

Kibo Utilization Scenario toward 2020 in the field of Physical Science

The Kibo Utilization Promotion Committee

The Scenario Examination Working Group in Physical Science

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1. Basic Approach

1.1 Objective of Research Scenarios in the Field of Physical Science

The physical effects of microgravity conditions, which include suppression of phenomena such as convection, buoyancy, and sedimentation in the liquid and gaseous states and containerless levitation (buoyancy) of samples, impact a broad range of fields, including physical science as well as fundamental physics and chemistry, fluid science, and combustion science. Recognizing that the field traditionally known as materials science encompasses a broad range of physical phenomena, the Scenario Examination Working Group in Physical Science has elected to identify the target of its endeavors as the field of physical science.

Since the First Material Processing Test (FMPT) on the Space Shuttle in 1992 (Fuwatto '92), Japanese experiments utilizing the space environment in the field of physical science, including sounding rocket experiments and other short-duration microgravity experiments, have yielded pioneering results in high-quality semiconductors and new functional material research. Experimental subjects for Kibo have been planned based on these results, and currently the Second Phase Utilization (2011 to 2013) experiments have begun, following the First Phase Utilization (2008 to 2011), and we are preparing to solicit subjects for Third Phase Utilization (2013 to 2015) activities.

A decision made by the Strategic Headquarters for Space Policy in August 2010 has led to Japan's continued participation in the ISS Program beyond 2016. A report prepared by the Expert Examination Committee for Space Policy in August 2011 shows that "Results in fields such as life sciences and observation have been obtained. However, it is necessary to expand upon the research through the characteristics of manned missions and to achieve concrete results from this point forward". While considering certain political situations, such as the financial situation of Japan and the fourth term of the Science and Technology Basic Plan, the president of JAXA commissioned the Kibo Utilization Promotion Committee, an external consultative body chaired by Dr. Makoto Asashima, to prepare Kibo utilization scenarios toward 2020. Examination started in October 2010.

The Kibo Utilization Promotion Committee has provided the following approaches as indicators of prioritization of the Kibo utilization until 2020:

View point 1: Forefront scientific research only enabled by ISS/Kibo

1. Obtaining scientific knowledge in life sciences and material sciences over a long term (more than 5 years)
2. Creating such breakthrough technologies and making such findings in the short term (approximately 3 years) as those listed below:

- Contributions to social problem solving, disaster recovery, etc., on the ground
- Contributions to green/life innovation, creation of new industries, education, general use, etc.

View point 2: Fundamental research and development for the future space activities

Accumulating fundamental technology and knowledge in life sciences, space medicine, and technology development for Japan's lunar planetary exploration and manned expeditions

The Scenario Examination Working Group was established under the Kibo Utilization Promotion Committee in order to study what approach to take in the field of physical science based on the above directions as identified in Committee discussions. Members include experts in the fields of materials science and physical science as well as members of the Committee for Science of Space Environmental Utilization. These scenarios were put together by the Working Group after reviewing directions for research in those fields in space for 2020 and beyond based on views from the research community on what goals should be pursued in the field and what type of experimental equipment and organization would be required in order to achieve those goals through the utilization of the ISS and Kibo by 2020.

1.2 Prioritized Areas in Physical Science Research Utilizing the Space Environment

Various utilization scenarios have been proposed in the fields of materials science, fundamental physics, and fundamental chemistry, but research utilizing Kibo has not been adequately pursued in line with these previous scenarios. Additionally, it has become clear that it will be difficult to implement utilization scenarios by relying exclusively upon research programs from individual researchers. In order to pursue world-class research within the resource and R&D budgetary constraints to which space experiments are subject, a strategic research program led by an organized research group is needed. To that end, it is necessary to establish the prioritized areas proposed in this report and to implement the associated scenarios by means of an organized research groups, while simultaneously maintaining the bottom-up research programs that have been pursued to date.

At the same time, from the standpoint of disseminating scientific output that is readily understood by the general public and promoting the effectiveness of space experiments, it is necessary to pursue timely subjects with immediate results that will make significant contributions to the development of industry or become the top of internationally competitive position, and at the same time to establish research areas in which the active cooperation of the research community can be obtained.

This Working Group has studied future prioritized areas by analyzing the following five areas based on domestic and overseas research trends and results in the field of physical science and on the stance described above:

- Field of fluid science
- Field of combustion science
- Field of materials science, with a focus on crystal growth
- Field of fundamental science
- Field of applied research

We conducted a study from the following perspectives in order to narrow down those broad fields of research and select which prioritized areas should be pursued through 2020. Specific prioritized area proposals can be found in Chapter 3.

(1) Scientific areas that are most academically significant or expected to have significant social spillover effects as well as the systems that are most notably and significantly affected by gravity.

Prioritized areas in the field of physical science should give precedence to research topics in which the effects of gravity are most notable, that is, in which the effects of gravity are most important. For the purposes of these scenarios, the field of physical science is understood to comprise physics and chemistry as well as the physical and chemical sciences, as is understood overseas. Because discussions that categorize areas, for example as either fundamental or applied science, run the risk of introducing errors into the selection of subjects in which the effects of gravity are most important, we have conducted a broad study that is not predicated on assumptions such as these.

(2) Placing priority on new research areas where microgravity experiments have not been sufficiently conducted.

Because Kibo is a very unique national shared facility and because it should be opened for use to a broad range of fields, we will provide high-priority utilization opportunities to new fields wherever possible by identifying them as prioritized areas through 2020, as long as the values outlined in section 3.1.1 can be recognized.

On the other hand, proposals from following research areas should be treated as bottom-up topics, and should get certain amount of Kibo utilization opportunities, as described in chapter 5;

- embryonic and yet-to-mature research areas.
- Research area where the research community can independently and systematically

propose experimental topics

- (3) It is not necessary for experiment themes to be connected with the existing facilities in setting priority areas.**

If, in the future solicitation of research topics, proposals are restricted to those which utilize existing experimental equipment on Kibo, there is a risk that the resulting limitation on research concepts and ideas may prevent the realization of outstanding, advanced research findings. Consequently, we have studied research areas with significance from the standpoint of creating appealing and truly important research results in compiling these scenarios, even if some degree of consideration was given to the financial difficulty of placing new equipment on Kibo.

2. Current Status, Past Results, and Future Direction for Space Experiments in the Field of Physical Science

2.1 Summary of Previous Scenarios and Objectives through the Second Phase Utilization

Japanese experiments utilizing the space environment in the field of physical science were conducted comparatively frequently during the 1990s. Activities have included 22 experiments under the First Material Processing Test (FMPT) during Fuwatto '92 in 1992, 14 experiments under the Second International Microgravity Laboratory (IML-2) in 1994, 4 experiments under the First Microgravity Science Laboratory (MSL-1) in 1997, 4 experiments under the Space Flyer Unit (SFU) in 1996, and one experiment under the Unmanned Space Experiment Recovery System (USERS) in 2003. However, long-duration, serious experiments using microgravity conditions were not conducted again until the 2008 Kibo experiment. During the intervening years, researchers worked to establish experimental technologies and conducted preparatory experiments in anticipation of ISS/Kibo using sounding rockets (TR-IA), aircraft, and drop towers. It is note worthy that Japanese researchers made active use of these short-duration microgravity techniques to develop advanced experimental devices for long-term scientific utilization of “Kibo”.

One notable effect of microgravity in the field of physical science is suppression of convection in the liquid and gaseous state and sample buoyancy. Pioneering experiments into the utilization of these effects in order to create high-quality semiconductors and new functional materials were conducted during Fuwatto '92 (FMPT), but it became clear that the establishment of the field as a new research area would require additional terrestrial research and the development of experimental equipment to be used on Kibo with an awareness of the need to utilize limited resources as well as the accumulation of experimental support and operational expertise. Consequently, the basic approach for utilization scenarios in the field of physical science established in 2002 sought not to create high-quality materials in a single bound, but rather to pursue detailed observation of the fundamental steps of crystal growth and to deepen scientists' understanding of related phenomena by using a simple experimental environment in which convection was suppressed so that materials and heat were transported solely by diffusion. Due to the fact that the high cost of transporting material to space made the concept of a space-based factory unrealistic, the focus was on bringing intellectual property rather than materials back from space. In this way, the following two priorities were established in 2002:

- Understanding fundamental processes of crystal growth through in-situ observation
- Developing a systematic understanding of surface tension driven convection that emerges in microgravity conditions

During the First Phase Utilization (2008 to 2011) of Kibo, the world's first two pieces of in-situ observation equipment for fluid physics and solution crystallization as well as a gradient heating

furnace intended for use as a high-temperature crystal manufacturing device were placed on Kibo, marking a resumption of activity in the field after the hiatus that occurred since the SFU experiments in 1996. Japanese researchers worked to develop unique in-situ observation technologies not available in other countries, including an interferometer to observe temperature and concentration distribution in solution phase simultaneously

As for the Second Phase Utilization (2011 to 2013) of Kibo, scientific scenarios were set in 2006. The scenarios sought to expand the scientific goals based on the results obtained in First Phase Utilization, including to discover hidden phenomena by eliminating or controlling the fluctuations due to gravity, to confirm the fundamental principles in physical science, and to get design principles for the creation of new functional materials.

(a) Elucidation of crystal growth mechanisms

Researchers will seek to elucidate macroscopic phenomena based on the understandings of the extreme behaviors of microscopic atoms and molecules at interfaces, and to elucidate mechanisms of high-quality crystal growth based on those results.

(b) Creation of highly functional material

Researchers will seek to elucidate principles of materials science under extreme and non-equilibrium condition and to create new materials by applying the resulting understanding.

(c) Thermophysical properties of high temperature melts

Researchers will seek to elucidate the principles that determine material characteristics and to make high-precision measurements of the thermophysical properties of useful material melts.

(d) Elucidation and control of fluid science and thermal-fluid phenomena

Researchers will seek to create a science of macroscopic and mesoscopic interfacial thermal fluid and to develop the science and control of thermal fluid to support human space activities.

(e) Fundamental physics and chemistry

Researchers will seek to elucidate the non-equilibrium that emerges through the use of microgravity.

(f) Combustion science

Researchers will seek to elucidate interactions between high-speed chemical reactions and flows.

(g) Space utilization engineering

Researchers will seek to develop new technologies for expanding Japan's production activities in space.

2.2 Implementation Status of Space Experiments in Japan and Overseas and Related Trends

With the completion of Kibo, Japanese space experiments in the field of physical science based on the 2006 scenarios were finally ready to begin in 2008. This section summarizes principal Japanese achievements up to the First Phase Utilization as well as overseas implementation status, trends, and other information in each field.

2.2.1 Field of Fluid Science

Looking at past terrestrial experiments and research results in the field of fluid science, Japanese research in this area has been extremely sophisticated, generating achievements and potential that outpace those of Europe and the United States. Even when only microgravity experiments are considered, Japan has a store of experimental technologies built on numerous innovative ideas and the technological capability to support them. In ongoing liquid bridge Marangoni convection experiments on the ISS, researchers have been able to implement extremely precise experiments for the conditions that oscillating flow occurs, which results is different from past findings. Japanese researchers also boast numerous achievements in boiling and two-phase flow, including the discovery of pioneering projections on the impact of gravity through terrestrial experiments using a unique heating element and the implementation of dramatic improvements in heat removal limits through the development of a new heat pipe using self-rewetting media. Similarly, outstanding accomplishments and potential can be found in research targeting areas such as gas bubbles, droplets, and liquid films.

2.2.1.1 Implementation Status of Japanese Space Experiments and Related Trends

Space experiments in the field of fluid science on Kibo consist primarily of experiments on Marangoni convection. During the First Phase Utilization, these experiments addressed three theme selected in 1993 as well as one theme proposed by an international research team. By exploring these four theme,, scientists are seeking to develop a systematic understanding of the Marangoni convection phenomenon. By 2011, experiments had been conducted into the following two of those four theme:

(1) Chaos, Turbulence and Its Transition Process in Marangoni Convection (Marangoni Exp./MEIS)

Mian target of this is to investigate the fluid mechanics of surface tension driven convection (Marangoni convection), which emerges under microgravity conditions. Steady flow (laminar flow) transitions to oscillating flow when the temperature difference in the liquid bridge is increased, and it was thought that the critical condition could be explained with the Marangoni number. However, past experiments using aircraft and other means had shown that the critical number fluctuated greatly in dependence on the length of the liquid bridge, and the findings

were not consistent with theory. Consequently, a long-duration microgravity experiments in which stable liquid bridges were formed in Kibo explained that the critical Marangoni number is constant and not as a rule dependent upon the length of the liquid bridge, revealing that the theory that the behavior could be explained by the Marangoni number was correct.

(2) Spatio-temporal Flow Structure in Marangoni Convection (Marangoni UVP)

This experiment set out to reveal the transitional process leading Marangoni convection from laminar flow to oscillating flow, chaos flow, and turbulent flow. In addition to engineered flow visualization and surface temperature distribution measurements using thermography, researchers used the Ultrasonic Velocity Profile (UVP) method using an ultrasonic wave Doppler effect. The experiment sought to elucidate mechanisms for the generation and growth of three-dimensional flows by quantitatively calculating the flow stability limit, flow characteristics, and average flow velocity distribution through measurement of the non-steady flow field with the UVP method.

In addition to the above, preparations are underway for the following space experiments to be conducted in 2012 and beyond:

(3) Experimental Assessment of Dynamic Surface Deformation Effects in Transition to Oscillatory Thermo Capillary Flow in Liquid Bridge of High Prandtl Number Fluid (Dynamic Surf)

When Marangoni convection transitions to oscillating flow, minute wave-like surface deformation (dynamic surface deformation, DSD) occurs and is closely related to the flow. Based on the hypothesis that DSD is closely related to the mechanism of transition to oscillating flow and that it plays an important role in sustaining oscillating flow, researchers developed a new model of Marangoni convection transition. In addition to precisely measurement of DSD to validate this hypothesis, this experiment will make detailed observations of the flow that occurs.

(4) Interface Susceptibility and Control of Instability in Thermocapillary Convection (JEREMI)

This experiment seeks to elucidate the effect of the thermal and mechanical conditions at the gas-liquid interface to the surface tension driven flow so as to understand the role of interface susceptibility in surface tension flow from a fluid mechanics perspective. Further, it is designed to yield systematic data from terrestrial and space experiments with the goal of suggesting a new approach in applied fields that involve surface tension flow.

**(5) Detailed Validation of the New Atomization Concept Derived from Drop Tower Experiments:
Aimed at Developing a Turbulent Atomization Simulator**

This experiment seeks to establish the validity of the new concept of liquid atomization (a mechanism whereby the existence of an end of a liquid bridge causes the bridge to destabilize in a self-induced manner and repeatedly divide itself), through detailed observation of capillary waves in microgravity. In the experiment a liquid is sprayed at low speed into air from a large-radius nozzle, It is designed to develop a subgrid model describing the process of turbulent atomization based on this concept of liquid atomization, and to create a full-blown Japanese spray combustion simulator.

(6) Establishment of Database in 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)

This research conducts systematic experiments under microgravity conditions in boiling and two-phase flow, with which highly efficient heat exchange and heat transfer, can be available. By accumulating highly reliable data describing the details of gas-liquid interface behavior and transport phenomena (i.e. pressure loss and the heat transfers) t, a useful database for the next-generation space heat rejection system with high output and high heat-generation densities will be established..

2.2.1.2 Implementation Status of Overseas Space Experiments and Related Trends

The European Space Agency (ESA) is the most aggressive in its pursuit of research prioritizing scientific results. Whereas the experiments conducted or planned by Japan to date prioritize Marangoni convection and boiling and two-phase flow, the ESA has targeted a broad range of systems with gas-liquid interfaces, including gas bubbles, droplets, and liquid films. Since the agency has conducted numerous aircraft-based experiments on a preparatory basis and planned the development of general-purpose experimental devices for use in fluid experiments on the ISS, it is expected that a comparatively large number of experiments on the ISS will address these topics. While publicly available information suggests a low level of activity at NASA in this field by comparison, its efforts do include advanced elements, as indicated by experience conducting an experiment to verify two-phase flow loop type heat exhaust technology with a separate team in addition to experiments addressing fundamental phenomena led by researchers in the field of boiling and two-phase flow.

2.2.2 Field of Combustion Science

The world's first microgravity experiment in the field of combustion science was a droplet

combustion experiment conducted by Professor Seiichiro Kumagai (?) of Tokyo University. Numerous Japanese researchers have been conducting research into droplet combustion researches for some time, consistently leading the world in this field. Additionally, a series of large-scale drop towers (JAMIC and MGLAB) were constructed in Japan during the 1990s, yielding numerous results in gas combustion (extinction limit, soot formation process, etc.) and solid combustion (ignition, flame spread, etc.) Activities of this research field in Japan are receiving international praise. For example, Japanese researchers earn opportunities of oral presentation every year at the International Symposium on Combustion, which are considered the most difficult-to-obtain opportunities of their kind. Additionally, Japan has been involved in many joint international microgravity combustion research projects, proving its high level of international competitiveness in the field.

Japan has not had any combustion experimental devices in the ISS to date, but due to the selection of topics related to droplet combustion, gas combustion, and solid combustion for inclusion in the Second Phase Utilization, numerous combustion experimental devices using multipurpose racks are being developed to conduct those experiments. Development by the U.S. of a solid combustion experimental device that was to be placed on the CIR/ISS has been halted, leaving Japan's solid combustion experimental device as the only means of orbital experimentation allowing precise control of flow velocity and atmospheric composition.

2.2.2.1 Implementation Status of Japanese Space Experiments and Related Trends

The following research topics were selected for the Second Phase Utilization in the field of combustion science. Currently, preparations are underway for space experiments in 2014 and beyond.

(1) Elucidation of Flame Spread and Group Combustion Excitation Mechanism of Randomly-distributed Droplet Clouds (Group Combustion)

In order to elucidate the fundamental processes of combustion, this experiment seeks to build a model providing an accurate description of how group combustion occurs through flame spread by articulating how liquid droplets arranged on a lattice combust and spread. Researchers will compare the associated experimental results with a hypothesis relating to randomly distributed droplet clouds derived from percolation theory as well as the results of drop tower and other experiments in order to validate the hypothesis.

(2) Very-low-speed Counterflow Flame Experiment in Space for Constructing Unified Flammability Theory on Oxy-fuel Combustion Limit

Using the very-low-speed counter-flow flame method, this experiment will clarify the

relationship between normal deflagration waves and the flame ball phenomenon that was discovered under microgravity conditions. The obtained results will develop a theory that consistently describes the mechanism of combustion limits. Researchers will also seek to acquire the world's first standard data suitable for use in validating simulations related to combustion limits under oxygen combustion conditions.

(3) Quantitative Description of Gravity Impact on Solid Material Flammability as a Base of Fire Safety in Space (Solid Combustion, Firewire)

This experiment seeks to clarify differences in materials flammability under normal gravity and microgravity conditions in order to improve fire safety on spacecraft. NASA's Spacecraft Materials Flammability Test is typically conducted under normal gravity conditions. However, the researchers proposing this experiment have determined that flammability may increase in microgravity conditions, making it necessary to build a new space safety evaluation system.

2.2.2.2 Implementation Status of Overseas Space Experiments and Related Trends

Because combustion phenomena are significantly influenced by gravity, much research has been conducted under microgravity conditions, both in Japan and overseas. In the United States, research is being conducted using the Combustion Integration Rack (CIR) in the ISS U.S. module. Experiments have also been conducted on the Space Shuttle. Multiple orbital experiments are being conducted across the fields of gaseous, liquid, and solid fuel, with typical projects including research into flame balls, which are stable spheres that are formed in pre-mixed gas at lean flammability limits with low Lewis numbers; sooting effects of droplet combustion; and smoldering combustion inside foamed urethane. However, combustion research has become less common since President Bush announced a new space policy in 2004, with subsequent research focusing on technological development (for example, fire detection and firefighting technologies). Lacking a means of conducting orbital experiments, European researchers use large-scale drop towers, parabolic flight-producing aircraft, and TEXUS rockets to conduct combustion research.

2.2.3 Field of Materials Science with a Focus on Crystal Growth

Japan possesses some of the world's most advanced technology for growing and evaluating crystals in space. In particular, in-situ observation methods is one of the most effective way to maximize the experimental results with the limited resources in space experiments, and the story of their development shows the Japanese initiative and leadership. Examples include the simultaneous measurement of temperature and density distribution using microinterferometry, precise measurement of the speed of crystal growth, and observation of changes in crystal format and surface structure. Japan is particularly adept at developing technologies such as high-precision

temperature control and nucleation control that play an essential role in increasing the reproducibility and reliability of these experiments.

Japan has made steady progress in developing electrostatic levitation method technology, and the country has already obtained technology for levitating superheated melts at temperatures in excess of 3,000°C in terrestrial facilities. Concerning electrostatic levitation technology and techniques for the measurement of the thermophysical properties (density, surface tension, viscosity coefficient, etc.) of melts at elevated temperatures, Japanese researchers have enjoyed a series of successes, including the first measurements in the world on the viscosity of molten refractory metals such as tungsten, which has the highest melting point among metal elements. The electrostatic levitation method makes it possible to process oxides that are difficult to handle with electromagnetic levitation furnaces, and development of equipment designed primarily for use with oxide samples has begun for the ISS.

Containerless processing is an effective tool to pioneer the unexplored domain of new functional material syntheses through supercooled states. JAXA research has already led to the development of BaTiO₃, which has a huge dielectric constant that is 100 times larger than normal levels, and a new form of glass whose index of refraction is as high as that of diamonds, highlighting the fact that the containerless processing of oxide melts promises to yield a treasure trove of new functional materials. Still, such materials are currently discovered by chance through a process of trial and error, and the development of mechanisms for creating them is a major domain for future research.

2.2.3.1 Implementation Status of Japanese Space Experiments and Related Trends

(1) Experiment name: In-situ Observation of Crystal Growth (ICE)

This dendritic crystal experiment uses highly anisotropic ice. While its primary objective was the detailed measurements of the critical thickness of ice crystal when interfacial instability causes a disk-shaped crystal to become dendritic crystal, the experiment also revealed other information, including the fact that the transition from disk growth to dendritic growth under microgravity conditions differs from the corresponding transition under terrestrial conditions. In fact the transition is observed only in an extremely limited range of supercooling states, A numerical simulation suggested that crystal stabilization is determined by the shape of the edges, Furthermore, it is revealed that the tip radius and speed of growth for dendritic crystal is unambiguously determined by the degree of supercooling, and showed a good agreement with the theory, which has been established for the isotropic materials such as succinonitrile.

(2) Experiment name: In-situ Observation of Crystal Growth (FACET)

Research into the mechanism of faceted cellular array growth, which is observed in

semiconductor and ceramic melt growth, has lagged behind compared with that of cellular array growth in solidified metals, due to a lack of precise experimental data necessary to establish possible theories. This experiment conducted in-situ observation of the crystal growth process in a mixture of salol (phenyl salicylate) and butanol, a model substance that exhibits similar growth patterns as metals, to elucidate the mechanism by which faceted cellular array growth occurs. As a result, it is discovered that observed values characterizing the distribution of the degree of supercooling at the growth interface differed significantly from the values that had been expected based on existing cellular growth models, leading them to conclude that the degree of interface supercooling and its gradient determine the occurrence of new cellular interfaces.

In addition to the above, preparations are underway for the following space experiments to be conducted in 2012 and beyond in this field:

(3) Research into Growth of Homogeneous SiGe Crystals in Microgravity by the TLZ Method (Hicari)

Neither of two FMPT experiments seeking to achieve density uniformity in concentration along the growth axis by using a gradient heating furnace yielded a non-uniform concentration distribution. Consequently, JAXA pursued terrestrial research and developed the travelling liquidus zone (TLZ) method, which seeks to achieve uniform density by converting difficult-to-control concentration gradients along the axis into controllable temperature gradients by making use of the saturated liquidus zone. Use of this method with small-diameter (of about 2 mm) samples that are not susceptible to counterflow allows uniformity along the axis, even in terrestrial settings. Researchers are planning to apply the method to large-diameter samples using crystals with a diameter of 10 mm in experiments on Kibo.

(4) Alloy Semiconductor Crystal Growth under Microgravity Conditions (Alloy Semiconductor)

Designed to establish a process of high-quality, homogeneous bulk alloy semiconductor crystal growth, this experiment will attempt to quantify the impact of (1) the solution transport process and (2) crystal surface orientation dependence on the growth of ternary alloy semiconductor crystals in space and terrestrial environments.

(5) Measurement of Thermophysical Properties of High-temperature Oxide Melts Using an Electrostatic Levitation Furnace

This experiment will measure the viscosity, surface tension, and density of oxides melts which cannot be melted and levitated in terrestrial environments (particularly oxides with a melting

point above 2,000°C) under microgravity conditions. Additionally, researchers will explore the possibility of discovering new functional substances by recovering the processed oxides samples to the ground for detailed analyses of the samples' structure.

(6) In-situ Observation of Growth Mechanisms of Protein Crystals and Their Perfection under Microgravity (NanoStep)

Reports indicate that protein crystals grown in microgravity have exhibited increased perfection. In order to elucidate the reason of the increase in perfection, this experiment will seek to identify the mechanism of protein crystal growth and its relationship with defects introduced during growth, particularly minute defects that lower perfection.

(7) Crystal Growth Mechanisms Associated with the Macromolecules Adsorbed at a Growing Interface: Microgravity Effect for Self-oscillatory Growth (Ice Crystal2)

In order to describe the crystal growth mechanism in ice involving macromolecules such as antifreeze protein, this experiment will propose a new crystal growth kinetics model and two-step reversible adsorption model and attempt to verify them experimentally.

(8) Analysis of Colloidal Crystals under the Microgravity Environment by Laser Diffraction and Investigation of Colloidal Interaction

Researchers will gather detailed information about colloidal crystals and conduct detailed research into the interactions of colloidal particles by conducting the world's first precise observation of the structure of a water-soluble, electrostatically stable colloidal dispersion system in space.

2.2.3.2 Implementation Status of Overseas Space Experiments and Related Trends

Concerning use of the ISS, microgravity scientific experiments have been declining in the United States since 2005. Since the launch of the experimental module in 2008, Europe's focus has been on experiments in the life sciences and space medicine, with experiments in microgravity science comprising about 10% of all experiments. However, the emphasis appears likely to shift to fields such as fluid physics, advanced highly functional materials, and industrial processes in the future. European research teams have a strong interest in Japanese semiconductor crystal growth experiments and protein crystal growth in-situ observation experiments and have expressed a desire to pursue joint research with their Japanese counterparts. Such space experiments based on international cooperation not only maximize use of resources, but also play an essential role in increasing the sophistication of research being conducted.

The ESA began developing an electromagnetic levitation furnace in the 1980s. Experiments on the measurement of thermophysical properties of high-temperature melts and the creation of a metastable phase using metals and alloys were conducted on Space Shuttle missions in 1994 and 1997. The first flight experienced issues with the positional stability of samples, but improvements on the second flight yielded useful results in areas such as the measurement of the thermophysical properties of Pd-Co alloy melts. Currently, the ESA is developing an electromagnetic levitation furnace for use on the ISS, and the system is scheduled for launch in or around 2012. By their nature, electromagnetic levitation furnaces can handle only conductive samples. NASA has already placed an acoustic levitator (the Space-Dynamically Responding Ultrasonic Matrix System, or SDRM) on the ISS, but only comparatively low-temperature experiments, for example using combustion synthesis, are planned due to the lack of a heating mechanism.

2.2.4 Fields of Fundamental Science

Fields of fundamental science include fundamental physics and chemistry, in which research is conducted using the space environment. In these fields, JAXA has adopted a Microgravity Physics Research Scenario (2001) and a Research Scenario of Fundamental Chemistry (2004), and most activity consists of terrestrial research based on an open proposal process as well as terrestrial research conducted by the ISAS Committee for Science of Space Environmental Utilization's Research Working Group. However, no specific space experiments have been selected for use on Kibo at the present time.

In Europe and Russia, dusty plasma research using the German plasma crystal laboratory on the ISS has yielded results, and a team from Japan has participated in the effort, which has generated findings in both theory and plasma measurement.

Ongoing terrestrial research including aircraft experiments in Japan includes the development of a continuous adiabatic demagnetization refrigerator (ADR) for cooling solid ^4He to temperatures of 60 mK to 100 mK to facilitate observation of macroscopic quantum phenomena, and teams are working to gain experience and collect data from not only terrestrial experiments, but also from short-duration microgravity experiments using aircraft. In Europe, scientists are developing a device to facilitate research into particle behavior known as Interactions in Cosmic and Atmospheric Particle Systems (ICAPS). Examples of related efforts by researchers in Japan include research into the effects of electrical charges on particle agglomeration on protoplanetary disks. Research into critical point and supercritical phenomena under microgravity conditions (abnormal heat transport phenomena caused by the piston effect) was once conducted on the ground based on a model developed by Japanese researchers, who have led the world in their field, but no researchers are currently planning microgravity experiments.

While there are no plans or results in the field of fundamental chemistry from other countries,

research into subjects such as asymmetric photoreaction, colloids, and honeycomb porous films is being conducted under the aegis of the ISAS Committee for Science of Space Environmental Utilization's Research Working Group, which is pursuing terrestrial and short-duration microgravity experiments in these areas. These efforts are gradually shedding light on the effects of gravity. Colloids were selected as a candidate topic for the second part of the ISS Second Phase Utilization, and preparations are underway for experiments in that area.

2.2.4.1 Implementation Status of Japanese Space Experiments and Related Trends

Japan has not yet led a long-duration microgravity experiment in these fields. However, Japanese researchers are participating in dusty plasma experiments using the German plasma crystal laboratory (PK-3 Plus) on the ISS as part of a collaborative international research effort. Dusty plasma refers to electrically neutral plasma consisting of a mixture of ions, electrons, and fine particles. In the natural world, dusty plasma exists in phenomena such as interstellar molecular clouds and protoplanetary disks. Based on a Japanese proposal, scientists have succeeded in observing the formation of Coulomb crystals using large particles and the agglomeration of particles after the dissipation of the plasma.

Short-duration microgravity experiments using aircraft in Japan have addressed such areas as ^4He crystallization, asymmetric photoreaction near the critical point, and self-organized honeycomb porous film formation reactions. Experiments in ^4He crystallization have succeeded in using a new freezer to cool solid ^4He to the super-low temperature of 0.6 K and in revealing that ^4He crystallization in microgravity exhibits significantly different shapes than in terrestrial settings. While it was previously believed that gravity did not affect the molecule- and atom-level phenomena typically studied in chemistry, researchers are accumulating experimental results and knowledge, which are pointing to the creation of a new, gravity-oriented field of chemistry. Such results include the fact that the products of asymmetric photoreactions vary depending on gravity level and the fact that mesoscopic-scale structures formed through the self-organization of molecules can be controlled by gravity.

2.2.4.2 Implementation Status of Overseas Space Experiments and Related Trends

(1) Dusty plasma research

In dusty plasma, which consists of a mixture that includes fine particles, the fine particles form regular arrangements known by such names as Coulomb crystals and plasma crystals. This is a new phenomenon that was experimentally verified for the first time in 1994. While a theoretical phase diagram has been created, it is believed that it would be impossible to validate the diagram experimentally in a terrestrial setting due to the gravity. In a joint dusty plasma

space experiment conducted by Germany and Russia (device name: PKE; February 2001 to July 2005), researchers were unable to validate the phase diagram due to the formation of a void in which no particles existed. An improved version of the apparatus known as PK-3 Plus was launched in December 2005 and remains in use. The research team consists of a total of 30 to 40 scientists from various countries (including Japan). Japanese research is concerned primarily with the critical point in charged particles. While the issue with voids has been improved in PK-3 Plus, it persists at high power levels. Consequently, an improved version of the system known as Plasma Lab is being developed. Additionally, a different type of laboratory known as PK-4 is scheduled to be launched in 2013 or 2014

Like terrestrial research, overseas research is characterized by its ongoing nature. Consequently, more than 50 academic papers have been published describing experiments conducted with PK-3 Plus, most of them in prominent academic journals. The principal objective of overseas dusty plasma research is the elimination of voids. Plasma Lab's possible use of an oscillatory electric field has raised concerns that the approach may bring a number of adverse effects. Additionally, its measurement system may be insufficiently capable. For this reason, it is desirable to have a separate Japanese system that can yield complementary data.

(2) Solid He research

It is not possible to validate theories concerning the ground state crystalline forms of macroscopic solids since specific experiments are impossible. Observing these forms during the roughening transition of solid He (the phase transition in which a particular crystalline surface changes from a vibrating state at the atomic level to an aligned, flat surface as the temperature falls) under microgravity conditions and super-low temperatures is practically the only method by which it is possible to approach the ground state experimentally. At super-low temperatures, the ^4He liquid state occurs as a superfluid, and the application of pressure in excess of 25 atmospheres results in a ^4He solid phase exhibiting a hexagonal close-packed structure (HCP). At that point, the phase transition between the solid and liquid phases generates almost no latent heat, so the speed of crystal growth is extremely high. This solid ^4He is a quantum solid in which the overlapping atomic wave functions cannot be ignored, and it is also a Bose particle solid.

With the shutdown of NASA's entire fundamental physics project around 2000, Japan is the only nation still studying the feasibility of space experiments into solid ^4He under microgravity conditions.

(3) Interactions in Cosmic and Atmospheric Particle Systems (ICAPS)

ICAPS, an experimental facility for the ISS being developed by the ESA, is currently in the

manufacturing phase. The phenomena targeted by ICAPS can be broadly classified into three categories: (1) interactions between particles and droplets, (2) interactions between particles or droplets and surrounding gases, and (3) interactions between particles or droplets and electromagnetic radiation. More specifically, the research addresses aerosols, the impact of sound waves, particle interactions and agglomeration, physical properties of regoliths, optical and structural characteristics of aggregates, validation of classic radiation transfer theory, and the light scattering method. Since the target particles in particle agglomeration are on the order of millimeters in size, there is the possibility that this research will complement research into agglomeration of micrometer-scale particles targeted by dusty plasma research at some point in the future. ICAPS participants consist of international research teams that include Japanese scientists.

(4) Atomic Clock Ensemble in Space (ACES)

The ACES is an atomic clock being developed by ESA for the ISS. Researchers plan to take advantage of the fact that it will provide dramatically higher precision than the clocks on current GPS satellites to: (1) conduct a high-precision validation of the gravitational red shift predicted by Einstein, (2) measure time variations in fundamental constants such as the fine structure constant that determine the properties of our universe, and (3) conduct research into the Lorentz invariant through high-precision measurements of the speed of light. Planned research into relativity also includes the Quantum Test of the Weak-Equivalence Principle (Q-WEP). In its use of the effect of the gravity environment on the progress of time, this plan represents an unprecedented microgravity experiment. Preparations for the ACES experiment are global in scope due to the need for terrestrial stations to receive signals, and multiple research institutions and universities in Japan are slated to participate.

(5) Critical point and supercritical research

The phenomenon of abnormal, high-speed heat transfer discovered by a German microgravity experiment conducted on the Space Shuttle is well known in this field. Today, the phenomenon is known as the piston effect. Japanese researchers have made a significant contribution to the mechanism's explication.

Currently, use of the DECLIC experimental facility developed by France's CNES has begun. DECLIC consists of three test pieces known as module inserts, two of which address phenomena near the critical point and supercritical phenomena.

(6) Fundamental chemistry

Even in areas other than critical point and supercritical phenomena, no country other than

Japan has conducted serious, long-duration microgravity experiments in the field of fundamental chemistry. However, an intermediate space experiment investigating crystal growth and chemistry (not fundamental chemistry) of zeolite synthesis was conducted by the United States on the Space Shuttle (USML-1 and -2). Additionally, the ESA's Zeolite Synthesis Topical Team is currently continuing a program of activities.

2.2.5 Materials Space Experiments in the Applied Research Center Promotion Program

JAXA's International Space Station (ISS) Applied Research Center Promotion Program was launched in 2004, and the ISS Applied Research Center Promotion Committee has since selected three institutions as applied research promotion centers, which are conducting experiments on Kibo.

The Applied Research Center Promotion Program advocates research activities that bridge the space between fundamental research and project development as part of an initiative to eliminate the gap between fundamental science and product commercialization. To that end, it targets research in which specific outlets (returning the results of research to industry) are the clear objective.

Consequently, universities and research leaders are spearheading an effort to build joint research entities consisting of companies involved in product commercialization and university researchers to pursue joint research projects with JAXA. Companies are working to apply results obtained by centers during the preparatory terrestrial phase, and universities are exploring new corporate needs and striving to develop partnership-oriented entities.

The research objects in the three research areas targeted by Kibo are characterized by being larger than 10 nm but smaller than 1 μm , and researchers are focusing on and utilizing phenomena in which interaction forces such as Coulomb's force and attractions between molecules and substances that affect the formation of structures through ordered self-organization under conditions of Brownian motion react with a high level of sensitivity to buoyancy and density gradients created by gravity.

(1) Dusty plasma research

Sub-angstrom-level protein structure and function analysis and application using high-resolution crystals

This research area seeks to analyze and apply super-high-density structures based on high-quality protein crystal formation under microgravity conditions over extended periods of time on the ISS.

Four space experiments in this area have already been completed. Examples of the application of their findings include analyses of the super-high-density crystal structure of proteins related to congenital metabolic disorders and proteins related to nylon breakdown, in

which scientists were able to identify a high-density structure at a resolution of 0.88 to 1.1 Å. This data is being used to develop pharmaceuticals and new enzymes.

Scientists at this research center discovered that when the ratio of the diffusion coefficient to the protein uptake coefficient is less than a certain value (index), microgravity effects are more pronounced in the development of high-resolution crystals, increasing the efficiency with which useful results from scientific experiments can be found through high-purity refining of protein solutions and the creation of high-viscosity solutions. These technologies have played an essential role in experiments on Kibo, and they continue to be improved by researchers.

(2) Creation of a two-dimensional nano template under microgravity conditions

This research area seeks to create new materials using a phenomenon in which peptide molecules on a flat substrate align themselves into regular belts. By utilizing this phenomenon, peptide macromolecules are self-aligned in such belts over a large area under microgravity in order to make a masking material on the surface of a silicon carbide (SiC) substrate on which a step-like layer of carbon atoms has been formed by means of ultraprecision machining. After being brought back to Earth, the masking material is used to create a substrate with surface irregularities on the order of several nanometers by means of ion beam irradiation, and development work is progressing to use this substrate as a mold for the manufacture of high-quality monocrystal for gallium nitride (GaN) semiconductors, which are expected to be used as amplifying elements to increase communications capacity in the near future. The results of the first space experiment confirmed that microgravity works effectively only in a narrow range, so researchers are currently analyzing theories concerning the effects of microgravity and studying experimental conditions based on those findings.

(3) Creation of Nanoskeletons under microgravity conditions

This research area seeks to create new functional materials using nano-level self-organization phenomena exhibited by surfactants with hydrophobic and hydrophilic functions. It is known that by regulating the density of a surfactant it is possible to form pore-structure patterns in the shape of spheres, rods, layers, and honeycomb structures. These findings are being utilized in applications ranging from daily life to industrial uses, including in gas chromatograph analysis by taking advantage of the honeycomb structure with uniform pores, which is used to identify and quantify compounds that are easily vaporized, and in efficient purification of contaminated air by taking advantage of the ability of the large surface areas of these materials to retain more catalyst particles.

Currently, researchers are working through space experiments to create new Nanoskeleton® functional skeletal structures with a large diameter (7 to 15 nm) made of high-quality titanium

oxide crystals. These new materials activate honeycomb-shaped walls that normally exhibit low catalytic activity or use oil to achieve nano-level control of pore diameters. To achieve the desired results, the generated particles must not sink, but rather mix uniformly over extended periods of time with water and oil, and the tendency of particles under microgravity conditions to levitate rather than precipitating is expected to be used to create more effective catalysts. The results of the first space experiment confirmed that the uniform diffusion of oil and particles helps increase pore diameters. Additionally, researchers were able to confirm where microgravity does and does not work effectively, so they are now analyzing theories concerning the effects of microgravity and studying experimental conditions based on those findings.

3. Directions and Research Topics in the Field of Physical Science

In order to pursue strategic research in the field of physical science on the ISS and Kibo, the Working Group has identified the following priority objectives through 2020 after considering the results of, and trends in, experiments under microgravity conditions as described in Chapter 2 in light of the directions and priorities characterizing Kibo utilization as outlined in Chapter 1.

We started with the three directions set forth in section 1.1:

(1) Prioritized areas (long-term topics)

Areas in which researchers obtain scientific knowledge in life sciences and material sciences over a long term (more than 5 years) under “View point 1: Forefront scientific research only enabled by ISS/Kibo”.

(2) Prioritized areas (short-term topics)

Areas in which researchers create such breakthrough technologies and making such findings in the short term (approximately 3 years) under “View point 1: Forefront scientific research only enabled by ISS/Kibo”.

(3) Prioritized areas (fundamental research and development for the future space activities)

Areas in which researchers obtain scientific knowledge under “View point 2: Fundamental research and development for the future space activities”.

We then grouped research areas from (1) above in which the focus for the time being is on the use of overseas experimental facilities through international cooperation as:

(4) Prioritized areas (long-term topics through international cooperation)

Separate Table 1 at the end of this document outlines the correspondence between these prioritized areas and the view points in the utilization of Kibo described in section 1.1.

3.1 Prioritized Areas (Long-term Topics)

We have identified the following two research areas as “(1) Areas in which researchers obtain scientific knowledge in life sciences and material sciences over a long term (more than 5 years) under ‘View point 1: Forefront scientific research only enabled by ISS/Kibo’ as outlined in section 1.1.

3.1.1 Prioritized Area 1: Contribution to new combustion technology for mitigating environmental loads.

Japanese energy policy is grappling with the difficulty of developing scenarios to replace previous CO₂ emission reduction measures that depend on nuclear power. In this context, it is essential to develop new combustion systems that enable the reduction of CO₂ emissions from combustion, which currently accounts for more than 80% of Japan’s primary energy supply. This research area seeks to develop the combustion science that will form the foundation for those systems (new oxygen combustion, etc.).

(1) Scientific importance

The Great East Japan Earthquake has triggered changes in Japan’s energy systems. The future of plans that assumed increasing dependence on nuclear power would assure the availability of sufficient power into the indefinite future while allowing CO₂ emissions reductions has been thrown into doubt. As a result of these new circumstances, pressure to reduce CO₂ emissions from combustion (existing natural gas and fuel spray combustion) is certain to become more intense even as the importance of thermal power generation, which accounted for 60% of all power generation before the earthquake, grows.

In order to accommodate such changes in the status of the existing energy systems, it will be essential to achieve breakthroughs in combustion devices based on deep knowledge in the field of combustion science. To develop these new combustion systems, it will be essential to elucidate basic physical and chemical processes, making it necessary to study the relevant phenomena in an environment free of the effects of gravity. The combination of advanced experimental technology and microgravity conditions is expected to yield dramatic progress in new combustion research.

This section describes the scientific importance of prioritized area (1) using the fundamental science of oxygen combustion as an example. Oxygen combustion refers to the use of pure oxygen instead of air to oxidize fuel. However, during the actual combustion process, a large volume of recirculated exhaust gas is mixed with fuel and oxygen prior to combustion. In addition to increasing thermal efficiency by allowing exhaust gas energy to be recovered, this approach yields exhaust gases consisting primarily of CO₂ that can then be recovered and

stored. The critical knowledge here involves the science of combustion in an atmosphere of exhaust gas and other inert components (CO_2 , H_2O). Combustion science in the past has assumed combustion in the air, and a change in the basic preconditions of combustion such as this will require that a new system of combustion science be developed. Scientists in Japan and overseas have been actively pursuing research in this area, known as oxy-fuel combustion, in recent years. However, it is extremely difficult to investigate combustion limits—the most important issue in this area—under normal gravity conditions, and previous research must be concluded to be inadequate. This is due to the fact that extinction limits are determined by competition between the speed of the chemical reaction in the observed area and the physical characteristic time, which is determined by the flow field, making it difficult to conduct research into true extinction phenomena in environments where the process cannot be controlled so as to produce an extremely low-speed flow field.

(2) Reason that research can only be conducted on the ISS/Kibo

As described above, the most important research topic for new oxygen combustion systems is combustion limits. That is to say, fundamental data is needed detailing to what extent the combustion environment can be diluted with CO_2 when combustion occurs in recirculated exhaust gas without interrupting the combustion process, to what extent continuous combustion can be maintained with low-caloric-value fuel, and up to what speed the flame at the base of the burner can be maintained when using high-speed combustors.

In discussions of combustion limits, the most basic and important concept is the ratio of the reaction characteristic time and the gas retention time in the combustion field (known as the Damkohler number). In order to provide an academic definition of combustion limits, it is necessary to clarify the effects of the reaction characteristic time (as well as the factors that influence it) while holding the physical characteristic time constant. For this reason, the use of microgravity has intrinsic significance. In short, it is necessary to completely remove all flow that cannot be controlled from the observation field in order to hold the physical characteristic time constant, and this can only be accomplished under microgravity conditions.

In particular, because combustion phenomena react with a high degree of sensitivity to even slight fluctuations in gravity, experiments must be conducted either using drop towers at terrestrial facilities or in space in order to obtain experimental data which have enough quality to stand up to scientific discussions is to be obtained. The duration of microgravity is limited when using terrestrial drop towers, and once a certain limit is exceeded, the experiment itself cannot be performed. More involved experiments must rely upon either sounding rockets or orbital experimental facilities, and repeating or long-duration experiments can only be conducted on the ISS/Kibo at the present time.

(3) International research trends

Extensive oxy-fuel combustion research as described above has begun in Japan and overseas, but almost no research is being conducted in microgravity. In particular, combustion limits, the most basic phenomenon in this area, remains an essentially unknown area. At the same time, Japan leads the world in microgravity experiments in gas fuel combustion using counterflow.

(4) Novel, advanced, and challenging aspects of research

Because control of the flow field is difficult under normal gravity conditions, it is difficult to observe intrinsic flame extinction phenomena. Additionally, it is difficult to make conclusions in short-duration microgravity experiments when reaction speeds are very slow (extinction due to dilution with large volumes of CO₂ or use of low-quality fuel), necessitating high-quality, long-duration microgravity conditions (as can be achieved during experiments on the ISS).

(5) Connection with past space experiments

Japan has not conducted orbital combustion experiments in the past. While there are many examples of extinction research with gas fuels using counterflow flames conducted using drop towers, researchers have not conducted experiments with long reaction characteristic times requiring long-duration microgravity conditions due to the difficulty of doing so. Research into flame extinction with gaseous and solid fuel is planned for the second stage of the Second Phase Utilization, but experimental variables are limited, and no research is planned to address combustion in the presence of exhaust gas and inert gas components, necessitating new research.

(6) Ability to parlay research to create new technological fields and industries in 10 to 15 years

The process of setting new boundary conditions and developing combustion science systems to accommodate them will lead to the creation of new energy devices and energy industries. For example, the process of oxygen combustion used as an example here is not yet being utilized on a serious industrial scale. However, the technology holds the promise of providing a fundamental solution to the problem of controlling CO₂ emissions and may lead in the future to the creation of new industries.

(7) Objectives and approach through 2020

- Up to about 2015: Present a theoretical background for combustion limits, including radiation and chemical reactions.
- Up to about 2020: Contribute to the development of new combustion science systems to

lay the groundwork for the implementation of super-high-efficiency combustion technologies and CO₂ recovery combustion.

3.1.2 Prioritized Area 2: Science and Technology of Vapor Bubbles, Droplets, and Liquid Films—Application to the Space System

The gas-liquid interface is extremely sensitive to gravity effects due to the presence of a large density jump across the interface. As a critical part of space systems, related technologies find many important applications in a wide range of areas from boiling bubbles to fuel droplets, liquid films inside heat pipes, electrode gas bubbles in fuel batteries, shower droplets, dew condensation liquid films, and biological liquid films. In order to better understand such interfacial phenomena as well as the basic science behind vapor bubbles, droplets, and liquid films, we are pursuing ideal fluid studies in the absence of convection under microgravity conditions.

(1) Scientific Significance

Fluid dynamics plays a key role in many areas of science, from engineering to physics, chemistry, biology, and medicine. Understanding—and actively utilizing—fluid phenomena are essential for the welfare of mankind, whether on Earth or in space. Supported by a growing body of scientific knowledge, our understanding and application of these highly dynamic and diverse fluid phenomena have come a long way insofar as we are living on the surface of the Earth, which is justifiably known as the “water planet.”

On the International Space Station (ISS), where resources to investigate diverse and changing fluid phenomena are limited, scientific understanding and control of vapor bubbles, droplets, and liquid films are the most important prioritized areas in our research. Since fluid phenomena with phase interfaces and density gradients are significantly affected by gravity, understanding and applying fluid behavior in a space environment are indispensable for the future advance of our space activities. Such knowledge will also be valuable for the development of basic and applied science on the ground.

(2) Reason that research can only be conducted on the ISS/Kibo

As described in the previous section, fluid phenomena with phase interfaces and density gradients are significantly affected by gravity. As is made clear by the example of Marangoni experiments, some phenomena become clear for the first time only with long-duration observation. Based on these facts, research into the behavior and control of multi-phase fluids with interfaces and density gradients is a treasure trove of “forefront scientific research only enabled by ISS/Kibo.”

(3) International research trends

While researchers have the technology development-oriented objective of enabling high-efficiency heat exchange by controlling thin-film evaporation at the three-phase interface of liquid film flow and deposited droplets, much remains unknown about behavior at the interface, including differences in wettability and dynamic effects due to evaporation. There is high scientific value in explicating that behavior.

This research remains at the initial stage, even from an international standpoint, and demands long-term investigation. By contrast, Japan leads the world in terrestrial experiments designed to achieve dramatically high performance for heat pipes by controlling surface tension, and recently the ESA has also shown interest in this area. Concentration and temperature gradients occurring at the gas-liquid interface as mixed media evaporate can both induce Marangoni convection in the direction that accelerates evaporation, and not only heat pipe heat removal limits, but also the extent to which thermal resistance can be reduced, remain an open question.

Cooperation between Japan and Europe has already been established at the researcher level and is a short-term issue. It is desirable that a support system be established on the Japanese side at the earliest possible opportunity.

(4) Novel, advanced, and challenging aspects of research

Our understanding and use of fluid phenomena in the space environment, which differs from terrestrial settings in terms of its lack of gravity and high vacuum conditions, remain inadequate. As humankind seeks to exploit space in the future, it will be essential to accumulate knowledge through sustained research activities.

(5) Connection with past space experiments

The Fluid Physics Experiment Facility (FPEF), which provides a series of support systems and which has already been used to perform experiments in liquid bridge Marangoni convection, is an experimental facility on the ISS that could be used for experiments in this field. The FPEF's mission module, a replaceable component, can be designed and manufactured to satisfy the specifications needed for specific research topics. Additionally, the Multi-purpose Small Payload Rack (MSPR), which offers little in the way of support equipment but significant work volume that can be utilized by users, is already in the ISS. We believe that the comparative lack of constraints means that it would be possible to develop equipment in a relatively short period of time. Separately, the general-purpose fluid experimental facility whose development is recently being planned by the ESA will offer replaceable components in a compact footprint, and it will likely be possible to conduct experiments addressing certain interface phenomena in

cooperation with European researchers.

(6) Ability to parlay research to create new technological fields and industries in 10 to 15 years

In addition to developments in engineering fields, for example through advances in heat exchange technologies such as heat pipes, the potential applications of fluid phenomena are extremely broad and extend from fundamental to applied science due to their occurrence in a large number of fields in science (physics, chemistry, and biology) and medicine. For example, questions such as how behavior of dispersed droplets in gases, vapor bubbles in boiling liquids, crystal cores and coagulated particles in solutions, and blood cells in blood differs between microgravity conditions on the ISS and normal gravity conditions should be targeted by cross-disciplinary research in the multiple fields listed above. Findings from such research have the potential to contribute to the creation of new industries.

(7) Objectives and approach through 2020

Due to the advanced nature of the research topics in this research area, it is appropriate to divide them into long-duration research topics that will require about five years before experiments can be carried out on the ISS (to allow preparatory research to be conducted and experimental facilities to be developed), and short-duration research topics for which ISS experiments can be implemented in about three years (to allow for new perspectives and experimental innovations to be incorporated into research that is already being carried out overseas).

- Up to about 2015: Strive to assess and develop a scientific understanding of fundamental phenomena relating to gas bubbles, liquid droplets, and liquid films.
- Up to about 2020: Strive to obtain (certification under microgravity) innovative thermal control technologies through the control of the behavior of gas bubbles, liquid droplets, and liquid films.

3.2 Prioritized Areas (Short-term Topics)

We have identified the following two research areas as “(2) Areas in which researchers create such breakthrough technologies and making such findings in the short term (approximately 3 years) under ‘View point 1: Forefront scientific research only enabled by ISS/Kibo’ as outlined in section 1.1.

3.2.1 Prioritized Area 3: Producing New Materials from Super Cooled Phase by Containerless Processing

Research in this area seeks to find new metastable materials with exceptional functionality by suspending high-temperature melted substances by means of containerless processing and solidifying them from a super-cooled state. Additionally, through the systematic, high-precision measurement of the values of their physical properties (viscosity, surface tension, density, etc.), which are difficult to measure in terrestrial settings, it seeks to contribute to physical science. Systematic measurements of the physical properties of high temperature materials with high melting points that are in high demand in industry (alloys used as high-hardness materials, oxides used as optical materials and heat insulation coatings, etc.).

Containerless levitation experiments have been conducted in terrestrial settings using such methods as electromagnetic levitation, acoustic levitation, and magnetic levitation, but it has been difficult to levitate insulation materials such as oxides. Electrostatic levitation furnaces can be used for materials that are difficult to levitate using other methods, allowing super-cooled states with significantly lower disturbance levels than is possible in terrestrial settings to be achieved and making it possible to search for new, metastable materials. Because progress is already being made in Japan in the search for, and structural measurement of, metastable-phase oxides such as BaTi₂O₅ glasses using containerless processing, and because an electrostatic levitation furnace being developed for the ISS is designed primarily for use with oxide melts, it will be possible to pursue metastable-phase research with a focus on oxides in an effective manner. It is possible that this method will allow the formation of bulk samples and new metastable phases that cannot be achieved using the very fast cooling method. In order to create metastable materials with exceptional functionality, it is desirable not to rely simply on a process of trial and error, but rather to select the composition of samples used in research based on forecasts from first principle calculations.

In-situ observation of material structure and phase transition processes using X-rays are useful techniques in research using electrostatic levitation furnaces, and it is extremely desirable that a compact device that could be placed on the ISS be developed.

(1) Scientific importance

To date, metastable-phase research typified by metallic glass and quasicrystals, for which the Nobel Prize in Chemistry was awarded in 2011, has been conducted using techniques such as splat quenching and the very fast cooling method. Consequently, it has been faced with issues that the obtained samples are minute or limited to a thin, ribbon-like shape and that the cooling process is extremely too short duration, to observe the metastable phase selection process. Containerless processing differs from the very fast cooling method in that solidification occurs from a super-cooled state at very low levels of disturbance, raising the possibility of the creation of new metastable phases. Further, it allows a deeply undercooled state to be maintained for extended periods of time so that research into the mechanism by which metastable phases are created can be pursued at the same time.

This research is conceived to (1) explore metastable-phase materials and (2) systematically measure the structure and physical properties of melts of those metastable-phase materials. By clarifying information such as the compositions from which metastable phases can be obtained, the characteristics of metastable phases that can be obtained, and the processes that yield metastable phases (cooling speed, degree of super-cooling, etc.), it promises to facilitate the design of metastable-phase materials.

Additionally, Japan has already amassed experience in the systematic measurement of the physical properties (density, viscosity, and surface tension) of molten refractory metals in terrestrial settings, and most technical issues have been overcome. However, levitation of oxides and other materials remains difficult, necessitating use of microgravity conditions and highlighting the importance of conducting experiments in the space environment.

(2) Reason that research can only be conducted on the ISS/Kibo

Methods such as electromagnetic levitation, acoustic levitation, and magnetic levitation have been used in terrestrial settings to conduct experiments into the containerless levitation of materials. However, on the ISS, it is possible to target materials whose levitation is difficult on Earth, and highly reliable experiments can be conducted under conditions characterized by levels of disturbance that are significantly lower than those associated with terrestrial settings.

(3) International research trends

Metastable-phase research using containerless processing is also being carried out in Europe and the United States. Experiments on the Space Shuttle have already been conducted as part of research into quasicrystal alloy melts using an electromagnetic levitation furnace. Structural measurements using light emitted from a quasicrystal melt (TiNiZr) using an electrostatic levitation furnace have also been conducted as part of a terrestrial research program. The ESA

plans to place an electromagnetic levitation furnace on the ISS, and plans call for the instrument to be used to conduct metastable-phase research similar to what has been conducted in Japan using alloy materials with a high level of participation from Japanese researchers. By contrast, there are no organization-level initiatives addressing oxide melts underway in Europe or the United States, which have yielded the initiative to Japan in this area.

(4) Novel, advanced, and challenging aspects of research

Dating to the 1980s, the discovery of quasicrystals and metallic glass is an extremely new development in materials science, giving this research area a pronounced novel, advanced, and challenging character. As described above, the mechanisms by which metastable phases are created remain unknown. Particularly in the area of oxides, very little systematic research has been pursued to date.

(5) Connection with past space experiments

The connection between space experiments and metastable-phase research lies in the use of a super-cooled state achieved by means of containerless processing. During the 1990s, the usefulness of microgravity experiments was questionable due to the lack of maturity of levitation technology. However, technological progress since that time has been remarkable. Technological research is now being pursued aggressively, primarily by space agencies, and stable levitation has been achieved even in terrestrial settings.

(6) Ability to parlay research to create new technological fields and industries in 10 to 15 years

Ferroelectric BaTiO_3 (used in micro-miniature capacitors) and BaTi_2O_5 glass (a high-refractive-index optical material), both of which were discovered as part of JAXA research, have already been patented, and companies are currently pursuing commercialization research. The samples that can be obtained using levitation methods in these two cases are limited in size to about 2 mm in diameter, but if the production processes of these new functional materials can be created become clear, it will pave the way for high-volume manufacturing and commercialization on Earth. In particular, recent progress toward the miniaturization of devices has triggered a shift in research objectives away from the goal of obtaining larger crystals. Spherical silicon monocrystals with diameters on the order of several millimeters obtained by means of levitation solidification have already been commercialized as new photovoltaic power generation elements. In the future, use of newly discovered phases such as these and new material processes derived from space experiments will make a direct contribution to industry.

(7) Objectives and approach through 2020

- Up to about 2015: Search for metastable-phase materials and systematically measure the values of physical properties of materials with high melting points (particularly oxides).
- Up to about 2020: Clarify information such as the compositions from which metastable phases can be obtained, the characteristics of metastable phases that can be obtained, and the processes that yield metastable phases (cooling speed, degree of super-cooling, etc.)

3.2.2 Prioritized Area 4: Survey of Useful Soft Matter to Society Using the Space Environment

As a short-term priority topic being pursued in an effort to commercialize research findings, this research seeks to obtain new materials and high-quality crystals by targeting materials that consist of aggregates of molecules with high molecular weights (macromolecules and soft matter). Whereas the weak intermolecular interactions characterizing these molecules cause the effects of gravity segregation and convection to be highly pronounced in terrestrial settings and therefore make crystallization difficult, these difficulties can be overcome, and molecules regularly arranged, under microgravity conditions. In particular, this research is conceived to search for soft matter that can play a useful role in society, for example protein crystals that will lead to the discovery of new pharmaceuticals and new functional materials.

Under the Pilot Applied Research Program, which focuses on research using the space environment, various studies and investigations have been conducted since 1999 into a wide range of research areas with potential industrial applications (highly functional materials, highly functional semiconductors, combustion, protein crystal generation, color materials and fragrances, the environment, regeneration medicine, contactless processes, and bubble growth). As a result, the Project identified protein crystal generation and photonic crystal generation as promising areas for short-term investigation, and researchers conducted space experiments and succeeded in synthesizing protein crystals with the world's highest-resolution analysis and in producing some of the world's largest colloid crystals.

In its own search for research areas, the ISS Applied Research Center Promotion Program, which has taken the place of the Pilot Applied Research Program, identified the fields of protein crystal generation and creation of materials through self-organization as promising research areas, and space experiments designed to prepare for industrial applications of related technologies are being carried out through collaboration with industry and academia.

Through these studies and space experiments, it has become clear that the creation of materials with unique, fine structures formed from macromolecules that are dominated by comparatively weak intermolecular interactions may become the principal topic of investigation in the applied

utilization of the space environment. Approaches taking advantage of self-organization in material creation are being energetically pursued in normal terrestrial research, leading to the discovery of innovative concepts and new phenomena that would be unthinkable through the extension of conventional technology and making this an appealing area where industrial applications can be expected in a variety of fields.

In the selection and implementation of these application-oriented research topics, it is necessary to bear in mind the need to narrow down the targets and conditions for space experiments after making adequate terrestrial preparations (setting experimental conditions and theoretical hypotheses, etc.), which are essential to the achievement of successful outcomes.

(1) Scientific importance

In self-organizing processes driven by weak interaction forces of macromolecules and substances in solution, the completeness of the product in terrestrial settings is obstructed by gravity-caused sedimentation and convection. By contrast, researchers are currently verifying the ability to achieve highly complete self-organization under microgravity conditions on the ISS and the Japanese Experiment Module Kibo.

For example, the formation and composition of substances including colloids, polymers, colloid gels, large protein molecular crystals, foams, emulsions, and soap solutions under gravity are affected by density gradients. Consequently, it is possible to conduct research with the objective of creating innovative new materials and assessing material characteristics under microgravity conditions by eliminating these density gradients.

(2) Reason that research can only be conducted on the ISS/Kibo

Because interactions between molecules in soft matter are characterized by weak forces, molecules can be expected to align themselves regularly in extremely undisturbed environments such as microgravity. The molecules serving as “raw materials” in this type of experiment are in constant irregular motion (Brownian motion) in solutions such as water, and this motion disrupts regular alignment. Moreover, in terrestrial settings, the effects of gravity cause molecules to float and precipitate, making it impossible to synthesize highly complete aggregates or crystals. While Brownian motion occurs under the microgravity conditions of space just as it does on Earth, when the raw material molecules are distributed evenly in a solution, the regularity of alignment increases gradually even though the forces between the molecules are weak, allowing highly complete materials and crystals to be synthesized. This process normally requires several weeks to complete, making Kibo essential as a setting for such experiments. Since this research and development field does not require large-scale, special experimental facilities, results can be expected in a comparatively short amount of time.

(3) International research trends

While NASA recognized the area of complex fluids as an important field of microgravity research, the ESA established a lead in research initiatives. After coming to a renewed understanding of the importance of this area, NASA cultivated knowledge in the field through joint research with the ESA and space experiments, and today it is an advanced research topic at major universities. The U.S. National Research Council (NRC) has identified the field as a prioritized research area in the physical sciences for NASA over the next 10 years. Many papers with a high impact factor have been published, including about space experiments on the Space Shuttle and other facilities and terrestrial research.

(4) Novel, advanced, and challenging aspects of research

Research in this area seeks to create large, high-quality single crystals and highly efficient catalysts using nano-structures that are difficult to obtain in terrestrial settings. Projects address advanced topics that can only be carried out in space to realize the world's first, largest, or highest quality new materials in space.

(5) Connection with past space experiments

Under the Pilot Applied Research Program, which started in 1999, various studies and investigations with potential industrial applications have been conducted using the space environment in a wide range of research areas (highly functional materials, highly functional semiconductors, protein crystals, etc.). As a result, the Project identified protein crystal generation and photonic crystal generation as promising areas for short-term investigation, and researchers conducted space experiments and succeeded in synthesizing protein crystals with the world's highest resolution and in producing some of the world's largest colloid crystals. These experiments highlighted the essential role to be played by microgravity conditions in accelerating self-organizing crystallization with a high degree of completeness due to the extremely weak nature of the interactions between macromolecules compared to those of atoms and ions and the importance of steadily pursuing quantitative research into the effects of microgravity in order to apply findings in industry.

The ISS Applied Research Center Promotion Program has identified the fields of protein crystal generation and the creation of materials through self-organization as promising research areas and pursued a program of space experiments targeting the industrial application of associated technologies through collaboration with industry and academia. Experiments in protein crystal generation in particular have led to the accumulation of technologies for increasing the effects of microgravity, giving researchers an understanding of the effectiveness

of techniques such as the generation of high-purity protein samples and control of diffusion speed and making it clear that they can be applied in experiments in generating macromolecular aggregates formed by self-organization using diffuse fields of molecules.

Through these studies and space experiments, it has become clear that the creation of materials with unique, fine structures formed from macromolecules that are dominated by comparatively weak intermolecular interactions may become the principal topic of investigation in the applied utilization of the space environment. Approaches taking advantage of self-organization in material creation are being energetically pursued in normal terrestrial research, leading to the discovery of innovative concepts and new phenomena that would be unthinkable through the extension of conventional technology and making this an appealing area where industrial applications can be expected in a variety of fields. However, space experiments conducted in microgravity have a major role to play due to the large number of research targets where explication of phenomena and ordering of molecules are difficult as a result of convection and sedimentation in terrestrial settings.

(6) Ability to parlay research to create new technological fields and industries in 10 to 15 years

Research into this area is being conducted in a wide range of industries, including food, chemical substances, oil, cosmetics, pharmaceuticals, LCD devices, and plastics, and it has become essential in current and future technology. It has been reported that the direct economic effects of these materials and processes total 5% of GDP in the United States, equivalent to \$1 trillion. They also play an important role in the construction, textile, printing, and electronics industries.

For example, it is expected that highly functional pulse delay elements obtained from the space environment will create a market valued at about ¥1 billion, dye-sensitized cells about ¥50 billion, and photocatalysts about ¥10 billion.

Experiments in the field of structure formation through self-organization of macromolecules with comparatively weak interactions have demonstrated that techniques for refining and producing raw materials are extremely important, and it has become clear through research that the formulation process requires expertise that cannot be captured in a manual—in short, the intuition and skill of the craftsman. Since this field is founded on craftsmanship, an area where Japan has an utmost level of skill, it is appropriate that it be given a high level of priority.

(7) Objectives and approach through 2020

There are many material formation techniques that can be classified as belonging to the field of structure formation through self-organization of macromolecules with comparatively weak interactions. In selecting targets of research on the ISS from among related topics, researchers

should draw on the experience gained and lessons learned in past experiments using the space environment to choose subjects that benefit more from microgravity, that provide clear experimental systems, and that should be prioritized in terms of industrial applications. However, it is not desirable to continue past research and develop methods in the conduct of space experiments, which have lacked sufficient backing and relied on a combination of intuition and trial and error to speed the recovery of research and development investments in the short term. Instead, it will be important to adopt a more scientific approach while drawing on meticulous, theoretical study and computational science.

For research topics in applied utilization fields, the achievement of results for industrial applications and their application are important. During a period of about three years after specific topics have been selected, it will be necessary to select space experiment targets, study feasibility, design and develop space experiment facilities, and optimize space experiment conditions. Then researchers should work to conduct space experiments in about two years and return the results to Earth.

- Up to about 2013: Search for macromolecules for which microgravity effectively contributes to structure formation and establish refining and space experiment techniques.
- Up to about 2016: Strive to apply the results of space experiments to terrestrial industry.

3.3 Prioritized Areas (Fundamental Research and Development for the Future Space Activities)

We have identified the following research area as an “Area in which researchers seek to acquire scientific knowledge under “View point 2: Fundamental research and development for the future space activities” as outlined in section 1.1.

3.3.1 Prioritized Area 5: Fundamental Research for International Fire Safety Standard in Space

Fire safety technology in space is a key technology for future manned activities. Based on previous drop tower experiments and other studies, combustion characteristics of solid materials in microgravity differ significantly from those in terrestrial settings, and important aspects of those differences, such as the expansion of combustion limits, have become clear. For this reason, answers are needed to questions about fire phenomena in microgravity, for example the lower limit of energy needed in order to ignite flammable materials and the lower limit of oxygen concentration needed to sustain continuous combustion. In addition to explicating fire phenomena in microgravity from a fundamental standpoint, it is necessary to establish international space fire safety standards based on those phenomena.

(1) Scientific importance

The problem of safety will become increasingly important as we plan future manned space activities. In particular, it is assumed that international (ISO) standards addressing material fire safety will be adopted as countries pursue plans for manned spacecraft and space stations. As a space-exploring nation, Japan must make a contribution in this area. Particularly with regard to the combustibility of solid materials, Japan plans to lead other countries in conducting ISS experiments as a topic for the second stage of the Second Phase Utilization, and the country should play an international leadership role from the standpoint of combustion science as relates to space fire safety standards.

(2) Reason that research can only be conducted on the ISS/Kibo

Out of all combustion phenomena, solid combustion in particular exhibits large time constants, necessitating long-duration, high-quality microgravity conditions (which can be achieved in experiments on the ISS).

(3) International research trends

NASA has been involved in experiments on the Space Shuttle and other studies into the combustion of solid materials. However, past research has addressed only an extremely limited range of experimental variables, and NASA recently halted solid material combustion research as a fundamental science, contributing to a lack of significant progress in the area in recent

years. By contrast, Japan is currently developing a solid combustion experimental facility that will be capable of precisely varying the oxygen concentration and speed of airflow in the combustion field and plans to conduct experiments on the ISS in several years. Based on these facts, Japan is extremely competitive in the area of fundamental research relating to the combustibility of solid materials.

(4) Novel, advanced, and challenging aspects of research

ISS experiments can be considered to be preparatory research for future long-term manned space activities. Typical of such research is the study of space fire safety. Because the combustibility of materials is determined by the interrelationship between local reaction speed and the physical characteristic time given by the flow field, it is difficult to obtain data relating to combustion limits in microgravity under normal gravitational conditions. Consequently, the effort to clarify materials' intrinsic combustion limits in microgravity experiments and then to elucidate their relationship to combustion standards based on various terrestrial standards constitutes extremely important and advanced research.

(5) Connection with past space experiments

Japan has never conducted an orbital experiment in solid material combustion. Currently, preparations are underway for experiments as part of a second-stage topic for the Second Phase Utilization. This topic seeks to investigate combustion limits of solid materials with a simple composition, and it is believed that broader research into material dimensions and quality effects will be needed in order to establish a relationship with terrestrial material fire resistance standards.

(6) Ability to parlay research to create new technological fields and industries in 10 to 15 years

This research area is not one in which results lead to the creation of new industries. However, it can contribute to new space technologies insofar as it leads to the development of new evaluation standards relating to the space fire safety of solid materials.

(7) Objectives and approach through 2020

- Up to about 2015: Obtain data detailing combustion limits from the standpoint of solid material fire safety.
- Up to about 2020: Contribute to the formulation of fire safety standards, which will form the basis of future manned space activities.

3.4 Prioritized Area (Long-term Topics through International Cooperation)

We have identified the following research area as an “Areas in which researchers obtain scientific knowledge in life sciences and material sciences over a long term (more than 5 years) under ‘View point 1: Forefront scientific research only enabled by ISS/Kibo’ as outlined in section 1.1, specifically as an area where advanced knowledge may be acquired through the use of other nations’ experimental facilities on the ISS by means of international cooperation.

3.4.1 Prioritized Area 6: Equilibrium and Non-equilibrium Phenomena under Extreme and Plasma Environments

This area consists of research into non-equilibrium phenomena in extreme environments characterized by extremely low temperatures and vacuum conditions and in plasma environments consisting of groups of dissociated ions and electrons. Looking at other research areas addressed in this document, solid ^4He research corresponds to the former, and dusty plasma research to the latter. Solid ^4He research seeks to investigate the effects of quantum fluctuations and the properties of Bose particle solids and to explicate the physics of solid ^4He crystal formation, which remains unexplained. On the other hand, research in dusty plasma, in which a mixture of ions, electrons, and fine particles behaves collectively as plasma, seeks to elucidate the physics (phase diagrams and phase transitions, interface phenomena, crystal growth, etc.) of regular structures (Coulomb crystals) formed by fine particles. It is believed that dusty plasma can be found inside white dwarfs and at the periphery of neutron stars, and the field promises to make a contribution to the development of models describing microscopic crystal growth and the formation of interstellar molecular clouds and solar systems.

(1) Scientific importance

Solid ^4He is generated at extremely low temperatures by applying pressure of 25 atmospheres or greater to superfluid-phase helium. Since latent heat released during solidification, which limits crystal growth, disappears almost entirely at sufficiently low temperatures, crystals grow extremely quickly. Helium atoms exhibit a high degree of quantum oscillation in solid ^4He , and the spread of the wave function is very large compared to normal solids, causing atoms to exchange positions by means of the tunnel effect. This type of solid is known as a quantum solid. At low temperatures, solid ^4He assumes a hexagonal close-packed (HCP) structure. Even at extremely low temperatures, roughening transitions can be observed in solid ^4He . In particular, there has been extensive terrestrial research into roughening transitions on the c -facet, which comprises the basal plane. Transitions on the a -facet, which is perpendicular to the c -facet, have also been confirmed in terrestrial experiments. These roughening transitions are mathematically equivalent to two-dimensional Kosterlitz-Thouless (KT) transitions, and the

transition point is determined by the surface stiffness and Miller index. Incidentally, roughening transitions observed at extremely low temperatures down to 2 mK include only the above two types as well as s-facet transitions and differ significantly from those predicted by KT transitions for reasons that remain a mystery. Due to the high degree of quantum fluctuation exhibited by solid ^4He and the manifestation of a high degree of fluctuation in atomic steps on the crystal surface, crystals that are about 10 times larger than the facets are necessary in order to observe facets in the equilibrium state. However, the crystal form is prone to change due to the effects of gravity in terrestrial settings when the crystal is that large, causing it to behave as if it were a liquid by assuming the shape of the container holding the solid. For this reason, roughening transitions themselves are masked on Earth. However, distortion of the crystal form can be prevented in microgravity, and scientists expect this research to yield an understanding of roughening transitions, the exact nature of which has remained a mystery for many years.

By contrast, dusty plasma is a natural phenomenon that is widely observed in space, including, for example, in the form of interstellar molecular clouds, protoplanetary disks, planetary rings, and the tails of comets, all of which are believed to consist of dusty plasma. In dusty plasma, the electrostatic interactions between fine particles can be easily increased to a level that exceeds the particles' kinetic energy. This state is known as strong Coulomb coupling, and when the strongly Coulomb-coupled state becomes sufficiently powerful, the particles align themselves regularly and exhibit a type of solid phase. The theoretical existence of this phase, which is known as a Coulomb crystal or plasma crystal, was predicted in 1986. Subsequently, the discovery of groups of airborne particles in semiconductor and other plasma processes gave scientists a new opportunity to investigate the phenomenon, and research into the formation and observation of solid phases in strongly Coulomb-coupled plasmas began. In 1994, researchers in Germany, the United States, Taiwan, Japan, and other countries successfully observed Coulomb crystals.

In nature, bare atomic nuclei inside white dwarfs and at the periphery of neutron stars are said to be strongly Coulomb-coupled, but it is nearly impossible to directly observe this phenomenon. However, the fact that strongly Coulomb-coupled plasmas can be relatively easily created using dusty plasma has given rise to expectations that our understanding of the physics of strongly Coulomb-coupled plasmas will evolve. Coulomb force is a long-distance force, and dusty plasma research is expected to contribute to our understanding of the fundamental phenomena driving the mechanisms of Coulomb crystal formation and growth, which involve multibody interactions.

Another characteristic of dusty plasma is the ability to directly calculate the coordinates of individual particles. Consequently, it is possible to ascertain local fluctuations in the form of spatial differences in the time variation of number density. This means, for example, that if a

sufficiently broad range of observation can be established, our longstanding lack of understanding of the statistical mechanical problem of the critical points of charged particle systems can be improved, even if conditions are somewhat distant from the critical point. Scientists are also interested in research into the similarities of Coulomb crystals and real crystals from the standpoint of solid-state physics and in the agglomeration of charged particles, a recently discovered phenomenon. In particular, research in this area is expected to contribute to the development of models explaining solar system formation as well as particle agglomeration at the early stages of the formation of protoplanetary disks when gravity is just beginning to act.

(2) Reason that research can only be conducted on the ISS/Kibo

As described above, it is nearly impossible to observe roughening transitions in 4He crystals in terrestrial settings due to their tendency to deform under their own weight. Consequently, it is necessary to conduct experiments under microgravity conditions. Additionally, while it is desirable to use a continuous ADR, which does not use refrigerant and can be used over an extended period of time as a freezer, the size and weight of such equipment makes it well suited to inclusion in Kibo's Exposed Facility. Further, the extended amount of time required in order to reach the desired temperature makes it necessary to conduct experiments in this research area on the ISS/Kibo.

In dusty plasma research, the formation of three-dimensional, isotropic Coulomb crystals is a longstanding topic of investigation. In terrestrial settings, researchers often obtain crystals exhibiting a two-dimensional structure or a non-isotropic simple hexagonal structure, which is a three-dimensional structure. This outcome is due to the fact that on Earth, it is necessary to suspend the particles, and this is accomplished by using an electric field in the vicinity of an electrode. The crystal structure is distorted to a significant degree by the flow of ions that is generated by the electric field. Isotropic crystal structures known as face-centered cubic or body-centered cubic are predicted by theory and used to draw phase diagrams, but the distortion of the structures makes them extremely difficult to verify in a terrestrial setting.

Microgravity conditions are extremely useful in order to achieve three-dimensional, isotropic Coulomb crystals. Fine particles with diameters ranging from $1\text{ }\mu\text{m}$ to dozens of micrometers are typically used in dusty plasma experiments, but even when using an electric field in the vicinity of an electrode, the largest particles that can be suspended in terrestrial experiments have a diameter of about $10\text{ }\mu\text{m}$. It is thought that particle charge varies directly with diameter. Since it is anticipated that a particle diameter of at least $20\text{ }\mu\text{m}$ is needed in order to increase the degree of strong coupling, for example at the critical point, use of microgravity conditions is essential.

(3) International research trends

Professor A. Babkin proposed research into solid 4He under microgravity conditions to NASA around 2000, but the agency shut down its entire fundamental physics project before the proposal could be adopted. Subsequently, only Japan has studied the prospect of attempting a solid 4He space experiment. By contrast, extensive research into dusty plasma is ongoing in Europe (in Germany and Russia) at the present time. Experiments have been conducted using small rockets, aircraft, and the ISS, and many academic papers have been published. However, the observable area is reduced in size at high levels of power (1 W and above) due to the formation of voids (spaces with no particles). To address this issue, the “next-next” generation of experimental facilities (Plasma Lab) will attempt to limit void formation through the use of an oscillating electric field. Research in Japan, which began with proposals of critical point research into charged particle systems, is being carried out across a broader range of related topics with a high level of originality. Japanese researchers expect to be able to create Coulomb crystals with no, or extremely small, voids in the near future.

(4) Novel, advanced, and challenging aspects of research

While only three types of flat crystal faces (facets) have been observed on Earth in solid 4He , it would not be odd in theoretical terms if more existed, and some predictions raise the possibility of facets occurring on all rational index faces. However, it has also been predicted that there is a possibility that flat faces do not occur due to quantum roughening. In this way, the question of the true form of solid 4He has been a longstanding mystery. While reports of observations of multiple facets are beginning to appear thanks to progress in experimental technologies used in terrestrial research, more results are necessary at this stage due to the extremely high level of difficulty associated with such experiments. Observation in the equilibrium state provides the best way to obtain a precise answer to this question. A crystal about 10 times the size of the expected facets is needed, as are adequately long observation times and microgravity conditions. Despite technical challenges including the completion of the continuous ADR, stable cooling to achieve the equilibrium state, and technology for observing phenomena at a high level of resolution at extremely low temperatures, researchers expect to be able to conduct experiments in Kibo’s Exposed Facility in the future.

Strongly Coulomb-coupled plasmas and a solid phase known as Coulomb crystals are a comparatively new phenomena, with researchers first succeeding in forming them in 1994, and numerous unresolved issues remain. For example, topics important in understanding self-organization in strongly Coulomb-coupled plasmas include (1) the mechanisms of Coulomb crystal formation (repulsion and other interactions) and growth (adhesion or some other mechanism, etc.); (2) verification of Coulomb crystals’ true crystal structure, phase diagram,

and solid phase transitions; (3) the critical point in charged-particle systems; (4) similarity to real crystals; (5) power balance and particle balance; and (6) particle agglomeration.

While it is necessary to develop a device in which voids do not form at high power levels (at least 10 to 20 W) in order to conduct such experiments, such development requires an understanding of the mechanism of void formation.

(5) Connection with past space experiments

Initially, scientists involved in solid ^4He research worked with continuous ADR researchers in an effort to conduct short-duration microgravity experiments using aircraft. However, the tendency of continuous ADR prototypes to repeatedly malfunction due to such causes as the vibration of the aircraft has led to a transition to use of normal freezers in recent years. Researchers have succeeded in observing solid ^4He , albeit at the somewhat high temperature of 0.6 K. However, because such freezers gradually lose their refrigerant, it is not possible to sustain operation in space for extended periods of time. Researchers are expected to work toward cooling samples to temperatures near 0.1 K and to accumulate crystal data.

Although Japanese scientists have no experience in developing devices and conducting microgravity experiments in the area of dusty plasma research, they have made many theoretical contributions on international research teams. Noteworthy contributions include proposals concerning the possibility of critical points that do not occur in repulsion phenomena and the potential for observing them under microgravity conditions. Additionally, Japanese researchers are beginning to make new findings (in such areas as plasma parameter measurement) through the use of a European experimental facility (PK-3 Plus) through international cooperation, and a greater level of contributions and findings is expected in the future.

(6) Ability to parlay research to create new technological fields and industries in 10 to 15 years

Both solid ^4He research and dusty plasma research are currently at the stage of accumulating fundamental knowledge and deepening our understanding of associated phenomena, and the likelihood of findings in either of these areas leading to the creation of a new industry over the next 10 to 15 years is low. However, researchers can be expected to publish many scientific findings in prestigious journals. It goes without saying that to the extent scientific utilization of the ISS is praiseworthy, the top priority is to obtain an adequate level of academic achievement.

However, if a continuous ADR designed for use with solid ^4He were competed, it could be placed on a scientific satellite and used to cool sensors over extended periods of time in a stable manner. Such an outcome could be expected to facilitate the accumulation of more space knowledge. Similarly, if void-free plasma could be achieved in dusty plasma research, it would

signify an ability to achieve uniform potential distribution in the bulk plasma region. The ability to produce highly uniform plasma would likely contribute to the development of large-area, uniform plasma processing. The completion of any of a number of measurement technologies for which research is currently underway could be expected to allow application to the measurement of low-density process plasmas with a high neutral gas density. Further, if the mechanisms of Coulomb crystal growth become clear, that knowledge will have application in observation simulating the uptake of atoms and molecules at real crystal interfaces and in the development of microscopic crystal growth models. If new discoveries continue in the area of particle agglomeration, they can be expected to find application in the development of models of the planetary formation process.

(7) Objectives and approach through 2020

Due to the anticipated difficulty of conducting experiments in solid 4He research in Kibo's Pressurized Module due to the large size of associated equipment, the pursuit of activities intended to use the Exposed Facility is thought to be the most appropriate approach.

In dusty plasma research, in the short term, scientists will accumulate fundamental knowledge and technology as a precursor to developing an experimental facility for use with Kibo's multi-purpose rack. It is expected that the size of this facility will allow its use with the multi-purpose rack. At that point, researchers will focus on developing an understanding of the mechanism of void region formation and establishing plasma parameter measurement technology for liquid and solid phases in the strongly Coulomb-coupled state. Once they have developed an understanding of the void formation mechanism, they will work to develop experimental facilities in which voids do not form and prepare for orbital experiments. In those experiments, it is anticipated that principal research topics will be (1) verification of the generation of void-free plasma, (2) verification of solid-phase crystal structure and solid-phase transition as well as verification of solid- and liquid-phase phase diagrams, (3) achievement of the critical point in charged-particle systems, (4) explication of the mechanisms of solid phase formation and crystal growth, (5) elucidation of power balance and particle balance, and (6) explication of the mechanism of fine particle agglomeration. Basic data for dusty plasma includes electron density and temperature, ion density and temperature, and particle three-dimensional coordinates in particle number density. Using this data, researchers will obtain data describing the characteristics of liquid and solid phases in charged-particle systems, including solid phase structure and average inter-particle distance, the pair distribution function, and the particle velocity distribution function. By comparing this data with associated theories and models, they will work to resolve the challenges associated with these research topics.

- Up to about 2015: accumulate fundamental knowledge and technology with the goal of conducting flight experiments in and after 2015 and assess the prospects for resolving certain important issues (void-free plasma).
- Up to about 2020: develop an understanding of topics including phase transitions between Coulomb crystals and liquid phases, crystal growth, and the critical point.

4. Measures for Pursuing Research into Prioritized Areas

The Scenario Examination Working Group in Physical Science has identified the prioritized areas described above concerning utilization of the space environment in the field of physical science. In order to pursue those activities efficiently and generate outstanding findings, it is necessary to consider and act on the considerations outlined below.

4.1 Selection of Priority Topics

The Working Group proposed prioritized areas in the field of physical science after considering current research trends and future directions. However, it did not identify priority topics due to its belief that the appropriate topics which research institutions and organizations planned executed under appropriate leading researchers should be selected. That is, we believe that the appropriate process for selecting priority topics is to solicit topic proposals based on the prioritized areas proposed by these scenarios and then have the Kibo Utilization Promotion Committee screen and select topics. This decision is based on our belief that it is necessary to stipulate project objectives and goals, identify which lead researchers and research organizations will conduct research, and clarify roles and responsibilities.

4.2 Considerations in the Selection of Priority Topics

- 1) In selecting topics from submitted proposals, it is necessary to evaluate proposals based not only on the creativity and excellence of the research objectives and goals, but also on the basis of such factors as the research organization, research timeframe, research plan, and research costs.
- 2) It is necessary to impose conditions on participating research organizations to ensure their ability to continue and sustain a full-time focus not only during the project term, but also until the summarization and scientific and technological evaluation of the research findings are complete.
- 3) Research into these priority topics makes use of research resources that are unique in the world, and it is essential to bring an international perspective to their selection and evaluation. That is to say, research into priority topics on the ISS must satisfy international standards, and information about associated activities should be widely disseminated both in Japan and overseas. To that end, reference should be made to the opinions and evaluations of overseas researchers in the selection of topics. For example, leading researchers in Europe and the United States should be asked to screen and evaluate proposals.

4.3 Evaluation System

In implementing selected priority topics and projects, outside observers should make regular

evaluations, check progress toward objectives and goals, evaluate research findings, and strive to ensure efficient management, including by revising execution plans and taking action to halt activities when necessary.

4.4 Considerations Related to Experimental Support Technologies and Research Project Teams

- 1) Concerning onboard experimental facilities, researchers should not limit themselves to existing (or planned) general-purpose equipment, but should rather consider placing facilities optimized for the topics being investigated on the ISS. Obtaining outstanding, creative research findings in many cases demands use of proprietary experimental facilities, and the development of such should not be limited as long as the associated technological challenges can be resolved.

In the past, researchers in the field of physical science have developed a wide variety of experimental cartridges, which contains experimental samples and associated mechanism to satisfy experiment-specific requirements, and conducted experiments by inserting them into existing experimental facilities. However, specifications of the existing facilities were set more than 10 years ago. Therefore, research teams should design their experimental equipment to utilize the latest technologies to maximize the scientific output.. For example, by replacing individual elements or adding functions, rather than replacing an entire facilities,, it should be possible to transform the equipment into a shared resource that is more appealing for researchers. It is realistic from a development timeframe and cost standpoint to specialize the development of new experimental facilities using multipurpose racks for priority research topics.

- 2) In carrying out research into priority topics, it is necessary to develop a cooperative research organization dedicated to implementing projects in JAXA. Because projects involve space-unique works including hardware development and project management experienced JAXA personnel should be included in the research teams. During their developments and operations, the experimental hardware are required a high degree of reliability, though malfunctions tends to occur. The research organization should have a close link with JAXA hardware development team, and the suitability of these joint research organizations should be evaluated as part of the priority topic selection process.
- 3) In ISS experiments, crew participation must be eliminated or at least minimized. Experiments in physical science in particular should incorporate telemetry systems capable of controlling all work from Earth, including the loading and unloading of experimental samples, control of experimental facilities, and acquisition of data and its transmission to Earth. Further, experiments should be planned so that there is no need to return experimental samples to Earth.

- 4) The ISS is the world's only shared-use research facility, and it should be used in accordance with international evaluation standards. Research projects should be subject to international evaluation and conducted alongside efforts to develop organizations capable of conducting international cooperative and joint research.

4.5 Other Considerations, Handling of Findings, and Vision of International Cooperation

(1) Publishing and publicizing research findings and building databases

Researchers and lead researchers must recognize that research in the space environment exists by virtue of the broad support of the Japanese people, and they should strive to publish and publicize the research findings and data generated by experiments on Kibo based on a strong awareness that these are the shared intellectual property of the Japanese people. Specifically, all data must be incorporated into databases, including raw experimental data. The lead researcher will enjoy preferential rights to experimental data for a period of one year after the completion of the associated experiment, but even so information about progress in the experiment should be published, along with data and other materials, as soon as they are ready. The database should be built in English so that it can be shared with overseas space agencies.

Such databases must be managed in an integrated manner by JAXA, but it is necessary to consider how to control access privileges for data, build systems for sharing data internationally, and handle data that can only be analyzed by the team that conducted the experiment (the principal investigator [PI] and co-investigator [CI]).

(2) Approach to findings from space experiments

Direct and derived research findings from space experiments selected by JAXA to be conducted on Kibo should be labeled in a manner that indicates the findings were obtained through the use of Kibo, and data should be credited to JAXA as well as the PI and CI.

(3) Use of other nations' ISS experimental facilities

In addition to working to build cooperative international relationships and pursue cooperation in research, project teams should seek to generate findings effectively by working to diversify experimental facilities, resources, and means of use.

5. Opening Up New Research Areas with a Bottom-up, Open Process

The pursuit of the prioritized area research topics described above is important from the standpoint of generating outstanding research findings and efficiently allocating resources. However, it is also important to continue soliciting topic proposals using a bottom-up approach in an


effort to identify creative subjects for investigation and encourage and expand participation in a broad range of research fields. These “bottom-up topics” reflect individual researchers’ originality and should be selected based on an open and broad-based proposal process.

Following are some examples of fields that hold scientific and technological promise, embryonic and yet-to-mature research topics, and fields that can be expected to yield new knowledge through the broad use of Kibo assets (experimental facilities), despite having little history of space experimentation and not having been selected as prioritized topics or areas by JAXA.

As described in section 2.2.3, the field of materials science with a focus on crystal growth is an area where Japan has delivered world-class results, and state-of-the-art experimental facilities such as the Solution Crystallization Observation Facility (SCOF) and the Gradient Heating Furnace (GHF) are already on the ISS. In particular, the implementation of methods for precisely evaluating crystal growth using in-situ observation is a world-class technology developed by Japan. Experiments that use these facilities can be expected to address a diverse range of topics, and it is appropriate for those topics to be selected through a bottom-up proposal process. For example, the growth of high-quality, mixed-crystal semiconductors using the GHF could have applications in the development of useful materials for electronic devices such as mixed crystals with a uniform structure and controlled bandgap or other characteristics, or in research attempting to analyze the model of such crystal growth. Experiments using the SCOF could help explicate diffusion phenomena based on the Soret effect in mixed crystals and multicomponent melts, their impact on mechanisms of crystal growth, and mechanisms of crystal core formation.

It is our hope that a bottom-up process will also yield proposals based on free ideas in the fields of fundamental physics and chemistry. For example, research into crystal growth of quantum solids in solid helium, which is already underway using aircraft, is considered to be a unique research topic that can both clarify basic problems of physics and allow the visualization of quantum phenomena. In the field of chemistry, gravity effects do not generally manifest themselves conspicuously because they are much weaker than intermolecular interactions, but research in this area could effectively make use of microgravity conditions since those effects are much more pronounced in mesoscopic systems such as colloids, proteins, and other macromolecular aggregates. Despite the fact that this field is likely to contribute to the chemical industry thanks to its close links to actual use, initiatives to conduct space experiments remain inadequate. Terrestrial research in these fields should be pursued with the goal of gaining priority treatment when future topics are solicited.

Table 1. Correspondence between “Prioritized areas” and “View points”

indicators of prioritization 	Prioritized Area 1	Prioritized Area 2	Prioritized Area 3	Prioritized Area 4	Prioritized Area 5	Prioritized Area 6
View Point 1: Forefront scientific research only enabled by ISS/Kibo						
(1) Over a long term	◎	◎	○			◎
(2) In the short term						
Contributions to						
▪ social problem solving				◎		
▪ green/life innovation	○	○	◎	◎		
▪ disaster recovery,						
View point 2: Fundamental research and development for the future space activities						
	○	○			◎	