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Development of a new MLI for orbital cryogenic propulsion systems - thermal performance under one atmosphere to a vacuum

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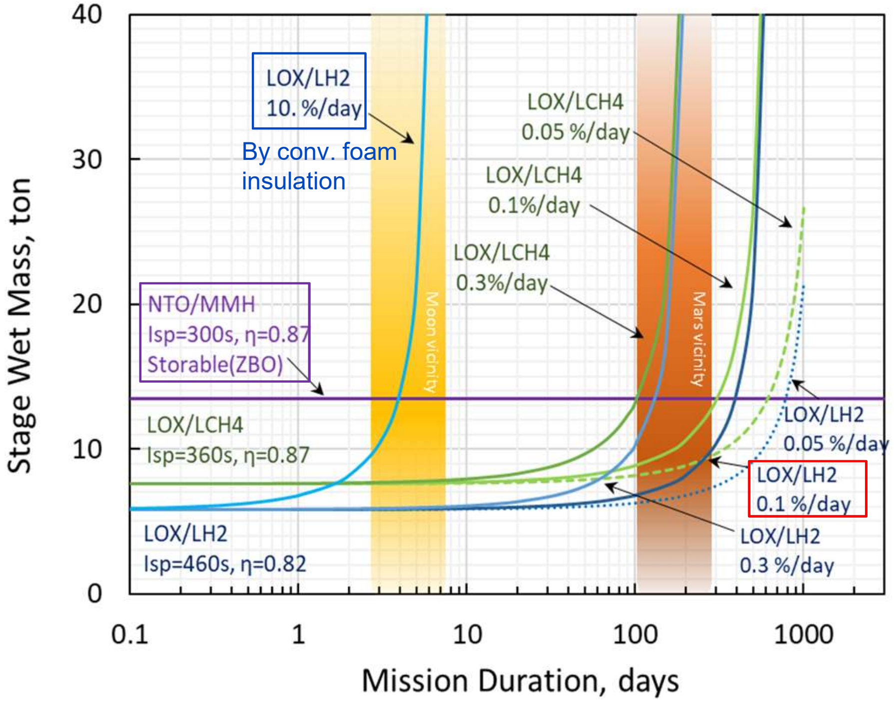
Contents

1 Introduction

- The efficient storage of cryogenic propellants is among the key technologies for long-duration space exploration missions.
- For the orbital transfer vehicle, required thermal insulation performance is more than ten 10 times higher than that of conventional spray-on foam insulation.



Stage wet mass of reference mission
(Δv=2km / payload=2ton)

- **Storable propellant is adopted**
  - Zero boil-off
  - Small specific impulse
  - ➡ Large and heavy system

- **Cryogenic propellant is adopted**
  - High boil-off rate
  - Large specific impulse
  - ➡ The boil-off of propellant must be reduced..

- **Purpose of the study**

  To develop high-performance insulation applicable to orbital transfer vehicle.

2-1 Conventional insulations and Previous research

Conventional insulations

- A spray-on foam insulation is currently used in rocket fuel tank and it is usable both in vacuum and under 1 atmosphere.
- Multi-Layer Insulation (MLI) are the most efficient thermal insulation element in space vacuum environment.
  Conventional MLI does not perform under pressure and is inferior to existing foam insulation.

	Spray-on foam insulation	Conventional MLI
Insulation performance under vacuum	**good**	**excellent**
Insulation performance under 1 atm	**good**	**unavailable**

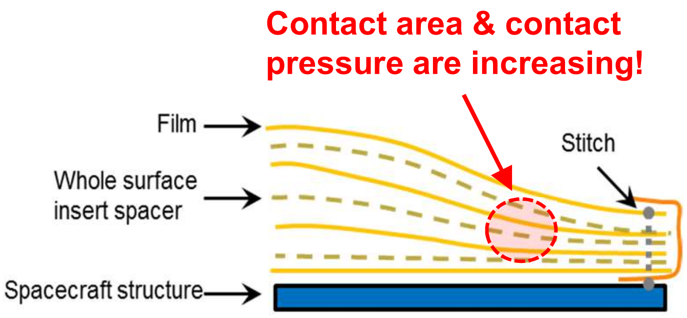
2-2 Conventional insulations and Previous research

Drawbacks of conventional MLI

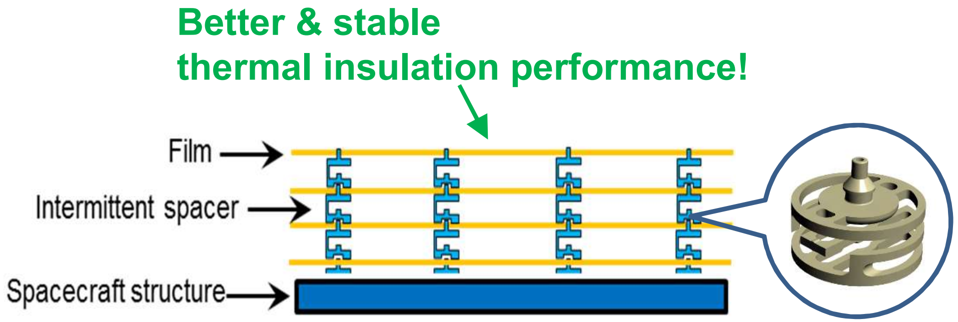
- Netting spacers of conventional MLI are not able to prevent interlayer-contacts between film and netting spacer completely.
- Thermal insulation performance depends on mounting arrangements on spacecraft and easily degrade because the conductive heat leak through MLI depends on the degree of interlayer contact.

Previous research of new MLI for vacuum use

- A new type of spacer, non-interlayer-contact spacers (NICS) has been developed.
- While conventional spacers such as netting spacers are inserted in the whole surface layer, these new spacers are intermittently arranged and hold up the film to exclude any incidental interlayer contact.
- The thermal insulation performance of NICS MLI is superior to conventional MLI and is easily estimated.



Conventional MLI



NICS MLI, previous research

2-3 Concept of LB-NICS MLI

■ Concept of Load Bearing NICS MLI

⇨ Vacuum pack the NICS-MLI developed in the previous research!

■ Improvements from NICS-MLI

① The spacer is strengthen to withstand 1 atmosphere load.

② The outer layer (CFRP) shell is added to prevent the contact of the inner radiation film by compressing to the outermost layer.

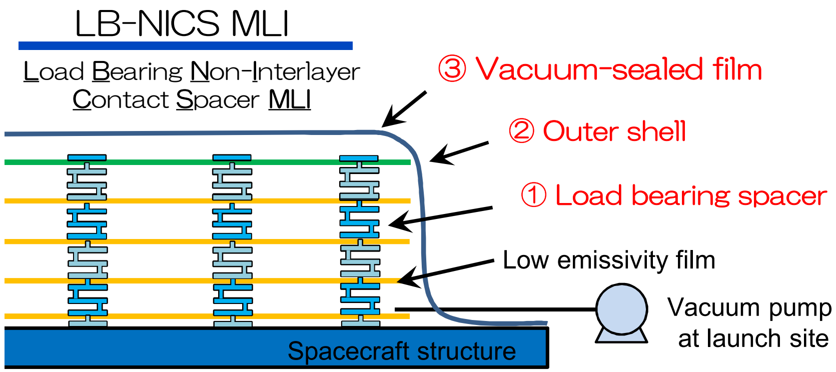
③ Thin film (vacuum-sealed film) covering the whole of insulation is added and inside of insulation is evacuated.

■ Advantage of LB-NICS MLI

① In the launch site under pressure, the inside of the insulation layer is maintained in vacuum, and perform as thermal insulation.

② Because pressure difference between inside and outside occurs, the insulation is compressed and it can withstand dynamic pressure and vibration by becoming a rigid structure.

③ Support the load intermittently with a spacer and keep the vacuum with a lightweight film so it can be lighter than covering the normal vacuum double vessel .



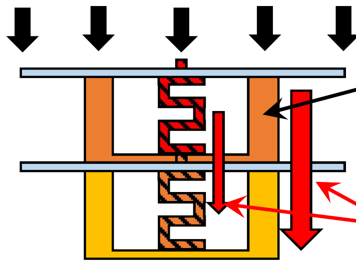
2-4 Concept of LB-NICS MLI

■Spacer design

The spacer needs to withstand a compression load of 1 atm at the launch site. Because the load path is a heat path as it is, leaving the load path as is under pressure environment during orbital navigation where compression load does not work is not a promising idea.

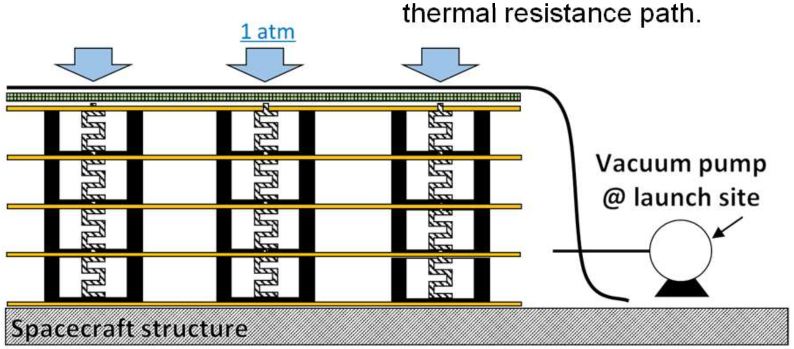
Therefore, the LB-NICS was designed so that the heat path switches at the time of compression (under pressure) and at the time of release (under a vacuum).

At the time of compression (under 1 atm)

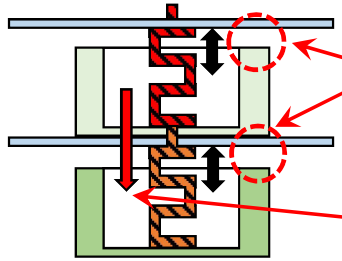


Lower outer chassis sticks up to upper part and supports the load.

The heat path is two paths of the load structure part and the inner spring-like high thermal resistance path.

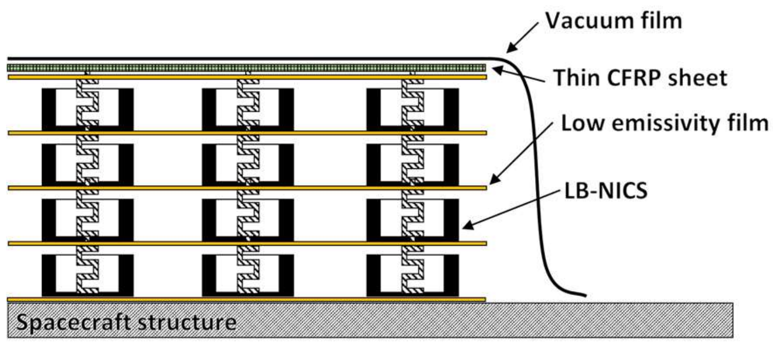


At the time of release (Under a vacuum)



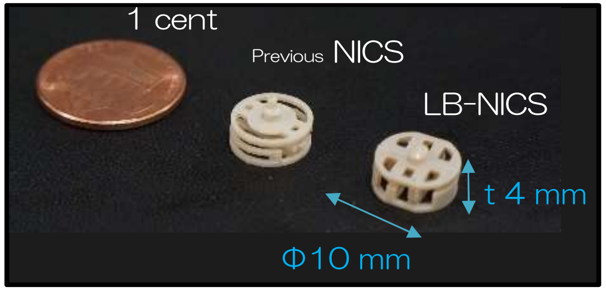
The load bearing structure is detached by the restoring force of the internal high thermal resistance path.

The heat path is only the inner high thermal resistance path.



2-4 Concept of LB-NICS MLI

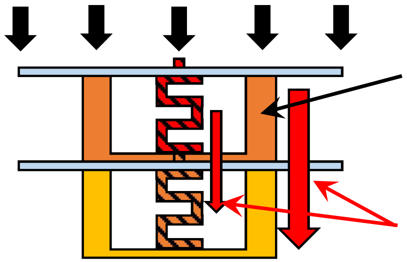
■Spacer design



Design of LB-NICS	At the time of compression (under 1 atm)	At the time of release (Under a vacuum)
The ratio of heat path length to the cross-sectional area L/A, m^{-1}	2.6×10^{2}	3.4×10^{4}

The spacer (10 mm in diameter and 4 mm in height) was molded using polyetheretherketone (PEEK) by injection molding.

At the time of compression (under 1 atm)



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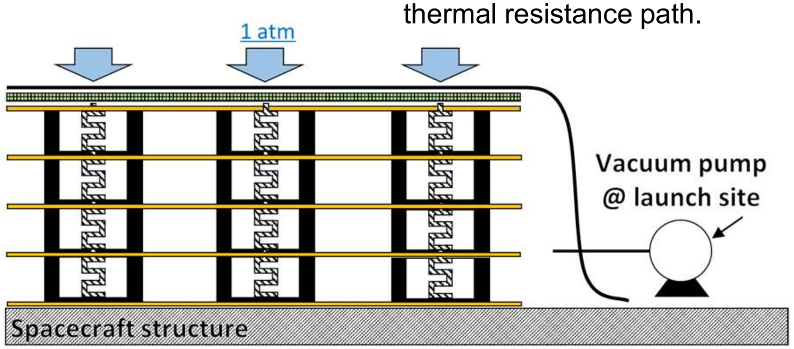
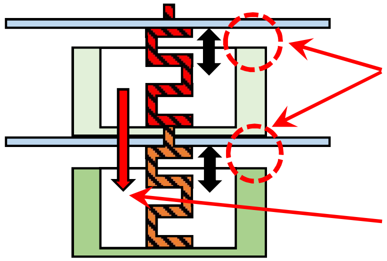
The heat path is two paths of the load structure part and the inner spring-like high thermal resistance path.

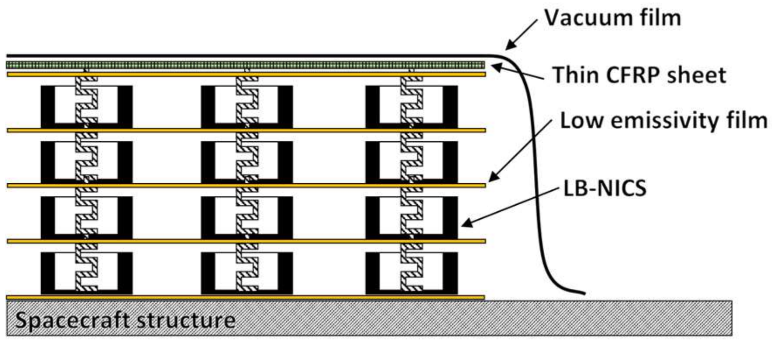


At the time of release (Under a vacuum)



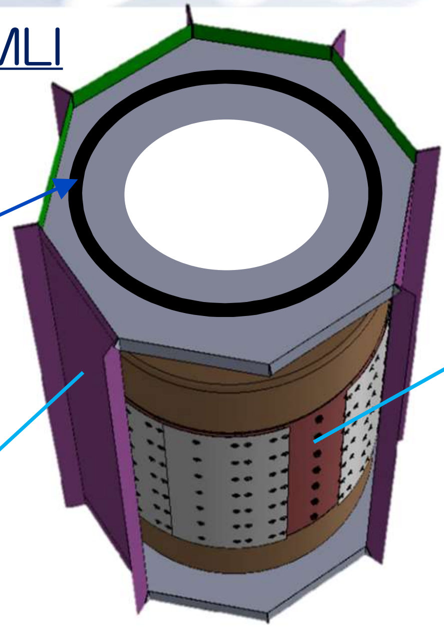
The load bearing structure is detached by the restoring force of the internal high thermal resistance path.

The heat path is only the inner high thermal resistance path.

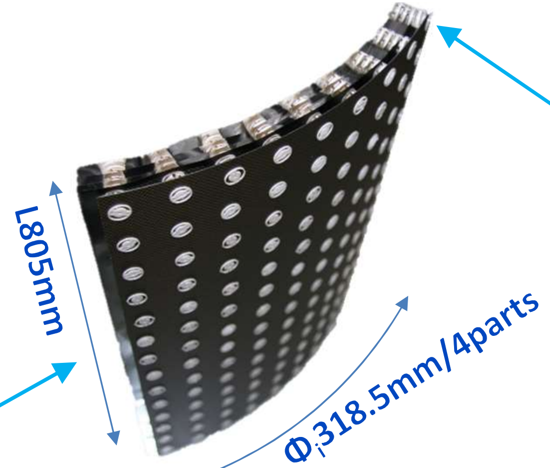


3-1 Thermal performance test

■Test piece / LB-NICS MLI



As the vacuum-sealed film, a heat laminate film containing an aluminium layer was used..



LB-NICS MLI was divided into 4 parts in the circumferential direction

The double-sided aluminum vapor deposited polyester film of 50 μm had 5 layers.

The pitch of the LB-NICS was arranged at a maximum of 50 mm and a minimum of 30 mm, and the outermost shell was made of CFRP with a thickness of 0.7 mm.

Table 3.1. Specifications of LB-NICS MLI

Low emissivity film layer	[-]	5
Low emissivity film thickness	[μm]	50
Low emissivity film surface density	[g/m^2]	71
LB-NIC spacer pitch	[mm]	30-50
Spacer surface density	[g/m^2]	400
CFRP sheet thickness	[mm]	0.7
CFRP sheet surface density	[g/m^2]	1132
Vacuum-sealed film surface density = a heat laminate film containing an aluminum layer	[g/m^2]	142
Total thickness of insulation /Non-compressed	[mm]	16
Total surface density of insulation	[kg/m^2]	2.0

3-2 Thermal performance test

■Test piece / Vacuum-packed conventional MLI

To compare the performance with LB-NICS MLI, we prepared a sample containing conventional MLI in vacuum-sealed film. The vacuum-sealed film used is the same as that used for LB-NICS MLI.
The spacer was double netting spacers.
There is a total of 21 low emissivity film layers,
and the total thickness of the insulation is 16 mm (equivalent to LB-NICS MLI).
The seam is connected at one place with interleaved lapping.

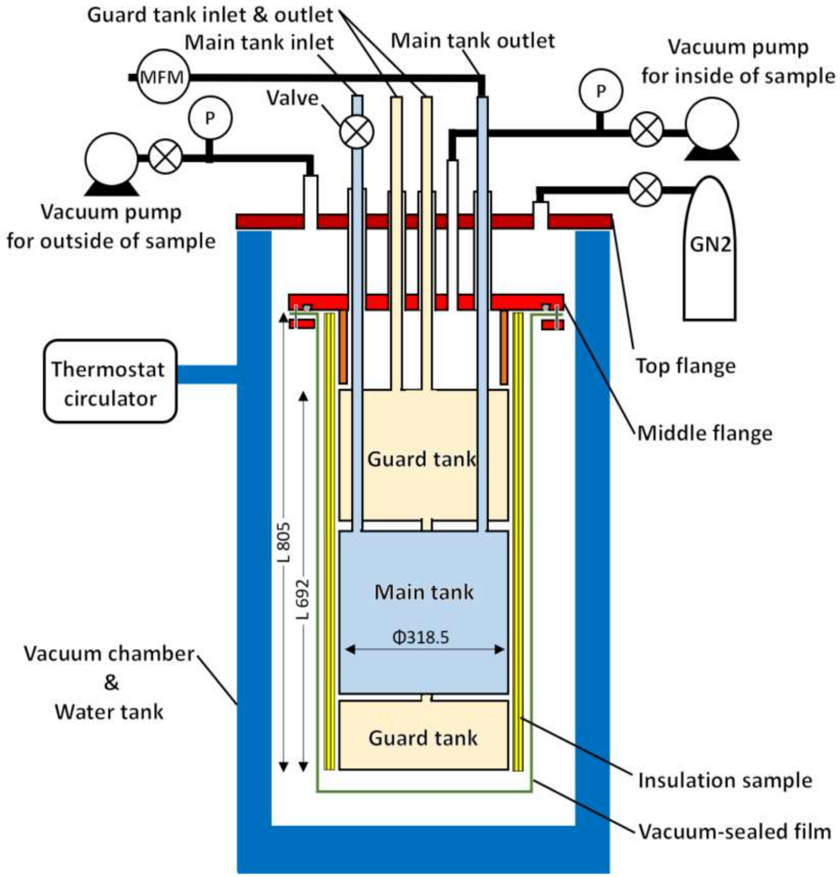
Vacuum-sealed film

Table 3.3. Specifications of vacuum-packed conventional MLI

Thickness of low emissivity film layer (outermost/inner)	μm	25/6
Low emissivity film layer	-	21
Spacer	-	double netting spacer
Spacer surface density	g/m^2	158
Total thickness of insulation	mm	16
Total surface density of insulation	kg/m^2	6.7

3-3 Measurement equipment

■Schematic of the boil-off calorimeter



■Thermal performance of insulation samples ware evaluated with **boil-off calorimeter**

▼There are 3 liquid nitrogen tanks which are covered with MLI sample in a vacuum chamber.

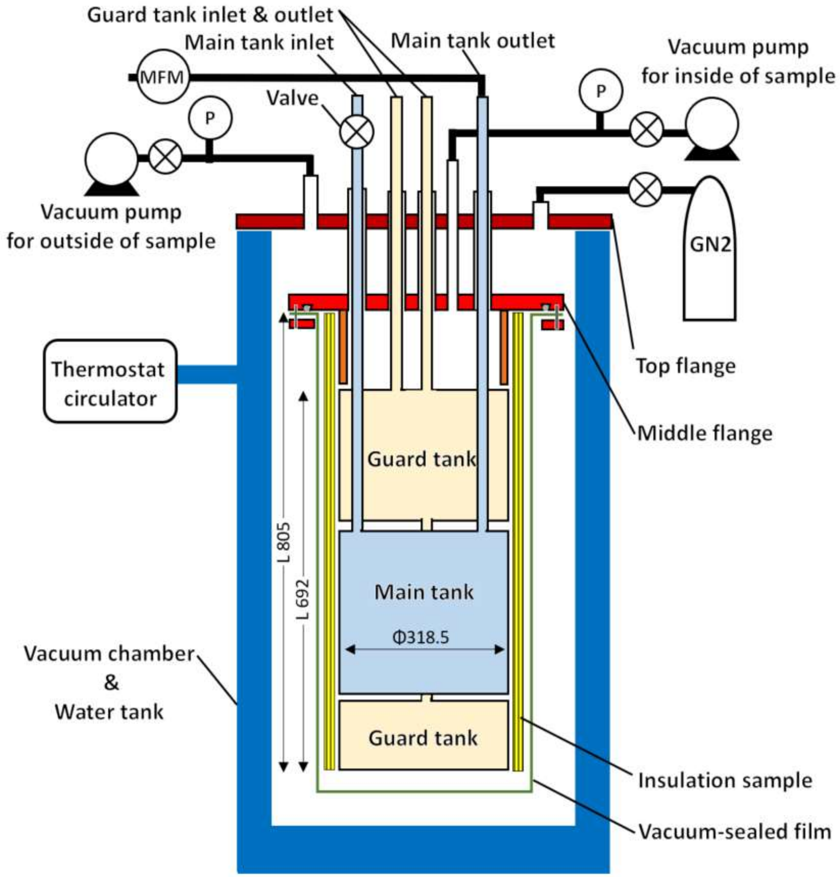
▼ The flow rate of nitrogen gas evaporated from the center tank is measured.

▼ From the latent heat of nitrogen h_{lg} and the area of tank S_{BT}, we can calculate the heat flux through the MLI.

$$q = \frac{\dot{m} \cdot h_{lg}}{S_{BT}}$$

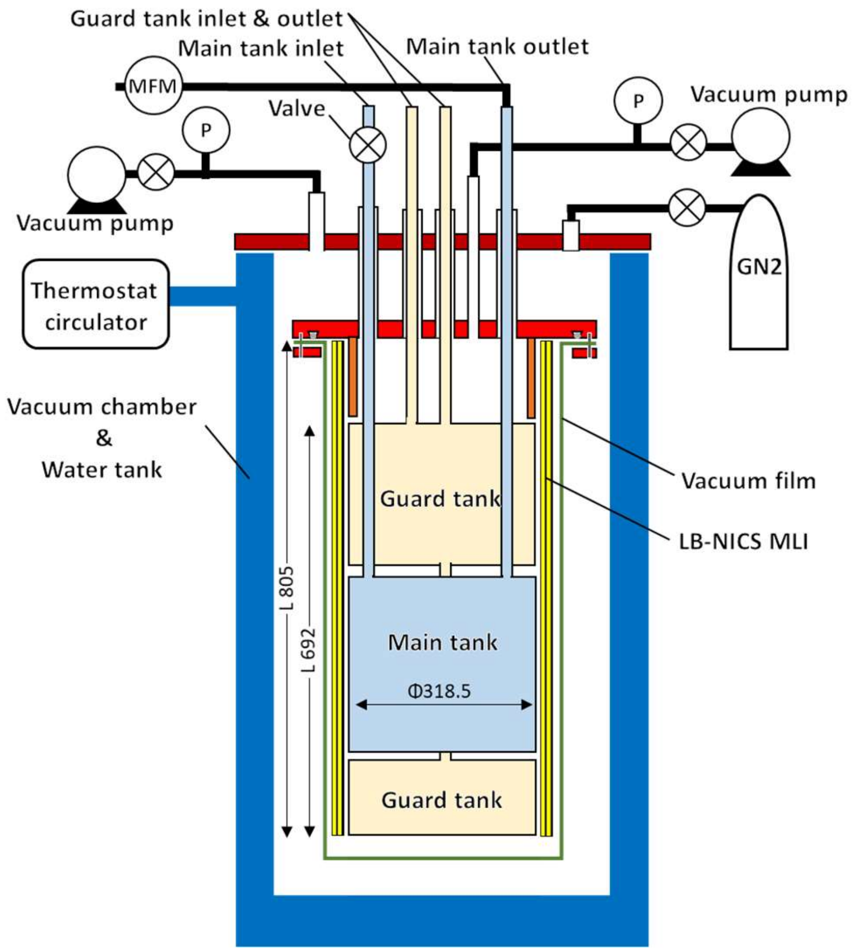
3-4 Measurement equipment

■Schematic of the boil-off calorimeter



- ▼ The main boil-off tank is 300 mm (height) × 318.5 mm (diameter) in size.
- ▼ A middle flange is installed on top of the upper guard tank for closing the upper aperture of the vacuum-sealed film of the sample.
- ▼ **Shroud temperature** is set on **3 different values** to evaluate temperature dependency.
- ▼ The inside and outside of the insulation sample are connected to the separate vacuum evacuation pumps, and the degree of vacuum outside of the insulation sample can be controlled **from 1 atm to a high vacuum**.

3-5 Measurement condition

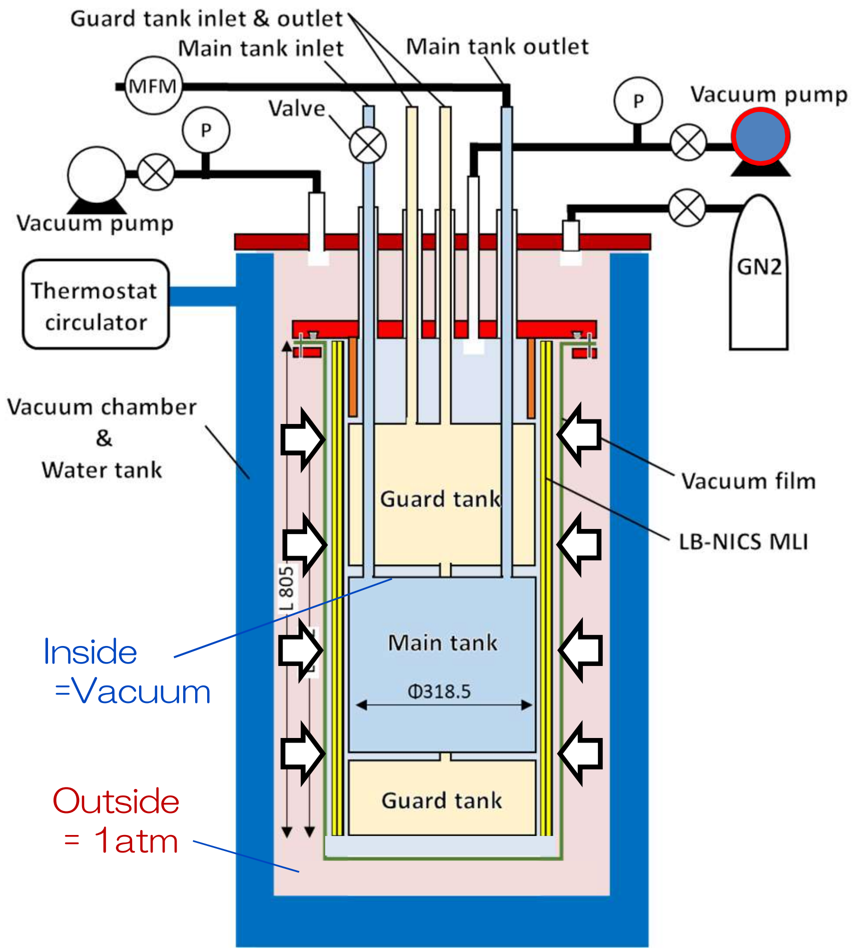


■Before starting the experiment:
both inside and outside of insulation sample maintain1 atm.

▶First, the inside of the insulation is evacuated and liquid nitrogen is transferred into the inner tanks.

Test case	Degree of vacuum		Temp. of shroud
	Inside of insulation	Outside of insulation	
1	$<10^{-3}$ Pa	1 atm	23 deg C
2	$<10^{-3}$ Pa	$<10^{-3}$ Pa	80 deg C
3	$<10^{-3}$ Pa	$<10^{-3}$ Pa	27 deg C
4	$<10^{-3}$ Pa	$<10^{-3}$ Pa	3 deg C
5	$<10^{-3}$ Pa	1 atm	3 deg C
6	$<10^{-3}$ Pa	1 atm	27 deg C
7	$<10^{-3}$ Pa	1 atm	80 deg C

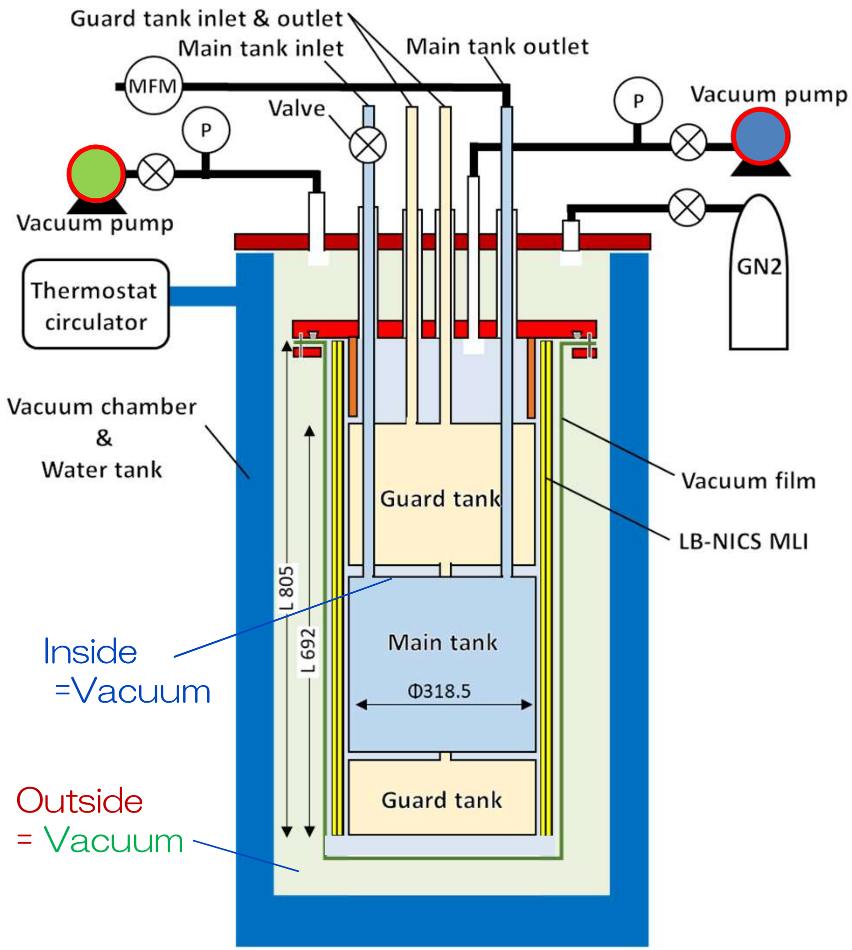
3-5 Measurement condition



■Test case 1:
Inside of insulation is evacuated
Outside of insulation is maintained 1 atm.
Shroud temp, is 23 deg C
▶Insulation is compressed.

Test case	Degree of vacuum		Temp. of shroud
	Inside of insulation	Outside of insulation	
1	<10^{-3} Pa	1 atm	23 deg C
2	<10^{-3} Pa	<10^{-3} Pa	80 deg C
3	<10^{-3} Pa	<10^{-3} Pa	27 deg C
4	<10^{-3} Pa	<10^{-3} Pa	3 deg C
5	<10^{-3} Pa	1 atm	3 deg C
6	<10^{-3} Pa	1 atm	27 deg C
7	<10^{-3} Pa	1 atm	80 deg C

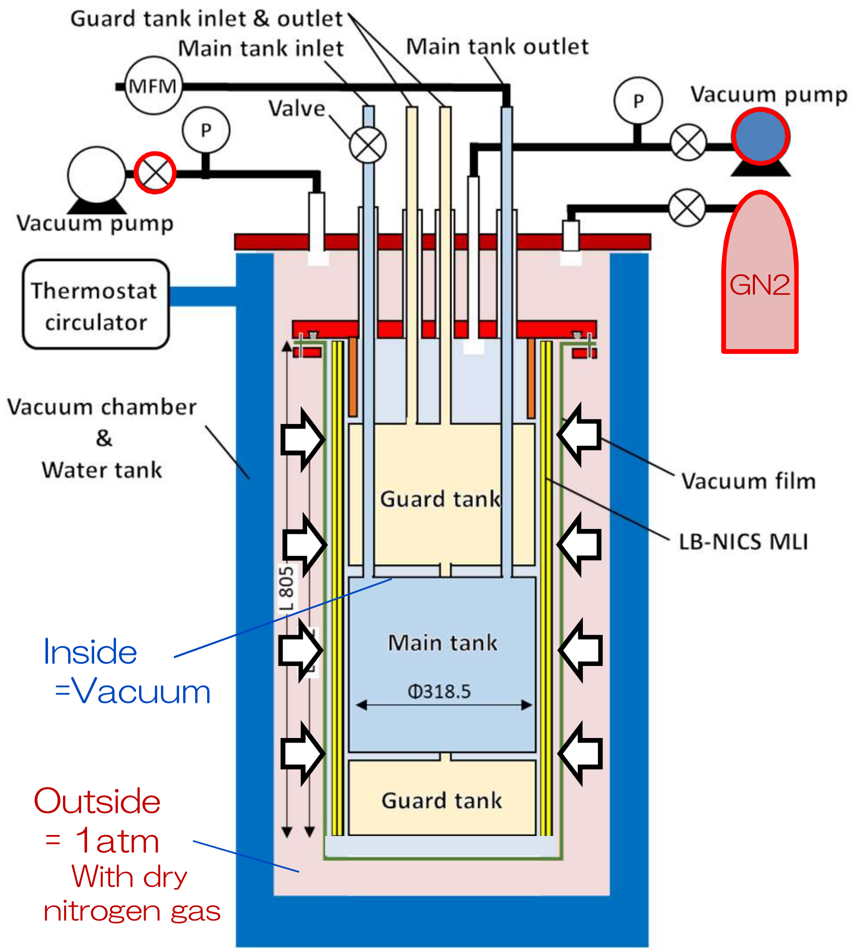
3-5 Measurement condition



■ Test case 2, 3 and 4:
Inside of insulation is evacuated
Outside of insulation is also evacuated.
Shroud temp, is controlled to 80, 27 and 3 deg C.
▶ Insulation is released.

Test case	Degree of vacuum		Temp. of shroud
	Inside of insulation	Outside of insulation	
1	$<10^{-3}$ Pa	1 atm	23 deg C
2	$<10^{-3}$ Pa	$<10^{-3}$ Pa	80 deg C
3	$<10^{-3}$ Pa	$<10^{-3}$ Pa	27 deg C
4	$<10^{-3}$ Pa	$<10^{-3}$ Pa	3 deg C
5	$<10^{-3}$ Pa	1 atm	3 deg C
6	$<10^{-3}$ Pa	1 atm	27 deg C
7	$<10^{-3}$ Pa	1 atm	80 deg C

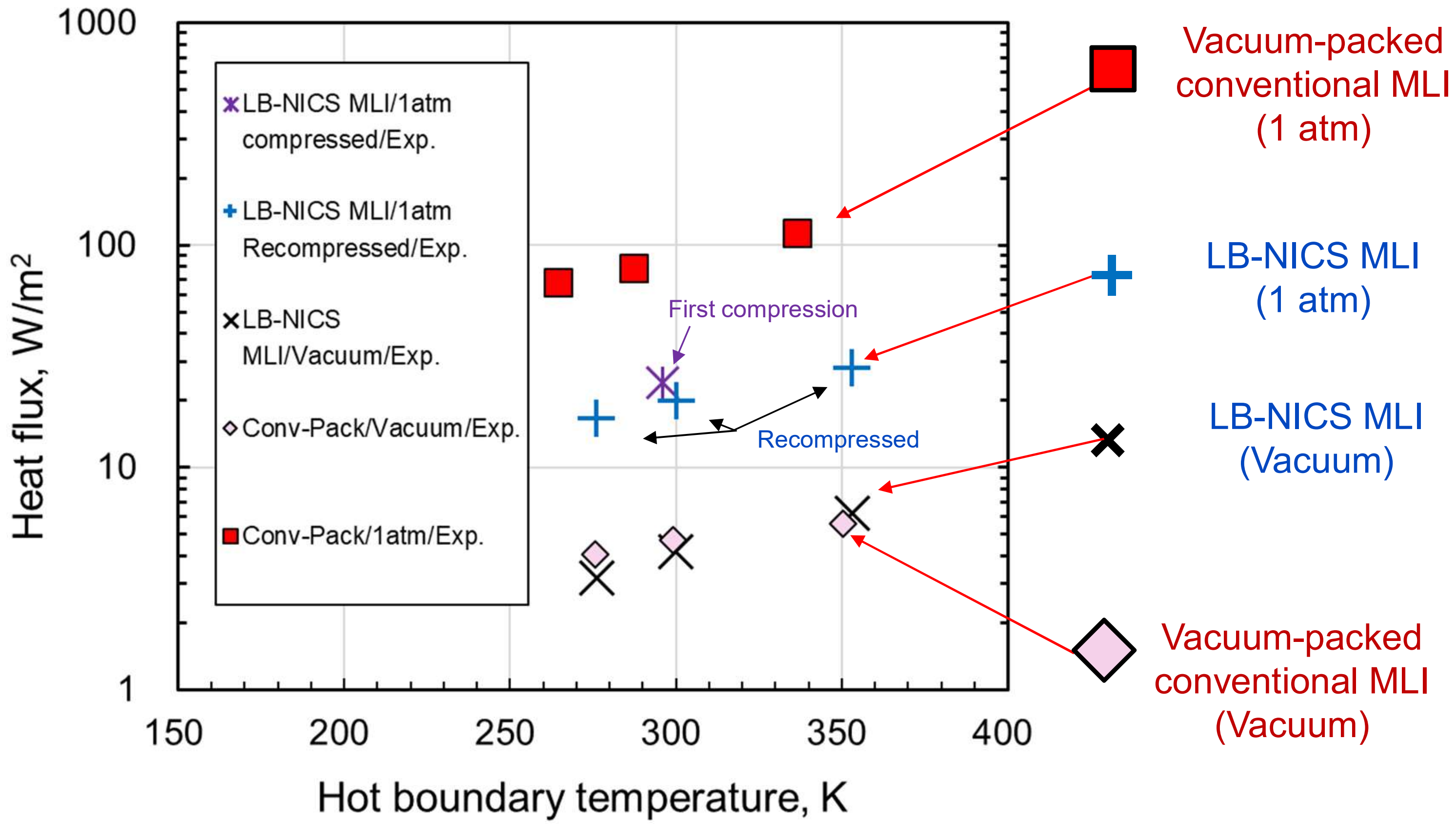
3-5 Measurement condition



■Test case 5, 6 and 7:
Inside of insulation is evacuated
Outside of insulation is pressurized to 1 atm.
Shroud temp, is controlled to 3, 27 and 80 deg C
▶Insulation is re-compressed.

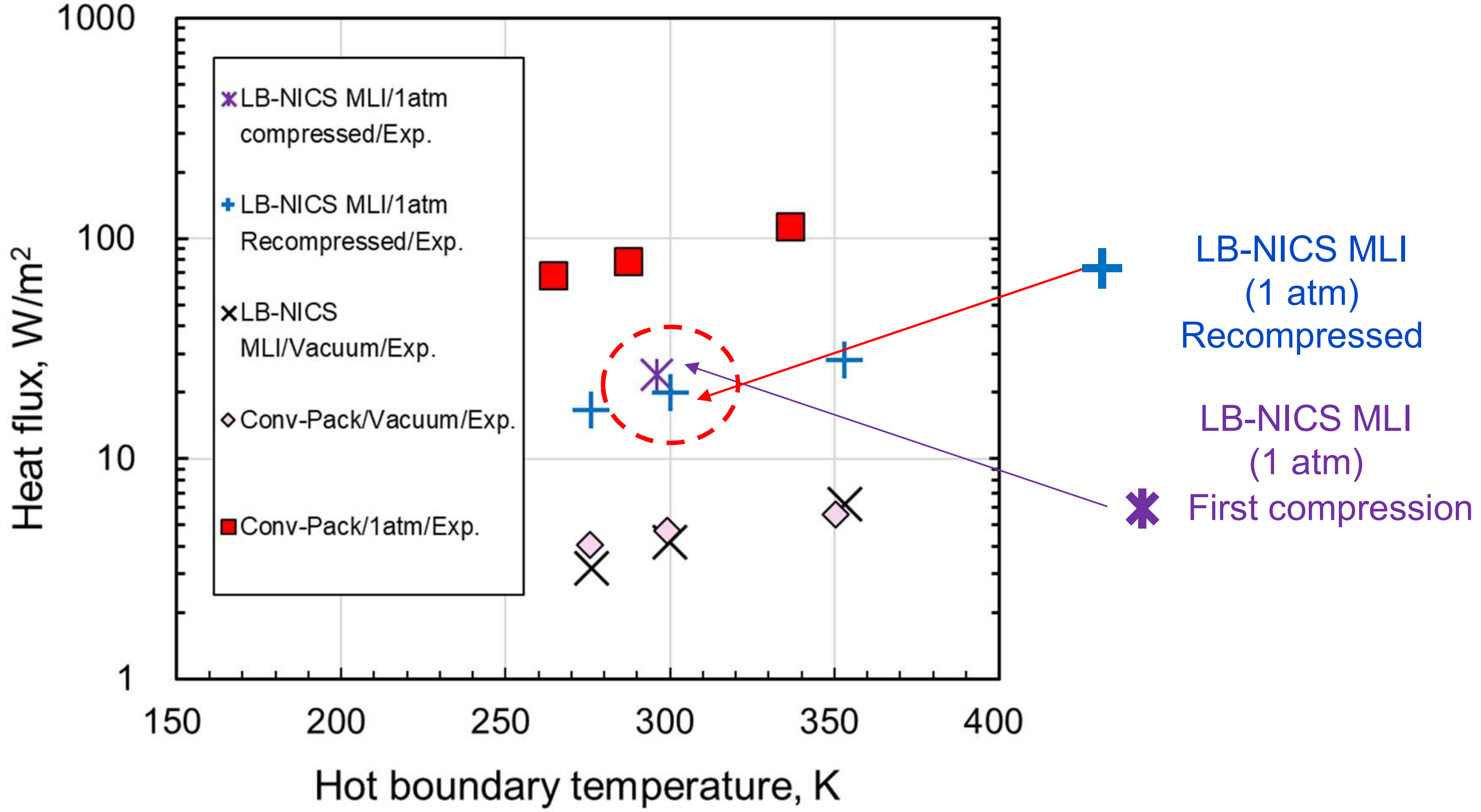
Test case	Degree of vacuum		Temp. of shroud
	Inside of insulation	Outside of insulation	
1	<10^{-3} Pa	1 atm	23 deg C
2	<10^{-3} Pa	<10^{-3} Pa	80 deg C
3	<10^{-3} Pa	<10^{-3} Pa	27 deg C
4	<10^{-3} Pa	<10^{-3} Pa	3 deg C
5	<10^{-3} Pa	1 atm	3 deg C
6	<10^{-3} Pa	1 atm	27 deg C
7	<10^{-3} Pa	1 atm	80 deg C

4-1 Test results



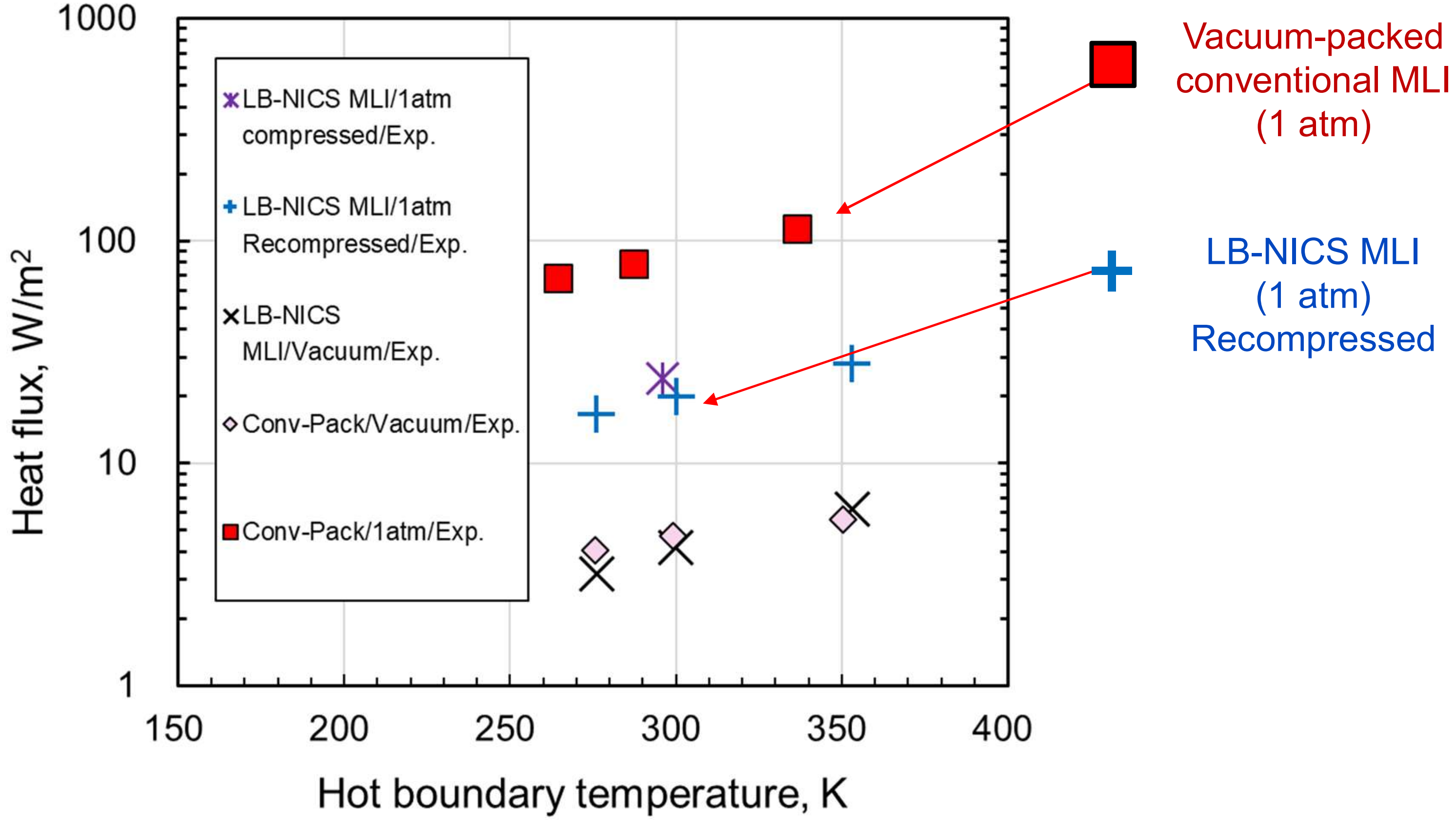
4-1 Test results

- The thermal insulation performance does not change much in the compressed state and recompressed state, and the state of the thermal insulation layer is thought to be maintained without degradation.
- Actually, the vacuum-sealed film was removed for observing the thermal insulation layer after the measurement, but breakage or deformity of the spacer was not confirmed.



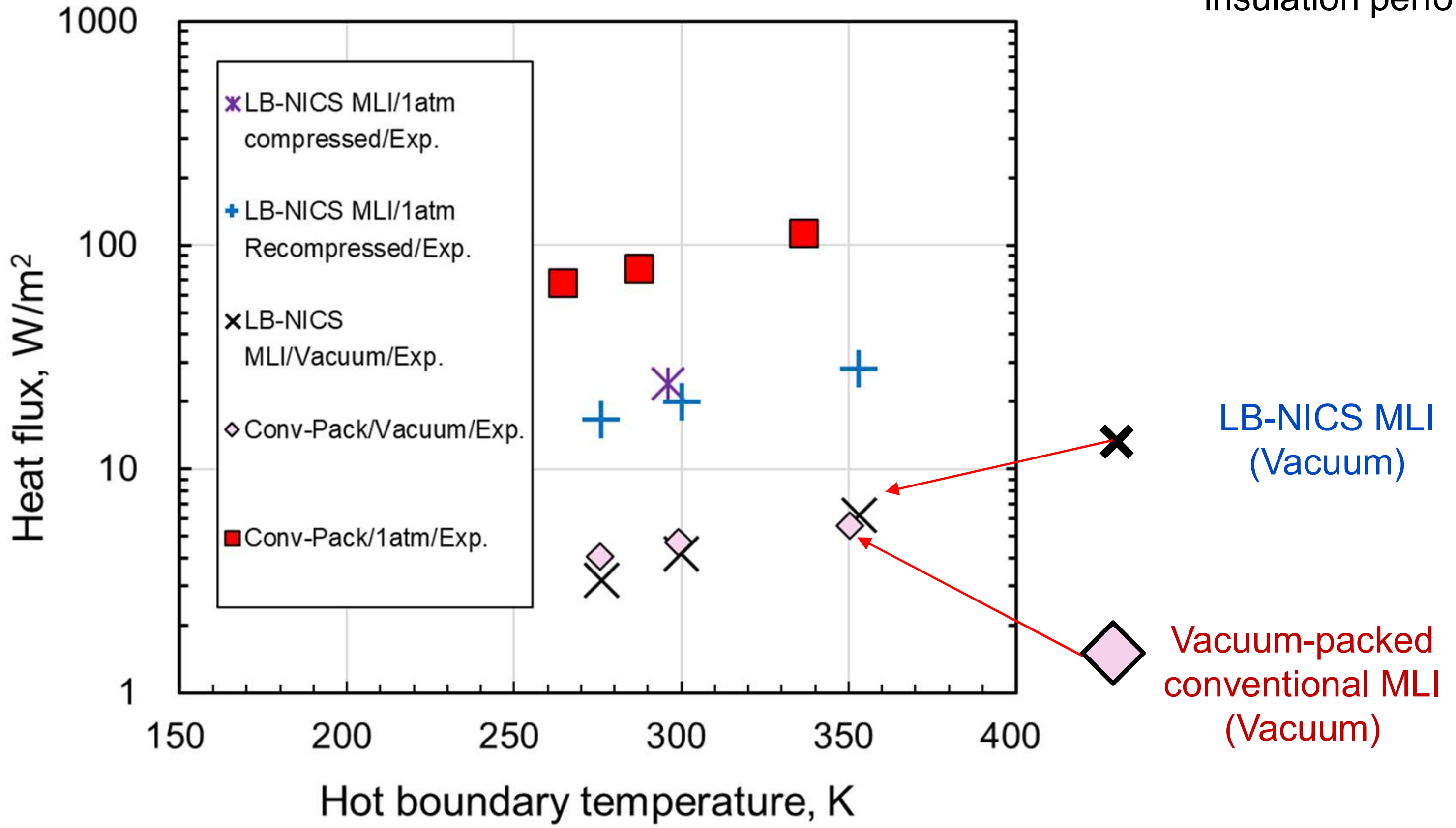
4-1 Test results

- The thermal performance of LB-NICS MLI is far superior to vacuum-packed conventional MLI under 1 atm.
- Under 1 atm, the low emissivity film of conventional MLI is strongly compressed and heat leaks due to conductive heat transfer increase, whereas LB-NICS MLI maintains low conductive heat by controlling the interlayer space with intermittent spacers.



4-1 Test results

- By releasing compression of the insulation layer, heat transfer due to conduction is suppressed, and both conventional MLI and LB-NICS MLI significantly improve thermal insulating performance.
- LB-NICS MLI does not change the contact area between the film and spacer, but by changing the heat path of the spacer, it gains thermal resistance and improves the thermal insulation performance.

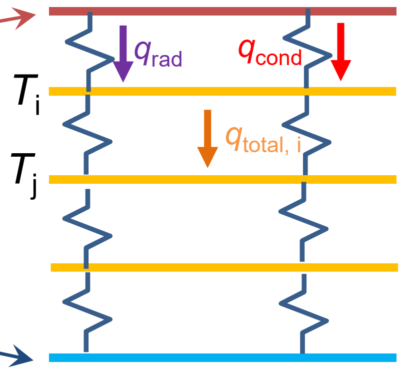


4-1 Test results

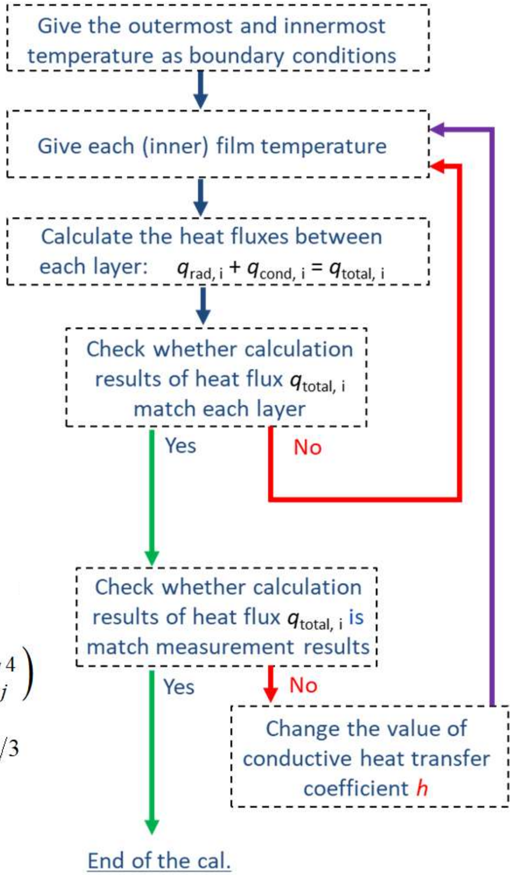
- In order to estimate the temperature dependence of MLI performance and the performance per layer, consider a simple mathematical model of MLI.
- The temperatures of the outermost and innermost layers are given as boundary conditions, and the heat flux between each of the films is repeatedly calculated until the calculated heat flux matches the measured value by changing the conductive heat transfer coefficient h_c and the temperature of each layer.

Mathematical model of MLI

Give the Outermost film temp.
= shroud temp. as boundary temp.



Give the Innermost film temp
(77K) as boundary temp.



Heat flux through insulation $q_{total} = q_{rad} + q_{cond}$

Radiative heat flux (radiation exchange between large parallel plates)

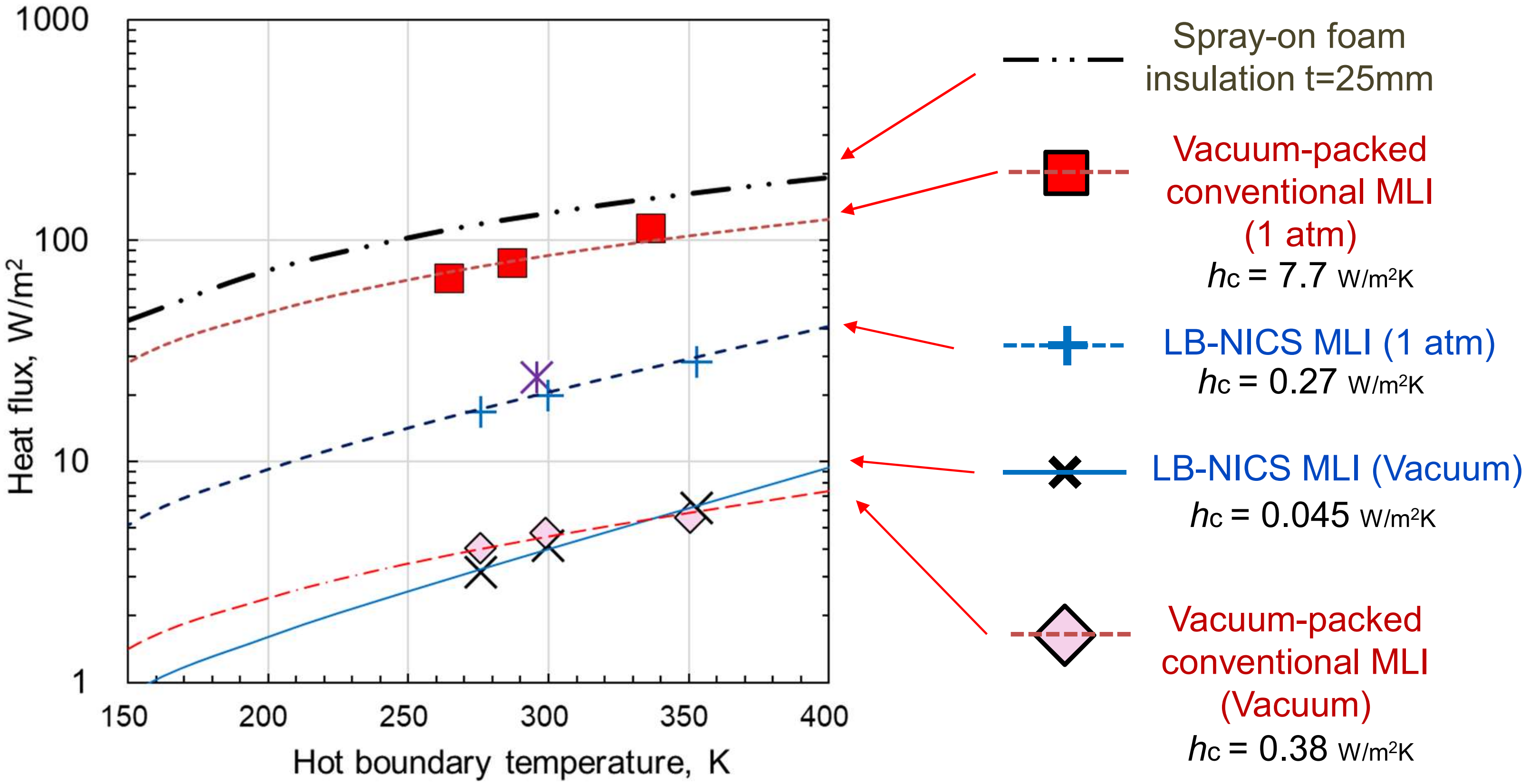
$$q_{rad} = \frac{1}{(1/\varepsilon_i) + (1/\varepsilon_j) - 1}\sigma\left(T_i^4 - T_j^4\right)$$

Temperature dependency of film surface emissivity $\varepsilon_i = 6.69 \times 10^{-4} \times T_i^{2/3}$

Conductive heat flux $q_{cond} = h_c\left(T_i - T_j\right)$

4-1 Calculation results

- Although vacuum-packed conventional MLI has a lot of low emissivity film layers, radiative heat transfer is kept small, but since h_c is large, thermal insulation performance cannot be expected at low temperature where conduction is dominant.
- Conversely, LB-NICS MLI can keep the thermal conductance of the spacer very low, so it can maintain high performance even at low temperature, thereby increasing the difference in performance from vacuum-packed conventional MLI.



5 Conclusion

- A new type of MLI using new spacers, the load-bearing, non-interlayer-contact spacer MLI or LB-NICS MLI was developed, and thermal performance tests in both atmospheric and vacuum environments were conducted using a cylindrical boil-off calorimeter.
- According to the experimental results, the thermal insulation performance of LB-NICS MLI is far superior to existing spray-on foam insulation and vacuum-packed conventional MLI, particularly at low temperature, where conduction dominates.

Table 4.2. Insulation specifications

	[Unit]	LB-NICS MLI 5 layers	Conv-Pack MLI 21 layers	Spray-on foam insulation
Total thickness	[mm]	16	16	25
Total surface density ρ	[kg/m²]	2.0	6.7	0.84
Heat flux @ 1 atm/77 K-300 K	[W/m²]	19.9	78.4	168
Heat flux @ Vacuum/77 K-300 K	[W/m²]	4.2	4.7	168
Total heat transfer coefficient h @ 1 atm/77 K-300 K	[W/m²K]	0.089	0.35	0.60
Total heat transfer coefficient h @ Vacuum/77 K-300 K	[W/m²K]	0.019	0.021	0.60
h×ρ@ Launch	[W·kg/m⁴K]	0.18	2.36	0.50
h×ρ@ Orbit	[W·kg/m⁴K]	0.038	0.14	0.50

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and MLI manufacturer /Orbital engineering INC. is participating with samples.
Please contact if you are interested ☺