Cryogenic Thermal Performance of the Vacuum Insulation System for LH_2 Storage Tanks

D.H. Lee[1], H.J. Jeon[1], **Y.J Jeong**[1*], T.U Park[2], T.M. Cho[2],
T.W Kim[3], S.K Kim[3], C.S. Bang[2] J.M Lee[1,3†]

[1]Department of Naval Architecture and Ocean Engineering, Pusan National University

[2]Green Energy Technology Center (Hydrogen Technology), Samsung Heavy Industries

[3]Hydrogen Ship Technology Center, Pusan National University

CEC/ICMC-2023 Hawaii Convention Center

The 25th joint CEC/ICMC Conference

Honolulu, Hawaii, July 9-13, 2023: www.cec-icmc.org

CEC ICMC 23

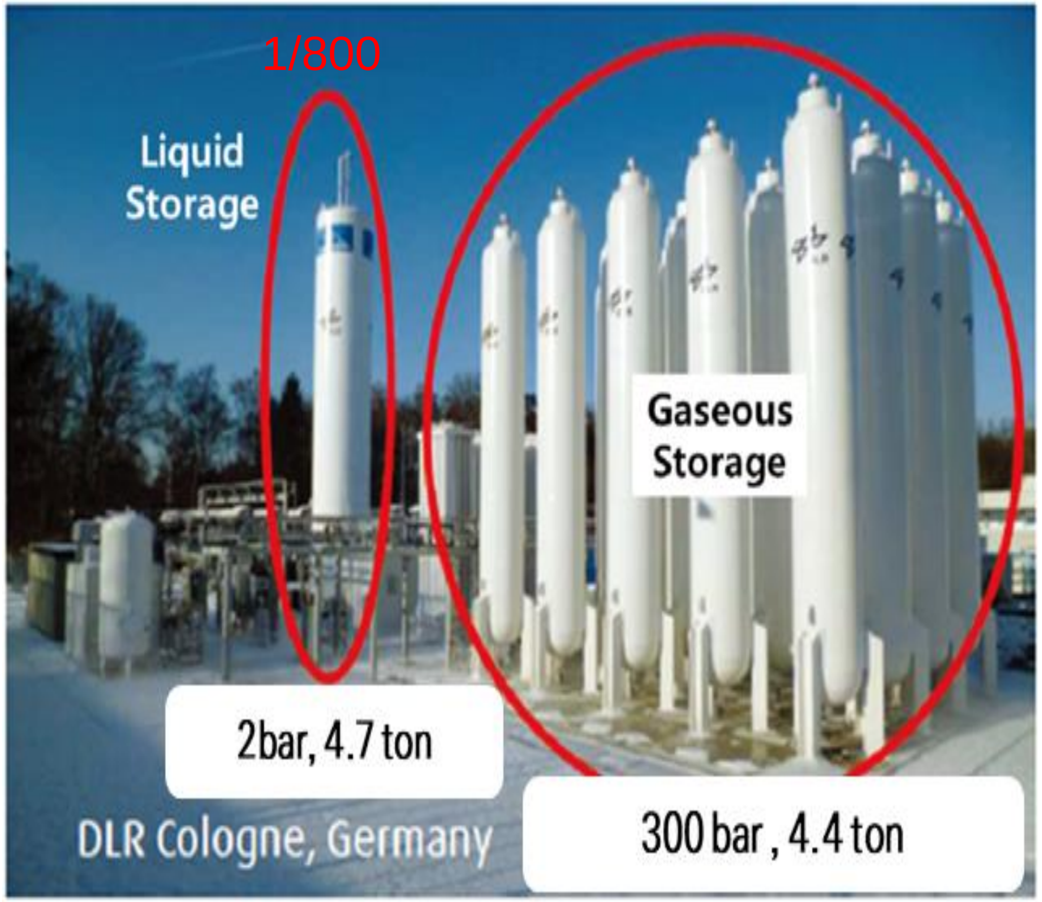
ECOSL Eco Ship Laboratory

INTRODUCTION

INTRODUCTION

- ✓ **Cryogenic liquids**: liquefied gases that are kept in their liquid state (boiling point below -150°C)
- ✓ Extremely cold and small amounts of liquid can expand into very large volumes of gas
- ✓ Most cryogenic liquids can be placed into Inert gases, Flammable gases, and Oxygen:
  - **Inert Gases**: They do not react chemically to any great extent (Nitrogen, Helium, Neon, Argon, and Krypton, etc.)
  - **Flammable Gases**: They produce a gas that can burn in air (Hydrogen, Methane, Liquefied natural gas, etc.)

Gas	Boiling point(°C)	Latent heat(kJ/kg)	Type	Volume ratio (liq→gas)
LNG	-161.5	512	Flammable	600
H_2	-252.75	447	Flammable	800
N_2	-196.15	199	Inert	800
He	-268.95	21	Inert	700
O_2	-183.15	213	Reactive	800
Ar	-185.85	162	Inert	800



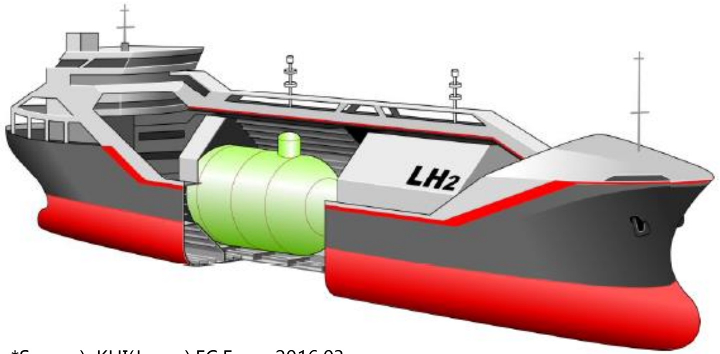
INTRODUCTION

➢ Hydrogen Energy

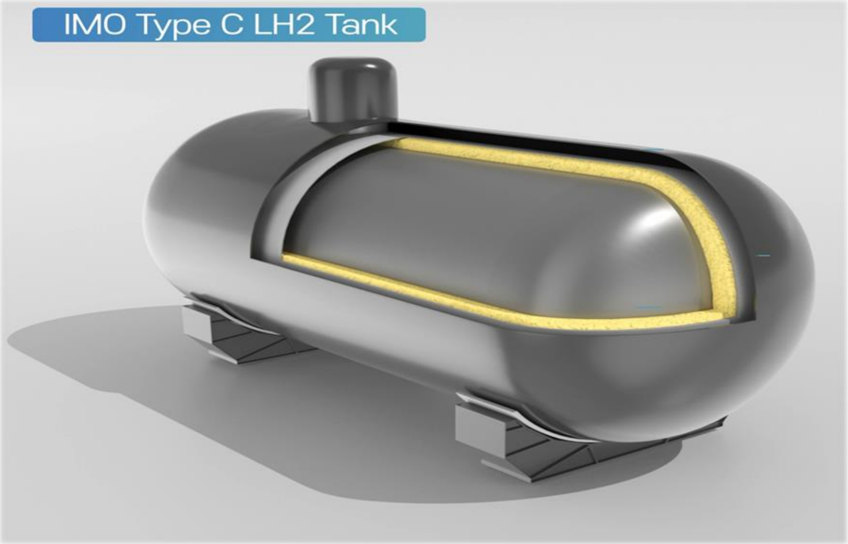
- ✓ Hydrogen Energy: Enormous quantities in water, hydrocarbons, and organics.
- ✓ Zero-emission fuel when burned with oxygen.
- ✓ No restriction on the energy resource because it produced from water.
- ✓ Current application: Vehicles, electric devices, and the propulsion of spacecraft, etc.

➢ Storage and Transport

- ✓ Stored and transported as a liquid state (like LNG)
- ✓ Liquid hydrogen requires cryogenic storage and boils around -253 °C.
- ✓ Necessity to develop well insulated LN2 CCS to prevent boil-off gas.



*Source) KHI(Japan) FC Expo, 2016.03



INTRODUCTION

Cylindrical tank for calculation of insulation thickness to achieve BOR 0.3%/day

- Gross Volume : 1,800 m^3 (typical fuel tank size on board)
- Diameter : 9,000 mm
- Material : 9% Nickel
- Design Pressure : 5 barg (IMO Type-C)
- Insulation : Polyurethane Foam (0.0245W/mK)
- Target BOR : 0.3% vol./day

$$BOR = \frac{\sum Q \times 3600 \times 24}{H \times V \times \rho} \times 100\%$$

$\sum Q_i$ = Total Heat Ingress (W) V = Volume (m^3)

ρ = Liquid Density (kg/m^3) H = Latent heat (KJ/kg)

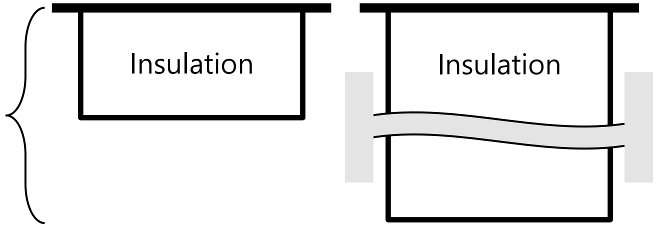
$$\sum Q_i = A_i \cdot \Delta T \cdot \frac{\lambda_i}{L_i}$$

λ_i = Thermal Conductivity (W/mK) A = Surface Area (m^2)

$\triangle T$ = Temperature Difference Li = Thickness of Insulation

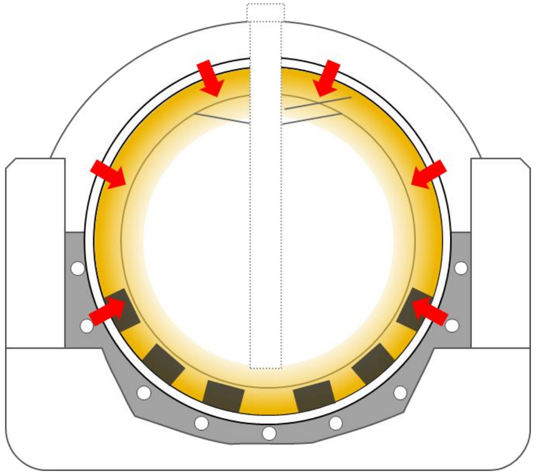
	LNG	LH_2
Latent Heat, MJ/m^3	216	32
BOR, %/day	0.309	0.302
Insulation Thickness, mm	300	3300

Over 10 times



Liquefied Hydrogen(LH2)

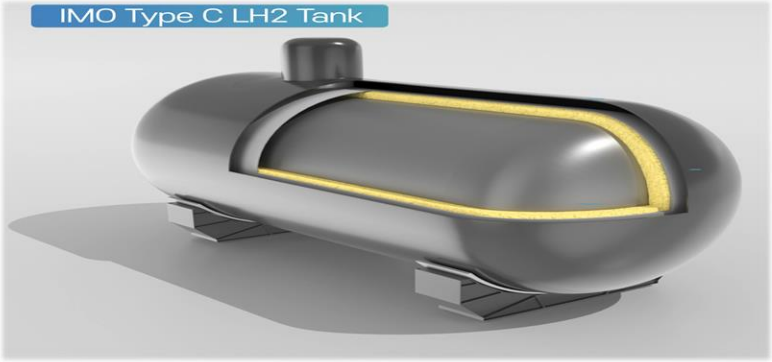
- **Density : 70.9 kg/m^3**
  ※ (1/7 to 1/6 compared to LNG)
- **Latent heat : 32 MJ/m^3**
  ※ (1/7 compared to LNG)



Reduced storage due to increased insulation thickness

INTRODUCTION

LH2 Storage tank



(CCS Overview)

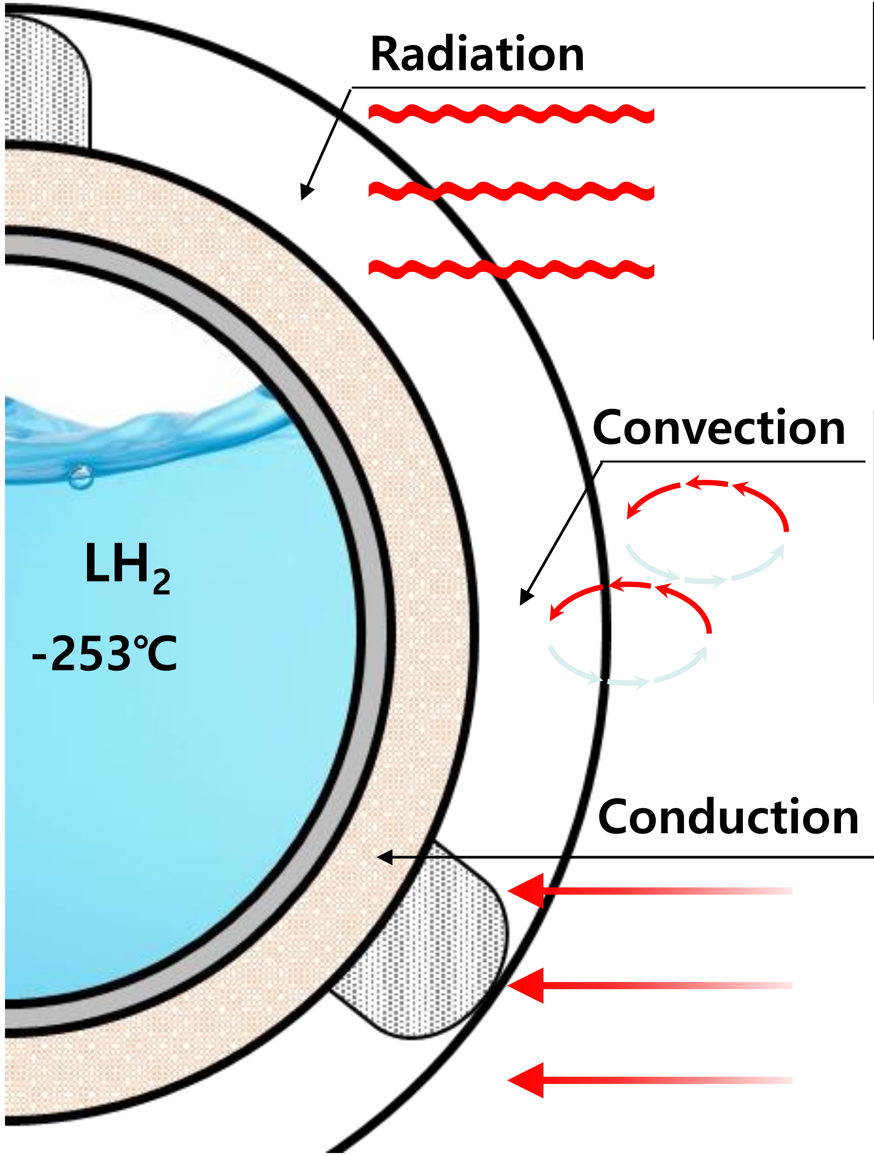
- Cylinder-shaped pressure tank verified as cargo hold for vessel
- Easier to manufacture than membrane type, but insulation problem exist in the curved part

(Insulation System)

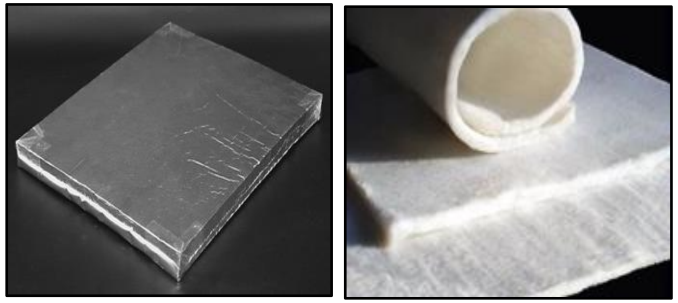
- MLI and Powder type vacuum insulation system
- Strength/Thermal conductivity compared to high-performance FRP support

(Material and Structure)

- High manganese steel, Stainless steel
- Internal stiffened and vacuum ring



Radiation Shield/Filer

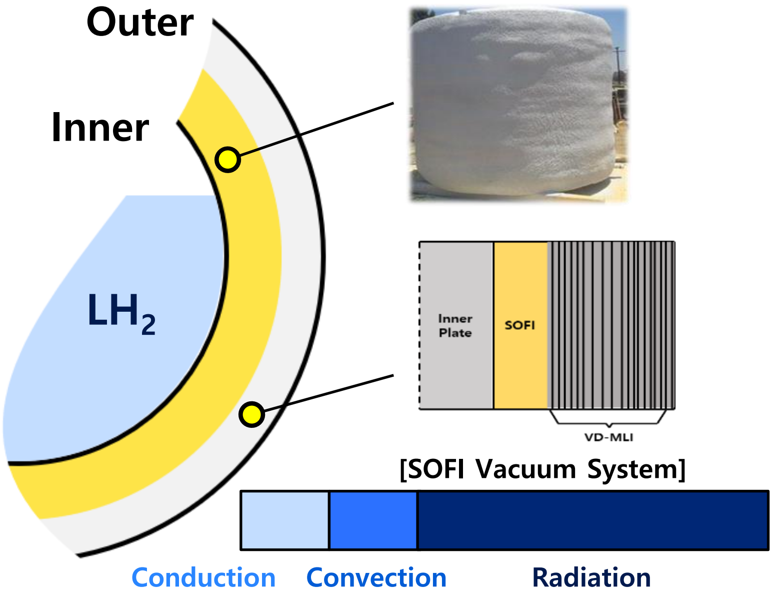


Vacuum Insulation

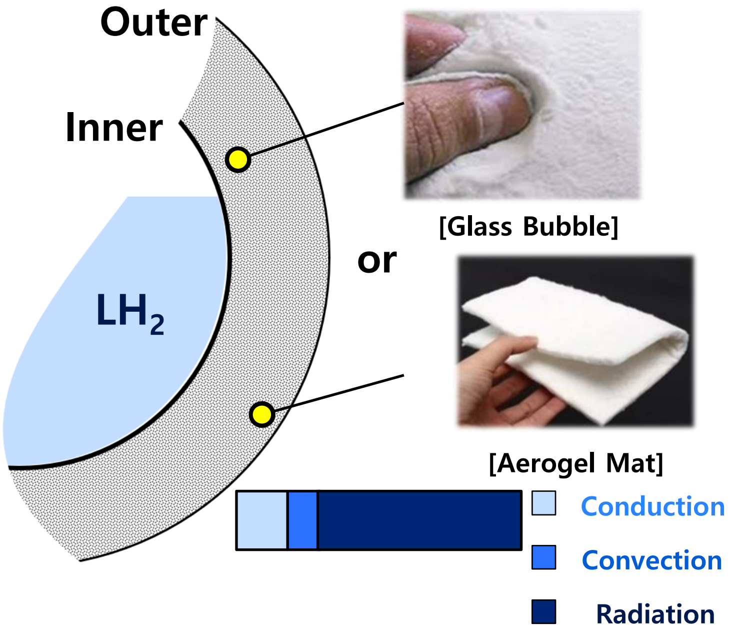
Polyurethane Spray foam

INTRODUCTION

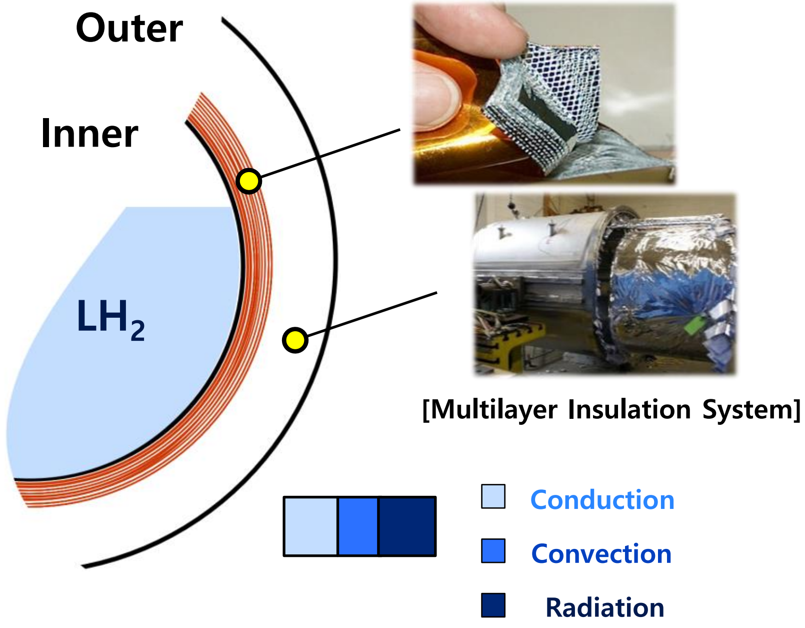
Low Vacuum System



Mid Vacuum System



High Vacuum System



Option 1. Low Vacuum System

❖ **Vacuum Pressure : 1000 millitorr <**
❖ **Effective Thermal Conductivity : 10mW/m-K**
❖ **SOFI + Vacuum Insulation System**

- Spray on the foam insulation + MLI system
- Prevent conduction with polyurethane foam
- Advantages for large size due to low vacuum

Option 2. Mid Vacuum System

❖ **Vacuum Pressure : 1 – 1000 millitorr**
❖ **Effective Thermal Conductivity : 1mW/m-K**
❖ **Filler + Vacuum Insulation System**

- MAT and powder type material as inner filler
- Radiant heat shielding effect by the material itself
- High thermal insulation performance at low vacuum

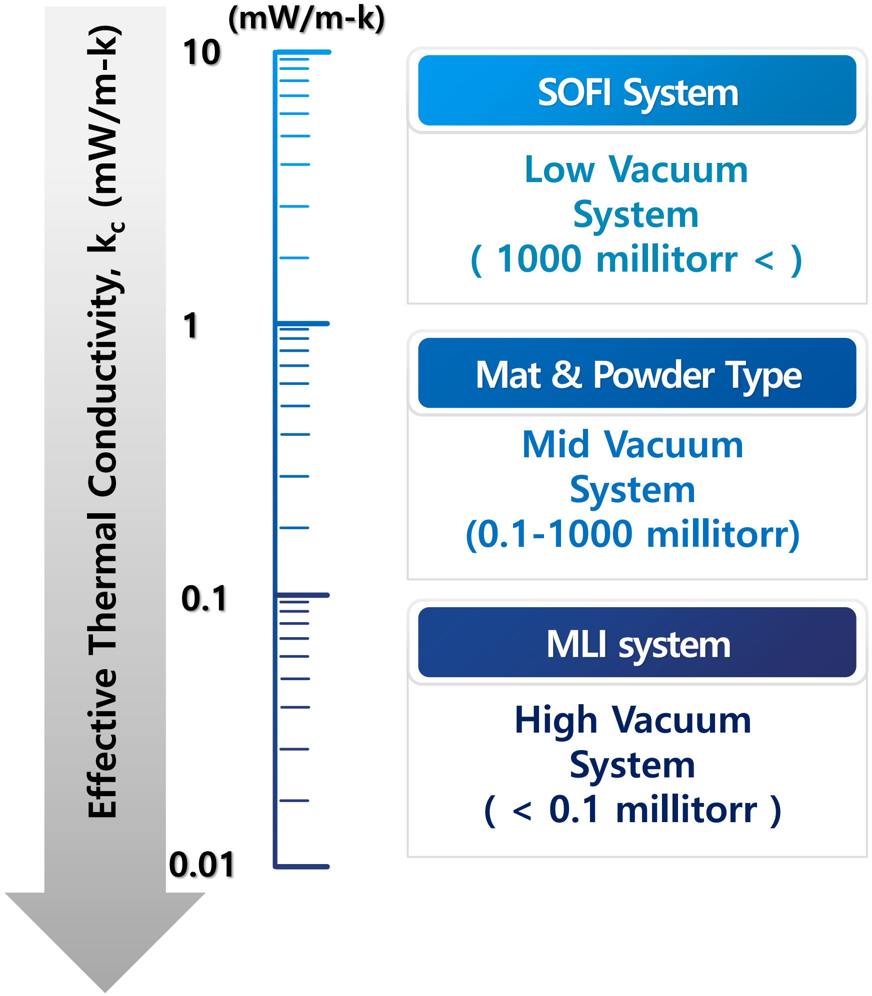
Option 3. High Vacuum System

❖ **Vacuum Pressure : < 1 millitorr**
❖ **Effective Thermal Conductivity : 0.1mW/m-K**
❖ **MLI + Vacuum Insulation System**

- Highest thermal insulation performance
- Prevent conduc. and convec. heat by high vacuum
- Suitable for small and medium LH_2 storage tank

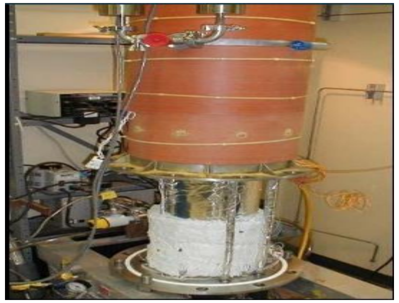
INTRODUCTION

- ✓ High vacuum system is the best in terms of thermal conductivity, but exist limitation of technology & expense cost
- ✓ Applying the low - medium vacuum system for ships cargo tank is realistic in large amount of LH2 storage



Method	Type	Sample	Delta Temp	Temp Range (K)	k-value (mW/mK)	Heat Flux Range (W/m^2)
ASTM C518	Comparative, Heat Flow Meter	Flat, square	Small	273 to 383	5 to 500	---
ASTM C177	Absolute, Guarded Hot Plate	Flat, disk	Small	93 to 773	14 to 2000	---
ASTM C745	Absolute, Boil off Calorimeter	Flat, disk	Large	250 to 670	---	0.3 to 30
Cryostat-1	Absolute, Boil off Calorimeter	Cylindrical	Large	77 to 350	0.03 to 30	0.8 to 120
Cryostat-2	Comparative, Boil off Calorimeter	Cylindrical	Large	77 to 350	0.1 to 50	2 to 400
Cryostat-4	Comparative, Boil off Calorimeter	Flat, disk	Large	77 to 350	0.5 to 80	6 to 900

➡ ASTM C1774


Cryostat-1


Cryostat-2


Cryostat-4

INTRODUCTION

✓ **Specimen Type**

Cylindrical

- Sample type : Film, Powder, Foam

$$k_e = \frac{Q\ln(\frac{d_0}{d_i})}{2\pi L_e \Delta T}$$

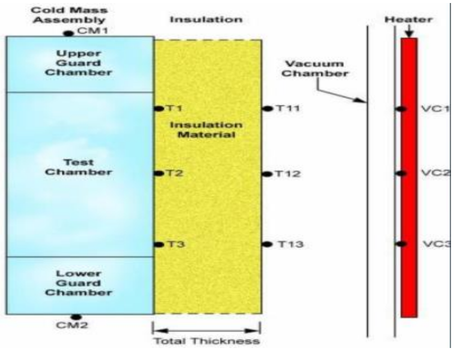
Spherical

- Sample type : Powder

$$k_e = \frac{Qx}{\pi d_0 d_i \Delta T}$$

Cryostat-1

Cryostat-2



Flat Plate

- Sample type : Film, Powder, Foam

$$k_e = \frac{4Qx}{\pi d_e^2 \Delta T}$$

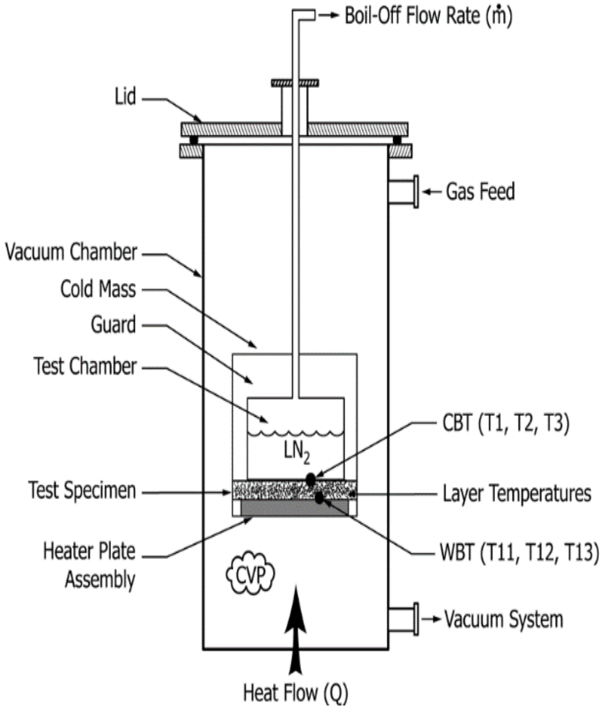
※ Calculated heat flow rate (Q)

$$Q = V_{gSTP}\rho_{gSTP}h_{fg}\frac{\rho_f}{\rho_{fg}}$$

Nomenclature

Symbol	Description	Unit
V_g	Volumetric Flow Rate of Gas	m^3/s
P_g	Density of Gas	Kg/m^3
H_{fg}	Heat of Vaporization	J/g
X	Insulation thickness	m
d_e	Diameter, effective heat transfer	m
ΔT	Temperature difference (WBT-CBT)	K
Q	Heat flow rate	W

Cryostat-4



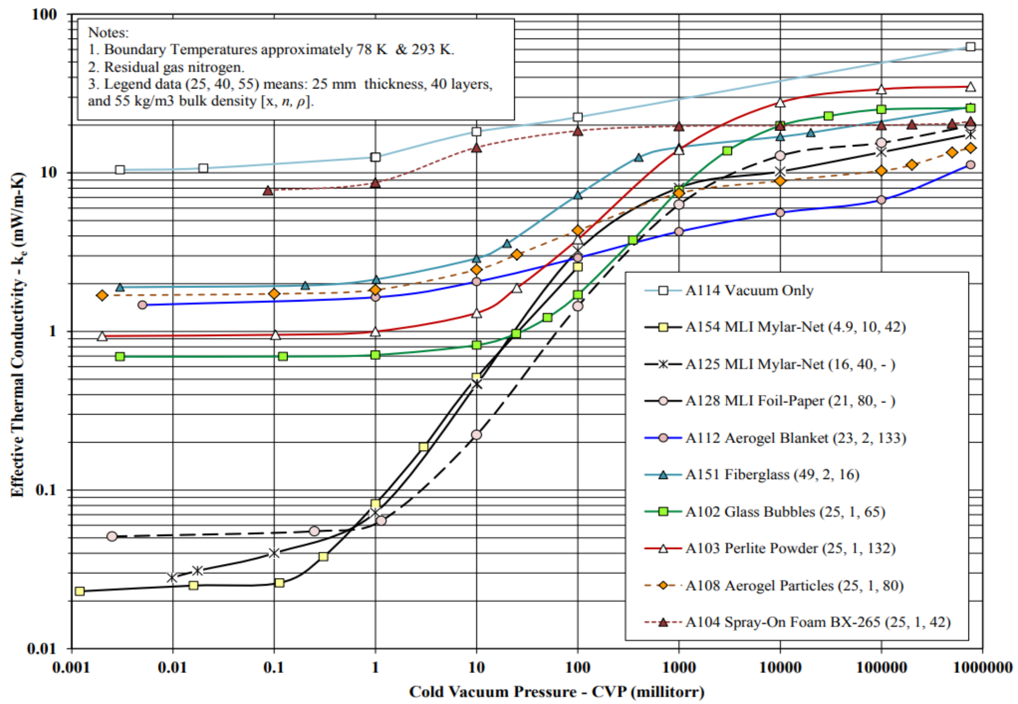
Method by C1774

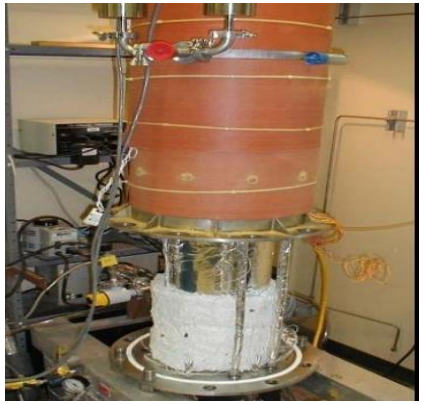
TEST SCENARIO

- ✓ Verification of Previous studies for data of manufacturing facility
- ✓ High Vacuum application material : MLI, Glass Bubble
- ✓ Medium vacuum application materials : MLI, Glass Bubble, Aerogel Blanket
- ✓ Low vacuum application materials: Glass Bubble, Aerogel Blanket

Classification		Insulation	Deg. of vacuum	Keff (mW/mK)
Vacuum	High vacuum	MLI	0.001	0.023
		Vacuum only	0.003	10.44
		Glass bubble	0.003	0.69
	Soft vacuum	MLI	1	0.082
		Vacuum only	1	12.52
		Glass bubble	1	0.71
		Aerogel blanket	1	1.64
No-Vacuum		Vacuum only	760000	62.37
		Glass bubble	760000	25.61
		Aerogel blanket	760000	11.24

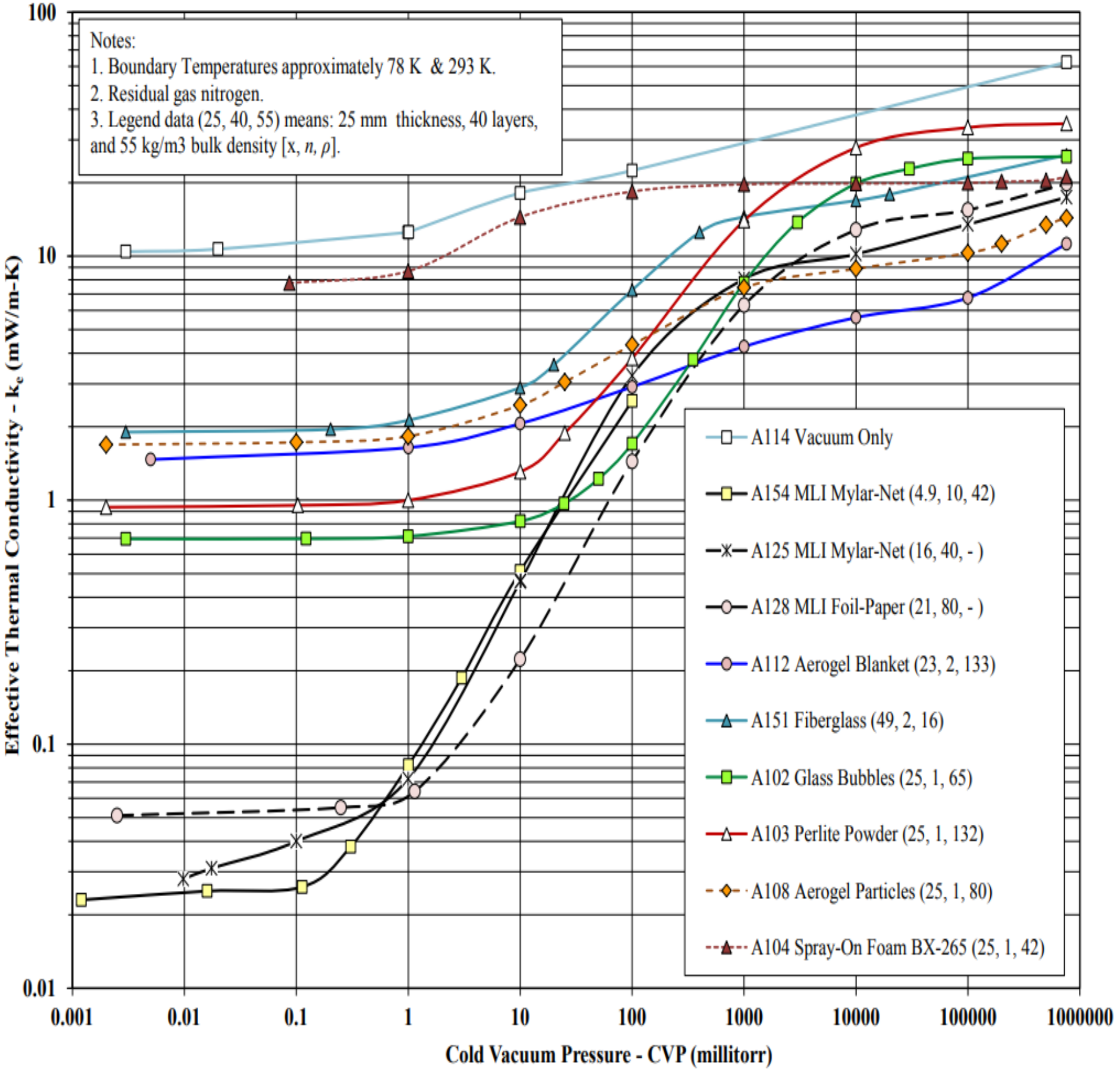
(Fesmire, 2015)



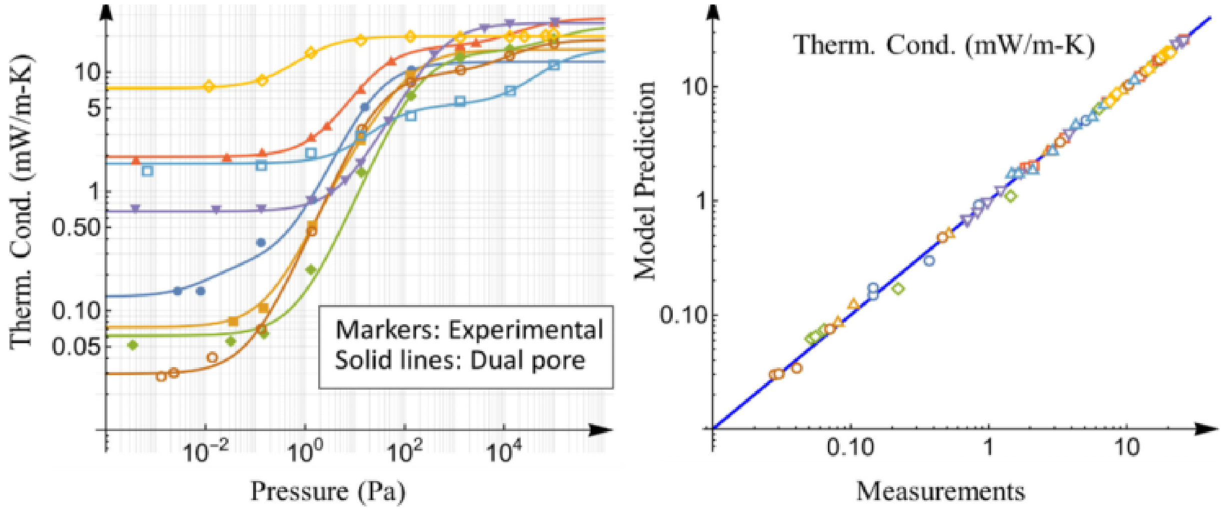


INTRODUCTION

(Fesmire, 2015)



Thermal conductivity for various material and fitted results

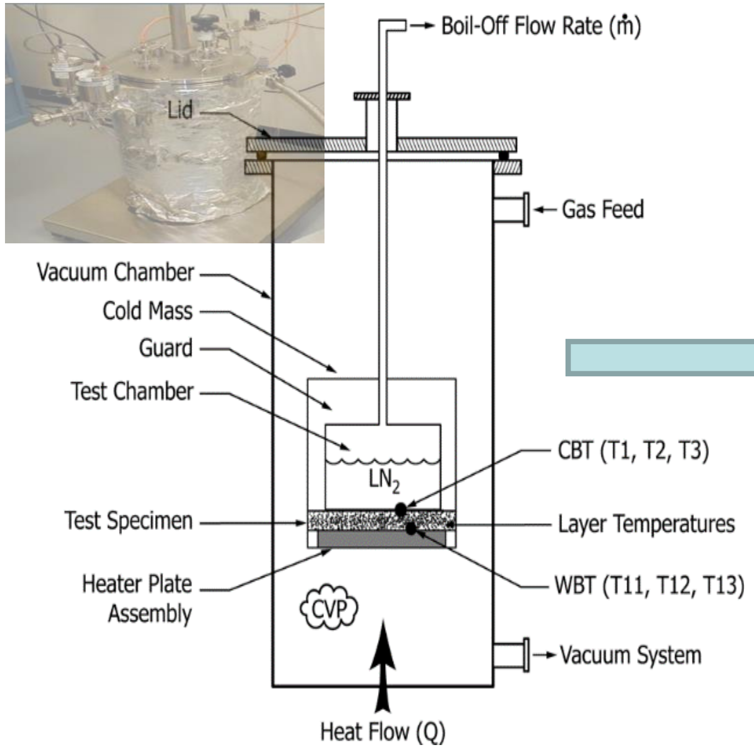


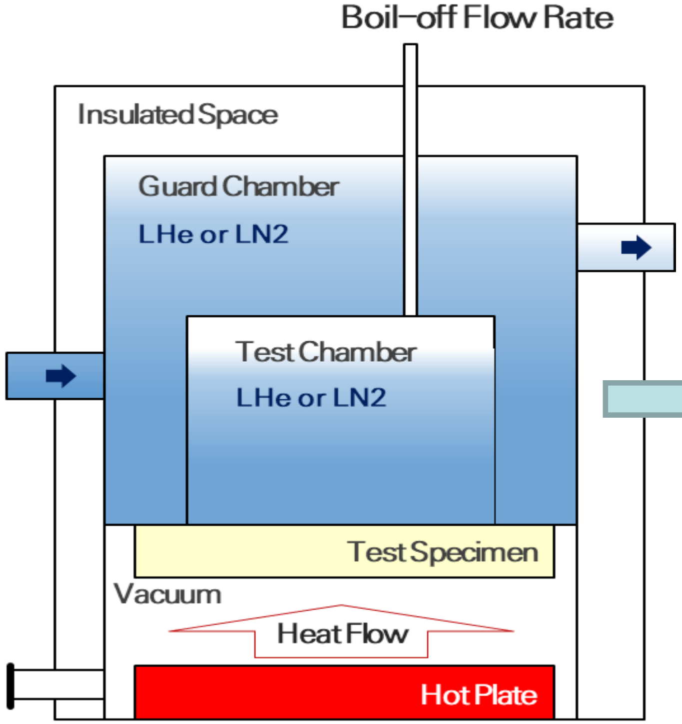
15 Layers Fabric/Foil (18.7mm)	$k_{e,\text{fabric}} = 0.13 + \frac{0.1P}{P+0.02} + \frac{11.9P}{P+23.5}$
40 Layers MLI (22.3mm)	$k_{e,\text{MLI40}} = 0.07 + \frac{1.9P}{P+8.8} + \frac{13.4P}{P+105.0}$
MLI Foil Paper (21,80)	$k_{e,\text{foil}} = 0.06 + \frac{14.8P}{P+179.3} + \frac{9.4P}{P+120165}$
Fiber Glass (49,2,16)	$k_{e,\text{FG}} = 1.95 + \frac{14.5P}{P+22.2} + \frac{11.8P}{P+23499}$
Glass Bubbles (25,1,65)	$k_{e,\text{GB}} = 0.68 + \frac{1.3P}{P+39.8} + \frac{23.7P}{P+398.4}$
MLI Mylar − Net (16,40)	$k_{e,\text{MLInet}} = 0.03 + \frac{9.8P}{P+28.4} + \frac{8.7P}{P+16528}$
Aerogel Blanket (23,2,133)	$k_{e,\text{AB}} = 1.7 + \frac{3.6P}{P+33.8} + \frac{10.3P}{P+70535}$
Spray − On Foam BX − 265 (25,1,42)	$k_{e,\text{SOF}} = 7.3 + \frac{12.6P}{P+1}$

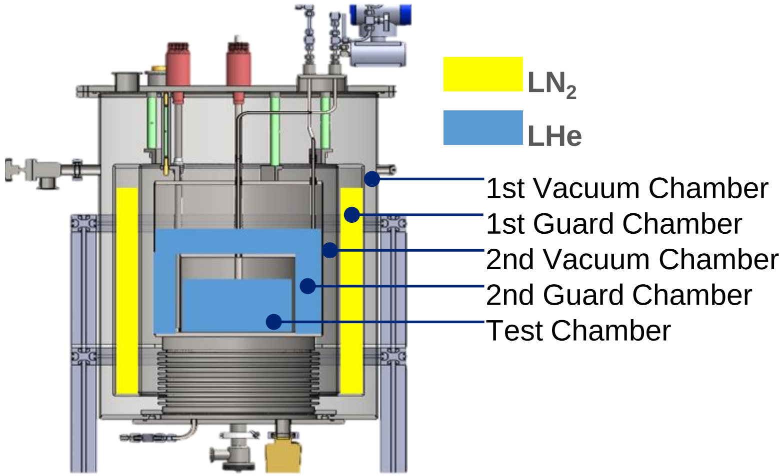
(Ram, 2023)

TEST PROCEDURE

TEST APPARATUS







Equation of K_{eff}(ASTM C1774)

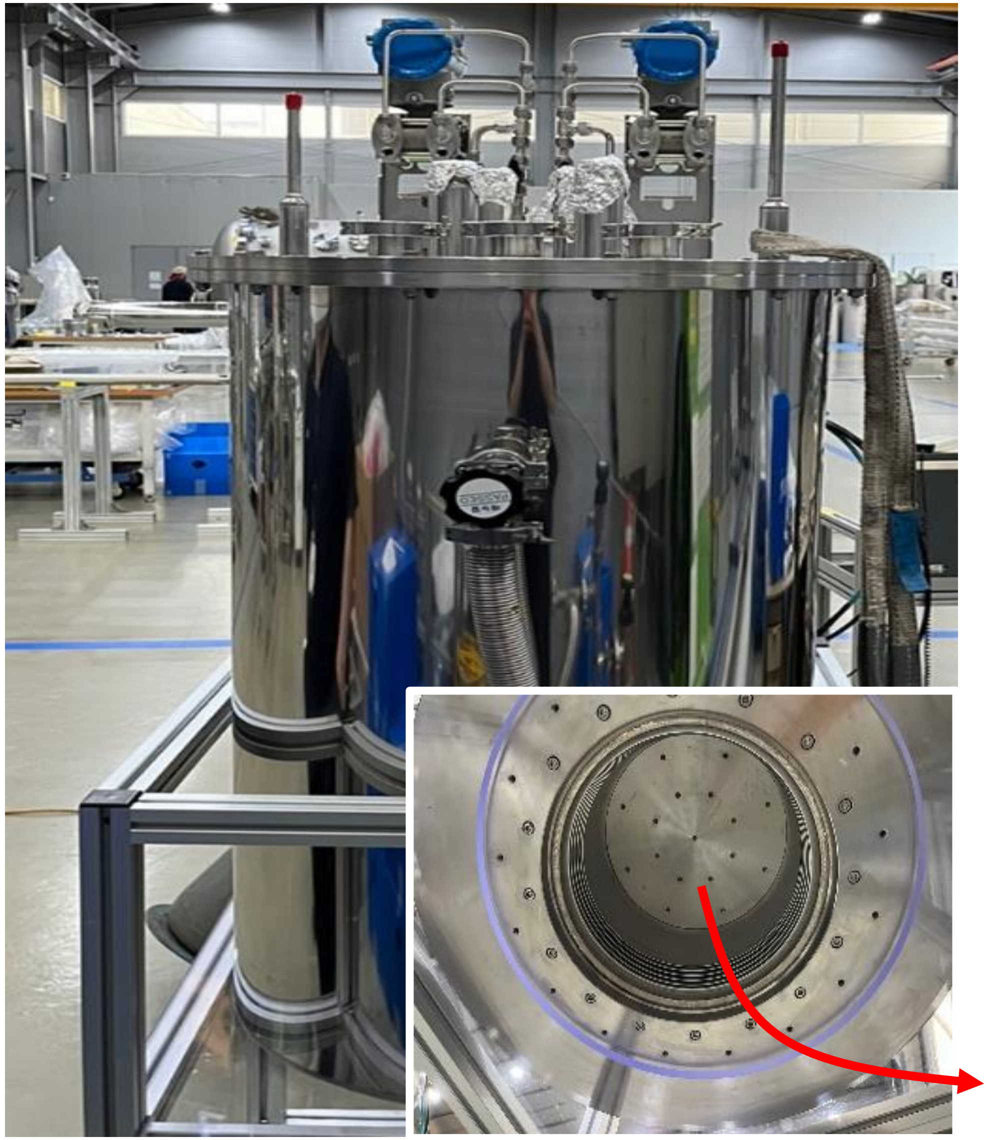
$$Q = V_{gSTP}\rho_{gSTP}h_{fg}\left(\frac{\rho_f}{\rho_{fg}}\right)$$

$$k_e = \frac{Q\ln((d_i+2x)/d_i)}{2\pi L_e \Delta T}$$

Method by C1774 (Cryostat) – Flat plate

- Mounting part of thermal insulation test specimen : Atmospheric to 10-5 torr pressure environment implementation
- Measuring and analyzing thermal insulation performance at wider temperature range (4K to 293K) than existing temperature (78K to 293K) in NASA Data
- Calculate effective thermal conductivity (k_e) by measuring heat flux (Q) according to temperature gradient through cold and hot plates

TEST APPARATUS

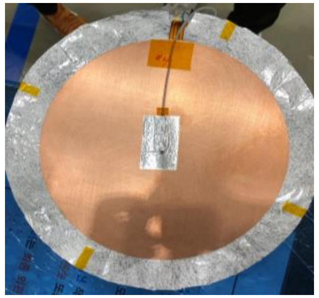


- ✓ Dimension of specimen : diameter (280 mm~ 300mm) / thickness (max. 100mm)
- ✓ Applied filling material: MLI (RUAG 社, Polyester foil) / Glass Bubble(3M 社, K1) / Aerogel Mat
- ✓ In case of glass bubble powder, sample container is prepared for specimen mounting

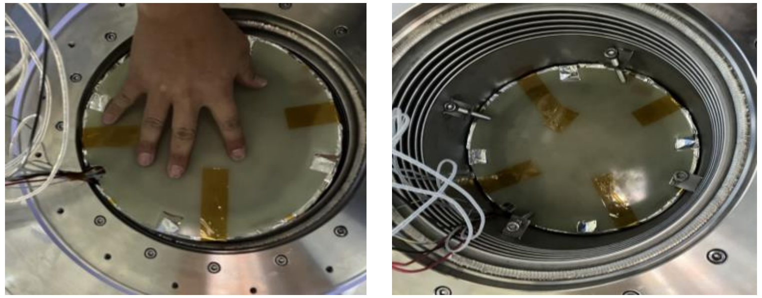
MLI & Aerogel Mat

MLI

Aerogel Mat

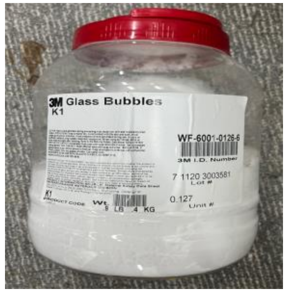


Heat fulx sensor



Specimen installation

Glass Bubble

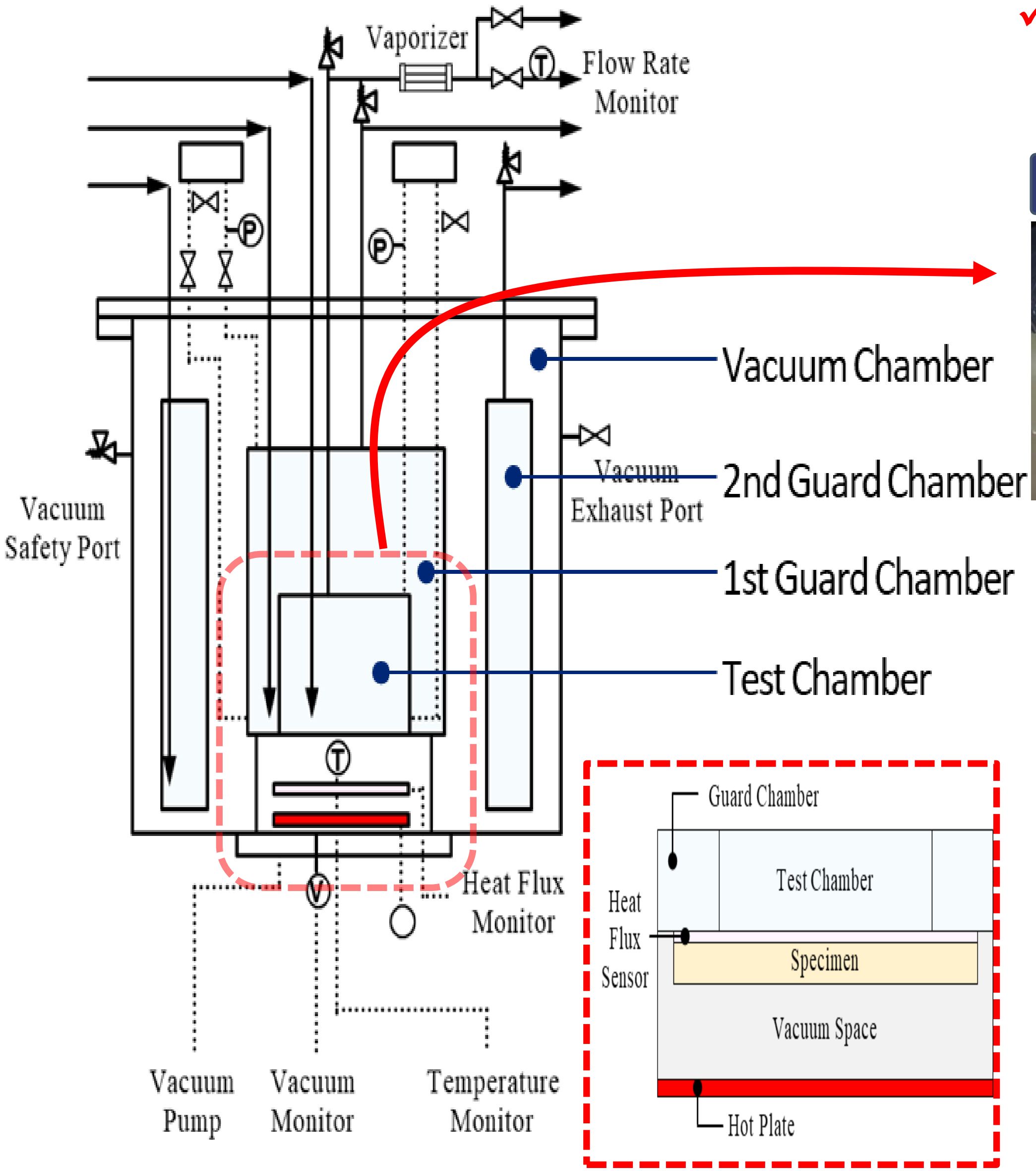


Glass bubble

Filter

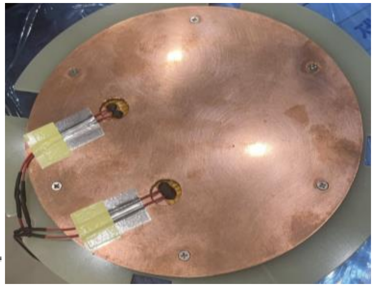
Sample container with glass bubble

TEST APPARATUS

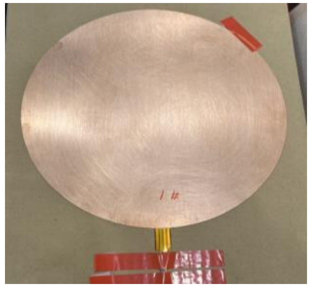


- ✓ Main Sensor : Heat Flux Sensor, Flow meter, Temp. sensor, Differential press. sensor, Vacuum sensor

Sensor & Part

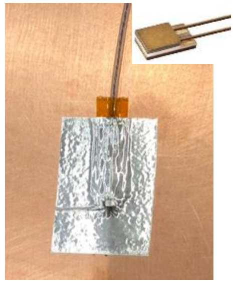


Hot plate



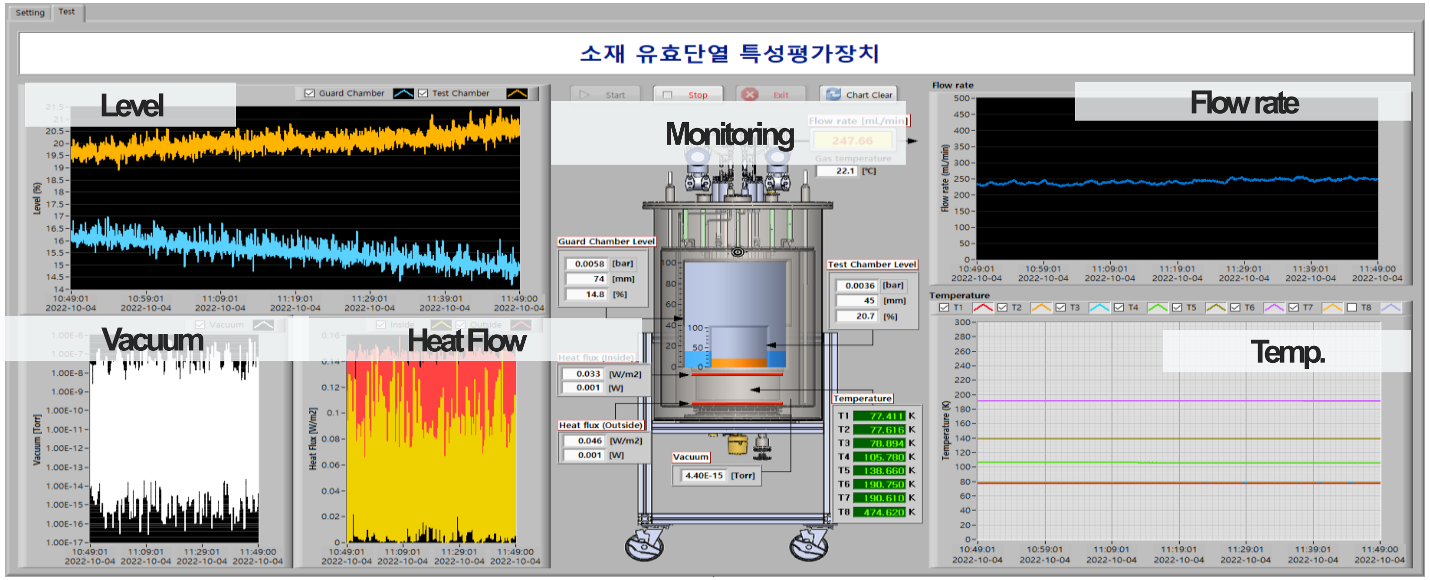
Heat flux sensor

Flow meter



Temp. sensor

Differential press. sensor

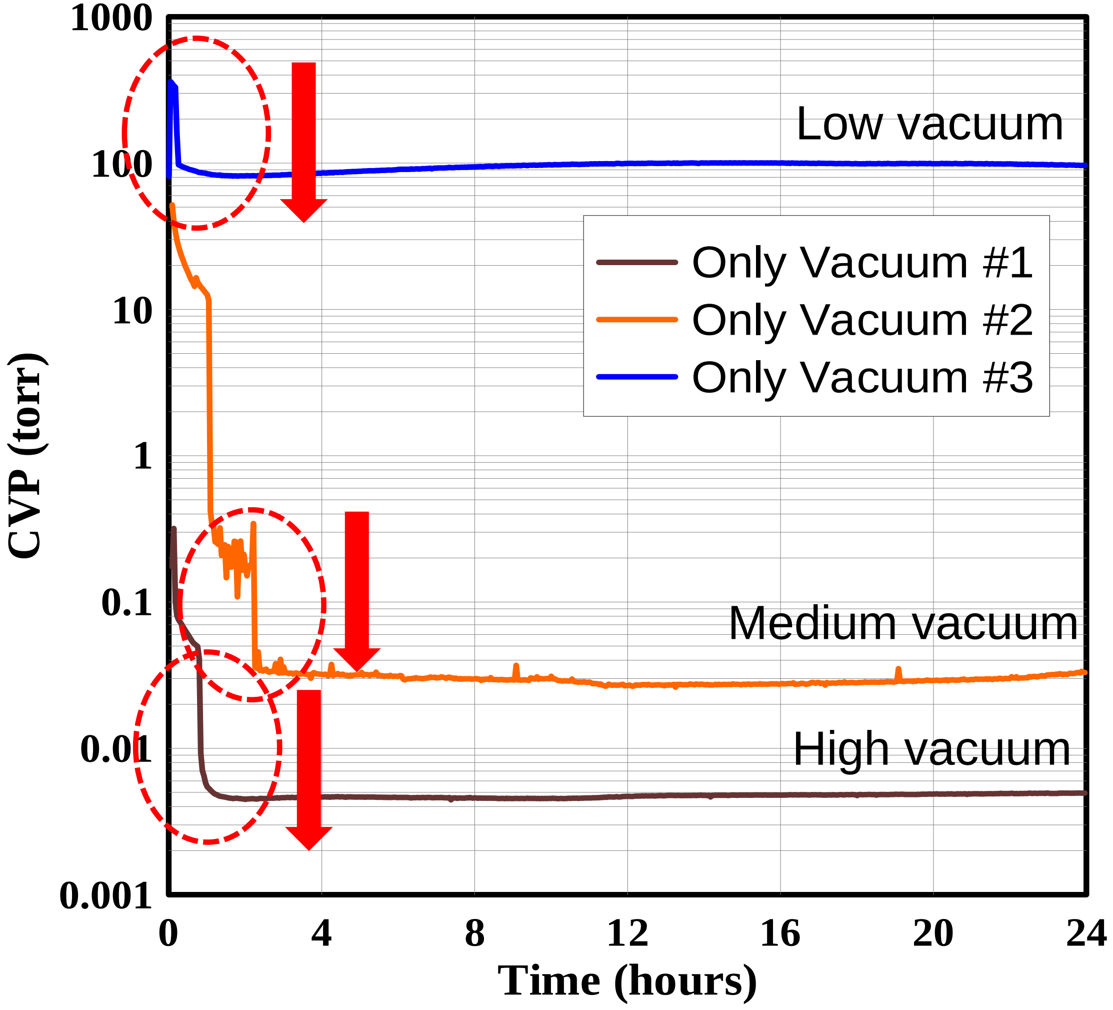


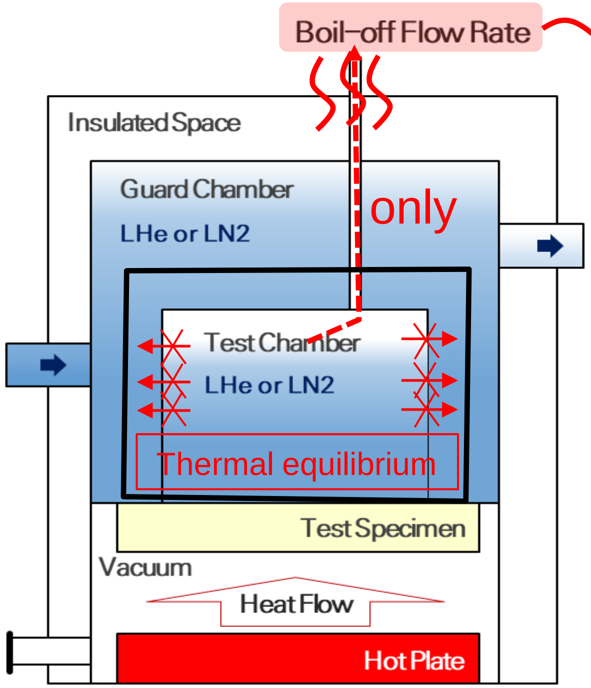
TEST RESULT

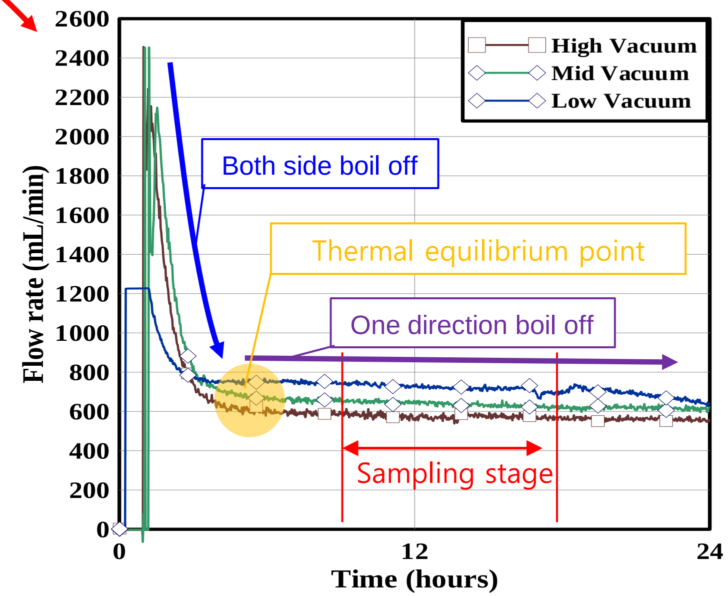
Results and Discussion

- ✓ Vacuum deterioration due to lowering molecular motion of the remaining air inside when LN2 is injected
- ✓ Through vacuum pumps and oil diffusion pumps, implement various Cold Vacuum Pressures (CVPs)
- ✓ In the condition of CVP, measure heat flow rate Q and calculate k_{eff} for applied filling materials

Cold Vacuum Pressure (CVP)



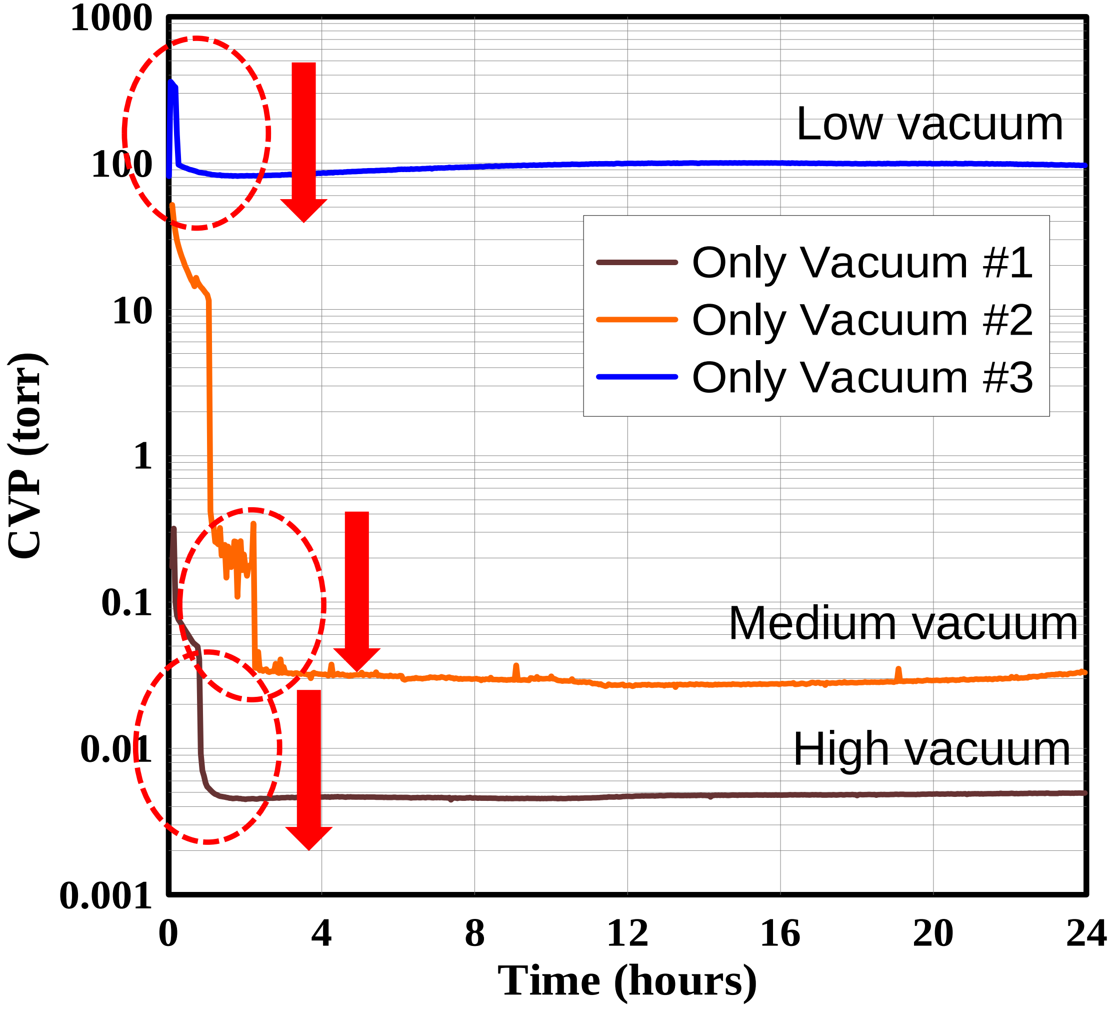




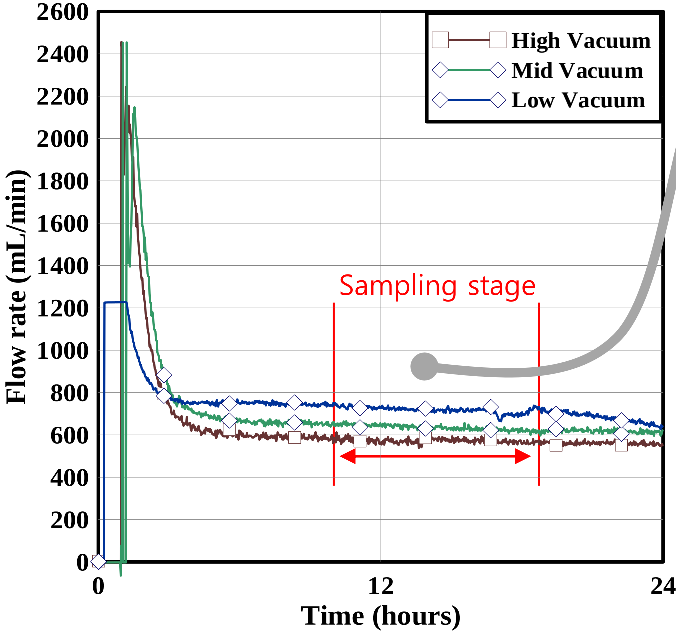
Flow rate time history of Vacuum Only

Results and Discussion

Cold Vacuum Pressure (CVP)



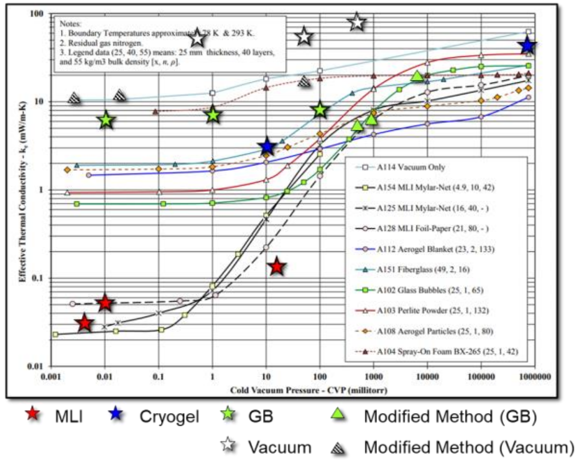
- ✓ Vacuum deterioration due to lowering molecular motion of the remaining air inside when LN2 is injected
- ✓ Through vacuum pumps and oil diffusion pumps, implement various Cold Vacuum Pressures (CVPs)
- ✓ In the condition of CVP, measure heat flow rate Q(=heat leakage) and calculate k_{eff} for applied filling materials



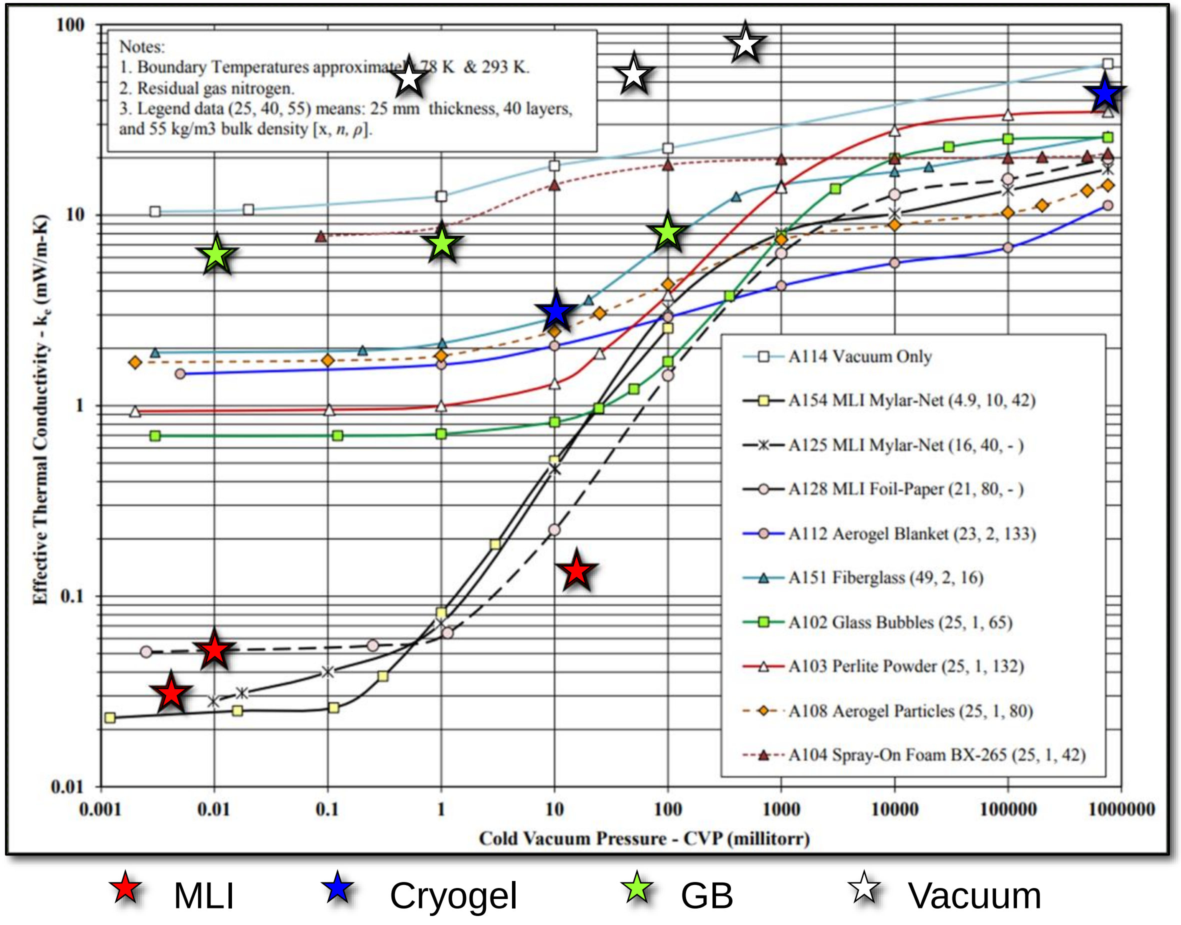
Flow rate time history of Vacuum Only

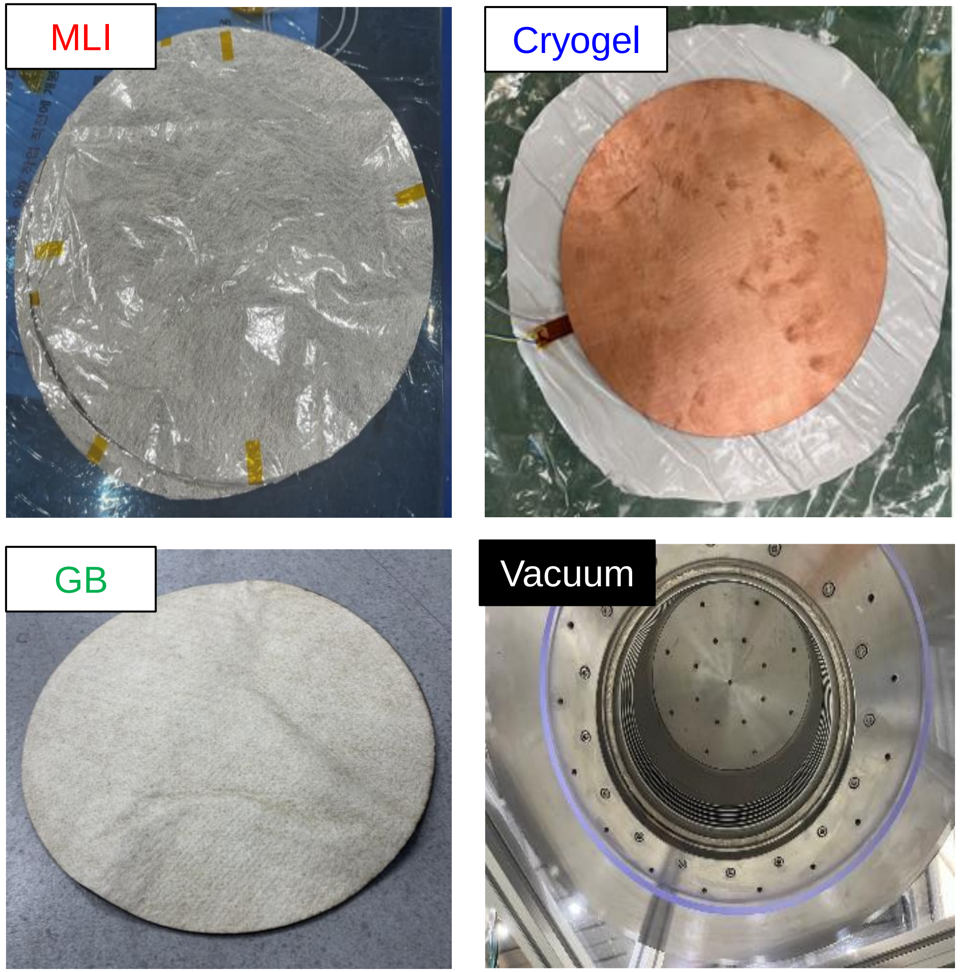
$$Q = (mass\ flow\ rate)(h_{fg})$$

$$k_e = \frac{Q \ln((d_i + 2x)/d_i)}{2\pi L_e \Delta T}$$



Results and Discussion



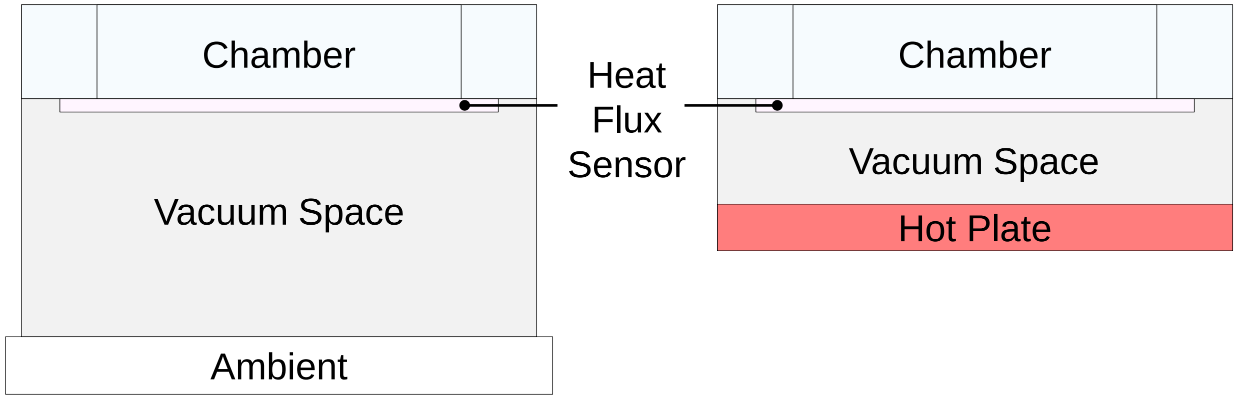


✓ Verification of comparison with previous research NASA data through only vacuum results

✓ Additional verification for MLI, Powder, Mat Type specimen

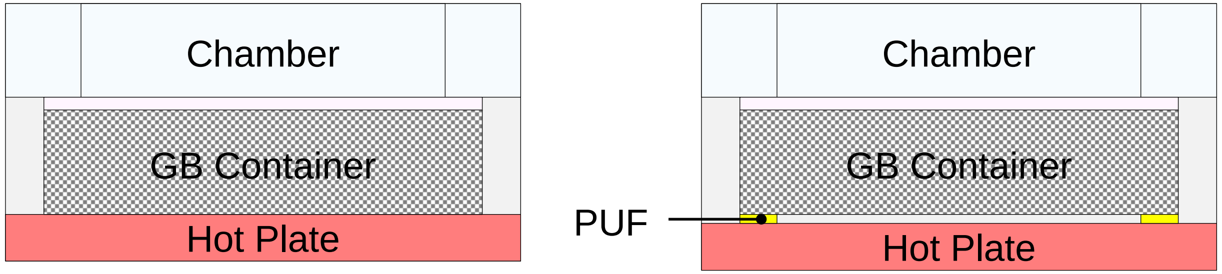
Results and Discussion

Modified Only Vacuum

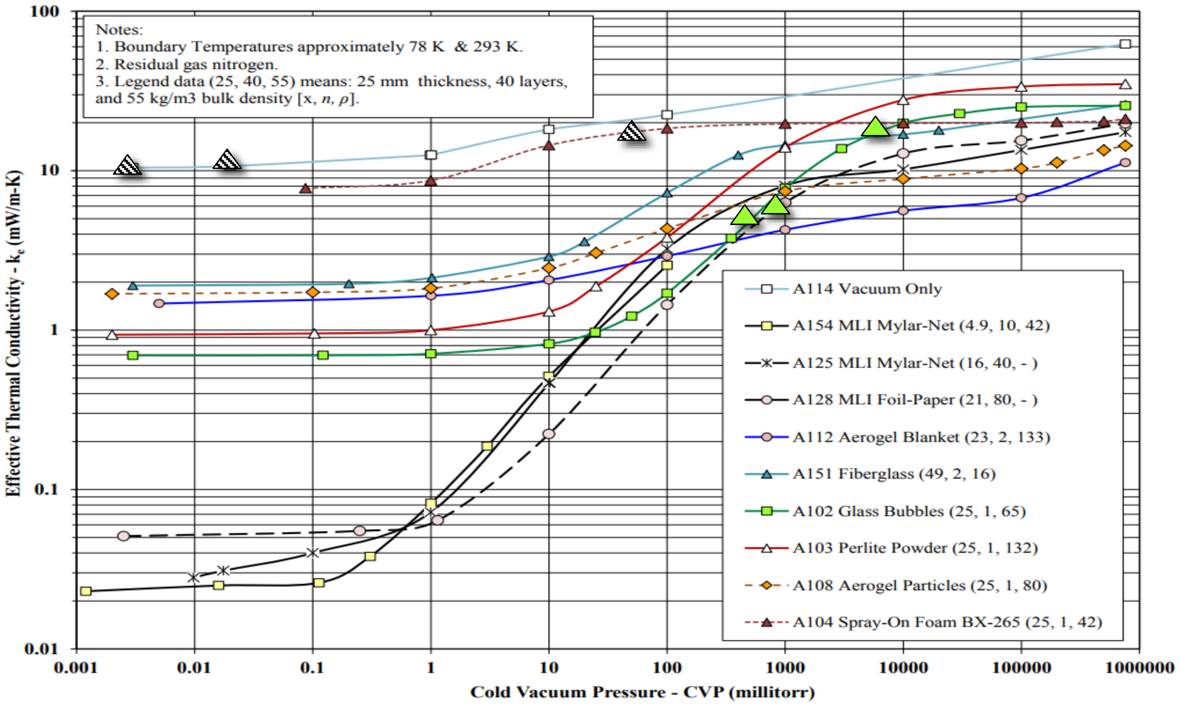


Atmospheric exposure of specimen mounting part → Control Hot plate installation

Modified Glass Bubble



Hot Plate, Container contact → Keeping separation to block direct heat transfer conduction



Modified Method (GB) Modified Method (Vacuum)

Specimen	Vacuum Only			GB	
Vacuum (mtorr)	0.0034	0.0262	81.35	1583.46	496.84
Flow rate (mL/min)	597	637	735	1040	261
Ke (mW/mK)	11.608	12.386	14.282	20.930	5.252

Results and Discussion

Conclusion

- ✓ In this study, a cryogenic effective thermal conductivity evaluation facility was designed for the liquid hydrogen storage.
- ✓ To validate the data of the evaluation facility, the effective thermal conductivity was measured and verified for various filling materials in an environment similar to that of liquid nitrogen in a similar existing facility.

Future work

- ✓ Conduct evaluation of effective thermal conductivity for the complex composite insulation system.
- ✓ Acquire effective thermal conductivity data below 77K. (Liquid helium at 4K)
- ✓ Validate the existing predictive model for effective thermal conductivity.

Thank you for your attention