

Simulation experiment of vacuum insulation deterioration in liquid hydrogen tank due to minute air leaks

Suguru Takada^{1*}, Shinji Hamaguchi¹, Shigeyuki Takami¹, Masakazu Nozawa² and Hiroaki Kobayashi³

¹ National Institute for Fusion, National Institutes of Natural Science, Toki, Gifu, Japan, ² KOSEN of King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand, ³ Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Japan

*E-mail: takada.suguru@nifs.ac.jp

Background of this study

To Safe Liquid Hydrogen Tank and Transfer Tube

Deterioration of vacuum insulation may be happened in Long-term. O-ring Seal must be deteriorated by aging such as Hydrolyzing or UV radiation.



Aging O-ring of Seal off valve of the transfer tube

Liquid Hydrogen tank at Noshiro rocket testing center JAXA

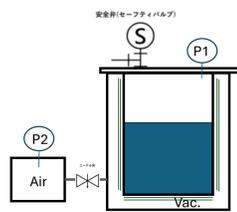


“The cause of the accident”
Evaporation of large amount LHe in 10000 L Dewar at our Lab.

Hydrolyzed rubber O-ring of seal off valve in Liquid Helium tank (30 years of aging)

Under 20 K (T_{sat} at 1atm), most of all air contents must be condensed !

Question:
When can we find aging deterioration of O-ring valve of Vacuum Insulation in LH₂ tank?
What happened in vacuum insulation when minute air leak?



Normal experiment to safety study

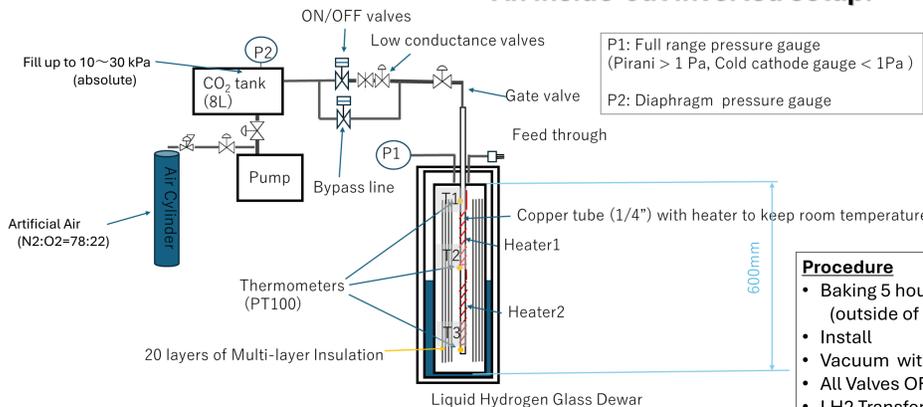
Conducting an experiment to introduce air into the vacuum layer of a liquid hydrogen tank without preliminary testing is terrifying.



We tried the simulation experiment with Small setup & Low cost

Experimental setup

An inside-out inverted setup.



Liquid level was measured by the several Pt-Co resistor on outer wall & Eye observation



Procedure

- Baking 5 hour to dry inside (outside of Glass Dewar)
- Install
- Vacuum with Scroll pump < 5 Pa
- All Valves OFF without gate valve
- LH₂ Transfer
- After pressure down to 0.1Pa
- Leak start (ON/OFF valve open)
- Measurement P1 & P2

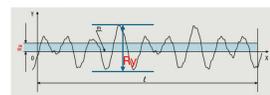
Ratio between Volume and Surface area is small
⇒ Quick experiment of slow leak can be done
(It is like Accelerated Aging Test for large application)

This experiment
(Volume V)/(cold area A) ≈ 30 mm
For example,
ID 400mm(Cryostat), OD 300mm (LH₂ vessel), length 1m
V / A ≈ 116 mm (filled 50 %)

Sample vacuum vessel
Geometry: ID 39.4 mm, OD 42.7mm, Length: 600 mm
Material : SUS 304 smooth pipe (BA type*/ Transfer Tube quality)
Flange: ICF70

*BA type(Bright Annealing)
Ra<0.8, Ry<3.0 micron

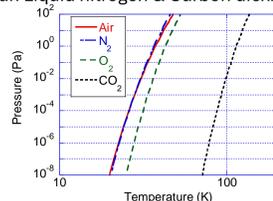
EP (Electrolytic Polishing; not Tested)
Ra<0.1 Ry<0.4 micron



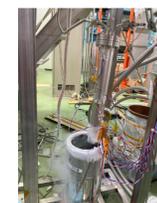
We also tested experiments using LN₂ and CO₂.

(Opportunities for liquid hydrogen experiments are limited because of few facilities available and Increasing demand)

Can Liquid nitrogen & Carbon dioxide experiments be used instead?



	LH ₂ & Air	LN ₂ & CO ₂
Saturate Pressure (Pa)	~10 ⁻⁸	~10 ⁻⁶
Capture Coefficient	0.8~0.9	0.65
Mean Free Path@1Pa(mm) @ room temp	6.6 :N ₂ 6.4 :O ₂	3.9



In LN₂ & CO₂ Case, Liquid level keeps 280-270 mm ← Refilling is Easy

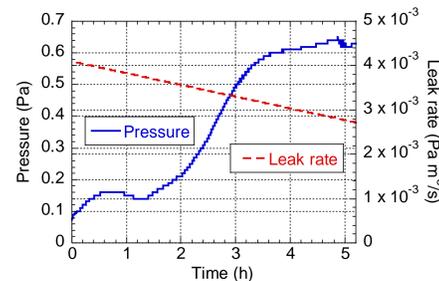
Saturation line of Air, Nitrogen, Oxygen and Carbon dioxide from REFPROP by NIST
Air, N₂:O₂:Ar = 0.7812:0.2096:0.0092

LN₂ & CO₂ experiments produce a safer answer ?

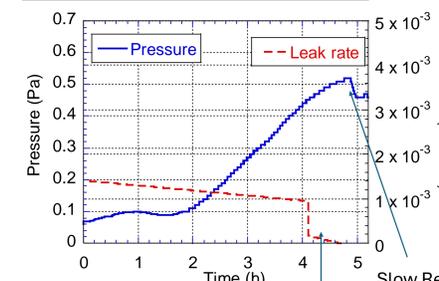
Results and Discussion

In LH₂ & Air, Experiment, Liquid level decrease from 280-160 mm linearly in 6 hours.

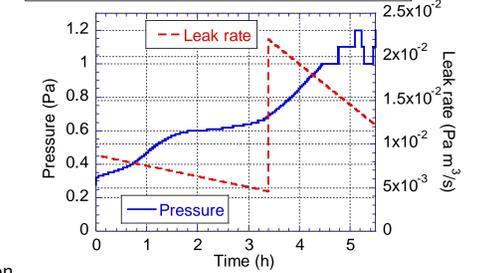
Case1: 4.0 ~ 2.7 x 10⁻³ Pa m³/s



Case2: reaction when leak stop
1.4 ~ 0.9 x 10⁻³ → 1.0 < 10⁻⁴ Pa m³/s



Case3: sudden growth of leak rate
8.6 ~ 4.4 x 10⁻³ → 2.2 ~ 1.2 x 10⁻² Pa m³/s

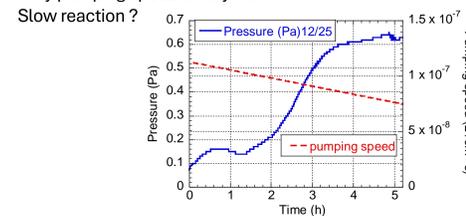


Case 1 ~ 3 : Vacuum chamber against minute Artificial Air leak in Liquid Hydrogen
Time variation of pressure growth P1 in the test chamber and the leak rate calculated by the measurement of pressure decrease in the buffer tank P2

* Phenomena with long time constants (comparison with past research of sudden vacuum loss) / Not reach steady state within 5 hours

- There is a bump around 0.1 Pa that cause is unclear
- The condensation speed of the wall inside test chamber is very small (the order is about 1 x 10⁻⁷ L/cm s)
That may be cause of low thermal conductivity of SUS 304 and the rather large heat penetration from leak tube ()controlled with room temp

Why pumping speed is very slow ?



Leak rate can be converted to Pumping speed
“Case 1 “

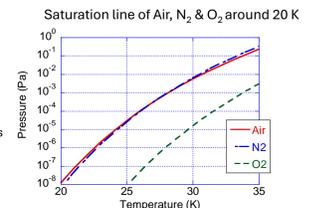
Pumping speed expressed S with capture coefficient C

$$S = CS_{theo}$$

Theoretical Maximum pumping speed S_{theo}

$$S_{theo} = \sqrt{\frac{RT_g}{2\pi M}} \left(1 - \frac{P_s}{P_c}\right)$$

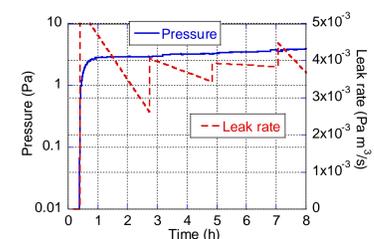
R: universal gas constant
M: molecular weight
P_s: vapor pressure of condensate at T_s
P_c: vapor pressure of chamber
T_s: Temperature of cryo-surface
T_g: temperature of gas



This term was essentially 1 in the past study
However, it may be small according to the temperature of inner cryo-surface due to low thermal diffusivity. Small Air Frost may cause rather thermal resistance according to past paper*.

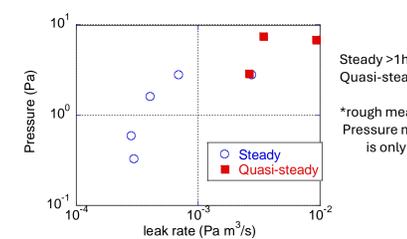
[*]. Hord, Cryogenics 1966 pp.285-293

Comparison with the case of CO₂ leak in LN₂



Typical Time variation in the case of LN₂ test against minute CO₂ leak

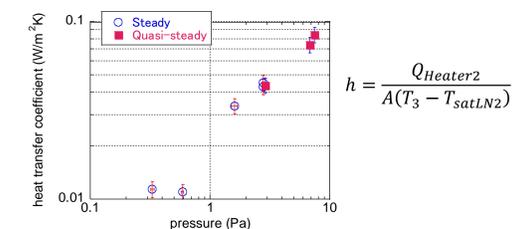
- No bump were observed.
- Time constant “Earlier”
- Pressure growth “Larger”



Steady state pressure against minute leak

Liquid Hydrogen leak Test rather moderate than LN₂ test with CO₂.

This tendency is suggested to be
“Free molecular region” ⇒ “Transition region”



Heat transfer coefficient on pressure calculated by the heat load of Heater 2 and Temperature different between T₃ and 77 K

Summary

A simulation experiment was conducted to know the process of the deterioration of vacuum insulation in a liquid hydrogen tank when minute air leaks due to aging of an O-ring or other factors. We conducted a small-scale experiment using an inside-out inverted configuration of a vacuum insulation of liquid hydrogen tank. After immersing a vacuum chamber, equipped with a temperature-controlled leak tube at room temperature, into liquid hydrogen, artificial air at an order of 10⁻³ Pa·m³/s was injected, and the resulting pressure variations were measured.

The findings of the experiment revealed the following:

- In over 5 hours experiment with minute leak in the order of 10⁻³ Pa·m³/s, the pressure kept increasing gradually below 1 Pa.
- The cryo-pumping speed was extremely slow on inner wall. This may be caused by the thermal properties of stainless steel and condensate Air frost, and increased heat flux due to deteriorating vacuum pressure.
- To verify whether an alternative experiment could replicate Air leakage into a vacuum layer at LH₂ temperature, we conducted a test by injecting CO₂ into a vacuum layer at LN₂ temperature. The CO₂ with LN₂ experiment led to faster and more pronounced pressure increases. This suggests that the experiment could serve as a conservative indicator for safety assessments.

Acknowledgments

This work was funded by a grant (No. MIS014) of National Institute for Fusion Science from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan. This experiment was supported by many support staff of JAXA Noshiro rocket test centre at Akita in Japan. We also thank Mr. Hiroki Noguchi and Hiroyuki Tanoue (NIFS) for their help in development of the control system.