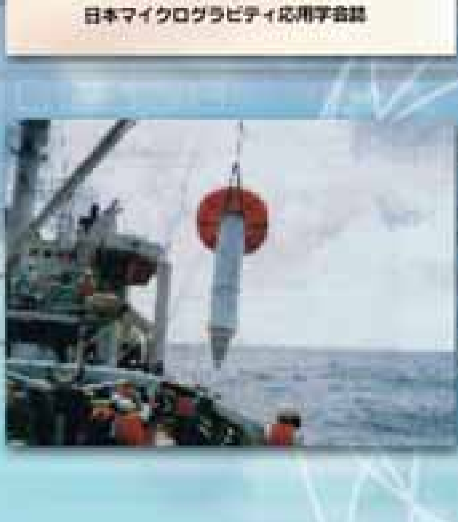
Memoir of Japanese Space Experiments -Accomplishments and Lessons Learned-

Edited by Hiroo Inokuchi

Executive Summary



EXECUTIVE SUMMARY

Foreword

This booklet is the executive summary of a report, " Memoir of Japanese Space Experiments-Accomplishment and Lessons Learned ," published in March 2005 by the Japan Society of Microgravity Application. The original volume, intended for Japanese scientists, exceeded 400 pages with text in the local language. This English language version of executive summary was thus edited to obtain wider circulation. We hope to share the delights of worthwhile research efforts utilizing wonderful space environment with many people not confined to the specialists.

PDF files of the original publication (in Japanese) can be downloaded at:
http://idb.exst.jaxa.jp/jdata/02494/200509J02494000.html

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Life Science

Material Science

Life Science 生命科学分野

Why Study Biology in Space?

Objectives of Space Life Science Research

Expanding human activities to outer regions

- Identifying and overcoming problems involved in human space activities.

The pursuit of universal law of life

- Analyzing phenomena of life under conditions free from the restriction of earth's surface.

Method of Space Life Science Experiment

Capturing newest technologies into ISS activity

- High-throughput analyzers and nano devices
- Biospecimen retrieval to ground for leading-edge analyses

Taking full advantage of ISS

- Observation of plants and animals over generations
- Sophisticated experimental operations by crew
- Medical studies of crew themselves as subject

Astronaut Dr. Mamoru Mohri conducts life science experiments onboard the Space Shuttle Endeavour (September 1992).

The first selection of astronauts prompted Japanese organizations to start formal biomedical research programs in late 1970s. The National Space Development Agency of Japan (NASDA) conducted investigations on trends in space medicine in Europe and USA, as well as those in Russia who had experienced long-stay in space. Ground based joint researches with these countries and among local institutions were also conducted on long-term bed-rest and isolation, and on short-term microgravity conditions by parabolic flights.

The First Material Processing Tests (FMPT/SL-J:STS-47, 1992), the Second International Microgravity Laboratory (IML-2:STS-65, 1994), Neurolab (STS-90, 1998) and STS-95 (1998) were full-scale space experiments onboard the Space Shuttle. Total of 96 biological and medical experiments had been performed by local organizations until the year 1998. In addition, some Japanese investigators took parts in foreign programs. The methods of space experiments, equipment development, operations technologies were learned through these activities, and yielded results ranking with advanced counties in the space utilization research.

Space Life Science Experiments

Flight/Mission	Vehicle	Organizatio	Date	No. Subjects
Gemini 3	Manned Capsule	NASA・Kondo*	1965.3	(1*)
Gemini 11	Manned Capsule	NASA・Kondo*	1966.9	(1*)
COSIMA 2	Capsule	Fujitsu, Ltd.	1989.9	1
COSMOS-2044	Capsule	USSR・Ohira*	1989.9	(1*)
MIR	Space Station	TBS	1990.12	3
MIR	Space Station	JGC Corp.	1991.5	1
STS-40 (GAS)	Space Shuttle	Sakata Seed Corp.	1991.6	1
STS-42 (GAS)	Space Shuttle	Suntory Ltd.	1992.1	1
MIR	Space Station	Fujitsu Ltd.	1992.1	1
STS-42 (IML-1)	Space Shuttle	NASDA	1992.1	1
STS-47 (FMPT)	Space Shuttle	NASDA	1992.9	15
MIR	Space Station	JGC Corp.	1993.5	1
STS-59 (GAS)	Space Shuttle	MITILS	1994.4	1
STS-65 (IML-2)	Space Shuttle	NASDA	1994.7	10(3**)
STS-64 (GAS)	Space Shuttle	Green Cross	1994.9	1
MIR	Space Station	Kyoto Univ.	1994	1
MIR	Space Station	Univ. Tokyo	1994	1
SFU	Free Flyer	ISAS	1995.3-96.1	1
STS-72 (GAS)	Space Shuttle	Fujitsu Ltd.	1996.1	1
STS-77	Space Shuttle	Obayashi Corp.	1996.5	(1*)
STS-79 (S/MM-4)	Shuttle/MIR	NASDA	1996.9	5(1*)
MIR	Space Station	NASDA	1997.2	3
STS-84 (S/MM-6)	Shuttle/MIR	NASDA	1997.5	15
MIR	Space Station	NASDA	1997.7	7
TR-IA#6	Sounding Rocket	NASDA	1997.9	1
STS-86 (S/MM-7)	Shuttle/MIR	Obayashi Corp.	1997.9	(1*)
STS-89 (S/MM-8)	Shuttle/MIR	NASDA	1998.1	7
STS-90 (Neurolab)	Space Shuttle	NASDA	1998.4	1(6*)
STS-91 (S/MM-9)	Shuttle/MIR	NASDA	1998.6	7
STS-95	Space Shuttle	NASDA	1998.1-11	6
TR-IA#7	Sounding Rocket	NASDA	1998.11	1

*Japanese researchers took parts in foreign programs as CI (not counted)
**Japanese agency provided equipment for foreign researchers (not counted)

Total of 96 flight experiments had been conducted by researchers of domestic institutions during the period between 1989 and 1998.

Research Area	No. of Flight Experiments
Space Medicine	
Physiology in General	4
Cardiovascular Function	2
Vestibular Function	5
Muscloskeletal Function	3
Gravitational Biology	
Animals	4
Plants	7
Cells and Microorganisms	10
Bioengineering	
Protein Crystals	16
Production and Purification	6
Space Radiation	
Dosimetry	15
Radiation Biology	23
Other	1

Summary of Major Accomplishments in Space Life Science

1 Expanding human activities to outer regions

- Risk of prolonged exposure to high-energy cosmic particle and electromagnetic radiation in combination was identified.
- Mechanism of space motion sickness was analyzed with aquatic animal handling technology.

2 The pursuit of universal law of life

- Some potentials of living organisms were found hidden on earth.
- Ability of vertebrate (Medaka fish) to breed under space conditions was proved.

3 Achievement of top-level space life science

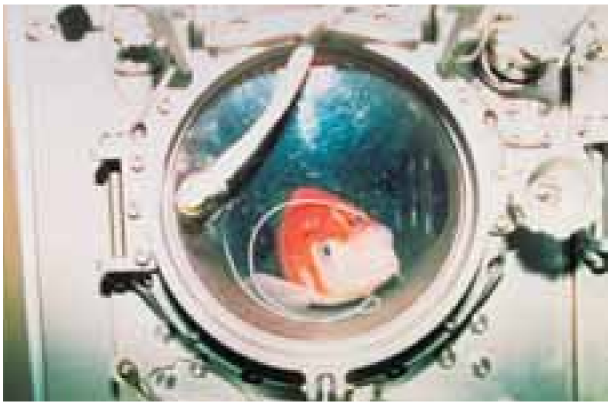
- Equipment and operation, especially in aquatic animal technologies, became of the highest order.
- Proposals for space life sciences on ISS received were highly regarded by international science board.

4 Maturation of experimental technologies on orbit

- Aquatic habitat technology enabled animal care over generations.
- Integrated system for cell culture and small organisms.
- Real time monitors for heavy ions and neutrons, and a neuclear track detector system.

Major Accomplishments

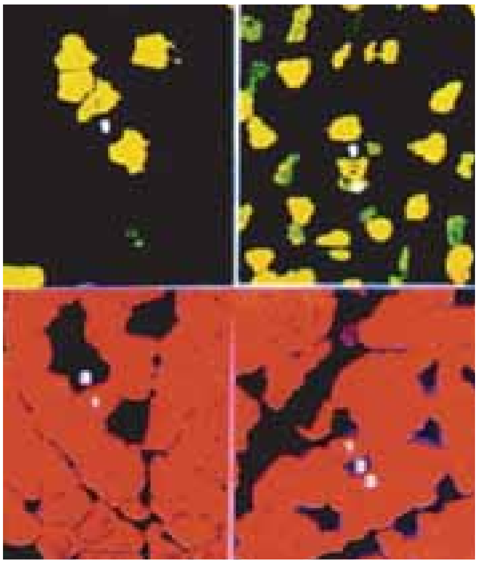
Sensorimotor System



Analyzing space motion sickness with Koi (*Cyprinus carpio*) on FMPT (1992).

Animals like birds or fish who move around three dimensional space are suitable for studies of vestibular (otolith) functions. Fish were found to swim circling when exposed to the microgravity in darkness. The dorsal light response, a righting response in which a fish balances it vertical body axis along the directions of gravity and light, was examined onboard the Space Shuttle. The results supported the visual-vestibular sensory conflict hypothesis for space motion sickness.

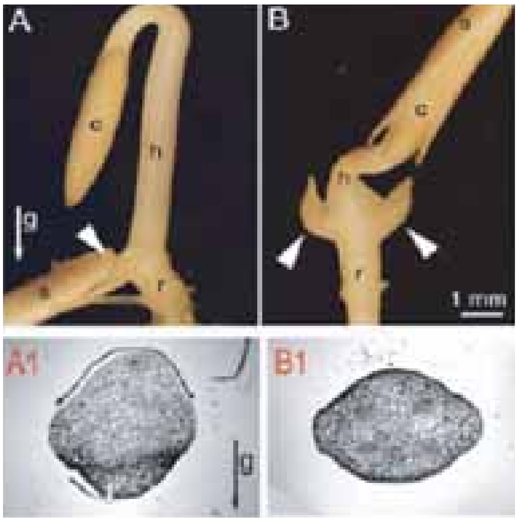
Muscle Atrophy



Changes of slow twitch fibers into fast twitch fibers shown in serial cross sections of a rat hind limb antigravity muscle (soleus) after spaceflight (SLS-2, 1993).

Antigravity muscles shrink under microgravity due to loss of continuous loading. Changes of slow-twitch muscle fibers are more evident than fast-twitch fibers. Some of the slow-twitch fibers were found to express traits of both slow and fast fibers. The figure shows serial sections of soleus of space flown (right) and ground control (left) animals. Upper panels show fast-twitch fiber staining (2), and slow-twitch fibers (1)were stained in lower panels. Some fibers (3) were positive to both fast- and slow-fibers staining. Studies are carried out to reveal cellular and molecular nature of the phenomena, as well as developing counter measures such as effective physical exercise.

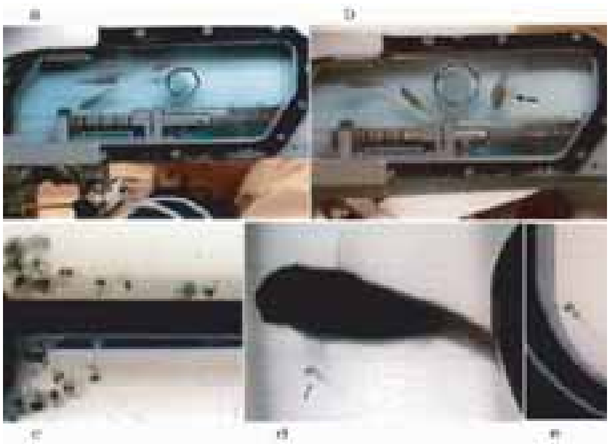
Plant Growth and Morphogenesis



Peg formation of cucumber seedling under microgravity (STS-95, 1998)

Cucumber seedlings were grown on the ground (A) or on orbit (B). Peg (arrowhead), root (r) seed coat (s) hypocotyl (h) cotyledon (c) are shown. Lower panels show expressions of an auxin-responsive gene CS-IAA1. Cucumber seedlings develop single peg on their lower side. The space experiment revealed that the seedling naturally has potential to develop pegs on both sides and the upper one is inhibited by gravity, rather than induced on the lower side.
The space experiment derived a concept that plants have great variety of potentials, concealed behind the gravity, and only a small part is expressed under normal ground conditions. Expectations are raised for discoveries of unexpected capabilities of the terrestrial creature through future space experiments.

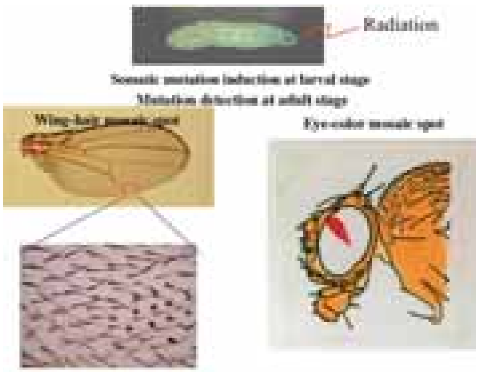
Animal Development



Demonstration of vertebrate breeding capability on orbit (IML-2, 1994)
a: Medaka (*Oryzias latipes*) on orbit b: spawning and insemination c: developing embryo d,e: hatched fry.

Cleavages of amphibian eggs start along with the gravity direction. The gravity greatly affect the morphology of developing embryo, but become normal in later phases. The experiment with small fish Medaka, spawning, insemination and development proceeded without any obvious problem. Space born baby fish grew up and left their offspring after return to the earth.

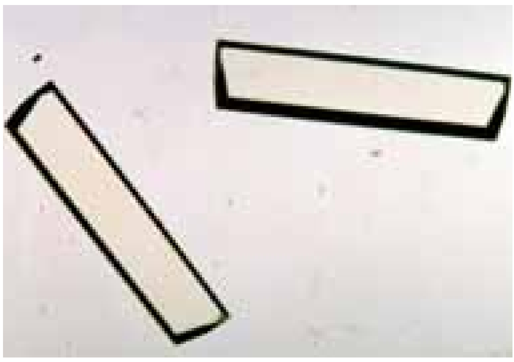
Space Radiation Biology



A scheme of highly sensitive detection for radiation effect with somatic mutation of fruit fly (*Drosophila sp.*) and fly vials used for an experiment on the Space Shuttle.

The ionizing radiation dose on the low earth orbit a day roughly equals to that of a year on the ground. Such a dose would not be an immediate hazard, but the risk should be analyzed for longer stays on the ISS or at lunar bases, or for explorations to the Mars. Many experiments have been carried out on orbit, and the need for further study has been strongly suggested, because of the complexity of radiation quality including high-energy heavy particles and secondary neutrons, and possible synergistic effect with the microgravity.

Protein Crystal Growth



Protein crystal grown under microgravity (ω-amino acid:pyruvate amino-transferase, *Pseudomonas sp*. F-126)

Being free from disturbances such as convection or sedimentation, microgravity has been considered favorable for growing protein crystals. Since the early phase of space experiments, efforts has been made to obtain good quality protein crystals suitable for structure analyses with X-ray diffractometry. Today, systematic flight experiments utilizing various opportunities are operated under the collaboration of industry, academia and government.

Experimental Technology and Equipment

The Thermoelectric Incubator (left) and cell culture instruments (right).

Space experiments are far apart from those on the ground in terms of dependency on the hardware. It will be more efficient to collaborate with mechanical and space operations engineers than a biologist struggle with developing the hardware and other tedious tasks by himself. Supports by space experiment specialists are essential for preliminary planning, refinement of experimental conditions, equipment designing, verifications and flight operations.

Lessons Learned

Space experiments must be planned with the understanding that there are considerable differences from ground laboratory practices.

Some critical processes are not accessible to researchers.

Limited numbers of samples and trials.

Long lead time and tight schedule.

Procedures including sample preparations are tightly scheduled.
Time-line is not biospecimen-oriented.
Long lead time leaves experiment far behind the advancement life sciences.

All-or-nothing criteria is often hardly applicable to the biospecimen conditions.

Poor availability of past experimental results.

Difficulties in publishing the results.

Importance of Resolving Practical Problems

Are practical problems inferior?

Regardless the problem is scholarly or popular, it can equally lead to failure.

Reconsider high regard to academism and less esteem to practical work.

experimental skills or instrumentation not be an academic discipline?

Eliminate fixed idea that the scientist does the science only.

Attaching importance not only to the narrow scientific achievement but also to supporting technologies.

Systematization of experimental technologies in space.

Behavioral science for effective collaboration among broad variety of specialists.

Need for fair appreciation to program coordinators and support engineers.

Proper evaluation system should be established for the efforts done by the mission

Improve the Analysis of the Results to a Satisfactory Level

Reconsideration over succeeded mission is important.

Failure analysis should not be an excuse.

Nothing may not be regarded as a failure, even if the situation is observed as such.

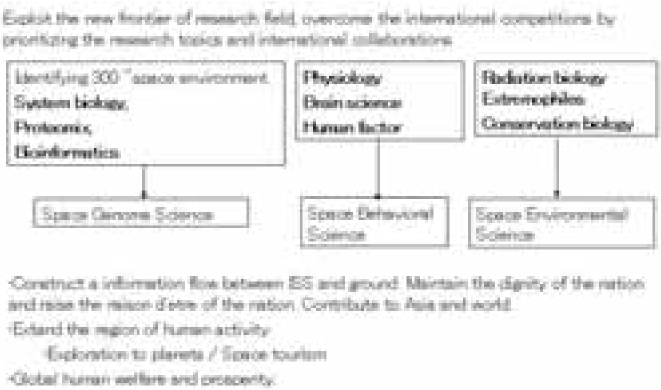
Emphasis of the successful part of the mission result might be necessary under a certain circumstance, the researcher should refrain from being too much of propagandist.

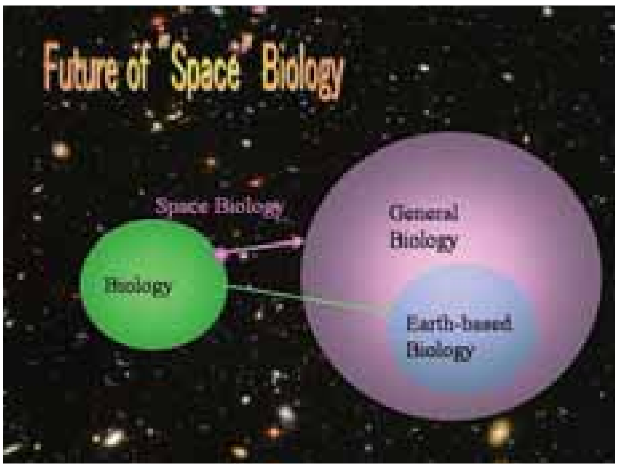
Institutionalize the process to evaluate the results, extract the lessons learned and transfer the accumulated knowledge/experiences to the next mission.

Collection of the flight data, the scheme for everybody to access those data.

Encourage the scientists to carry out the analysis of the flight data.
The whole process of space experiment from planning, preparation on the ground, flight operation, data analysis, documentation of the research result, etc. should be elevated to the level of academism.

Prospect of Space Life Science





Background image credit: NASA and STScI

Material Science 物質科学分野

Objectives of Space Experiments

1 Promotion of science and technology utilizing microgravity environments without disturbances induced by gravity.

- Progress of material science utilizing no-buoyancy, no-sedimentation, no thermal convection, no hydrostatic pressure.
- Theoretical development in sciences on fluid, combustion and so on.
- Theoretical development in fundamental physics and fundamental chemistry
- Advancement of manufacturing techniques and processes

2 Establishment of gravity-dependent sciences

- Creation and promotion of a new science in which phenomena are described as a function of gravity.
- Exploration of new phenomena and new principles in the field of physics, chemistry, materials science, fluid science and so on.

3 Contribution to the manned space activity

- Development of lightweight noninflammable new materials.
- Progress in heat transport under microgravity, heat exhaustion, anti-flaming technologies and so on.
- Development of efficient generation and storage of energy, and energy-saving technology

Total number of space experiments and classification

Total of 122 experiments were performed in the period between 1973 and 1998,and their organizations are classified into NASDA 83, Ministry of International Trade and Industry 21,Private companies 9, ISAS 3, Individual Study 6. Their research areas are classified as follows.

Research Area	No. of Experiments
Material Processing (79)	
Semiconductors	29
Metals/Alloys	20
Composites	7
Glass/Ceramics	6
Organic Materials	10
Oxides	2
Others	5
Fluid Science (37)	
Diffusion	19
Marangoni Convection	8
Thermal Conductivity	2
Drop Dynamics	1
Bubble Dynamics	3
Boiling and Heat Transfer	3
g-jitter	1
Combustion Science (2)	
Fuel Drop Combustion	2
Others (4)	4

Classification of Materials Processing Experiments by Techniques

Methodology	No. of Experiments
Solidification from Melt	
(Non-contact Floating)	
Crystal Growth from Solution	39
(In-Situ Observation)	(4)
Crystal Growth from Melt	18
Crystal Growth by Floating Zone Method	(12)
Crystal Growth from Vapor Phase	11
Combustion Synthesis	3
Sintering	6
	1
	1

*( ) denotes the double counting.

Major accomplishments

Density Distribution Measurements around a Growing Crystal

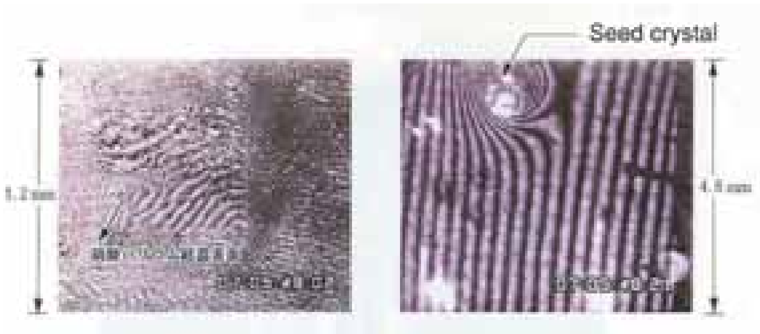


Figure 1. In-situ observation of the liquid density around a growing crystal by interferometry.

Above two photos show liquid density difference around a growing $BaNO_3$ crystal in aqueous solution. They were observed by an interferometer. Such observation in microgravity was first made possible by developing a small and rigid interferometer for space experiments. Curving fringes around the crystal show the high gradient of density distribution in the vicinity of the crystal. Relation between the growth rate and the degree of supersaturation of the solution was obtained by a series of experiments as shown in Fig. 2.

Mechanism of Crystal Growth from a Solution

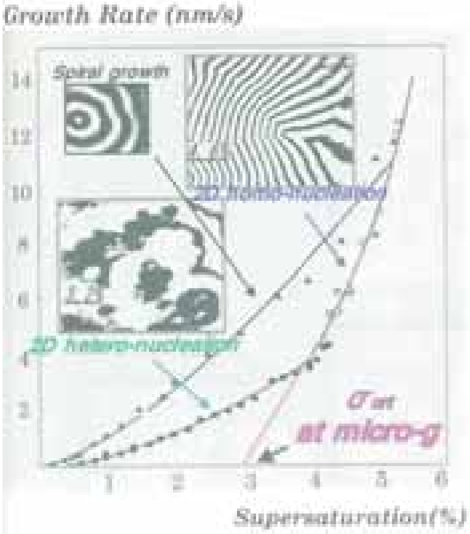


Figure 2. Relation between the growth rate and the degree of supersaturation in the growth of $BaNO_3$ from aqueous solution.

▲ denotes the growth rate observed on the ground. Note that the growth rate increased almost linearly proportional to the degree of supersaturation. While, growth rate suddenly increased at the 3% of supersaturation in microgravity. (● and ○). This difference is interpreted as follows: two-dimentional heterogeneous nucleation occurs on the ground due to impurities and/or particles transported to the surface of a growing crystal by convection in a liquid, while homogeneous nucleation occurs in microgravity by the suppression of convection. This is the first example showing gravity influences nucleation in the crystal growth from a solution.

Solidification Mechanism of Eutectic Alloys

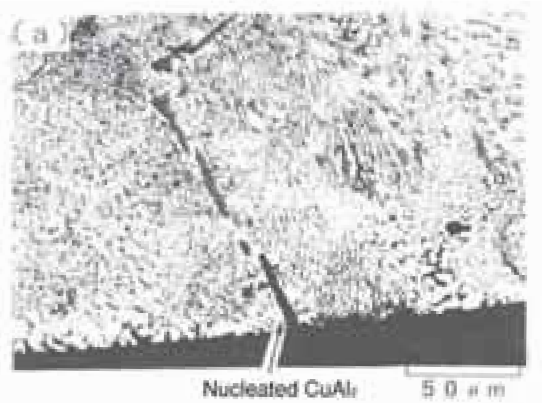


Figure 3. Texture of an Al-Cu alloy solidified in microgravity.

This photograph shows a texture of an alloy with composition of Al 33.5 mass% Cu, whose composition is a little excessive to the eutectic composition. Initial crystal of $CuAl_2$ starts its nucleation on the inner wall of the crucible as indicated by the arrow. This result verified the nuclei migration model in which nucleation occurs at a cooler region in a crucible such as on the wall and nuclei were transported into a melt by convection. Nuclei creation models such by break of dendrite arms and nucleation in a melt were denied. This discovery is used for the improvement of quality of casting materials such as turbine blades.

Manufacturing of High Quality Semiconductor Crystals, the Largest ever Processed in Space

Figure 4. An InSb crystal grown by the floating zone method in space.

On the ground 6mm diameter InSb melt is the maximum size that can be floated because the melt drops by its weight. While in microgravity, larger size melt can be suspended due to the weightlessness and as a result an InSb crystal with 20mm in diameter (the largest size ever grown in space) has been obtained by the floating zone method as shown in the figure. Etch pit density was about $10^2 cm^{-2}$, which is about two orders smaller than that grown on the ground and avoiding mechanical stress from the crucible wall may contribute such reduction of dislocations.

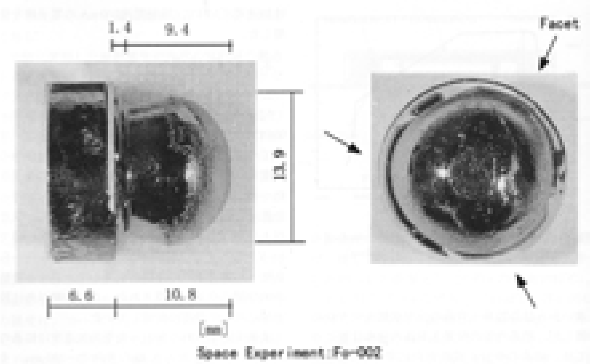


Figure 5. Detouched growth of a CdTe crystal in space.

Tip of the crystal is the detouched growth part and arrows show facetted region. CdTe crystals tend to form twins but twinning was avoided in this experiment owing to mechanical stress free growth by detouching to the crucible wall. Dislocation density was about $2\times10^{4}cm^{-2}$, which was about one order smaller than the strained part. Such technique for suppressing dislocation is useful for large scale integrated circuits fabrication of compound semiconductor because uniform specification is required in such devices.

An Invention of Compositionally Uniform Semiconductor Crystal Growth in Space

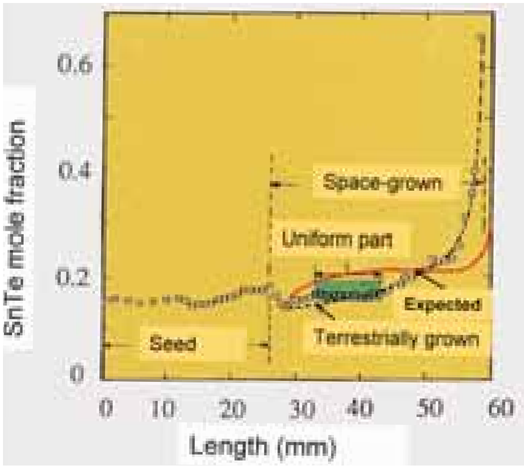


Figure 6. Comparison of compositional profiles of in-space/on-ground processed $Pb_{1-x}Sn_{x}Te$ semiconductors.

The length of homogeneous crystallization in space was not long enough as expected as shown in the red line and its composition was not expected one either, which indicates that the effect of convection still exists presumably due to the remaining gravity. Analysis showed that 10^{-6}g is required for growing uniform crystals. Based on this experiments, a new crystal growth method named as the Traveling Liquidus-Zone (abbreviated as TLZ) method has been invented and uniform alloy crystals are to be grown by the TLZ method.

The Effect of Convection on the Dendrite Growth

(a) Microgravity (b) Ground

Figure 7. Comparison of dendrite growth in microgravity and on the ground.

Growth in microgravity (left a) shows the symmetrical dendrite arms, while one on the ground (right b) shows the asymmetrical growth, ie., the dendrite arm is hanging down due to natural convection.

Exact Temperature Dependence of Diffusion Coefficients

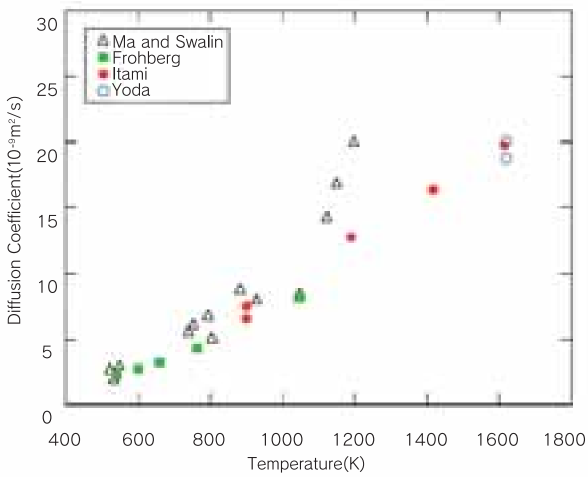
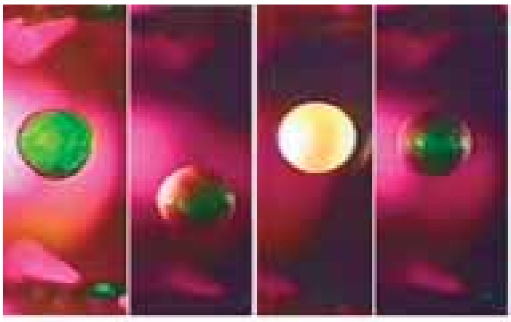


Figure 8. Self-diffusion coefficients of Sn; comparison of new and old results.

Diffusion coefficients are found to be proportional to the 1.8～2.0 power of the temperature based on accurate measurements by suppressing convection in diffusion couples in microgravity, which denies the Arrhenius type temperature dependence of diffusion coefficients. △ indicates the ground data and the rests are those measured in microgravity. This discovery requests us a new model of diffusion instead of the traditional thermal activation model via vacancies.

Synthesis of a New Material by an Electrostatic Levitation Furnace

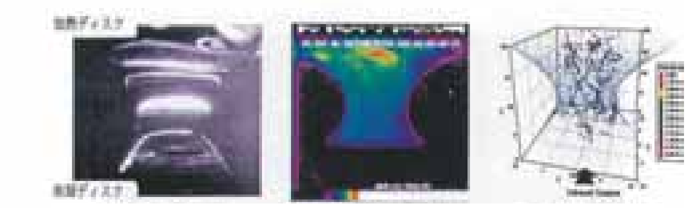


(a) (b) (c) (d)

Figure 9. Processing of $BiFeO_3$ ceramics, (a): floating, (b): heating, (c): melting and (d): cooling.

Ceramic sample processing by floating has been succeeded for the first time by using electrostatic levitation furnace. Sample analysis shows existence of microcrystal in the amorphous texture, directional change in magnetization jump around 50K, and very high dielectric constant of more than 15000.

3-D Observation of Marangoni Flow



(a) Liquid column (b) Surface temperature (c) 3-D velocity

Figure 10. Observation of 3-D oscillatory flow in the silicon oil liquid column.

Figures show (a): Silicon oil liquid column, (b): Image of surface temperature distribution by an infrared thermometer, (c): Flow velocity distribution obtained by tracking the particle tracers in the liquid, respectively. 3-D observation was first successful in this experiment.

Observation of Boiling Bubbles and Thin Liquid Film

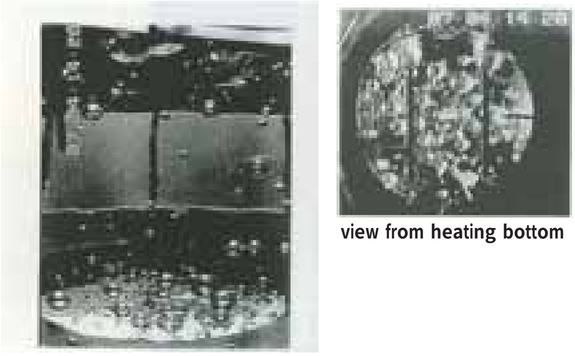


Figure 11. Observation of boiling bubbles under microgravity.

When bubbles of evaporated steam are formed on the heated surface, there appears the thin film like membrane sticking to the surface at the bottom of the bubble. This micro-scale film plays a major role to decide the heat transfer characteristics in the macro-scale.

Boiling Curve; Nukiyama Law

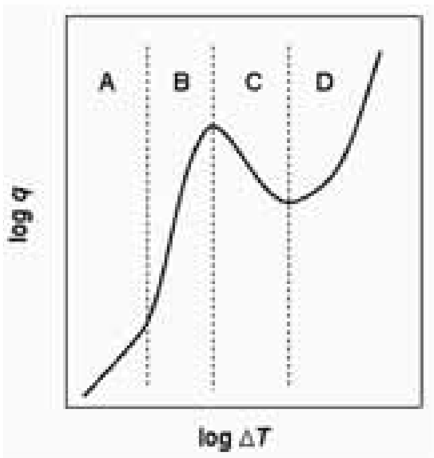


Figure 12. Temperature difference of wall and flowing liquid ΔT vs. heat flux q.

The boiling curve has the tendency shown in the left picture; proportionally growing region A, steep growing region B, degradation region due to steam film C, second growing region due to liquid film effect D. Typically in case of water, the wall temperature between the boundary B and C is around 120℃, between C and D more than 200℃. Be careful that abscissa and longitudinal are both exponential scale.

Propagation of Weak Combustion Flame

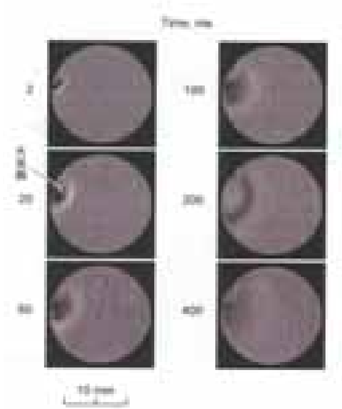


Figure 13. Observation of combustion flame for injected mist fuel droplet into the chamber.

These photos show a series of flame propagation observed in the TR-IA sounding rocket experiment. Very weak flame propagated from the upper left and disappears on the half way. Such weak flame propagation in the environment of oxygen supply by diffusion was first observed in this experiment. This results forces us to reconsider the effect of fluid convection and heat radiation during combustion.

Apparatuses for experiments

Phenomena peculiar to microgravity should be born in mind.

1. Removal of bubbles by density difference impossible.
2. Heat transfer is primarily due to conduction, rather than convection.
3. Marangoni convection becomes dominant, when free liquid surface exists.
4. Wettability (compatibility between the material and the container) becomes predominant, and the molten materials are prone to leak climbing along the surface of the crucible.

Obtained techniques by a series of space experiments

Experimental techniques obtained by FMPT (First Materials Processing Tests in 1992) and sounding rockets experiments are summarized in the following table. Data acquisition and development of experimental techniques are important and should be continued. In addition, establishment of data base and its publication are desired for wide use of valuable results.

Obtained experimental techniques.

Technology	Mission	Hardware and software , experiences
Numerical Simulation of Thermodynamics for Temperature Control	FMPT、IML-2、MSL-1、TR-IA	Electric Furnaces, Software for analyzing the temperature distribution of furnace interior, for predicting convection by residual g, and crystal growth rate etc.
In-situ Observation	TR-IA	Inrterferometry using 2 waves real time phase-shift interferometer, and a high speed camera
Utilization of Electronics of Commercial Use	FMPT、IML-2、TR-IA	Digital VTR, Video Camera
Long Storage of Experimental Samples	FMPT、IML-2、MSL-1、TR-IA	Crystal growth experiments (organic, inorganic), Fluid experiments
Transportation of Experimental Samples	FMPT、IML-2、MSL-1、STS-95 STS-107	Colloid experiments Vibration monitor and control, Temperature monitor and control

Experiences and Lessons Learned

1 Ground experiments 95%、Space experiments 5%

Importance of ground experiments (preparation), a space experiment is an extension of the ground experiment.

Parameter change while the space experiment is very difficult.

2 Space experiments are based on the team work

Collaboration and cooperation amongst scientists, hardware builders, operation engineers, clerical personnel, managerial executives seems essential.

3 Importance of the numerical simulation

Fluid motion is most exemplified by the state of microgravity, and prediction of the anticipated phenomena under microgravity can be achieved by the numerical simulation to a satisfactory level.

4 Combination of Science and Technology

To achieve the scientific goal, the appropriate methodology (technology & engineering) is necessary.

5 Familiarization with the flight hardware

Ground preparation should be carried out by the exactly identical hardware as the one for the flight, and samples/procedures as well.

6 Plenty of practice would not allow you to switch off the vigilance.

When the size of the sample is changed, handle the sample as brand new one.

7 Unexpected happening leads to new achievements: Serendipity.

8 Original research comes from original hardware

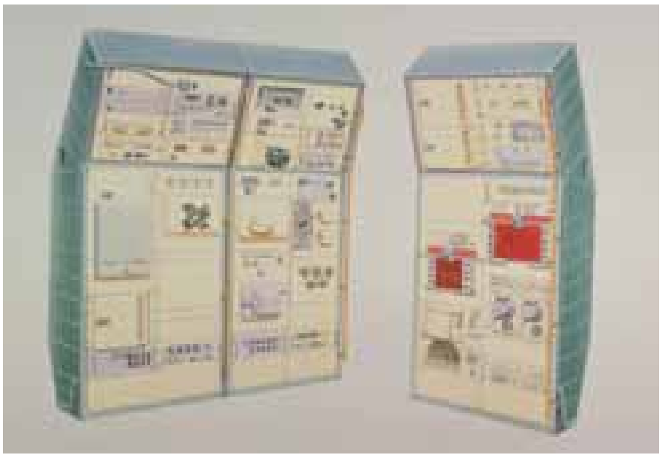
In-situ observation by a phase shift interferometer revealed the crystal growth mechanism.

3-D observation of flow fields developed Marangoni flow researches.

Sheer cell technique enabled us precise measurements of diffusion coefficients.

Space Environment Utilization Resource Sites

- **JAXA top**
  http://www.jaxa.jp/index_e.html
- **JAXA Space Station**
  http://iss.sfo.jaxa.jp/index_e.html
- **JAXA Space Environment Utilization**
  http://iss.sfo.jaxa.jp/utiliz/index_e.html
- **International Space Environment Utilization Research Data Base (ISRDB)**
  http://idb.exst.jaxa.jp/english/home_e.html
- **Japan Space Forum (JSF)**
  http://www.jsforum.or.jp/en/index_e.html
- **Asia-Pacific Regional Space Agency Forum (APRSAF)**
  http://www.aprsaf.org/index.html
- **The Japan Society of Microgravity Application (JASMA)**
  http://www.jasma.info/index_E.html
- **Japanese Society for Biological Sciences in Space (JSBSS)**
  http://wwwsoc.nii.ac.jp/jsbss/index_e.html
- **Japanese Society of Aerospace and Environmental Medicine (JSASEM)**
  http://wwwsoc.nii.ac.jp/jsasem/English/index-e.html



Japan Aerospace Exploration Agency

Tsukuba Space Center

2-1-1 Sengen, Tsukuba, Ibaraki,
305-8505 Japan
phone: +81-29-868-3697 facsimile: +81-29-868-3957

http://www.jaxa.jp

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