Development of Experiment Equipment and Racks of the JEM-PM (Japanese Experiment Module-Pressurized Module)

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Japanese Experiment Module-Pressurized Module (JEM-PM) was launched to the International Space Station (ISS) on the STS-124 (1J) in June 2008. The experiment equipment (FPEF, SPCF, FPEF experiment cells, ICE cell, Facet cell, and JAXA PCG Cell) and experiment racks (RYUTAI rack, SAIBO rack) developed by IHI Aerospace (IA) under the contract with JAXA (Japan Aerospace Exploration Agency) were installed on JEM-PM. With these experimental cells, Japan performed experiments including Marangoni convection, ice crystal, and facet cell experiments from August 2008 to September 2009. This report describes experiment equipment and racks together with the results of experiments. The racks under development for launching in the future is outlined.

1. Introduction

The pieces for the Japanese Experiment Module (JEM : also called “Kibo,” which means “hope” in Japanese) for the International Space Station (ISS) were launched on three separate space shuttle missions between March 2008 and July 2009. The Pressurized Module, JEM’s main component, was launched on June 1, 2008 Japan time. Various types of space experiments have been conducted in this module since August 2008, and experiments continue to be conducted there today. The experiment equipment, which was developed by IHI Aerospace Co., Ltd. (hereinafter called IA), has been performing as intended and producing the expected experimental results.

IA developed the following in accordance with a contract they entered into with the Japan Aerospace Exploration Agency (JAXA) : ① experiment equipment for use in space experiments to be conducted in the Pressurized Module, ② features to supply electricity, gas, and other resources required for the operation of the experiment equipment, and ③ experiment racks that provide a support function for the obtaining and recording of experimental data. In order to continue to contribute to space experiments conducted on the ISS, IA is now developing new experiment equipment and racks for future space experiments.

2. Experiment equipment for the JEM pressurized module

2.1 JEM Pressurized Module (JEM-PM)

JEM consists of five main systems : ① the pressurized module, ② the exposed facility, ③ the experiment logistics module - pressurized section, ④ the experiment logistics module - exposed section, and ⑤ the remote manipulator system (**Fig. 1**). The pressurized module is a space experiment facility that provides the crew with an environment in which they can work with no special equipment, such as spacesuits.

The pressurized module (**Fig. 2**) is used for various types of space experiments using microgravity (e.g. material experiments, life science experiments, and space medicine experiments) as well as for education and public relations activities. It is a cylindrical structure with an outer diameter of about 4.4 meters, inner diameter of about 4.2 meters, total length of about 11.2 meters, and mass of 14.8 tons.

The pressurized module contains racks, which are box-shaped structures in which various types of equipment are installed. The racks are placed at four points around the circumference of the structure at six levels, five of which have four racks and the sixth has three, giving 23 racks in total (11 racks for system equipment and 12 racks for experiment equipment).

2.2 Experiment equipment in pressurized module

This section describes the experiment equipment developed by IA that is currently being used in the JEM-PM and the experiment racks in which this equipment is installed.

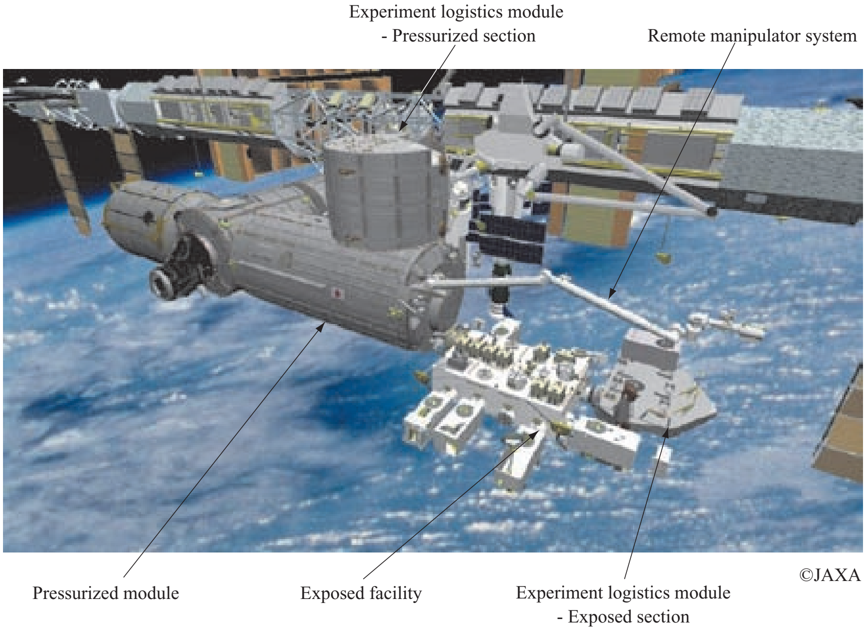

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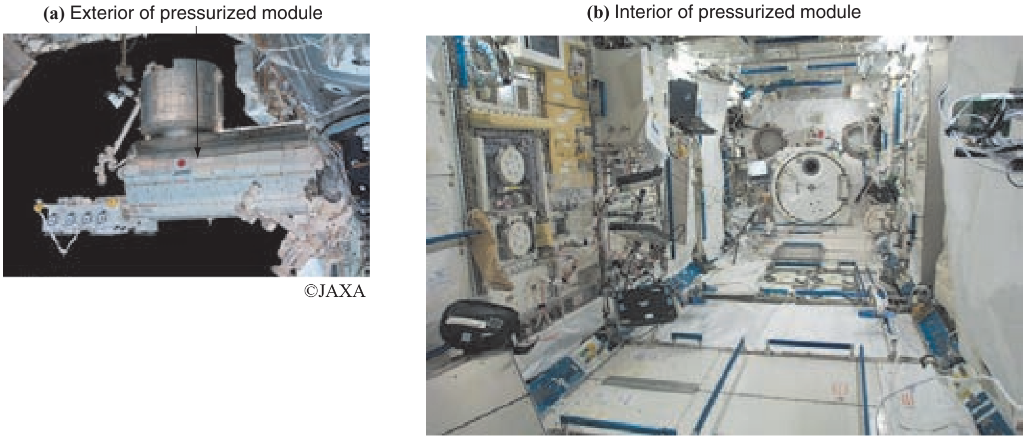
Fig. 1 Japanese Experiment Module (JEM, "Kibo")


(a) Exterior of pressurized module

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(b) Interior of pressurized module

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Fig. 2 Pressurized module of JEM

2.2.1 Experiment rack for cell biology experiment facility (Fig. 3) and experiment rack for fluid physics experiments (Fig. 4)

The experiment rack for the cell biology experiment facility (SAIBO rack) is equipped with experiment equipment (cell biology experiment devices and a clean bench) for cultivating plants and cells that is used to clarify the effect of a space environment on living matter. The experiment rack for fluid physics experiments (RYUTAI rack) is equipped with experiment equipment for conducting fluid physics experiments and crystal growth experiments to ① clarify the physical properties of fluids, ② clarify crystal growth mechanisms, and ③ develop crystal growth control technologies (see **Sections 2.2.2 and 2.2.3** for further details on experiment equipment developed by IA).

One of the difficulties the authors encountered in the development of the experiment racks was how to reduce the noise they emitted to a tolerable level (NC 40) for the space station. Due to the tight schedule under which the authors were obliged to operate in the simultaneous development of several pieces of experiment equipment and racks, there was no time for them to provide feedback regarding the reduction of noise from the experiment equipment, and noise from some pieces of equipment became apparent only after they had been installed on experiment racks. The authors tested sound absorbing materials to obtain data on their sound absorption coefficients, and then selected the optimum sound absorbing material accordingly. They also conducted noise tests for all of the experiment racks to measure their noise levels and employ countermeasures to address individual noise sources, before finally achieving a reduction in noise levels.

Fig. 3 SAIBO rack

Fig. 4 RYUTAI rack

As a result, the authors were able to achieve a reduction in noise for the Japanese experiment racks that was sufficient enough to enable the realization of a laboratory environment that is comfortable for the crew working on board, who have reported that JEM is quiet when actual operations are being performed in orbit.

2.2.2 Fluid physics experiment facility (Fig. 5)

The fluid physics experiment facility (FPEF) is installed on the RYUTAI rack in an environment close to normal room temperature. In a microgravity environment in space, natural convection has less influence, while Marangoni convection, which is caused by surface tension, is more obvious. This experiment equipment is designed mainly to facilitate observations of the effect of Marangoni convection on space experiments. Observations of Marangoni convection are considered to contribute to

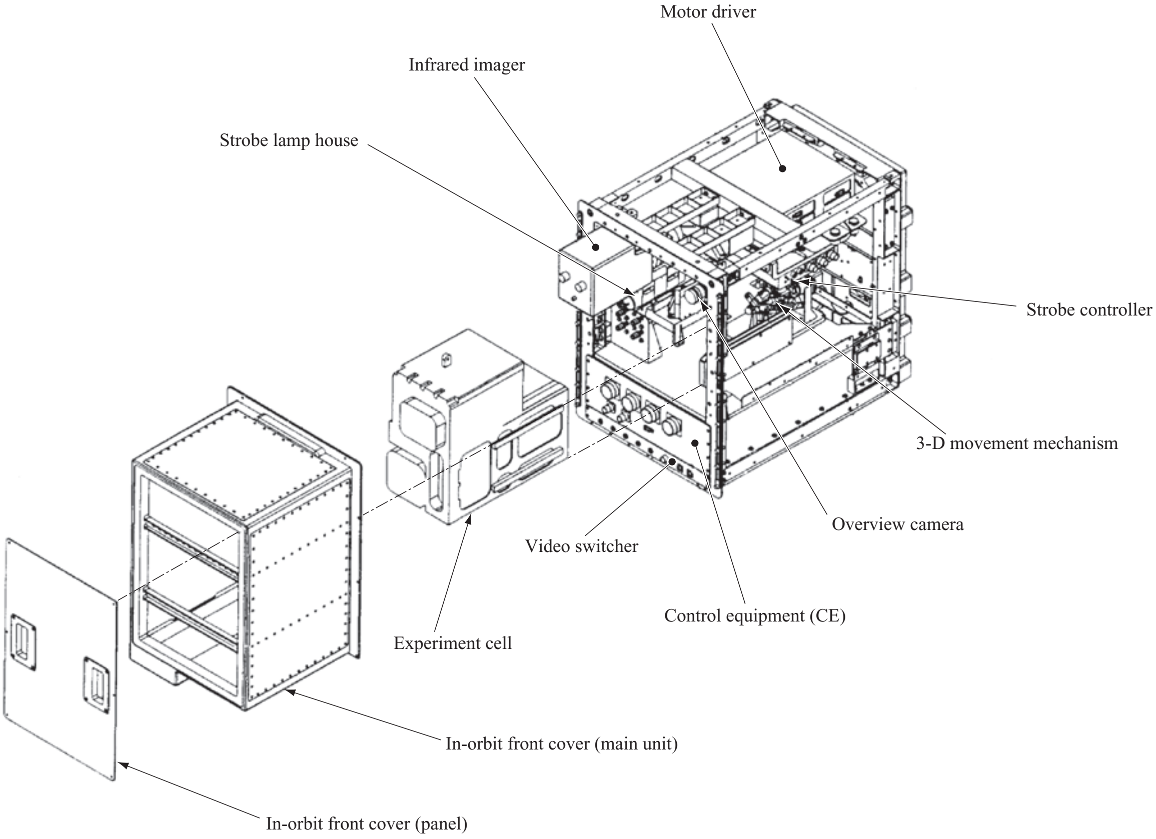


Fig. 5 Fluid physics experiment facility

its control by some type of physical means and its active utilization for bubble removal.

The FPEF has in-situ observation functions such as ① 3-D flow rate measurements, ② surface temperature measurements, ③ speed profile measurements using ultrasound, and ④ surface flow velocity observations. A study to observe Marangoni convection by forming silicone oil liquid bridges (cylinders made of silicone oil) has been adopted as a standard experiment. Some types of experiment cells (described in **Sections 2.2.4 and 2.2.5**) have been developed, and these are already being used for some experiments in space.

The authors had to equip the FPEF with as many observation devices, optical devices, electronic devices, and fluid components as possible within its space and weight limitations. There was no room in the structure design because of the need to equip the FPEF with many commercial off-the-shelf products that have unknown vibration resistance levels and weight limitations. The authors had to verify whether the FPEF is sufficiently resistant to vibration in a launch environment, which was one of the difficulties in developing the FPEF. To evaluate its resistance to vibration environments, they conducted acoustic and other tests on the FPEF, estimated an actual launch vibration environment, and confirmed that there was no problem in vibration resistance, enabling them to realize a high-density equipment design.

2.2.3 Solution/protein crystal growth facility

Installed on the RYUTAI rack, the solution/protein crystal growth facility (SPCF) consists of a solution crystallization observation facility (SCOF) and a protein crystallization research facility (PCRF).

(1) SCOF (**Fig. 6**)

The SCOF is an experiment facility that enables in-situ observations of crystal growth to be made. The shape of a crystal is related to the temperature, concentration, and other conditions of crystal growth. SCOF is equipped with various observation devices, such as an amplitude modulation microscope for the accurate observation of crystal shapes, a polarization microscope for the examination of crystal compositions, and a two-wavelength Mach-Zehnder microscopic interferometer.

The SCOF can be equipped with crystal growth cell cartridges, on each of which up to four crystal growth cells are mounted for the growing of crystals at controlled temperatures and pressures and the conducting of various kinds of in-situ observations. The cell cartridges can be replaced in orbit from the SCOF front operation panel operated by the crew, which provides many opportunities for experiments.

Experiments are automatically conducted according to preset experiment program parameters. It is possible to fine-tune the optical systems and change the

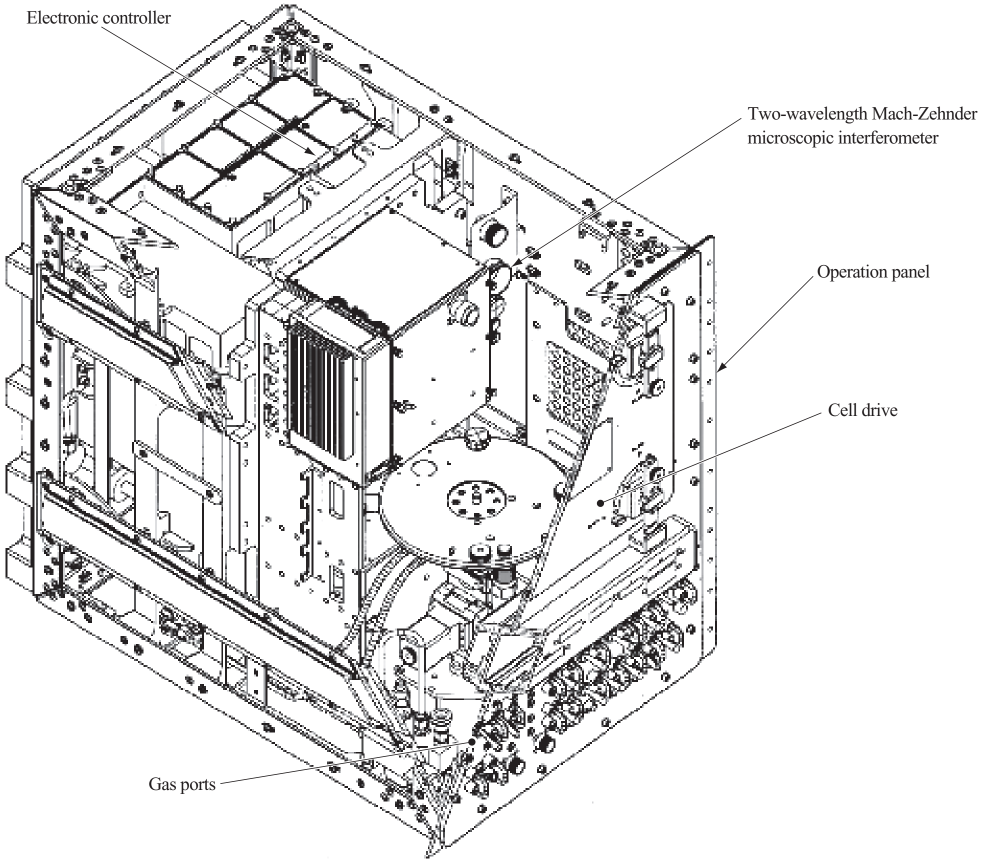


Fig. 6 Solution crystallization observation facility

experiment parameters during an experiment by using uplink commands from the ground.

(2) PCRF (**Fig. 7**)

The PCRF is an experiment facility designed to conduct crystallization experiments under as many different conditions as possible in order to clarify the crystallization conditions of specimens such as proteins and nucleic acids. The PCRF contains six cell cartridges, on each of which up to six cell units are mounted for the growing of crystals under controlled temperature conditions in many crystal growth cells and the monitoring of individual cells at fixed intervals using charge-coupled device (CCD) cameras.

The cell units can be replaced in orbit from the PCRF front operation panel operated by the crew, which provide many opportunities for experiments. Experiments are automatically conducted according to preset experiment program parameters. It is possible to fine-tune the optical systems and change the experiment parameters during an experiment by using uplink commands from the ground.

2.2.4 General-purpose experiment cells for liquid bridge marangoni convection (MS30 and MI50) (Figs. 8 and 9)

General-purpose experiment cells for liquid bridge Marangoni convection (hereinafter called general-purpose experiment cells) are installed in the FPEF. These experiment cells can form liquid bridges in microgravity environments, and heat and cool both ends of these bridges to generate Marangoni convection in them.

The general-purpose experiment cells can be roughly divided into MS30 and MI50 cells. The former are experiment cells for the surface observation of liquid bridges with a diameter of 30 mm. The latter are experiment cells for the cross-sectional observation of liquid bridges with a diameter of 50 mm.

MS30 experiment cells enable observations to be made of flows on liquid bridge surfaces by utilizing the phenomenon that special dyes mixed with silicone oil react with ultraviolet lasers to generate colors.

MI50 experiment cells enable the following to be performed by utilizing the FPEF observation functions and the MI50 observation and measurement functions : ① 3-D observations of flows in liquid bridges (using a FPEF 3D camera), ② liquid bridge surface temperature measurements (using FPEF infrared cameras), ③ observations of the entire liquid bridge (using FPEF CCD cameras), ④ measurements of flow velocities in liquid bridges (using MI50 experiment cell ultrasonic velocity meters), and ⑤ measurements of temperatures in liquid bridges (using MI50 cooling disc thermocouples and thermocouples inserted into the liquid bridges radially).

2.2.5 Experiment cells for the microscopic imaging displacement meter in the FPEF (MD10 and MD30) (Fig. 10)

Experiment cells for the microscopic imaging displacement meter (MIDM) in the FPEF are used for observations of changes in liquid bridge interfaces caused by the heating and cooling of both ends of silicone oil liquid bridges formed under certain conditions, which generates vibrating Marangoni convection. These experiment cells can be divided into two types, MD10 and MD30 cells, which are designed for liquid bridge diameters of 10 mm and 30 mm, respectively.

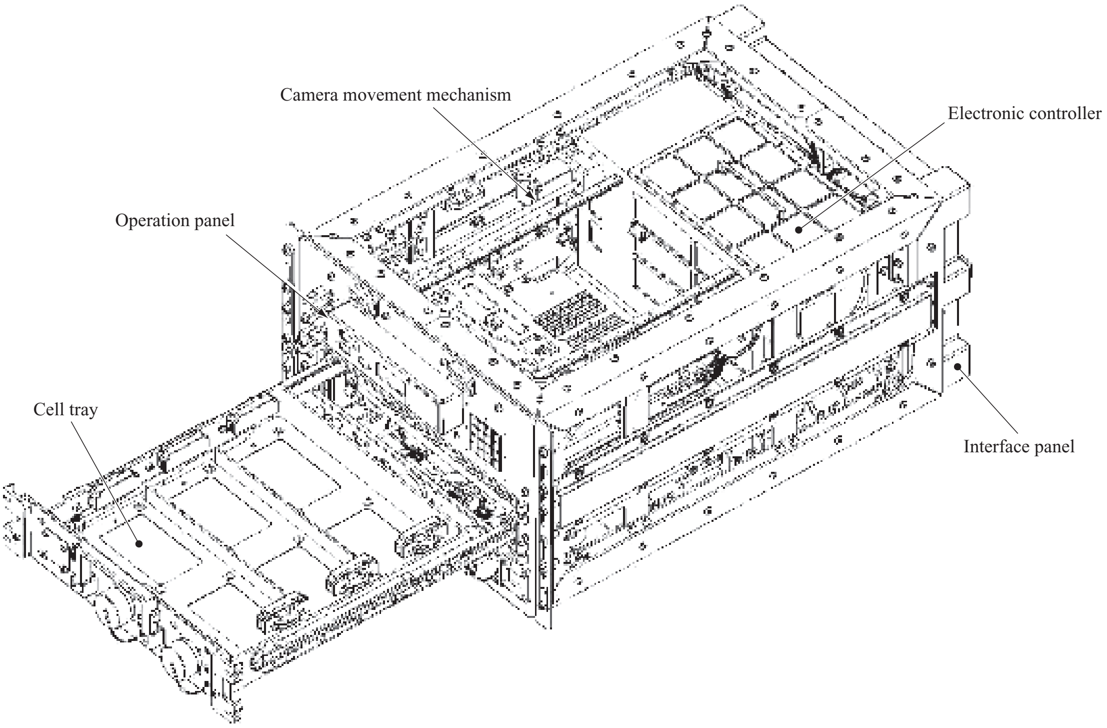


Fig. 7 Protein crystallization research facility

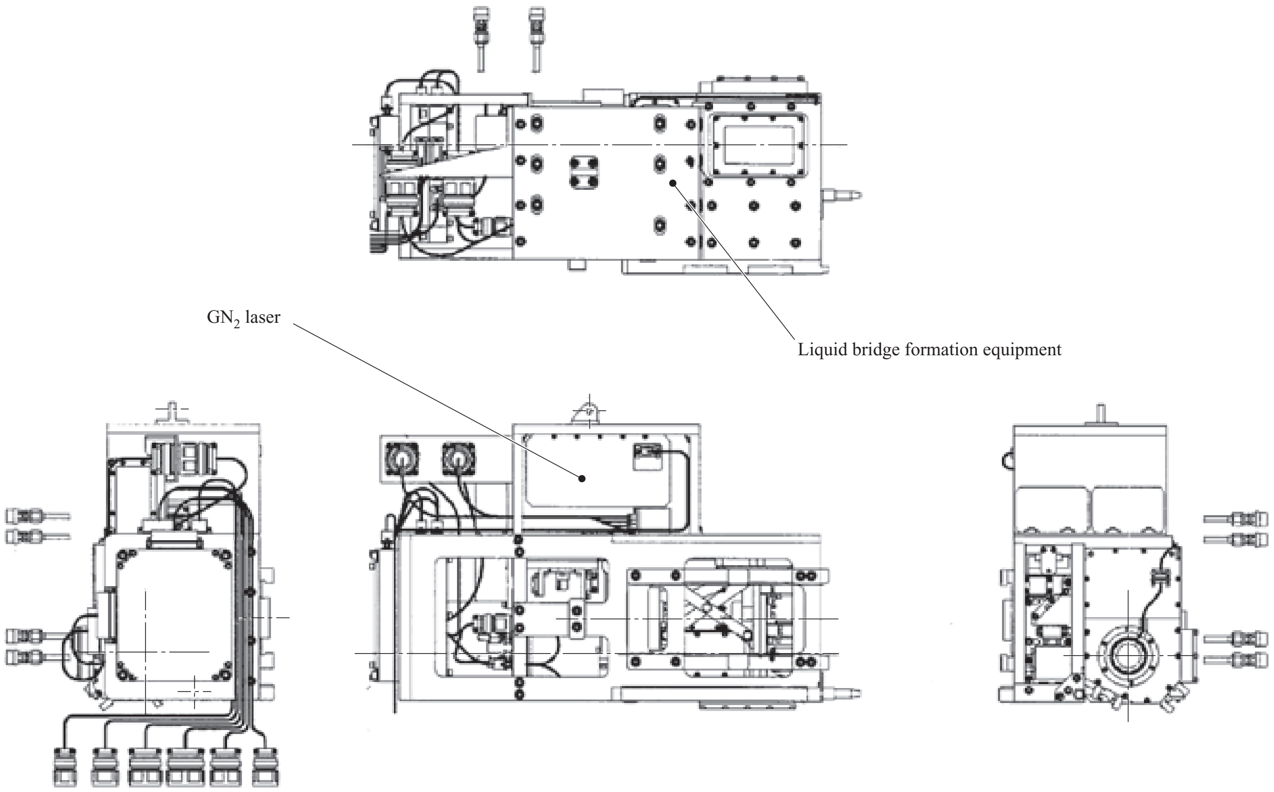


Fig. 8 FPEF experiment cell (MS30)

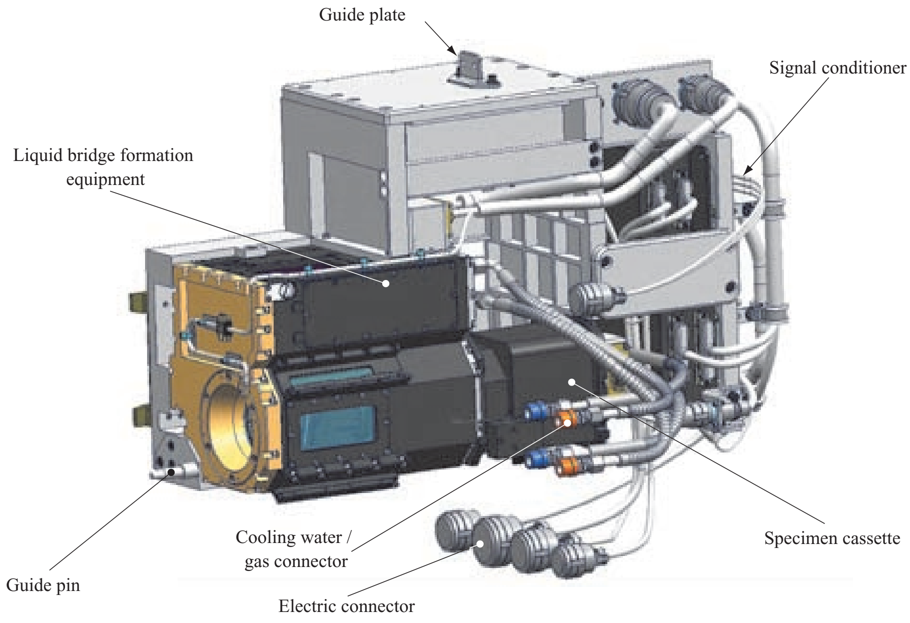
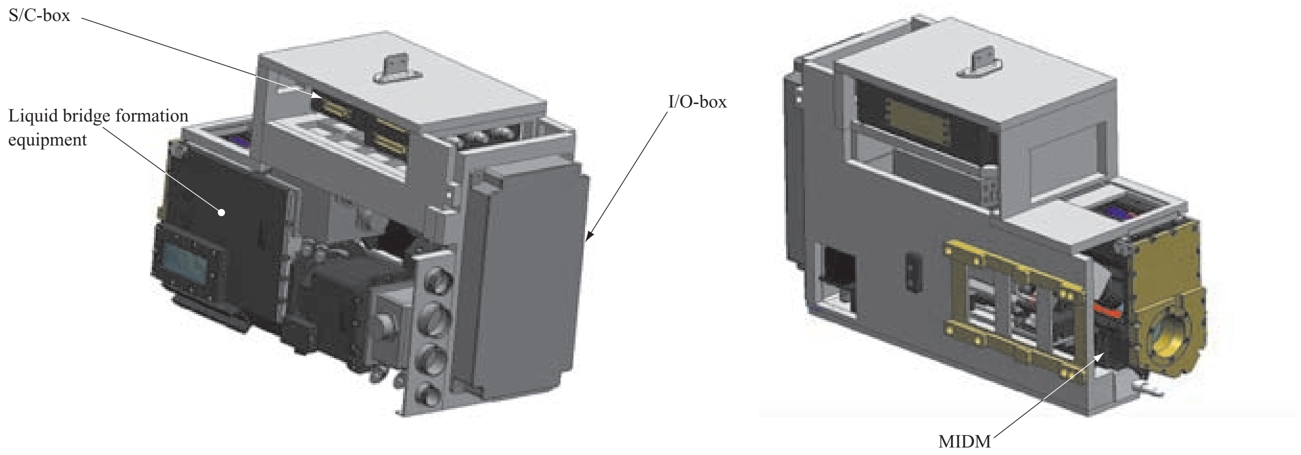


Fig. 9 FPEF experiment cell (MI50)

2.2.6 High-quality protein crystal growth experiment cell unit (JAXA PCG) (Fig. 11)

The high-quality protein crystal growth experiment cell unit (JAXA PCG) is an experiment cell mounted in the PCRF to enable protein crystal growth experiments to be conducted. It contains a JAXA crystallization box unit (JCB : a crystallization container developed by JAXA) and a Granada crystallization box unit (GCB : a crystallization box developed by the European Space Agency (ESA) and the University of Granada, Spain). Protein crystallization experiments are conducted in the JCB and GCB at certain temperatures controlled by the PCRF and JAXA PCG.

Crystallization is achieved inside the JCB and GCB by using a method called liquid-liquid diffusion, in which a protein solution and a crystallization solution are diffused in opposite directions inside a capillary via a gel layer. In



(Note) S/C : Signal conditioner

Fig. 10 FPEF experiment cell (MD30)

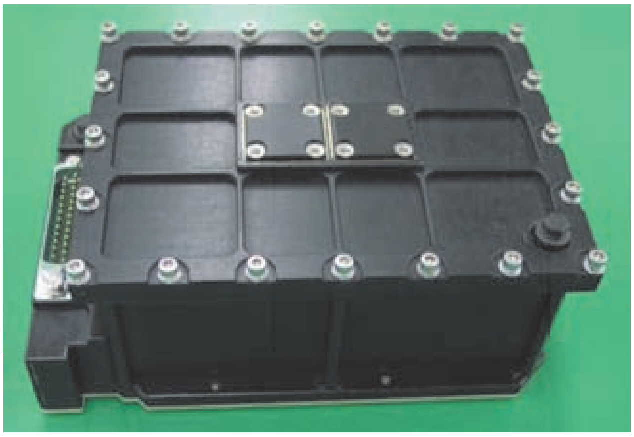


Fig. 11 JAXA PCG cell

other words, protein diffuses out of the capillary, while the crystallization solution diffuses into the capillary. The resultant concentration gradient changes over time, with the crystallization beginning when and where the crystallization conditions are satisfied.

The JAXA PCG consists of ① an air-tight cell structure that ensures a mechanical and thermal interface with the PCRF, ② a holder that secures the JCB and GCB to the cell structure, and ③ a temperature measurement and control device that measures and controls the temperatures of the JCB and GCB.

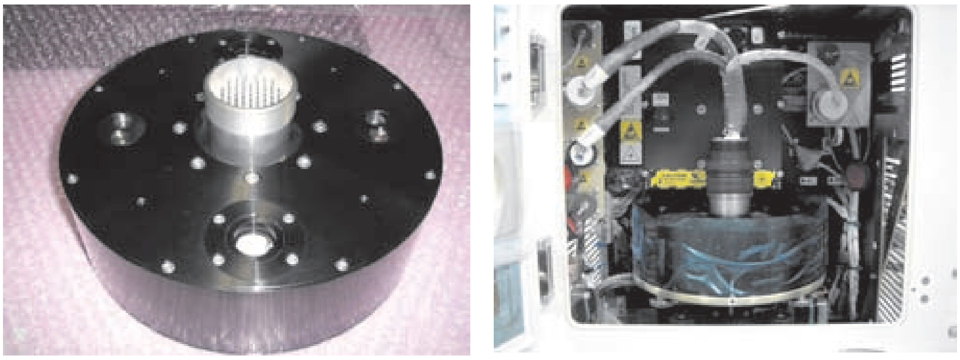
NTC thermistors are used to measure the temperature at two points (temperature range : 0 to 35°C). Peltier elements are used to maintain the temperature at 20°C (allowable temperature range : 0 to 35°C).

2.2.7 Facet crystal growth experiment cell (Fig. 12)

The facet crystal growth experiment cell (hereinafter called facet cell) is an experiment cell mounted in the SCOF to enable solution crystal growth experiments to be conducted.

A salol-butanol solution specimen is charged in a silica glass cell and a high-temperature block in the facet cell. The glass cell is maintained at a lower temperature at one end and a higher temperature at the other end in order to generate a temperature gradient within the specimen, thereby forming a solid-liquid interface at a point where the specimen temperature is equal to its melting point. This state is maintained so as to homogenize the concentration of the solution, and both ends of the glass cell are cooled at the same speed so that the solid-liquid interface begins crystallizing near the warmer end (unidirectional solidification).

The interface remains flat during homogenization, and



(a) Facet cell

(b) Facet cell mounted in the SCOF

Fig. 12 Facet cell

then becomes increasingly facet shaped (i.e. shaped like a crystal with small surfaces) as the crystallization proceeds. The crystal shape is observed under an amplitude-modulation microscope mounted on the SCOF. Interference images near the interface are obtained by using a two-wavelength Mach-Zehnder microscopic interferometer mounted on the SCOF.

The facet cell has a function that enables a crystal to be grown in a specimen that has been introduced into a specimen cell enclosure under controlled temperature conditions in a nitrogen gas atmosphere. The temperature can be maintained at a point between the ambient temperature and 90°C at the high-temperature end and between -10°C and the ambient temperature at the low-temperature end, with a gradient of 10 to 20 K/cm.

2.2.8 Type II ice crystal cell (Fig. 13)

The type II ice crystal cell (hereinafter called ICE cell) is an experiment cell mounted in the SCOF to enable solution crystal growth experiments to be conducted. A heavy water specimen (D_2O : melting point 3.82°C) is introduced into a specimen cell (mainly composed of a nucleation cell and a crystal growth cell) in the ICE cell.

The specimen cell is housed in an enclosure maintained with a nitrogen gas atmosphere. The crystal growth cell is maintained in a supercooled state ($\Delta T = 0.3$ to 1.0 K), after which the nucleation cell is cooled to about −5 to −8°C so as to generate a nucleus of ice crystal in the nucleation cell. The generated nucleus grows one-dimensionally through a glass capillary, escaping through the end of the capillary into the crystal growth cell, where it then grows freely. Growth of the ice crystal is observed in-situ along two orthogonal axes under the two-wavelength Mach-Zehnder microscopic interferometer and amplitude modulation microscope mounted on the SCOF, as well as with the Mach-Zehnder interferometer and a bright-field microscope mounted in the ICE cell.

The ICE cell has a specimen cell (composed of a crystal growth cell and a nucleation cell) to which a specimen (heavy water) is charged, and its functions are ① controlling the specimen temperature, ② growing the ice crystal, and ③ observing the crystal. The temperature can be maintained between 2.8 to 3.8°C in the crystal growth cell and between the ambient temperature and -10°C in the nucleation cell. The following devices can be used for observations : ① a Mach-Zehnder interferometer with a laser diode (LD) light source (wavelength : 670 mm) at a magnification of one using a 1/2-inch CCD monochrome camera as the video device, and ② a bright-field microscope with a light-emitting diode (LED) light source (wavelength : 590 mm) at a magnification of one using a 1/2-inch CCD monochrome camera as the video device.

3. Experiment results

A variety of space experiments have been conducted in the pressurized module since August 2008. The experiment equipment and racks have been performing almost as intended, demonstrating the authors' success in developing experiment equipment to produce the world's first experiment results in the areas described above.

3.1 Marangoni convection experiments

A Marangoni convection experiment was conducted using general-purpose experiment cells (MS30) by a team of researchers led by Dr. Kawamura, Professor at Tokyo University of Science, Suwa (experiment theme : "Chaos, Turbulence, and its Transition Process in Marangoni Convection"). The team successfully formed liquid bridges with a diameter of 30 mm and a length of about 60 mm (**Fig. 14**) and obtained the experiment data they had expected.

It is not possible to form silicone oil liquid bridges with a length of 60 mm on Earth, so this is the first time that detailed and clear experiment data have ever been obtained on such large liquid bridges. The data is expected to provide new knowledge and results that will contribute to clarifying the phenomenon of liquid bridge Marangoni convection.

3.2 Ice crystal growth experiment

An ice crystal growth experiment was conducted for

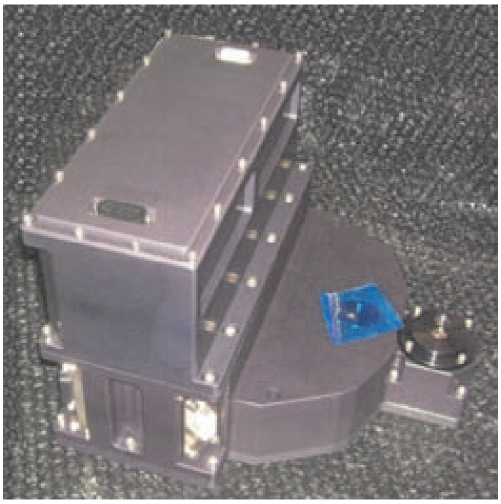


Fig. 13 ICE cell

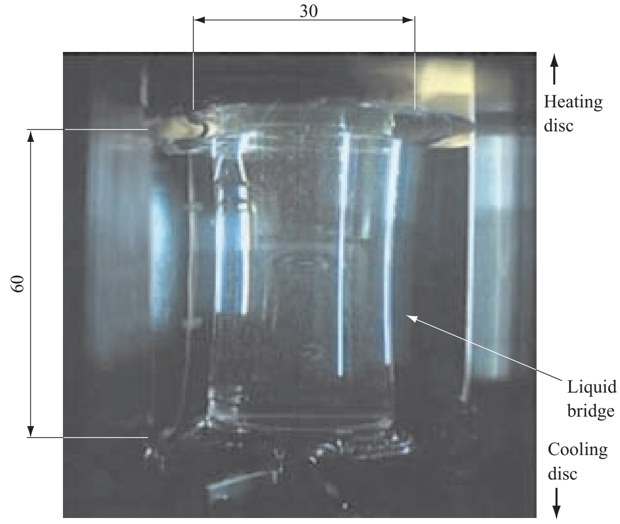


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Fig. 14 Liquid bridges formed in MS30 (unit: mm) the first time in space using the ICE cell by a team of researchers led by Dr. Furukawa, Professor at Hokkaido University (experiment theme : "Pattern Formation during Ice Crystal Growth"). Over 130 experiments were conducted, more than had been planned, over a period of about three months from December 2008. Crystal shapes, growth speeds, and local temperature changes around the crystals were observed, and a great deal of data was obtained from the experiment. The team is now analyzing and evaluating the data in detail.

3.3 Protein crystal growth experiments in space

The JAXA PCG was used to conduct protein crystal growth experiments. The experiment equipment performed as intended until the end of the experiments. The JAXA PCG was returned to Earth (Russia) on October 11, 2009. The specimens will be brought back to Japan for detailed analysis and evaluations to determine, among other things, whether crystals grew.

Table 1 Japanese experiments to be conducted in the JEM-PM

Type of experiment	No.	Experiment theme	Experiment equipment	Experiment rack
Life science field (8 themes)	1	Studies on the role of auxin efflux facilitators in the gravity-influenced growth and development of plants	Cell biology experiment facility	SAIBO rack [*1]
	2	Gravity resistance mechanisms in plants: From signal transformation and transduction to response	Cell biology experiment facility	SAIBO rack
	3	Regulation of bone metabolism in space: Analysis using an in-vitro assay system with goldfish scales used as a model for bone	Cell biology experiment facility	SAIBO rack
	4	Hypothesis testing of the osteopontin function	Cell biology experiment facility	SAIBO rack
	5	Detection of male germ cell mutagenesis in a space environment using Japanese killifish as a model for vertebrates	Aquatic habitat (AQH)	Multipurpose small payload rack
	6	Analysis of blood circulation in space	Aquatic habitat (AQH)	Multipurpose small payload rack
	7	Study of microbiota on board the ISS and their relationship to health problems	—	—
	8	Structure and functional relationship of erythrocyte band 3 proteins	Protein crystallization research facility (PCRF)	RYUTAI rack [*2]
Material science (6 themes)	9	In-situ observation of growth mechanisms of protein crystals and their perfection under microgravity	Solution crystallization observation facility (SCOF)	RYUTAI rack
	10	Crystal growth mechanisms associated with macromolecules adsorbed at a growing interface : Microgravity effect on self-oscillatory growth	Solution crystallization observation facility (SCOF)	RYUTAI rack
	11	Interface susceptibility and control of instability in thermocapillary convection	Fluid physics experiment facility (FPEF)	RYUTAI rack
	12	Crystal growth of alloy semiconductors under microgravity	Gradient heating furnace (GHF)	KOBAIRO rack [*3]
	13	Elucidation of flame spreading and group combustion excitation mechanism of randomly-distributed droplet clouds	Combustion experiment facility	Multipurpose small payload rack
	14	Establishment of database regarding microgravity boiling and two-phase flow for the design of high-performance thermal management systems in the next generation of space development	Two-phase flow experiment facility	Multipurpose small payload rack

(Note) *1 : Experiment rack for cell biology experiment facility
*2 : Experiment rack for fluid physics experiment facility
*3 : Experiment rack for gradient heating furnace

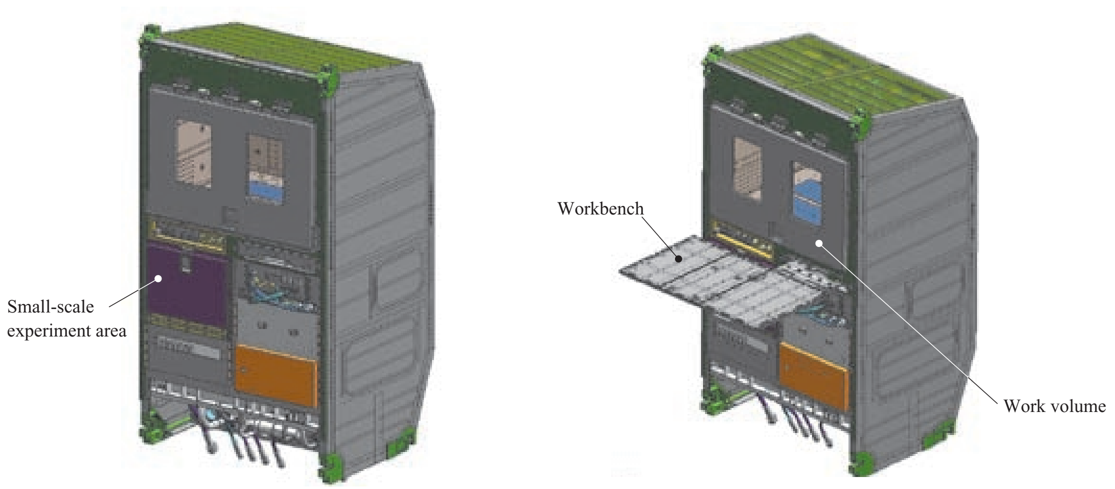
(a) For launch
(b) For operation in orbit

Fig. 15 Multipurpose small payload rack

4. Development of future experiment equipment

Fourteen themes have been selected for space experiments to be conducted in the pressurized module by fiscal 2011 (**Table 1**). IA has already begun development of the experiment equipment and racks that will be required for some of these experiment themes.

IA is now developing a multipurpose small payload rack as described below.

A multipurpose small payload rack (**Fig. 15**), equipped with experiment spaces and a workbench that can be used in the same way as laboratories on Earth are, is being developed for various types of space experiments to be conducted in the pressurized module. At present, it is assumed that, in addition to being used for educational, cultural, and other types of events, this rack will be used for ① combustion experiments, ② two-phase flow experiments, and ③ aquatic organism experiments.

The multipurpose small payload rack has a work volume and small-scale experiment area that will serve as a space in which experiments can be conducted and a workbench that will serve as a work table. It provides electricity, a communication system, and fluid resources for experiment equipment and other users. It is now under development, with a view to its being launched with the H-II Transfer Vehicle (HTV) in fiscal 2010.

5. Conclusion

Through the development of JEM-PM experiment equipment and racks, the authors obtained the design techniques required to reduce the level of noise emitted by the experiment equipment, the techniques required to develop experiment equipment that utilizes commercial-off-the-shelf products, and the know how required to realize a high-density equipment designs. The experience they have gained will prove invaluable in their future designing, development, and verification of experiment equipment. IA hopes to make use of these achievements in the development of experiment equipment and racks for future space experiments and to continue to play a substantial role in space experiments.

— Acknowledgements —

The authors would like to extend a special thank you to those persons at the Japan Aerospace Exploration Agency (JAXA) who provided them with guidance and cooperation in their development of the JEM-PM experiment equipment and racks.