Experimental Analysis of Cryogenic Storage System by Using Different Techniques

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Abstract- Study of production and behavior of materials at very low temperature is known as cryogenics. Cryogenic fuels require storage at extremely low temperature to maintain them in liquid state. One such substance is liquid hydrogen (LH_2), which is used as a cryogenic fuel. A chemical substance used in production of energy to generate propulsion of vehicle or other object is known as propellant. Liquid Oxygen (LOX) is commonly used as a cryogenic liquid oxidizer propellant. In order to maintain cryogenic propellant in liquid state, they need to be stored at extremely low temperature. It is challenging to store the propellants in space for long duration missions. Challenge is to prevent temperature fluctuations that results in fuel losses due to boil off. In space due to absence of pressure i.e. vacuum, the temperature at which liquid starts to boil, drops. Hence it is critical for most of the liquids to remain in liquid state. Until now many liquid propellants have undergone lab testing. Liquid hydrogen has proved to be most promising. To avoid cryogenic propellants from evaporating or boiling- off, they must be insulated from all possible sources of heat. In space, its protection from radiant heat of sun should be taken care of. They expand rapidly when it absorbs heat. Thus to prevent tank from exploding, venting is necessary. As metals are exposed to extreme cold temperatures of liquid hydrogen, they become brittle. It can even leak through microscopic pores of welding seam. Hence for solving these problems, storage of cryogenic propellant is an important factor. Here, we have studied a few techniques and methods for cryogenic storage of propellants, some of which are improvements to the existing techniques such as multi-layer insulation, while the others are new methods which have been found to be more efficient. The main purpose here is to achieve a state of zero boil-off (ZBO). To this end, various degree of success has been obtained using the different methods mentioned here.

Keywords- Liquid hydrogen, Multilayer Insulation (MLI), Cryogenic, Liquid Oxygen, Propellants, Storage, Insulation, Zero boil-off (ZBO)

I. INTRODUCTION

For storing cryogens, special types of vacuum flasks known as cryogenic storage dewars are used. These dewars have wall constructed from two or more layers. High vacuum is maintained between these layers. Due to this very good thermal insulation is provided between the exterior and interior of dewar. About 55 to 45 years ago, developing MLI systems for cryogenic propellant tanks was active, but it stopped at the end of 1970. Multilayer insulation (MLI) system for cryogenic storage dewars showed very high thermal performance. During this period effective development of multilayer insulation (MLI) took place. Most of the MLI system subsist of thin reflective layers which are separated from each other by thermally insulating layers. Goal is to prevent the layers of foil from contacting. If they come in contact, thermal short circuit will occur. This will increase the heat transfer. These thermally insulating layers may be made of silk or nylon netting. Here aim is to reduce the heat leak into cryogenic storage tanks. Insulating capability will be more if number of layers are increased. MLI is designed to work for pressure below 1×10^{-4}.For easier installation, MLI systems are made of blankets. The effectiveness of MLI system will get reduced if layers are wrapped too tightly. During installation of MLI, seams and gaps are created. If not properly treated, significant heat loss can take place. Materials ability to deflect solar energy is known as absorption and ability to radiate energy in the form of heat is known as emittance. For MLI systems to be effective they should have good absorption and good emittance. Advancements and progress are being made in multi-layer insulation systems (MLI) for overcoming these shortcomings. Another method of decreasing heat transfer is foam insulation. They have low density. Moisture gets accumulated in the spaces of the foam structure. This will form ice. Hence thermal conductivity will increase as surface area has increased. This is one of the disadvantage of foam insulations. Silica aerogels are also used as an insulator. They are light in weight, have low density and have a remarkable insulating property. Hence they are also used for cryogenic insulation.

II. CRYOGENIC LIQUIDS

Liquefied gases kept in their liquid state at extremely low temperatures are known as cryogenic liquids. At normal temperature and pressure all cryogenic liquids are gases. Each of them becomes liquid at different temperature and pressure. But all are extremely cold. Out of all these cryogenic liquids, liquid hydrogen and liquid oxygen are popularly used as cryogenic propellants in space missions. The major reason behind this is the amount of specific impulse they provide. Greater amount of energy will be produced if the specific impulse is higher. Hence heavier payload can be carried to orbits.

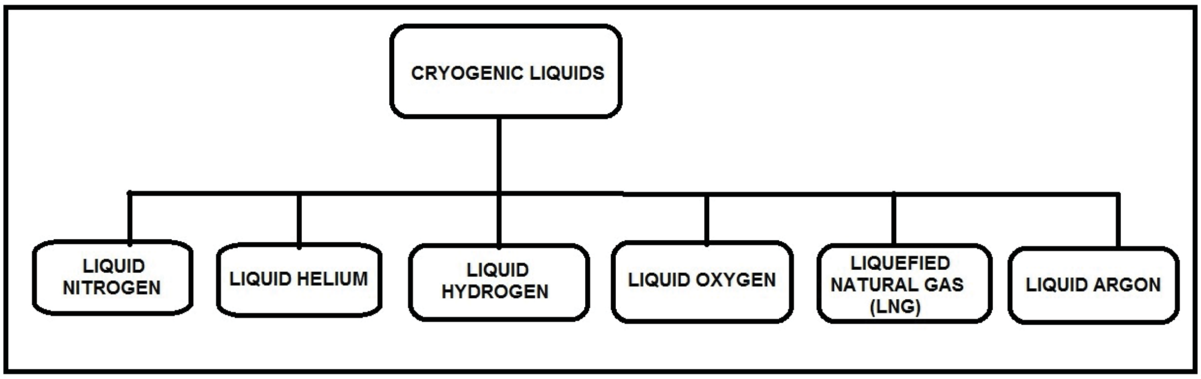

Figure1. Different Cryogenic Liquids

III. LIQUID HYDROGEN (LH_2)

Hydrogen is light and has the lowest atomic weight. It is the simplest and the most abundant element in the universe. Hydrogen in liquid state is known as liquid hydrogen. To remain in liquid state it needs to be stored below -252.87˚C. It is an extremely powerful component of rocket propellant. In combination with liquid oxygen, liquid hydrogen produces highest specific impulse. Specific impulse measures the efficiency of rocket and jet engines. When used with liquid oxygen as an oxidizer, the only byproduct is water. Hence it is considered to be the cleanest.

Table- 1 Properties of liquid hydrogen

Sr. No.	Chemical Formula	H_2
1	Appearance	Colourless liquid
2	Molar Mass	2.02 gm/mol
3	Specific heat at 0 °C and 1.013 bar	9.78 kJ/kgK
4	Melting point	-259.34 °C
5	Boiling Point	-252.87 °C
6	Heat of vapourisation at 0 °C and 1.013 bar	445.6 kJ/kg
7	Density	70.97 kg/m^3
8	Critical pressure	1.293 MPa
9	Critical temperature	-240.174˚C
10	Phase at room temperature(20 °C)	Gas
11	Temperature at triple point	-259.347˚C at 7.04 MPa

IV. LIQUID OXYGEN (LOX)

Liquid oxygen is pale blue in colour. It is a powerful oxidizing agent and is classified under cryogenic liquid. It is also strongly paramagnetic in nature. Due to its cryogenic nature, if any metal touches LOX, it becomes brittle.

Table- 2 Properties of liquid OXYGEN

Sr. No.	Molecular Formula	O_2
1	Freezing Point @ 1 atm	–218.8°C
2	Boiling Point @ 1 atm	–183.0°C
3	Critical Pressure	49.8 atm
4	Critical Temperature	–118.6°C
5	Density, Gas @ 20°C, 1 atm	0.0831 lb/scf
6	Density, Liquid @ BP, 1 atm	71.27 lb/scf
7	Specific Gravity, Liquid (water=1) @ 20°C, 1 atm	1.14
8	Specific Gravity, Gas (air=1) @ 20°C, 1 atm	1.11
9	Latent Heat of Vaporization	92 Btu/lb
10	Solubility in Water @ 25°C, 1 atm	3.16% by volume
11	Expansion Ratio, Liquid to Gas, BP to 20°C	1 to 860

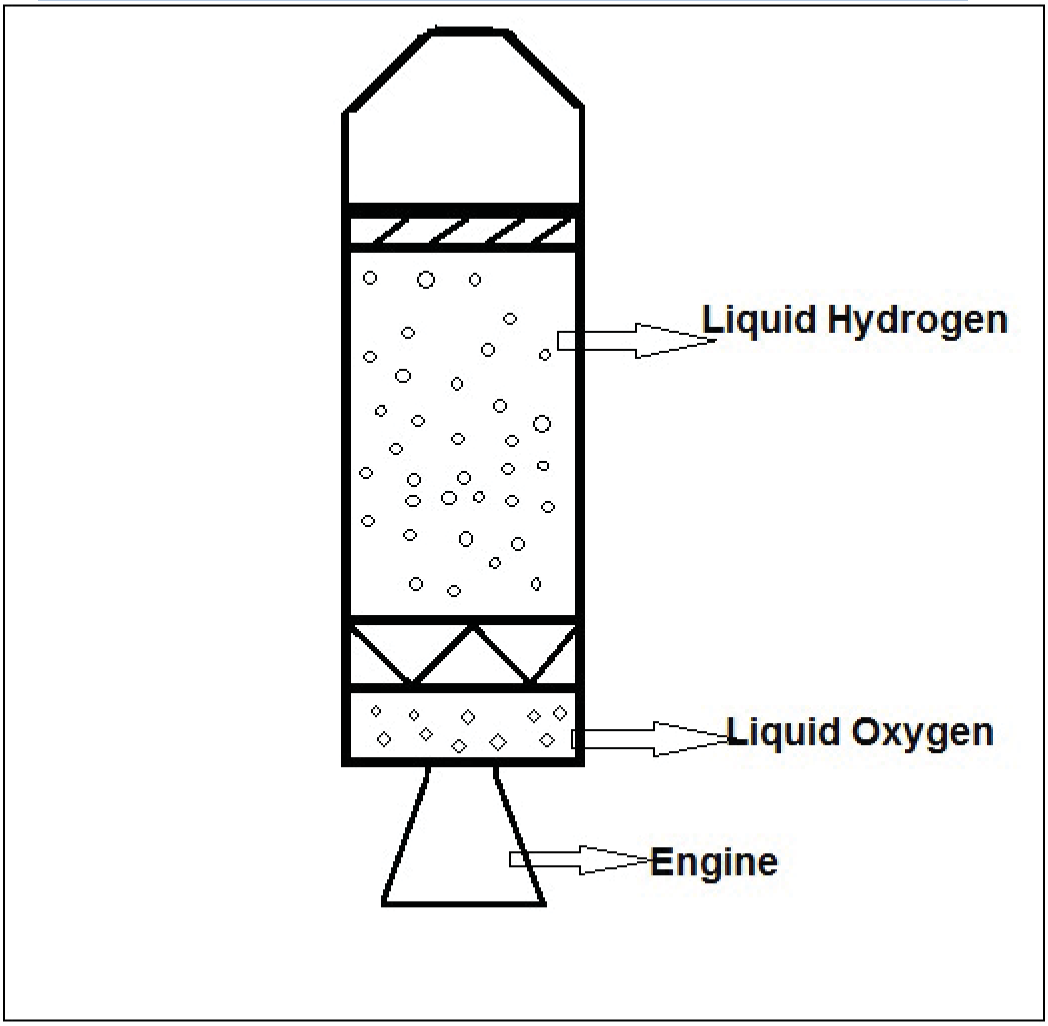

Figure 2. Cryogenic Upper Stage

V. REVIEW OF SOME RESEARCHERS

5.1 *J.E Fesmire et al [1]:-*The researchers have investigated the use of Spray- On Foam Insulation (SOFI) on External Tank (ET) of the space shuttle. The heat leakage rate, cryogenic moisture uptake are the important factors taken into consideration. Emphasis has been given on cryogenic thermal performance of

SOFI under large temperature variations. For comparing the values of thermal conductivity and heat flux, testing was performed over entire pressure range from high vacuum to ambient temperature. Rigid foams and cork were some materials used earlier for cryogenic tank insulation. Modern SOFI are light in weight. They have remarkable combination of thermal and mechanical properties.

5.1.1 Experimental Setup

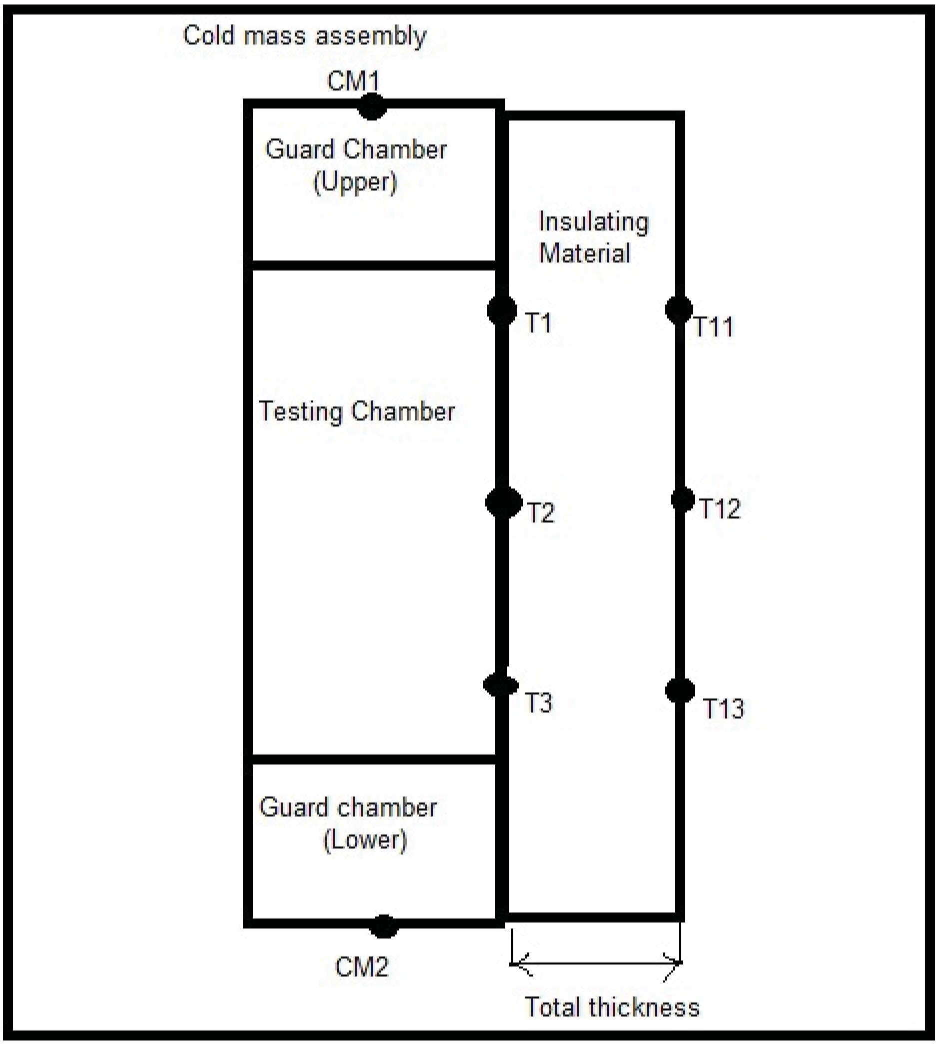

Figure 3. Experimental setup (Cryostat 100)

Table 3- Setup Nomenclature and Surface Temperatures

Surface Temperature Measurements		
Sr. No.	**Sensor**	**Location**
1	**T1, T2, T3**	**Cold Boundary Temperature (CBT)**
2	**CM1, CM2**	**Cold Mass Temperature**
3	**T11, T12, T13**	**Warm Boundary Temperature (WBT)**

5.1.2 Material Specification

- Three types of foams :-
  1. NCFI (North Carolina Foam Industries) 24-124 (203 mm diameter , 25 or 32 mm thick)
  2. NCFI 27-68 (203 mm diameter , 25 or 32 mm thick)
  3. BX-265 (203 mm diameter , 25 or 32 mm thick)

  Before testing the densities of all specimens were between 37 to 40 kg/m^3.

- Five 1m long, 25 mm thick cylindrical test articles.

5.1.3 Experimental Procedure

In this experiment, to measure the heat flux and thermal conductivity, the cryostat-100 instrument which uses the steady-state liquid nitrogen evaporation rate (boil off) calorimeter was used. Temperature sensors were installed through the thickness of insulation approximately at an interval of 6.4mm. Series of four stainless steel bands were used to tightly secure the two halves of SOFI test article in place. To prevent any damage to the foam, thin Polyvinyl Chloride (PVC) plastic foils were positioned underneath the band clamps. To the outer surface of the test article three temperature sensors were fixed. Fitting of BX-265 test article was accurate as no deformities or visible gaps were seen at the two longitudinal seams. The remaining two test articles had gaps less than 4mm. To complete the insulation, these gaps were filled with fibre glass insulating material.

5.1.4 Result and Conclusion

Lowest thermal conductivity was shown by NCFL 27-68. At 760 torr,its value of k (thermal conductivity) was 20.7 mW/mK and at 0.5 millitorr cold vacuumpressure it was 7.3 mW/mK. BX-265 showed the lowest value of kat ambient pressure. NCFL 27-68 recorded lowest value of k (thermal conductivity) under vacuum conditions.

5.2 F.Sabri et al [2]:-In this paper researchers have examined the thermal behavior of a double-phase combination material for cryogenic storage tank. The new material is the combination of Polyurea Crosslinked Silica-based aerogels (PCSA) and elastomeric polymer-RTV 655 (room temperature vulcanizing rubber 655). Aerogels are embedded in RTV-655 matrix. PCSA is nanoporous and mesoporous. They are even the most effective and lightest solid thermal insulators. While RTV-655 compound has space qualified mechanical and chemical stability. Thus, combinations of such unique properties make them a novel type of insulating material. At room temperature and at 77K the effect of different concentrations and different shapes or sizes of PCSA encapsulated in a RTV 655 matrix is studied.

5.2.1 Samples Used

- Baseline Samples
  PCSA (Polyurea Crosslinked Silica-based aerogels)
  RTV 655 (room temperature vulcanizing rubber 655)
- Encapsulated microparticle samples (At different aerogel-RTV volume percentage)
  (RTV 655 + MP) 28%
  RTV 655 + MP) 57%
  (RTV 655 + MP) 62%
- Encapsulated block samples (At different aerogel-RTV volume percentage)
  (RTV 655 +BI) 22%
  (RTV 655 + BI) 35%
  (RTV 655 + BI) 53%

5.2.2 Experimental Procedure

For room temperature measurements

A therm test TPS1500 system was used for measuring the conductivities of RTV 655- encapsulated aerogel samples and PCSA samples. Ensuring the ASTM (American Society for Testing and Materials) standards C1770-10 and C518-10, the transient plane source method was used. A guarded-hot-plate apparatus was used for transient plane source measurements. A probe consisting of a flat double spiral nickel sensor was used. This sensor was protected by a thin kapton film. The probe was kept between two flat samples. Each sample had identical area, density and thickness. The calculation of thermal conductivity was done based on time versus temperature response.

For low temperature measurements

A custom designed sample holder was used for conducting low temperature measurements. Sample holder consists of top and bottom steel plates. For securing the two required samples, stainless steel sheet metal casing around the sample and a sensor, these stainless steel plates were used. The outside casing allowed direct heat transfer by conduction to the samples as it was in direct contact with the bottom plate. For performing the test at low temperature, the sample holder was kept in a liquid nitrogen dewar. After reaching the steady state, temperature measurements were taken. For assessing the errors in the measurements, each sample was measured five times.

5.2.3 Results

Table- 4Thermal conductivity (k) at room temperature (297K)

Sr.No.	Sample	k ,mean (W/mK)	Error, W/mK
	Baseline Samples		
1	PCSA	0.0604	0.0015
2	RTV 655	0.1843	0.0007
3	Encapsulated microparticle samples		
4	(RTV 655 + MP) 62%	0.2283	0.0009
5	(RTV 655 + MP) 57%	0.2285	0.0016
6	(RTV 655 +MP) 28%	0.2034	0.0009
7	Encapsulated block samples		
8	(RTV 655 + BI) 53%	0.1198	0.0049
9	(RTV 655 + BI) 35%	0.1315	0.0082
10	(RTV 655 +BI) 22%	0.1481	0.0030

Table- 5Thermal conductivity (k) atlow temperature (77 K)

Sr. No.	Sample	k,mean (W/mK)	Error, W/mK
	Baseline Samples		
1	PCSA	0.0214	0.0026
2	RTV 655	0.0833	0.0042
3	Encapsulated microparticle samples		
4	(RTV 655 + MP) 62%	0.0943	0.0042
5	(RTV 655 + MP) 57%	0.0885	0.0060
6	(RTV 655 +MP) 28%	0.0849	0.0028
7	Encapsulated block samples		
8	(RTV 655 + BI) 53%	0.0492	0.0040
9	(RTV 655 + BI) 35%	0.0625	0.0053
10	(RTV 655 +BI) 22%	0.0687	0.0069

5.3 S. Dye et al. [3] :- In this paper, the researcher studied about the triple layered LRLMI (Load Responsive Multilayer Insulation) which has an integrated vacuum shell which is light in weight. This provides very good thermal performance for both in-air and on-orbit conditions. Various improvement in the design have been made in the phase II, which includes a flexible, modular, thin vacuum shell and which showed an improvement in on-orbit performance. The LRMLI employs a dynamic beam polymer spacer which helps in providing lower thermal conductivity as well as supports the light weight, integrated vacuum shell. The spacer tends to support dynamically the atmospheric load. It tends to disconnect when at high altitudes or on-orbit (low pressure conditions). These spacers also perform the job of separating and support of the metalized polymer thermal radiation shield layers.

5.3.1 Material Specifications

- Triple layered LRMLI(Load Responsive Multilayer Insulation) blanket (thickness 0.63 cm, 295 K hot, 77 K cold)

5.3.2 Results and Conclusion

Table- 6 Performance of insulation in-air at 1 atm pressure (-196.5°C cold, 21.85°C hot)

In-atmosphere thermal performance								
Sr. No.	**LRMLI Layers**	**LRMLI Heat Leak (W/m^2)**	**LRMLI Thickness (cm)**	**Aerogel Same Heat Leak Thickness (cm)**	**SOFI Same Heat Leak Thickness (cm)**	**LRMLI Mass (kg/m^2)**	**Aerogel Same Heat Leak Mass (kg/m^2)**	**SOFI Same Heat Leak Mass (kg/m^2)**
1	5	25 (estimated)	1	16.6	18.4	2.82	20.7	7.7
2	4	31 (estimated)	0.82	13.4	14.8	2.63	16.7	6.2
3	3	41 (measured)	0.63	10.1	11.3	2.44	12.6	4.7

Table- 7 Performance of insulation (vacuum) (-196.5°C cold, 21.85°C hot)

In-atmosphere thermal performance								
Sr.No.	**LRMLI Layers**	**LRMLI Heat Leak (W/m^2)**	**LRMLI Thickness (cm)**	**Aerogel Same Heat Leak Thickness (cm)**	**SOFI Same Heat Leak Thickness (cm)**	**LRMLI Mass (kg/m^2)**	**Aerogel Same Heat Leak Mass (kg/m^2)**	**SOFI Same Heat Leak Mass (kg/m^2)**
1	5	4.0 (estimated)	1	6.6	82	2.82	8.3	34.4
2	4	5.0 (estimated)	0.82	5.3	65.6	2.63	6.6	27.5
3	3	6.6 (measured)	0.63	4	49.2	2.44	5	20.7

- In-air results (for LRMLI* heat leak per unit thickness): 18 times advantage over SOFI, 16 times advantage over aerogel.
- On-orbit results (for LRMLI* heat leak per unit thickness): 78 times advantage over SOFI, 6 times advantage over aerogel.
  *LRMLI - Load Responsive Multilayer Insulation

5.4 Takeshi Miyakitaet al [4]:-In this paper, the use of NICS MLI (Non-Interlayer-Contact Spacer Multi Layer Insulation) has been shown so as to overcome the shortcomings of conventional MLI (Multi Layer Insulation) systems. For MLI, it is hard to control the density of layer, and this is accompanied by a reduction in thermal conductivity performance. This occurs due to the increased heat leak through the contact between the layers. The NICS MLI system incorporates discrete spacers which tend to exclude the interlayer contacts which are not certain. Polyetheretherketone (PEEK) is used for manufacturing the NICS MLI.

5.4.1 Material Specifications

- Double guarded rectangular boil-off calorimeter
- Boil-off tank with dimensions 300x236x236 mm^3
- Aluminum shroud with inner surface temperature as 276 to 353 K
- Liquid nitrogen (B. Pt. 77K)
- Wet type volume flow meter W-NK-0.5
- Soap film volume flow meter (50 ml)
- Mass flow meter CMS-9500

Table- 8 NICS MLI Specifications

Thermal Resistance	Diameter	Mass	Height	Cross-sectional area to length ratio
3.32x105 K/W	10 mm	0.101 g	6.9 mm	1.0x10-5 m

5.4.2 Result and Conclusion

- It was recorded that the NICS MLI(Non-Interlayer-Contact Spacer Multi Layer Insulation) showed poor thermal performance at higher temperatures compared to conventional MLI.
- This can be attributed to the fact that it has a smaller number of layers.
- However it was also observed that the NICS MLI had better thermal performance at lower temperatures and was found to be consistent.
- The resultant emissivity of the NICS MLI blanket is 0.0046 at temperature of 300 K.

5.5 D.W. Plachta et al [5]:-In this paper, the difficulties of storage of liquid hydrogen and liquid oxygen are discussed. The two liquids are to be used as propellants for space crafts and other applications. The researchers were able to obtainzeroboil off (ZBO) condition for both liquid hydrogen as well as liquid oxygen without the use of cryocoolers. The use of several shades was employed so as to protect the tanks from the sun, as well as the spacecraft bus. The colder liquid hydrogen tank was also protected from the comparatively hotter liquid oxygen tank. This also had a major effect on the insulation of the surface temperatures of the propellant tanks. These passive concepts of insulation improve the application of cryogenic propulsion dramatically.

5.5.1 Material Specifications

- MLI (Multi Layer Insulation) blankets with emissivity of 0.004
- FOSR (Flexible Optical Solar Reflector) cover sheet for MLI
- Foam thickness of 1.8 cm and consisting of 45 MLI layers
- PODS (Passive Orbital Disconnect Struts)
- SOTA (State-of-the-art) struts

5.5.2 Result and Conclusion

- Zero boil off [ZBO] of cryogenic propellants can be achieved using passive cooling when not in low planetary orbits.
- Liquid Hydrogen tank requires protection from liquid oxygen tank for achieving passive cooling.
- Single shades can be used for passively cooling the liquid oxygen tank which protects it from the spacecraft bus.
- For reducing the strut heating, PODS(Passive Orbital Disconnect Struts) are necessary.

VI. REVIEW TABLE

Sr. No	Name of reviewer	Material used	Result
1	J.E FESMIRE	SOFI	Heat transfer minimization
2	F.SABRI	PCSA And RTV 655	Low thermal conductivity and improved mechanical strength.
3	S. DYE	LRMLI	Better performance than SOFI and aerogels.
4	TAKESHI MIYAKITA	NICS MLI	Good thermal performance at lower temperatures.
5	D.W. PLACHTA	MLI and PODS	Zero Boil offachieved.

- SOFI- Spray On Foam Insulation
- PCSA- Polyurea Crosslinked Silica-based aerogels
- LRMLI- Load Responsive Multilayer Insulation
- NICS MLI- Non-Interlayer-Contact Spacer Multi Layer Insulation
- MLI- Multi Layer Insulation

- PODS- Passive Orbital Disconnect Struts
- RTV 655- Room Temperature vulcanizing rubber 655

VII. CONCLUSION

Thus, we have covered several techniques of storage of cryogenic propellants here. We saw that the Load Responsive Multi Layer Insulation (LRMLI) has a distinct advantage over other methods when it comes to storage of cryogenic fluids (propellants in this case) at lower temperature spectrum. However, further advancements are required to improve the existing methods so as to achieve zero boil-off state in a more efficient manner.

- The thermal performance of Load Responsive Multi Layer Insulation (LRMLI) is much better than SOFI and aerogels.
- Zero Boil-off can be achieved by passive cooling without the use of cryocoolers.
- For better thermal Performance than conventional MLI, NICS MLI can be used.
- Combinations of PCSA and RTV 655 have thermal conductivities close to that of the individual components and provide better mechanical strength.

Key

- SOFI- Spray On Foam Insulation
- PCSA- Polyurea Crosslinked Silica-based aerogels
- LRMLI- Load Responsive Multilayer Insulation
- NICS MLI- Non-Interlayer-Contact Spacer Multi Layer Insulation
- MLI- Multi Layer Insulation
- PODS- Passive Orbital Disconnect Struts
- RTV 655- Room Temperature Vulcanizing rubber 655

REFERENCES

[1] J.E. Fesmire, B.E. Coffman, B.J. Meneghelli, K.W. Heckle: "Spray-on foam insulations for launch vehicle cryogenic tanks". Cryogenics 52 (2012) 251-261

[2] F.Sabri, J.Marchetta, K.M.Smith:"Thermal conductivity studies of a polyurea cross-linked silica aerogel-RTV 655 compound for cryogenic propellant tank applications in space". Acta Astronautica 91(2013)173–179

[3] S. Dye a, A. Kopelove, G.L.Mills: "Novel load responsive multilayer insulation with high in-atmosphere and on-orbit thermal performance". Cryogenics 64 (2014) 135–140

[4] Takeshi Miyakita, Ryuta Hatakenaka, Hiroyuki Sugita, Masanori Saitoh, Tomoyuki Hirai: "Development of a new multi-layer insulation blanket with non-interlayer-contact spacer for space cryogenic mission". Cryogenics 2014 http://dx.doi.org/10.1016/j.cryogenics.2014.04.008

[5] D.W. Plachta, R.J. Christie, J.M. Jurns, P. Kittel: "Passive ZBO storage of liquid hydrogen and liquid oxygen to space science mission concepts". Cryogenics 46 (2006) 89–97

[6] T.C. Nast, D.J. Frank, J.Feller: "Multilayer insulation considerations for large propellant tanks". Cryogenics 2014 http://dx.doi.org/ 10.1016/j.cryogenics.2014.02.014

[7] Son H. Ho, Muhammad M. Rahman: "Three-dimensional analysis for liquid hydrogen in a cryogenicstorage tank with heat pipe–pump system". Cryogenics 48 (2008) 31–41

[8] Mark S. Haberbusch, Robert J. Stochl, Adam J. Culler: "Thermally optimized zero boil-off densified cryogen storage system for space". Cryogenics 44 (2004) 485–491

[9] Ryuta Hatakenaka, Takeshi Miyakita, Hiroyuki Sugita, Masanori Saitoh, Tomoyuki Hirai:"Thermal performance and practical utility of a MLI blanket using plastic pins for space use". American Institute of Aeronautics and Astronautics, 2013, 1–11

[10] Thermal performance of multilayer insulations". NASA CR-134477,April 1974

[11] J. Fesmire, W. Johnson: "Thermal performance data for multilayer insulation systems tested between 293 K and 77 K". Space cryogenics workshop, 2013

[12] S. Mustafi, E. Canavan, W. Johnson, B. Kutter, J.Shull: "Subcooling Cryogenic Propellants for Long Duration Space Exploration". AIAA Space 2009 Conference &Exposition, AIAA 2009-6584

[13] A. Hoffman: "The thermal conductivity of cryogenic insulation materials and its temperature dependence". Cryogenics 46 (2006) 815-824

[14] William Notardonato: "Active control of cryogenic propellants in space". Cryogenics 52 (2012) 236–242

[15] Patrick R. Chai, Alan W. Wilhite: "Cryogenic thermal system analysis for orbital propellant depot". ActaAstronautica 102 (2014) 35–46