# Experimental Investigation of Pressure-Volume-Temperature Mass Gauging Method under Microgravity Condition by Parabolic Flight

**Mansu Seo[a], Hana Park[a], DonGyu Yoo[a],**

**Youngsuk Jung[b], and Sangkwon Jeong*[,a]**

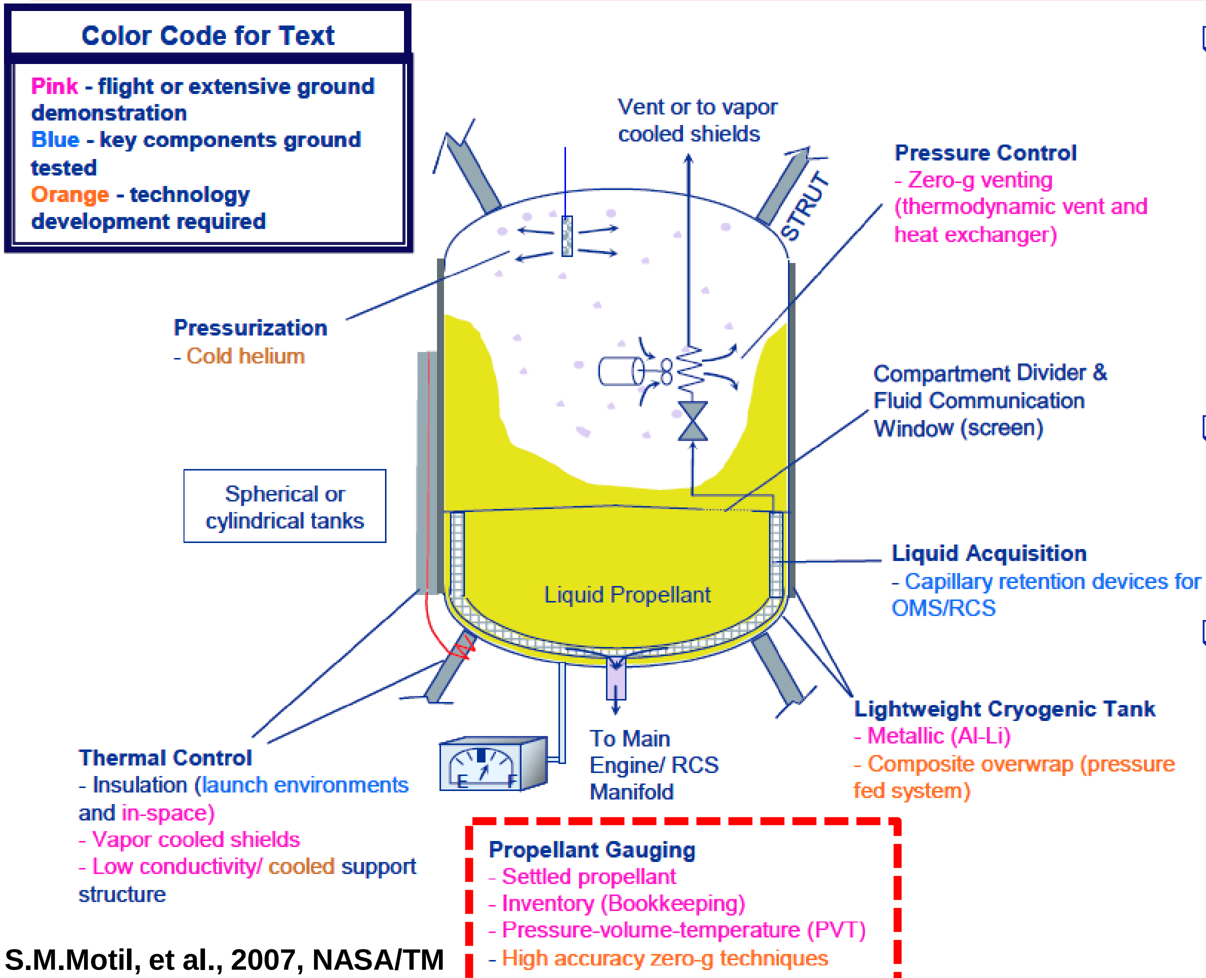
*[a]Cryogenic Engineering Laboratory, Department of Mechanical Engineering, KAIST, Daejeon, Republic of Korea*

*[b]Launcher Systems Development Team, Korea Aerospace Research Institute, Daejeon, Republic of Korea*

# Introduction

# Motivation of our research

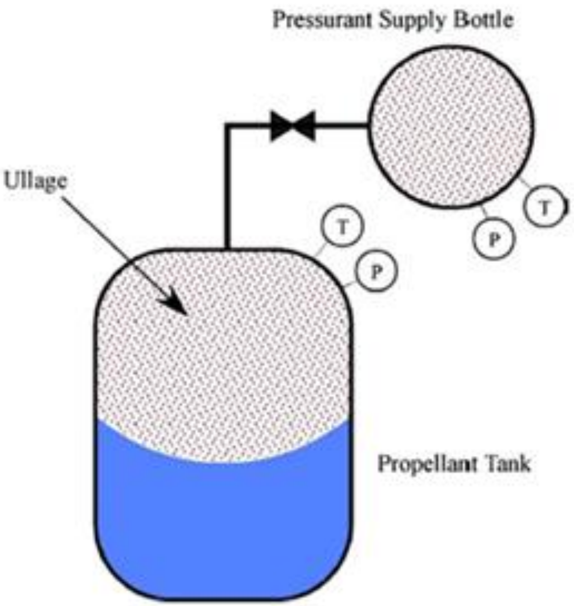
Cryogenic Propellant Storage and Transfer (CPST):
the development of cryogenic storage systems,
low-gravity propellant management systems, cryogenic transfer and handling technologies



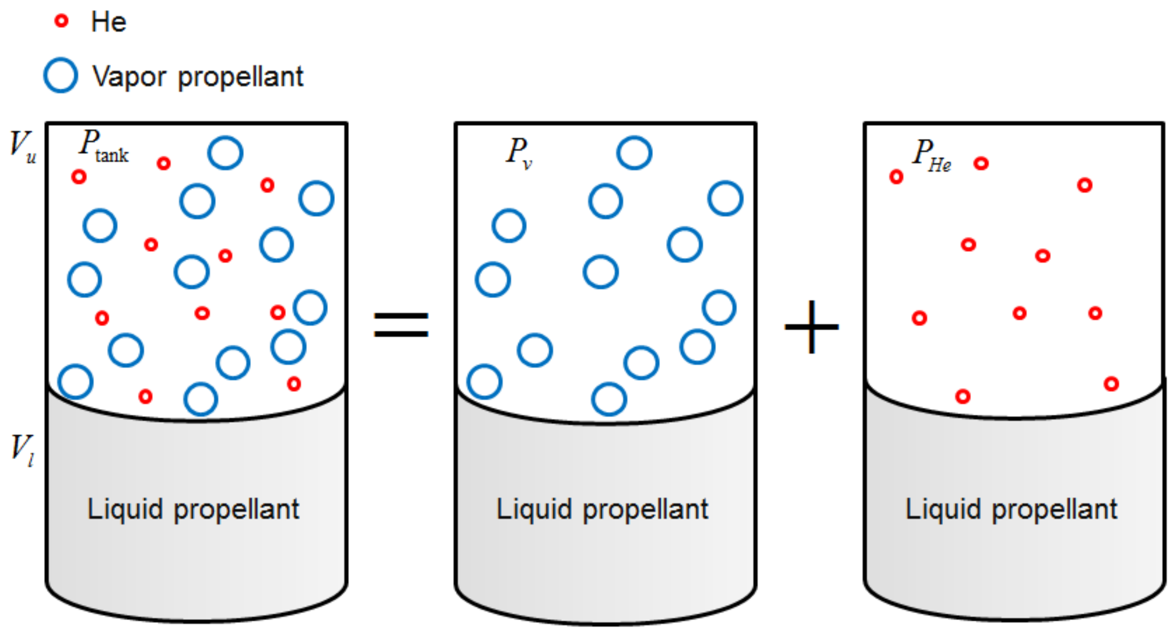

S.M.Motil, et al., 2007, NASA/TM

- ❑ Technology for susceptibility to environmental heat, complex thermodynamic and fluid dynamic behavior in low gravity and the uncertainty of the position of the liquid–vapor interface
- ❑ Important technology for lunar exploration and deep space mission for Korea space plan
- ❑ Propellant gauging: the interface of liquid propellant under microgravity in space becoming uneven and globular unlike that on the ground and this fact making the usual gauging liquid amount under microgravity impossible

# PVT (Pressure-volume-temperature) mass gauging method




N.T. Van Dresar, 2003, Cryogenics

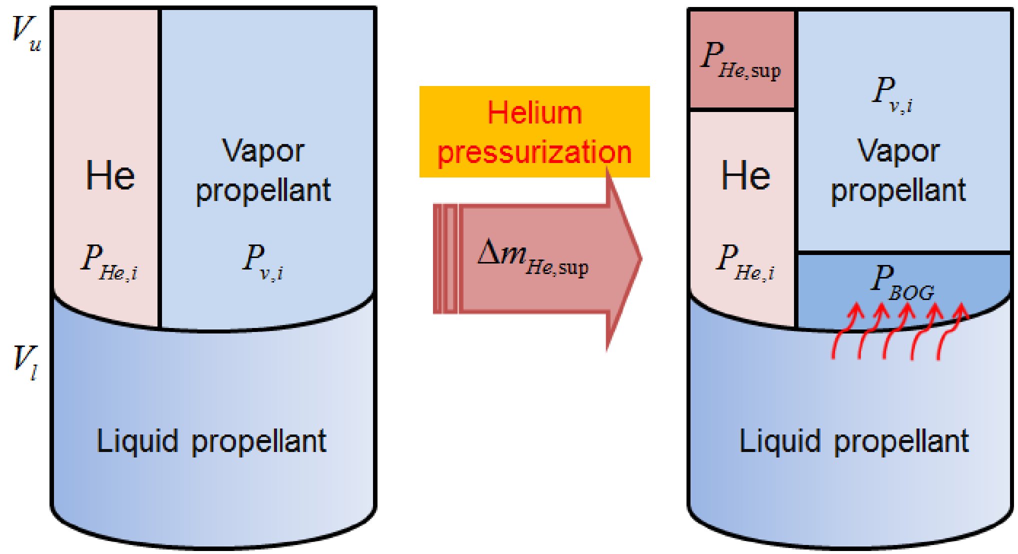



1. Minimal hardware
2. Simple measurement process

=> one of the most attractive gauging methods for transition period of self-development of Korea space rocket vehicle

$$V_u = \frac{m_{total}}{\rho_{total}} = \boxed{\frac{m_{He}}{\rho_{He}(T, P_{He})}}$$ by Dalton's law

# PVT (Pressure-volume-temperature) mass gauging method

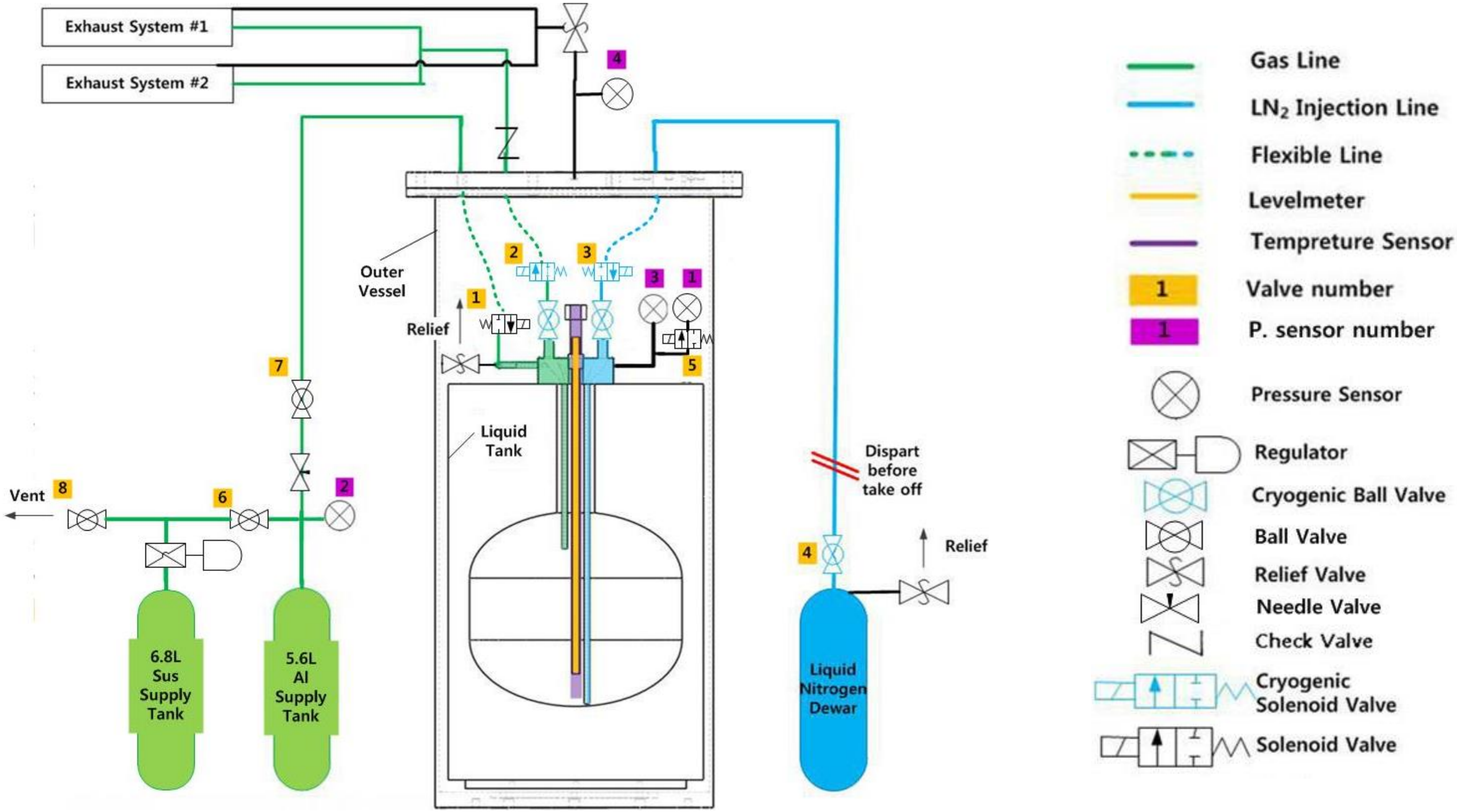



Calculating the ullage volume from the gas state equation using the measured mass, temperature, and the partial pressure of the injected non-condensable pressurant gas

$$V_u = \left.\frac{m_f - m_i}{\rho_f - \rho_i}\right|_{He} \quad \begin{cases} m_{He,f} = m_{He,i} + \Delta m_{He,\sup} \\ \left.\rho_f - \rho_i\right|_{He} = f(P_{He,f}, T_f) - f(P_{He,i}, T_i) \end{cases}$$

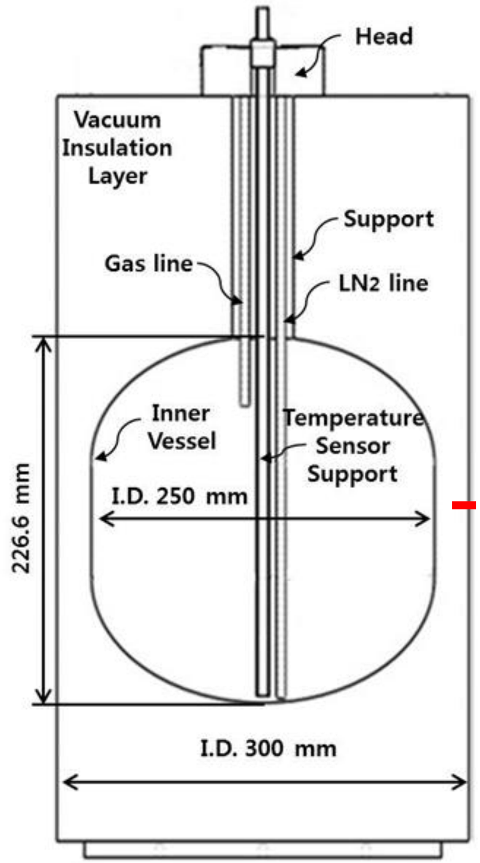
# Experimental set-up

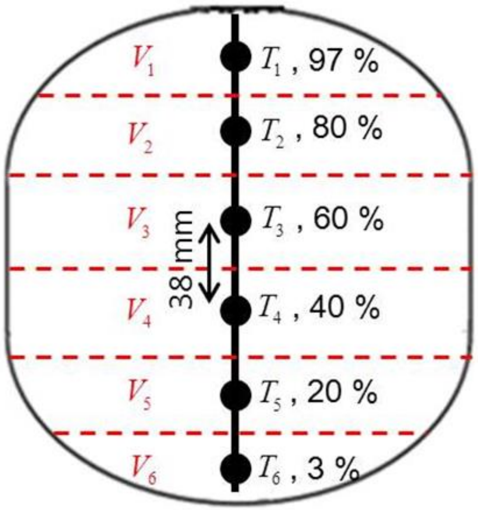
# Experimental apparatus for microgravity flight




- Experimental set-up consisting of a liquid nitrogen storage tank, an outer vessel for safety, a helium gas supply tank, a liquid nitrogen supply tank, and an exhaust system
- Operating all control of fluid injection or venting solenoid valves for convenience during the short parabolic flight experiment (~ 20 sec)

# Experimental apparatus for microgravity flight





- The geometric dimensions of the tank with 227 mm in height, 250 mm in diameter, and 9.2 L in internal volume
- Installation of a liquid nitrogen level meter, a liquid nitrogen injection pipe, a helium gas injection and vent line, and a guide rod for temperature sensor in the tank
- Vertical installation of six silicon diode cryogenic temperature sensors (Lakeshore DT-670-SD, ±0.25 K accuracy) to measure the temperature gradient in the tank

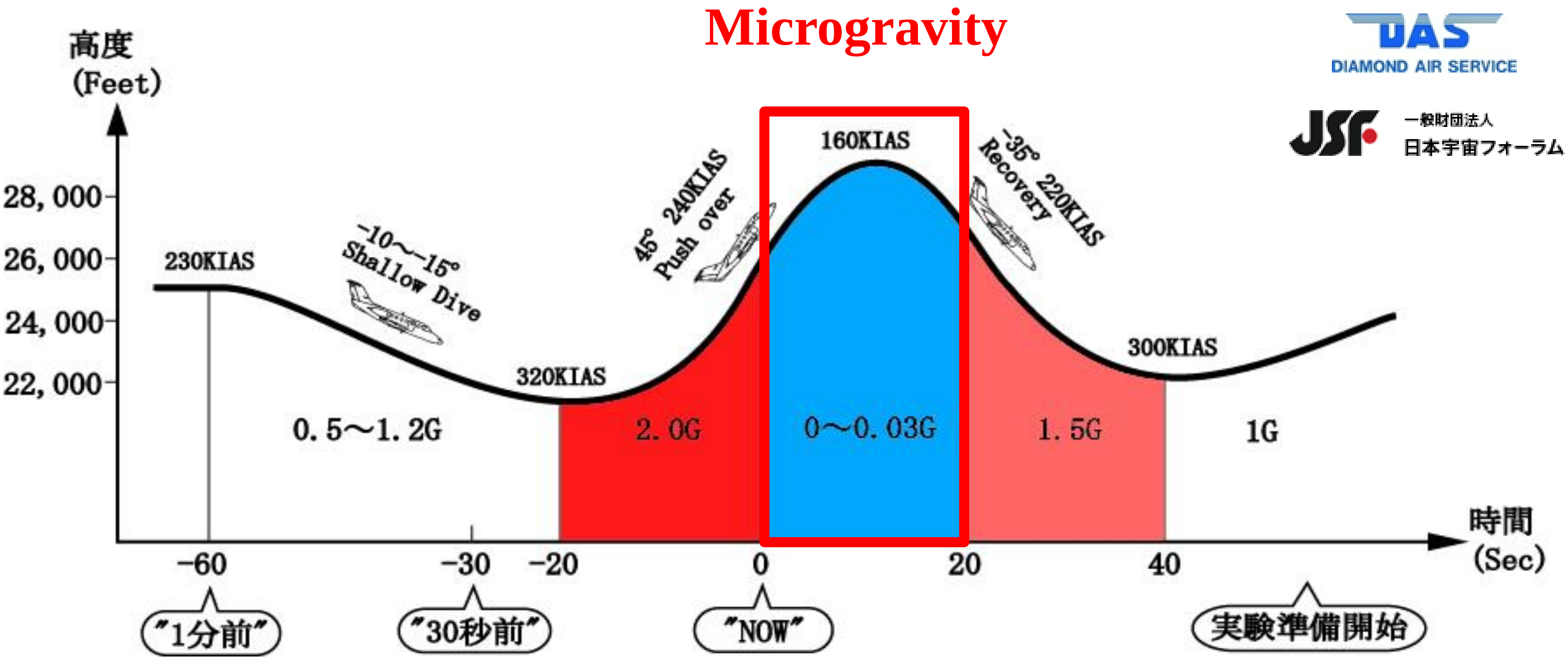
# Experimental apparatus for microgravity flight

## ❑ Photos

Liquid nitrogen storage tank


# Background of microgravity parabolic flight

# Microgravity parabolic flight

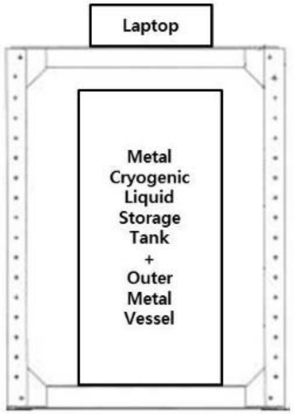



- One minute before entering microgravity, the aircraft performing rapid descent and ascent to reach its maximum velocity at the point where microgravity begins
- Achieving microgravity condition under $3 \times 10^{-2}$ G for 20 seconds with a parabolic flight
- Japan Space Forum (JSF) coordinating a parabolic flight experimental program for foreign scientists and Diamond Air Service (DAS) in Nagoya, Japan

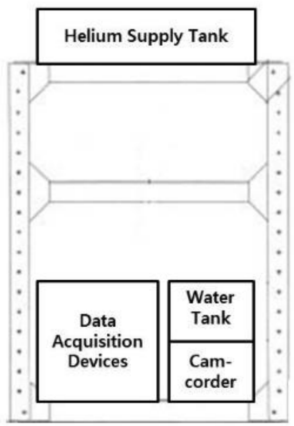
# On-board equipment

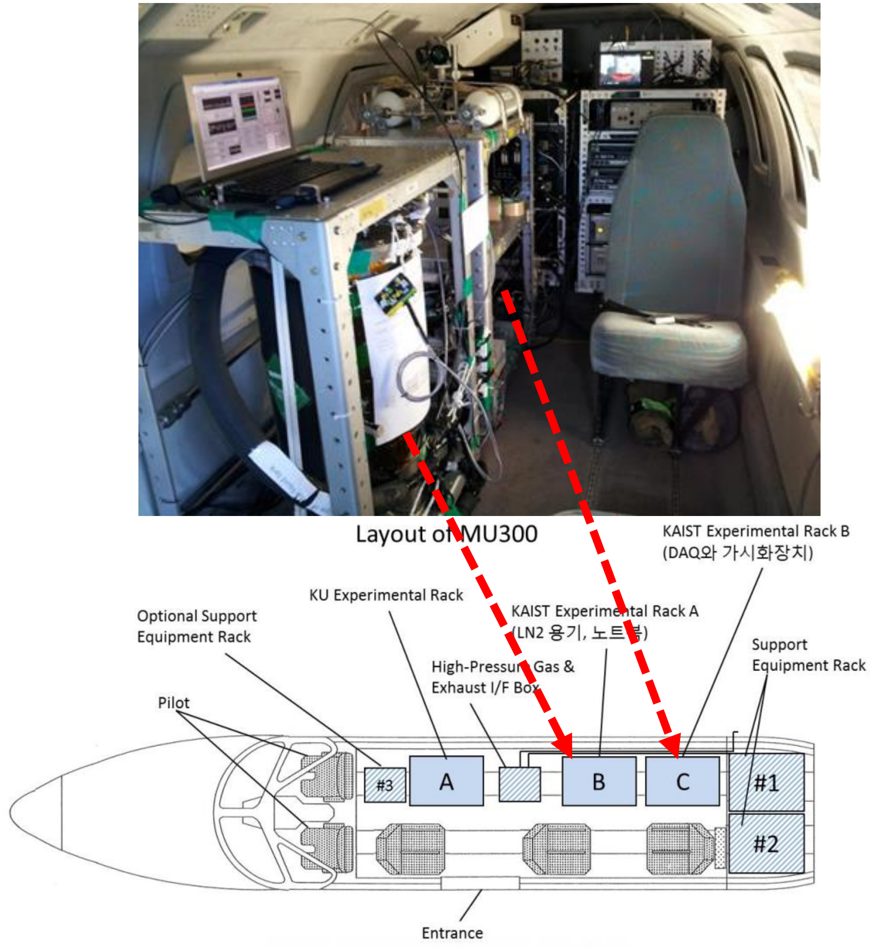
## ❑ Photo of installation in the airplane

Rack A



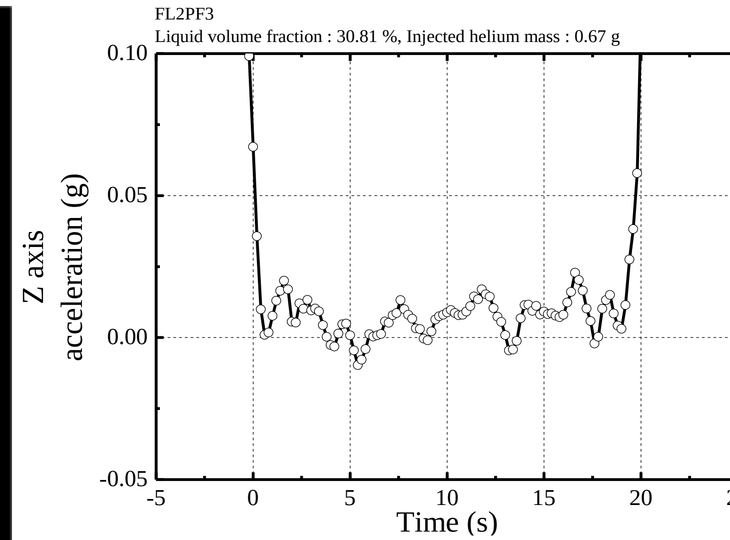

Rack B

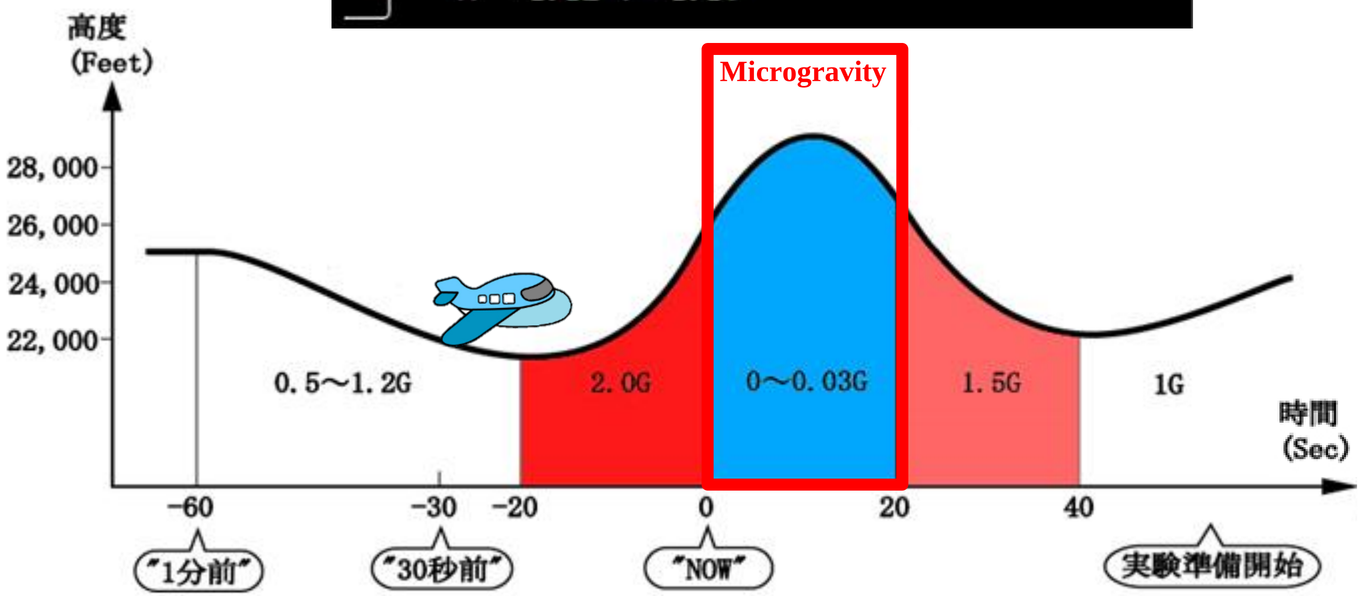


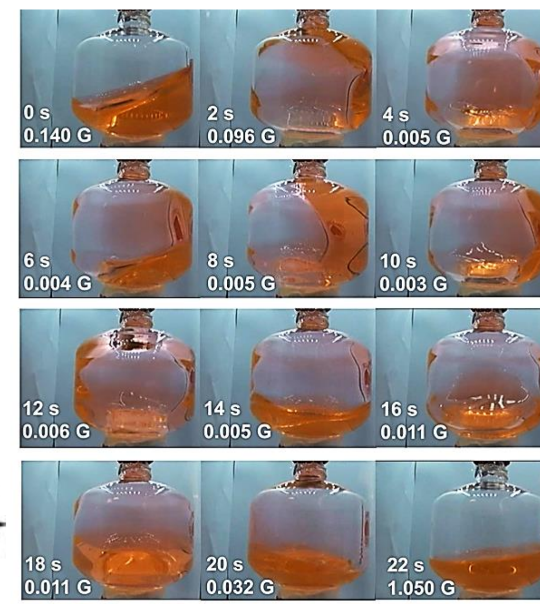



# Experiment and results

# Water configuration under microgravity

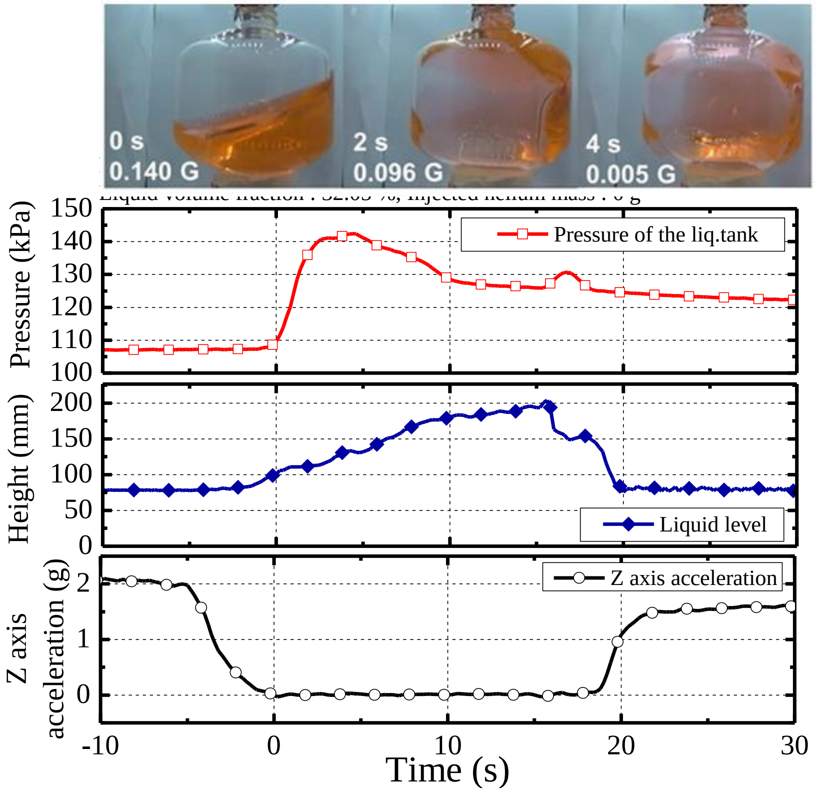



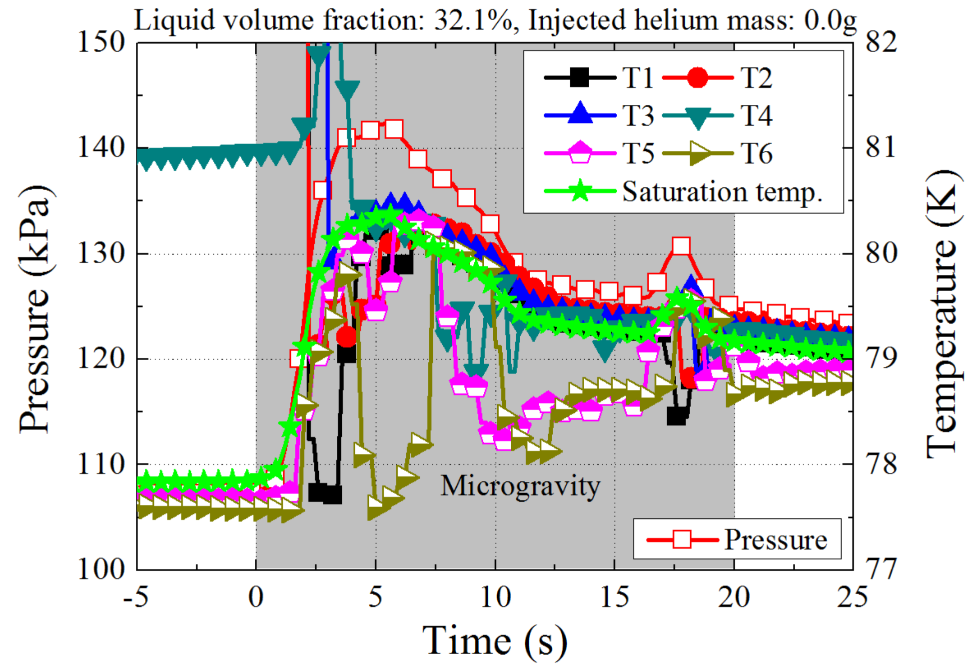
# Experimental condition for microgravity flight

| Experimental conditions | #1 flight (10th, Oct., 2013) | #2 flight (14th, Oct., 2013) |
| --- | --- | --- |
| Liquid filling fraction (%) | Low fraction, 30~32 | |
| He supply tank pressure (kPa) | 300 | 350 |
| He mass flow rate (slpm) | 15 ~ 3<br>(80 with needle valve) | 50 ~ 13<br>(150 with needle valve) |
| The number of experiment (times) | 11 | 12 |
| Initial pressure (kPa) | 106 ~ 107 (after self-pressurization) | |
| Preparation period before helium pressurization at 0G (sec) | ~3<br>(~10 for last 3 exp.) | ~10 - 12 |
| Pressurization period at 0G (sec) | ~5 | |
| After pressurization period (sec) | ~30 - 40 | |

# Characteristics under closed condition

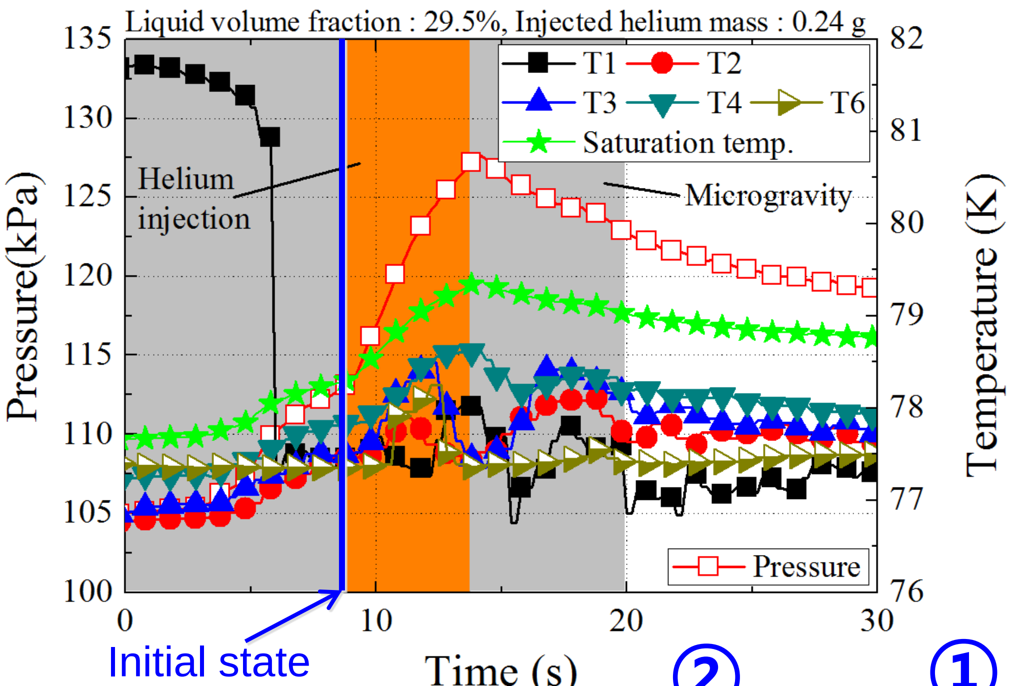


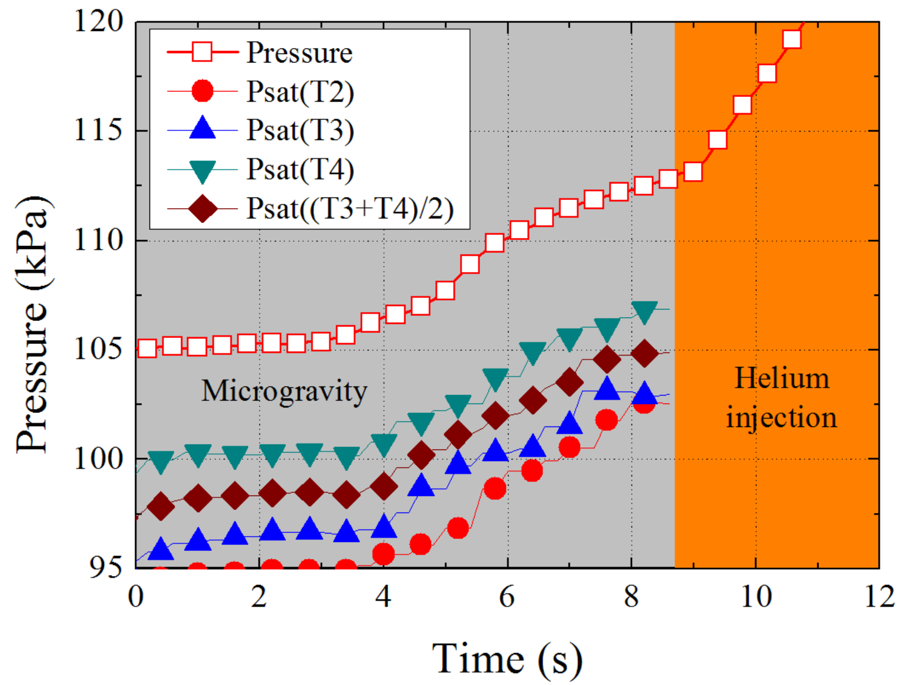

Pressure and temperature variation during parabolic flight without helium gas injection




- Self-pressurization experiments without helium gas injection to observe the thermodynamic characteristics of liquid nitrogen in the tank during microgravity condition
- T1 ~ T4, the superheated temperature which is varied between 81 and 115 K before microgravity (they are invisible due to the graph scale), quickly becoming saturation temperature and move along the saturation temperature curve several seconds after the microgravity condition begins => thermal equilibrium state under microgravity

# 1. Initial He partial pressure before injection




② ①

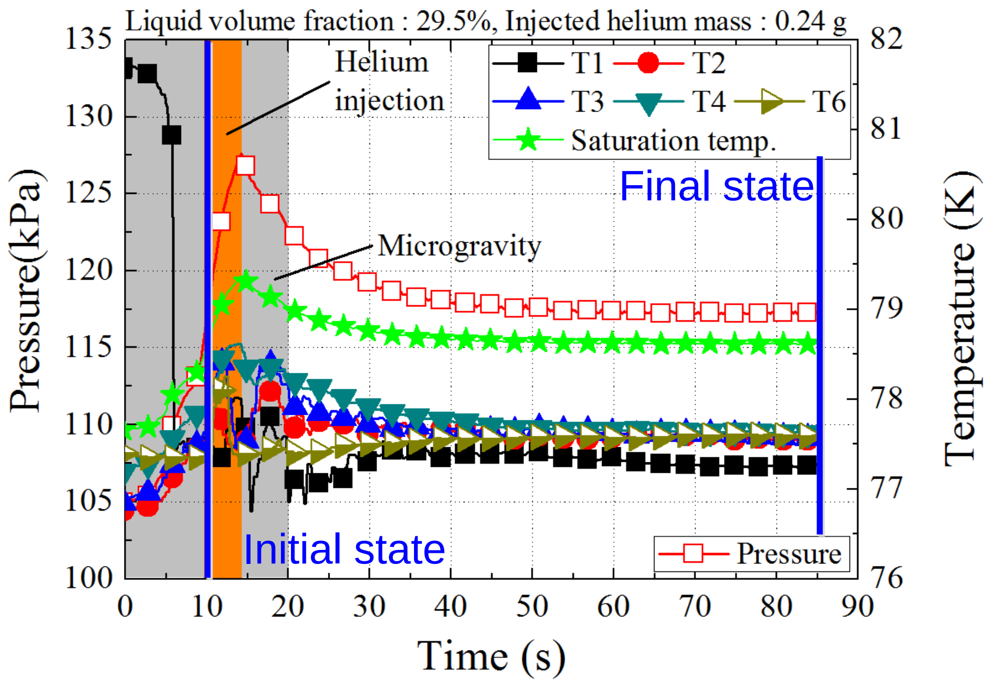
$$V_u = \frac{\Delta m_{He,\sup}}{\rho_f - \rho_i}\Bigg|_{He} \quad , \qquad \rho_f - \rho_i\Big|_{He} = f(\boxed{P_{He,f}}, T_f) - f(\boxed{P_{He,i}}, T_i)$$

Want to know!

$$P_i - P_{sat}(T_i) = P_{He,i} + \cancel{P_{v,i}} - \cancel{P_{sat}(T_i)} = \boxed{P_{He,i}} \quad ①$$

- Assigning the preparation period about 10 seconds to ensure adequate stabilization period for saturated condition
- To obtain the quantity of the initial helium partial pressure, comparing the total tank pressure and the saturation pressure from the measured temperature data during microgravity condition before helium injection

# 2. Final He partial pressure after injection



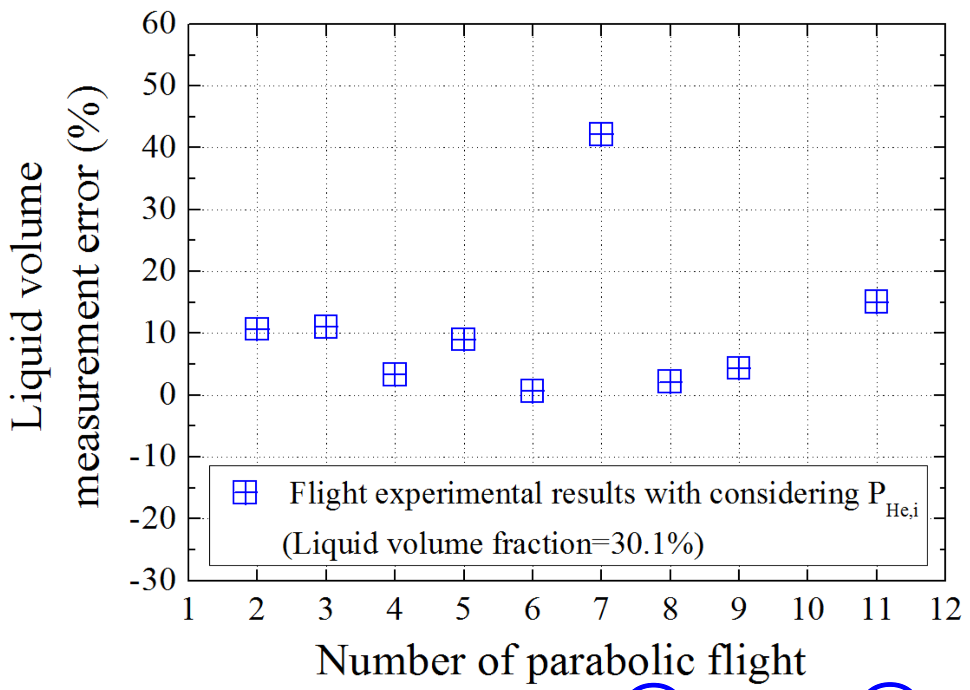

$$P_f - P_{sat}(T_f) = P_{He,i} + \cancel{P_{v,i}} + \cancel{P_{BOG}} + P_{He,\sup} - P_{sat}(\cancel{T_f}) = P_{He,i} + P_{He,\sup}$$

$$= \boxed{P_{He,f}} \quad ②$$

- Obtaining thermal equilibrium and saturated condition after enough stabilization period longer than 60 seconds after helium pressurization despite of the condition under normal gravity

=> calculating the final helium partial pressure by the same procedure as for the initial one

# Microgravity experimental results




② ① Complete to obtain!

$$V_u = \left.\frac{\Delta m_{He,\sup}}{\rho_f - \rho_i}\right|_{He}, \qquad \rho_f - \rho_i\big|_{He} = f(\boxed{P_{He,f}}, T_f) - f(\boxed{P_{He,i}}, T_i)$$

$$e_l = \left|(V_{l,PVT} - V_{l,true}) / V_{\text{tank}}\right| \times 100(\%)$$

- The average error and the standard deviation => 10.9% and 11.9, respectively
- Two experimental limits in the parabolic flight: the charged mass limitation of helium gas due to pressure safety and short helium injection duration for approximately 5 seconds

# Conclusion

- **Accurate measurement is achieved within 11% average at 30% liquid filling fraction when a sufficient stabilization period longer than 10 seconds is assigned before helium gas injection to guarantee saturated condition.**

- **Thermal equilibrium condition is very important to measure the initial and the final helium partial pressures in a storage tank.**

- **Temperature variation due to non-fully homogeneous condition with the limitation of short duration of parabolic flight experiment results in the experimental uncertainty.**

- **PVT gauging method is suitable for lunar or deep space exploration program with long microgravity duration in that thermal equilibrium condition is easily obtained in a storage tank.**