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Life Support Systems Trade Study for Lunar Habitation with Greenhouse Food Production

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The Japan Aerospace Exploration Agency (JAXA) established the Space Exploration Innovation Hub Center called TansaX (Technology Advancing Node for SpAce eXploration) in 2015. TansaX specializes in technology research applicable to daily life as well as future lunar and Mars exploration. The author has been a member of the lunar farm group and its system design sub-group at the center since 2017. The author conducted a trade study to support lunar farm design by using a bioregenerative Life Support System (LSS) analysis tool and a life support system size analysis tool. This paper describes the analysis tools and the computational design procedures; in addition, an LSS design with the lunar farm for six crewmembers was analyzed. The initial mass, logistics mass, and Equivalent System Mass (ESM) of the LSS and its subsystems were compared. Increasing the utilization efficiency of mass and volume by increasing the vertical stacked layers of crops is recommended if the amount of crop cultivation is large, because the LSS initial mass can be decreased by this approach. The total mass value of the closed LSS with a downsized biomass production system was less than those of the open LSS and International Space Station (ISS)'s LSS after 600 days and 1,050 days of operation, respectively. However, the ESM value of the closed LSS with a downsized biomass production system was more than the ESM values of the open LSS and ISS' LSS systems until 2,000 days and 3,950 days, respectively.

Nomenclature

4BMS = 4 Bed Molecular Sieve
ALS = Advanced Life Support
BLSS = Bioregenerative Life Support System
BLSSAT = Bioregenerative Life Support System Analysis Tool
BVAD = Baseline Values and Assumptions Document
CEEF = Closed Ecology Experiment Facilities
CHX = Condensing Heat Exchanger
CM = Crewmember
ESM = Equivalent System Mass
EVA = Extra-Vehicular Activity
IEB = Ion Exchange Bed
ISRU = In-Situ Resource Utilization
ISS = International Space Station
JAXA = Japan Aerospace Exploration Agency
LED = Light-Emitting Diode
LiOH = Lithium Hydroxide
LMLSTP = Lunar-Mars Life Support Test Project
LSSAT = Life Support System Size Analysis Tool
MF = Multifiltration
PS = Phase Separator
TansaX = Technology Advancing Node for SpAce eXploration
VCD = Vapor Compression Distillation
VPCAR = Vapor Phase Catalytic Ammonia Removal Assembly
VRA = Volatile Removal Assembly

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I. Introduction

AFTER the Japanese government announced their policy titled "Comprehensive Strategy on Science, Technology, and Innovation 2014 - A Challenge for Creating Japan in a New Dimension,"[1] the Japan Aerospace Exploration Agency (JAXA) established the Space Exploration Innovation Hub Center called TansaX (Technology Advancing Node for SpAce eXploration) in 2015.[2] TansaX specializes in technology research applicable to daily life as well as future lunar and Mars exploration. Among the various working groups at the center, the author has been a member of the lunar farm group and its system design sub-group since 2017.

Historically, development of technologies for food production on the lunar surface has not attracted much interest because of a roughly 30 days day-night cycle that requires a lot of battery power to store solar power for the two-week night period. Space agriculture research has mainly focused on Mars missions because of the roughly 24 hour day-night cycle existing. The first space agriculture research was conducted on plants used for food production in the BIOS projects in Russia. The studies also included tests with human crews living in a closed environment where crops are grown for the crews' food and for facilitating atmospheric regeneration.[3,4] The Lunar-Mars Life Support Test Project (LMLSTP)[5] in the US and the Closed Ecology Experiment Facilities (CEEF)[6] in Japan are similar studies, and Lunar Palace 1 in China is the latest project.[7] A recent significant improvement in plant production is the use of LEDs. They are more energy efficient, lighter, and have a longer life-span than high-pressure sodium lamps, which have been traditionally used for plant production. Advanced designs for lunar farms can be achieved with the use of LEDs. Goto and Watanabe, who are lunar farm working group members, have been operating plant factories and collecting data regarding the crops and facilities for decades.[8-10] Our working group proposes a new lunar farm design based on the knowledge they acquired on crops and plant factories.

In this study, a trade study is conducted to support lunar farm design by using a Bioregenerative Life Support System Analysis Tool (BLSSAT)[11] and a Life Support System Size Analysis Tool (LSSAT),[12] which were developed for the CEEF and lunar surface systems. In this paper, the developed analysis tool and the computational design procedures conducted are described; moreover, the results of a design analysis for a life support system (LSS) with a lunar farm are demonstrated on the basis of provisional values of our working group.[13]

II. Lunar Farm Assumptions

The lunar farm working group's ground rule and assumptions discussed in other working groups are presented below.

Ground Rule 1: Six crewmembers live in the lunar outpost where they produce their own food.
Assumption 1: H_2O, O_2, and N_2 are produced by In-Situ Resource Utilization (ISRU) around the lunar outpost.
Assumption 2: Concrete is produced from lunar regolith around the lunar outpost.
Assumption 3: Photovoltaic cells can be used during 90% of the time when the outpost is located at the lunar South Pole.
Assumption 4: Nuclear power generation is one option for power supply.

The candidate crops were selected by considering their energy, protein, and fat according to the nutrient requirements described in the Japanese Dietary Reference Intakes 2015.[14] A 30-49 age man activity II (medium level) was selected as the reference model. Supplements provided the required animal proteins and micronutrients.

The eight crop candidates (rice, potato, sweet potato, soybean, lettuce, tomato, cucumber, and strawberry) and their biomass requirements for the lunar farm are shown in Table 1. The data of the crops that have the highest biomass production per square meter in the plant factory were selected by Goto.[8,9] The biomass requirements for each crop were based on the nutrient requirements for a single person. Biomass production per day was calculated by the biomass produced per square meter in one growth (not shown in Table 1) divided by the crop's growth cycle. Then, the cultivation area required per crop was calculated by the biomass requirements and biomass production per day. Furthermore, considering the number of vertical stacked layers, the net floor area was calculated.

In addition, animal protein brought in from Earth was also included to compensate for nutritional insufficiency.

Table 1. Crop candidates in lunar farm.

Crop	Energy	Biomass requirement	Growth cycle	Harvest Index	Biomass production per day	Cultivation area	Number of vertical stacked layers	Net floor area
	kcal/CM-day	dry-g/CM-day	day	-	dry-g/m^2/day	m^2/CM	-	m^2/CM
Rice	1421.1	335.2	90	0.50	8.5	40.0	1 (2)	40.0 (20.0)
Potato	58.6	15.6	100	0.82	4.6	3.4	3	1.13
Sweet potato	206.2	52.0	120	0.65	7.0	7.5	3	2.5
Soybean	646.9	131.9	100	0.52	5.6	25.0	1 (2)	25.0 (12.5)
Lettuce	26.3	7.4	30	0.91	4.2	1.8	5	0.36
Tomato	48.8	12.4	100	0.70	13.9	0.9	1	0.9
Cucumber	18.3	4.8	80	0.70	9.7	0.5	1	0.5
Strawberry	12.2	3.1	60	0.70	2.8	1.1	5	0.22
Subtotal	**2438.5**	**562.4**				**80.2**		**70.6 (38.1)**
Animal protein	211	50						
Total	**2649.5**	**612.4**						

Number in parentheses reflect values of two vertical stacked layers of rice and soybeans.

The crew's requirements for life support are shown in Table 2. The requirements were based on Baseline Values and Assumptions Document (BVAD) and International Space Station (ISS) data.[15-17] Oxygen, food (dry), and food (in water) amounts will vary depending on the crops crew consume as shown in Table 1.

Table 2. Crew Requirements.

Requirements	Lunar surface design, kg/CM
Oxygen	0.835
Food (dry)	0.66
Food (in water)	1.05
Water for cooking	0.76
Drinking water	2.10
Washing water	0.20
Shower water	2.72
Flush water	0.30
Laundry water	12.5
Miscellaneous	0.78

III. Mass Balance Analysis

The mass balance was calculated by biochemical stoichiometry,[18,19] as described in Appendix A. Table 3 shows the human model, plant model, waste-process model, and nitrogen fixation model assuming the crewmembers eat eight crops cultivated in the lunar farm and 50 g of animal protein supplied from the Earth.

Table 3. Mass balance model.

Item	Input 1-4	Input 5	Output 1	Output 2	Output 3	Output 4	Output 5
Human	Food	O_2	Urine	Feces	Other	CO_2	H_2O
dry-g/CM-day	612.4	599.0	51.7	105.2	0.00	778.7	275.9

The values in this table were calculated by Eq. (A1) in Appendix A.

Item	Input 1	Input 2	Input 3	Input 4	Output 1	Output 2	Output 3
Plants	CO_2	H_2O	NH_3	HNO_3	Edible	Inedible	O_2
dry-g/CM-day	1741.2	621.7	19.1	42.4	562.4	497.8	1364.2

The values in this table were calculated by Eqs. (A2) and (A3) in Appendix A.

Item	Input 1-4 or Input 1	Input 2 or Input 5	Output 1	Output 2	Output 3	Output 4
Waste process	Waste	O_2	CO_2	H_2O	N_2	Residues
Urea, dry-g/CM-day	43.9	33.2	36.5	22.4	11.6	6.6
Feces, dry-g/CM-day	105.2	208.7	228.4	76.8	8.7	0.0
Inedible, dry-g/CM-day	497.8	602.1	789.6	301.5	8.9	0.0
Total, dry-g/CM-day	646.9	849.8	1060.9	404.6	31.2	6.6

The values in this table were calculated by Eqs. (A4), (A5), and (A7) in Appendix A.

Item	Input 1	Input 2	Output 1	Output 2
N_2 Fixation	N_2	H_2O	NH_3	HNO_3
Total, dry-g/CM-day	25.1	36.4	19.1	42.4

The values in this table were calculated by Eq. (A8) in Appendix A.

IV. Life Support System Design

Equivalent System Mass (ESM) described in Appendix B was used for comparing the LSS configurations.[20,21] ESM is expressed in terms of mass, volume, power, thermal cooling, and labor man hours. The total ESM is calculated as the sum of ESMs of all the subsystems. All the subsystem masses, volumes, powers, thermal cooling, and labor man-hours were scaled linearly according to a number of crew as described in Appendix C.[20,21]

A. Computational Design Procedure

The computational procedure of the combined LSS design tools (BLSSAT and LSSAT) for this study is shown in Figure 1. The procedure involves the following steps: define mission requirements, select crops to cultivate, calculate mass balance of system elements, select subsystem technologies, calculate ESM, and compare ESM of the design proposals. Two feedback loops change the selected crops and selected subsystem technologies (process B). The extent of decrease in the calculated ESM is examined. During the design phase, if updated crop cultivation data and subsystem technology data are available, then those data are applied to the entire design procedure (process A).

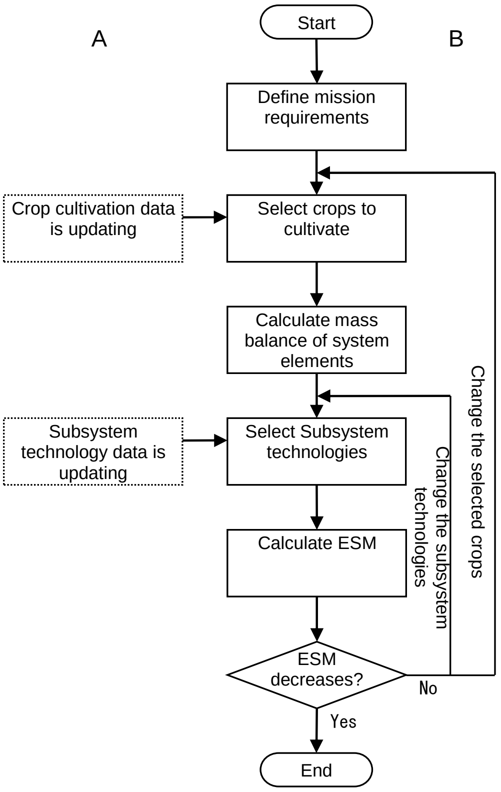

Figure 1. Computational procedure of design tool.

B. Life Support System Configuration

Table 4 shows three types of LSS configuration: the OPEN, ISS, and CLOSED systems. The OPEN system is similar to the LSS on the space shuttle. The ISS system is similar to the LSS on the ISS. The CLOSED system consists of a biomass production subsystem as well as subsystems for recycling air, water, and waste. The biomass production subsystem can regenerate air, water, and food with crops. Therefore, Sabatier, VPCAR, and Wet Oxidation were used as backup systems in the CLOSED system. A washing machine was installed in the CLOSED system because a lot of water was produced by biomass production. The LSS configurations in Table 4 are based on the values given in Tables C1 and C2 in Appendix C.

Table 4. Comparison of subsystem technology for lunar surface system.

Subsystem	Sub-function	OPEN system	ISS system	CLOSED system
Air	Carbon Dioxide Removal (CDRA)	LiOH	4BMS	4BMS
	Carbon Dioxide Reduction System (CRS)	-	Sabatier	Photosynthesis/Sabatier
	Trace Contaminant Control System (TCCS)	Activated carbon and air filter	Activated carbon and air filter	Activated carbon and air filter
	O_2/N_2 Storage	High pressure	High pressure	Cryogenic
	Oxygen Generation	-	Electrolysis	Photosynthesis
	Temperature and humidity control	CHX	CHX	CHX
Biomass	Biomass Production	-	-	Lunar Farm
Food	Food Supply	ISS Food	ISS Food	Supplements, Refrigerator, and Freezer
Water	Water Storage	Storage	Storage	Storage
	Water Recovery System (WRS)	-	ISS WRS (MF, VRA, PS, and IEB)	Photosynthesis/VPCAR
	Waste Water Collection System	Discharge	Storage	Storage
Waste	Urine Process	Waste Water Tank	VCD	VPCAR
	Feces Process	Feces bag	Feces bag, Compactor	Bioreactor/Wet Oxidation
Accommodations	Laundry	-	-	Washing machine

4BMS: 4 Bed. Molecular Sieve, CHX: Condensing Heat Exchanger, IEB: Ion Exchange Bed, LiOH: Lithium Hydroxide, MF: Multifiltration, PS: Phase Separator, VCD: Vapor Compression Distillation, VPCAR: Vapor Phase Catalytic Ammonia Removal Assembly, VRA: Volatile Removal Assembly

C. Lunar Farm Design for Biomass Production

The net floor area of the lunar farm was 70.6 m^2/CM, considering the vertical stacks shown in Table 1. Assuming the height of the cultivation chamber was 3 m, its volume was 242 m^3. When the unshielded inflatable infrastructure was used for the crop growth chambers, the mass of modules was 1,940 kg (242 m^3 × 9.16 kg/m^3) on the basis of the mass equivalency factor for an unshielded inflatable infrastructure as described in BVAD.[16] The ESM for the designed biomass production subsystem is shown in Table 5.

The biomass production subsystem's initial mass, volume, power, cooling, logistics mass, and crew time requirements were estimated on the basis of the plant factory values. In this estimation, a downsized design that was based on 2000s technologies, such as LEDs, was used.

The initial mass for eight crops, 5.76 kg/m^2, was calculated as the sum of the masses of N_2 supplied from Earth and CO_2, H_2O, NH_3, and HNO_3, shown in Table 3.

To estimate the required power of the LED, the biomass production per the number of photons (mol) by photosynthesis was assumed to be 0.4 g/mol.[8,23] The requirement of 1,060.2 g/CM-day of dry biomass (edible 562.4 g/CM-day and inedible 497.8 g/CM-day in Table 3) resulted in a photosynthetic photon flux of 2,651 mol/CM-day (1,060.2 g/CM-day / 0.4 g/mol). The photosynthetic photons per joule of electrical energy was assumed to be 1.66 μmol/J,[15] and the photosynthetic photon flux was 1,596,728 kJ/CM-day (2,651 mol/CM-day / 0.00166 mol/kJ). If the photon flux was provided for 10 hours per day (36,000 s/day), the maximum electrical energy would be 44.4 kW/CM (1,596,728 kJ/CM-day / 36,000 s/day). The electrical energy 44.4 kW/CM was divided by 70.6 m^2/CM area, and the ESM for the LED lamps was calculated to be 0.691 kW/m^2 (0.553 kW/m^2 and 20% margin). Finally, the LED power was approximately one third of the high pressure sodium lamp used in the plant growth chamber model from Drysdale[20].

The initial mass, power, cooling of lamps and ballasts were scaled down from the plant growth chamber model designed by Drysdale[20] in proportion to the LED power of 0.691 kW/m^2 calculated by the author. The initial masses for mechanization systems and secondary structures were left unchanged from the plant growth chamber model.

Crew time for crop cultivation was estimated as 1.3 CM-h/m^2-year, one tenth the time of the original plant growth model from Drysdale[20], which assumed that a majority of farm operations were automated.

Table 5. ESM for biomass production subsystem.

Component	Initial mass	Volume	Power	Thermal cooling	Logistics mass	Crew time
	kg/m^2	m^3/m^2	kW/m^2	kW/m^2	kg/m^2-year	CM-h/m^2-year
Crops	5.76	2.6	0.14	0.14	0	1.3
Lamps	7.54	0.4	0.691	0.138	0.19	0.0027
Ballasts	2.77	0	0.02	0.02	1.07	0.0032
Mechanization System	4.1	TBD	TBD	TBD	TBD	TBD
Secondary Structure	5.7	-	-	-	-	-
Total	25.9	3.00	0.86	0.31	1.25	1.31
Shielded Inflatable Infrastructure	9.16	-	-	-	-	-

D. Bioreactor Design for Waste Processing

Inedible biomass is produced as a byproduct of biomass production. The recycling technology sub-group estimated the size of the reaction container required for methane fermentation on the basis of the following assumptions:

1. Inedible mass was 497.8 dry-g/CM-day, as shown in Table 3. The waste mass without additional water was assumed to be 736.0 g (fresh weight)/CM-day, including 497.8 dry-g/CM-day and 238.2 g/CM-day of H_2O. After adding 2,250.9 g/CM-day of water, the water content ratio became 80% and the density of waste was set at 1,000 g/L.
2. The hydrological residence time was assumed to be 20 days for calculating the total volume of the reaction container. Usable volume of the reaction container for methane fermentation (L) = volume of waste in the reaction container (L/day) × hydrological residence time.
3. Methane fermentation was assumed to be a continuous operation under a wet mesophilic condition.
4. The recycling ratio was assumed at 60% for a bioreactor. Ultimately, the total recycling ratio improved to 85%-100 % by using both a bioreactor and a wet oxidation system.

According to the above assumptions, the total volume of waste that can be introduced in the reaction container for methane fermentation was calculated to be 3.0 L/CM-day (2,987 g/CM-day / 1,000 g/L). The total volume of the reaction container for methane fermentation was 60 L/CM (3.0 L/CM-day × 20 days) (0.06 m^3/CM), which can be installed in a bioreactor system with volume 0.96 m^3/CM.

The ESM values for the bioreactor were 25.0 kg/CM, 0.96 m^3/CM, 0.02 kW/CM, and 0.01 kW/CM, which are values obtained on the basis of the methane fermentation plant specification described in Appendix C.[24]

Table 6. ESM for bioreactor.

Initial mass	Volume	Power	Thermal cooling	Logistics mass	Crew-time
kg/CM	m^3/CM	kW/CM	kW/CM	kg/CM-year	h/CM-year
25.0	0.96	0.02	0.01	TBD	TBD

V. Comparison of System Design Proposals

The system diagram of the lunar LSS that includes a lunar farm is shown in Figure 2. The system consists of an air revitalization subsystem, a biomass production subsystem, a food storage subsystem, a thermal control subsystem, a water recycling subsystem, a waste process subsystem, an EVA subsystem, and human accommodations. Using the tool described here, the effect of changing the design parameters of a subsystem on other subsystems can be examined. System design studies of the biomass production subsystem, crop cultivation methods, and waste-processing technologies can be conducted. In this study, four types of LSS configuration, namely, an OPEN system, ISS system (A+W; air and water recycling), and two CLOSED systems, were compared. One CLOSED system consists of a lunar farm with a single vertical stacked layer of rice and soybeans and multiple vertical stacked layers of the other five crops (CLOSED 1) and the other CLOSED system consists of a lunar farm with two vertical stacked layers of rice and soybeans and multiple vertical stacked layers of the other five crops (CLOSED 2). Nine 150-m^3 modules were required for the CLOSED 1 system and five modules for the CLOSED 2 system. One habitation module, one experimental module, and one utility module were installed for the four types of LSS. These modules were covered with lunar regolith, as shown in Figure 3.

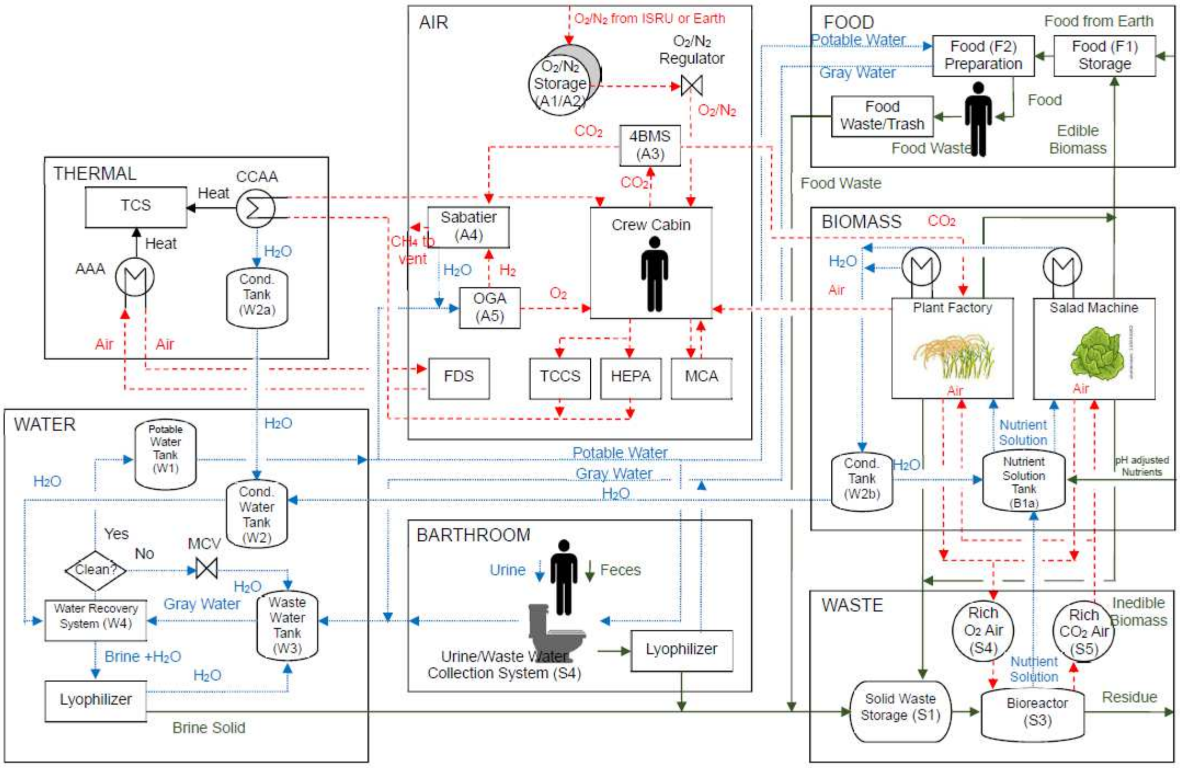

Figure 2. Lunar LSS based on closed system technology with lunar farm.

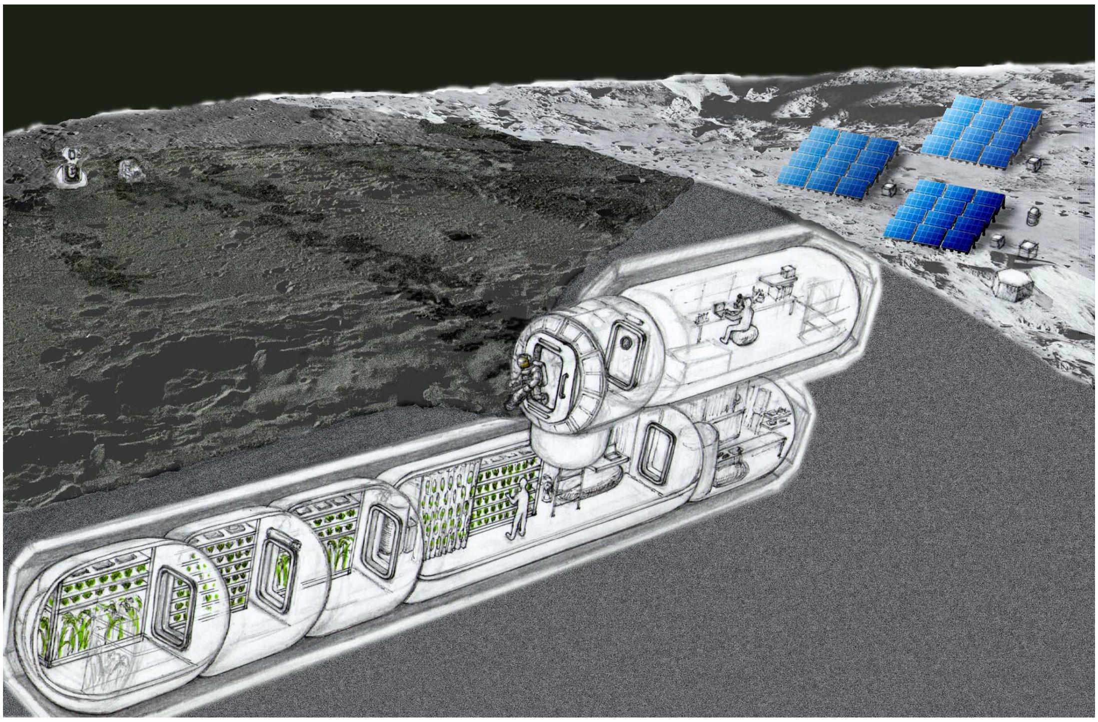

Figure 3. Overview of lunar outpost under lunar regolith.

Table 7 shows the calculated results of the LSS's fixed initial mass, the logistics mass for one year, initial ESM, and incremental ESM for one year with six crewmembers living in the lunar outpost. The numbers in parentheses are the recycling rates of the four LSS configurations.

The LSS initial mass for the CLOSED 1 system was 17.1 times more than the OPEN system. Although the biomass production subsystem mass at 22,599 kg was larger, air and water subsystem masses were less in the CLOSED 1 system than in the ISS (A+W) system; this is because some of the functions of those subsystems are replaced by the biomass production subsystem. The air subsystem mass of each CLOSED system was not less than the subsystem mass of the OPEN system because the LiOH mass was included in the logistics mass. The LSS initial mass for the CLOSED 2 system was 14.6 times more than the OPEN system because the 19,026 kg biomass production subsystem was less than that of the CLOSED 1 system. This reduction is because the volume of the biomass production subsystem is 0.54 times of the volume of the CLOSED 1.

The logistics masses of the CLOSED 1 and CLOSED 2 systems were 0.23 and 0.21 times that for the OPEN system, respectively. The air, food and water logistics masses were significantly less than the logistics masses of the OPEN and ISS (A+W) systems because a majority of the CLOSED systems' logistics masses were recycled by the biomass production subsystem. As crop photosynthesis can reproduce biomass, oxygen, and water simultaneously, the one-year supply mass for the CLOSED 2 system was the least among the four systems. The LSS initial masses and logistics masses of the four system configurations are listed in Table 7 (a) and (b) and graphically illustrated in Figures 4 and 5, respectively.

The mass (initial mass and logistics mass) with respect to time are shown in Figure 6. The mass of the CLOSED 1 system was less than that of the OPEN system after 700 days and less than that of the ISS (A+W) system after 1,250 days. The mass of the CLOSED 2 system was less than that of the OPEN system after 600 days and less than that of the ISS (A+W) system after 1,050 days. If the vertical stack layers of rice and soybeans are changed to two layers, the CLOSED 2 system with the biomass production subsystem is preferable over the ISS (A+W) system after 1,050 day.

The initial ESM values of four the system configurations are shown in Table 7 (c). The ESM values of the CLOSED 1 and 2 systems were 37.9 times and 31.1 times that of the OPEN system, respectively. The incremental ESM values of the four system configurations for one year are shown in Table 7 (d). The ESM values of the CLOSED 1 and 2 systems were 0.4 times and 0.3 times that of the OPEN system, respectively. The LSS initial ESM and incremental ESM of the four system configurations are listed in Table 7 (c) and (d) and graphically illustrated in Figures 7 and 8, respectively.

The ESM values with respect to time are shown in Figure 9. The ESM values of the CLOSED 1 and 2 systems are significantly larger than those of the OPEN system or the ISS system. The ESM value of the CLOSED 1 system was less than that of the OPEN system after 2,750 days of operation. The ESM value of the CLOSED 1 system did not become less than that of the ISS (A+W) system within 4,000 days. Even when the CLOSED 2 system with a downsized biomass production subsystem was used, the ESM value of the CLOSED 2 system did not become less than that of the OPEN system until after 2,000 days and did not become less than that of the ISS (A+W) system until after 3,950 days.

Table 7 (a) LSS initial mass, (b) logistics mass for one-year, (c) initial ESM, and (d) incremental ESM for one-year. Mass equivalency factors are V_{eq}=9.16 kg/m^3, P_{eq}=76 kg/kw, C_{eq}=102 kg/kw, and CT_{eq}=variable kg/CM-h.

Initial mass, kg	**OPEN (0%)**	**ISS (A+W) (37%)**	**CLOSED 1 (77%)**	**CLOSED 2 (79%)**
Air	586	847	653	653
Biomass	0	0	22,599	19,026
Food	0	0	321	321
Thermal	390	390	390	390
Waste	115	115	348	348
Water	164	1,062	141	141
EVA	196	196	196	196
Accommodations	0	0	80	80
Total	**1,450**	**2,609**	**24,728**	**21,155**
System/OPEN	**1.0**	**1.8**	**17.1**	**14.6**

Logistics mass, kg	**OPEN (0%)**	**ISS (A+W) (37%)**	**CLOSED 1 (77%)**	**CLOSED 2 (79%)**
Air	1,709	32	32	32
Biomass	0	0	531	323
Food	4,073	4,073	149	149
Thermal	19	19	19	19
Waste	0	0	0	0
Water	6,462	2,206	3	3
EVA	757	757	757	757
Accommodations	3,024	3,024	2,131	2,131
Total	**16,045**	**10,112**	**3,622**	**3,414**
System/OPEN	**1.00**	**0.63**	**0.23**	**0.21**

Initial ESM, kg	**OPEN (0%)**	**ISS (A+W) (37%)**	**CLOSED 1 (77%)**	**CLOSED 2 (79%)**
Air	730	1,110	900	900
Biomass	0	0	75,262	61,160
Food	0	0	339	339
Thermal	628	628	628	628
Waste	138	138	413	413
Water	179	1,338	145	145
EVA	382	382	204	204
Accommodations	0	0	195	195
Total	**2,058**	**3,596**	**78,086**	**63,985**
Total/OPEN	**1.0**	**1.7**	**37.9**	**31.1**

Incremental ESM, kg	**OPEN (0%)**	**ISS (A+W) (37%)**	**CLOSED 1 (77%)**	**CLOSED 2 (79%)**
Air	1,709	43	96	85
Biomass	0	0	2,670	1,266
Food	4,073	4,073	149	149
Thermal	36	32	96	82
Waste	0	0	5	4
Water	6,462	2,206	3	3
EVA	983	928	757	757
Accommodations	3,024	3,024	2,410	2,359
Total	**16,288**	**10,307**	**6,186**	**4,703**
Total/OPEN	**1.0**	**0.6**	**0.4**	**0.3**

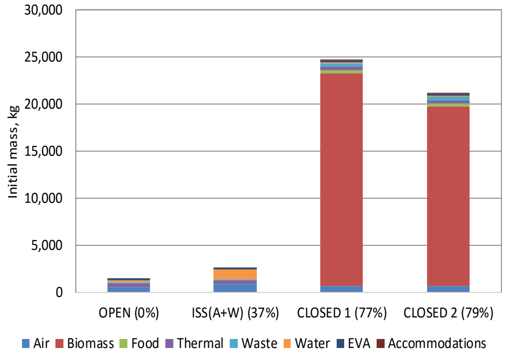

Figure 4. Comparison of initial mass among four LSS configurations.

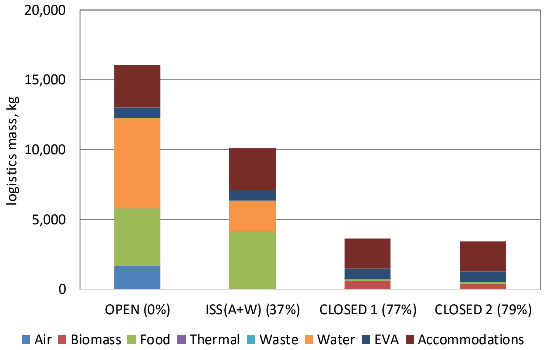

Figure 5. Comparison of one-year operation logistics mass among four LSS configurations.

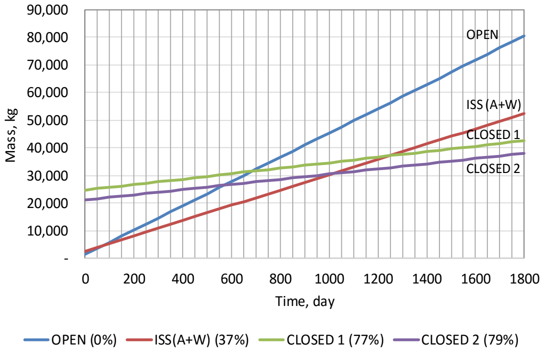

Figure 6. Comparison of initial mass and logistics mass among four LSS configurations versus time.

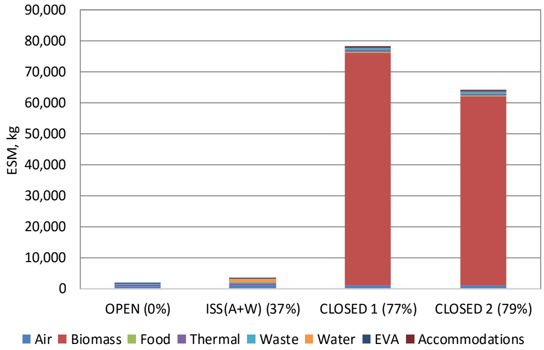

Figure 7. Comparison of initial ESM among four LSS configurations.

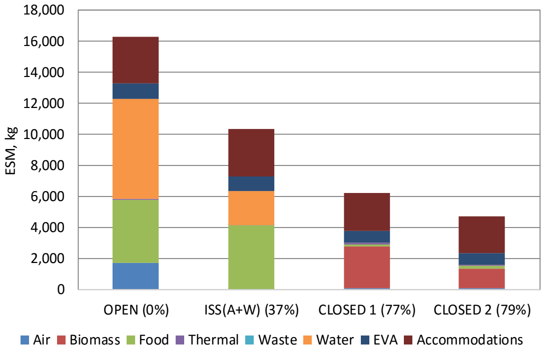

Figure 8. Comparison of one-year operation ESM among four LSS configurations.

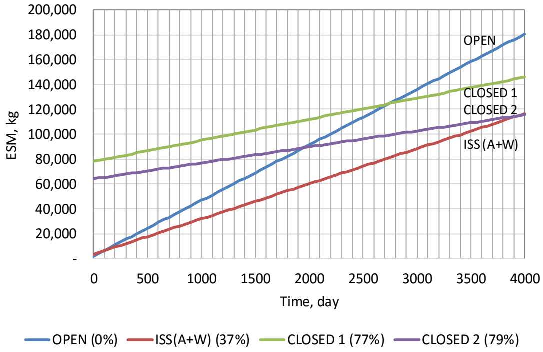

Figure 9. Comparison of ESM among four LSS configurations versus time.

VI. Conclusion

A Bioregenerative LSS Analysis Tool (BLSSAT) was developed to study the designs of LSSs with lunar farms. Total LSS mass values for lunar outposts utilizing biomass production subsystems were compared using initial mass, logistics mass, the initial ESM, and the incremental ESM for the LSS. The results of the analysis showed that increasing vertical stacked layers of rice and soybeans increases utilization efficiency of mass and volume and is recommended for crop cultivation when the quantity is large to decrease a LSS's fixed initial mass. The total mass of the CLOSED 1 system was less than the total mass of the OPEN and ISS (A+W) systems after 700 days and 1,250 days of operation, respectively. The total mass of the CLOSED 2 system with a downsized biomass production subsystem was less than the total mass of the OPEN and ISS (A+W) systems after 600 days and 1,050 days of operation, respectively. However, when the CLOSED 2 system was used, its ESM value did not become less than the ESM of the OPEN system until more than 2,000 days after and did not become less than the ESM of the ISS system until more than 3,950 days after. The author proposes the reasonable design from the simulation results and hopes to contribute to the lunar farm working group's future study on achieving a lower cost alternative to a non-bioregenerative LSS for an operation spanning 10 years or less.

Appendix A: Biochemical Stoichiometry

Biochemical Stoichiometry is used for the mass balance model describing the human, plant, waste process, and nitrogen fixation. Human model is expressed by the mass balance equation (A1).

$$e_1 \cdot C_4H_5ON + e_2 \cdot C_{16}H_{32}O_2 + e_3 \cdot C_6H_{12}O_6 + e_4 \cdot C_6H_{10}O_5 + e_5 \cdot O_2 \rightarrow$$

$$e_6 \cdot C_2H_6O_2N_2 + e_7 \cdot C_{42}H_{69}O_{13}N_5 + e_8 \cdot C_{13}H_{28}O_{13}N_2 + e_9 \cdot CO_2 + e_{10} \cdot H_2O \qquad \text{(A1)}$$

e_1, e_2, e_3, and e_4: are the molar numbers for protein, fat, carbohydrates, and fiber contained in food, respectively. e_5 and e_9 are the molar numbers for oxygen absorbed and carbon dioxide discharged by respiration, respectively. e_6, e_7, and e_8 are the molar numbers for urine, feces and other organic materials, respectively. e_{10}, is the molar number for metabolic water.

The plant model is expressed by the mass balance equations for edible parts of plant (A2) and inedible parts of plant (A3) of a single crop.

Edible parts of plant

$$a_1 \cdot CO_2 + a_2 \cdot H_2O + a_3 \cdot NH_3 + a_4 \cdot HNO_3 \rightarrow$$

$$b_1 \cdot C_4H_5ON + b_2 \cdot C_{16}H_{32}O_2 + b_3 \cdot C_6H_{12}O_6 + b_4 \cdot C_6H_{10}O_5 + b_5 \cdot O_2 \qquad \text{(A2)}$$

Inedible parts of plant

$$a_5 \cdot CO_2 + a_6 \cdot H_2O + a_7 \cdot NH_3 + a_8 \cdot HNO_3 \rightarrow$$

$$b_6 \cdot C_4H_5ON + b_7 \cdot C_{16}H_{32}O_2 + b_8 \cdot C_6H_{12}O_6 + b_9 \cdot C_6H_{10}O_5 + b_{10} \cdot O_2 \qquad \text{(A3)}$$

a_1 and a_5 are the molar numbers for carbon dioxide absorbed, respectively. a_2 and a_6 are the molar numbers for water absorbed, respectively. a_3, a_4, a_7 and a_8 are the molar numbers for nutrients absorbed, respectively. b_1, b_2, b_3, b_4, b_6, b_7, b_8, and b_9 are the molar numbers for protein, fat, carbohydrates, and fiber in the edible parts of plant and protein, fat, carbohydrates, and fiber contained in the inedible parts of plant, respectively. b_5 and b_{10} are the molar numbers for oxygen produced. The ratio of protein, fat, carbohydrates, and fiber in each type of crop were determined by referring to the Standard Tables of Food Composition in Japan 2015. [26]

The waste process models for urine, feces, other organic material, and inedible parts of plant are expressed by the mass balance equations (A4) through (A7), respectively.

Urine

$$g_1 \cdot C_2H_6O_2N_2 + g_2 \cdot O_2 \rightarrow h_1 \cdot CO_2 + h_2 \cdot H_2O + h_3 \cdot N_2 \qquad \text{(A4)}$$

Feces

$$g_3 \cdot C_{42}H_{69}O_{13}N_5 + g_4 \cdot O_2 \rightarrow h_4 \cdot CO_2 + h_5 \cdot H_2O + h_6 \cdot N_2 \qquad \text{(A5)}$$

Other organic materials

$$g_5\cdot C_{13}H_{28}O_{13}N_2 + g_6\cdot O_2 \rightarrow h_7\cdot CO_2 + h_8\cdot H_2O + h_9\cdot N_2 \qquad \text{(A6)}$$

Inedible parts of plant

$$g_7\cdot C_4H_5ON + g_8\cdot C_{16}H_{32}O_2 + g_9\cdot C_6H_{12}O_6 + g_{10}\cdot C_6H_{10}O_5 + g_{11}\cdot O_2 \rightarrow h_{10}\cdot CO_2 + h_{11}\cdot H_2O + h_{12}\cdot N_2 \qquad \text{(A7)}$$

g_1, g_3, and g_5 are the molar numbers for urine, feces, other organic materials, respectively. g_7, g_8, g_9, and g_{10} are molar numbers for protein, fat, carbohydrates, and fiber contained in the inedible parts of plant, g_2, g_4, g_6, and g_{11} are the molar numbers for oxygen used for wet oxidization, respectively. h_1, h_4, h_7, and h_{10} are the molar numbers for carbon dioxide, respectively. h_2, h_5, h_8, and h_{11} are the molar numbers for water, respectively. h_3, h_6, h_9, and h_{12} are the molar numbers for nitrogen produced by reaction, respectively.

The nitrogen fixation model is expressed by the material balance equation (A8).

$$h_{13}\cdot N_2 + h_{14}\cdot H_2O \rightarrow h_{15}\cdot NH_4 + h_{16}\cdot HNO_3 \qquad \text{(A8)}$$

where, h_{13}, h_{14}, h_{15} and h_{16}: molar numbers of the nitrogen, water, ammonia, and nitric acid.

Appendix B: Equivalent System Mass (ESM)

Equivalent System Mass (ESM) is used for comparing system configurations. ESM is expressed as equation (B1) using mass, volume, power, cooling, and labor man hours. The total ESM is calculated as the sum of all the subsystems' ESM from i=1 to i=n.

$$ESM = \sum_{i=1}^{n}\left[\left(M_{I_i}\cdot SF_{I_i}\right)+\left(V_{I_i}\cdot V_{eq_i}\right)+\left(P_i\cdot P_{eq_i}\right)+\left(C_i\cdot C_{eq_i}\right)+\left(CT_i\cdot D\cdot CT_{eq_i}\right)+\left(M_{TD_i}\cdot D\cdot SF_{TD}\right)\right] \qquad \text{(B1)}$$

where ESM = the equivalent system mass value of the system of interest [kg],
M_{Ii} = initial mass of subsystem i [kg],
SF_{Ii} = initial mass stowage factor for subsystem i [kg/kg],
V_{Ii} = initial volume of subsystem i [m^3],
V_{eqi} = mass equivalency factor for the pressurized volume support infrastructure of subsystem i [kg/m^3],
P_i = power requirement of subsystem i [kW$_e$],
P_{eqi} = mass equivalency factor for the power generation support infrastructure of j subsystem i [kg/kW$_e$],
C_i = cooling requirement of subsystem i [kW$_{th}$],
C_{eqi} = mass equivalency factor for the cooling infrastructure of subsystem i [kg/kW$_{th}$],
CT_i = crew-time requirement of subsystem i [CM-h/y],
D = duration of the mission segment of interest [y],
CT_{eqi} = mass equivalency factor for the crew-time of subsystem i [kg/CM-h],
M_{TDi} = time- or event-dependent mass of subsystem i [kg/y], and
SF_{TDi} = time-or event-dependent mass stowage factor for subsystem i [kg/kg]

Mass equivalency factors (V_{eq}, P_{eq}, C_{eq}, and CT_{eq}) are used to convert the non-mass parameters (V, P, C and CT) to mass equivalencies. Equivalency factors are determined by computing the ratio of the unit mass of infrastructure required per unit of resource.

Appendix C: LSS Subsystem Breakdown

A subsystem breakdown for the lunar surface LSS is shown in Table C1. The subsystem mass, volume, power, cooling, and crew time are based on baseline technology and advanced technology described in MSAD-04-0306 (Hanford, 2004)[21], in NASA CR-2006-213694 (Hanford, 2006),[22] and in NASA, JSC-47804 (Hanford, 2002).[25] The green cells are variable values depending on the human activity and crop selection. The subsystem configurations of OPEN, ISS (A+W), and CLOSED systems are shown in Table C2.

Table C1. Lunar surface LSS subsystem breakdown for six crewmembers.

No.	Subsystem	Tech.	Mass	Volume	Power	Cooling	Resupply Mass	Resupply Parts Mass	Resupply Volume	Crew time	Ref. No
			kg	m^3	W_e	W_{th}	kg/day	kg/yr	m^3/yr	CM-h/yr	
100	**Air Subsystem**										
110	**Atmospheric Control System**										
111	Atmospheric Pressure Control	ISS	119.4	0.26	70.5	70.5	0	0.00	0	0	22
120	**Atmosphere Revitalization System**										
121	Carbon Dioxide Removal	LiOH	0	0	0	0	0.00	365.00	1.095	0	
122	Carbon Dioxide Removal	4BMS/ISS	185.1	0.44	556.21	556.21	0.00	0.00	0	2.76	22
123	Carbon Dioxide Reduction	Sabatier	75.91	0.14	82.94	82.94	-3.59	0.00	0	0	22
125	Oxygen Generation	SPE/ISS									22
126	Gaseous Trace Contaminant Control	ISS	388.97	1.02	3421.67	1868.34	4.04	50.32	0	10.1	22
127	Atmosphere Composition Monitoring Assembly	ISS	68.41	0.14	194.35	194.35	0.00	21.29	0.322	0	22
128	Sample Delivery System	ISS	54.3	0.09	103.5	103.5	0.00	0.00	0	0	22
129	Airlock Carbon Dioxide Removal	ISS	35.11	0.04	0	0	0.00	0.00	0	0	22
180	**Gas Storage**		181.3	0.23	397	397	0.00	0.00	0	0	
181	Nitrogen Storage	High Pressure									24
182	Nitrogen Storage	Cryogenic	1	0.00	0	0	0.02			0	24
183	Oxygen Storage	High Pressure	28	0.02	0	0	0.02			0	24
184	Oxygen Storage	Cryogenic	118	0.09	0	0	3.59			0	24
190	**Fire Detection and Suppression**		139	0.11	0	0	3.59			0	
191	Fire Detection System	ISS									22
192	Fire Suppression System	ISS	1.5	0	1.48	1.48	0	0.00	0	0.01	22
200	**Biomass Subsystem**										
220	**Plant Growth Chamber / Salad Machine**										
221	Plant Growth Chamber	Drysdale	43004	436	1107923	1107923		1614.22		922	18
223	Plant Growth Machine I	Lunar Farm	10956	1271	364716	130405		531.38		92	13 (WG)
224	Plant Growth Chamber unshielded	Lunar Farm	11643								17
225	Plant Growth Chamber shielded	Lunar Farm	169175								17
226	Plant Growth Machine II	Lunar Farm	7384	764	331657	97346		323.40		50	13 (WG)
260	**Food Subsystem**										
262	Food Storage without food production	Shuttle	0	0	0	0	11.16	0.00	0	0	13 (WG)
263	Refrigerator/Freezer	ISS	321	2	0.204	0.228					24
264	Food Storage with biomass production	Lunar Farm	0	0	0	0	0.41	0.00	0	0	13 (WG)
300	**Thermal Subsystem**										
310	**Temperature and Humidity Control**										
311	Common Cabin Air Assembly	ISS	118.08	0.5	530.52	530.52	0		0	0	22
312	Avionics Air Assembly	ISS	12.4	0.03	175	175	0		0	0	22
313	Atmosphere Circulation	ISS	9.8	0.02	61	61	0		0	0	22
314	Atmosphere Microbial Control	ISS	100	0.27	0	0	0	19.06	0.13	3.33	22
320	**Internal Thermal Control System**										
321	Internal Thermal Control System	-	149.28	0.3	517.71	517.71	0		0	0	22
400	**Waste Subsystem**										
410	**Solid Waste Collection**										
411	Solid Waste Collection	ESDM	36.36	0.13	14	14	0	0.00	0	0	22
420	**Solid Waste Processing System**										
421	Solid Waste Treatment	Storage	78.33	2.18	0	0		0.00	0	0	22
422	Incinerator	ALS	200	1.4	0.3	1.3		10.00		0.2	24
423	Supercritical Water Oxidation	ALS	200	1.4	0.5	1.5				0.2	
424	Bioreactor	ALS	231	0.46	0	0.59		1.50		1059.00	24
425	Bioreactor	LCS	148	6	0.1	0.1					13 (WG)
500	**Water Subsystem**										
510	**Urine/ Waste Water Collection System**										
511	Urine/ Waste Water Collection System	ISS	4.55	0.02	4	4	0	1.62	0	0	22
512	Urine/ Waste Water Collection System	ALS	4.55	0.02	4	4	0	1.62	0	0	22
520	**Water Recovery System**										
521	Water Treatment Process	ISS WRS	541.63	1.93	788.76	788.76		1295.75	0	0	22
522	Water Treatment Process	VPCAR	557.56	1.69	4011.45	1808.87		100.96	0	0	22
523	Urine, Hygiene & Potable Water, and Brine Storage	ISS	133.34	0.35	13.68	13.68			0	0	22
524	Urine, Hygiene & Potable Water, and Brine Storage	ALS	205.12	0.53	19.81	19.81			0	0	22
525	Microbial Check Valve	ISS	3.56	0.01	0	0		1.41	0	0	22
526	Microbial Check Valve	ALS	6.67	0.02	0	0		2.65	0	0	22
527	Process Controller	ISS	36.11	0.08	156.18	156.18			0	0	22
528	Process Controller	ALS	63	0	180	180			0	0	22
529	Water Quality Monitoring	ISS	14.07	0.04	4.72	4.72			0	0	22
530	Water Quality Monitoring	ALS	14.07	0.04	4.72	4.72			0	0	22
531	Product Water Delivery System	ISS	37.99	0.09	2.65	2.65			0	0	22
532	Product Water Delivery System	ALS	58.37	0.14	3.83	3.83			0	0	22
540	**Water Storage**										
541	Hygiene Water Storage	-	132	1.32			14.70		0	0	
542	Potable Water Storage	-	27	0.27			3.00		0	0	
543	Urine Storage	-					9.02		0	0	
544	Waste Water Storage	-					4.80		0	0	
600	**Human Accommodations**										
610	**Clothing**										
611	Clothing	Supply					2.92		6.24	0	
612	Clothing	Laundry					0.12		0.26	0	
620	**Laundry Equipment**										
621	Water/Dryer	-	80	0.26	633.33	633.33	0.00		0	12.045	22
622	Detergent	-	0.01	0	0	0	0.35		0	0	22
630	**Whips**										
631	Hand/Face/Shower Wet Whips	-					0.31				
640	**Miscellaneous Items**										
641	Miscellaneous Items	-					5.06				
700	**Extravehicular Activity**										
711	Maximum Absorbency Garments	-	196	0.82			0.05		0.0001	44.8	22
712	Carbon Dioxide Removal (LiOH)	-					0.50		0.0015		
713	Airlock Recycle Pump for EVA	-			1000	1000	0.48		0.0014		
714	Oxygen Recharge Compressor Assembly for EVA	-					0.27		0.0008		
715	Food, O2, and Water Add						0.77		0.0023		

Table C2. Subsystem configurations of OPEN, ISS (A+W), and CLOSED systems.

	Subsystem	OPEN system	ISS (A+W) system	CLOSED 1 and 2 systems
1	Air	111, 121, 126, 127, 128, 129, 181, 183, 191, 192	111, 122, 123, 124, 126, 127, 128, 129, 181, 183, 191, 192	111, 122, 126, 127, 128, 129, 181, 191, 192
2	Biomass			223 (226), 224
2	Food	262	262	263, 264
3	Thermal	311, 312, 313, 314, 321	311, 312, 313, 314, 321	311, 312, 313, 314, 321
4	Waste	411, 421	411, 421	423, 425
5	Water	511, 541, 542	511, 521, 523, 525	511, 523, 525
6	Accommodations	611, 631, 641	611, 631, 641	612, 621, 622, 631, 641
7	EVA	711, 712, 713, 714, 715	711, 712, 713, 714, 715	711, 712, 713, 714, 715

The subsystem numbers correspond to the numbers in Table C1.

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