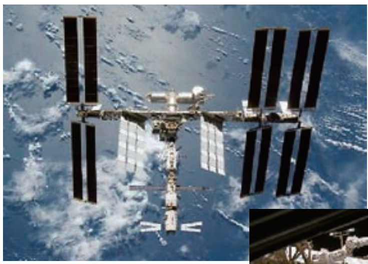

Courtesy of NASA

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Kibo: The Successful Launch and Start of Permanent Manned Space Operations

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The Japanese Experiment Module, Kibo, is part of the International Space Station (ISS) and the first Japanese manned space facility. Mitsubishi Heavy Industries, Ltd. (MHI) manufactured the Pressurized Module (PM) and the Experiment Logistics Module-Pressurized Section (ELM-PS). The PM and ELM-PS were launched in March and June 2008, respectively. They were assembled at the ISS at an altitude of 400 km and were successfully activated. Japan's first long-term manned space operation has begun. Kibo provides the world's largest pressurized volume in space. There were few problems with its assembly and activation. Space experiments inside Kibo started in August 2008, the beginning of its expected more than 10 year lifespan.

1. Introduction

Japan is a participant in the International Space Station (ISS) Program, an international joint project headed by the U.S. Government and the National Aeronautics and Space Administration (NASA) and started in 1984. As part of this program, the Japan Aerospace Exploration Agency (JAXA) has developed the Japanese Experiment Module (JEM), Kibo. MHI supported the overall system integration, and manufactured the Pressurized Module (PM) and the Experiment Logistics Module-Pressurized Section (ELM-PS), two core components of the JEM. This paper describes the development of Kibo, the key technologies obtained through its development, and its efforts for the international joint project.

2. Development history

When the ISS program was established in 1984 by the U.S. Government, Japan decided to participate, along with Europe and Canada. In 1985, and JAXA started the development of Kibo. However, with time, the ISS development costs increased significantly from the original budget, and the whole ISS program was severely scaled back in 1988 and 1993. Russia joined in 1993; there are now 15 countries participating in the ISS program. In this multinational situation, the requirements and interfaces for the JEM changed frequently, causing design changes and schedule delays. The first module of the ISS was launched in November 1998, and the ISS assembly started in orbit. The ISS has had a resident crew of three since November 2000. However, the ISS assembly schedule was further delayed for two and a half years by the space shuttle Columbia accident in February 2003, and is now expected to be complete in 2010. Under these circumstances, MHI completed and delivered the PM and the ELM-PS to JAXA in 2002. JAXA transported the PM and the ELM-PS by ship in 2003 and 2007 from the Tsukuba Space Center (TKSC) to the Kennedy Space Center (KSC) for launch, and has conducted pre-launch functional tests with MHI support at the KSC. The ELM-PS was finally launched by space shuttle on March 11, 2008, and the PM followed on June 1, 2008. Both modules were successfully assembled on the ISS. The initial activation of the system went smoothly, completing the main component of Kibo. Japanese astronaut Akihiko Hoshide was the first to enter the PM, starting its long-term manned space operation. Once the system functional tests were completed, the first experiment in Kibo started on August 22, 2008.

The JEM development in Japan was performed under the "All Japan" framework of cooperating space-related companies. JAXA performed the overall system integration, and MHI manufactured the PM and ELM-PS. Other modules were fabricated as follows: the Exposed Facility (EF) by IA (IHI Aerospace Co. Ltd. formerly IHI Co., Ltd.), the Experiment Logistics Module-Exposed Section (ELM-ES) by IA (IHI Aerospace Co. Ltd. formerly Nissan Motor Co., Ltd.), and the Remote Manipulator System (RMS) by NTS/NEC (formerly Toshiba Corp.). The PM includes JAXA-provided domestic equipment such as the main computer, and the ISS common equipment procured from abroad. MHI fabricated and delivered the system that incorporated all this equipment.

MHI used a three-stage development method, similar to that used for launch vehicles, progressing through the breadboard model (BBM), engineering model (EM), and preflight model (PFM). Due to the multinational situation of the program, various requirement changes occurred even

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after starting PFM manufacturing. However, despite some temporary confusion at the manufacturing site due to the PFM redesign, MHI was able to complete the development successfully.

In addition, since 1990, MHI has participated in the operational preparation of the JEM, developed the JEM command and control trainer, and streamlined the command/status-data source for the JEM ground control center database. MHI also supported the verification of operational procedures for JEM assembly and initial activation. During the approximately two-week PM launch mission, approximately 25 MHI engineers supported JAXA's JEM initial operation in orbit to assess JEM health, to review any anomalies, and to identify corrective action in shifts at the U.S. Johnson Space Center (JSC) and the TKSC. Finally we completed the initial activation.

3. Kibo overview

As shown in **Fig. 1**, Kibo consists of six components: PM, ELM-PS, RMS, EF, ELM-ES, and the Inter-orbit Communication System (ICS).

As the core of Kibo, the PM is a cylindrical pressurized module approximately 4.4 m in diameter and 11 m long, with a weight of 14.8 t. The PM is the world's largest pressurized space, and the inside is maintained at almost room temperature and pressure so that the crew members do not require any special environmental clothing. The PM is composed of the following segments: structure, electrical power system, communications and data handling system, environment control and life support system (ECLSS), fire detection and suppression system (FDS), active/passive thermal control system (TCS), experiment support system (ESS), command and control system, mechanical system, and crew support system. The PM controls and manages the whole Kibo system, and provides various resources, such as experimental gas, electrical power, and communications, to a maximum of 10 payload racks for experimental equipment.

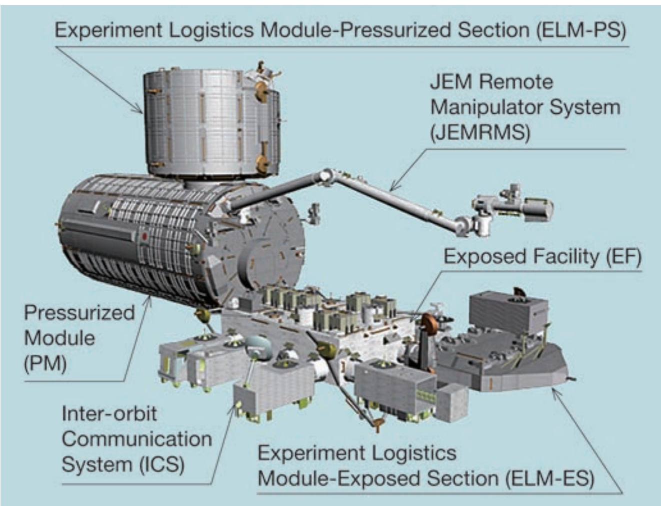

Fig. 1 Kibo overview (Courtesy of JAXA)

The ELM-PS is also maintained at room temperature and pressure, and is capable of holding eight ISS standard racks.

4. Kibo development

The key technologies for Kibo are described below. See the references for the structure, equipment, and other details.

4.1 Command and control system and software

Command and control (monitoring/management/control) of Kibo is performed using commands to operate the equipment and feedback of status data to show the condition of the equipment. The ISS command and control system consists of three hierarchical layers, where the ground control center, ISS crews, and command and control software in the ISS central computer are at the highest level. Overall, Kibo is controlled and managed by the JEM control processor (JCP) and MHI's flight application software (FAS), which are in the second level of the hierarchy. Individual equipment items are controlled by local control units and firmware, which form the third level of the hierarchy. These control units, on-board software and firmware form the JEM command and control system (**Fig. 2**).

When designing the command and control system, MHI attempted to allocate functions and performance appropriately to each hierarchical level and define the interfaces between the FAS and the hierarchical local controllers based on a unified design concept so that the command and control of the whole Kibo system would be consistent and reliable. However, as each controller and firmware was designed by different Japanese companies and Kibo had to use some existing foreign ISS common equipment, the allocation was not always logically consistent. Under these conditions, we did our best to unify the command and control design in a realistic way in collaboration with JAXA. For example, we managed to unify the design concept for function sharing in built-in testing (BIT); each type of equipment had its own very different BIT procedures for handling anomalies. In order to maintain the whole system's integrity, we substituted and absorbed some functions into the MHI data interface unit (DIU) and the FAS. This permitted us to provide an integrated Kibo command and control system with consistency and integrity.

The FAS processes about 3,000 commands and monitors 10,000 Health and Status items to provide integrated command and control of Kibo. The major functions of the FAS are to manage the running mode of the system, and identify whether the command execution in the current JEM system configuration is enabled or disabled in order to reject hazardous or inhibited commands, to execute the commands and to automatically execute system failure detection, isolation and reconfiguration on anomalies. For the flexible operation and utilization of Kibo, the FAS can process plural commands simultaneously with an event-driven design method, unless there is a contradiction in the commands. So system maintenance tasks and plural

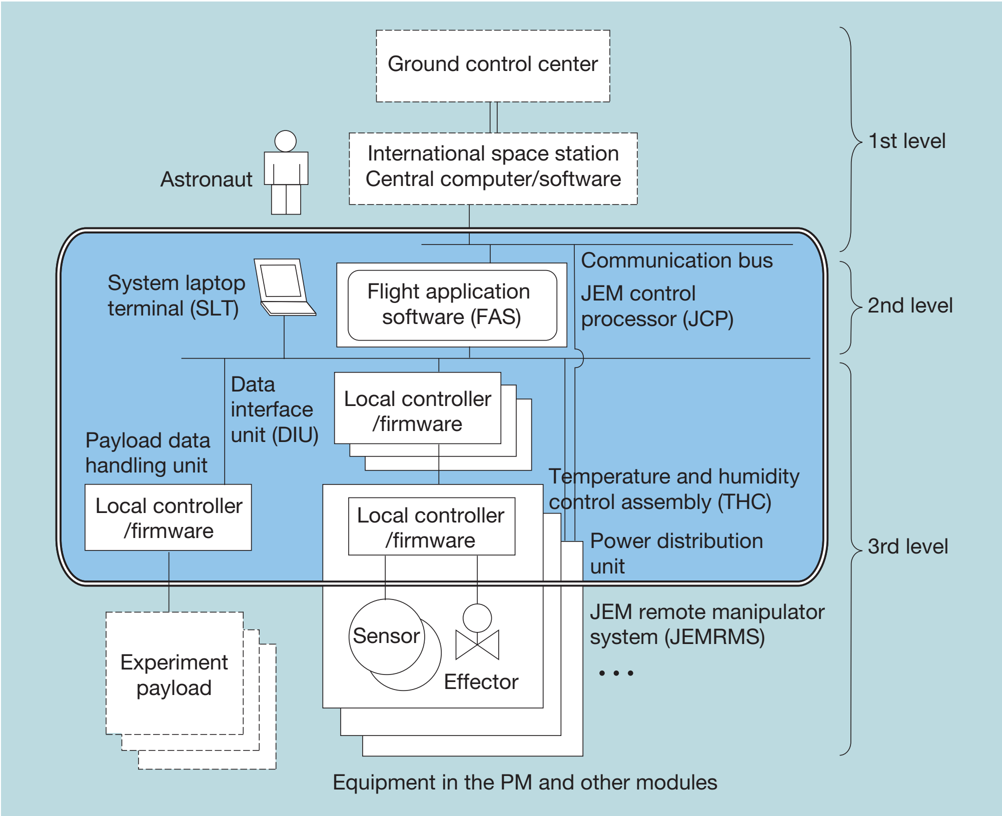

Fig. 2 Command and control system (▭)

experimental tasks can be executed in Kibo simultaneously. In addition, because the JEM will be operating for a long time, the FAS was designed for minimal updates, which are generally required each time equipment is changed or modified. In other words, this design maximizes the "data value" while minimizing the software "coding logic." For example, if a valve control sequence is defined only by a set of data, replacing the equipment requires only changing the related data value, not the program logic. Therefore, re-compiling on the ground is not necessary in many cases, and only transmission of the updated portion of the data is required, reducing communications between the ground and the space station. During Kibo operation, parameter values set in the FAS memory survive to be used after an update, so operations can be continuous.

4.2 Fluid system

(1) System design

MHI Kobe was responsible for integrating the Kibo fluid system under the cooperation of JAXA. This system consists of the TCS, ECLSS, FDS, and ESS, which are different from the systems in existing unmanned rocket systems.

The role of the TCS is to maintain the environmental temperature level without dewing or excessive component temperatures, despite the temperature of the space environment (–150 to 150°C in a 90 minute orbital period). In order to cool a lot of the large variable thermal loads from electronic equipment, MHI created a control system combining multilayer insulations (MLIs) and heaters as passive TCS, and water-cooling closed loops (maximum waste heat capability of 25 kW) as active TCS, using water as the refrigerant for the first time. The ECLSS control system is designed to prevent CO_2 concentration from building up in the microgravity environment without convective flow, and to maintain the temperature and humidity at appropriate levels (e.g. 18.3°C to 26.7°C and 25%–75%) by circulating the cabin air to supply a comfortable environment for the crew. The ECLSS also minimizes the noise level (NC-50 level) to make the PM the quietest module in the ISS and maintains the cabin air pressure at 97.9–102.7 kPa by depressurization and repressurization. The FDS provides a method of fire detection and suppression in the microgravity environment. The ESS provides a redundant safety vacuum system using the vacuum of space (10^{-6} Torr).

The fluid associated key technologies for the manned-operation facilities have been developed for the above systems.

(2) Breadboard model manufacturing and test

To obtain the design data for the TCS and the ECLSS after starting the preliminary design, a cabin air distribution system test and a TCS water-cooling loop distribution system test were conducted to confirm the validity of the design. Rack air ventilation test and a fire detection and suppression test were also conducted, and the diffusion properties in a closed area with limited fluid volume were confirmed. Furthermore, a passive TCS test was conducted to update the thermal analysis model, and the thermal analysis accuracy was improved.

(3) EM/PFM manufacturing and test

(a) Fluid component design and procurement

There are approximately 940 components in the fluid system related to the TCS cooling water lines, ECLSS cabin air ducts, and FDS/ESS fluid lines. These components include valves, quick disconnects (QDs), sensors, diffusers, return grills, and silencers (**Fig. 3**). Since this project is an international joint project, the valves, QDs, and sensors were designed to Kibo specifications based on ISS common components as much as possible, and procured from U.S. manufacturers. However, this required significant coordination effort because of the difficulties in export control for technology transfer.

(b) Development and supply of Kibo common components

In cooperation with other users, MHI developed, manufactured, and supplied cold plates (approximately 150 units) for the cooling electronics, and small accumulators for absorbing the water volume change during launch unique to Kibo (approximately 30 units) as Kibo common components.

(c) System rack integration

Two ECLSS/TCS racks were integrated to install the temperature and humidity control assembly (THC) and the TCS assembly (TCA) provided by JAXA. To meet the stringent Kibo system noise requirements, MHI took especial care to minimize the noise from pumps and fans by installing approximately 590 individually combined acoustic insulators and absorbent units. As a result, the stringent noise requirement was met on the KIBO system.

(d) ELM-PS thermal balance test

To confirm the passive TCS design of the MLI, heater, and heater controller (HCTL), etc. (approximately 1,620 items), a thermal balance test was conducted during the PFM test phase with the ELM-PS in the JAXA space environment chamber at the TKSC (**Fig. 4**). The thermal

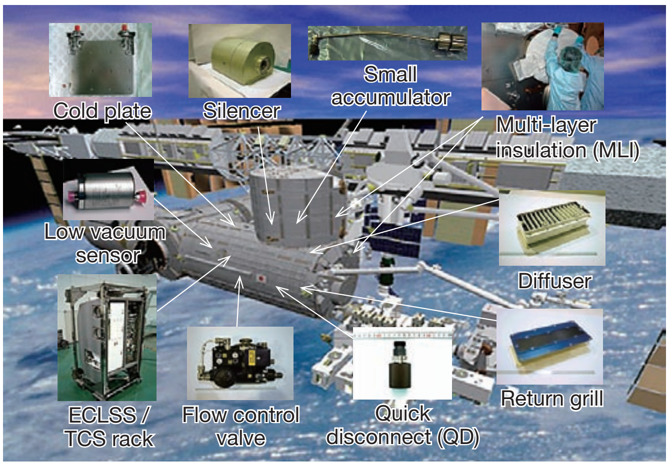

Fig. 3 Fluid components and ECLSS / TCS rack (Courtesy of JAXA)

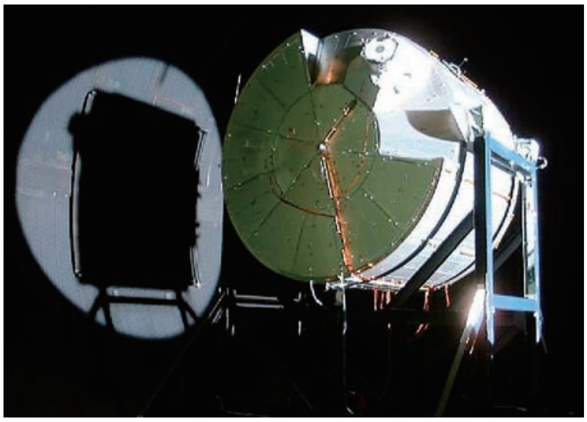

Fig. 4 ELM-PS thermal balance test (Courtesy of JAXA)
Irradiation of an artificial solar ray in the space chamber

design packaging of the MLI was improved based on the test results. Evidently the improved thermal design was able to maintain good results in that the analysis results were quite close to the data obtained during actual flight in space.

4.3 Launch site operations

The launch preparations at the KSC were affected by the delayed shuttle launches. This became a long-term project that lasted five years from April 2003 to June 2008, including the work suspension due to the Columbia shuttle accident. The project required 40 people from Japan at its peak, and it was our first overseas test and assembly experience. However, the onsite work was a success, not only because we achieved the goals of the project, but also because we completed it on schedule without any accidents. This success was due to our adopted management style suited to this particular mission and established by modeling the internally developed management style of rocket launch operations. We refined it through the various domestic development and manufacturing phases, and also integrated NASA expertise.

In particular, appropriate staffing was the key to our management success. The experience of taking a leading role in a special working environment that involved other companies, the relationship of trust with the NASA staff, which JAXA and MHI built through enhanced mutual understanding, and the maturity of each member contributed to creating a strong and cohesive team. Another important key factor in the management environment was the cultural acclimation of the team members because the most of them had never been abroad. We also made every effort to tailor communications to the personality and situation of each member. This type of care was helpful in maintaining the motivation of staff members throughout the operation.

The launch site operations consisted of the following basic phases:

1. Post-transportation check
2. NASA-JAXA joint test (connection testing between JEM and ISS)
3. Long-term storage and periodic inspection (PM only)
4. Improvement and additional inspection (PM only)

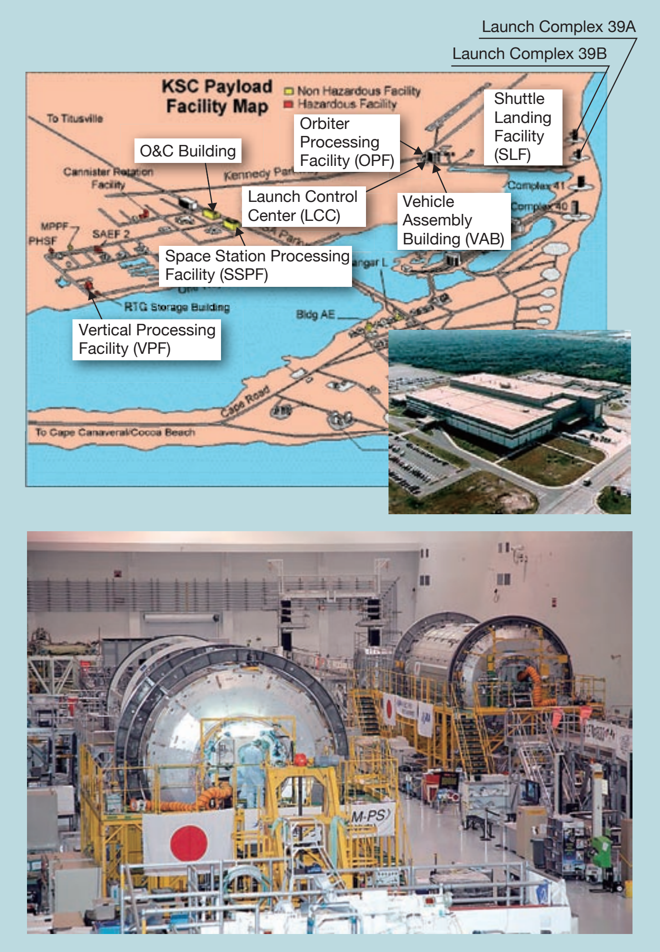

Fig. 5 Kibo launch preparations at the space station processing facility (Courtesy of JAXA)

5. Launch configuration
6. Final confirmation by NASA

For Step 4 in particular, there was the possibility of deterioration due to the prolonged storage after manufacture. As JAXA intended to complete this mission without any flaws, we repeated almost the whole range of inspections that had already been completed once in Japan, from the check of individual cables to the system functional tests. This required some overhaul and replacement of parts. Despite many problems that arose in the process, close cooperation with JAXA brought them under control.

The operations described above took place mainly at the Space Station Processing Facility (SSPF) (**Fig. 5**). The SSPF was like an exhibition hall with the space station modules from various countries waiting to be launched. We learned valuable lessons not only from NASA, which was the supervisor of the Space Station Program and with whom we worked, but also from the European Space Agency, the Canadian Space Agency, and various manufacturers. We were able to compare our skill level with theirs. Our success demonstrates that MHI has excellence in *genba-ryoku* or autonomy and onsite problem-solving skills. This is a valuable asset for our next assignments, and has contributed to our confidence.

4.4 Key technologies and skills acquired through the development of Kibo

Kibo is the first Japanese manned space facility development. It has met all requirements as MHI worked closely with JAXA to overcome the various technical issues encountered. There were very few problems during the in-

Table 1 Key technologies and skills acquired during the development of Kibo

(1) Structure:
- Large-scale welded thin wall structure design and manufacturing with high assembly accuracy (to support launch/orbital mechanical loading, minimum air leakage in pressurization)
- Meteorite debris defense design (bumper design, evaluation of high-speed collision phenomena)
- Structure life design
- Radiation shielding

(2) Electrical and power system:
- 120 volt direct current power supply, distribution, and switching
- Design and fabrication of an electrical harness adapted for the space environment (launch vibration, electromagnetic compatibility, extra vehicle environment)

(3) Communication and data handling system:
- Communication bus based on MIL-STD-1553B
- Communication between different types of in-orbit computers and networks
- Development of spacecraft computer that meets requirements, including electromagnetic compatibility

(4) ECLSS:
- Cabin air flow control and analysis in microgravity environment
- Cabin air pressure control in case of depressurization or over-pressurization
- Noise reduction design and analysis

(5) FDS:
- Fire detection and suppression in microgravity environment

(6) TCS:
- Heater control, and passive thermal design and analysis in space thermal environment
- Active thermal load control and analysis of water cooling closed loop in microgravity environment

(7) ESS:
- Vacuum gas vent analysis in space environment

(8) Command and control system and flight software:
- Design of integrated command and control architecture with system integrity
- Flight software for controlling various types of equipment
- Easy update of flight application software
- Man-machine interface based on human engineering in microgravity environment

(9) Mechanical system:
- Design and control of berthing mechanism in space environment

(10) Crew support system:
- Design and analysis of accessories (e.g. handrails) and electric wiring installation layout based on human engineering in microgravity environment

(11) Other skills:
- Safety analysis and hazard control
- Safety design (e.g. decrease of off-gassing and fire protection)
- Design and analysis of maintainability
- Material (resistance to atomic oxygen, off-gassing, flame resistance, etc.)
- Large-scale system integration

(12) Preparation for in-orbit operation
- Development of skills for contingency disposition, including function allocation between in-orbit system and ground control center
- Development and maintenance of crew training system (trainer) and flight software verification environment system on the ground

orbit assembly and initial activation due to the high quality of workmanship that was praised by space station crews and NASA engineers. The key technologies and skills for design and production acquired through the development of Kibo are shown in **Table 1**.

5. Kibo operations

Kibo operations are controlled by operators on the ground, i.e. the flight control team (FCT) in the TKSC and the NASA space centers, and the ISS crews (**Fig. 6**). In addition, the JEM Engineering Team (JET) provides technical support to JEM operations.

For the operation of the ISS and Kibo, the FCT defines the detailed short-term task plan down to the level of hours and minutes several weeks before the actual operations, based on a long-term plan such as onboard experiments and repair or checking of the Kibo system. The FCT also prepares the operational procedures in English for each task, which includes commands, verification methods, reference photos, and tools. The FCT and the ISS crews perform the planned tasks in accordance with the finalized daily timeline. The ISS crews can confirm anything by voice communication with ground operators during these tasks. But because of the expense of the valuable ISS crews with their 6.5-hour workdays, the FCT performs as many tasks as possible on the ground. In addition, safing procedures have been prepared to return the Kibo system from the assumed anomalies to a safe and stable condition, and action is taken in accordance with these procedures if the anomalies occur.

As a member of the JET, MHI supports Kibo operations from a technical viewpoint as the Kibo developer. MHI's major tasks are the preparation of Kibo operations; real-time monitoring and response for any symptoms of failure of the Kibo system during major events such as launch, onboard assembly, and initial activation; and technical assessment of Kibo's health, by means of offline evaluations including long-term trend analysis. The details are described below.

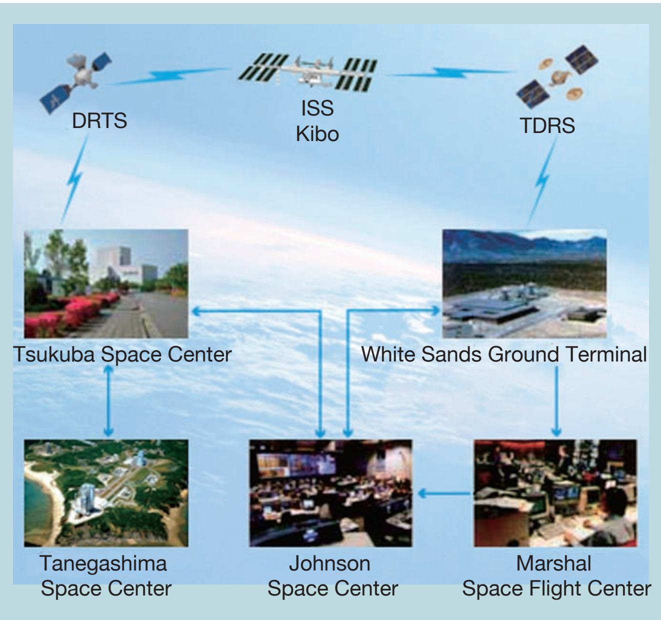

Fig. 6 Overview of the Kibo operations system (Courtesy of JAXA)

(1) Preparation for Kibo operations

MHI reviewed the initial activation procedures of Kibo immediately after the launch, and the initial safing procedures in case of anomalies. At the time of the initial activation, all ISS crews performed their assigned activation procedures in parallel based on their schedule in minutes, so any mistakes in the activation procedures could have resulted in significant impact on the system activation and the schedule. The activation procedures were revised considerably many times in coordination with NASA. MHI repeated the technical evaluation to complete the Kibo activation procedures based on the results of system tests in the development, restrictions on external thermal conditions according to the ISS attitude, and accessibility of the ISS crews. MHI also drafted safing scenarios corresponding with several Kibo operational situations as the basis of the initial safing procedures to be performed immediately in case of anomalies. In addition, MHI prepared for the actual operation by participation in many training simulations for Kibo activation in accordance with the actual schedule using the actual procedures before the actual launch in order to improve the procedures with the FCT and ISS crews.

MHI also conducted the following work based on Kibo design data:

- development of the ISS crew training facility (JEM command and control simulator)
- maintenance of the database source of command and status data necessary for command transmission and telemetry monitoring of ground control centers

(2) Real-time technical support of major events

During the Kibo launch, assembly, and activation, MHI technicians supported the real-time operation in the Engineering Support Room (ESR) of the TKSC and the Mission Evaluation Room (MER) in the JSC as a member of the JET to monitor the symptoms of failure of the Kibo system and to suggest safing procedures to be performed by the FCT. MHI technicians were also assigned to JET liaison in the Mission Control Room (MCR) in the TKSC to ensure smooth and quick communications between the FCT and the JET.

(3) Offline evaluation

MHI is currently confirming the health of the Kibo system, assessing detailed Kibo data, including long-term trend data, and confirmation of the ISS crew activities at MHI facilities and in the ESR at the TKSC by using telemetry data, down-linked video images and photos, and voice communications between the ISS crews and ground operators. In addition, MHI is investigating the causes of, and permanent solutions for, any anomalies. MHI will continue to perform these technical assessments throughout Kibo's entire operational lifetime.

6. Conclusion

The development of Kibo has covered 23 years, a very long time compared to other space programs. Kibo is fulfilling its required functions in orbit, and successfully initiated the first long-term Japanese manned space operation. Such a long-term operation of more than 10 years under the severe environment of space will require the first Japanese long-term maintenance operation for a manned space system. MHI has supported operations as a Kibo manufacturer. MHI will now build on that initial technical support experience and incorporate the experience acquired in the development of Kibo to focus on the development and operations of future space manned systems, such as space vehicles and a moon base. In addition, MHI will contribute to the space industry by raising public consciousness around the world about space-related subjects.

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