# Development of Electrostatic Levitation Furnace for the International Space Station

Takehiko Ishikawa, Keiji Murakami and Shin'ichi Yoda

Space Experiment Department, National Space Development Agency of Japan
2-1-1 Sengen Tsukuba, Ibaraki 305 Japan

## ABSTRACT

An electrostatic levitation furnace (ELF) is under development for the Japanese Experiment Module (JEM) in the International Space Station, which will be operational around 2000. This paper describes the features and development status of the furnace, and some expected experiments which utilize the ELF's containerless processing environment.

Keywords: International Space Station, electrostatic levitation, containerless processing

## 1. INTRODUCTION

For the International Space Station, National Space Development Agency of Japan (NASDA) has been developing the Japanese Experimental Module (JEM) and a variety of experiment facilities. The electrostatic levitation furnace is one of the facilities for material science research in the JEM's microgravity environment. We can obtain the following unique experiment conditions in a microgravity environment which can't be obtained on the earth.

1. Sedimentation, buoyancy and thermal convection are suppressed.
2. Hydrostatic pressure is avoided.
3. Sample will not move due to the lack of gravity force.

Levitation furnaces mainly take advantage of the feature of No. 3, and enable us to process samples in a containerless environment, which eliminates the possibility of contamination from container walls. Even though gravity force is not dominant, many disturbances such as g-jitters or air flow will make samples fluctuate. Therefore sample positioning is still important in Space. The main purpose of containerless processing by the levitation furnace is to study the process of matastable phases formation and to produce high purity materials. There are mainly three different methods which have been applied to the space levitation furnaces; acoustic levitation, electromagnetic levitation and electrostatic levitation.

Acoustic levitation method uses usually inert gas such as helium and argon to make standing sound wave for levitation and positioning of the specimen. When containerless processing is applied by this method, a steep temperature gradient is easily established around the melted specimen. It is hard to maintain stable standing wave due to this steep temperature gradient, and control of sample position is difficult during periods where high temperature levels are applied. Inert gases usually contain some impurities such as oxygen and hydrocarbon. The total amount of impurity is usually $10^{-5}$ Torr. which easily oxidizes or contaminates the sample. Space-DRUMS$^{TM}$ by Canadian Space Agency employs focused beams of sound to produce a force directly on the surface of the sample in a geometrically balanced manner, and overcomes this disadvantage [1] ,but unfortunately sample processing in vacuum can't be performed.

0-8194-2197-9/96/$6.00

TEMPUS by DARA, which employs electromagnetic levitation, has flown in the Second International Microgravity Laboratory mission (IML-2) and several experiments have been conducted. This method is based on the fact that an oscillating external magnetic field induces eddy currents at the surface of a conductive sample, which generates interactive force, Lorentz force resulting in stable positioning if the external magnetic field has a local minimum in all three dimensions.

Electrical resistivity strongly depends on temperature. This fact leads that the magnitude of electromagnetic field should be continuously modified with the change of sample's electrical resistivity. Reference experiments to get electrical resistivity data are necessary prior to the experiment under microgravity. Non-conductive sample can not be processed by this method. Most serious concern is disturbance on the surface of melted sample caused by Lorentz force. This disturbance might brake matastable state of the supercooled sample, and make the study of matastable phases difficult.

Electrostatic positioning method can solve all concerns described above. This system can deal with any kinds of materials including metals and glasses, and allows free drift of the sample as far as the sample exists within a certain region where temperature is almost uniform. This leads to less disturbance in specimen and makes the study of matastable phases easy. The ELF, under development by NASDA, employs this electrostatic levitation. An UV lamp will be equipped to charge samples, and sample position will be controlled by adjusting voltage of electrodes, which make coulomb forces between sample and electrodes. Heating will be performed by four lasers. Not only conductive but non-conductive samples can be levitated and processed in a vacuum or a controlled atmosphere.

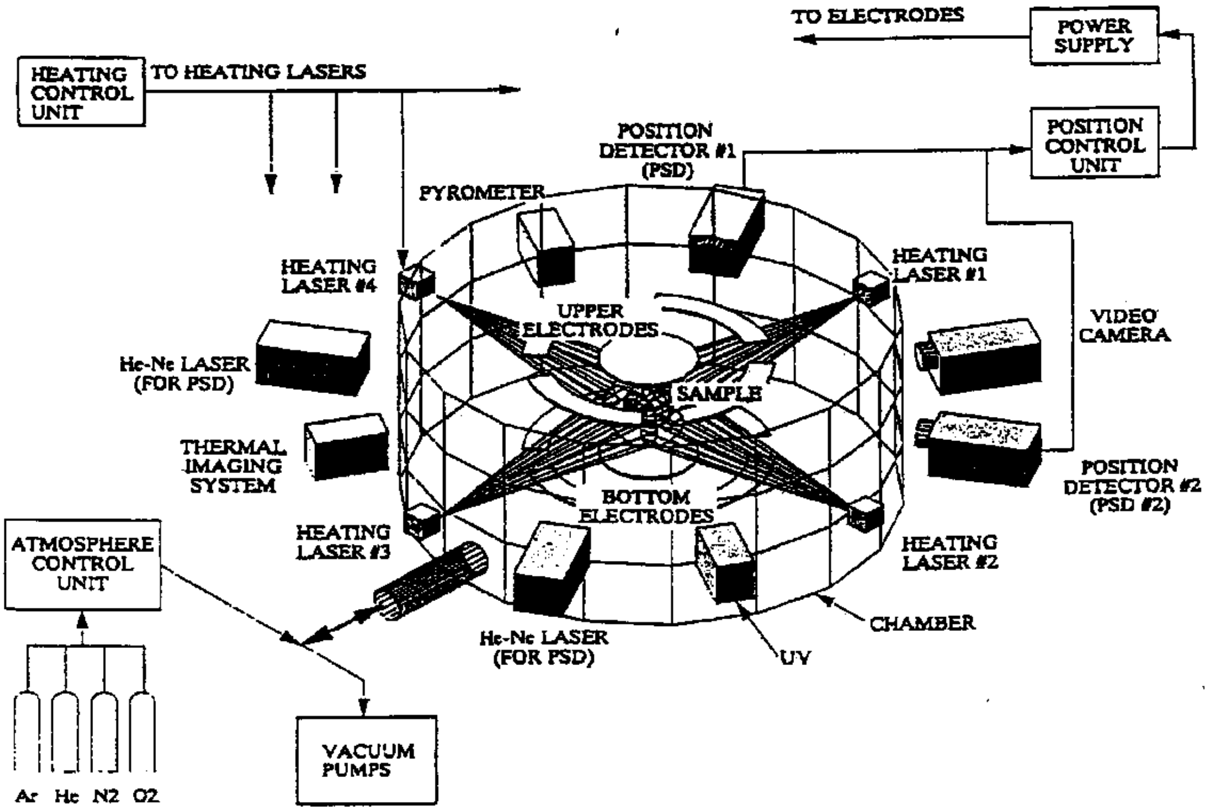


Fig. 1 Schematic Diagram of the ELF

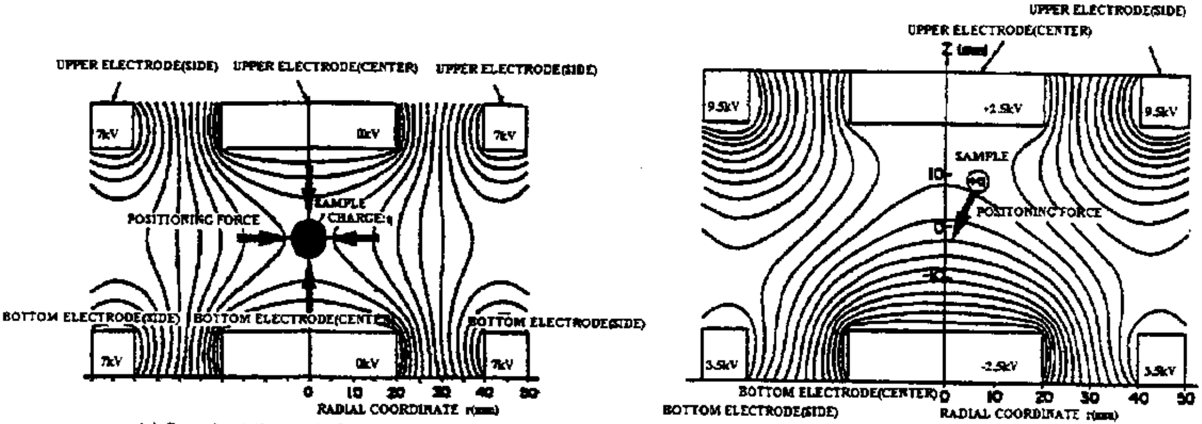
## 2. ELF OVERVIEW

Containerless processing is a key technology in material science research to investigate the formation of metastable phases and nucleation phenomena and to measure thermophysical material properties such as heat capacity, surface tension, thermal conductivity, and viscosity of melting samples.

The ELF represents the experimental equipment required for scientific investigation in such fields under microgravity. ELF enables containerless sample processing by means of electrostatic levitation. The ELF also has heating capability, gas environment control capability, contactless temperature measurement capability and automated sample exchange capability. Fig. 1 shows the schematic diagram of ELF.

### 2.1 Levitation section

The levitation section consists of two sample position detectors, an UV lamp, upper and lower electrode units and a position control unit. The sample set in the chamber is charged by an UV lamp, and position control is achieved by adjusting the balance between the sample inertia and coulomb forces generated by two electrode units. Fig. 2 shows the position control concept. Sample position is detected by two position detectors. A position detector is composed of a He - Ne laser and a detector. The position signals are sent to the position control unit. In the control unit, 3D position is calculated in accordance with the position signals and voltage of electrode units are adjusted. Each electrode unit has a center part electrode and four side electrodes, which enable not only vertical position control but horizontal position control. The use of four side electrodes will also allow sample rotation.



**(a) Sample at the central position**

**(b) Sample at the deviated position**

Fig. 2 Position Control Concept

### 2.2 Heating section

The heating section consists of a chamber, four heating lasers and their power control unit. According to the current design, four semi-conductor lasers with 0.80 $\mu$ m to 0.81 $\mu$ m wavelengths are employed, and a total of 1,000 W power will be added.

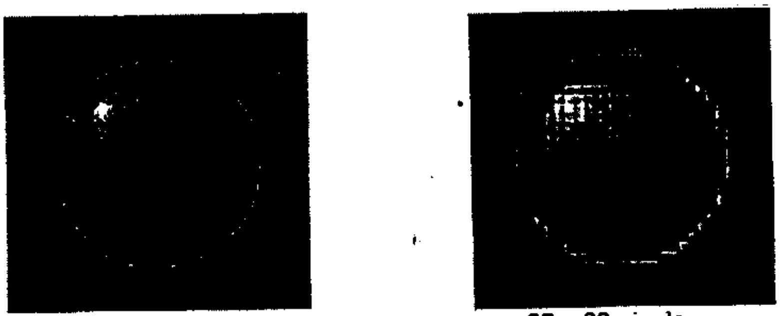
The four lasers are controlled independently; creating the capability for heterogeneous sample heating as well as homogeneous heating.

## 2.3 Measurement devices

The ELF has a pyrometer, a thermal imaging system and a video camera to measure the sample condition. The pyrometer will be used to measure the temperature center of the sample surface, while the thermal imaging system is for measurement of temperature distribution of the sample. In the thermal imaging system, the thermal image of the sample is divided into pixels, and average temperature of the pixel will be sent to the ground. Fig. 3 shows the thermal image of a sample.

In the current design, a range of 500 ℃ to 2100 ℃ can be measured by using these temperature measurement devices. Detailed specification of the temperature measurement system will be determined by considering the user requirements in the ELF advisory committee.

The video camera will be used to observe sample condition. By using this image, we can understand the status of the sample, status of levitation and positioning condition and status of the experiment. Detailed specification of the video is also under discussion in the committee.



128 x 128 pixels

32 x 32 pixels

64 x 64 pixels

16 x 16 pixels

Fig. 3 Thermal Image of the sample (Simulated)

## 2.4 Environment control system

The environment control system consists of vacuum pumps and an atmospheric control unit. A turbo molecular pump and a rotary pump are used to achieve vacuum levels which are monitored by a pirani and an ionization gauge.

Oxygen, Argon, Helium and Nitrogen gas will be supplied from the atmospheric control unit. Researchers can process specimens in a vacuum or a controlled atmosphere. Gas flow during heating is also allowed.

### 2.5 Automatic sample exchange unit

The automatic sample exchange unit is fully automated. Therefore, ELF experiment operations will be more flexible because crew time is one of the most critical resources in Space.

A robotic arm will be designed and developed for automatic sample exchange. It is also under consideration to require this arm to access processing samples; providing a origin of nucleation.

Table 1 shows the summary of current ELF specification.

Table 1 ELF Specification

| | |
|---|---|
| Applicable Sample | Metals, Semiconductors, Ceramics and Glasses<br>Shape: Spherical or quasi- spherical |
| Heating capacity | up to 2,000℃ (10 mm in diameter)<br>up to 1,600℃ (20 mm in diameter) |
| Stability of sample temperature | ±30℃ at 1,800℃ |
| Chamber Pressure | $10^{-5}$ Torr. to 1 atm |
| Gas Supply | Oxygen, Argon, Helium and Nitrogen |
| Measurement Devices | Contactless sample temperature measurement<br>(pyrometer and thermal imaging system)<br>Chamber Pressure measurement<br>Sample Image |
| Sample Positioning | Sample position should be controllable with $10^{-2}$ G level noise |
| Containment for safety | ELF should have triple containment |

## 3. EXPECTED EXPERIMENTS IN ELF

The ELF has the ability to process samples in a containerless environment, which eliminates not only contamination from container walls, but heterogeneous nucleation from the walls. Therefore, it is possible to sustain large undercooling for long periods of time in the ELF. Expected experiments in the ELF are related to measurement of various thermodynamic and kinetic properties of undercooled samples, study on non-equilibrium solidification with largely undercooled melts and study on properties of matastable solid phases.

### 3.1 Non-equilibrium solidification

Containerless processing allows to melt samples deeply below their melting point. Undercooled melts are in a non-equilibrium state and expected to solidify into metastable phases, which often have properties quite different from those of the equilibrium phase. It is reported that metallic glasses which have been produced by non-equilibrium solidification often have superior properties such as increased wear resistance and high ductility. Because of these superior properties, metastable materials such as metallic glasses have found applications in many technological areas. It is important to understand the relation between microstructure and superior properties of non-equilibrium solidification metal. Non-equilibrium study is one of the most attractive science fields in microgravity, but little knowledge has been derived from the past experiments. There is limitless possibility to find out new kind of materials and knowledge.

Experiments on non-equilibrium solidification are planned to be conducted often in the ELF. In these experiments, specimen such as metals and alloys will be levitated, melted and solidified. As heat is removed and the melt cools, a solid phase will nucleate and grow in the undercooled melt. Several hundred degrees of undercooling will be achieved and temperature profiles will be recorded. Samples will be returned to earth and researchers will study the microstructures and physical properties of the samples.

### 3.2 Measurement of thermophysical properties

It is thermodynamically interesting to describe the solidification process from the stable melt above melting point to the formation of glassy state and the nature of glass transition. Thermophysical properties such as specific heat, thermal conductivity or viscosity are important for this study. Specific heat is important because it allows us to calculate the Gibbs free energy and entropy difference between the undercooled and the crystalline states.

In the IML-2 mission, specific heat and thermal conductivity of undercooled metals and alloys were measured with the following method by TEMPUS [2)]. In the furnace, a sample was levitated and melted and sample temperature was continuously measured by a pyrometer. When the heating power was slightly modulated the sample responded with a periodic temperature change and an increase in an average temperature. The amplitude of temperature modulation was determined by a balance between the power absorbed and power radiated from the sample's surface, and depended on the specific heat, thermal conductivity, surface characteristics and the amplitude of input power modulation. Fig. 4 shows the typical example of the temperature response.

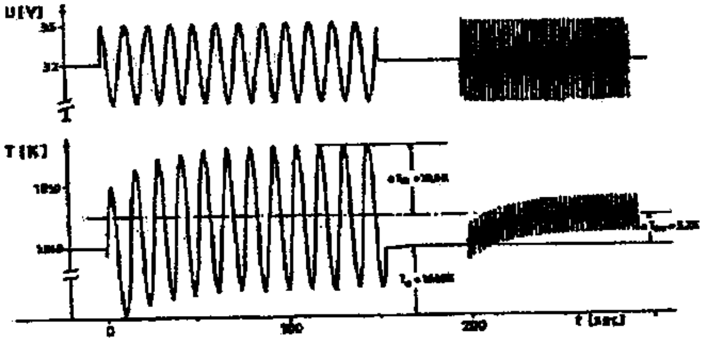


Fig. 4 Heating power modulation and temperature response [2)]

The influence of finite thermal conductivity and radiative heat loss could be characterized by internal and external relaxation times, respectably. These time constants could be measured by performing the modulation at different frequencies. At slow frequencies (~0.1 Hz), radiative heat loss was dominant and external relaxation time could be measured, from which specific heat was calculated. At higher frequencies(1 to 5 Hz ), thermal conductivity could be obtained. In addition, heat of fusion, emissivity and the hypercooling limit temperature could be measured [3]. With the same modulation method, the ELF will be used to measure the samples' thermophysical properties in the undercooled state.

### 3.3 Measurement of surface tension and viscosity

Knowledge of the viscosity and surface tension of melts in undercooled state will make an important role on the hydrodynamic description of fluids in the matastable state. Surface tension and viscosity can be measured by detecting surface oscillations of a levitated drop. The frequency of the oscillation is related to the surface tension, while the damping yields by the viscosity. By measuring the frequency and damping constant from the sample image, these values can be calculated.

Even if it can be levitated, a liquid drop is not spherical in a gravity environment. Therefore, it is difficult to conduct a precise evaluation of the frequency spectrum of spherical drops. The microgravity environment offers the unique possibility to analyze the oscillation spectrum of spherical drops. Surface tension and viscosity of melt in deeply undercooled regime, which has not been obtained can also be measured.

### 3.4 Production of high performance materials

Other than the experiments described in 3.1 to 3.4, the following experiments will be performed in the ELF.

1. Under the microgravity condition, it is expected that several components can be mixed uniformly because sedimentation, buoyancy and thermal convection are suppressed. By taking advantage of this feature, experiments for producing new material will be conducted in the ELF. Other conventional facilities such as Isothermal Furnaces also accommodate these kinds of experiments, but the ELF will be used when the experiment requires contamination free processing.
2. Experiments with conventional furnaces require containers, which becomes a restriction on maximum experiment temperature. Since the container is not necessary for the ELF, samples can be heated to higher temperature. This enables researchers to conduct experiments on materials with high melting points.
3. By controlling electrode voltages and sample charges, it is possible to deform molten sample melt from spherical shape to desired shape. Experiment on contactless glass shaping in the ELF is under consideration.

## 4. ELF DEVELOPMENT STATUS

The ELF for International Space Station is in a fundamental design phase; key technology development and overall configuration design is in progress. Concerning levitation and heating, a Bread-Board Model (BBM) has been manufactured and ground based tests have been conducted. During these tests, a YAG laser with 100W power has been employed as a heating device. Thus far, samples of pure aluminum and zirconium, with 2 mm in diameter have been successfully levitated and melted in vacuum conditions. Fig. 5 shows the raw data of a ground based experiment with a Zr sample. In this experiment, the undercooled state was observed. Functional tests in a reduced gravity have also been performed by using parabolic flight airplane and will be conducted by TR-IA sounding rocket.

In order to design and develop an user-friendly facility, the ELF advisory committee has been established and the specifications of ELF have been discussed with the users: In addition to the specifications on table -1, important parameters for experiment planning such as maximum cooling rate, sampling rate of thermal imaging system etc. have also been discussed.

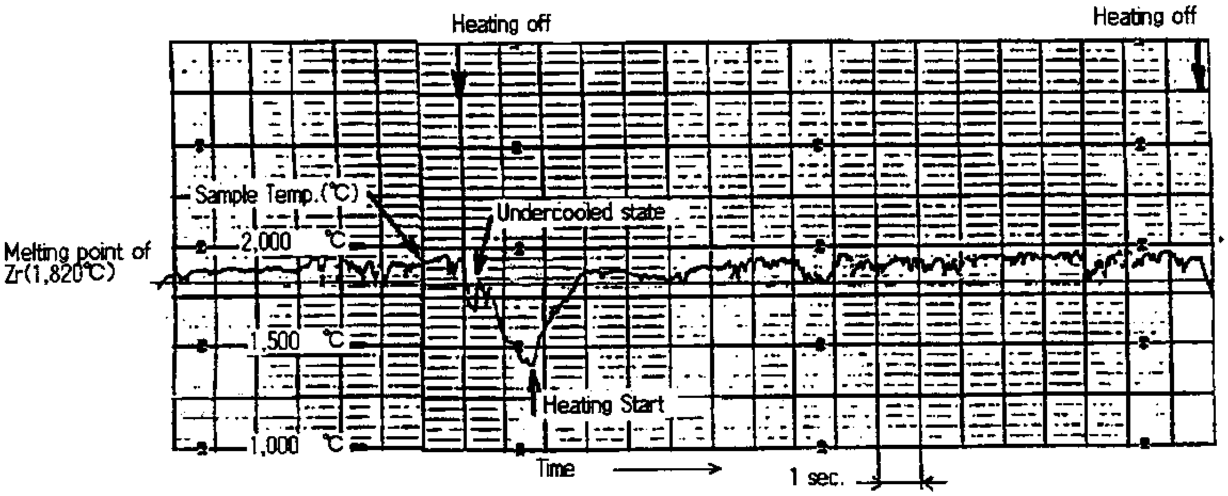


Fig. 5 Temperature data of ground based experiment with Zr sample

## 5. CONCLUSION

NASDA has been developing ELF with electrostatic levitation method, which has superior features in comparison with the other levitation methods such as acoustic method and electromagnetic method. Containerless processing is one of the most attractive experiment fields in the microgravity science. NASDA plans to conduct systematic studies in this field and new knowledge for human being form microgravity experiments in ELF are expected.

## 6. ACKNOWLEDGMENT

The Electrostatic Levitation Furnace is being developed by Mitsubishi Electric Co. under a NASDA contract. The ELF advisory committee, chaired by Prof. Suzuki of Tokyo University, is organizing user requirements and providing useful comments for the ELF development.

## 7. REFERENCES

1. J. Y. Guigne et al. "Space-DRUMS$^{TM}$-A Dynamically Controlled Multi-Beam Levitator-Positoner," J. Jpn. Soc. Microgravity Appl. Vol. 13, No. 1, pp 20-26,1996.
2. H. -J. Fecht et al. "Thermodynamic and Glass Formation of Undercooled Metallic Melts", TEMPUS leaflet for IML-2 mission
3. R. K. Wunderlich et al. "Measurement of the Specific Heat of Liquid Zr-Alloys by Contactless Modulation Calorimetry with the TEMPUS Facility under Microgravity Conditions", *ninth European symposium gravity dependent phenomena in physical sciences Abstracts*, pp. 217, DARA, Berlin, 1995.