

Lunar Night Power Supply: Circulative Renewable Energy System Capable of Continuous Power Generation

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ABSTRACT

Development is proceeding on a circulative renewable energy system for lunar night power supply. For proof of principle of the circulative renewable energy system, a system with approximately 1/10 the power of the expected launch unit was constructed, and a cycle test with 39 cycles was conducted, which is equivalent to three years of lunar use.

In the fuel cell stack, the membrane electrode assembly was designed in consideration of changes in the electrolyte membrane properties due to pure oxygen supply. In the electrolysis cell stack, component materials were selected that have reliable flame-retardant properties and oxidation resistance under high-pressure oxygen. In the electrochemical hydrogen compressor stack, discharge of stagnant water on the reaction surface was enhanced by optimizing the flow path structure. In addition, controls and systems were constructed to establish stable water circulation.

Through these initiatives, a cycle test was achieved and demonstrated the feasibility of continuous power generation through water circulation, which is the concept of the circulative renewable energy system and completed the proof of principle.

1. Introduction

Lunar development efforts such as the Artemis program continue to gain momentum⁽¹⁾. The Artemis program aims for astronauts to remain on the lunar surface for long periods of time and carry out sustainable exploration activities. This calls for methods that ensure stable electric power supply while keeping down the cost of lunar transport, which becomes expensive in proportion to the weight. From the perspective of space as a new destination for use of hydrogen technology, development is proceeding on a Circulative Renewable Energy System (CRE system) that combines a fuel cell system⁽²⁾ and a differential-pressure water electrolysis system⁽³⁾ to enable stable lunar power supply. The CRE system has a high weight-energy density that provides advantages in terms of transport cost and achieving large electric power capacity, so further development is expected going forward. This paper introduces the configuration of the CRE system being developed as well as initiatives carried out for proof of principle of its concept, “continuous power generation through water circulation.”

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2. CRE System

2.1. Significance of CRE System

A key challenge for long-term lunar stays is stable night power supply. The moon has a rotation period of approximately 27 days and, while it varies depending on the lunar region, night lasts for around 8 to 14 consecutive days. As it is assumed that a single mission will require approximately 2 kW of electric power to operate an unmanned exploration vehicle and other survey equipment, an electric power amount of up to 672 kWh is needed for nights lasting for 14 consecutive days. This amount of electric power needs to be produced by solar power generation during the day and retained to be used during the night. A commonly considered method is to store sufficient electric power for night use in a battery. However, a high-mass battery would result in a higher lunar transport cost, which is said to be 100 million yen or more per 1 kg⁽⁴⁾. Also, to help prevent battery performance from deteriorating in the low-temperature lunar environment, it is necessary to store electric power to heat the battery itself, which would further increase the weight.

The CRE system in development uses electricity obtained by solar power generation to electrolyze water and supplies the obtained hydrogen and oxygen to the fuel cell stack (FC stack) at night to generate power. Furthermore, the concept is to continuously regenerate power by electrolyzing the water produced in power generation. Table 1 shows the expected mass of each component of the future CRE system, assuming electric power generation of 672 kWh. The total mass of the entire system is 1,911 kg, and the weight energy density is 352 Wh/kg. In addition, as shown in Fig. 1, the weight energy density is greater than that of a Li-ion battery^{(5), (6)}, which is thought to be advantageous in terms of helping reduce transport cost and achieving large electric power capacity.

2.2. Overview of CRE System

Figure 2 shows an overview of the CRE system. First, water is supplied to the electrolysis cell stack (EC stack), which electrolyzes the water to produce hydrogen and oxygen. The EC stack has a structure similar to that of the differential-pressure water electrolysis stack used to produce high-pressure hydrogen in the Smart Hydrogen Station⁽⁷⁾, and produces high-pressure oxygen. Meanwhile, the produced hydrogen moves together with the water, separates from the water, and is then supplied to the electrochemical hydrogen compressor stack (EHC stack). In the EHC stack, high-pressure hydrogen is produced by pressurization through an electrochemical reaction. The produced high-pressure hydrogen and oxygen are stored in tanks and then supplied to the FC stack to generate power when electric power is needed. In addition, since water is produced in the reaction in the FC stack, continuous power generation can be achieved by resupplying this water to the EC stack and circulating it.

2.3. CRE System Development Challenges

There are two challenges for lunar use of the CRE system.

The first is the challenge of stable use in space, which calls for addressing various external factors that differ from those on earth. Examples include changes in components over time due to radiation from the sun and other sources, changes in fluid behavior due to low gravity, and launch vibrations in lunar transport.

The second challenge is to realize continuous power generation. Various measures are needed to realize this through water circulation, e.g. it is necessary to balance the amount of gases produced and consumed between connected stacks. When larger amounts are produced, the resulting increase in internal pressure may result in component deformation, and when smaller amounts are produced, the voltage may rise. The CRE system, however, is intended for use in a lunar environment where resources are not easily obtained, rendering the method of balancing by fluid discharge to outside the system unable to achieve continuous power generation. This calls for realization of

Table 1 Expected mass of each component of CRE system

Items	Mass (kg)
CRE system	727
Storage system	814
Fuel water	370
Total mass	1911

a system configuration and control methods that achieve smooth circulation within the system.

This initiative focused on the second challenge, namely the realization of continuous power generation. The contents of initiatives and the demonstration test conducted for proof of principle of the concept are introduced below.

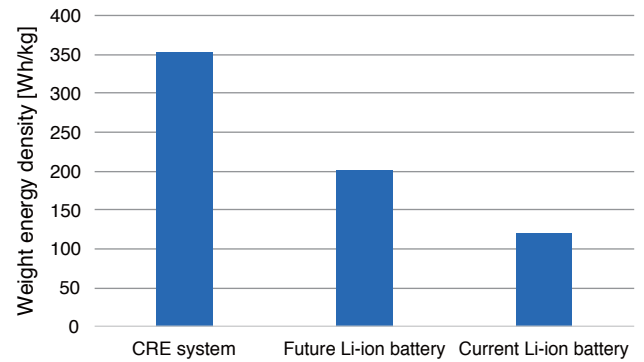


Fig. 1 Comparison of energy density between CRE system and Li-ion battery

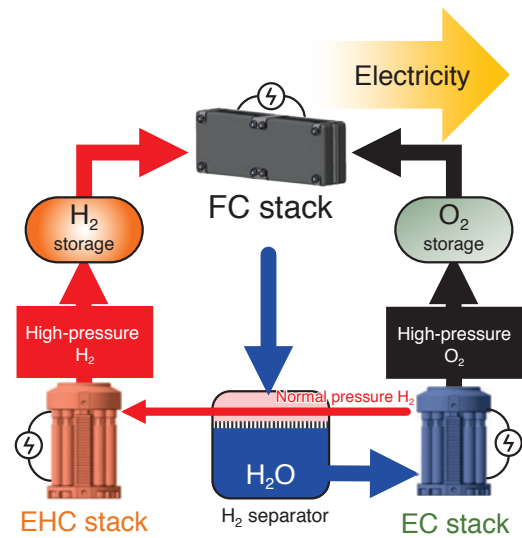


Fig. 2 Schematic diagram of CRE system

3. Initiatives for Proof of Principle

There are three main stages of development before actual lunar use of the CRE system. The first stage is proof of principle of the CRE system. The second stage is evaluation in a lunar equivalent environment using a system with nearly the same specifications as the expected launch unit. The third stage is evaluation of the actual unit that will be launched into space, and mission use.

This time, as the first stage of development, a demonstration test was conducted for proof of principle of continuous power generation through water circulation. In the demonstration test, circulation was performed for a number of cycles assuming actual operation in space and confirmed the feasibility of continuous power generation.

First, the changes to the specifications of each stack comprising the CRE system that were made for the demonstration test, and the contents of system control- and system configuration-related initiatives are described below.

3.1. Control in Gas Pressurization

The hydrogen produced by the EC stack is supplied via the H_2 separator to the EHC stack as shown in Fig. 3. When the H_2 separator pressure drops, the reaction rate slows because less hydrogen is supplied, and the operating voltage of the EHC stack rises. Conversely, when the H_2 separator pressure rises, it applies an extra load to the components. Thus, the operating current of the EHC stack is determined by feedback control using the difference between the H_2 separator pressure and the target pressure, and the amount of reaction hydrogen is adjusted.

An event that lowers the H_2 separator pressure is when oxygen mixes into the supplied hydrogen. Since this oxygen is transformed into water by reacting with hydrogen in the oxygen eliminator installed before the EHC stack, the amount of hydrogen and the pressure become lower. Events that increase the H_2 separator pressure are when high-

pressure hydrogen passes through the electrolyte membrane in the EHC stack and moves to the gas flow path on the low-pressure side, and when water generated by the FC stack is supplied from storage to the H_2 separator. In these cases, controlling the operating current of the EHC stack enables operation within the component strength reliability range while also helping to prevent a rise in the operating voltage, even if the pressure inside the H_2 separator fluctuates.

3.2. System Configuration for Stable Depressurization

The EC and EHC stacks have a high-pressure side on one side and a low-pressure side on the other side of the electrolyte membranes inside the cells, which produces a differential pressure. Therefore, when stopping the system or when a tank has reached the specified pressure, it is necessary to depressurize the remaining high-pressure gas in order to lessen the load on the internal components of the stack. However, since external discharge would waste the produced hydrogen and oxygen, this CRE system performs depressurization by supplying the excess gas directly to the FC stack and reactivating it. Hydrogen and oxygen react in the FC stack at a molar ratio of 2:1, but the amount of gas remaining in each stack differs depending on the situation. Therefore, the case can be assumed where either the EC stack or the EHC stack completes depressurization before depressurization of both stacks has been completed.

The set pressures of the depressurizing valves (regulators) shown in Fig. 3 were determined in a manner to address this. The set pressures of regulators A and C between the EC and EHC stacks and the FC stack were set to the depressurization completed pressure. In addition, the set pressures of regulators B and D between each tank and the FC stack were set to a pressure several tens of kPa higher than the depressurization completed pressure.

As a result, the gas remaining on the EC and EHC stack sides is preferentially consumed. When the EC or EHC stack reaches the depressurization completed pressure,

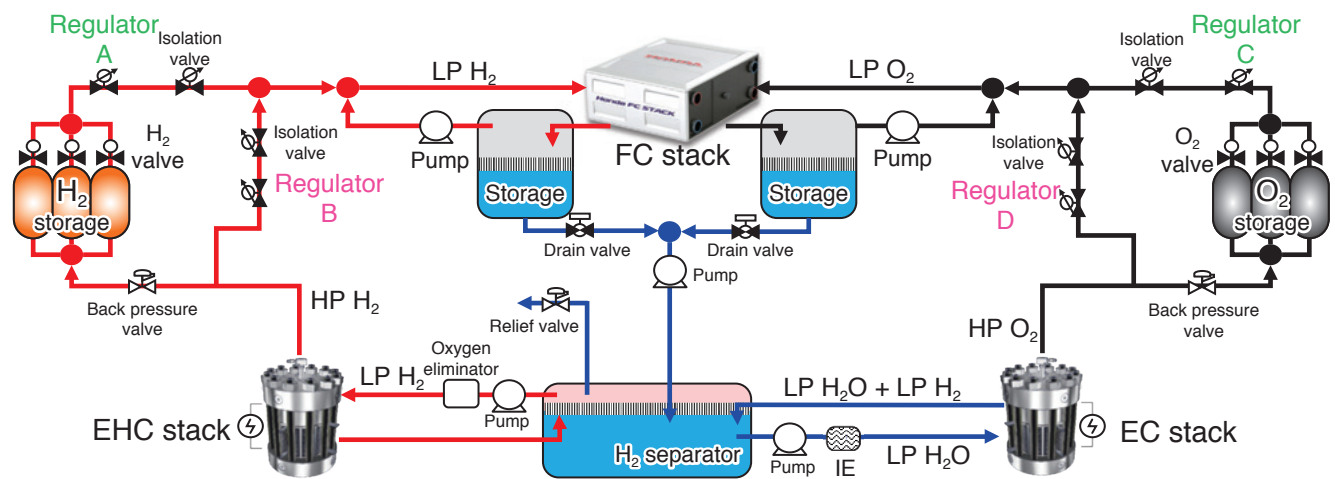


Fig. 3 CRE system configuration

the gas inside the tank that reached the depressurization pressure starts to be consumed. This enables the reaction in the FC stack to continue and depressurize both the EC and EHC stacks by power generation.

3.3. FC Stack

The FC stack is a device that converts chemical energy into electrical energy by the following electrochemical reaction of hydrogen and oxygen in the electrolyte membranes and has a structure that stacks multiple cells that have reaction parts.

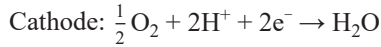
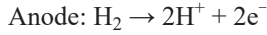


Figure 4 shows the FC stack used in the demonstration test. Although in an FC stack for terrestrial use, the oxygen contained in the air is used for power generation, in the CRE system, pure oxygen manufactured by the EC stack is supplied. One effect of pure oxygen is that the changes in the electrolyte membrane properties over time are more pronounced than those for air. An electrolyte membrane degradation model⁽⁸⁾ was constructed by conducting a unit durability test with pure oxygen supply and quantifying the reduction in the membrane molecular weight after durability. This model was then used to design a membrane electrode assembly (MEA) that was expected to exhibit a decrease in performance in the demonstration test.

3.4. EC Stack

The EC stack is a device that performs water electrolysis to produce high-pressure oxygen and low-pressure hydrogen. The goal of the EC stack used in the demonstration test was to produce high-pressure oxygen of 14.7 MPa. Figure 5 shows the EC stack used in the demonstration test, and Fig. 6 shows the schematic diagram of the EC stack. Like the FC stack, the EC stack has a structure of stacked multiple cells. Water is supplied to the electrolyte membranes inside the cells, and oxygen and hydrogen ions (H^+) are generated by applying voltage to the stack. The oxygen outlet is sealed, so the pressure rises over time, enabling high-pressure oxygen to be obtained. Voltage is applied to both ends of the electrolyte membrane, and the

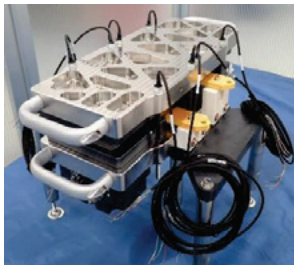
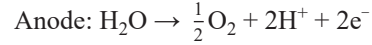


Fig. 4 FC stack

oxygen and hydrogen ions generated by water electrolysis pass through the electrolyte membrane and move to the cathode side and are separated. The hydrogen ions are then converted into hydrogen, discharged from the hydrogen outlet of the EC stack, and supplied to the EHC stack.



Oxidation of components present under high-pressure oxygen is promoted, and due to a lower ignition temperature and an increase in the combustion rate, even materials that are non-combustible in the atmosphere may become combustible. Thus, material selection for the EC stack components around the electrolyte membrane on the anode side was performed from the perspective of helping to prevent oxidation and combustion.

3.5. EHC Stack

The EHC stack is a device that electrochemically pressurizes the supplied hydrogen. The goal of the EHC stack used in the demonstration test was to produce high-



Fig. 5 EC stack

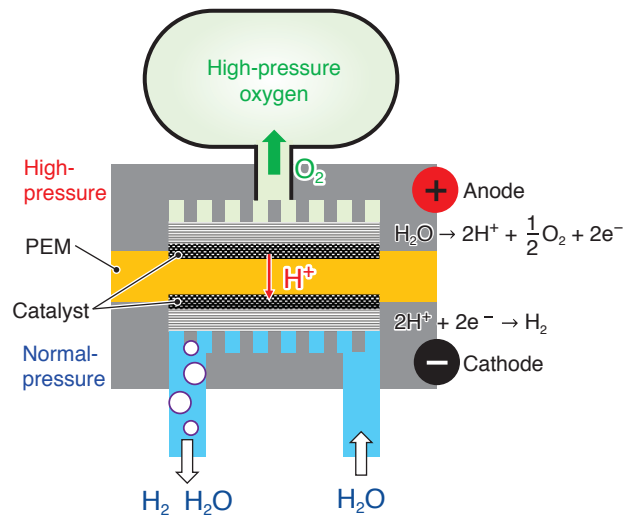
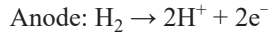


Fig. 6 Schematic diagram of EC

pressure hydrogen of 70 MPa. Figure 7 shows the EHC stack used in the demonstration test, and Fig. 8 shows the schematic diagram of the EHC stack. The EHC stack also has a structure of stacked multiple cells, and when voltage is applied, hydrogen ions generated by the following reaction in the electrolyte membrane inside each cell move to the cathode side that leads to the high-pressure tank. Since the tank is a closed space, the pressure rises over time.



As drying of the electrolyte membrane leads to lower conductivity, wet hydrogen is supplied to the EHC stack. The water in the hydrogen can permeate the membrane and move to the high-pressure side, but the greater the differential pressure via the membrane, the more the water is pushed back to the low-pressure side. As shown in Fig. 8, there is the issue that the water pushed back remains in the membrane reaction part with the result that hydrogen supply is not smooth and the voltage rises. Especially in the low-gravity lunar environment, water detaches less easily from the reaction membrane. To help prevent water retention, it is necessary to suppress local drops in the flow velocity of the

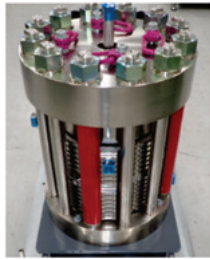


Fig. 7 EHC stack

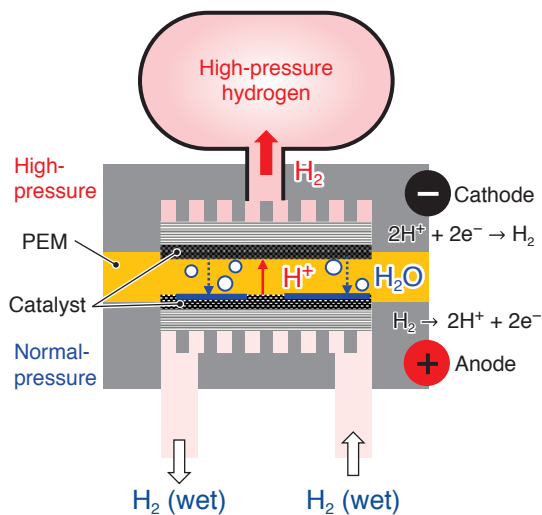


Fig. 8 Schematic diagram of EHC

hydrogen supplied to the reaction surface that contributes to water discharge. The hydrogen flow path structure was thus optimized to achieve a more uniform hydrogen flow velocity in the reaction part.

Figure 9 shows the flow of hydrogen in the EHC stack. The hydrogen supplied to the EHC stack originates from the inlet frame to each cell, then passes through the flow paths cut into the bottom surface of the inlet frame and flows to the spacer and the electrode. The electrode is a component located at the bottom of the electrolyte membrane, and the flow velocity distribution in this component was equalized to help prevent water retention. An L27 orthogonal table was prepared using 13 design factors such as the diameter and length of the flow paths cut into the bottom surface of the inlet frame, and variation in the flow velocity under each condition was obtained by fluid analysis. A response surface was created based on the analysis results, and the flow path structure was adapted to the shape that achieved the lowest flow velocity variation in the analysis. Figure 10 shows the hydrogen flow velocity for the base shape, and Fig. 11 shows the hydrogen flow velocity for the optimized structure. The gas flows from left to right in the figures.

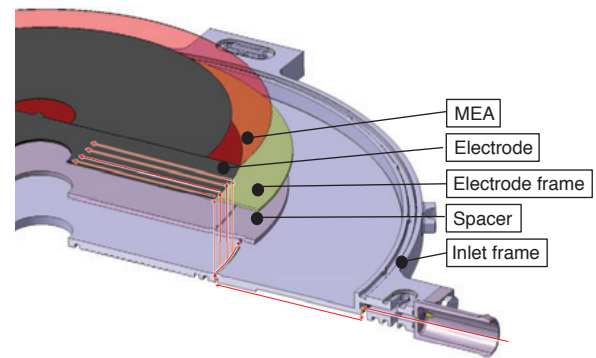


Fig. 9 Flow of hydrogen in EHC

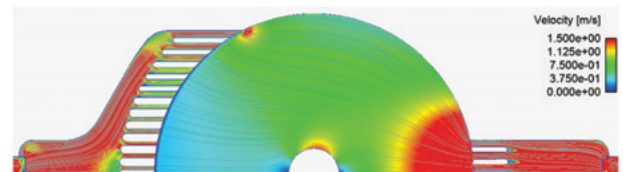


Fig. 10 Velocity distribution in base flow path structure of EHC stack

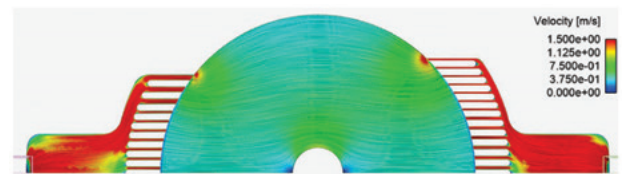


Fig. 11 Velocity distribution in optimized flow path structure of EHC stack

While the semicircular area in the center indicates the electrode, the number and width of flow paths outside the electrode have been changed, resulting in a more uniform flow velocity inside the electrode compared to before the structural change. The cell component with the altered flow path structure was used in the demonstration test to help prevent operational termination due to water retention.

4. Proof of Principle of CRE System

A demonstration test was conducted for proof of principle of the CRE system.

A CRE system with about 1/10 the power of the expected launch unit was created, and a cycle test was conducted as a demonstration test. There are 13 night-crossings per year on the moon. In addition, while the CRE system assumes continuous lunar use of several to 10 or more years, here, the specified number of cycles for the demonstration test was 39 cycles, which is the number of day/night cycles equivalent to three consecutive years, or the expected number of years for a single lunar mission⁽⁹⁾. The total amount of water present in the system at the start of the test was 1,900 ml, whereas the amount of water used for water electrolysis in one cycle is approximately 400 ml. Assuming circulation is established, therefore, proof of principle can be achieved by completing power generation for the specified number of cycles without any event that leads to termination of the test. In addition, this test was conducted using general grid power instead of electric power obtained by solar power generation.

Figure 12 shows the appearance of the created CRE system, and Table 2 shows the specifications. The operation of one cycle of the CRE system will also be introduced. Figure 13 shows the transitions in the operating current and outlet pressure of the EC and EHC stacks, the FC stack power, and the pressure of each tank. The timing of one cycle differs slightly for the EC and EHC stacks, but it can be divided into the four modes of 1) pressurization, 2) storage, 3) depressurization, and 4) generation.

In pressurization mode, gases are produced and pressurization within the stacks begins with the start of the electrochemical reaction. Fluctuations in the supplied hydrogen pressure are addressed by controlling the operating current of the EHC stack as mentioned in Section 3.1. Once the predetermined pressure is reached, operation transitions to storage mode.

In storage mode, gas supply to the tanks starts and the tank pressures begin to rise. After the tank pressures reach the target pressure, operation transitions to depressurization mode.

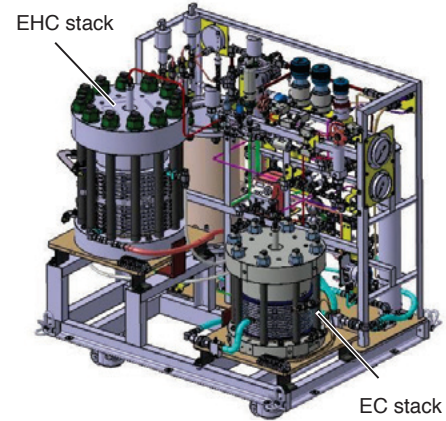
In depressurization mode, gas supply to the tanks stops and the pressure inside the tanks is retained. The pressure inside the EC and EHC stacks is decreased by supplying the extra gas remaining in the EC and EHC stacks directly to the FC stack and consuming it for power generation. As shown in the bottom graph of Fig. 13, the FC stack power

Table 2 Specifications of CRE system for demonstration test

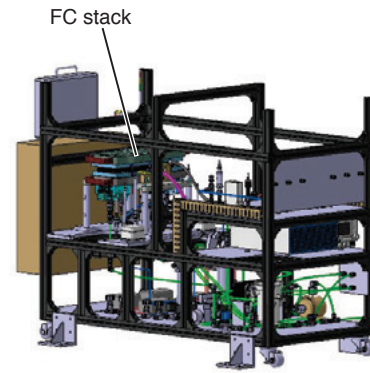
CRE system	System weight [kg]	2900
FC stack	Average power (generation mode) [W]	221.6
	Stack weight [kg]	50
	Stack dimensions [mm]	570 × 266 × 250
EC stack	Pressure of generated oxygen [MPa]	14.7
	Average oxygen production rate [g/h]	179.5
	Stack weight [kg]	260
EHC stack	Stack dimensions [mm]	Φ393 × 447
	Hydrogen pressure increase [MPa]	70.0
	Average hydrogen pressurization rate [g/h]	22.5
EHC stack	Stack weight [kg]	470
	Stack dimensions [mm]	Φ460 × 623

is not constant in depressurization mode. This is due to adjustment of the FC stack power to help prevent rapid depressurization of the EC and EHC stacks and blistering of the rubber seals and other EC and EHC stack internal components.

Then, in generation mode, the tank pressures drop because the gas stored in the tanks is supplied to the FC stack.



(a) EC and EHC systems



(b) FC system

Fig. 12 CRE system for demonstration test

There are two things to consider when setting the cycle test operation method: the first is that in the pressurization and depressurization modes, the operating current and the control times using the depressurizing valves, etc. may vary due to changes in the system specifications. However, these variations due to longer or shorter times can be addressed by maintaining the balance of fluid circulation.

The second is shorter storage mode and generation mode times. Both the capacity and storage pressure of the gas storage tanks are set lower than for actual operation, and one cycle is completed in about five hours. In actual operation, however, the operating time increases due to an increase in the amount of electric power needed. This is expected to have an impact on the durability of each stack and will be confirmed by individual durability in the future. As the purpose of this demonstration test is to confirm the circulation of the entire CRE system, verification can be achieved by conducting a cycle test with the set operation method.

Figure 14 shows the FC power generation amount in each cycle. As a result of this series of initiatives, it was

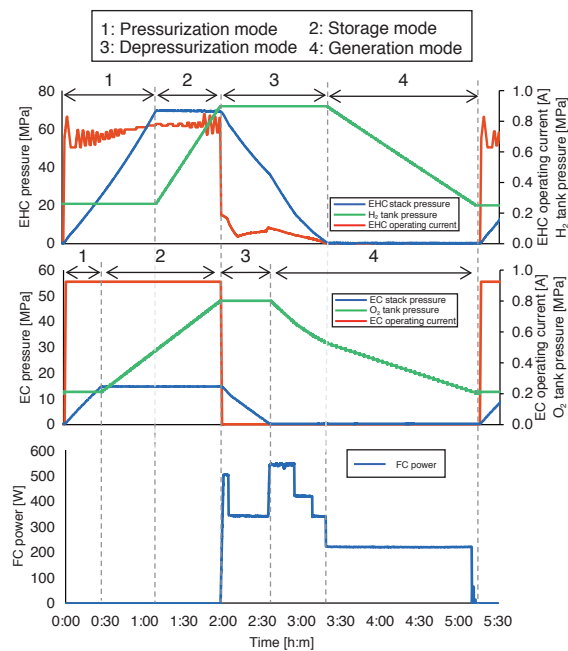


Fig. 13 Operation transition of CRE system

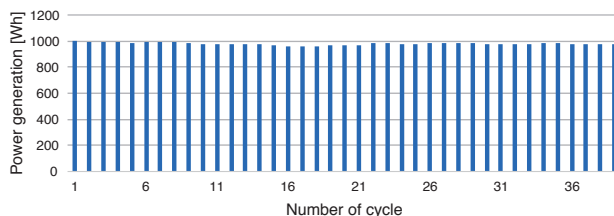


Fig. 14 Power generation in each cycle

confirmed that power could be generated through 39 cycles without terminating the test, and proof of principle was completed.

5. Initiatives for Stable Use in Space

As mentioned in Chapter 3, evaluation will be conducted in a lunar equivalent environment going forward. To achieve stable lunar use of the CRE system, it is necessary to consider various environments and disturbances that differ from those on earth. This paper introduces initiatives that should be taken going forward to address radiation, low gravity, transport vibrations, and weight reduction to achieve a lower transport cost.

5.1. Radiation

The moon is shielded by a weaker magnetic field than the earth, and the amount of radiation from the sun and other sources is higher in the lunar environment than on earth. Radiation exposure tests were conducted on the stack components to understand the property changes due to radiation. The results demonstrated that, among the stack components, changes in the electrolyte membrane properties were especially noticeable. As shown in Fig. 15, the molecular weight and tensile strength of the electrolyte membrane drop as the radiation-absorbed dose increases. However, as equipment such as presses and cranes are needed to assemble the stacks, disassembly and replacement of the electrolyte membranes cannot be performed on the lunar surface. Therefore, the specifications need to provide durability enabling complete operation, making it necessary to clarify the radiation-absorbed dose and the functional deterioration of each component, and to design a shielding structure that does not produce functional loss over the operation period.

5.2. Low Gravity

Lunar gravity is approximately 1/6 that on earth. The lower the gravity of the environment, the less the buoyancy of air bubbles acts. This means that in the EC stack, the produced gas is not expected to separate from the electrode

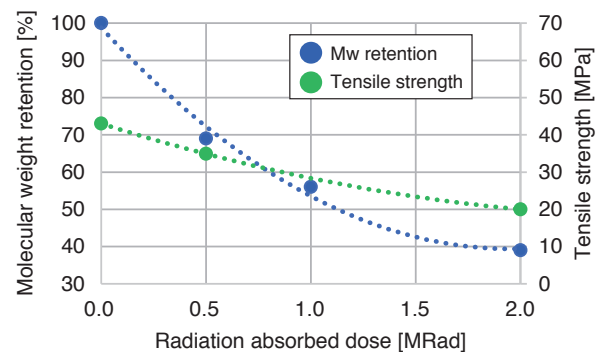


Fig. 15 Relationship between radiation absorption and membrane properties

surface, with the result that mass transport is hindered, and the electrolytic performance deteriorates. In future, tests will be conducted in low-gravity environments by means such as drop towers and parabolic flights on aircraft in order to clarify the influence of gravity and to design water supply conditions and structures for reliable discharge of produced gases.

5.3. Transport Vibrations

Transport rockets used to carry goods into outer space experience severe vibrations during launch. Therefore, the CRE system and each stack require structures that can withstand these vibrations without loss of functionality. Stabilizing with resonance suppression jigs is a generally effective vibration countermeasure, but from the viewpoint of transport costs to space, increases in weight for the purpose of suppressing vibration should be avoided as much as possible. A shaker is currently being used to produce vibrations at the same level as in actual transport, and vibration characteristics, such as the resonance frequencies of the stacks, are being evaluated. Going forward, these results will be fed back to CAE to enhance design estimation technology and utilized in system design.

5.4. Weight Reduction

In order to achieve a lower lunar transport cost, weight reduction is needed for each stack comprising the CRE system. Since the EC and EHC stacks have especially high weights, it is necessary to optimize the reaction part diameters. By increasing the reaction part diameters and the amount of hydrogen produced per cell, fewer cells need to be stacked, which enables shortening of the total length of the bolts securing the stacks. However, increasing the reaction part diameters also increases the diameter of the pressure-resistant components around the outer periphery of the reaction part, which is a factor that increases the weight. Future efforts will be made to optimize the reaction part diameters and achieve weight reduction within constraints such as space in transport.

6. Conclusion

- (1) The MEA of the FC stack was designed in consideration of membrane changes over time due to supply of pure oxygen.
- (2) Materials with reliable oxidation and flame resistance that can be used even in a high-pressure oxygen environment were selected for the EC stack.
- (3) Optimization of the flow-path structures of the EHC stack enhanced discharge performance of stagnant water in the reaction part.
- (4) Valve and stack operation control were established to realize stable water circulation within the CRE system.
- (5) 39 cycles of operation were achieved using the constructed CRE system, and proof of principle was completed.

References

- (1) <https://humans-in-space.jaxa.jp/en/future/>, (accessed 2024/07/25)
- (2) <https://global.honda/en/newsroom/news/2023/c230202eng.html>, (accessed 2024/07/25)
- (3) <https://global.honda.jp/news/2018/c181121.html>, (accessed 2024/07/25) (in Japanese)
- (4) <https://www.astrobotic.com/astrobotic-awarded-79-5-million-contract-to-deliver-14-nasa-payloads-to-the-moon/>, (accessed 2024/10/17)
- (5) Oka, T., Marutani, K., Hamada, S., Osako, Y.: Large Capacity Lithium Ion Battery for Space Use, Mitsubishi Electric Technical Report, Vol. 94, No. 2, p. 41-45, (2020), <https://www.giho.mitsubishielectric.co.jp/giho/pdf/2020/2002202.pdf>, (accessed 2024/07/25) (in Japanese)
- (6) Naito, H.: Energy Storage Devices for Space Exploration, GS Yuasa Technical Report, Vol. 13, No. 2, p. 1-7, (2016), https://www.gs-yuasa.com/jp/technology/technical_report/pdf/vol13_2/13_02_001.pdf, (accessed 2024/07/25) (in Japanese)
- (7) Ishikawa, H., Haryu, E., Kawasaki, N., Daimon, H.: Development of 70 MPa Differential-pressure Water Electrolysis Stack, Honda R&D Technical Review, Vol. 28, No. 1, p. 86-93
- (8) Kato, T., Nakahara, A., Ohkura, T., Yamamoto, M., Terada, S., Noda, A., Kanaoka, N.: Development of High-durability and Low-cost UEA for Fuel Cell Stack, Honda R&D Technical Review, Vol. 37, p. 27-33
- (9) Uehara, S., Ohama, N., Tagai, R., Takahashi, M., Murata, S.: Study Status of Regenerative Fuel Cell System for Pressurized Rover, 68th Space Sciences and Technology Conference, 3A09, (2024) (in Japanese)

■ Author ■



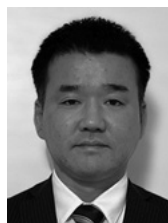
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