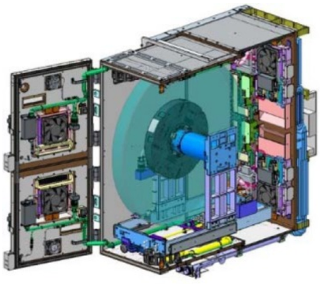
Development of Large-scale Centrifuge Facility for the International Space Station



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One of the most important aims of life science experiments in space is to study the effects of gravity on life, which is always subject to the earth's gravity. Such experiments have been carried out in orbiting artificial satellites and space shuttles. To identify the effects of gravity itself on orbit, it is important to create stable control experiment environments where other parameters, such as cosmic rays and electromagnetic waves are as identical as possible, and to specify the effect only of gravity. Creating on-orbit experiment conditions is difficult in ground-based experiments, but creating gravity in orbiting laboratories is easier, ensuring better contrast experiments. In order to create a gravitational environment in orbiting laboratories, gravity can be created by rotation part to generate centrifugal force on it. Larger rotation diameters are better to reduce the effects of Coriolis force and gravity gradients, but there is space limitation to the space available for spacecraft. In Kibo, the Japanese experiment module in the International Space Station (ISS), there is an orbiting experiment facility for centrifugal life science experiments. The facility has one of the largest rotation diameters in ISS by optimizing the available laboratory space. This facility can create gravity less than 1G by centrifugal force, which is difficult to create in ground-based facilities and keep it stable for a long time. The facility also can simulate gravity equivalent to such as Luna surface and Mars. Mitsubishi Heavy Industries, Ltd. (MHI) developed the experiment facility with a large centrifuge (rotation radius: 38 cm), which has operated since 2020. This report outlines the development and the first mission of the facility.

1. Introduction

Under the contract between the Japan Aerospace Exploration Agency (JAXA), MHI has developed several experimental facilities aboard ISS such as a cell biology experimental facility, an aquatic habitat and a mouse habitat unit. **Table 1** the development results of the life science experiment facilities.

The Cell Biology Experiment Facility (CBEF) is the first experiment facility equipped with a centrifuge. Since the operational start of Kibo in 2008, CBEF has served as the experimental base many times.

CBEF was upgraded to meet the requirements for mice habitat missions and to replace the control device with a newly-developed high fault-tolerance unit. To supplement CBEF, MHI started to develop Cell Biology Experiment Facility-Left (CBEF-L) in 2014 to mount a larger centrifuge. The first on-orbit mission using CBEF-L was successfully completed in 2020. The operational results of the original CBEF unit, the development outline and the first mission results of CBEF-L with a larger centrifuge are described from the next chapter.

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Table 1 Life science experiment facilities aboard ISS

Operational start	Name	Abbreviation	Description
2008	Cell Biology Experiment Facility	CBEF	Incubator with 17.5 cm radius centrifuge
2012	Aquatic Habitat	AQH	- Freshwater fish breeding such as killifish for 90 days - Water quality maintenance and observation functions
2016	Mouse Habitat Unit	MHU	- Mice breeding for 30 days - Feeding, water supply and observation functions
2020	Cell Biology Experiment Facility-Left	CBEF-L	Incubator with 38 cm radius large-type centrifuge

2. Operational results of the original CBEF unit with centrifuge

CBEF has served as the experimental foundation not only for cell culture, but also for plant cultivation. Most of the CBEF's basic functions as an incubator, such as controlling temperature, humidity and CO_2 concentration, are similar to those of ground-based experiment products. But CBEF has a centrifuge inside its incubator, ensuring it can apply artificial gravity and microgravity on specimens. CBEF is the world's first experimental facility capable of focusing on gravity itself by applying artificial gravity and microgravity on the specimen at the same time for comparison. It was considered to be impossible* to compare the effects deriving from only gravity.

(*: In the past, samples of on-orbit microgravity experiments were subject to gravitational acceleration effects due to launching and retrieving. So, it was impossible to eliminate the gravitational acceleration effects when comparing them with ground-based samples.)

In 2016, CBEF was used in a mice habitat mission for studying the long-term effects of gravity on mice bred in space for about one month. In 2016, an upgraded model compatible with CBEF was developed to increase its fault-tolerance and to add a new motor drive for larger centrifuge operation (described later). As of 2021, CBEF has still operated since the first operation in 2008 through several component replacements.

3. Development and mission results of CBEF-L with larger centrifuge

3.1 Facility overview

CBEF-L, installed next to CBEF (original unit), applies experimental environments to specimens. **Figure 1** shows the appearance, **Figure 2** illustrates the composition tree and **Table 2** lists the main specifications.

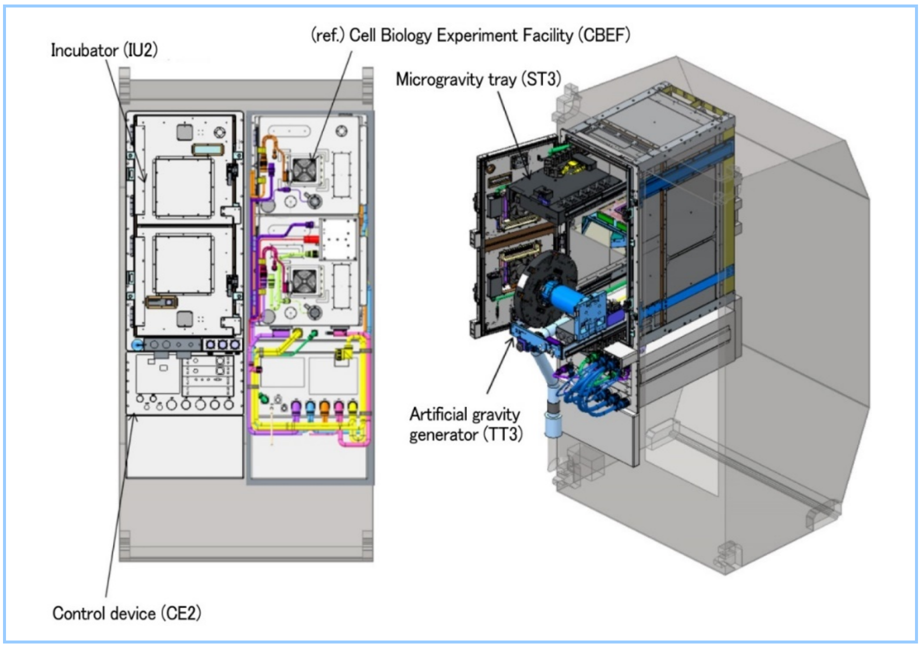

Figure 1 Appearance of CBEF-L

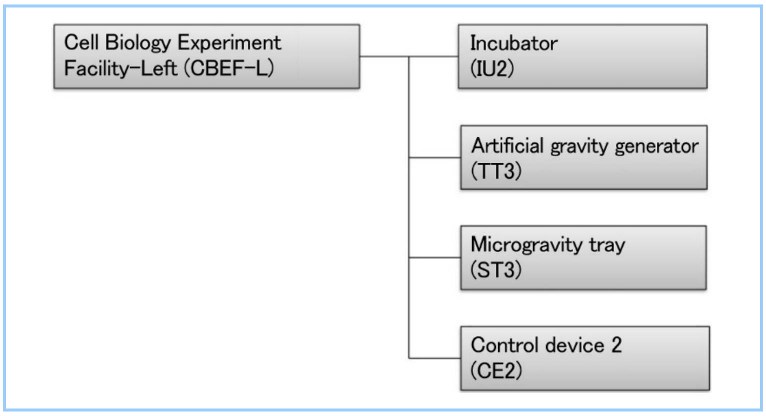

Figure 2 Main composition tree of CBEF-L

Table 2 Main specifications of CBEF-L

Incubator environment control	Temperature control	Control range: 15-40 deg.C Temperature distribution: ±1°C
	Humidity control	Control range: 30-65% (humidification only) Control accuracy: ±5%
	CO_2 control	Control range: 0-10% Vol (Minimum concentration depends on the environment)
Artificial gravity control	Rotation radius	Standard: 175 mm **Large: 380 mm**
	Rotation speed control (standard)	Control range: 15-140 rpm Control accuracy: ±2 rpm
	Rotation speed control (Large)	**Setting range: 15-82 rpm** **Control accuracy: ±1 rpm**
User Utility	Power	DC +5V, +12 V, +/- 15 V, **+24 V** **(Up to 190 W total power)**
	Communication	RS485 (LAN conversion) **LAN (Ethernet)**
	Video	NTSC (balanced) 1ch NTSC (unbalanced) 6ch＋2ch **HD-SDI 12ch**

Underlined portions indicate functions added to or upgraded from the original CBEF

As for artificial gravity environment, the most significant differences from CBEF include the larger-radius rotation (more than double) and higher-accurate rotation control. These features make it possible to handle larger specimens and to reduce gravity gradients (i.e., gravity differences due to the differences in sample positions in the radial direction), expanding experimental environment options. The incubator configuration is much more flexible, so astronauts can use various options (**Figure 3**).

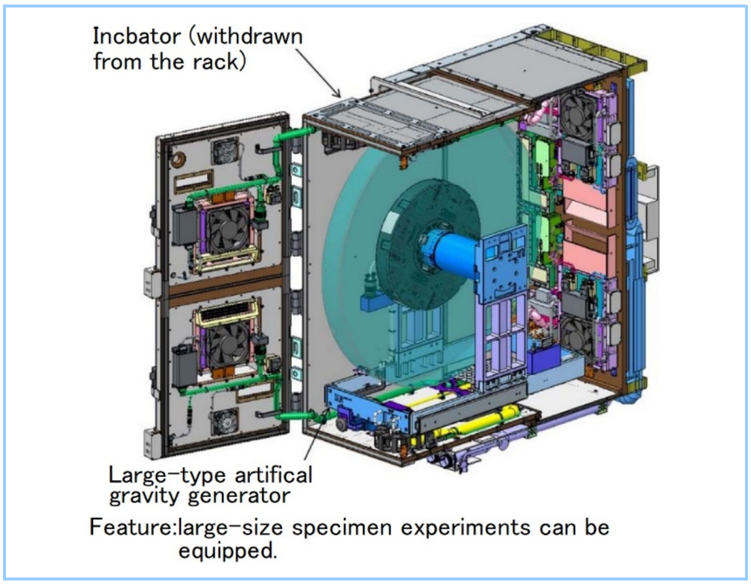

Figure 3 Configuration example No. 1 (Large-type artificial centrifuge equipped)

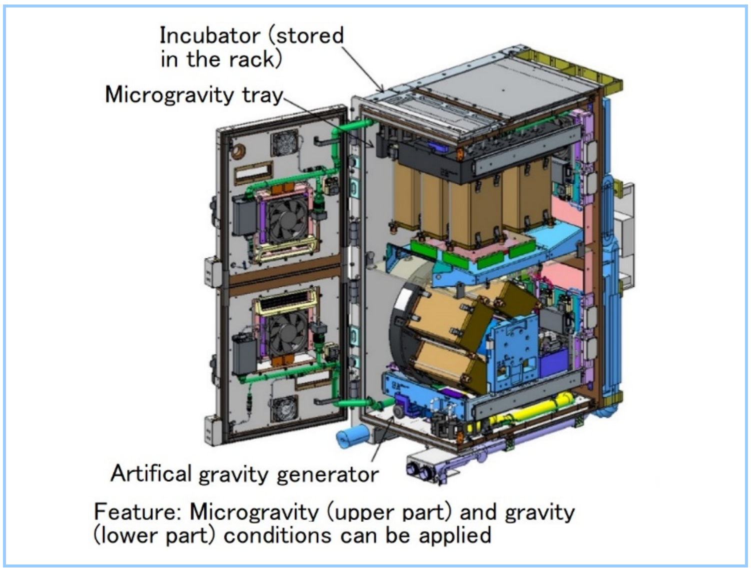

Figure 3　Configuration example No. 2 (Standard centrifuge and microgravity tray equipped)

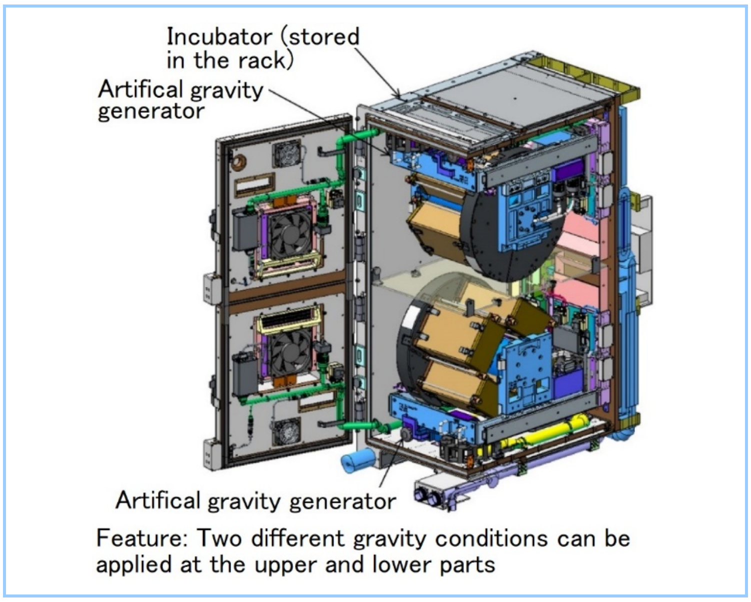

Figure 3　Configuration example No. 3 (Two standard centrifuges equipped)

Furthermore, as the main difference from CBEF, an Ethernet interface has also been added and the incubator's exhaust heat capacity has been improved to increase the power supply for specimens by twice.

The main components are explained below.

(1)　Incubator

The incubator is stored in the experimental rack of Kibo's laboratory. The incubator creates experimental environments using power, data communication, cooling water, CO_2, etc., from supply systems.

To balance lower cost, higher strength and better thermal insulation, the structure has been changed from the original resin honeycomb structure to a double wall structure (aluminum outer wall, resin inner wall) with a vacuum insulation material inserted between the double walls. The telescopic structural side walls allow the configuration variations mentioned above. The volume of the incubator is variable depending on the experiments (**Figure 4**).

As other features, the structural strength is sufficient to withstand unexpected collisions with crew members and the insulation and airtightness is sufficient to maintain the air temperature and CO_2 concentration of the internal environment.

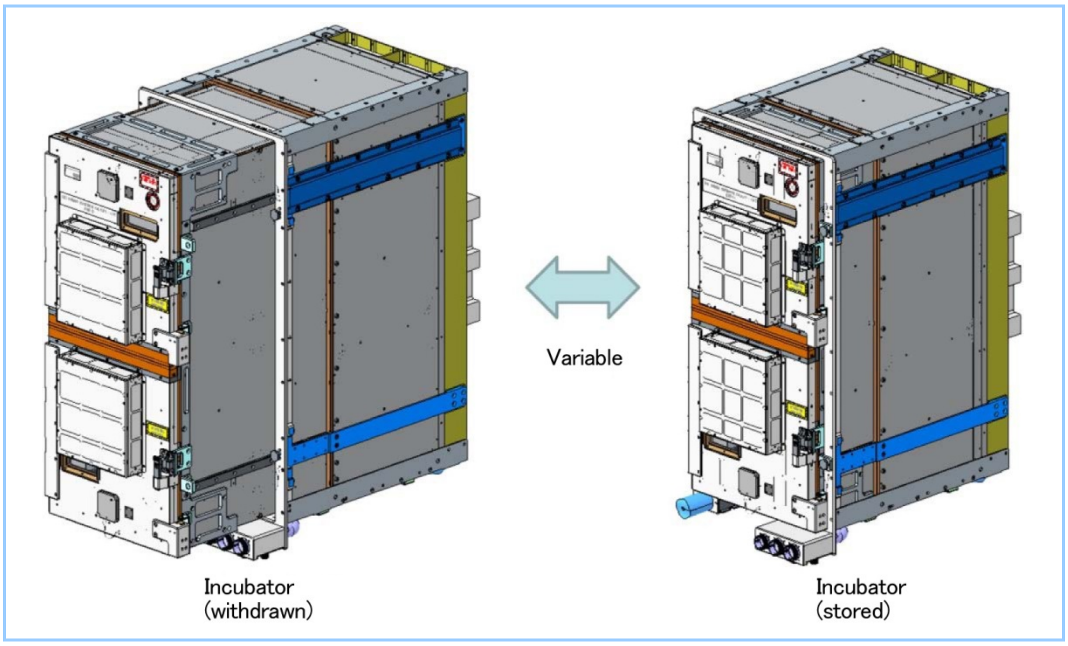

Figure 4 Incubator withdrawn from the rack (left) and stored in the rack (right)

(2) Artificial gravity generator, microgravity tray

The artificial gravity generator and microgravity tray are placed inside the incubator (experimental area). These components support the specimen and provide power and data communication.

Artificial gravity generator: Provides artificial gravity environments from 0.1 to 2G

Microgravity trays: Provide microgravity environments (gravity environments of Kibo)

As for the artificial gravity generator, the rotation diameter can be changed by replacing the frame and the rotation part with the motor is shared (**Figure 5**). The communication functions have been upgraded from CBEF, ensuring Ethernet and high-definition video communication. The microgravity tray also has the same functions. Multipole slip rings and optical fibers enable power and data communication interfaces with specimens placed on the rotating parts.

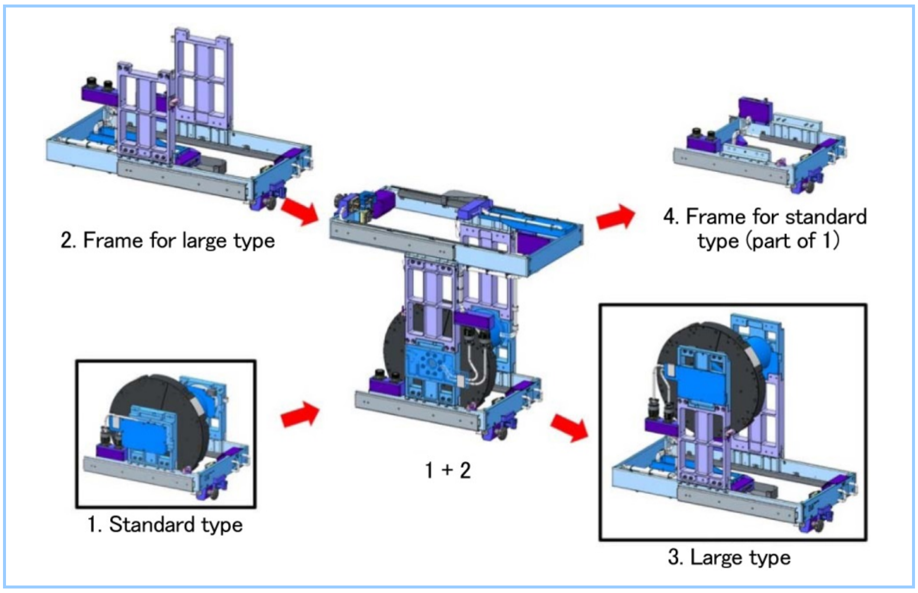

Figure 5 Various configurations of artificial gravity generator

(3) Control device

The control device has the same basic configuration as that developed as a spare of CBEF. The device receives power from the power distributor of the experimental rack, supplies power to the equipment, sensors and specimens and conducts measurement, control and data collection. Between the control device and the ground-based operation systems, real-time interactive communication such as command uplink and telemetry data downlink is possible through Ethernet and MIL-STD-1553 line using Kibo's communication system.

The control device consists of the housing and boards. The boards are mounted on the housing and each board can be replaced, fixed, maintenance and supplied separately in orbit. The installed software can be upgraded by file transfer through Ethernet.

The motor driver board for create artificial gravity generation was newly developed for CBEF-L. This device can control two artificial gravity generators simultaneously and has additional functions such as acceleration/deceleration control and more accurate speed control. The acceleration/deceleration control can be finely adjusted, allowing the handling of specimens sensitive to rapid gravity changes. Larger centrifuges are subject to higher influence of rotational speed fluctuation on the circumference due to the larger rotating diameter compared to standard devices. As a solution, the position detection sensor of the artificial gravity motor, the motor driver circuits and the control software were re-evaluated, resulting in higher control accuracy compared with CBEF.

3.2 First mission

CBEF-L was first used in the 5th on-orbit mice habitat mission. MHI's Mouse Habitat Unit (MHU), Japan's first small animal habitat device in space developed under contract with JAXA [(1)], was used in the mission. As of 2021, CBEF-L has operated in six missions for small animal habitat missions since its first operation in 2016.

Originally, mice habitat cages were developed for mounting on both the small-diameter artificial gravity generator and the microgravity tray. But in the first mission of CBEF-L, the already-developed habitat cages were used by developing only the interface between the cages and the large centrifuge (**Figure 6**). After the long-term low-gravity small animal habitat mission under 1/6 of gravity on the Earth, equivalent to the moon's surface gravity, all the mice survived and returned to Earth.

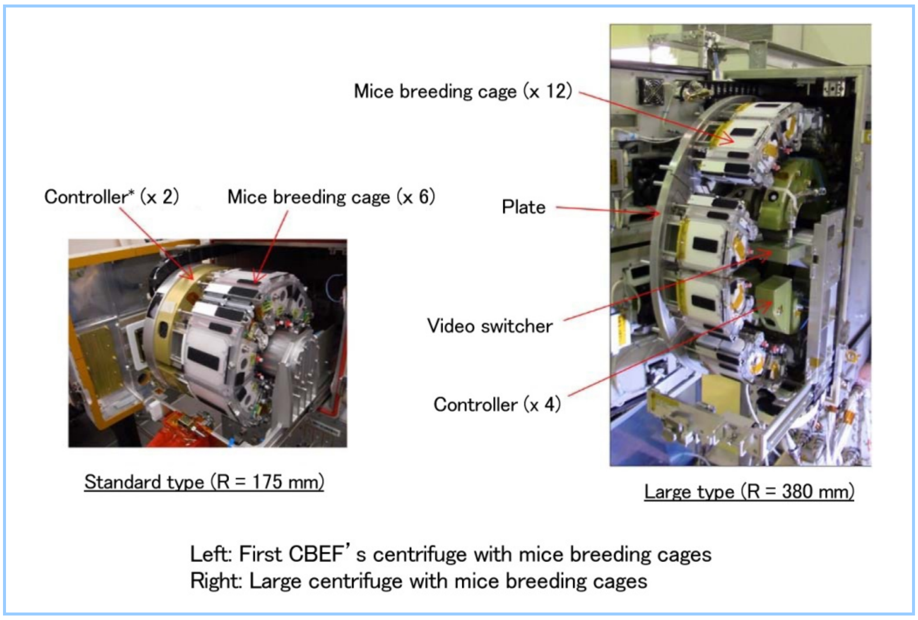

Figure 6 Large centrifuge in early missions (equipped with mice habitat cage)

4. Conclusion

Under the conditions of limited space and resources, MHI developed the CBEF-L supplemental experimental facility, which is equipped with one of the largest centrifuges in ISS. CBEF-L, compatible with the original CBEF unit, features new utilities, allowing various configurations in combination with CBEF. We believe that CBEF-L will contribute to future space experiments and studies by meeting various needs.

The newly-developed CBEF-L ensures the following:

- Centrifugal experiments using large rotation diameters up to 38 cm: allowing larger mission facility sizes and sample numbers.
- Simultaneous rotation of up to three centrifuges in combination with CBEF: allowing several different gravity settings in one experiment.

In order to make space experiments more accessible, it is necessary to develop products more quickly at a lower cost. Based on our ample experience and achievements in product development and operation, we would like to meet the needs of experiments under space environment.

References

(1) Hagiwara, et al., Development of Mouse Habitat Unit for Use in “KIBO” Japanese Experiment Module on International Space Station, Mitsubishi Heavy Industries Technical Review Vol.53 No.4 (2016)