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New ECLSS Simulation Software and Its Demonstration by Manned Mars Missions

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The role of the Environmental Control and Life Support System (ECLSS) is to create a sustainable environment for humans by utilizing plants and physicochemical systems. For future human space missions, more research and practical experiments are desired. Our team has been developing an ECLSS simulator, called SImulator for Closed Life and Ecology (SICLE), for use as a tool in satisfying a wide range of research in ecology and resource recycling. The most significant feature of this simulator is that it can construct environment models by simple operations, applied to both closed and open systems. We ran three simulations on two situations to investigate the behavior of the simulator and to obtain numerical data. The first two models were derived from our Mars exploration operations research at Mars Desert Research Station (MDRS) in the Utah desert. The MDRS model refers to water consumption in a two-week habitation by 6 crew members of Crew 137, Team NIPPON, in a habitat module of MDRS with open air and water systems. SICLE simulation results for the MDRS model show that water flow corresponds to actual measurement values, as well as indicating complete substance exchanges among factors such as air, water and human activities for a hypothetical closed-system model of MDRS. The other model was Inspiration Mars Mission, a partially closed ECLSS with 2 crew members for 501 days, designed by Team Kanau, winner of International Inspiration Mars Student Design Competition. The designed ECLSS model consisted of recycling systems and supplemental storage which compensated for recycling loss as the mission progressed. In the simulation, the tank size was effectively defined by reading possible maximum substance amounts in each tank, and failure event behavior was investigated. We believe that improving SICLE, as it can be applied to a variety of resource recycling and circulation models, contributes to accelerate research in this field.

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Nomenclature

CEEF	=	Closed Ecology Experiment Facilities
CELSS	=	Controlled Ecological Life Support System
CM	=	Crewmember
ECLSS	=	Environmental Control and Life Support System
ISS	=	International Space Station
L	=	Liter
MDRS	=	Mars Desert Research Station
SICLE	=	SImulator for Closed Life and Ecology

I. Introduction

50 YEARS or more have passed since the first human trip into space, and research and development of Environmental Control and Life Support System (ECLSS) corresponding to various missions have been carried out. Some detailed studies of long duration missions were performed as early as the 1960's and 1970's. Different mission scenarios, such as short term and long term missions, are reflected in the ECLSS design, and the most appropriate ECLSS is different for each mission. At present, human beings at the International Space Station (ISS), can remain in space for a long term with ECLSS recycling water and oxygen[1]. In the future, examination, research, and development of new life support systems will be required in preparation for exploration of the lunar outpost and manned Mars exploration. As for the development of ECLSS corresponding to these missions, the scale expands and becomes complex, and controlling whole resource recycling becomes more important. A short term mission can use a simple ECLSS that does not perform resource recycling, whereas a long term mission, such as the ISS or a manned Mars exploration, needs resource recycling to reduce resupply, storage requirements and cost[2]. ECLSS varies in function and duration demanded by each mission, and realistically examining performance in especially long term missions is not yet possible. In examination of these systems that consider various experiment conditions, analysis by simulation plays an important part. In fact, ECLSS simulation has been performed for various missions such as the ISS and Closed Ecology Experiment Facilities (CEEF) in Aomori, Japan[3]. In addition, those simulators are required operability with an interface that user can set easily and expandability that can support various missions and existing devices, with expanded and complex scale in development of ECLSS.

For supporting these investigations, we are developing new simulation software called SImulator for Closed Life and Ecology (SICLE), which simulates resource recycling and control of the ECLSS. At present, SICLE has operability and expandability, and it is able to help study of closed ecosystem. In addition, we have been improving SICLE to fit for other fields such as logistics.

In this paper, three simulations conducted by SICLE are described as test simulations to confirm the accuracy of simulation calculation and the utility for various missions.

II. Overview and Features of the Simulator, SICLE

Resource recycling in the ECLSS is to recycle substances that are needed for human activity and emission matters by utilizing plants and physicochemical devices. Water, oxygen, carbon dioxide and nitrogen are the main component substances.

Though some simulators that can simulate resource recycling have been released in the past, we have been developing a simulator with the three following features to accommodate research and development of more diversification and complex life support system. First, it is important to use a design concept that is based on scientific results. SICLE is a simulator designed based on the scientific results that have supported research of advanced life support system in a real ECLSS research facility, CEEF. Second, it is important to have an interface that attached importance to direct operability. In a life support system that a large variety of resources and devices cooperate complicatedly, it is important to cognize the detail setting of each device from grasp of system perspective visually and easily. Therefore, SICLE enables a selection operation of the device by icons and making of block diagrams for a designer can design systems easily. In addition, we can grasp and trace the process of simulation visually and change the status such as a device stop and trouble even though SICLE is running. Finally, it is important to be a software structure including expandability. In order to enable inserting various devices in simulation, SICLE provides a function to easily model various resource recycling systems such as producing and implementing user defined new device and human beings-plant model. Furthermore, SICLE adopts a class structure and algorithm including expandability for applicable to other field.

SICLE is a simulator for research and development of resource recycling control system, which can consistently carry out system design, simulation practice and data analysis. It can confirm and grasp a state of simulation anytime. We can easily set up system and change parameters, and can execute and analyze the simulation of various patterns. Figure 1 shows the position of simulator functions that SICLE aims at into a classification by the field of use and tasks, compared with other existing simulators at the time of the development of SICLE[4]. Existing simulators have characteristic function respectively such as ECLSS, closed ecological life support system (CELSS), instinctive interface, database based on scientific result, flexible scheduling and so on. SICLE has those functions comprehensively. Our ultimate goal is to make SICLE that interacts with hardware to realize Hardware-in-the-Loop simulation. Therefore, SICLE coverage in Figure 1 extends to "Operation." SICLE is a simulator that is specialized in system design of not only life support systems but also chemical plants and logistics, and will be more versatile simulator compared with existing simulators. In future, we will release the SICLE on the internet after the simulator is completed for research and educational uses.

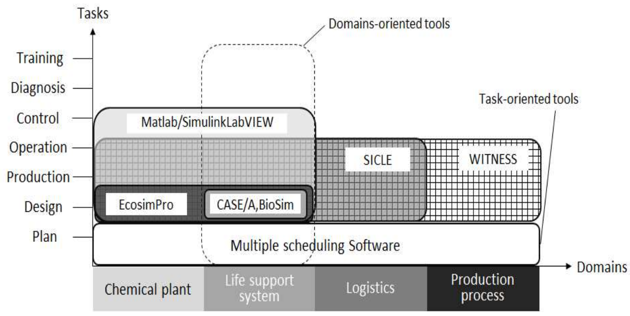


Figure 1. Comparison Diagram for Various Simulators.

III. Methodology

The items categorized in SICLE are tank, device, and pipe. Tank can store substances and device is a tank or a composite tank that processing function is added. The concrete examples of the processing function are substance conversion and valve control operation. These processing functions are defined as an "executer" in SICLE. The conversion executer in water recycling system, for instance, converts gray water into pure water. This executer works by defining substance and amount to be increased and decreased. Valve executer can control input and output of substances in a device by setting upper/lower limits. Once some substance reaches the lower limit, the valve executer runs to stop outflow. On the other hand, the substance reaches the upper limit, it stops the inflow. Pipe connects items such as tank-tank and tank-device. Pipe judges to flow substance or not by confirming available amount of connected tanks/devices. If receiver reaches the capacity, pipe would not send substance that overflows the receiver's capacity. Similarly, if sender does not have enough amount of substance to flow, pipe controls not to flow so that sender's substance amount does not become negative. The parameters of above items described can be defined by a template xml file, which allows adding new devices and tanks easily. In addition, it is able for user himself to add new device having different type of function by coding executer in JAVA.

The basic concept of this simulator is to flow a substance from one side (tank or device) to other side by connecting a pipe. Since SICLE envelopes functions for system design through simulation execution to analysis of the results, a user can easily follow the status of the simulation in progress.

At first, a user creates a system in Design View Window (Figure 2) by dropping items from the equipment and tank list. Each item is connected to another item with lines which represent pipes between device and tanks. In this phase, property window appears on the right by selecting a tank or a device in the design field, and user can set parameters such as substance to flow, initial value, and maximum capacity. For pipes, flow rate can be set in the property window. SICLE is able to group some items to treat them as a subsystem so that a complicated system consisting of many items can be simplified. With these parameters and executers, SICLE works and simulates substance flow.

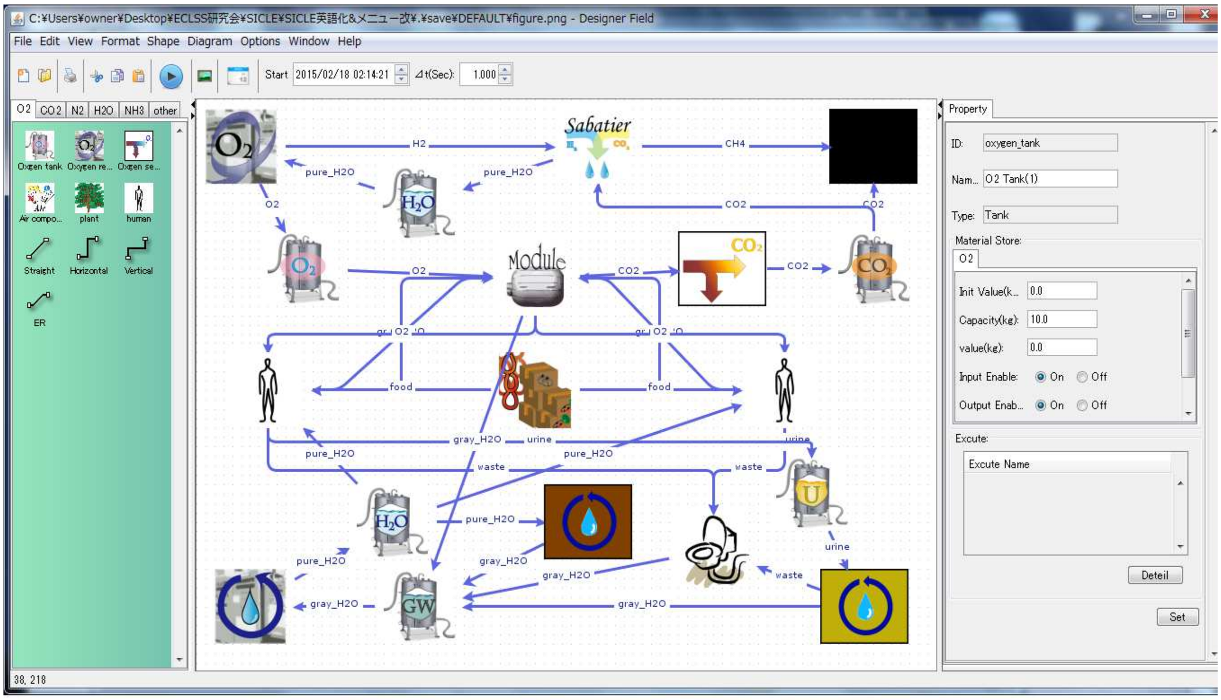
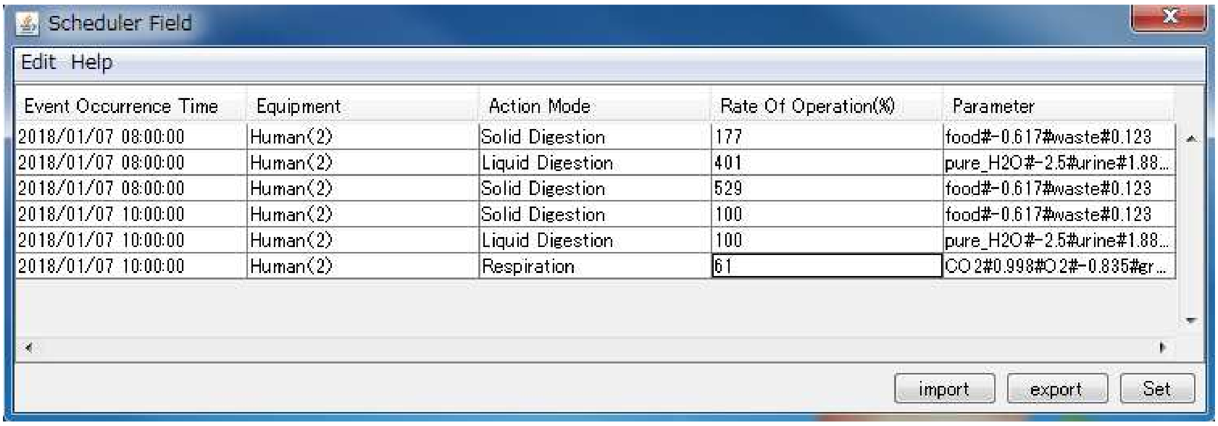


Figure 2. SICLE Design View Window.



Event Occurrence Time	Equipment	Action Mode	Rate Of Operation(%)	Parameter
2018/01/07 08:00:00	Human(2)	Solid Digestion	177	food#-0.617#waste#0.123
2018/01/07 08:00:00	Human(2)	Liquid Digestion	401	pure_H2O#-2.5#urine#1.88...
2018/01/07 08:00:00	Human(2)	Solid Digestion	529	food#-0.617#waste#0.123
2018/01/07 10:00:00	Human(2)	Solid Digestion	100	food#-0.617#waste#0.123
2018/01/07 10:00:00	Human(2)	Liquid Digestion	100	pure_H2O#-2.5#urine#1.88...
2018/01/07 10:00:00	Human(2)	Respiration	61	CO2#0.998#O2#-0.835#gr...

Figure 3. Schedule Setting Window.

The substance flow in a simulation can be controlled also by scheduling function. Figure 3 is the schedule setting window. Each device's executer can be manipulated its operation rate at particular time. SICLE pulls out the event defined in the scheduler at the fixed time and changes the device's operation mode and rate. To create a schedule, a user inputs the event occurrence date and time in the first column of the schedule setting window, and then, chooses the target device from the second column by pull-down. The third column shows the available operation modes of the device chosen in the second column so that user chooses one and finally input operation rate in the fourth column. The last column shows the executer's parameter defined in the xml template file.

Moreover, the user can export the created schedule into a file with "Export" button, and also can import a prepared schedule file with "Import" button.

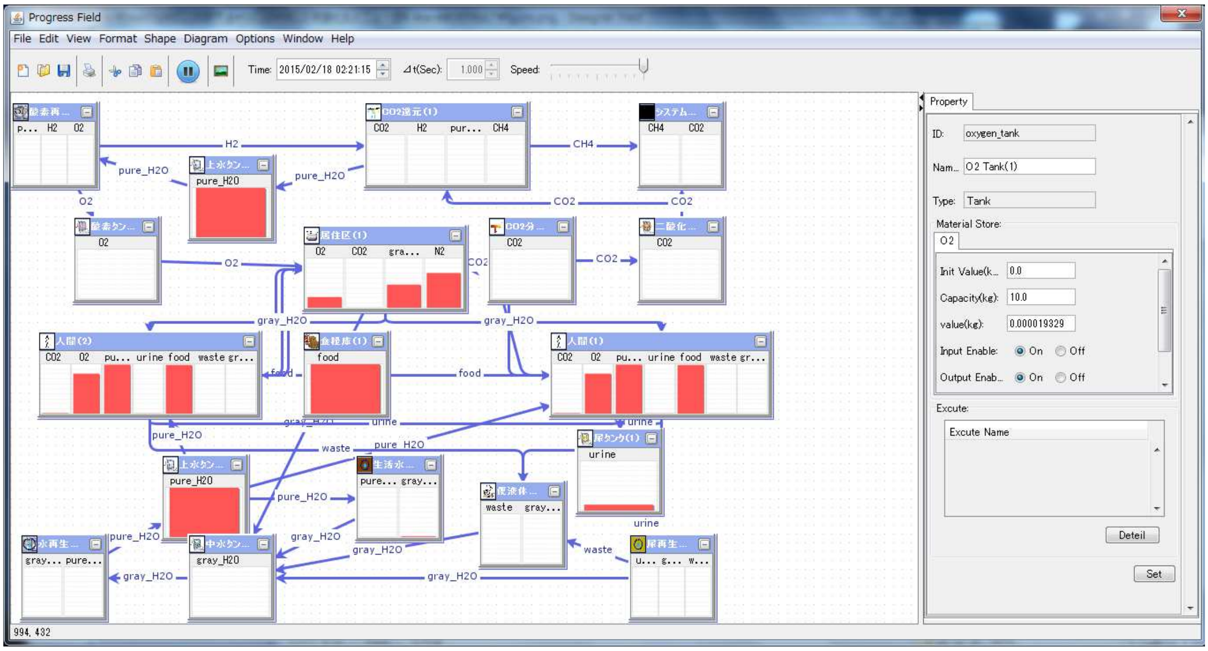


Figure 4. SICLE Progress View Window.

Once designing a system finishes, the simulation can be started immediately after systematical validation for connections and parameter setting. During the execution of a simulation, Progress View Window (Figure 4) appears showing the status and amount of substances for each item of equipment and each tank in real time. By defining some conditions, the simulation aborts when it meets the condition.

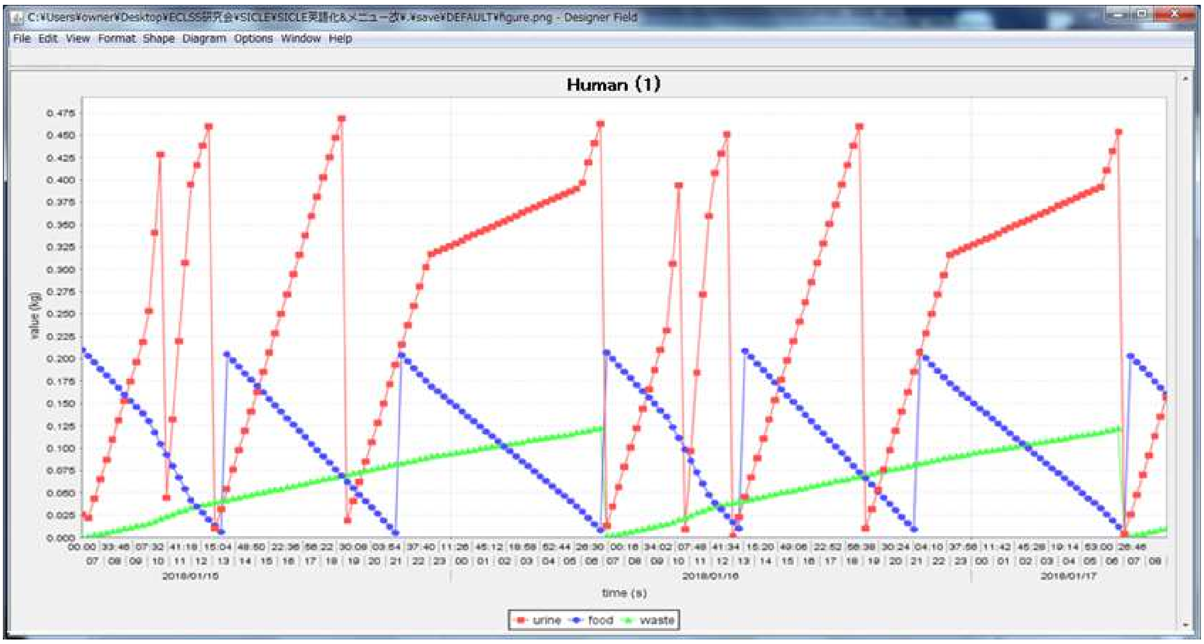


Figure 5. SICLE Report View Window.

Report View Window (Figure 5) displays a customized graph of each device/tank during a simulation in progress and after it completes by reading output log files, and some tools will be available for basic analysis. The simulation accuracy depends on the simulation time step which is a variable by the millisecond (default is 1,000 milliseconds), and output data interval is also a variable from seconds to minutes.

IV. Demonstration #1: MDRS Crew 137

The Mars Desert Research Station (MDRS), which is owned and operated by the Mars Society, is a simulated Mars Analogue Research Station in the Utah desert. Team NIPPON consisted of six researchers from Japan who conducted a mission at the MDRS as Crew 137 from March 1 to March 15, 2014, aiming to collect valuable data for further development of SICLE simulations. The crew handled a strong request for conserving water during the MDRS mission through carefully planned cooking and dish washing and reducing showers and toilet flushing. Meanwhile, the measurement of the amount of water supply and drainage was one of the significant research items on this mission, which consequently provided invaluable data of water consumption required for living with a restricted water supply for two weeks.

A. Model and Conditions

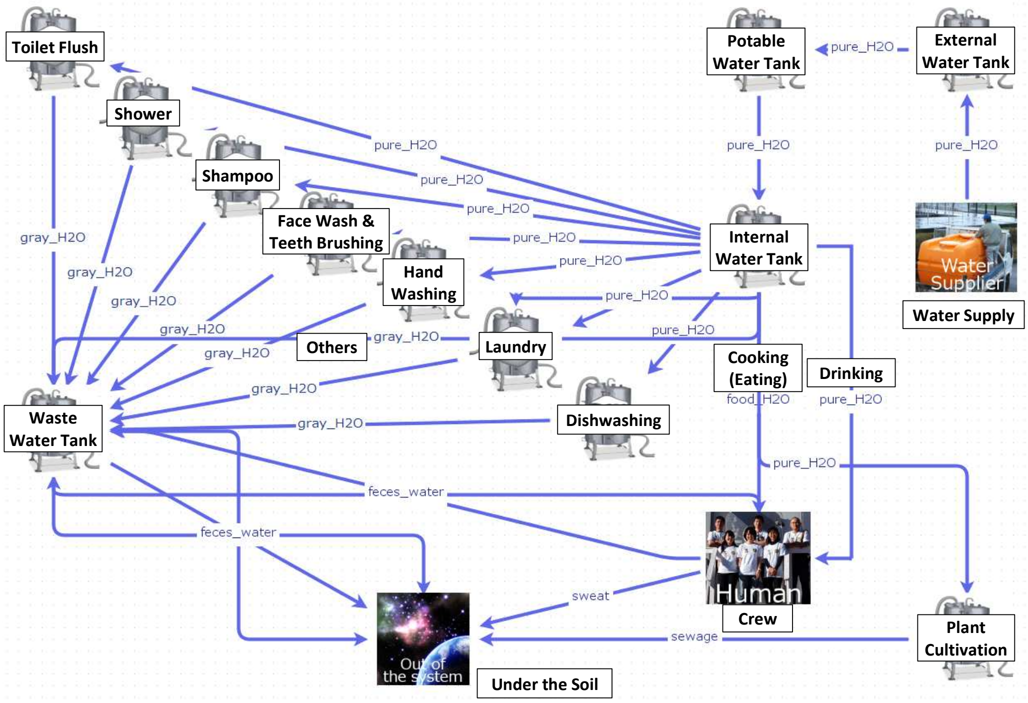


Figure 6. MDRS Water Consumption Model.

In MDRS, food and water are strictly restricted for a practical simulation of manned Mars exploration whereas the air is unlimited. By taking advantage of the situation of MDRS, the first model shown in Figure 6 is constructed on the basis of the actual water situation from the Crew 137 MDRS mission. The water settings applied to the model are defined by water supply as the beginning and sewage at the end as well as use such as toilet flushing, showering, shampooing, face wash and teeth brushing, hand washing, laundry, cooking, drinking, dishwashing, and plant cultivation. This model enables simulating the behavior of water consumption for each element based on the actual values of both the amount of water consumption and the frequency of water application. The purpose of the simulation of the model is a validation of SICLE modeling through a comparison between the actual values and simulation values of water consumption.

The conditions of the simulation performed with this model are the following:

- The amount of water consumption is based on the actual value data from Crew 137 MDRS mission report[5] shown in Table 1 and, the frequency of water application is based on the data shown in Table 2.
- The mission is conducted by six crew members.

- Chemical reactions of digestion and respiration are based on metabolic rates[3, 6].
- The simulation period is fourteen days.

Table 1. The Amount of Water Consumption at MDRS (For 13days)

Water Consumption	Quantities (L/mission)	Rate	Quantities (L/person-day)
Toilet Flush	2137	48%	27.4
Shower	422	10%	5.4
Shampoo	136	3%	1.8
Face Wash and Teeth Brushing	266	6%	3.4
Hand Washing	297	7%	3.8
Laundry	76	2%	1.0
Cooking	197	4%	2.5
Drinking	148	3%	1.9
Dishwashing	30	1%	0.4
Plant Cultivation	49	1%	0.6
Others	673	15%	8.6
Total	4431	100%	56.8

Table 2. The Frequency of Water Application at MDRS

Water Application	Frequency (times/6persons-day)
Water Supply	1
Toilet Flush	24
Shower	1
Shampoo	1
Face Wash and Teeth Brushing	3
Hand Washing	3
Laundry	0.23
Cooking(Eating)	3
Drinking	3
Dishwashing	3
Plant Cultivation	3
Drainage	Anytime

B. Results

The results of the fourteen-day simulation are shown in Figure 7 to 10.

Figure 7 shows drinking water tank remaining amounts. Internal water tank is refilled once a day through a water supply chain of three water tanks, which is consisted of external water tank, potable water tank, and internal water tank, with a water supplier delivery.

Figure 8 shows remaining water amounts in human body. First, human ingests water into its body by drinking and eating. Second, the body water is gradually converted to urine and feces. Finally, the water is excreted as urine and feces by the time of full tank of urine and feces tanks of human body. The graph

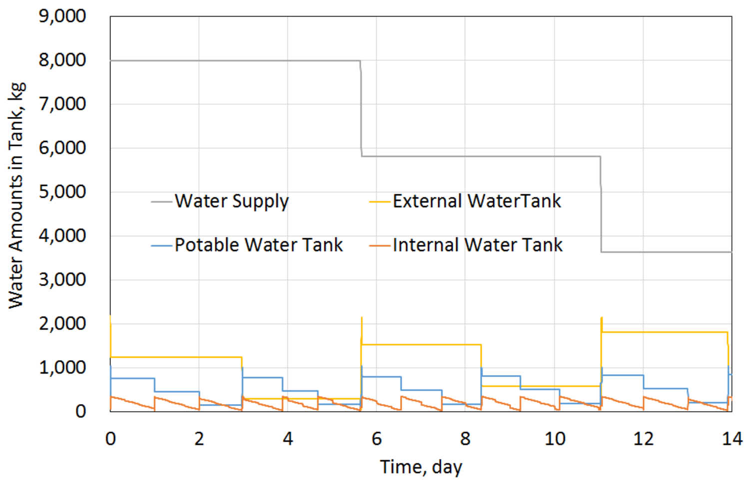


Figure 7. Drinking Water Tank Remaining Amounts.

illustrates continuous cycles of this inside process of human body.

Figure 9 shows remaining water amounts of hypothetical waste water tanks that are constructed into the model in order to control consuming water amount of each water application. The successive triangle shapes of the graph demonstrates a repetition of a short term input of consumed water and a longer term evacuation of waste water into the soil through waste water tank.

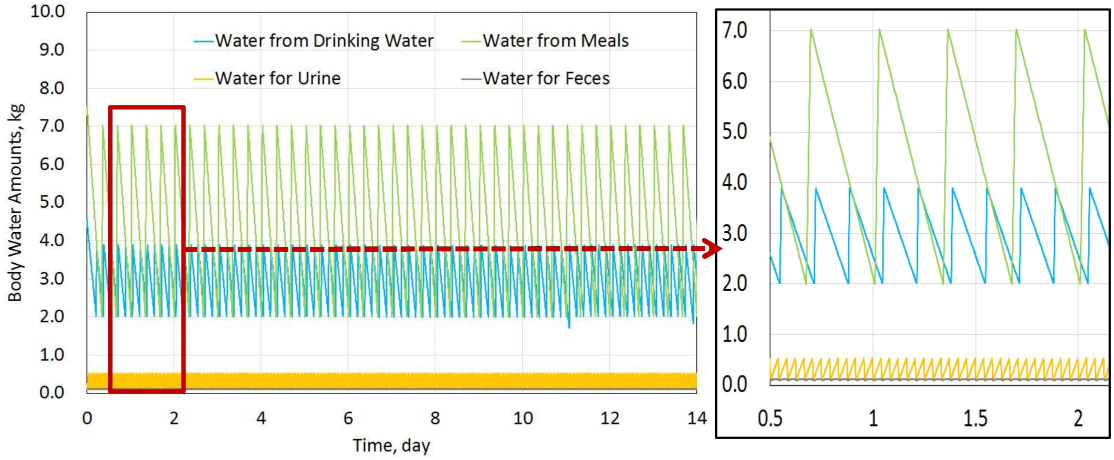


Figure 8. Body Water Tank Remaining Amounts.

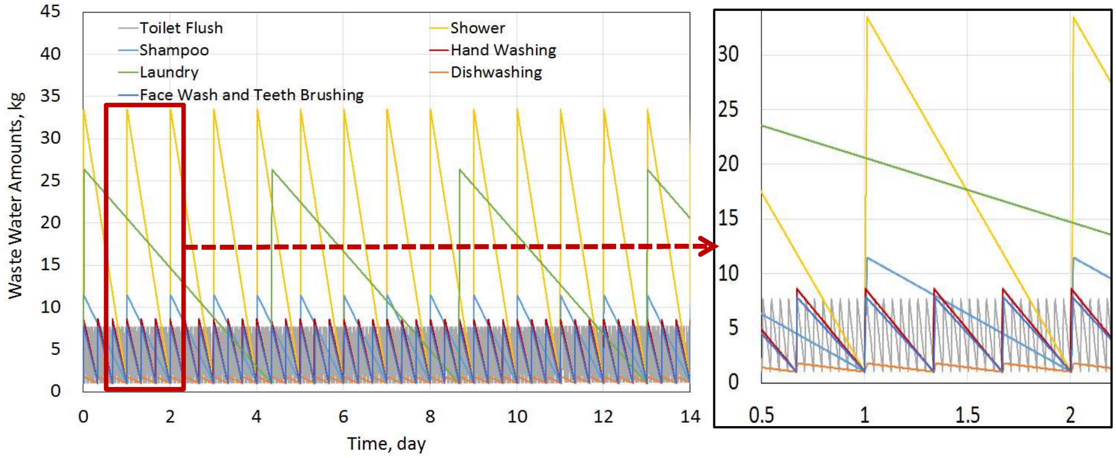


Figure 9. Hypothetical Waste Water Tank Remaining Amounts.

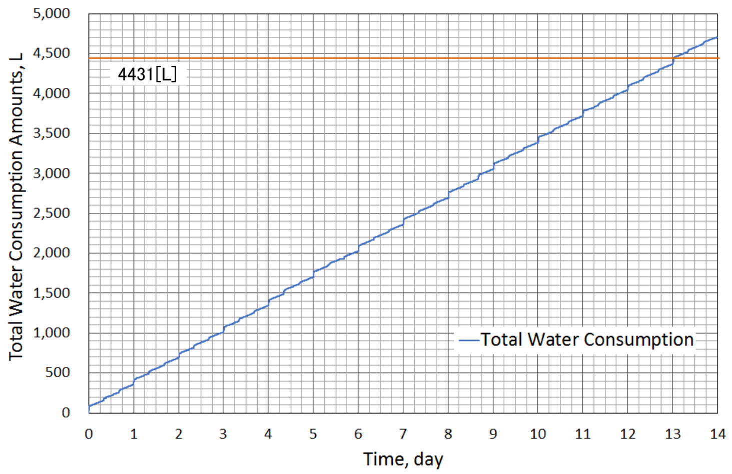


Figure 10. Total Water Consumption Amounts.

The amounts of water consumption of all the elements constantly change with steady fluctuations supported by a periodical water supply. Figure 10 shows the accumulation of all the water consumption at each moment. The total amount of water consumption right after the thirteenth day, which is 4437.5[L] at 190 seconds after the end of the thirteenth day, reaches the actual total amount of water consumption, 4431[L], at the end of the thirteenth day of the real MDRS mission. The simulation result indicates the validation of the model of water consumption created by SICLE.

V. Demonstration #2: MDRS Crew 137 in Closed Loop

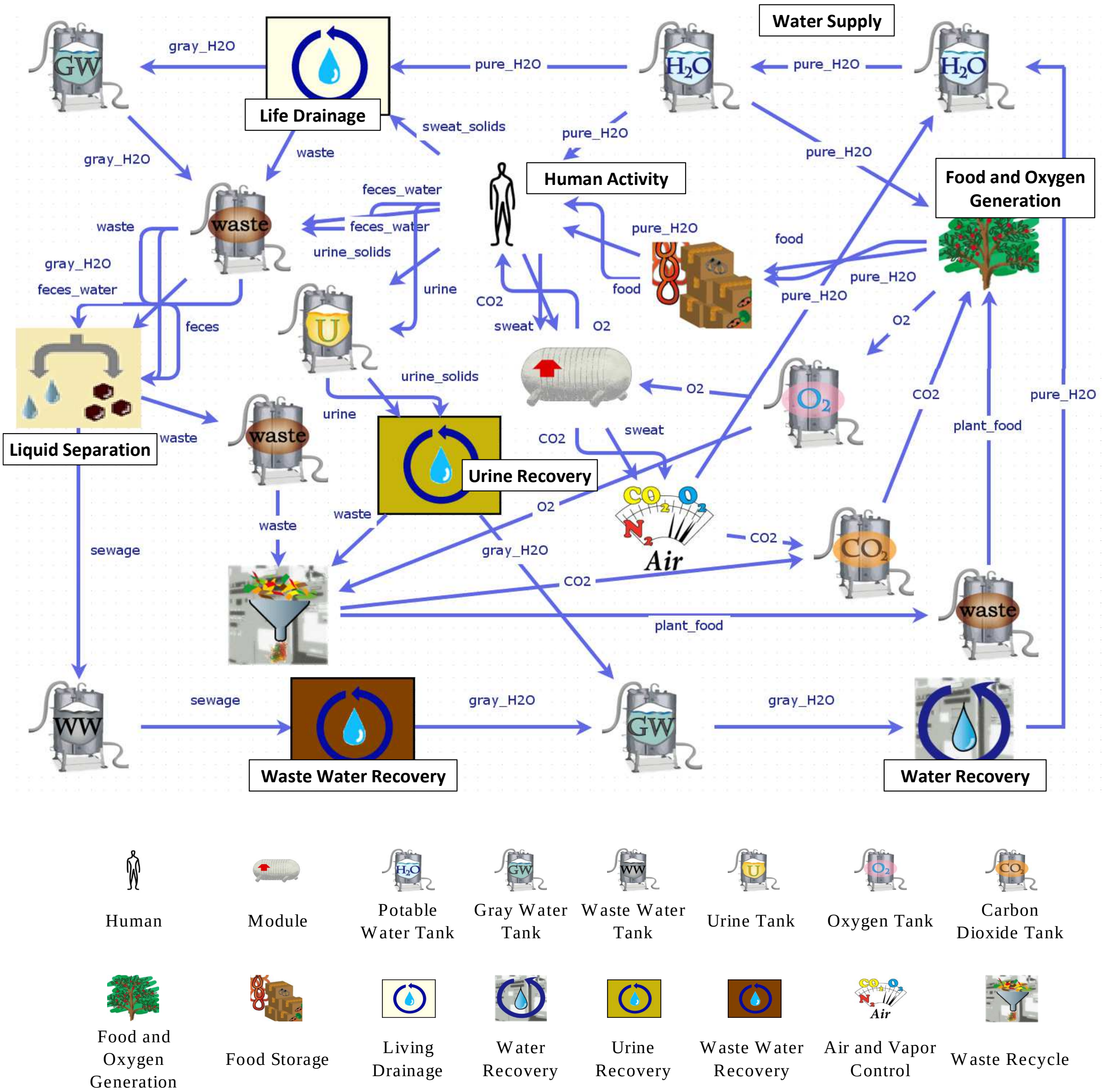


Figure 11. MDRS Closed-Loop Model.

A. Models and Conditions

The second model shown in Figure 11 is a virtual closed-loop model based on the water consumption of the first model, introducing human activities as respiration and digestion by defining input and output of substances such as food, water, waste, and respiratory air, as well as a virtual scheme of resource recycling to recover oxygen, pure water, and food through hypothetical devices and systems. Three simulation patterns are executed on the second model, including a nominal pattern, in which constant rates of input and output of substances for chemical reactions at all elements of the model occur throughout the entire simulation period, and two event-driven patterns, in which scheduled events with distinctive rates of input and output of substances on each element of the model enables to cause a failure of resource recycling cycle. The focal point of the simulations is to make a practical comparison among a simple constant rate model, a failed cycle model with an event, and a succeeded cycle model with multiple events by analyzing the dynamics of the substance amount changes.

1. Pattern 1

Constant rates of input and output of substances for productive processing by chemical reactions including respiration and digestion constantly occur on all the elements of the model. The productive processing indicates distributing substances from storage tank to processing equipment, respiration and digestion in the human body, and recovery of substances, considering substances as oxygen, carbon dioxide, pure water, gray water, urine, waste, and food. The simulation is expected to have a result so that even amounts of substances are constantly produced and transferred to the next for each element in the closed-loop system. Pattern 1 is a base model for comparison with Pattern 2 and Pattern 3, as well as for confirming if the closed-loop system works properly.

2. Pattern 2

A periodical event is added to one of the elements of the Pattern 1, which is expected to have a failure of resource recycling cycle. Water supply from potable water tank to human activity, life drainage, and food and oxygen generation is terminated once a day for 5 minutes for a refill of potable water. Initial amount of each substance in tank is quite small so that the effect of a shortage of substance is immediately found in simulation.

3. Pattern 3

More periodical events are added to the human activities in Pattern 2 with well-controlled amounts of substances, which is expected to create a success model of resource recycling cycle with multiple events. Human activities include three times inputs for eating and drinking, and six times outputs for urine and feces in a day. Initial amounts of all substances in tanks are maintained so that the tanks are able to regain their appropriate amount of remaining substance before causing a shortage of substances in other tanks.

Conditions are the same as demonstration#1.

B. Results

As the result of Pattern 1 shown in Figure 12, even amounts of circulation of substances in the closed-loop system by recovering with virtual recycling equipment is kept throughout the entire period. This expected result proves that SICLE is useful for a simple simulation with constant rates for productive processing in a closed-loop system.

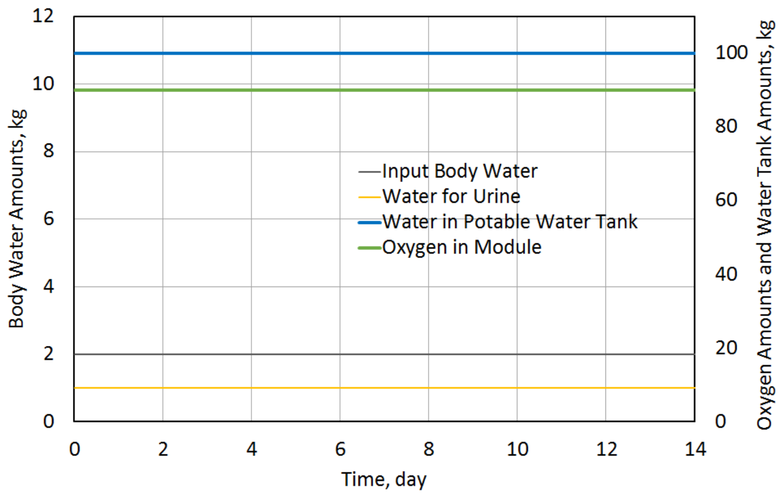


Figure 12. The Result of Pattern 1.

As the result of Pattern 2 shown in Figure 13, the stable circulation in the closed-loop environment of Pattern 1 is failed so that the amounts of some substances as oxygen are gradually decreased. This is because a periodical cease of water supply causes an accumulated shortage of productions, which is transferred to all the related elements. In fact, a short duration of periodical cease of water supply forces all the next elements of the potable water tank, which is human activity, life drainage, and food and oxygen generation, to consume remaining water of each element. Accumulated shortages of water make a tank to be empty at some point, the water tank of the food and oxygen generation in this case, resulting in a shortage of producing a substance, oxygen. As shown in Figure 14, water in the food and oxygen generation begins to decrease during the cease of water supply at the end of the first day, which causes to empty the water tank and to stop producing oxygen by the end of the third day. Since the remaining oxygen of the food and oxygen generation is emptied by the end of the fourth day, oxygen in module starts to decrease. This result shows that the value of SICLE modeling for incidental events of simulations such as equipment trouble, as well as it indicates that a SICLE simulation is applicable to estimate a required amount of substances for planning a manned space exploration.

The result of Pattern 3, which is shown in Figure 15, indicates that a stable circulation is regained from Pattern 2 by simulating the controls of equipment and human activities with more appropriate settings. The amount of substances such as input body water from meals and drinking water, body water for urine, and water in potable water tank, keeps the constant oscillation as the scheduled events throughout the entire period while the amount of oxygen keeps even amounts.

Since the simulation of Pattern 1, 2, and 3 indicates that SICLE is applicable to various situations as an ECLSS simulation tool for both constant rate operation and periodical events application in a wide range of event-driven cases, more complicated scenarios with random incidental irregular events are required to have pracitce on SICLE for the development of diverse situation.

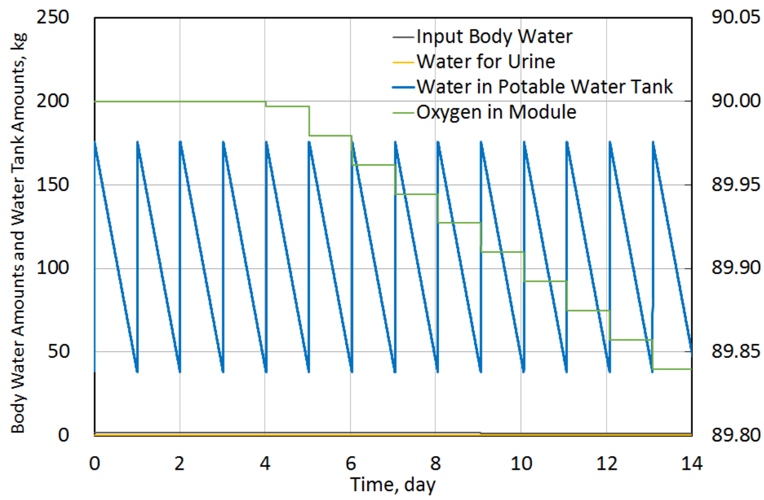


Figure 13. The Result of Pattern 2.

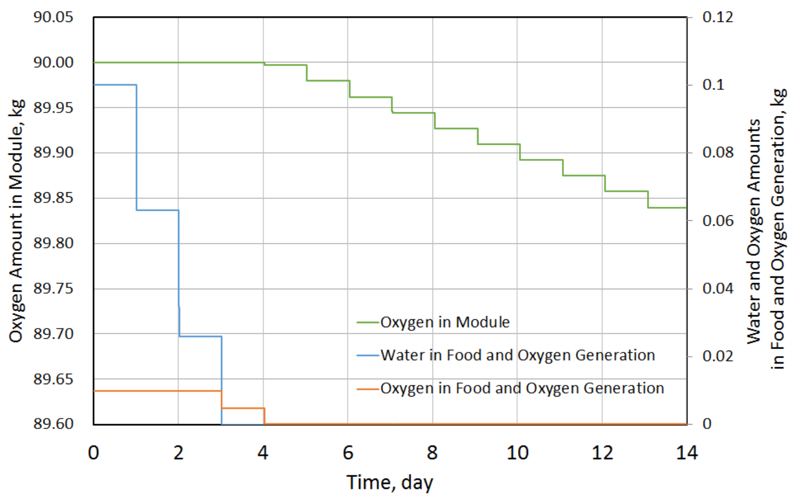


Figure 14. Production of Food and Oxygen Generation of Pattern 2.

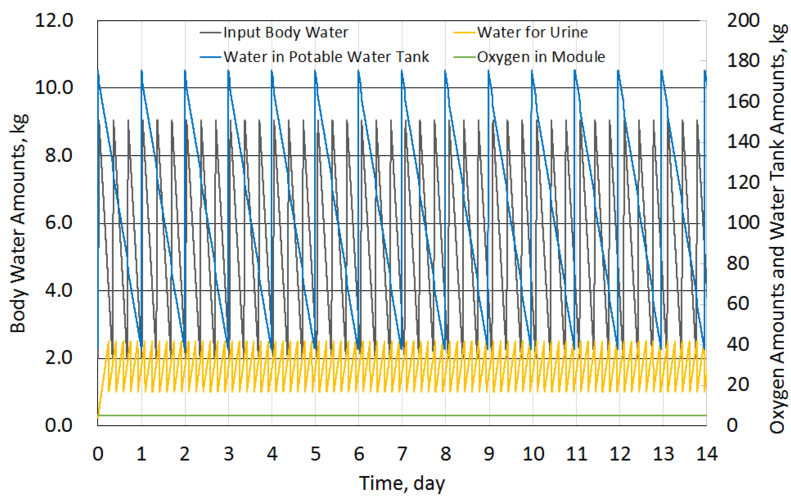


Figure 15. The Result of Pattern 3.

VI. Demonstration #3: Team Kanau's Inspiration Mars Mission Design

In the summer of 2014, The Mars Society held an international student design competition, Inspiration Mars Student Design Contest. Inspiration Mars is a manned spaceflight mission to Mars driven by Inspiration Mars Foundation[7]. The main concept described in its architecture study report[8] and feasibility analysis paper[9] is sending two Americans, one male and one female, into free-return orbit to Mars in 2018 so that the journey takes only 501 days owning to the special orbital positioning between Earth and Mars. Team Kanau is one of the student competition entry groups that consisted of students and young professionals from Japan and U.S. Team Kanau's mission design was selected as a finalist and won the first prize in the final presentation. Since ECLSS analysis is the key factor of this long duration mission design, we collaborated with Team Kanau to determine an optimal system design, especially to decide the size of recycling tanks.

A. Model and Parameters

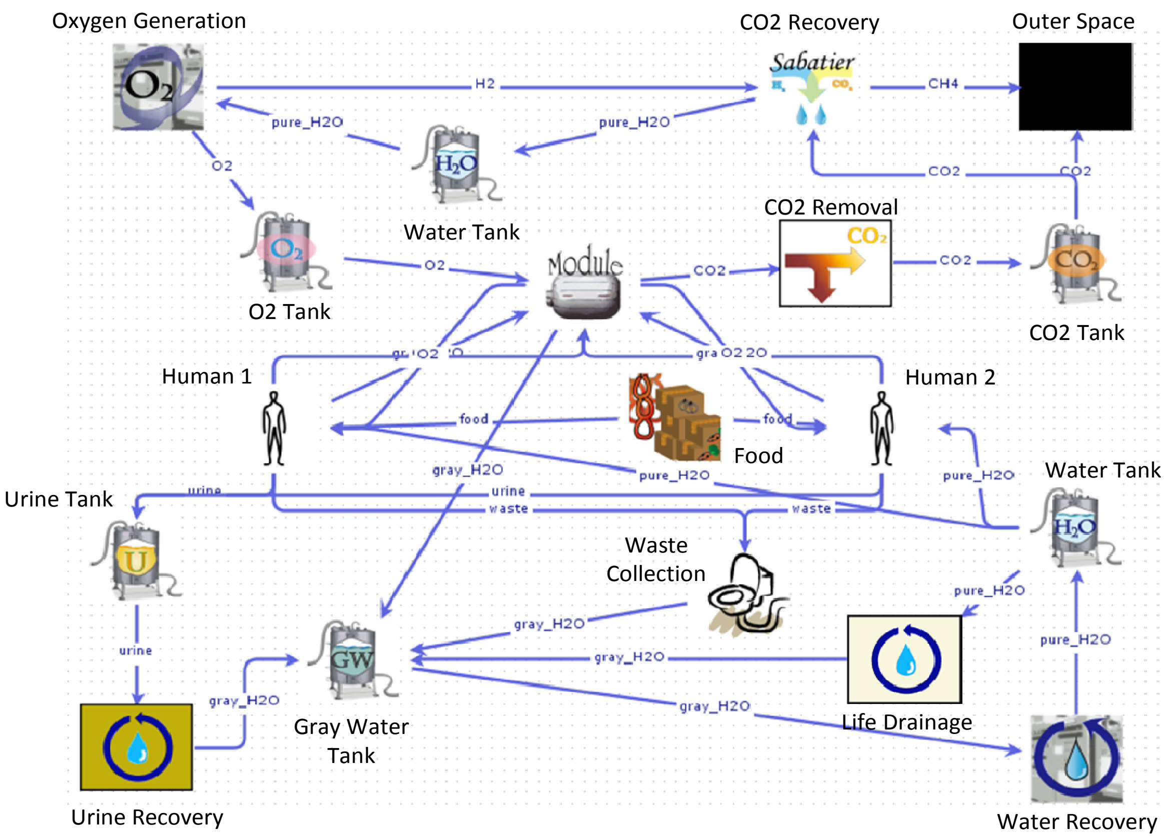


Figure 16. Team Kanau's ECLSS Model.

The ECLSS model designed by Team Kanau[10] is mainly based on existing life support systems currently running at the ISS for oxygen generation, carbon dioxide removal and reduction, and water recycling[1, 11]. As at the ISS, methane generated from Sabatier reactions and partial carbon dioxide are exhausted to outer space. Food and water that are expected to be required for the entire mission are brought as storage, which means Team Kanau's ECLSS model is a partially open loop system. The efficiency of urine recycling is assumed as 85% and that of water recycling from gray water is as 100%[1]. In Team Kanau's ECLSS model, this mechanical equipment is all triply redundant, and the reliability of entire system is also assured by additional stored supplies that can sustain crews life for at least 143 days in case of complete loss of the recycling system, but these backup systems are not included in this simulation because it is out of scope for this time. The entire spacecraft including habitat module has 72 m^3 of free space and the atmosphere pressure is 1 atm with the same composition as air (about 21% of oxygen and 78% of nitrogen). Figure 16 shows the model built by SICLE.

Using the scheduling function that allows users to set time dependent events, Team Kanau's mission design includes the crew's daily schedule, which is two-hour of exercise everyday to maintain their health. In the simulation, one crew performs exercise from 8am to 10am, and the other crew follows after that using the scheduling function. During the exercise, we suppose that respiration increases ten times as compared to normal breathing, and digestion also increases. See Table 3 for the scheduling and rate change of each activity in a day. This simulation starts at 7:00am on January 7, 2018. Simulation was carried out for the first 80 days of the mission duration to evaluate the stability of simulator and the build-in scheduling function. Parameters used in the simulation are from NASA technical documents[12,13] . See Appendix A for the detailed simulation parameter settings.

As an additional attempt, a failure of the oxygen generation system is inserted in the schedule on day 19 of the simulation day, January 26 at 13:34:27, to investigate the behavior during an unusual event.

Table 3 . Inspiration Mars Daily Schedule

Time	System	Executer	Operation Rate, %
08:00	Human2	Solid Digestion	177
08:00	Human2	Liquid Digestion	401
08:00	Human2	Respiration	529
10:00	Human2	Solid Digestion	100
10:00	Human2	Liquid Digestion	100
10:00	Human2	Respiration	61
10:00	Human1	Solid Digestion	177
10:00	Human1	Liquid Digestion	401
10:00	Human1	Respiration	529
12:00	Human1	Solid Digestion	100
12:00	Human1	Liquid Digestion	100
12:00	Human1	Respiration	61
23:00	Human1	Solid Digestion	78
23:00	Human2	Solid Digestion	78
23:00	Human1	Liquid Digestion	14
23:00	Human2	Liquid Digestion	14

B. Results

Figure 17 to 20 show the results of amount changes in urine, gray water, oxygen, and carbon dioxide tanks until day 30 with close-up views for the middle 3 days. These graphs indicate that the schedule of daily exercise and reduced activity level during asleep properly reflects the calculation process. In addition, the amounts in tanks repeat very stable increase and decrease throughout the 30-day simulation.

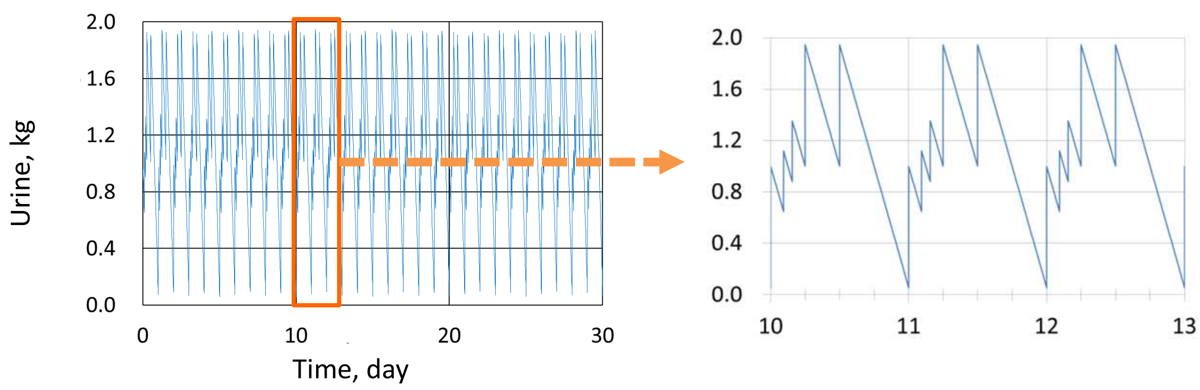


Figure 17. Amount in Urine Tank for 30 days.

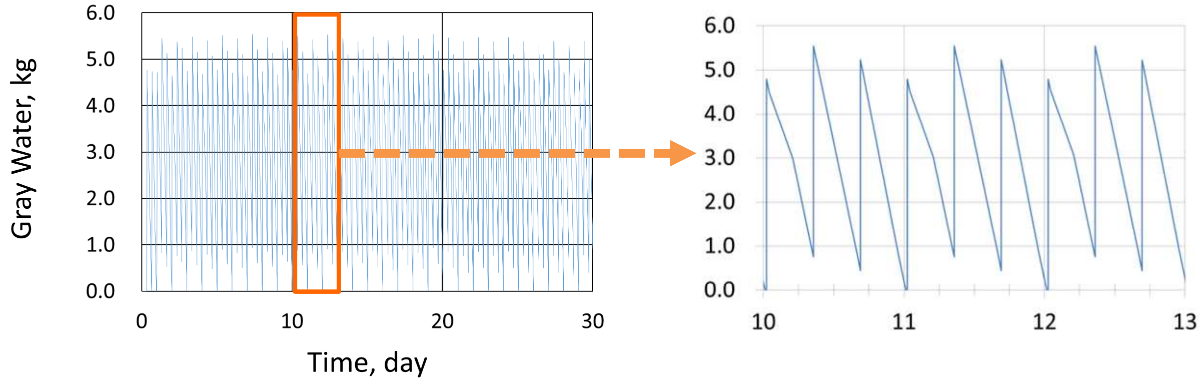


Figure 18. Amount in Gray Water Tank for 30 days.

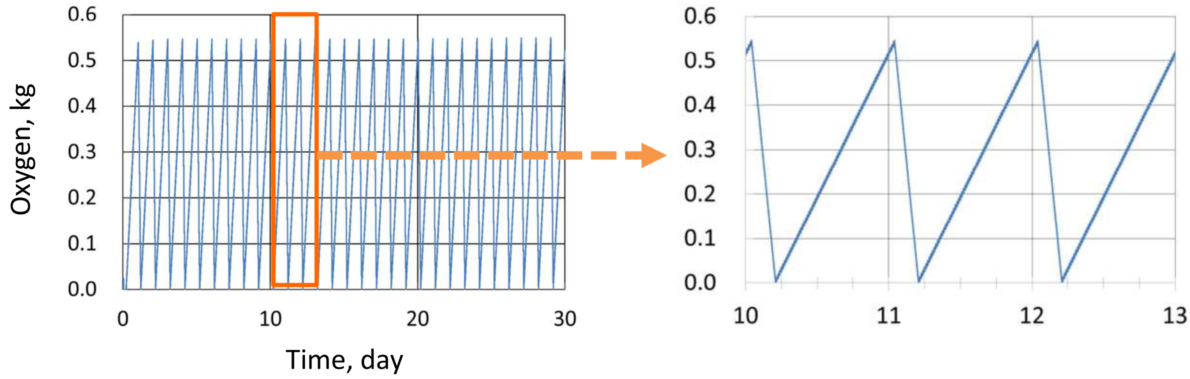


Figure 19. Amount in Oxygen Tank for 30 days.

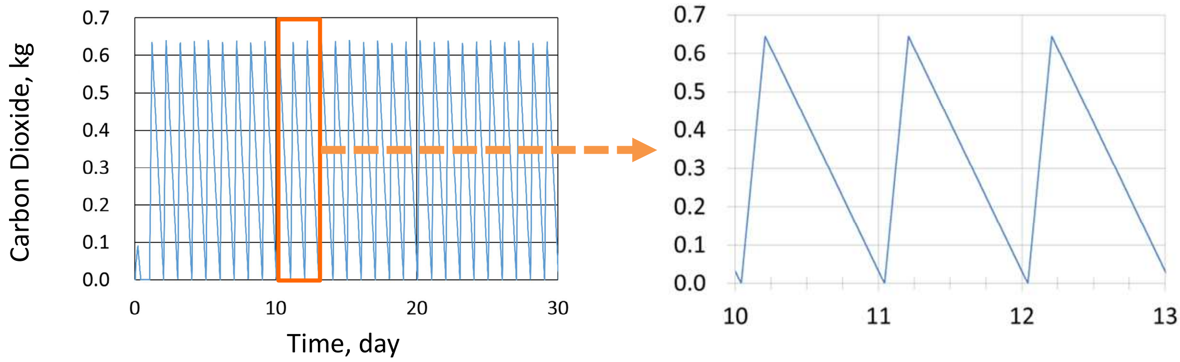


Figure 20. Amount in Carbon Dioxide Tank for 30 days.

The maximum amount of each tank is shown in Table 4 (Since the oxygen tank includes surplus for emergency as well, the pure maximum amount of the oxygen tank connected to oxygen generator must be subtracted by 238.81 kg from the total amount.). The expectation is that this stability continues another 471 days unless nominal operation fails. Considering irregular fluctuations due to the temporary system failure, the size defined by this simulation is reasonable for two person habitation compared with ISS ECLSS.

Table 4. The Maximum Amount of Storage Tanks

Tank	Maximum (kg)
Urine Tank	1.95
Gray Water Tank	5.55
Oxygen Tank	0.54
Carbon Dioxide Tank	0.64

The effect of the failure on the oxygen generator is shown in Figure 21. Since the simulation does not include oxygen storage for system failure, the spacecraft runs out of oxygen in 13 days. However, human cannot keep his health under 16% concentration of oxygen, 3 days is the limit of life sustainability. Note that human 1 and human 2 still perform daily exercise during the oxygen generation system failure. If they cease the exercise, they would survive little longer.

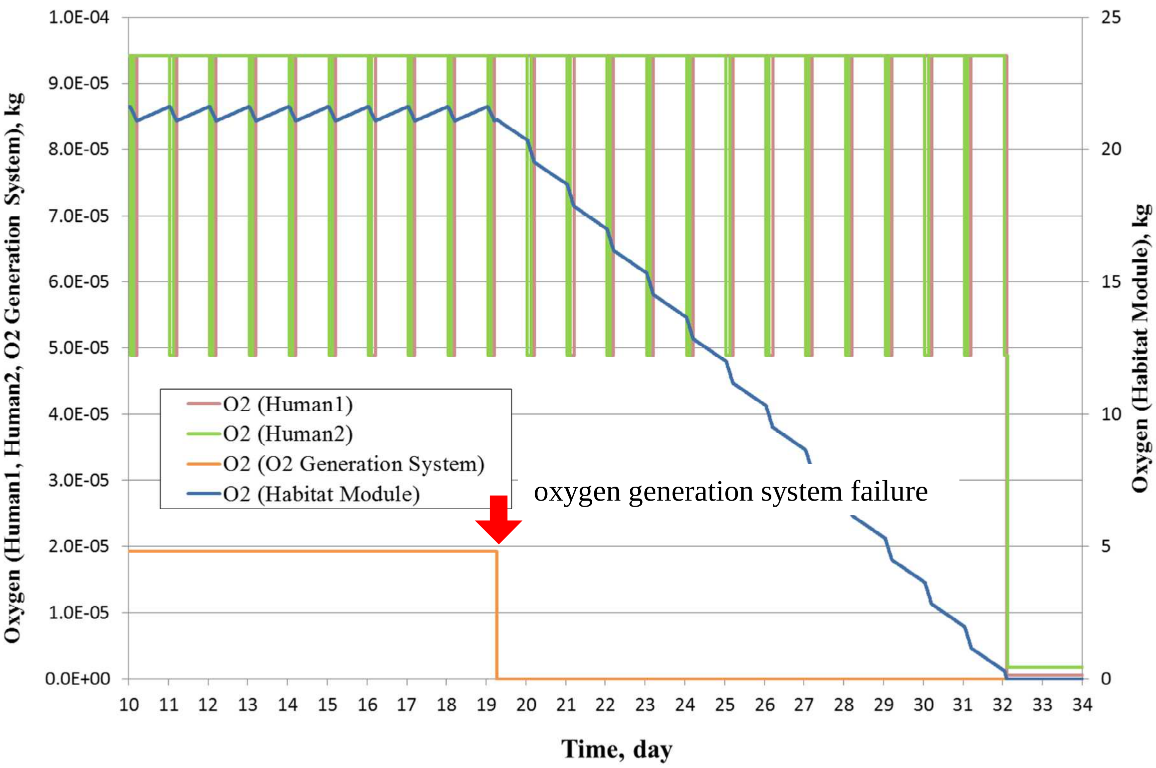


Figure 21. Influence of Oxygen Generation System Failure.

Since SICLE still cannot recognize nominal flow stop and off-nominal one, it must have some kind of switching function between an ordinary tank and a backup tank so that contingency situations with storage system can be also evaluated.

VII. Conclusion and Discussion

The results from the MDRS simulations confirmed that SICLE works numerically accurate flow in a system. Furthermore, by building a closed-loop model based on MDRS research data, the simulation showed complicated behavior, not just constant flow, of the system caused by a small fluctuation, generated at a single point, which communicates continuously to the entire system. As shown in pattern2, the oxygen level decreased due to the water supply termination once a day, but in reality, almost all elements such as human activity and equipment process do not go on at constant rates such that human drinks water once a few hours and eat only three times a day. Therefore, as pattern 3 indicates, a whole system should be balanced out so as not to collapse and simulation is useful to investigate how each element's performance influences each other.

Demonstration #3 became verification and a positive example of its utilization as an ECLSS simulation tool. The simulation results allowed us to estimate the necessary volume of tanks for the mission that leads to applying this tool not only to ECLSS design, but also to other design sectors, for example, habitable spacecraft. One of the important merits for using a simulator for ECLSS design is to analyze malfunction events such as machine failure. Using SICLE's scheduling function, various events including these malfunctions can be implemented. For future SICLE improvement, the goal is to randomly input unpredictable events randomly and to analyze system reliability.

By conducting these demonstrations for Mars missions, we confirmed that SICLE is useful for both an evaluation tool of ECLSS/CELSS and ECLSS design tool of long duration manned missions. However, we found points that require improvement and functions that should be added. Our goal is to contribute to ECLSS research and development with this simulator, and as stated in the overview, we are developing SICLE so that it can be applied beyond ECLSS designing.

Appendix A

Table 5. Simulation Parameters[12,13]

	Human (kg/day-CM)			Plant (kg/day)		
Consumption		**MDRS**	**Kanau**		**MDRS**	**Kanau**
	Drinking water (includes for food supply)	Refer to Table 1	2.500	Carbon Dioxide	6.217	N/A
	Hygiene water (oral, hand, face)		4.445	Pure Water	10.651	
	Water for shower (body wiping)		2.722	Plant Food	0.023	
	Food	0.617				
	Oxygen	0.835				
Production		**MDRS**	**Kanau**		**MDRS**	**Kanau**
	Urine	1.886		Oxygen	4.533	N/A
	Fecal water	0.091		Food	3.777	
	Fecal waste (dry mass)	0.032		Pure Water	8.544	
	Respiration water	0.885				
	Perspiration water	0.699				
	Perspiration waste	0.018				
	Carbon Dioxide	0.998				

Table 6. System Design Architecture for MDRS Water Consumption Model (Demonstration #1)

Equipment/Tank	Process	Input	Output
Human	Drinking & Eating	Pure Water	Urine Feces Water Sweat
Waste Water Tank 1	Toilet Flush	Pure Water	Gray Water
Waste Water Tank 2	Shower	Pure Water	Gray Water
Waste Water Tank 3	Shampoo	Pure Water	Gray Water
Waste Water Tank 4	Face Wash and Teeth Brushing	Pure Water	Gray Water
Waste Water Tank 5	Hand Washing	Pure Water	Gray Water
Waste Water Tank 6	Laundry	Pure Water	Gray Water
Waste Water Tank 7	Dishwashing	Pure Water	Gray Water
Waste Water Tank 8	Plant Cultivation	Pure Water	Sewage
Waste Water Tank 9		Pure Water Urine Feces Water	Sewage Urine Feces Water
Water Supplier			Pure Water
Pure Water Tank 1		Pure Water	Pure Water
Pure Water Tank 2		Pure Water	Pure Water
Pure Water Tank 3		Pure Water	Pure Water
Outer System		Sewage Urine Feces Water Sweat	

Table 7. System Design Architecture for MDRS Closed-Loop Model (Demonstration #2)

Equipment/Tank	Process	Input	Output
Human	Respiration	Oxygen	Carbon Dioxide Sweat Sweat Solids
	Drinking	Pure Water	Urine Urine Solids
	Eating	Food	Feces Feces Water
Urine Recycling System	Urine Recycling	Urine Urine Solids	Gray Water Waste
Water Recycling System	Water Recycling	Gray Water	Pure Water
Life Drainage Translation	Drainage Creation	Pure Water Sweat Solids	Gray Water Waste
Waste Water Recycling System	Waste Water Recycling	Sewage	Gray Water
Plant	Food and Oxygen Generation	Carbon Dioxide Plant Food Pure Water	Oxygen Food Pure Water
Waste Recycling System	Waste Recycling	Waste Oxygen	Carbon Dioxide Plant Food
Air and Vapor Control System	Air and Vapor Control	Sweat Carbon Dioxide	Pure Water Carbon Dioxide
Liquid Separation System	Liquid Separation	Waste Gray Water Feces Feces Water	Waste Sewage
Module		Oxygen Carbon Dioxide Sweat	Oxygen Carbon Dioxide Sweat
Oxygen Tank		Oxygen	Oxygen
Carbon Dioxide Tank		Carbon Dioxide	Carbon Dioxide
Pure Water Tank 1		Pure Water	Pure Water
Pure Water Tank 2		Pure Water	Pure Water
Food Storage		Food Pure Water	Food Pure Water
Urine Tank		Urine Urine Solids	Urine Urine Solids
Gray Water Tank 1		Gray Water	Gray Water
Gray Water Tank 2		Gray Water	Gray Water
Waste Tank 1		Gray Water Waste Feces Water Feces	Gray Water Waste Feces Water Feces
Waste Tank 2		Waste	Waste
Waste Tank 3		Plant Food	Plant Food
Waste Water Tank		Sewage	Sewage

Table 8. System Design Architecture for Kanau ECLSS Model (Demonstration #3)

Equipment/Tank	Process	Input	Output
Human 1	Respiration	Oxygen	Carbon Dioxide Gray Water
	Drinking	Pure Water	Urine Gray Water
	Eating	Food	Waste
Human 2	Respiration	Oxygen	Carbon Dioxide Gray Water
	Drinking	Pure Water	Urine Gray Water
	Eating	Food	Waste
Carbon Dioxide Removal System	Gas Separation	Carbon Dioxide	Carbon Dioxide
Sabatier System	Carbon Dioxide Reduction	Carbon Dioxide Hydrogen	Pure Water Methane
Oxygen Generating System	Oxygen Generation	Pure Water	Oxygen Hydrogen
Waste Collecting System	Waste Separation	Waste	Gray Water
Urine Recycling System	Urine Recycling	Urine	Gray Water
Water Recycling System	Water Recycling	Gray Water	Pure Water
Life Drainage Translation	Drainage Creation	Pure Water	Gray Water
Module		Oxygen Carbon Dioxide Gray Water	Oxygen Carbon Dioxide Gray Water
Oxygen Tank		Oxygen	Oxygen
Carbon Dioxide Tank		Carbon Dioxide	Carbon Dioxide
Pure Water Tank 1		Pure Water	Pure Water
Pure Water Tank 2		Pure Water	Pure Water
Food Storage			Food
Urine Tank		Urine	Urine
Gray Water Tank		Gray Water	Gray Water
Outer System		Carbon Dioxide Methane	

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