

Microgravity Utilization Technology Entering the Industrialization Phase

— In-Orbit Experiments Opening New Frontiers in Next-Generation Manufacturing —

Hideki Kinjo

Technology & Innovation Studies Div.
Mitsui & Co. Global Strategic Studies Institute

Why This Technology?

Outer space has long been regarded as a domain limited to a small number of researchers and national projects. In recent years, however, it has begun to attract attention as a new foundation for research and industry. Against the backdrop of declining launch costs and the growing participation of private companies, innovation across the space sector is accelerating. Of particular note are in-orbit experiments that leverage the unique microgravity environment of space, along with the commercial applications of the results. This environment, distinct from that on Earth, can lead to the creation of new products and manufacturing processes and may influence the formation of new markets and supply chains in the future. This report reviews these trends and considers future prospects.

Summary

- In a microgravity environment, the effects of natural convection and sedimentation/buoyancy are minimal, allowing processes such as crystallization to be observed and controlled with a high degree of precision. Leveraging these characteristics, applications are expanding primarily in the pharmaceutical, biotechnology, and materials fields.
- Each partner country has developed its own utilization model on the International Space Station (ISS), and a wide range of experiments, including research on the crystallization of pharmaceutical compounds, have been conducted. The ISS is now maturing as a platform for commercial use as well.
- In-orbit experiments technologies using "free flyers," in which experimental equipment is mounted on small satellites, have reached practical application. In addition, private space station projects are advancing in anticipation of the ISS's retirement, and a new ecosystem for in-orbit experimentation is expected to take shape.

1. What Is Microgravity Utilization Technology?

1-1. Why Does Microgravity Enable High-quality Crystal Growth?

Microgravity utilization technology is an umbrella term for initiatives that use platforms such as the International Space Station (ISS)¹ to precisely observe and control processes that are difficult to evaluate in isolation from gravity on Earth. Suppressing gravity-driven effects such as natural convection, sedimentation, and buoyancy, enables isolation of the phenomenon itself in a purer form, deepening fundamental understanding and enabling process optimization.

On Earth, gravity causes natural convection within liquids (including concentration convection and thermal

¹ The International Space Station (ISS) is an international space research facility orbiting at an altitude of approximately 400 km above Earth. It is operated jointly by five space agencies from the United States, Japan, Europe, Russia, and Canada. Construction began in 1998 and was completed in 2011. At present, experiments utilizing the microgravity environment, external exposure experiments leveraging the space environment, and life sciences research conducted under space conditions are being carried out onboard.

convection). Differences in concentration or temperature create regions with different densities, causing lighter (lower-density) fluid to rise and heavier (higher-density) fluid to sink. In crystallization, this convection disrupts concentration and temperature distributions in the solution during crystal growth, leading to non-uniform crystal growth and surface defects. In addition, crystal nuclei and impurity particles can become unevenly distributed due to sedimentation or buoyancy, causing microscopic strain and other distortions within the crystal.

By contrast, the ISS orbits in a continuous free-fall state, moving forward at high speed while being pulled by Earth's gravity. From the perspective inside the ISS, objects experience gravity that is balanced by apparent centrifugal force, resulting in a microgravity state. In this environment, objects receive almost no supporting force from floors or walls, and the sensation of being pressed upward or downward is extremely weak, inhibiting sedimentation or buoyancy-driven movement. As a result, natural convection is suppressed, and conditions within liquids become gradually uniform through diffusion alone. Under these circumstances, crystal nuclei tend to form uniformly, and crystals can grow slowly and evenly without disturbance. Applications of this technical effect are shown in Figure 1.

Figure 1: Applications of microgravity utilization technologies

Field	Application	Effects
Pharmaceuticals/ biotechnology	Protein crystallization	<ul style="list-style-type: none"> • Suppression of convection and sedimentation under microgravity makes it easier to obtain more uniform crystals with fewer impurities than on Earth. • Considered useful for pharmaceutical structural analysis and formulation design.
	Formation of regenerative medicine tissues	<ul style="list-style-type: none"> • Cells naturally aggregate three-dimensionally without settling, facilitating the formation of vascular networks and complex tissue structures.
	Development of probiotics	<ul style="list-style-type: none"> • Changes in microbial metabolism and properties are expected to lead to the emergence of new functionalities. • Changes in stress responses and gene expression have been reported.
Materials	Uniform crystal growth (wafer manufacturing)	<ul style="list-style-type: none"> • Greater temperature difference stability may reduce crystal defects. • Expected to lead to the realization of high-performance materials.
	High-strength polymers and nanocomposites	<ul style="list-style-type: none"> • Particles do not settle and disperse more uniformly, potentially enhancing material strength and other properties.

Source: Compiled by MGSSI based on various sources

1-2. Diversifying Microgravity Platforms

Platforms capable of utilizing microgravity environments are rapidly diversifying (Figure 2).

Figure 2: Comparison of microgravity platforms

Category	Platform [primary operator]	Microgravity duration	Features/applications
Ground-based	Drop tower [ZARM Institute (Germany)]	Up to approx. 9 s	<ul style="list-style-type: none"> · Dropped through a vacuum tube from a tower approx. 146 m high. · Lowest-cost and high-precision option for short-duration microgravity experiments. · Suitable for materials, fluids, etc.
	Aircraft [Novespace (France), etc.]	Approx. 20 s × multiple runs	<ul style="list-style-type: none"> · Parabolic flights conducted at altitudes of approx. 9 to 10 km. · Enables repeated experiments; widely used for life sciences, pharmaceutical development, and educational purposes.
Suborbital	Suborbital rocket [Blue Origin (US), etc.]	Approx. 3.5 to 4.5 min	<ul style="list-style-type: none"> · Ascends to approx. 100 km near the edge of space and goes into free fall. · Used for short-duration space experiments and equipment validation.
	Sounding rocket [NASA ^{Note} and other space agencies]	Approx. 6 to 10 min	<ul style="list-style-type: none"> · Flies in space at altitudes of approx. 100 to 300 km. · Provides a space environment for several minutes for technology demonstrations and material experiments.
Orbital	International Space Station (ISS) [NASA and other space agencies]	Months to 1 yr or more	<ul style="list-style-type: none"> · Orbits at approx. 400 km altitude. · Provides the most stable microgravity environment; widely used for pharmaceuticals, biotechnology, and materials research.
	Free flyer (small satellite) [Varda Space Industries (US), etc.]	Several days to weeks	<ul style="list-style-type: none"> · Orbits at approx. 450 to 550 km altitude. · Experiments conducted onboard small satellites. · Recovery capsule reenters the atmosphere, and experimental results are retrieved on Earth.
	Commercial space station [Axiom Space (US), etc.]	Months to 1 yr or more	<ul style="list-style-type: none"> · Orbits at approx. 400 to 500 km altitude. · Scheduled to begin operations sequentially from 2028.

Note: National Aeronautics and Space Administration (NASA)

Source: Compiled by MGSSI based on various sources

In addition to traditional drop towers and parabolic-flight aircraft, a variety of experimental platforms are being developed and utilized. These include suborbital rockets that reach the edge of space (approximately 100 km in altitude), the ISS orbiting at roughly 400 km, free-flyers (small satellites) that autonomously conduct experiments in orbit, and future private space stations under development. An ecosystem is emerging in which the optimal experimental method can be selected based on research objectives, cost, and duration. Free-flyers and private space stations are discussed further in "2. Noteworthy Trends."

1-3. ISS Utilization Models Differ by Country

The US, Japan, and Europe have each established distinct utilization models for the ISS, and researchers and companies can access these platforms regardless of nationality (Figure 3). The US has developed an advanced commercial model in which private experiment service providers permanently install their own equipment and continuously operate research programs for multiple companies. The Japanese experiment module "Kibo" allows users to access facilities operated by the Japan Aerospace Exploration Agency (JAXA) under established safety standards, and is characterized by its ease of use. In the European laboratory module "Columbus," private experiment service providers offer a flexible system that accepts compact experimental units brought in by customers. These diverse frameworks ensure experimental opportunities that meet a wide range of testing needs. Utilization fees depend on the scale of the experiment but range from several tens of millions to several hundreds

of millions of yen.²

Figure 3: ISS laboratory module utilization models

Item	US Laboratory Module	Japanese Laboratory Module (Kibo)	European Laboratory Module (Columbus)
Technical strengths	Cell and biotechnology research, manufacturing applications, materials science	Electrostatic levitation furnace, crystallization research, high-temperature materials	Fluid science, plasma crystallography, life sciences
Utilization point of contact	Center for the Advancement of Science in Space (CASIS) (US) ^{Note 1}	<ul style="list-style-type: none"> • Mitsui Bussan Aerospace • Japan LEO Shachu^{Note 2} • Space BD • Kanematsu / DigitalBlast / Japan Manned Space Systems 	Space Applications Services (SAS) (Belgium)
Users (customers)	Companies and research institutions worldwide; no nationality restrictions	Primarily Japanese companies; also available to overseas companies	Primarily European companies; no nationality restrictions
Entity conducting experiments	NASA-certified commercial experiment service providers	<ul style="list-style-type: none"> • Astronauts conduct experimental operations • In some cases, private operators or JAXA perform remote operations from the ground 	<ul style="list-style-type: none"> • SAS oversees primary operations • Astronauts conduct experimental operations • In some cases, ground control teams are responsible
Owner of experimental equipment	Commercial experiment service providers	JAXA	European Space Agency (ESA)
Items prepared by users	<ul style="list-style-type: none"> • Samples and materials • Experimental units inserted into commercial service providers' ISS experiment racks as needed 	<ul style="list-style-type: none"> • Samples and materials • JAXA-provided equipment used in general 	<ul style="list-style-type: none"> • Samples and materials • Experiment units inserted into ISS experiment racks

Note 1: A nonprofit organization entrusted by NASA with the operation and management of the utilization allocation U.S. National Laboratory within the U.S. on-orbit segment (USOS) of the ISS.

Note 2: Japan LEO Shachu, Inc. was initially established as a subsidiary of Mitsui & Co., with Mitsubishi Heavy Industries and Mitsubishi Electric later joining as equity participants.

Source: Compiled by MGSSI based on various sources

2. Noteworthy Trends

2-1. ISS Becoming an Orbital R&D and Manufacturing Demonstration Hub for Private Companies

The ISS is evolving from a facility for state-led fundamental research into a hub for commercial utilization by private companies. Since the mid-2010s, the number of experiments conducted in the US segment has expanded to more than 100 in FY2024³, of which approximately 80% were projects undertaken by private enterprises.⁴

Private-sector experiments on the ISS can be broadly classified into (1) ground-application-oriented research (knowledge feedback) and (2) in-space manufacturing demonstration. Under (1), pharmaceutical companies are advancing crystallization research and increasingly applying the resulting insights to product development on the ground. Under (2), NASA is promoting In Space Production Applications (InSPA)⁵, an initiative to utilize space as a manufacturing site, with demonstration projects underway for products such as artificial retinas and medical

² NASA, Commercial and Marketing Pricing Policy; JAXA, Fee Structure and Reduction Program for the Paid Utilization System (Non-Standard Services)

³ October 1, 2023, to September 30, 2024

⁴ “2024 ISS National Lab Annual Report Highlights Momentum in Space-Based R&D”, ISS National Lab, January 2025.

⁵ InSPA is a NASA program designed to promote manufacturing demonstrations in space by utilizing the ISS experimental environment and to apply the results to product development for terrestrial applications. Its policy objectives are to secure US leadership in the space manufacturing sector and to foster a sustainable low Earth orbit economy.

materials. Figure 4 shows examples of both (1) and (2). In addition, Figure 5 organizes experimental themes undertaken by private companies, focusing mainly on cases from the 2020s. Applications are expanding into more familiar domains, including food, consumer products, and lifestyle infrastructure.

Figure 4: Examples of private-sector experiments utilizing a microgravity environment

Category	Lead company	Experiment overview and key results	Period
Ground application	Merck & Co. (US)	<ul style="list-style-type: none"> Conducted an experiment to generate a crystalline suspension^{Note 1} of the anti-cancer immunotherapy Keytruda. Obtained a crystalline suspension with higher particle size uniformity under microgravity. Indicated potential contributions to formulation design and administration methods for antibody therapeutics. 	2017
	MicroQuin (US)	<ul style="list-style-type: none"> Conducted 3D cultures of breast and prostate cancer cells. Indicated potential changes in mechanisms related to cell survival maintenance. 	2022
	Colgate-Palmolive (US)	<ul style="list-style-type: none"> Analyzed the effects of microgravity on skin aging, hydration, and collagen production. Detailed experimental data have not yet been publicly disclosed. 	2022
Space manufacturing demonstration	Flawless Photonics (US)	<ul style="list-style-type: none"> Manufactured ZBLAN (heavy metal fluoride glass) optical fiber. Confirmed production of fiber exceeding 11 km in length. Indicated potential improvements in layer uniformity and reductions in crystal defects compared with terrestrial manufacturing. 	2024
	LambdaVision (US)	<ul style="list-style-type: none"> Repeatedly validated the manufacturing process for protein thin films used in artificial retinas. Indicated potential improvements in film uniformity and defect reduction under microgravity conditions. 	Ongoing since 2018
	United Semiconductors (US)	<ul style="list-style-type: none"> Conducted growth experiments of semiconductor-semimetal composite bulk crystals^{Note 2}. Analysis and evaluation of effects on crystal size and defect reduction currently underway. 	Launched 2024 / analysis 2025

Note 1: A liquid formulation in which fine crystalline particles of an active pharmaceutical ingredient are uniformly dispersed in a liquid. Such formulations offer properties that contribute to formulation stability and expanded administration options.

Note 2: A novel high-performance material that combines semiconductor properties enabling current control with semimetallic properties allowing high-speed current flow within a single crystal.

Source: Compiled by MGSSI based on various sources

Figure 5: Private sector experiment themes

Field	Lead company	Experimental theme
Pharmaceuticals / biotechnology	Eli Lilly (US)	Evaluation of novel drug candidates targeting muscle atrophy (loss of muscle mass) in microgravity environments
	PeptiDream (Japan)	Support for crystal generation and three-dimensional structural analysis of drug discovery targets
	Yakult (Japan)	Evaluation of stability and functionality of probiotics (lactic acid bacteria) in a microgravity environment
Materials	adidas (Germany)	Analysis of structural and rebound property changes in foam materials to enhance cushioning performance and durability
Food	Kirin Holdings (Japan)	Lettuce cultivation experiment using a bag-type culture tank
	AB InBev (Belgium)	Evaluation of barley germination and growth characteristics to improve grain quality and explore future applications in space food research
Consumer products and lifestyle infrastructure	Procter & Gamble (US)	Evaluation of detergent component degradability and cleaning performance for application in the design of water- and energy-efficient laundry processes
	Delta Faucet (US)	Analysis of droplet and bubble behavior mechanisms to develop water-saving shower designs that maintain comfort with low water usage
	Kao (Japan)	Demonstration of hair-washing and laundry solutions in microgravity environments where water use is extremely limited

Source: Compiled by MGSSI based on various sources

The activities of private experiment service providers, represented by Redwire (US) and Space Tango (US), which support these experimental initiatives, are also drawing attention. Using its proprietary crystallization device, PIL-BOX⁶, Redwire has continued joint research with multiple pharmaceutical companies⁷ and has built a track record in generating high-quality crystals. In 2025, the company launched a new business model under which it licenses seed crystals⁸ grown on the ISS to pharmaceutical companies. Space Tango has conducted more than 150 experiments and is also pursuing in-space manufacturing demonstrations of materials for regenerative medicine.

2-2. Free-flyers: The Emergence of Rapid and Flexible In-Orbit Experiments Platforms

One alternative to conducting experiments on the ISS is the use of free-flyers. A free-flyer is a small satellite equipped with experimental payloads that autonomously conducts experiments in orbit over a period of several days to several weeks. The resulting materials are returned to Earth using a reentry capsule⁹. In some missions, only experimental data are collected, without recovery of physical samples.

The key advantages lie in speed and flexibility. Free-flyers do not depend on ISS operational constraints or astronaut work schedules, enabling (1) completion of the entire cycle from launch to recovery within a matter of months, and (2) the continuous execution of multiple missions over short intervals. This allows companies to accelerate PDCA cycles for experimentation and significantly reduce lead times from test initiation to results acquisition.

A leading company in this field is Varda Space Industries (US). Using its proprietary small satellites, the company is conducting in-orbit manufacturing demonstrations for pharmaceuticals. In its first orbital mission in 2023, it successfully generated crystals of the HIV treatment drug ritonavir, which were recovered on Earth in 2024.¹⁰ In Japan, ElevationSpace plans to launch its first mission in the second half of 2026, marking what is expected to be the country's first free-flyer business, and is drawing attention as a domestic entrant in this area.

The key to the competitiveness of free-flyers lies not only in their in-orbit experiments capabilities but also in the atmospheric reentry capsule that safely and reliably returns experimental results to Earth. In particular, when targeting pharmaceuticals and other high-value materials, the reliability of the recovery process becomes a decisive factor in commercial viability. Figure 6 summarizes each company's approach to recovery.

⁶ To date, 28 PIL-BOX units have been deployed on the ISS, successfully achieving crystallization of 17 different compounds.

⁷ The company has conducted joint research with Bristol Myers Squibb (US) and Eli Lilly (US), among others.

⁸ Seed crystals are small crystals that serve as the starting point for crystal growth and enable highly reproducible crystallization. Obtaining high-quality seeds is challenging due to the extremely delicate formation conditions, making them a highly valuable research resource.

⁹ A heat-resistant capsule designed to return samples or manufactured products obtained in orbit to Earth. It is equipped with thermal protection materials that shield the interior from heating of several thousand degrees Celsius during reentry and autonomously performs functions required for deceleration and landing.

¹⁰ The second satellite was launched in January 2025 and recovered in Australia in February of the same year. The third spacecraft was launched in March and successfully recovered in May.

Figure 6: Free flyer operators and companies involved in reentry recovery capsules

Company	Business model	Development status and achievements
Varda Space Industries (US)	<ul style="list-style-type: none"> Provision of integrated experiment-to-recovery services Creation of proprietary products through in-space manufacturing 	<ul style="list-style-type: none"> Successfully manufactured crystals of the HIV treatment drug ritonavir in orbit and recovered them in 2023 to 2024. Has been conducting consecutive missions and transitioning to commercial operations since 2025. Strengthening its business foundation in both experimentation and manufacturing through expanded contracts with the US Department of Defense.
Space Forge (UK)	Creation of proprietary products through in-space manufacturing	<ul style="list-style-type: none"> Aims to manufacture high-performance materials such as gallium nitride (GaN) used in semiconductors for power electronics as proprietary products. Succeeded in generating plasma required for the manufacturing process in orbit in 2025, establishing the foundation for manufacturing demonstration. Supported by the UK government and the European Space Agency (ESA).
ElevationSpace (Japan)	Provision of integrated experiment-to-recovery services	<ul style="list-style-type: none"> Plans to launch its first mission in 2026. Formed a partnership with Exobiosphere^{Note 1} (Luxembourg) in September 2025. Exploring an operational model linked to future commercial space stations in collaboration with Axiom Space (US).
ATMOS Space Cargo (Germany)	Primarily focused on the design and manufacture of recovery capsules	<ul style="list-style-type: none"> Conducted orbital demonstration of the recovery capsule Phoenix 1 in 2025. Plans to launch Phoenix 2 in 2026. Collaborating with multiple experiment operators^{Note 2} as one of the few recovery technology providers in Europe. Planning capsule operations at a frequency of around once a month.

Note 1: Exobiosphere is a contract research organization (CRO) specializing in drug discovery and biotechnology experiments that utilize the microgravity environment.

By offering in-orbit experiments as a CRO service, the company significantly lowers the barriers for pharmaceutical and biotechnology firms to access in-orbit experimentation.

Note 2: In November 2025, the company announced a partnership with Space Cargo Unlimited (Luxembourg), which develops experimental equipment for installation on spacecraft.

Source: Compiled by MGSSI based on various sources

2-3. Commercial Space Stations: Building Core Infrastructure to Support the Low-Earth Orbit Economy

With the anticipated retirement of the ISS around 2030, efforts to develop commercial space stations are gaining momentum. These stations are positioned as essential core infrastructure for sustaining and expanding commercial activities in orbit over the medium to long term. At present, there are four representative examples of commercial space station projects supported by NASA.

- (1) Axiom Space (US) (station name: Axiom Station) is constructing commercial modules to be attached to the ISS, with plans to detach them in the future and operate them as an independent station. The company aims to establish a multipurpose commercial platform that can support research and manufacturing, crewed stays, and even orbital data centers.
- (2) Starlab Space (US) (Starlab) is developing an integrated small space station jointly with European partners. In collaboration with the European Space Agency (ESA), it seeks to create a research and industrial hub open to international customers, including those in Europe.
- (3) Blue Origin (US) / Sierra Space (US) (Orbital Reef) is building a multipurpose platform accessible to companies, universities, and government agencies under the concept of an industrial park in space.
- (4) Vast (US) (Haven-1) plans to begin with a small station capable of accommodating approximately four people for short stays, with the vision of developing it into a station suitable for extended habitation through the introduction of artificial gravity generated by a rotating structure.

These developments are also extending to Japan. Japan LEO Shachu is advancing the development of the Japan Module, envisioned as a successor to the Kibo module on the ISS. The participation of Japanese companies is expected to further accelerate the expansion of the orbital utilization ecosystem.

3. Future Prospects

The commercial utilization of microgravity is expanding primarily in the pharmaceutical, biotechnology, and materials sectors. Examples are beginning to emerge in which outcomes are translated into terrestrial industries, including applications in new drug development by pharmaceutical companies, manufacturing demonstrations of regenerative medicine devices such as artificial retinas, and the licensing of seed crystals grown in space. In the free-flyer domain, Varda Space Industries has presented a new service model that integrates in-orbit experimentation with payload recovery, offering a concrete vision for commercialization. Looking ahead, the addition of commercial space stations is expected to give rise to a new in-orbit experiment ecosystem encompassing R&D, manufacturing validation, and recovery. These developments are likely to become more closely linked with terrestrial value chains, accelerating the social implementation of results.

What benefits might these technologies bring to everyday life? In the pharmaceutical and biotechnology sectors, they are expected to advance the development of more effective medicines with fewer side effects, thereby reducing both the physical and economic burden on patients. The further advancement of cutting-edge medical devices, such as artificial retinas, also holds strong potential to help restore lost human functions and improve quality of life. In the materials sector, the practical application of lighter, stronger, and more efficient materials will advance energy savings, miniaturization, and longer product lifespans. In the food sector, the development of high-value functional foods is anticipated to contribute to the maintenance and enhancement of consumer health.

On the other hand, several challenges remain in moving toward industrialization. First, reducing launch and recovery costs continues to be critical, as it significantly influences business sustainability. Second, reliable autonomous operation technologies¹¹ capable of functioning over extended periods in the space environment are essential. Third, it is necessary to establish co-creation R&D frameworks with terrestrial companies in sectors such as pharmaceuticals, materials, and food. Fourth, progress must be made in developing quality standards and certification processes to commercialize and bring to market products derived from results obtained in orbit.

The market for microgravity utilization is already showing clear signs of expansion. Opportunities for corporate participation span a wide range of areas, including contract experimentation, in-orbit manufacturing support, materials supply, recovery logistics, use of data and intellectual property, and applications of materials derived in space. Achievements gained in orbit are helping address challenges faced by terrestrial enterprises, creating new markets. A new wave of manufacturing that connects space and Earth is beginning to take shape as a tangible industrial reality.

Any use, reproduction, copying or redistribution of this report, in whole or in part, is prohibited without the prior consent of Mitsui & Co. Global Strategic Studies Institute (MGSSI). This report was created based on information and data obtained from sources believed to be reliable; however, MGSSI does not guarantee the accuracy, reliability, or completeness of such information or data. Opinions contained in this report represent those of the author and cannot in any way be considered as representing the unified opinion of MGSSI and the Mitsui & Co. group. MGSSI and the Mitsui & Co. group will not be liable for any damages or losses, whether direct or indirect, that may result from the use of this report. The information in this report is subject to change without prior notice.

¹¹ Here, autonomous operational technologies refer to those that enable systems to independently assess current conditions, plan, carry out, and respond to anomalies without continuous human intervention.