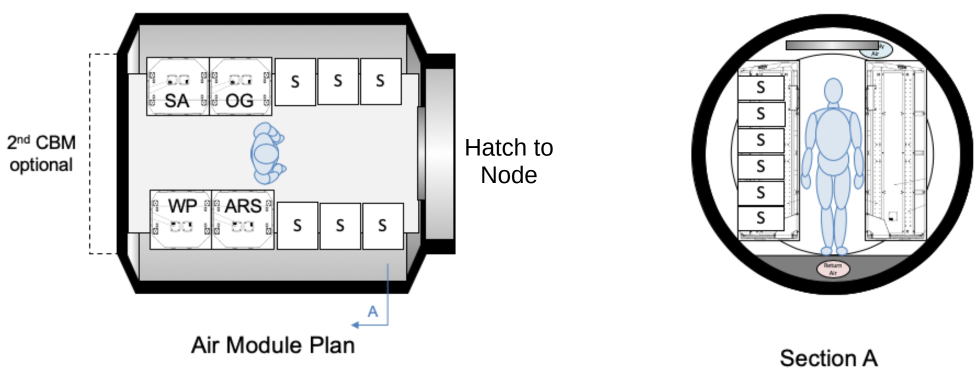


Fig. 19 ECLSS module with regenerative air systems.

2) Water Module. The water module provides for water requirements of the surface outpost and includes a waste management compartment that can recycle wastewater and provide for the buildup of extra water over time, Fig. 20. It includes two more water processing pallets, urine processing, brine processing, and a waste management compartment, all integrated to provide recycled waste products and produce pure potable water. Over time excess water will be generated from the water provided in food supplies as is the case today on the ISS. Appendix A, Fig. 30, indicates that the mass of this module would be about 5,238kg, similar to the mass range for the Air Module.

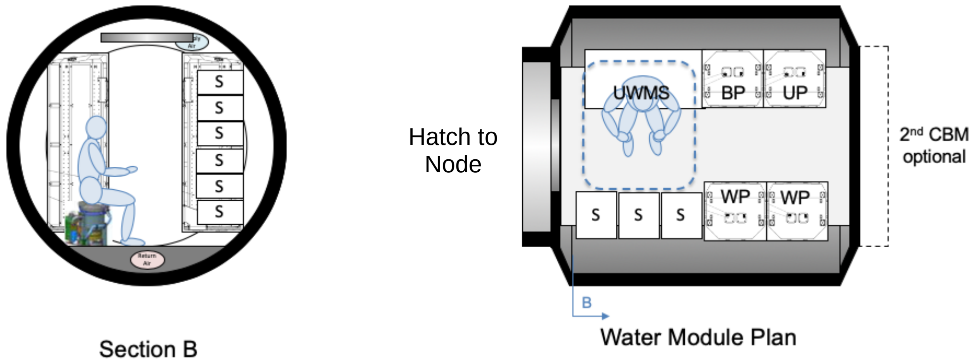


Fig. 20 ECLSS module with regenerative water and waste recycling systems.

D. Gray Water Module

A gray water module was also examined as a separate water processing system to support a shower and clothing washer and dryer system. The module concept is shown in Fig. 21 and includes one ARS pallet and two water processing pallets to clean and circulate filtered water for bathing and clothes cleaning. The Gray Water module with shower, washer, and dryer is estimated to have a mass of about 5t being similar in size and complexity to the potable Water Module cited above.

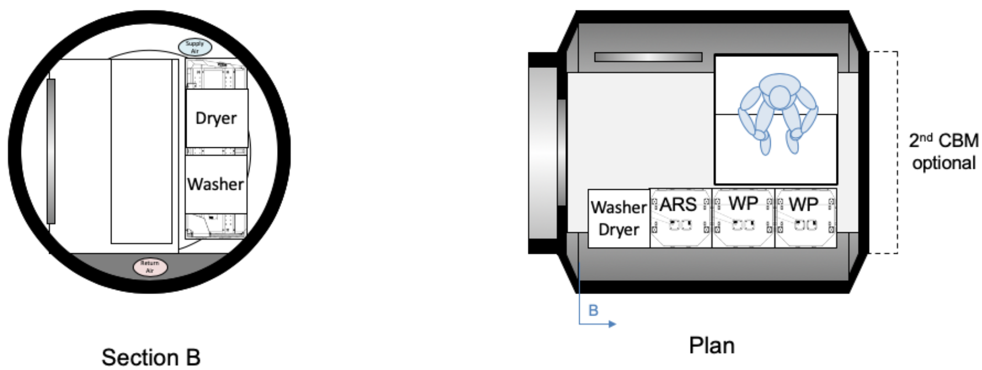


Fig. 21 Life support module with shower and washer / dryer systems.

E. Logistics to Plant Growth Module

Another idea generated in the studies was the possible use of excess logistics modules as plant growth chambers, Fig. 22. The basic concept would equip the logistics module with all the lighting and water distribution systems required for a plant growth chamber but utilize the open plant growth racks for stowage during its delivery to the surface. Once the stowage is relocated to other base modules, this module could then be utilized for plant growth activities that provide for additional research and input into the food and air quality of the surface base.[16]

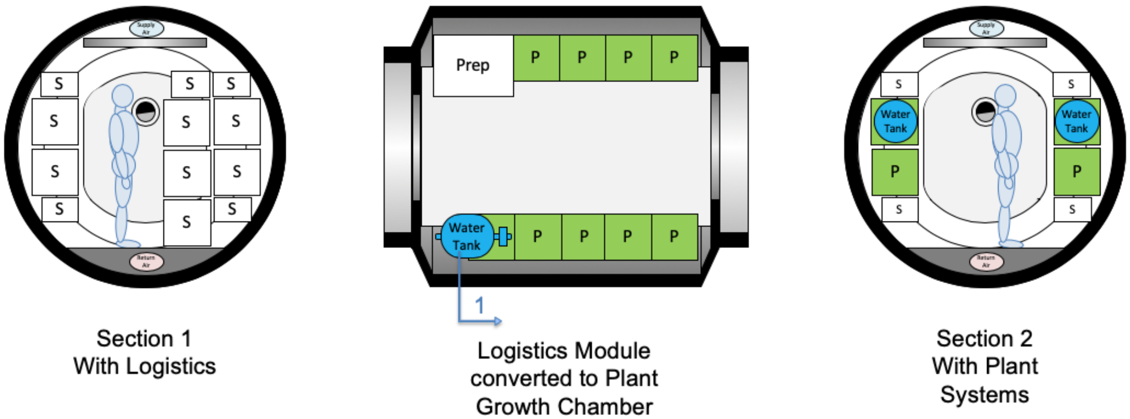


Fig. 22 Plant growth added to life support considerations.

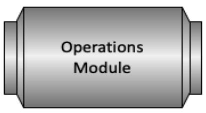
VI. Conclusion

In conclusion, it was found that the surface base module design and configuration selected has great dependency on the lander and surface transportation elements for off-loading and setup of the surface modules. The paper examined in detail a 3-meter diameter module in the 5t to 10t range, but other module sizes are possible. In addition, it was found that there are several approaches for transitioning from an open loop ECLS system for short term missions to a closed loop ECLS system that can support ongoing missions efficiently. This included the addition of ECLSS pallets to close the water and air cycles, the delivery of a complete closed loop ECLSS module for attachment to a surface base configuration already in place, and the delivery of two separate modules of reduced mass that provide closed loop air and water systems somewhat independently. Additional opportunities for the base planning include integrated ECLSS with gray water systems that can support a shower, washer/dryer, and plant growth.

Appendix A: Mass Properties

Appendix A provides the mass properties for the primary modules sized during the studies. In general, the sizing is based on flight proven systems with a high technology readiness level (TRL) from the ISS and Space Shuttle programs including new systems under development for Orion and Gateway. The mass growth allowance (MGA) is a weighted average applied to the systems basic mass based on AIAA mass estimating recommendations for the maturity of each systems design.

Description



Description

The lunar surface Operations Module is derived from a 3 segment Cygnus module pressure vessel.

This Operations Module is designed for minimal mass with built in systems that includes 2 crew bunks, Life Sciences, Waste Management Compartment, and Galley equipment.

Not included are Crew Medical, Crew Exercise, Radiation Protection, Stowed Provisions and Consumables which are assumed to be brought separately or with the Crew for installation in the module.

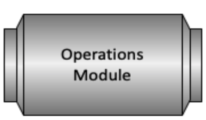
Design Constraints / Parameters		
Maximum Crew Size	2	
Max Crewed Mission Duration	TBD	days
Destination	Lunar Surface	
Pressurized Volume	26.10	m^3
Systems Volume	3.99	m^3
Stowage Volume	4.50	m^3
Habitable Volume	17.61	m^3
Operating Pressure	101.30	kPa
Oxygen Fraction	21.00	%
Life Support Closure - Water	Open	
Life Support Closure - Air	Open	
Habitat Structure	Aluminum	
Habitat Length	6.10	m
Habitat Diameter	3.10	m
Radiation Protection	0.00	kg
EVA Capability	0	
No. of EVAs Out of Hab	0	
RCS Engine Type		
RCS Propellant		
Power Generation	1.99	kW
Energy Storage	0.00	kW
Keep Alive Power (uncrewed)	1.38	kW
Solar array area	7.24	m^2
Thermal Radiator Area	39.39	m^2
Average TRL	8.02	
Mass Growth Allowance (MGA)	7.33%	

Mass Breakdown		Outfitted Mass
System		(kg)
1.1	Structures	3,056
2.0	Propulsion	-
3.0	Power	234
4.0	Avionics	454
5.0	Thermal	314
6.0	Radiation Protection	-
7.0	ECLSS	304
8.0	Crew Systems	431
9.0	EVA	-
10.0	Research	161
11.0	Robotics	-
Dry Mass		**4,954**
12.0	Stowed Provisions	
13.0	Consumables	
14.0	Nonpropellant Fluids	
Inert Mass		**-**
Subtotal		**4,954**
	Attached Payloads	
	Propulsion Stage	
15.0	Propellant	-
16.0	Payload Launch Adapter	-
17.0	In-Space Stage Adapter	-
		-
Total Gross Mass		**4,954**

Fig. 23 Operations Module empty mass.

The Operations Module above and below (Figs. 23 & 24) are the same module with the first being off-loaded to reduce mass for a 5t payload capacity lander and the second sized to fit on a 9t payload capacity lander. A logistics flight would be required to complete the outfitting for the 5t configuration.

Description



Description

The lunar surface Operations Module is derived from a 3 segment Cygnus module pressure vessel.

This Operations Module is fully outfitted with built in systems that includes 2 crew bunks, Life Sciences, Waste Management Compartment, and Galley equipment. Also included are Crew Medical, Crew Exercise, Radiation Protection, Stowed Provisions and Consumables to support 2 crew for 30 days or 4 crew for 15 days.

Design Constraints / Parameters		
Maximum Crew Size	2	
Max Crewed Mission Duration	30	days
Destination	Lunar Surface	
Pressurized Volume	26.10	m^3
Systems Volume	3.99	m^3
Stowage Volume	4.50	m^3
Habitable Volume	17.61	m^3
Operating Pressure	101.30	kPa
Oxygen Fraction	21.00	%
Life Support Closure - Water	Open	
Life Support Closure - Air	Open	
Habitat Structure	Aluminum	
Habitat Length	6.10	m
Habitat Diameter	3.10	m
Radiation Protection	699.30	kg
EVA Capability	0	
No. of EVAs Out of Hab	0	
RCS Engine Type		
RCS Propellant		
Power Generation	1.99	kW
Energy Storage	0.00	kW
Keep Alive Power (uncrewed)	1.38	kW
Solar array area	7.25	m^2
Thermal Radiator Area	39.39	m^2
Average TRL	8.09	
Mass Growth Allowance (MGA)	8.22%	
Project Management Reserve (PMR)	0.00%	

Mass Breakdown		Outfitted Mass
System		(kg)
1.1	Structures	3,056
2.0	Propulsion	-
3.0	Power	234
4.0	Avionics	572
5.0	Thermal	314
6.0	Radiation Protection	699
7.0	ECLSS	369
8.0	Crew Systems	1,315
9.0	EVA	-
10.0	Research	325
11.0	Robotics	-
Dry Mass		**6,884**
12.0	Stowed Provisions	423
13.0	Consumables	780
14.0	Nonpropellant Fluids	-
Inert Mass		**1,203**
Subtotal		**8,087**
	Attached Payloads	
	Propulsion Stage	
15.0	Propellant	-
16.0	Payload Launch Adapter	-
17.0	In-Space Stage Adapter	-
0.0%	Project Mgt. Reserve	-
Total Gross Mass		**8,087**

Fig. 24 Operations Module with crew systems and logistics.

Description

Logistics for open loop ECLSS

Description

The Logistics Module is derived from a 3 segment Cygnus module pressure vessel. Logistics includes stowed provisions and life support system consumables for 4 crew / 180 day missions using an open loop ECLS system.

Notes:
The module capacity is about 5t, so for 10t of stowed provisions and consumables, two logistics modules will be requried.
The volume required for 10t of logistics is about 30 to 32 cubic meters using standard CTB stowage systems, also indicating that two logistics modules will be required.

Design Constraints / Parameters		
Maximum Crew Size	4	
Max Crewed Mission Duration	180	days
Destination	Lunar Surface	
Pressurized Volume	26.10	m^3
Systems Volume	2.00	m^3
Stowage Volume	16.00	m^3
Habitable Volume	8.00	m^3
Operating Pressure	101.30	kPa
Oxygen Fraction	21.00	%
Life Support Closure - Water	Open	
Life Support Closure - Air	Open	
Habitat Structure	Aluminum	
Habitat Length	6.10	m
Habitat Diameter	3.10	m
Radiation Protection	0.00	kg
EVA Capability	0	
No. of EVAs Out of Hab	0	
RCS Engine Type		
RCS Propellant		
Power Generation	6.73	kW
Energy Storage	1.45	kW
Keep Alive Power (uncrewed)		kW
Solar array area	24.74	m^2
Thermal Radiator Area	29.59	m^2
Average TRL	7.44	
Mass Growth Allowance (MGA)	7.40%	

	Mass Breakdown	Outfitted Mass
System		(kg)
1.1	Structures	3,097
2.0	Propulsion	-
3.0	Power	265
4.0	Avionics	412
5.0	Thermal	221
6.0	Radiation Protection	-
7.0	ECLSS	322
8.0	Crew Systems	155
9.0	EVA	-
10.0	Research	-
11.0	Robotics	-
Dry Mass		**4,472**
12.0	Stowed Provisions	2,228
13.0	Consumables	7,511
14.0	Nonpropellant Fluids	-
Inert Mass		**9,739**
Subtotal		**14,211**
	Attached Payloads	
	Propulsion Stage	
15.0	Propellant	-
16.0	Payload Launch Adapter	-
17.0	In-Space Stage Adapter	-
		-
Total Gross Mass		**14,211**

Fig. 25 Logistics for open loop ECLSS.

The Logistics Module above and below (Figs. 25 & 26) are the same module with the first showing the logistics requirements for an open loop ECLS systems and the second showing the logistics requirements for a closed loop ECLS system to support four crew for 180-day missions. The module capacity using standard CTB stowage systems is about 144 dbl. CTBs with a mass of about 5t and a volume of about 16 cubic meters indicating that the logistics for an open loop ECLS system at 9,739kg will require two flights using this size module.

Description

Logistics for closed loop ECLSS

Description

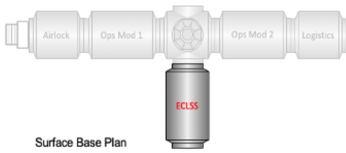
The Logistics Module is derived from a 3 segment Cygnus module pressure vessel. Logistics includes stowed provisions and life support system consumables for 4 crew / 180 day missions using a closed loop ECLS system.

Design Constraints / Parameters		
Maximum Crew Size	4	
Max Crewed Mission Duration	180	days
Destination	Lunar Surface	
Pressurized Volume	26.10	m^3
Systems Volume	2.00	m^3
Stowage Volume	16.00	m^3
Habitable Volume	8.00	m^3
Operating Pressure	101.30	kPa
Oxygen Fraction	21.00	%
Life Support Closure - Water	Open	
Life Support Closure - Air	Open	
Habitat Structure	Aluminum	
Habitat Length	6.10	m
Habitat Diameter	3.10	m
Radiation Protection	0.00	kg
EVA Capability	0	
No. of EVAs Out of Hab	0	
RCS Engine Type		
RCS Propellant		
Power Generation	6.73	kW
Energy Storage	1.45	kW
Keep Alive Power (uncrewed)		kW
Solar array area	24.74	m^2
Thermal Radiator Area	29.59	m^2
Average TRL	7.44	
Mass Growth Allowance (MGA)	7.40%	
Project Management Reserve (PMR)	0.00%	

	Mass Breakdown	Outfitted Mass
System		(kg)
1.1	Structures	3,097
2.0	Propulsion	-
3.0	Power	265
4.0	Avionics	412
5.0	Thermal	221
6.0	Radiation Protection	-
7.0	ECLSS	322
8.0	Crew Systems	155
9.0	EVA	-
10.0	Research	-
11.0	Robotics	-
Dry Mass		**4,472**
12.0	Stowed Provisions	1,487
13.0	Consumables	2,169
14.0	Nonpropellant Fluids	-
Inert Mass		**3,656**
Subtotal		**8,128**
	Attached Payloads	
	Propulsion Stage	
15.0	Propellant	-
16.0	Payload Launch Adapter	-
17.0	In-Space Stage Adapter	-
0.0%	Project Mgt. Reserve	-
Total Gross Mass		**8,128**

Fig. 26 Logistics for closed loop ECLSS.

Phase 1 ECLSS Module



Description

The ECLSS Module is based on a 3-segment Cygnus that is designed for installation of a closed loop air and water system to support the entire surface base configuration shown. Phase 1 provides open loop sytems to support 2 crew for 30 days. Alternatively it could also support 4 crew for 15 days with an attached pressurized rover to provide the habitable volume required. When completed it can support 4 crew for ongoing operations.
Mass included open loop ECLSS designed for expansion into a closed loop systems along with stowed provisions, spares, and consumables for a 2 crew / 30 day mission.

Design Constraints / Parameters		
Maximum Crew Size	2	
Max Crewed Mission Duration	30	days
Destination	Lunar Surface	
Pressurized Volume	26.10	m^3
Systems Volume	4.00	m^3
Stowage Volume	4.50	m^3
Habitable Volume	17.60	m^3
Habitat Structure	Aluminum	
Habitat Length	6.10	m
Habitat Diameter	3.07	m
EVA Capability		
Crew per EVA		
Radiation Protection	-	kg
RCS Engine Type		
RCS Propellant		
Power Generation	12.10	kW
Energy Storage	803.60	kW
Keep Alive Power (uncrewed)	4.80	kW
Solar array area	44.60	m^2
Thermal Radiator Area*	30.33	m^2
Operating Pressure	101.30	kPa
Oxygen Fraction	21.00	%
Life Support Closure - Water	Open	
Life Support Closure - Air	Open	
Average TRL	8.05	
Mass Growth Allowance (MGA)	22.55%	

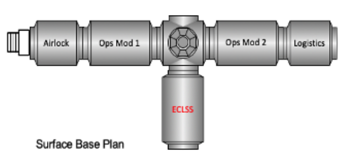
Mass Breakdown		Outfitted Mass
System		(kg)
1.0	Structures	2,403
2.0	Connection & Separation	-
3.0	Launch Support	-
4.0	Environmental Protection	342
5.0	Propulsion	11
6.0	Power	1,386
7.0	Command & Data Handling	199
8.0	Guidance, Navigation & Control	65
9.0	Communications & Tracking	25
10.0	Crew Displays & Controls	128
11.0	Thermal	842
12.0	Environmental Control & Life Sup.	1,130
13.0	Crew & Habitation Support	344
14.0	Extra-Vehicular Activity Support	-
15.0	In-Situ Resource Equip.	-
16.0	In-Space Mfg. and Assembly	-
17.0	Manipulation & Maintenance	-
18.0	Payload Provisions	-
19.0	Payloads & Research	-
Manufacturer's Empty Mass (MEM)		**6,875**
A-H	Stowed Provisions	295
I-J	Spares	108
K-L	Consumables	800
M	Fluids	-
N-P	Pyrotechnic Items	-
Q-S	Propellant	-
T-V	Propulsion Consumables	-
Inert Mass		**1,202**
		-
Total Gross Mass		**8,077**

* Installed surface-mounted radiator area is less than the required area

Fig. 27 Phase 1 ECLSS module.

The ECLSS Module above and below (Figs. 27 & 28) represent two configurations of the same module. The first configuration, Fig. 27, assumes the ECLSS Module is the first element for a phased development with the remaining systems brought up in pallets and installed by the crew during later flights with additional modules. The second configuration, Fig. 28, shows a complete ECLSS module that could be added to the base at any point during the buildup.

Complete ECLSS Module



Description

The ECLSS Module is based on a 3-segment Cygnus design and is equiped with a closed loop air and water system to support the entire surface base configuration shown. Once added to the base or completed through phased equipment installations, the ECLSS module will support 4 crew for ongoing operations with assumed logistics supplies and crew rotations every 180 days.
Mass includes ECLSS equipment but does not include stowed provisions, spares, or consumables.

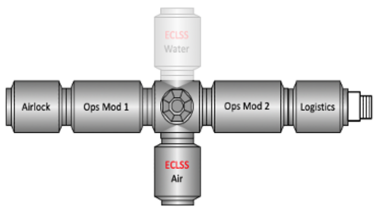
Design Constraints / Parameters		
Maximum Crew Size	4	
Max Crewed Mission Duration	180	days
Destination	Lunar Surface	
Pressurized Volume	26.10	m^3
Systems Volume	17.10	m^3
Stowage Volume	3.00	m^3
Habitable Volume	6.00	m^3
Habitat Structure	Aluminum	
Habitat Length	6.10	m
Habitat Diameter	3.07	m
EVA Capability	N/A	
Crew per EVA	N/A	
Radiation Protection	-	kg
RCS Engine Type		
RCS Propellant		
Power Generation	12.10	kW
Energy Storage	803.60	kW
Keep Alive Power (uncrewed)	4.80	kW
Solar array area	44.60	m^2
Thermal Radiator Area*	30.33	m^2
Operating Pressure	101.30	kPa
Oxygen Fraction	21.00	%
Life Support Closure - Water	Closed	
Life Support Closure - Air	Closed	
Average TRL	7.79	
Mass Growth Allowance (MGA)	22.82%	

Mass Breakdown		Outfitted Mass
System		(kg)
1.0	Structures	2,403
2.0	Connection & Separation	-
3.0	Launch Support	-
4.0	Environmental Protection	342
5.0	Propulsion	11
6.0	Power	1,386
7.0	Command & Data Handling	199
8.0	Guidance, Navigation & Control	65
9.0	Communications & Tracking	25
10.0	Crew Displays & Controls	128
11.0	Thermal	842
12.0	Environmental Control & Life Sup.	3,350
13.0	Crew & Habitation Support	103
14.0	Extra-Vehicular Activity Support	-
15.0	In-Situ Resource Equip.	-
16.0	In-Space Mfg. and Assembly	-
17.0	Manipulation & Maintenance	-
18.0	Payload Provisions	-
19.0	Payloads & Research	-
Manufacturer's Empty Mass (MEM)		**8,853**
A-H	Stowed Provisions	-
I-J	Spares	-
K-L	Consumables	-
M	Fluids	-
N-P	Pyrotechnic Items	-
Q-S	Propellant	-
T-V	Propulsion Consumables	-
Inert Mass		**-**
		-
Total Gross Mass		**8,853**

* Installed surface-mounted radiator area is less than the required area

Fig. 28 Completed ECLSS Module.

ECLSS Air Module



Surface Base Plan

Description

The ECLSS Air module is based on a 2-segment Cygnus design and is equiped with a closed loop air system to support the entire surface base configuration shown. The surface base will support 4 crew for ongoing operations with assumed logistics supplies and crew rotations every 180 days.
Mass includes module and regenerative air systems for ongoing operations, but does not include stowed provisions, spares, or consumables.

Design Constraints / Parameters		
Maximum Crew Size	4	
Max Crewed Mission Duration	180	days
Destination	Lunar Surface	
Pressurized Volume	18.90	m^3
Systems Volume	9.90	m^3
Stowage Volume	2.00	m^3
Habitable Volume	7.00	m^3
Habitat Structure	Aluminum	
Habitat Length	6.10	m
Habitat Diameter	3.07	m
EVA Capability	N/A	
Crew per EVA	N/A	
Radiation Protection	-	kg
RCS Engine Type		
RCS Propellant		
Power Generation	11.30	kW
Energy Storage	723.00	kW
Keep Alive Power (uncrewed)	4.30	kW
Solar array area	41.60	m^2
Thermal Radiator Area*	20.22	m^2
Operating Pressure	101.30	kPa
Oxygen Fraction	21.00	%
Life Support Closure - Water		
Life Support Closure - Air	Closed	
Actual Estimated Loss of Mission		
Average TRL	8.95	
Mass Growth Allowance (MGA)	20.50%	
Project Management Reserve (PMR)	1.00%	

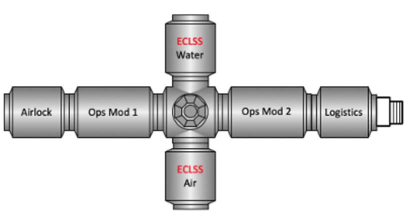
Mass Breakdown		Outfitted Mass
System		(kg)
1.0	Structures	2,096
2.0	Connection & Separation	
3.0	Launch Support	-
4.0	Environmental Protection	258
5.0	Propulsion	11
6.0	Power	-
7.0	Command & Data Handling	199
8.0	Guidance, Navigation & Control	65
9.0	Communications & Tracking	25
10.0	Crew Displays & Controls	96
11.0	Thermal	655
12.0	Environmental Control & Life Sup.	2,152
13.0	Crew & Habitation Support	-
14.0	Extra-Vehicular Activity Support	-
15.0	In-Situ Resource Equip.	-
16.0	In-Space Mfg. and Assembly	-
17.0	Manipulation & Maintenance	-
18.0	Payload Provisions	-
19.0	Payloads & Research	-
Manufacturer's Empty Mass (MEM)		**5,557**
A-H	Stowed Provisions	-
I-J	Spares	-
K-L	Consumables	-
M	Fluids	-
N-P	Pyrotechnic Items	-
Q-S	Propellant	-
T-V	Propulsion Consumables	-
Inert Mass		**-**
1%	Project Mgt. Reserve on MEM	-
Total Gross Mass		**5,557**

* Installed surface-mounted radiator area is less than the required area

Fig. 29 ECLSS Air Module.

The ECLSS Air and Water Modules above and below (Figs. 29 & 30) represent a complete regenerative ECLS system designed to support the base configuration shown for ongoing operations with four crew and assumed logistics supplies and crew rotations every 180 days. The system is broken into two modules to reduce payload mass.

ECLSS Water Module



Surface Base Plan

Description

The ECLSS Water module is based on a 2-segment Cygnus design and is equiped with a closed loop water and waste managment system to support the entire surface base configuration shown. The surface base will support 4 crew for ongoing operations with assumed logistics supplies and crew rotations every 180 days.
Mass includes module with watse management and regenerative water systems for ongoing operations, but does not include stowed provisions, spares, or consumables.

Design Constraints / Parameters		
Maximum Crew Size	4	
Max Crewed Mission Duration	180	days
Destination	Lunar Surface	
Pressurized Volume	18.90	m^3
Systems Volume	9.90	m^3
Stowage Volume	2.00	m^3
Habitable Volume	7.00	m^3
Habitat Structure	Aluminum	
Habitat Length	6.10	m
Habitat Diameter	3.07	m
EVA Capability	N/A	
Crew per EVA	N/A	
Radiation Protection	-	kg
RCS Engine Type		
RCS Propellant		
Power Generation	7.60	kW
Energy Storage	307.70	kW
Keep Alive Power (uncrewed)	1.83	kW
Solar array area	27.80	m^2
Thermal Radiator Area*	20.22	m^2
Operating Pressure	101.30	kPa
Oxygen Fraction	21.00	%
Life Support Closure - Water	Closed	
Life Support Closure - Air		
Actual Estimated Loss of Mission		
Average TRL	9.13	
Mass Growth Allowance (MGA)	19.42%	
Project Management Reserve (PMR)	1.00%	

Mass Breakdown		Outfitted Mass
System		(kg)
1.0	Structures	1,976
2.0	Connection & Separation	-
3.0	Launch Support	-
4.0	Environmental Protection	258
5.0	Propulsion	11
6.0	Power	-
7.0	Command & Data Handling	199
8.0	Guidance, Navigation & Control	65
9.0	Communications & Tracking	25
10.0	Crew Displays & Controls	96
11.0	Thermal	514
12.0	Environmental Control & Life Sup.	1,826
13.0	Crew & Habitation Support	268
14.0	Extra-Vehicular Activity Support	-
15.0	In-Situ Resource Equip.	-
16.0	In-Space Mfg. and Assembly	-
17.0	Manipulation & Maintenance	-
18.0	Payload Provisions	-
19.0	Payloads & Research	-
Manufacturer's Empty Mass (MEM)		**5,238**
A-H	Stowed Provisions	-
I-J	Spares	-
K-L	Consumables	-
M	Fluids	-
N-P	Pyrotechnic Items	-
Q-S	Propellant	-
T-V	Propulsion Consumables	-
Inert Mass		**-**
1%	Project Mgt. Reserve on MEM	-
Total Gross Mass		**5,238**

* Installed surface-mounted radiator area is less than the required area

Fig. 30 ECLSS Water Module.

Acknowledgments

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References

[1] NASA Publication, "Reference Guide to the International Space Station" NP-2015-05-022-JSC, Utilization Edition, September 2015.
[2] NASA graphics by Lee Kolb, April 2020.
[3] NASA Fact Sheet, "Space Launch System" FS-2019-10-MSFC, 2019.
[4] NASA Special Publication, "Commercial Orbital Transportation Services" NASA/SP-2014-617, 2014.
[5] NASA.gov website, "More About Gateway," https://www.nasa.gov/johnson/exploration/gateway, visited May 28, 2020.
[6] NASA news release, "NASA Names Companies to Develop Human Landers for Artemis Moon Missions," Release 20-048, April 30, 2020.
[7] Doggett, W., C. Roithmayr, J. Dorsey, T. Jones, "Automation of a Versatile Crane (the LSMS) for Lunar Outpost Construction, Maintenance and Inspection," Paper No. AIAA 2009-6546, AIAA Space 2009 Conference & Exposition, Pasadena CA, September 14-17, 2009.
[8] NASA Fact Sheet, "Space Exploration Vehicle Concept," FS-2011-08-045-JSC, 2011.
[9] Toups, L., K. Kennedy, et al, "Constellation Architecture Team-Lunar Habitation Concepts," Paper No AIAA 2008-7633, AIAA Space 2008 Conference & Exposition, San Diego CA, September 9-11, 2008.
[10] Dempsey, R., ed., "The International Space Station: Operating an Outpost in the New Frontier," NASA-SP-2017-634, 2017.
[11] Boyle, R., L. Rodriggs, C. Allton, M. Jennings, L. Aitchison, "Suitport Feasibility – Human Pressurized Space Suit Donning Tests with the Marman Clamp and Pneumatic Flipper Suitport Concepts," Paper No. 10.2514/6.2013-3399, 43rd International Conference on Environmental Systems (ICES), Vail CO, July 14-18, 2013.
[12] Agui, J. H., C. Erickson, J. Perry, "Analytical and Computation Particulate Load Models in Planetary Surface Spacecraft Cabins," Paper No. AIAA 2011-5046, 41st International Conference on Environmental Systems (ICES), Portland OR, July 17-21, 2011.
[13] Howe, A. Scott, K. Kennedy, P. Guirgis, R. Boyle, et al, "A Dual-Chamber Hybrid Inflatable Suitlock (DCIS) for Planetary Surfaces or Deep Space," Paper No. AIAA 2011-5064, 41st International Conference on Environmental Systems (ICES), Portland OR, July 17-21, 2011.
[14] O'Neil, J., J. Bowers, R. Corallo, M. Torres, T. Stapleton, "Environmental Control and Life Support Module Architecture for Deployment across Deep Space Platforms," 49th International Conference on Environmental Systems (ICES), Boston MA, July 7-11, 2019.
[15] Wikipedia.org website, "International Standard Payload Rack," https://en.wikipedia.org/wiki/International_Standard_Payload_Rack, visited May 28, 2020.
[16] Wheeler, R., "Agriculture for Space: People and Places Paving the Way," Open Agriculture 2017 (2) 14-32, 2017.