Development status of air revitalization system in JAXA closed ECLSS for future crew module

Yoko Sakai,[1] Toshiharu Oka,[1] Shinpei Waseda,[1] Tatsuya Arai,[1] Tomoya Suehiro[1] and Tsuyoshi Ito[2]
Japan Aerospace Exploration Agency, Tsukuba, Ibaraki, 305-8505, Japan

Asuka Shima[3] and Masato Sakurai[4]
Japan Aerospace Exploration Agency, Chofu-shi, Tokyo, 182-8511, Japan

The Japan Aerospace Exploration Agency (JAXA) has been developing the closed Environmental Control and Life Support System (ECLSS). The air revitalization system in the closed ECLSS consists of five subsystems; CO_2 removal assembly, trace contaminant control assembly, CO_2 reduction assembly, O_2 generation assembly, and methane decomposing assembly. This paper reports the development status of each subsystem, except the trace contaminant control assembly. In CO_2 removal system development, CO_2 for almost four crew members was collected using the low and narrow range of temperature swing of a newly developed adsorbent. A full-scale test model of the CO_2 reduction system, loaded with a low temperature catalyst developed by JAXA, has been completed. Prolonged testing of the electrolysis cell is underway to examine the O_2 generation system architecture. Fundamental data for a scale-up test of methane decomposition was also obtained.

Nomenclature

ECLSS = Environmental Control and Life Support System
CO_2 = carbon dioxide
O_2 = oxygen
H_2 = hydrogen
CH_4 = methane

I. Introduction

FOR future manned space exploration of Mars and other planets, the Environmental Control and Life Support System (ECLSS) should have a higher regeneration rate and reliability than that in the ISS. The Japan Aerospace Exploration Agency (JAXA) has been developing a closed ECLSS system (Figure 1) with three goals: no supply of water and O_2, no consumables, and high reliability. Our system consists of three parts—the air revitalization system, water recovery system, and waste management system. In the air revitalization system, CO_2 discharged by the breathing of crew members is collected using CO_2 adsorbent and reduced it by Sabatier reaction. The methane yielded is decomposed by microwave under catalysts to generate H_2, which is used for Sabatier reaction. On one hand, O_2 is generated from water by electrolysis, and H_2 generated at the same time is also used for Sabatier reaction. This system can generate the same volume of O_2 as that of discharged CO_2, but humans need extra O_2 due to our metabolism, which means that extra water is needed for a fully closed system. JAXA's system is designed to collect extra water from waste by using the waste management system.

This paper discusses the development status of the air revitalization system in JAXA's closed ECLSS for future manned spacecraft (based on a scale of four crew members).

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[1]Engineer, JEM Mission Operations and Integration Center Human Spaceflight Technology Directorate, JAXA, Tsukuba, Ibaraki, 305-8505, Japan
[2] Manager, JEM Mission Operations and Integration Center Human Spaceflight Technology Directorate, JAXA, Tsukuba, Ibaraki, 305-8505, Japan
[3] Manager, Research Unit II, Research and Development Directorate
[4] Researcher, Research Unit II, Research and Development Directorate

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \text{ } (CO_2 \text{ reduction or Sabatier reaction})$$

$$2H_2O \rightarrow O_2 + 2H_2 \text{ } (O_2 \text{ generation})$$

$$CH_4 \rightarrow C + 2H_2 \text{ (methane decomposition)}$$

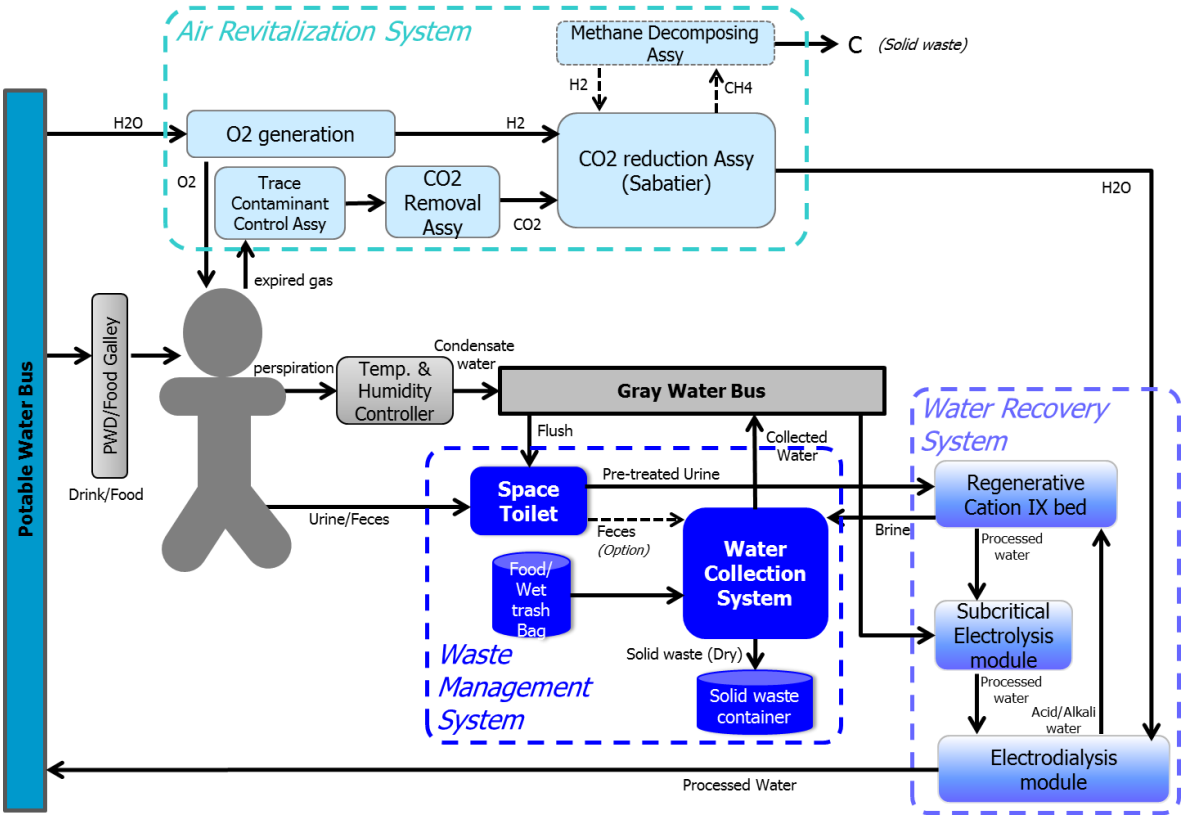

Figure 1. Concept of JAXA's closed ECLSS

II. CO_2 removal system

In the ISS CO_2 removal assembly, zeolite is used as CO_2 adsorbent and the system has been improved for future systems.[1] JAXA's CO_2 removal system uses a newly developed amine-based adsorbent. The system architecture is considered from a single column scale-up test. Although the adsorbent does not inhibit CO_2 adsorption capacity even in the presence of moisture, moisture is also adsorbed and desorbed together with CO_2. For example, in cabin air with humidity of 50% and temperature of 23°C, about twice as much moisture as CO_2 will be adsorbed, which not only increases the load on the vacuum pump but also reduces the performance of the adsorbent due to its temperature change. In order to shorten the cycle time (which leads to a reduction of equipment volume) and reduce the pump load and temperature change of the adsorbent, cabin air is dehumidified in the front stage of CO_2 adsorption in our system. CO_2 adsorbent is regenerated by pressure (1~2 kPa) and a temperature swing (~60°C) due to its high temperature sensitibity, and because the combination of temperature and decompresstion make it possible to collect CO_2 with high purity. As the crew's performance largely depends on the CO_2 concentration, we targeted keeping the cabin CO_2 concentration at 2000 ppm and collecting CO_2 from four crew members. In terms of safety and efficiency of the latter-stage Sabatier reaction, the targeted purity of collected CO_2 is 99% or more. The single column full-scale test model shown in Figure 2 was prepared and a performance test was conductued to investigate such design parameters as airflow rate and adsorbent quantity.

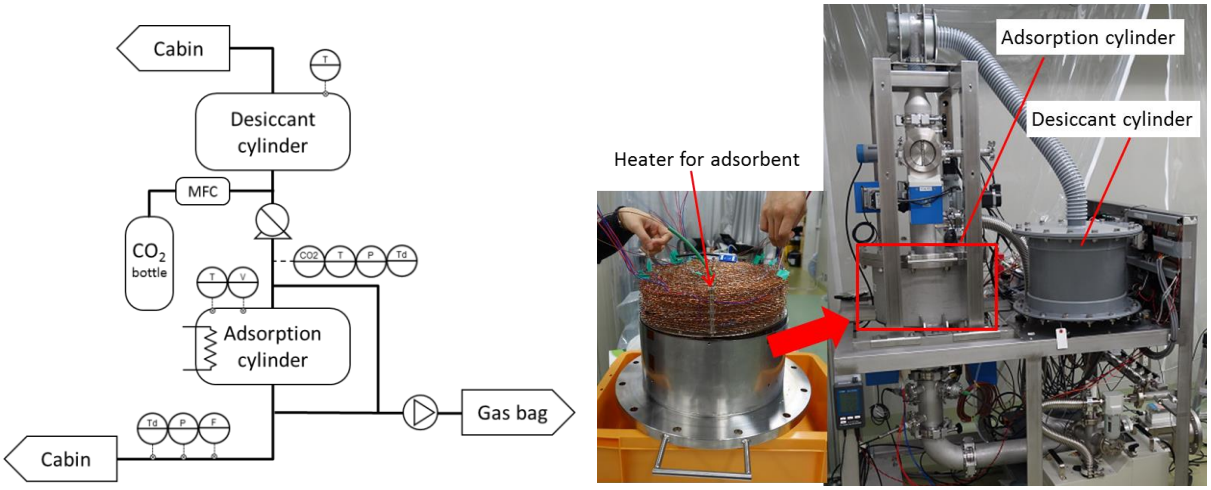

Figure 2. Block diagram of the full-scale single column test model

The airflow distribution to the adsorbent and uniform control of temperature inside the column are important factors at the time of scale-up, and often become nonuniform so that adsorbent performance cannot be sufficiently elicited and the system becomes larger. To achieve full performance from the adsorbent, we first examined the airflow distribution and temperature uniformity regarding the adsorbent in the test model. Fluid analysis confirmed that the air stream was nearly homogenized due to the high drop in pressure of the adsorbent bed, though a perforated plate was added for further homogenization. In practice, by passing air to the uniformly heated adsorbent bed without CO_2 adsorption and measuring the internal temperature, no behavior suggesting distribution was found as shown in Figure 3. According to this uniformity, it is confirmed that the temperature distribution of the adsorbent bed was almost uniform during adsorption, though the adsorbent temperature increased due to adsorption heat. The heater was designed based on thermal analysis and introduced inside the adsorbent bed to heat it during desorption. It is confirmed that temperature of the adsorbent ranged roughly from 50°C to 60°C when using the heater.

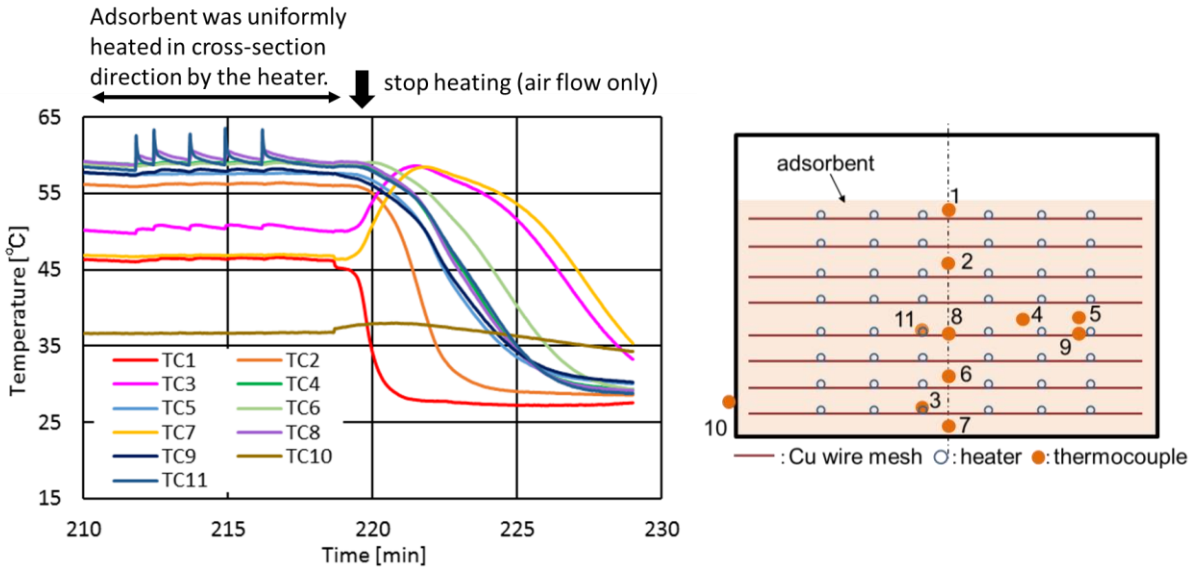

Figure 3. Temperature change and thermometric points inside the adsorption cylinder

An adsorption/desorption test was conducted to investigate the design parameters. The CO_2 recovery rate and cycle time were temporarily set for a CO_2 concentration of 2000 ppm and 8.7 L of adsorbent (including the heater), and the airflow rate was set to 60 m^3/h (35CFM). The dew point of inlet air was adjusted under -35°C, based on the required amount of dehumidification calculated from the adsorption isotherm. Adsorption for 35 minutes was

carried out to obtain a breakthrough curve, and then a desorption curve was acquired by heating the adsorbent up to 60°C and reducing the pressure to 1 kPa. Figure 4 shows the ratio of the cumulative amount of adsorption/desorption CO_2 to the amount of CO_2 emitted by four crew members against the adsorption/desorption time (orange line/orange marker). The purity of removal CO_2 was almost 99% except during the first two minutes following the start of decompression. The 1% inpurity in the CO_2 was air remained in the column. This suggests that CO_2 from four people can be collected in case of a 15-minute cycle. However, the peak power consumption of the heater becomes higher as the cycle time becomes shorter, so that further study is required to improve the amount of desorption. The data on adsorbent temperature during desorption shows that the upper part of the adsorbent bed decreased in temperature to 45~35°C, while temperature of the middle part was regulated at around 50~60°C (Figure 5). The desorption rate is expected to be improved by the optimization of heater control. As another means, it may be effective to increase the displacement of the vacuum pump or the amount of adsorption. When the temperature of inlet air was lowered by 2~3°C, the ratio of the cumulative amount of adsorption CO_2 increased by around 7% as shown in Figure 4 (blue line). Despite expectations, however, the ratio of the cumulative amount of desorption CO_2 decreased. The temperature of the adsorbent was 2~3°C lower overall than in the foregoing test, which caused the decrease in the amount of desorption.

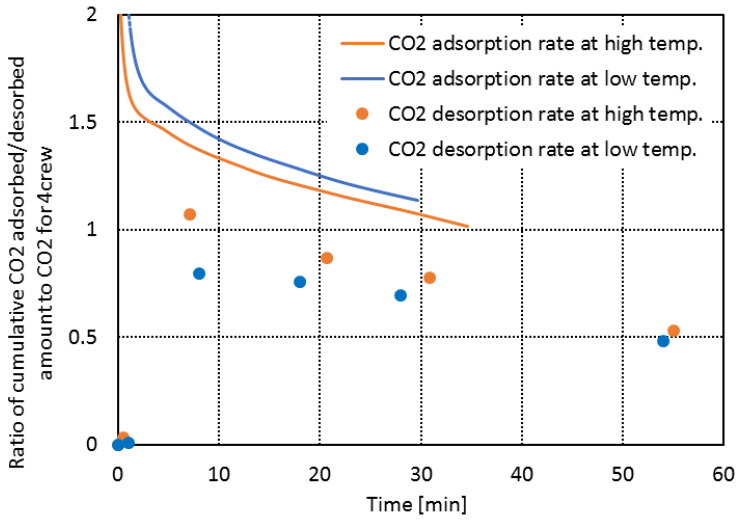

Figure 4. Ratio of cumulative amount of adsorption/desorption CO_2 to amount of CO_2 emitted by four crew members

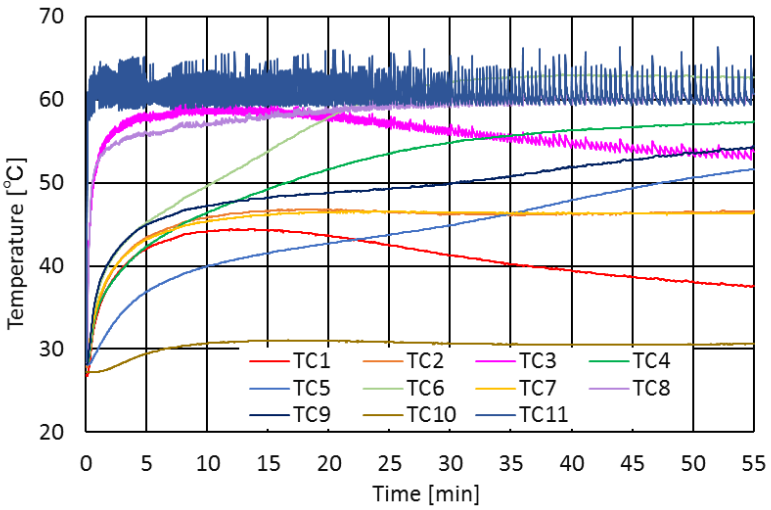

Figure 5. Temperature change inside the adsorption cylinder during desorption

As shown before, this system has good temperature sensitivity, so CO_2 can be collected compactly at low energy under precise temperature control. In the future, we will work to establish more precise temperature control to elicit maximum absorbent performance, while making a trade-off between power consumption and size. Furthermore, by using another full-scale test model for four-cylinder cycle operation combining a desiccant cylinder and an adsorption cylinder, we will optimize the design parameters. Evaluation for lifetime and offgas of the absorbent has been conducted in parallel. We plan to build a ground model in 2018~2019 and an ISS demo in 2020~.

III. CO_2 reduction system

CO_2 recovered by the CO_2 removal system is reduced by H_2 generated by the O_2 generation system. JAXA has been developing a low-temperature catalyst for Sabatier reaction.[2] Although this catalyst has the advantage of a lower reaction temperature (~230°C) than that of other commercially available catalysts, the deactivation temperature is 250°C and relatively close to the reaction temperature, so precise catalyst temperature control is required to take advantage of the catalyst's strength. In the subscale test conducted up to last year, the following problems regarding catalyst temperature control were identified.

- The reaction gas did not sufficiently diffuse into the container.
- Heat transfer from the catalyst to the exhaust heat surface was insufficient and a temperature gradient occurs.
- As both the air-cooling device and heater are installed outside the reaction vessel, reaction heat could not be sufficiently removed.
- The catalyst temperature rose in the upper stage of the reaction vessel as the reaction mainly occurred there, but could not be maintained in the lower stage due to inadequate reaction.

To address these problems, we built a full-scale prototype whose design incorporates following features (Figure 6): To improve the thermal conductivity between the catalysts, the small catalyst block was surrounded by an aluminum plate. An air-cooling device is installed on the surface of the container, while a bar heater is installed inside. The catalyst blocks are overlapped in four columns and temperature can be controlled column by column. We are preparing a test to evaluate the effect of each effort and optimize the design.

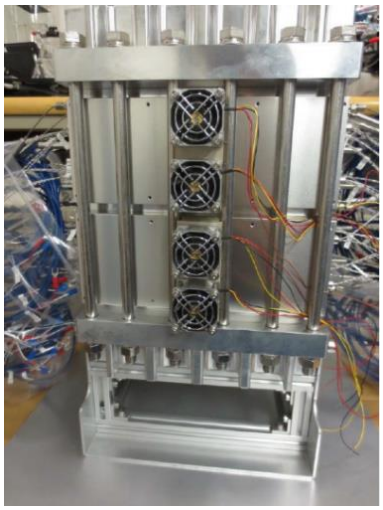

Figure 6. Reaction vessel of full-scale prototype

IV. O_2 generation system

We are studying a water electrolysis system using a cathode feed-type electrolysis cell using a solid polymer membrane. JAXA has developed its own water electrolysis cell and worked on acquiring fundamental data.[3] In system design, such operating conditions as electrolytic current density, water temperature, and pressure are important parameters. The larger the electric current density, the smaller the cell, but with higher power consumption. The higher the water temperature, the lower the power consumption, but with more difficult gas-liquid separation. By increasing the pressure, the dew point of the generated gas can be lowered, but at the risk of bubbles forming in the circulating water line. In determining the operating conditions, in addition to these trade-offs, it is important to evaluate the service life of the cell because in the cathode feed system, cell life is closely related to operating conditions, especially electrolytic current, and the risk of cell breakage. Therefore, we are currently conducting a long-term test using a sub-scale water electrolysis cell to investigate the impact of electrolytic current intensity on the lifetime of a cell. Three water electrolysis cells in three cell stacks were prepared. By changing the electrolysis current (0.2/0.4/0.8 A/cm^2), electrolysis was conducted for five to seven hours per day, four days a week, and the I-V curve was acquired one day per week to check the trend in performance. As the test is ongoing, the progress is reported below. The electrolytic voltage at the start of electrolysis on each day was plotted against the cumulative operation time as shown in Figure 7, and remarkable deterioration was not observed after about 25 hours. We will continue to test and accumulate operating time.

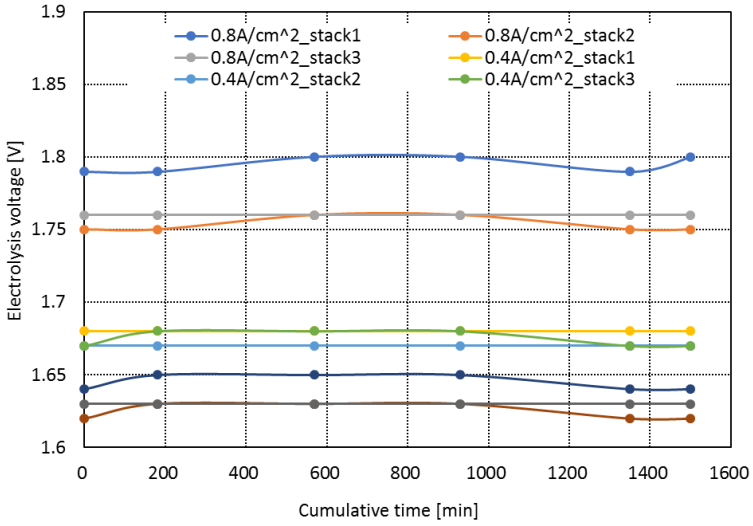

Figure 7. Time course of electrolysis voltage

V. Methane decomposition

It is possible to reduce the amount of water supply by obtaining hydrogen from methane produced by the Sabatier reaction. The direct decomposition of methane to obtain carbon and hydrogen occurs by heating under a catalyst, but high reaction temperature (700~1200°C) and short catalytic activity (tens of minutes) due to the carbon yield covering the catalytic activity point make it difficult to apply this reaction to the closed ECLSS. However, when microwaves are irradiated to SiC and mixed catalysts of Ni, molybdenum carbide, and zeolite while passing methane through them, a decomposition of methane occurs with high efficiency (~93%) even at about 650°C, long continuity (33h), and almost no byproducts.[4,5] The reaction proceeds at 450~500°C or higher. SiC absorbs microwaves and plays a role as a heating source in the early stage of the reaction, thereby promoting the reaction on the surface of the mixed catalyst. As the reaction progresses, the generated carbon forms dissolve in Ni and precipitate in the form of graphene, which becomes a dominant heating source over SiC, and at the same time contributes to maintaining the activity. In a multi-mode type of microwave generator such as a microwave oven, microwaves are diffused in a cabinet and irradiated and absorbed by a sample, although it is difficult to quantitatively evaluate its behavior. We prepared a large microwave generator with full-scale methane treatment, in an effort to attempt a scale-up test.

Figure 8 Microwave methane decomposing test equipment

Figure 8 shows the test equipment. As the first step in scale-up, 100% methane gas was passed through the catalysts at 50 mL/min. and microwaves were irradiated to these catalysts for 10 hours to reach a catalyst temperature of 500°C. As a result, it was confirmed that a high reaction rate of about 70% could be maintained (Figure 9). As some reports have indicated a reaction rate exceeding 90%,[4,5] it is necessary to optimize the flow rate against the amount of catalysts. The rest 30% was unreacted CH_4 and byproducts were not observed by gas chromatography. Input power gradually increased and reached 1000 W. Observation of the catalysts during the reaction revealed an apparent gradual movement of the red-hot layer, and the amount of the carbon yield differed depending on the position in the catalysts. This suggested that the absorption condition of microwaves, which affect the catalyst temperature or reaction rate, differed depending on configuration of the reaction tube and catalysts, and the irradiation direction of microwaves. It is thus important to optimize the reaction configuration as well as the reaction conditions. The carbon formed by the reaction was in a powdery state and deposited between SiC layer and

mix catalysts layer. Contamination or poisoning of the catalysts by the formed carbon was not observed after 10 hours reaction. However, the yield carbon may infiill the flow path and disturb the reaction, so removing the yield carbon by mechanical means are under consideration.

In the future, in parallel with the scale-up test, we will clarify the microwave irradiation characteristics of the equipment. Also, we will cope with some technical challenges to improve TRL (Technical Readiness Level) such as handling the formed carbon and separation of H_2 from unreacted CH_4.

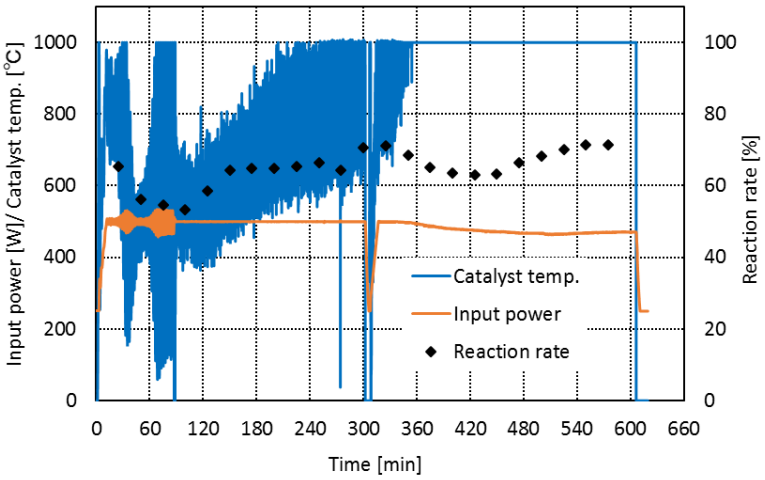

Figure 9 Methane decomposition rate and input power

VI. Summary

The development status of each subsystem of the air regeneration system in JAXA's closed ECLSS was introduced. In CO_2 removal system development, CO_2 from four crew members was collected by using the low and narrow range of temperature swing of a newly developed adsorbent. In the future, we will improve the temperature control, optimize the parameters by cyclic operation, and advance the system design. The fabrication of a full-scale test model of the CO_2 reduction system using a low-temperature catalyst has been completed, and the reaction rate and power consumption will be confirmed. For the O_2 generation system, long-term operation is ongoing to study the operating conditions of the water electrolysis cell for system design. For the methane decomposition system, we will acquire the fundamental data for scale-up, and then advance scale-up and establish the necessary technology.

References

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