7. STUDY OF THE LUNAR FARMING SYSTEM

~ Examination of the lunar farm from the viewpoint of life support system design ~

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7.1 Introduction

On the moon, there is a day and night for approximately 2 weeks each in a cycle of approximately 4 weeks, and it is necessary to store electricity at night. Thus, conventionally, food production on the moon has not been an attractive option, and food production has often focused on Mars, which has a day and night cycle of approximately 24 h and 40 min. Since the study in Russia in the 1960s, there have been numerous research examples of crop cultivation for food production in space. Typical examples of simultaneous food production and residence at ground-based experimental facilities include Russia's BIOS [33,4)], the United States' Lunar Mars Life Support Test Project (LMLSTP) [5)], and Japan's Closed Ecology Experiment Facilities (CEEF) [6)]. A recent example is Lunar Palace [17)] in China. Especially in recent crop cultivation, the use of LEDs has become common. It has become possible to design products significantly different in durability, weight reduction, and energy utilization efficiency than when high-pressure sodium lamps were used [8,9,10)].

Therefore, in this study, we will design a lunar farm system that incorporates the latest knowledge of plant factories using the bioregenerative life support system analysis tool [11,12)]. In particular, food production is greatly involved in the design of life support systems, such that the specifications of the entire lunar farm will be examined from the perspective of life support system design. In this report, after presenting the design method and calculation procedure of the analysis tool, an example of designing a lunar farm using set values [13)] examined by the working group is shown.

7.2 Assumptions for the lunar farm design

First, the assumptions for the working group's lunar farm design are shown. The following ground rule and assumptions have been set for the overall system parts required for the lunar base system that other groups are considering.

Ground Rule 1: Six crewmembers live in the lunar outpost where they produce their own food.

Assumption 1: Water, oxygen, and nitrogen can be produced on the moon using ISRU.

Assumption 2: Concrete can be manufactured on the moon.

Assumption 3: Assuming that the base is located in the highlands of Antarctica, solar cells can be used with a sunshine rate of 90%.

Assumption 4: The use of nuclear power is also an option for power sources.

With reference to the nutritional values published in the Japanese Dietary Intake Standards 2015 [14)], cultivated crop candidates were determined to consider the balance of energy, protein, and fat, and the standard model was a 30–49-year-old male (physical activity level II; 2,650 kcal/d). Considering that the nutrition from agricultural products is only plant-derived, animal protein is supplied from Earth. Other deficient nutrients will be supplied from Earth as supplements.

The crop species were selected to consider the cultivation area, energy requirement, labor hours, and the number of cooking menus. Table 7.1 shows the cultivated crops and cultivated amounts currently set by the working group. The required area was determined from the production volume and harvest index obtained at the plant factory on the ground. The eight crop types of rice, potatoes, sweet potatoes, soybeans, lettuce, tomatoes, cucumbers, and strawberries are produced internally. Additionally, the energy and protein that are insufficient for these eight types are calculated on the assumption that 50 g of animal protein will be brought from Earth. Table 7.1 shows the actual floor area considering the energy, required amount, number of days until harvest, harvest index, daily production of edible parts, cultivation area required for food production for one person, and number of cultivation shelves. We consider the three types of rice and soybean cultivation shelves and the floor area shown here.

Table 7.1. Candidate cultivated crops on a lunar farm

Crop	Energy	Required amount*	Days to harvest	Harvest index*	Daily Production*	Cultivated area per capita	Number of cultivated shelves†	Floor area†
	Kcal/d	g/d	d	-	$g/m^2/d$	m^2	-	m^2
Rice	1421.1	335.2	90	0.5	8.5	40.0	1 2 3	40.0 20.0 13.3
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 3	25.0 12.5 8.33
Lettuce	26.3	7.4	30	0.91	4.2	1.8	5	0.36
Tomato	48.8	12.4	100	0.7	13.9	0.9	1	0.9
Cucumber	18.3	4.8	80	0.7	9.7	0.5	1	0.5
Strawberry	12.2	3.1	60	0.7	2.8	1.1	5	0.22
Subtotal	2438.5	562.4				80.2		70.6 38.1 27.3
Animal protein‡	211.0	50.00						
Total	2649.5	612.4						

* Numbers set at the WG were converted to dry mass
† The number of cultivation shelves for rice and soybeans is examined three ways: one, two, and three. These are called CLOSED 1, CLOSED 2, and CLOSED 3.
‡ Assumes that animal protein was additionally consumed

Based on NASA's advanced life support system standard values [15,16,17], the set values related to human life are shown in Table 7.2.

Table 7.2. Set values related to human life (kg/person/d)

Required items	Lunar base, kg/CM-d
Oxygen	Depending on the settings in Table 7.1
Food (dry)	Depending on the settings in Table 7.1
Food (in water)	Depending on the settings in Table 7.1
Metabolized water	Depending on the settings in Table 7.1
Cooking water	0.76
Drinking water	2.10
Water for handwashing	0.20
Water for showering	2.72
Water for flushing toilet	0.30
Laundry water	12.5
Other	0.78

7.3 Mass balance calculation

Table 7.3 shows the mass balance calculation by biochemical stoichiometry (Appendix 7A) [18, 19] based on the amount of crops cultivated in Table 7.1. The deficient substance becomes the amount supplied from the outside.

Table 7.3. Mass balance model

	Input 1	Input 2	Input 3	Input 4	Output 1	Output 2	Output 3
Plant	CO_2	H_2O	NH_3	HNO_3	Edible	Inedible	O_2
Dry g/CM	1741.2	621.7	19.1	42.4	562.4	497.8	1364.2

Calculations are based on Equations (A1) and (A2) in Appendix 7A

	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	612.4	599.0	51.7	105.2	0.00	778.7	275.9

Calculations are performed using the equation (A3) in Appendix 7A

	Input 1–4 or Input 1	Input 2 or Input 5	Output 1	Output 2	Output 3	Output 4
Waste processing	Waste	O_2	CO_2	H_2O	N_2	Residues
Urine, dry-g/CM	43.9	39.0	42.9	26.3	13.7	6.6
Feces, dry-g/CM	105.2	208.7	228.4	76.8	8.7	0.0
Inedible, dry-g/CM	497.8	602.1	789.6	301.5	8.9	0.0
Total, dry-g/CM	646.9	849.8	1060.9	404.6	31.2	6.6

Calculations are based on Equations (A4), (A5), and (A7) in Appendix 7A

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

Calculations are based on Equation (A8) in Appendix 7A

7.4 Design of life support system

Using the Equivalent System Mass (ESM) [20] shown in Appendix 7B, we will compare life support systems incorporating lunar farms. ESM consist of mass, volume, power, cooling, and working hours. Based on the life support system element technology candidates [20,21] in Table 7C1 of Appendix 7C, values proportional to the number of people are used. The replenishment mass varies depending on the technology used.

7.4.1 Procedure for calculation

The calculation procedure of the design tool is shown in Fig. 7.1. The procedure of the mission requirement setting, cultivated crop setting, mass balance calculation, subsystem technology setting, and ESM calculation were examined. There are two loops [cultivated crop change and element technology change (B)], and methods for reducing ESM were examined. Additionally, if the cultivated crop data and technical data are updated during the study, the data can be reflected in the overall calculation (A).

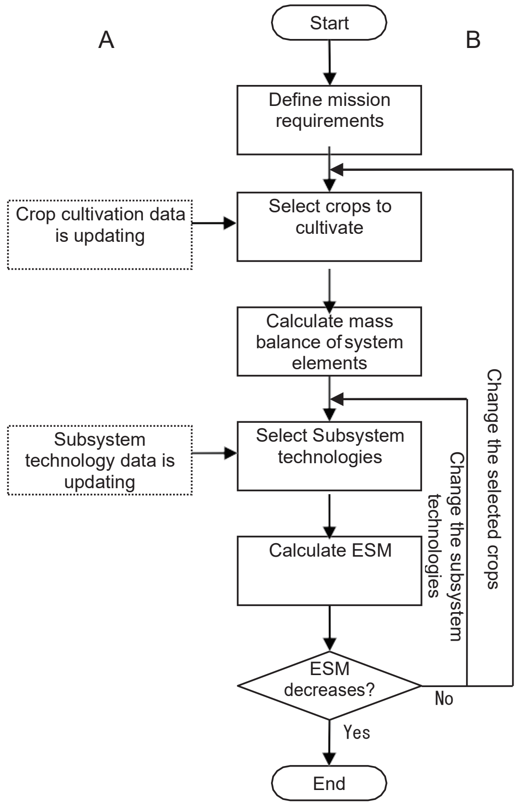

Fig. 7.1 Calculation Procedures for Design Tools

7.4.2 Configuration of the life support system

Table 7.4 shows the elemental technologies of open system, ISS system, and closed system. The combination of mass, volume, power, cooling, and working hours of these three types of subsystems is shown in Table 7C2 of Appendix 7C. The open system does not regenerate the substance after use. The ISS system regenerates carbon dioxide and water and dries and stores waste without regenerating it. The closed system uses plant photosynthesis to regenerate carbon dioxide and water. Waste is processed and reused.

Table 7.4 Subsystem technologies for the lunar base

Subsystem	Subfunction	Open system	ISS system	Closed system
Air revitalization	Carbon Dioxide Removal (CDRA)	LiOH	4BMS	4BMS
	Carbon Dioxide Reduction System (CRS)	-	Sabatier	Crop cultivation
	Trace Contaminant Control System (TCCS)	Activated carbon and air filter	Activated charcoal and air filters	Activated charcoal and air filters
	O_2/N_2 Storage	High pressure	High pressure	Cryogenic
	Oxygen Generation	-	Electrolysis	Photosynthesis
	Temperature and humidity control	CHX	CHX	CHX
Water recycling	Water Storage	Storage	Storage	Storage
	Water Recovery System (WRS)	-	ISS WRS (MF, VRA, PS, and IEB)	Photosynthesis/VPCAR
	Waste Water	Discharge	Storage	Storage

	Collection System			
Waste process	Urine Process	To wastewater tank	VCD	Bioreactor
	Feces processing	Feces bag	Feces bag, Compactor	Bioreactor/wet oxidation
Biomass production	Biomass production	-	-	Crop cultivation
Food storage	Food supply	ISS Food	ISS Food	Supplements, Refrigerator, and Freezer
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

7.4.3 Food production system

Table 7.5 shows the ESM of the lunar farm food production system. This design value is based on LED lighting, hydroponics, and an inflatable structure. The initial mass of 6.51 kg/m^2 of the crop part in Table 7.5 is the total mass of N_2, CO_2, NH_3, and HNO_3 from Earth, and the mass of N_2 is calculated from the volume of the cultivation space and the mass of CO_2, NH_3, and HNO_3 was calculated based on the mass balance in Table 7.3.

The LED power required for crop cultivation shown in Table 7.1 was calculated assuming the biomass production per the number of photons (mol) by photosynthesis is 0.4 g/mol [8,23], and the photosynthetic amount per photon flux required for the production of 1,090 g (edible portion 562 g, non-edible portion 498 g) is 2,651 mol (1,090 g/0.4 g/mol). Assuming that the photosynthetic photons per joule of the LED are 1.66 μmol/J [15], the photosynthetic photon flux is 1,596,728 kJ (2,651 mol/0.00166 mol/kJ). If this energy is irradiated in 8 hours, the required power will be 44.4 kW/CM-d (1,596,728 kJ/36,000 s). Dividing this by the cultivation area of 80.2 m^2 gives 0.553 kW/m^2. The cooling (exhaust heat) was set to 20% of the LED lighting power based on the plant factory's data. Working hours 1.3 h/m^2-year is a figure assuming that most agricultural work is automated.

Table 7.5. Food production system for the lunar farm

Components	Initial mass	Volume	Electric power	Heat load	Logistics mass	Working Hours
	Kg/m^2	m^3/m^2	kW/m^2	kW/m^2	Kg/m^2-year	h/m^2-year
Crop portion	6.51	2.6	0.14	0.14	0	1.3
Lighting equipment	7.54	0.4	0.691	0.138	0.19	0.0027
Electric power system	2.77	0	0.02	0.02	1.07	0.0032
Mechanical system	4.1	0	0.1	0.1	0.5	0.1
Secondary structure systems (shelves)	5.7	0	0	0	0	0
Total	26.6	3.00	0.96	0.41	1.75	1.41
Primary structural system (inflatable)	9.16	0	0	0	0	0

7.4.4 Resource regeneration system

With the production of food, inedible parts corresponding to the amount of edible parts were generated. We calculate the ESM of the bioreactor based on the mass balance in Table 7.3. The dry mass of the inedible portion per person was 497.8 g/d. The wet mass before water addition was 736 g/d (inedible portion 497.8 g/d, water 238.2 g/d). If 2,175 g of water is added to bring the water ratio to 80% before treatment, the total amount will be 2,987 g (736 g/d, 2,251 g/d). Assuming that the density of the processed material was 1,000 g/L, the volume was 3.0 L/d (2,987 g/d/1,000 g/L). Assuming a reaction time of 20 day, the reaction vessel's size was 60 L/d (3.0 L/d × 20 d), that is, 0.06 m^3.

Next, based on the specifications of the methane fermentation facility (processing capacity 17,500 kg, device mass 865,000 kg, device volume 33,600 m^3, electric power 566 kW, cooling 361 kW) shown in the report [24] of the Low Carbon Social Strategy Center. Table 7.6 shows the specifications of a bioreactor that can process 497.8

g/person/d. The volume of 1.17 m^3 is large enough for 0.06 m^3. The volume is 1.17 m^3, including the reaction vessel and other equipment.

Table 7.6. Bioreactor on lunar farm

Mass	Volume	Electric power	Heat load	Logistics mass	Working Hours
Kg/CM	m^3/CM	kW/CM	kW/CM	Kg/CM-yr	h/CM-yr
30.0	1.17	0.02	0.01	TBD	TBD

7.5 Comparison of system design proposals

Fig. 7.2 shows the system configuration of the lunar farm. The system has eight subsystems of air revitalization (Air), biomass production (Biomass), food storage (Food), thermal control (Thermal), waste recycling (Waste), water process (Water), extravehicular activity (EVA) (not shown in Fig. 7.2), and human accommodations (Accommodations). Here, we compared five life support system design proposals: open system (OPEN), ISS system (regeneration of air and water) (ISS (A + W)), and three closed system (CLOSED 1, CLOSED 2, CLOSED 3). Of these, the closed system was composed of biomass production on the lunar farm. Compared with CLOSED 1, CLOSED 2 changed the number of rice and soybean cultivation shelves from one to two and CLOSED 3 changed it from one to three. The settings for the plant cultivation module (inflatable outer shell), excluding the food production system at this time, are as shown in Table 7.7. For example, CLOSED 1 has a floor area of 70.6 m^2, a cultivation space height of 3 m, and a volume of 267 m^3, including a 20% margin. If this is constructed with an inflatable structure without a shield, the outer shell mass will be 2,444 kg (267 m^3 × 9.16 kg/m^3). For the mass of 9.16 kg/m^3 per unit volume, the standard value [15] of NASA's advanced life support system was used.

For the food supply of six people, a plant cultivation space with a volume of 1,601 m^3 (267 m^3 × 6) and a mass of 14,661 kg (2,444 kg × 6) was required, which was equivalent to 11 modules of 150 m^3. If CLOSED 2 is used, there will be six modules, and if CLOSED 3 is used, there will be four modules. Additionally, there is one habitation module, one experimental module, and one utility module. These modules are covered and protected with regolith, as shown in Fig. 7.3.

Table 7.8 shows the ESM equivalency factor of the lunar base. The equivalency factor of electric power is a numerical value when nuclear power generation is used. The labor hours' equivalency factor varies depending on the available time, but the calculation method [21] was omitted.

Table 7.7. Settings for plant cultivation modules (inflatable outer shell)

	CLOSED 1	CLOSED 2	CLOSED 3
Cultivated area, m^2 per person	80.2	80.2	80.2
Floor area, m^2 per person	70.6	38.1	27.3
Floor area/cultivation area	0.88	0.48	0.34
Volume of plant cultivation space (including 20% margins), m^3 per person	267	144	103
Mass of Plant Cultivation Space, kg/person	2,444	1,319	944
Plant cultivation module volume (for six people), m^3	1,601	864	618
Plant cultivation module mass (for six people), kg	14,661	7,913	5,664
Number of plant cultivation modules (for six people)	11	6	4

Table 7.8 ESM- Equivalency Factor [21] for Lunar Base

Element	Equivalency factor
Mass kg/kg	1
Volume kg/m^3	9.16
Electricity (nuclear power use) kg/kW	76
Cooling kg/kW	102
Working hours kg/h	(variable)

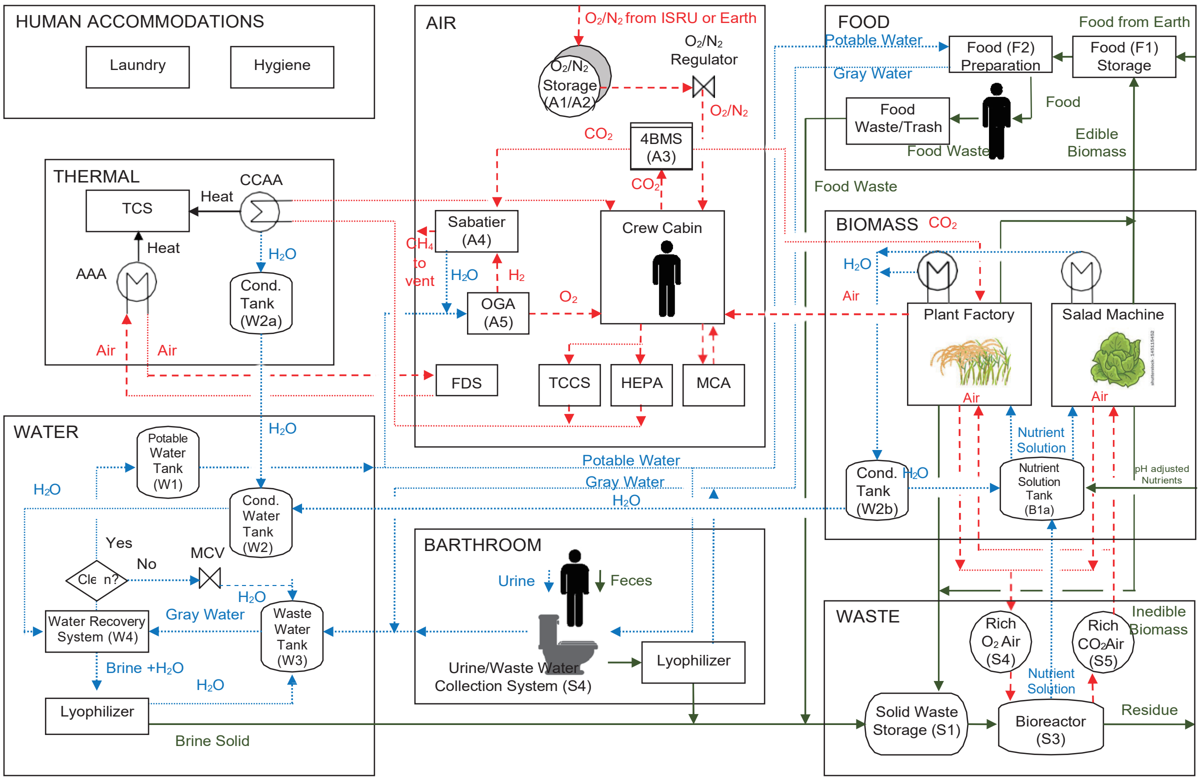

Fig. 7.2. Configuration of life support systems for lunar base including farm

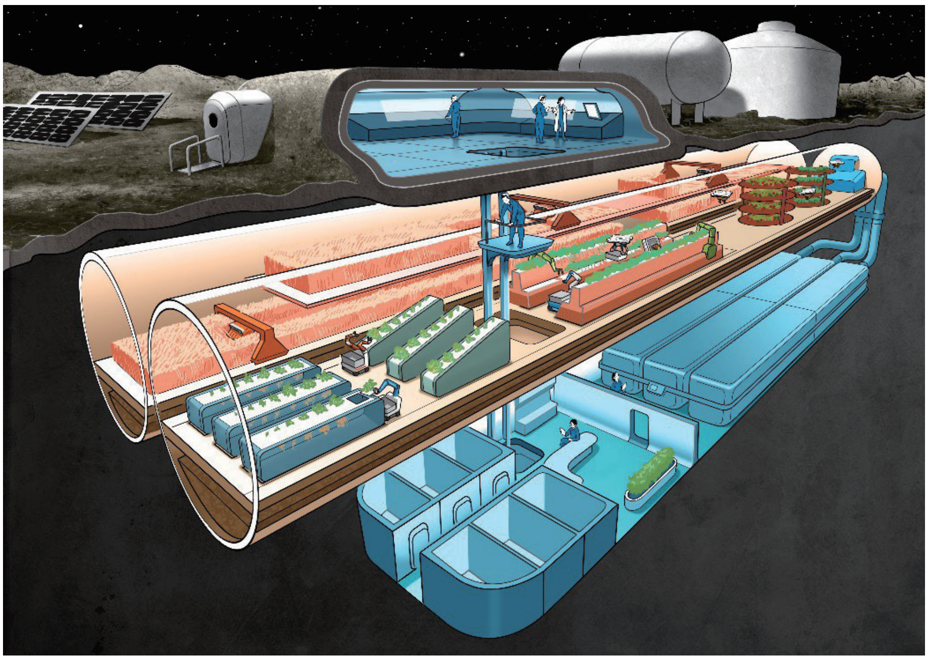

Fig. 7.3. Lunar base covered by regolith

Table 7.9 shows the calculation results of mass and ESM when six people live on the moon for 1 year. The graphs of OPEN, ISS (A + W), CLOSED 1, CLOSED 2, and CLOSED 3 are shown in Table 7.9 and Fig. 7.4 to 7.9. Fig. 7.4, 7.5, 7.7, and 7.8 show the initial mass, 1-year logistics mass, initial ESM, and 1-year ESM increment for each subsystem, Fig. 7.6 shows the time variation of the total mass of the five life support systems, and Fig. 7.9 shows the time variation of the ESM of the five life support systems. The number in parentheses is the regeneration rate in terms of mass. Finally, Fig. 7.10 shows the number of days in which the ESM of CLOSED 2 was less than that of ISS (A + W) and ESM of CLOSED3 was less than that of ISS (A + W) when the agricultural work automation rate was changed.

Comparison of initial and logistics mass (Table 7.9(a) (b), Fig. 7.4, Fig. 7.5)

Table 7.9 (a) and (b) show the initial mass of the five life support systems and the logistics mass for 1 year. The initial mass of CLOSED 1 was 19.3 times that of OPEN. In CLOSED 1, the air and water process subsystems' functions were replaced by biomass production, such that the initial mass of the two subsystems was less than the ISS (A + W), but the mass of the food production system was 26,534 kg. The initial mass of CLOSED 1 was much larger than that of OPEN.

Next, the initial masses when the number of rice and soybean cultivation shelves was set to two (CLOSED 2) to make the biomass production system less than in CLOSED 1 and when the cultivation shelves was set to three (CLOSED 3) that were 12.7 times and 10.4 times that of OPEN. CLOSED 2 and 3 had a less initial mass because of a less pressurized volume than CLOSED 1 but were still considerably larger than the initial mass of OPEN and ISS (A + W).

The logistics mass of CLOSED 1, 2, and 3 was 0.24, 0.22, and 0.21 times, respectively, that of OPEN. Biomass production could regenerate air (oxygen), food, and water and significantly reduce their logistics mass compared with OPEN and ISS (A + W).

Time-series comparison of initial mass and logistics mass (Fig. 7.6)

Fig. 7.6 shows the 1,800 days change of the total mass (initial mass and logistics mass) of the five life support systems. The mass of CLOSED 2 was less than OPEN after 550 days and less than ISS (A + W) after 900 days. The mass of CLOSED 3 was less than OPEN after 450 days and less than ISS (A + W) after 750 days.

Comparison of initial ESM and 1-year ESM increments (Table 7.9 (c) (d), Fig. 7.7, Fig. 7.8)

Table 7.9 (c) (d) shows the initial ESM of the five life support systems and the ESM increments when operated for 1 year. The initial ESM of CLOSED 1 was 44.4 times that of OPEN. CLOSED 2 was 33.1 times OPEN, and CLOSED 3 was 29.4 times OPEN. The 1-year ESM increments for CLOSED 1, 2, and 3 were 0.4, 0.3, and 0.3 times OPEN, respectively.

ESM time-series comparison (Fig. 7.9)

Fig. 7.9 shows the 4,000 days changes in ESM of the five life support systems. CLOSED 1 fell below the OPEN ESM after 3,600 days and never fell below the ISS (A + W) ESM within 4,000 days. CLOSED 2 fell below the OPEN ESM after 2,200 days and did not fall below the ISS (A + W) ESM within 4,000 days. CLOSED 3 was below the OPEN ESM after 1,850 days and below the ISS (A + W) ESM after 3,650 days. When rice and soybeans are cultivated in three stages, the system became more advantageous than the ISS (A + W) in approximately 10 years.

Rate of farming automation and the breakeven point (Fig. 7.10)

Fig. 7.10 shows the change in the mission period when the ESM of CLOSED 2 and 3 was less than the ESM of the ISS (A + W) when the agricultural work automation rate was changed. An automation rate of 0 indicated farm work at 13 h/m^2/year [22], and 1 indicated full automation. The results shown in Fig. 7.1 to 7.9 are the values calculated at the automation rate of 0.9. As the automation rate drops to 0.8 and 0.7, the mission period in which the ESM of CLOSED 2 fell below the ESM of ISS (A + W) became remarkably longer. The breakeven point of CLOSED 3 was less sensitive to the automation rate decrease than in CLOSED 2. The automation of farm work on lunar farms was important for reducing operating costs.

Table 7.9 (a) Initial mass, (b) Logistics mass, (c) Initial ESM, and (d) ESM increments when operated for 1 year

Initial mass、 kg	OPEN (0%)	ISS(A+W) (37%)	CLOSED 1 (76%)	CLOSED 2 (78%)	CLOSED 3 (79%)
Air	585	846	653	653	653
Biomass	0	0	26,534	16,623	13,320
Food	0	0	321	321	321
Thermal	390	390	390	390	390
Waste	115	115	348	348	348
Water	164	1,062	141	141	141
EVA	196	196	196	196	196
Accommodations	35	35	115	115	115
Total	**1,485**	**2,644**	**28,698**	**18,787**	**15,484**
System/OPEN	**1.0**	**1.8**	**19.3**	**12.7**	**10.4**

Logistics mass, kg/year	OPEN (0%)	ISS(A+W) (37%)	CLOSED 1 (76%)	CLOSED 2 (78%)	CLOSED 3 (79%)
Air	1,705	28	28	28	28
Biomass	0	0	733	437	339
Food	4,073	4,073	149	149	149
Thermal	19	19	19	19	19
Waste	0	0	0	0	0
Water	6,462	2,206	3	3	3
EVA	757	757	757	757	757
Accommodations	3,024	3,024	2,131	2,131	2,131
Total	**16,041**	**10,108**	**3,819**	**3,524**	**3,425**
System/OPEN	**1.00**	**0.63**	**0.24**	**0.22**	**0.21**

Initial ESM, kg	OPEN (0%)	ISS(A+W) (37%)	CLOSED 1 (76%)	CLOSED 2 (78%)	CLOSED 3 (79%)
Air	730	1,110	900	900	900
Biomass	0	0	90,115	66,511	58,644
Food	0	0	339	339	339
Thermal	628	628	628	628	628
Waste	138	138	413	413	413
Water	179	1,338	145	145	145
EVA	382	382	204	204	204
Accommodations	35	35	231	231	231
Total	**2,093**	**3,631**	**92,974**	**69,371**	**61,503**
Total/OPEN	**1.0**	**1.7**	**44.4**	**33.1**	**29.4**

ESM increment, kg/year	OPEN (0%)	ISS(A+W) (37%)	CLOSED 1 (76%)	CLOSED 2 (78%)	CLOSED 3 (79%)
Air	1,705	39	104	85	78
Biomass	0	0	3,446	1,528	1,032
Food	4,073	4,073	149	149	149
Thermal	36	32	111	87	79
Waste	0	0	6	4	4
Water	6,462	2,206	3	3	3
EVA	984	929	757	757	757
Accommodations	3,024	3,024	2,462	2,377	2,349
Total	16,284	10,303	7,037	4,990	4,452
Total/OPEN	1.0	0.6	0.4	0.3	0.3

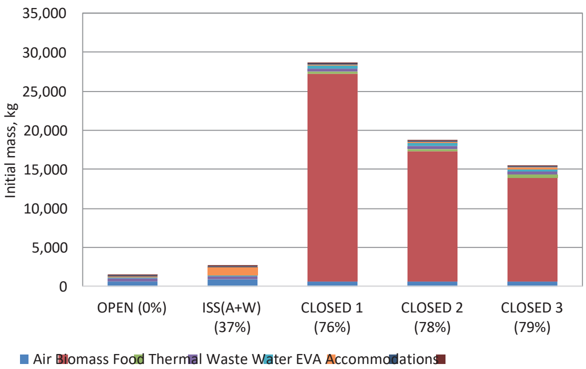

Fig. 7.4 Comparison of initial masses of the five system configurations

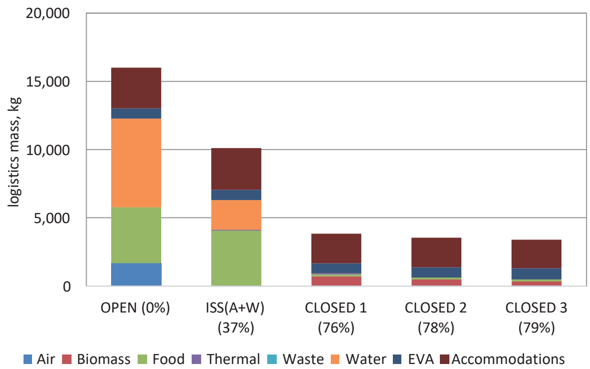

Fig. 7.5 Comparison of logistics mass of the five system compositions when operated for 1 year

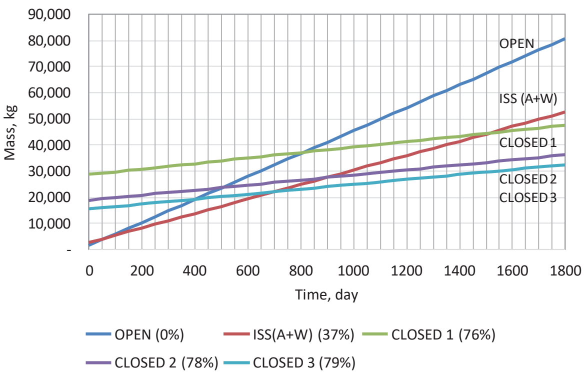

Fig. 7.6 Mass (initial + logistics) time change comparison of the five system configurations

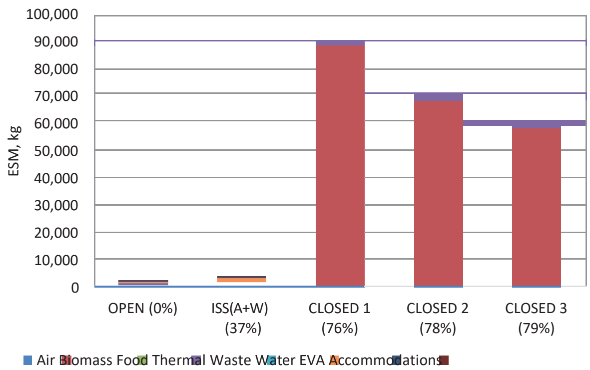

Fig. 7.7 ESM comparison of the five systems on day 0

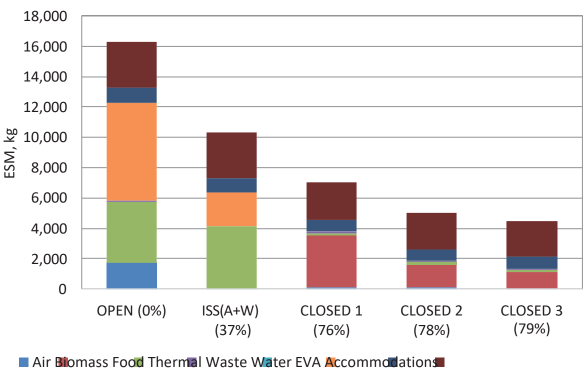

Fig. 7.8 One-year ESM incremental comparison of the five systems

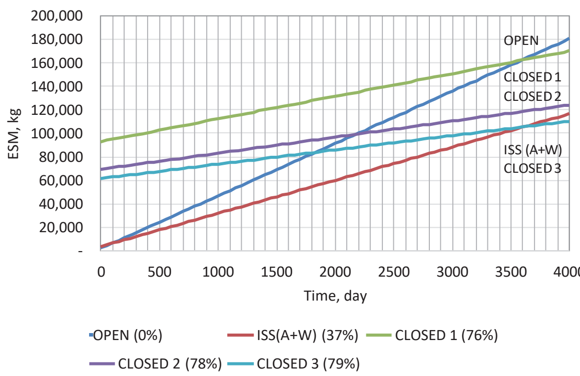

Fig. 7.9 Comparison of ESM time changes for the five system configurations

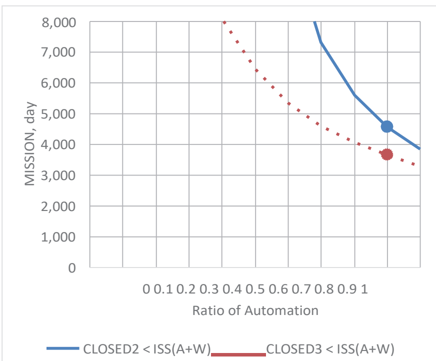

Fig. 7.10 Agricultural automation rate and breakeven point

7.6 Summary

We have developed a bioregenerative life support system analysis tool that allows us to consider introducing a lunar farm at a lunar base. We compared the mass and ESM of lunar-based life support systems, including biomass production systems, to introduce recent technologies, such as LEDs. When the number of cultivation shelves for crops with a large amount of cultivation increases and the space utilization efficiency is increased, the initial mass can be greatly suppressed. It was also confirmed that it is advantageous after 450 days from the total mass of the open system and after 750 days from the total mass of the ISS system. However, 1,850 and 3,650 days or more are required for the operation that is more advantageous than the open system and the ISS system, respectively, in the evaluation using ESM, including the labor hours, even if the number of cultivation shelves is increased and the space utilization efficiency is improved.

Here, it is shown that one of the lunar farms was more advantageous in terms of operating costs expressed in ESM than replenishing food from the earth in approximately 10 years when building materials and substances, such as water and oxygen, were procured on the moon and nuclear power was used. When using the eight types of crops envisioned at this time, multi-stage cultivation of rice and soybeans (approximately three stages) and automation technology, which have a large cultivation area, are particularly important for reducing operating costs.

Appendix 7A: Biochemical Stoichiometry

Biochemical stoichiometry [10] was used in the mass balance analysis of life support systems. Biochemical stoichiometry was developed by Volk T. and Rummel J. D. to analyze the mass balance of closed ecosystems. Biochemical stoichiometry approximates the metabolites of living organisms with chemical formulas, creates a mass balance equation for the metabolism, and solves the mass balance equation based on mass conservation law to obtain an unknown metabolite [11]. Four mass balance equations for plants, humans, waste process, and fertilizer production are shown.

Plants

The mass balance equation of plants consists of Equation (A1) and Equation (A2) in which "carbon dioxide, water, ammonia, and nitric acid" are changed to "proteins, fat, carbohydrate, fibers, oxygen" by photosynthesis.

Edible parts:

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

$$b_1 \cdot C_4H_5ON + b_2 \cdot C_{16}H_{32}O_2 + b_3 \cdot C_6H_{12}O_6 + b_4 \cdot C_6H_{10}O_5 + b_5 \cdot O_2 \quad \text{(A1)}$$

Inedible parts:

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

$$b_6 \cdot C_4H_5ON + b_7 \cdot C_{16}H_{32}O_2 + b_8 \cdot C_6H_{12}O_6 + b_9 \cdot C_6H_{10}O_5 + b_{10} \cdot O_2 \quad \text{(A2)}$$

Human beings

The human mass balance equation consists of the Equation (A3) in which "protein, fat, carbohydrate , fiber, and oxygen" changes to "urine, feces, other organic matter, carbon dioxide, and water."

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

$$e_6 \cdot C_2H_6O_2N_2 + e_7 \cdot C_{42}H_{69}O_{13}N_5 + e_8 \cdot C_{13}H_{28}O_{13}N_2 + e_9 \cdot CO_2 + e_{10} \cdot H_2O \quad \text{(A3)}$$

Waste process

The mass balance equation for waste process consists of Equation A4 that changes "urine and oxygen" to "carbon dioxide, water, and nitrogen," Equation (A5) that changes "feces and oxygen" to "carbon dioxide, water, and nitrogen," Equation (A6), in which "other organic matter and oxygen" changes to "carbon dioxide, water, and nitrogen," and Equation (A7) in which "protein, fat, carbohydrate, fiber, and oxygen " changes to "carbon dioxide, water, and nitrogen."

Urine:

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

Feces:

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

Other organic matter:

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

Inedible parts:

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

Fertilizer production

The mass balance equation for fertilizer production consists of the Equation (A8) in which "nitrogen and water" are changed to "ammonia and nitric acid."

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

Appendix 7B Equivalent System Mass

Equivalent System Mass (ESM) [6] used by NASA was used to compare the entire system. ESM expresses the cost of a life support system by mass, volume, power, cooling, and working hours as shown in equation (B1), and calculates ESM by summing subsystems i = 1 to n.

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

M_{Ii}: Initial mass of subsystem i [kg]
SF_{Ii}: Initial mass storage factor of subsystem i [kg/kg]
V_{Ii}: Initial volume of subsystem i [m^3]
V_{eqi}: Pressurized volume-mass equivalent factor of subsystem i [kg/m^3]
P_i: Required power for subsystem i [kW_e]
P_{eqi}: Subsystem i's power-mass equivalent factor [kg/kW_e]
C_i: Cooling requirement of subsystem i [kW_{th}]
C_{eqi}: Cooling-mass equivalent factor for subsystem i [kg/kW_{th}]
CT_i: Crew time required for subsystem i [CM-h/yr]
D: Mission period [y]
CT_{eqi}: Crew time equivalent factor for subsystem i [kg/CM-h]
M_{TDi}: Time-dependent mass of subsystem i [kg/yr]
SF_{TDi}: Time-dependent mass storage factor of subsystem i [kg/kg]

The mass equivalency factors (V_{eq}, P_{eq}, C_{eq}, and CT_{eq}) convert non-mass parameters (V, P, C, and CT) to mass.

Appendix 7C Elemental technology candidate(s) for life support system

Table 7C1 shows the elemental technology candidates for the lunar-based life support system. Subsystem mass, volume, power, cooling, and labor hours are available in the references MSAD-04-0306 (Hanford, 2004) [21], NASA CR-2006-213694 (Hanford, 2006) [22], NASA JSC-47804 (Hanford, 2002) [25]. Table 7C2 shows the OPEN system, ISS (A + W) system, and CLOSED system.

Tabular 7C1 Six lunar base life support system element technology candidates

No.	Subsystem	Tech.	Mass Kg	Volume m^3	Power W_e	Cooling W_{th}	Resupply Mass Kg/d	Resupply Parts Mass Kg/yr	Resupply Volume m^3/yr	Crew time CM-h/yr	Ref. No
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	20
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	20
123	Carbon Dioxide Reduction	Sabatier	75.91	0.14	82.94	82.94	-3.59	0.00	0	0	20
125	Oxygen Generation	SPE/ISS	388.97	1.02	3421.67	1868.34	4.04	50.32	0	10.1	20
126	Gaseous Trace Contaminant Control	ISS	68.41	0.14	194.35	194.35	0.00	21.29	0.322	0	20
127	Atmosphere Composition Monitoring Assembly	ISS	54.3	0.09	103.5	103.5	0.00	0.00	0	0	20
128	Sample Delivery	ISS	35.11	0.04	0	0	0.00	0.00	0	0	20
129	System Airlock Carbon Dioxide Removal	ISS	181.3	0.23	397	397	0.00	0.00	0	0	20
180	**Gas Storage**										
181	Nitrogen Storage	High Pressure	1	0.00	0	0	0.02			0	22
182	Nitrogen Storage	Cryogenic	22	0.02	0	0	0.02			0	22
183	Oxygen Storage	High Pressure	118	0.09	0	0	3.59			0	22
184	Oxygen Storage	Cryogenic	139	0.11	0	0	3.59			0	22
190	**Fire Detection and Suppression**										
191	Fire Detection System	ISS	1.5	0	1.48	1.48	0	0.00	0	0.01	20
192	Fire Suppression System	ISS	6.8	0.04	0	0	0	0.00	0	0	20
200	**Biomass Subsystem**										
220	**Plant Growth Chamber / Salad Machine**										
221	Plant Growth Chamber	Drysdale	43004	436	1107923	1107923		1614.22		922	16
222	Salad Machine	Takashima	120	0.602	500	500		2.40		91.25	
223	Plant Growth Machine I	CLOSED 1	11873	1303	442610	176489		732.83		92	WG
224	Plant Growth Chamber unshielded I	CLOSED 1	14661								15
225	Plant Growth Chamber shielded		213038								15
226	Plant Growth Machine II	CLOSED 2	8710	792	392001	125880		437.10		50	WG
227	Plant Growth Chamber unshielded II	CLOSED 2	7913								15
228	Plant Growth Machine III	CLOSED 3	7656	622	375132	109011		338.52		36	WG
229	Plant Growth Chamber unshielded III	CLOSED 3	5664								15
260	**Food Subsystem**										
262	Food Storage without food	Shuttle	0	0	0	0	11.16	0.00	0	0	WG

	production										
263	Refrigerator/Freezer	ISS	321	2	0.204	0.228					22
264	Food Storage with biomass production	Lunar Farm	0	0	0	0	0.41	0.00	0	0	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	20
312	Avionics Air Assembly	ISS	12.4	0.03	175	175	0		0	0	20
313	Atmosphere Circulation	ISS	9.8	0.02	61	61	0		0	0	20
314	Atmosphere Microbial Control	ISS	100	0.27	0	0	0	19.06	0.13	3.33	20
320	**Internal Thermal Control System**										
321	Internal Thermal Control System	-	149.28	0.3	517.71	517.71	0		0	0	20
400	**Waste Subsystem**										
410	**Solid Waste Collection**										
411	Solid Waste Collection	ESDM	36.36	0.13	14	14	0	0.00	0	0	20
420	**Solid Waste Processing System**										
421	Solid Waste Treatment	Storage	78.33	2.18	0	0		0.00	0	0	20
422	Incinerator	ALS	200	1.4	0.3	1.3		10.00		0.2	22
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	22
425	Bioreactor	LCS	148	6	0.1	0.1					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	20
512	Urine/ Waste Water Collection System	ALS	4.55	0.02	4	4	0	1.62	0	0	20
520	**Water Recovery System**										
521	Water Treatment Process	ISS WRS	541.63	1.93	788.76	788.76		1295.75	0	0	20
522	Water Treatment Process	VPCAR	557.56	1.69	4011.45	1808.87		100.96	0	0	20
523	Urine, Hygiene & Potable Water, and Brine Storage	ISS	133.34	0.35	13.68	13.68			0	0	20
524	Urine, Hygiene & Potable Water, and Brine Storage	ALS	205.12	0.53	19.81	19.81			0	0	20
525	Microbial Check Valve	ISS	3.56	0.01	0	0		1.41	0	0	20
526	Microbial Check Valve	ALS	6.67	0.02	0	0		2.65	0	0	20
527	Process Controller	ISS	36.11	0.08	156.18	156.18			0	0	20
528	Process Controller	ALS	63	0	180	180			0	0	20
529	Water Quality Monitoring	ISS	14.07	0.04	4.72	4.72			0	0	20
530	Water Quality Monitoring	ALS	14.07	0.04	4.72	4.72			0	0	20
531	Product Water Delivery System	ISS	37.99	0.09	2.65	2.65			0	0	20
532	Product Water Delivery System	ALS	58.37	0.14	3.83	3.83			0	0	20
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	20
622	Detergent	-	0.01	0	0	0	0.35		0	0	20
630	**Whips**										
631	Hand/Face/Shower Wet Whips	-					0.31				
640	**Miscellaneous Items**										
641	Miscellaneous Items	-					5.06				
642	N_2		35.42								
700	**Extravehicular Activity**										
711	Maximum Absorbency Garments	-	196	0.82			0.05		0.0001	44.8	20
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, O_2, and Water Add	-					0.77		0.0023		

Table 7 C2 OPEN, ISS (A + W), CLOSED system configuration

	Subsystem	OPEN system	ISS (A+W) system	CLOSED system
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, 224(CLOSED 1) 226, 227(CLOSED 2) 228, 229(CLOSED 3)
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 7C1.

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