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Analytical Study of Aluminum Alloy Based Liquid Helium Dewar Vessel

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Abstract – The existing work compacts with 100 liter nominal capacity liquid He(helium) dewar that utilizes multi insulation system employing the cold from evaporated vapor of the hold on cryogenic liquid, the analytical investigation of aluminium alloy based liquid helium Dewar vessel. The work is administrated by estimating the heat leak apparatuses because of numerous origins like Heat leak through the neck tube by apparent solid conduction and fluid conduction that might be determined from the balance of the heat inputs to the liquid and vapor columns, funneling radiation heat leak from the neck high flange, radiation heat leak from the radiation shield, and heat leak by residual gas conduction within the vacuum area etc.

Keywords: Liquid Helium Dewar, Heat In-leak Numerical modeling, Aluminum alloy, Superinsulation

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1. INTRODUCTION

A cryogenic storage dewar (named after James Dewar) is a specialized kind of vacuum flask used for storage cryogens (such as liquid N or liquid He), whose boiling points are much lower than room temperature. Cryogenic storage dewars can proceeds a number of different forms as well as open buckets, flasks with loose-fitting stoppers and selfpressurising tanks. All dewars have walls constructed from two or more layers, with a high vacuum maintained between the layers. This provides excellent thermal insulation between the inside and exterior of the dewar, that reduces the speed at that the contents boil away. Precautions are taken within the design of dewars to securely manage the gas which is released because the liquid slowly boils. The simplest dewars permit the gas to escape either through an open high or past a loose-fitting stopper to prevent the risk of explosion.

More sophisticated dewars trap the gas higher than the liquid, and hold it at high. This will increase the boiling purpose of the liquid, permitting it to be keeping for extended periods. Excessive vapour pressure is released automatically through safety valves. The strategy of decanting liquid from a dewar depends upon its design. Straightforward dewars could also be tilted, to pour liquid from the neck. Self-pressurising styles use the gas pressure within the top of the dewar to force the liquid upward through a pipe resulting in the neck.

Cryogens present many safety hazards and storage vessels are designed to reduce the associated risk. Firstly, no dewar will give excellent thermal insulation and therefore the cryogenic liquid slowly boils away, which yields an enormous amount of gas. as an example, the expansion ratio of cryogenic argon from the boiling point to close is 1 to 847, liquid hydrogen 1 to 851, liquid He 1 to 757, liquid nitrogen 1 to 696, and oxygen 1 to 860. Ne has the highest growth ratio with 1 to 1438. In dewars with an open top, the gas simply escapes into the surrounding space. However, very high pressures will build up within sealed dewars, and precautions are taken to minimize the risk of explosion. One or more pressure-relief valves allow gas to vent away from the dewar whenever the pressure becomes excessive. In an incident in 2006 at Texas A&M University, the pressure-relief devices of a tank of liquid nitrogen were sealed with brass plugs. As an outcome, the tank failed catastrophically and exploded.

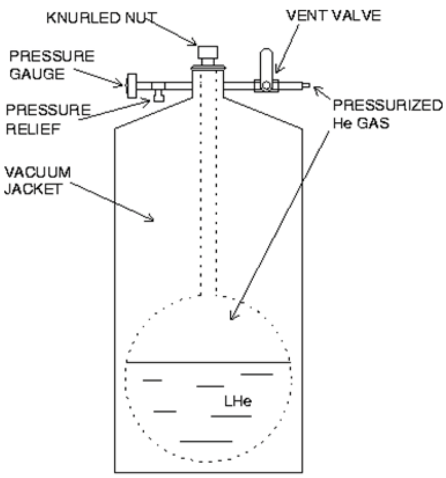

Figure 1 Diagram of Dewar

Ice will form on the inside of the dewar if it's left open to the air for extended periods. This may be very dangerous because the openings of the dewar can become blocked, resulting in a pressure build-up, and also the risk of explosion. The gas escaping from a dewar will step by step displace the oxygen from the air within the surrounding space, which presents an asphyxiation hazard. Users are proficient to only store dewars for the period of a well-ventilated space and earlier transferring dewars in an elevator, the excess gas pressure is vented away and also the dewars are sent unaccompanied to their destination [Randall F. Barron].

2. MATERIAL SELECTION

The choice of the materials and the design of the components are primarily dictated by their requirements, but one should not neglect their manufacturability and the capability of having them produced in an industrial context, in particular for large series production, where containment from economy of scale cost and commercial competition can be substantial.

In past various authors studied different materials and used for the several applications as per the requirement, these are tabulated in table 1.

Table 1 Different Materials Used for the Several Applications in Past

Application	Material
Lockheed ID dewar	6061 aluminum alloy
STEP dewar	Aluminum alloy
GP-B	8090 aluminum-lithium
Dewar for LEM spacecraft	6061 aluminum alloy
Storage tank by cryofab	SS304

2.1 Inner and Outer Shell

At present, Dewar vessels are made-up primarily using stainless steel. However, there are inherent associated limitations like increased weight and heat wastage in initial part of cooling. Consequently, material choice relies on thermal conductivity, Modulus of elasticity, Density, final tensile strength, manufacturability and price. As such, 6061-T6 serves as one of the prominent candidates for replacement of Dewar inner as well as outer vessel by using advanced construction such as waffle, ring stiffening for storage and vacuum shell to increase the strength.

Table 2 Dewar Vessel Materials Properties

Material	Yield strength (MPa)	Tensile strength (MPa)	Modulus (GPa)	Density (kg/m^3)
SS304	205	515	200	8030
6061-T6	240	290	70	2700
6063-T5	214	241	70	2710
7075-T5	95	220	70	2810
1100-H14	97	110	89	2780

2.2 Dewar Neck

Maximum heat in leak source to dewar is that the solid conduction over the neck wall, hence so as to maintain the lowest heat in-leak through apparent solid conduction, substantial is selected based on thermal conductivity, keeping final tensile strength constant. Comparison of various material based on thermal conductivity is presented in fig.2. Accordingly, glass fiber (G-10) has the lowest thermal conductivity and very good strength but a glass fiber becomes the brittle and fracture strength goes down so that needs to handle it properly. Joining of glass fibers with aluminum alloys by permanent join, so the optimized material for neck element amongst the available.

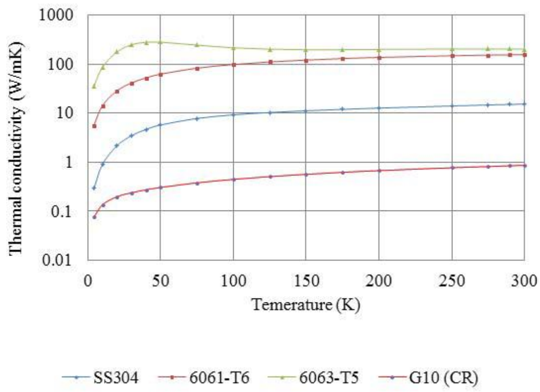

Figure 2: Thermal Conductivity of Neck Material

METHODOLOGY

Mechanical Design

Mechanical design is done as per requirement of 100 litres capacity with 10 percent of ullage space and found out the dimensions of vessel (shell and head dimensions).

Inner Vessel

Shell Design:

Total Volume of Vessel 100 lit+10% of 100 lit. 110 lit

Total volume consist the volume of shell and volume of torispherical head, for fining out the

length of shell we calculate the volume of torispherical head and shell separately.

Different parameters are given in Table 3, once we calculate the volume of torispherical head then use the equation 1 to find the volume of shell.

Total vessel volume = Volume of Shell +Volume of torispherical Head (1)

When we get the volume of shell, we **u**se equation 2 to find out the length.

$$\text{Volume of shell} = \frac{\pi}{4} D_i^2 L \qquad (2)$$

Table 3 Given Parameters of Dewar

	Parameters	SS304	Aluminium alloy
Inner Vessel	Total Volume (m^3)	0.11	0.11
	Internal design Pressure (MPa)	0.6	0.6
	Outside Diameter (mm)	508	450
	External Design Pressure (MPa)	0.101325	0.101325
Outer Vessel	Outside diameter (mm)	611	510
	Internal design Pressure (MPa)	0.3	0.3
Neck	Outer diameter (mm)	48	48

Torispherical head design:

1. Dimensions of torispherical head like depth of dish, inside corner radius, dish radius of head etc.

2. Thickness of head under internal pressure is calculated.

3. As mentioned in UG-32 for finding the allowable external pressure, need to calculate Factor A and Factor B. factor A is calculated and factor B find out from the intersection of factor A line and temperature/ material line in material graph as fig. 3 and fig. 4 respectively for SS304 and aluminium alloy.

4. After getting the value of factor B and get the value allowable external pressure.

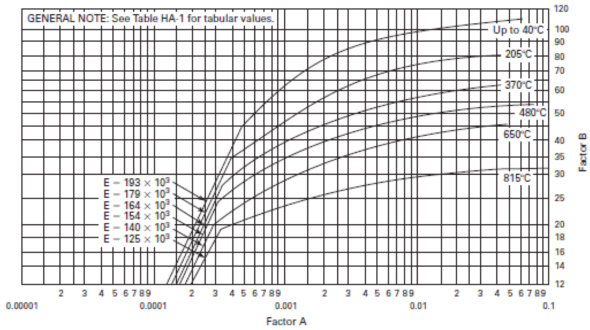

Fig. 3 Chart for Determining Shell Thickness Of Components Under External Pressure Developed For Austenitic Steel

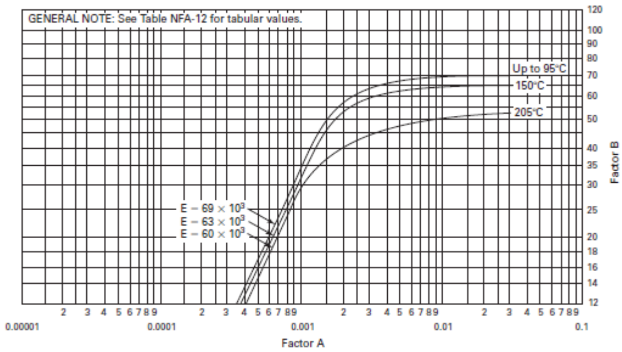

Fig. 4 Chart for Determining Shell Thickness of Components Under External Pressure Developed For Welded Aluminum Alloy

Calculation of reinforcement:

Reinforcement calculation on the opening on top torispherical head of inner vessel under the UG-37. For reinforcement calculation it is necessary to calculate the nozzle thickness, and done same thickness calculation of shell. Only change here that the material of aluminium alloys dewar is G-10 Glass fibre so need to take the strength of that respective materials. Thickness calculation is done. Once thickness is calculated, Area requirement and area available for reinforcement is calculated and check for adequate design.

Outer Vessel

Design of outer vessel is done by implementing the same procedure that is applied for inner vessel. Here design pressures selected are different than the inner vessel, 3 bar for internal design and 1.01325 bar for external design pressure.

Total length for outer vessel is considered as

Total length =Shell length of inner vessel +2×depth of dish +length of Neck

Finalized dimensions for SS304 based dewar are given in table 4.

Table 4 Finalized Dimensions for SS304 based Dewar.

		Length or Depth of Dish (mm)	Outer Diameter (mm)	Thickness (mm)	Materials
Inner Vessel	Shell	454	508	2	SS304
	Torispherical Head	84	508	3	SS304
Outer Vessel	Shell	900	611	3	SS304
	Torispherical Head	102	611	4	SS304
Neck		400	48	1	SS304

Table 5 Finalized Dimensions for 6061T6 based Dewar

		Length or Depth of Dish (mm)	Outer Diameter (mm)	Thickness (mm)	Materials
Inner Vessel	Shell	630	450	4	6061T6
	Torispherical Head	74	450	5	6061T6
Outer Vessel	Shell	1008	510	3	6061T6
	Torispherical Head	84	510	4	6061T6
Neck		400	48	3	Glass Fiber

Thermal Design

The following assumptions are made for the heat transfer calculations.

1. Steady state condition is used for the analysis.
2. Temperature of inner vessel, outer vessel over the control volume is constant for given time period.
3. Emissivity is assumed constant for analysis at 0.03 [11, 12].
4. Absorption of radiation occurs at inner vessel wall. Hence, funnelling possesses minimum value, which is negligible.
5. Constant heat flux condition and fully developed laminar flow of helium vapour through neck are approximated.

Schematic diagram of neck of dewar with discretization is shown below

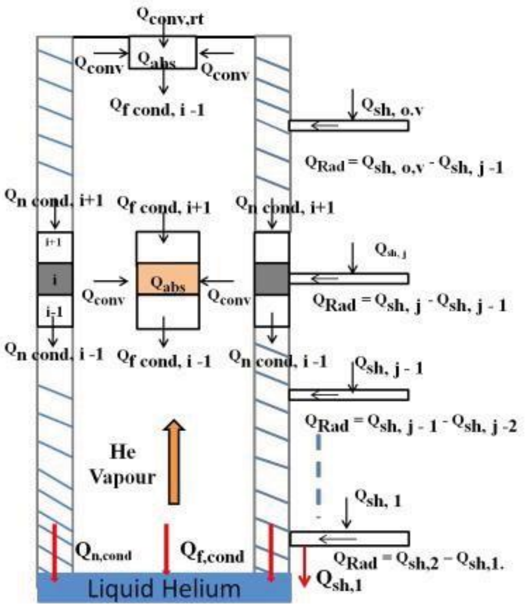

Figure 5 Heat Transfer Model for Neck

Schematic of thermal circuit as Shown in fig.

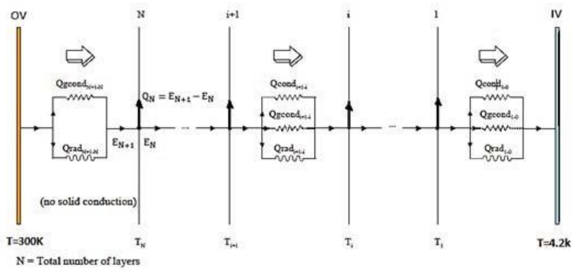

Figure 6 Thermal Network System for MLI after Anchoring to Neck

Details of Subparts of Dewar

Details of subparts of dewar are draw in Catia V5 modelling softer by using the dimensions. Figure 7, 8, and figure 9 shows the 3D models of dewar, cut section of 3D model and drafting of cut section with different views.

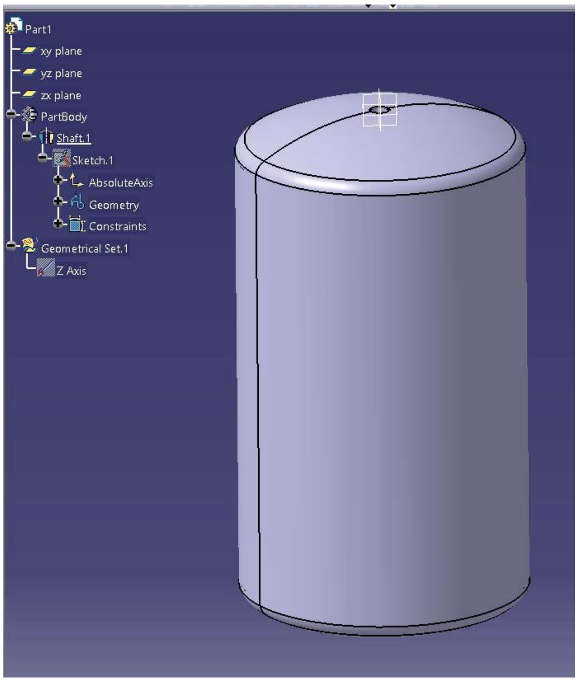

Figure 7: 3D Cad Models of SS304 based Dewar Vessel

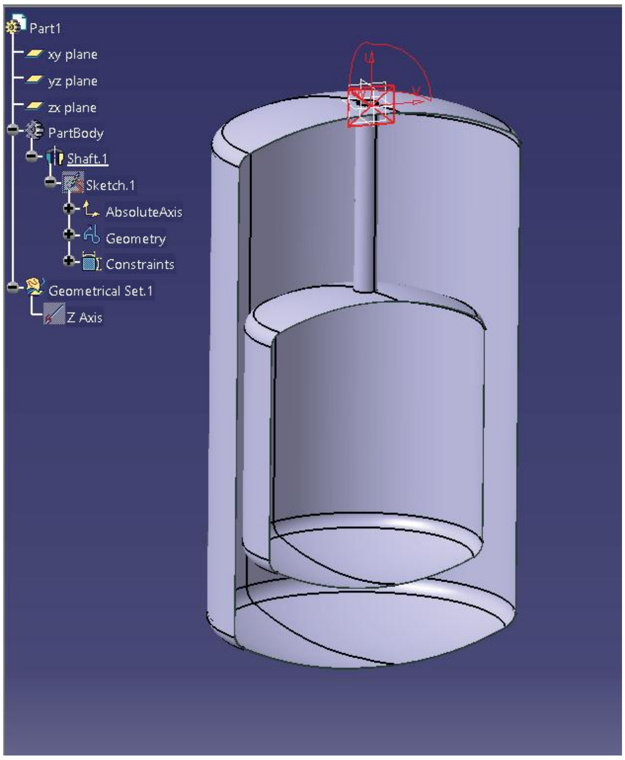

Figure 8 Sectional View Of 3D CAD Model of SS304 Based Dewar.

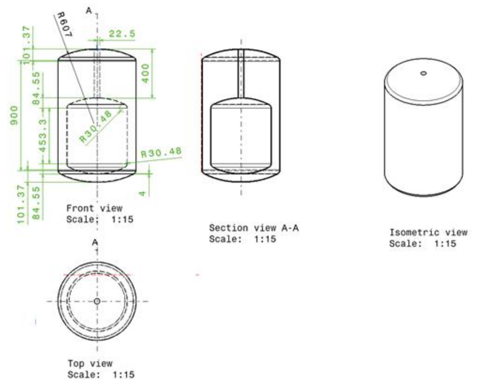

Figure 9 Drafting of Sectional View of 3D CAD Model of SS304 Based Dewar.

RESULT AND DISCUSSION

Model Validation

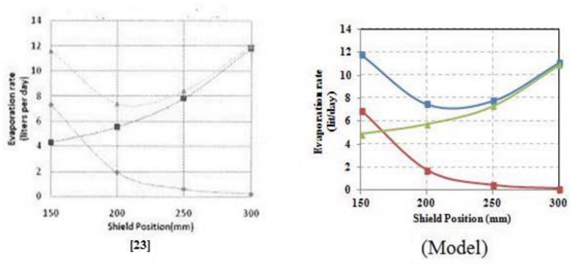

Figure 10 Validation of Theoretical Model

Different Cases for SS304 Based Dewar

Case1- No vacuum space (i.e. temperature of VCS is same as that of outermost layer of superinsulation blanket)

Case2- Always vacuum space provided in between VCS and MLI blanket & VCS and outer vessel

Case3- Comparison between heat in-leaks through VCS with superinsulation and without superinsulation (i.e. Vacuum alone).

Table 6 Heat in-leak (liters/day) to LHe Dewar, with Two Thermal Shields,20 layers between Outer Vessel and Shield-2, 20 Layers between Shield-2 and Shield-1, 10 Layers between Shield-1 and LHe, Shield-1 at 150 mm

	Conduction	Radiation	Total
Case 1	1.4274093	3.50538	4.93279
Case 2	2.9108775	0.6004	3.51127
Case 3	3.1020662	0.7007065	3.8027728

From the above comparison maximum and minimum possible heat in-leak might be calculated which requires the variety and deals better insight for further design.

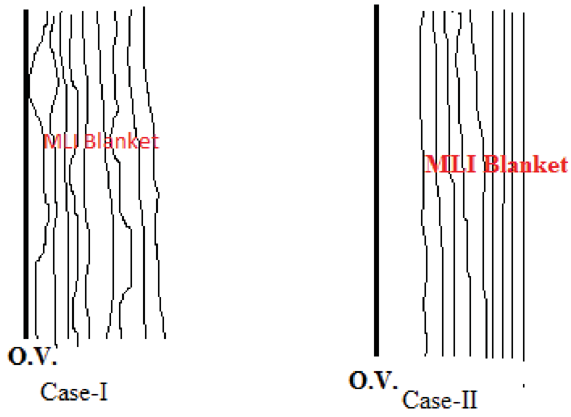

Figure 11 Different Cases for MLI Blanket and O.V or Thermal Shields.

Extension of Model for Al-Alloy Based Dewar

This is attributed to the increased area of inner vessel. The effect is also coupled with decrease in conduction due to low thermal conductivity of neck material.

Table 7 Heat in-leak to LHe Dewar (litters per day of LHe)

Material	By Conduction	By Radiation	Total
SS304	0.6808911	29.546359	30.22
6061-T6	0.000182	35.500995	32.501

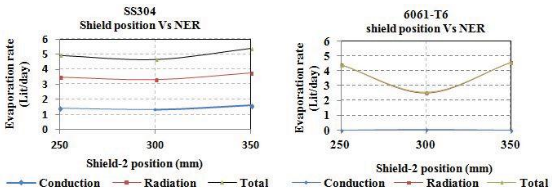

Figure 12: Comparison of Heat In-leaks for SS304 and 6061-T6 based Dewar for

Different positions of Shield-2

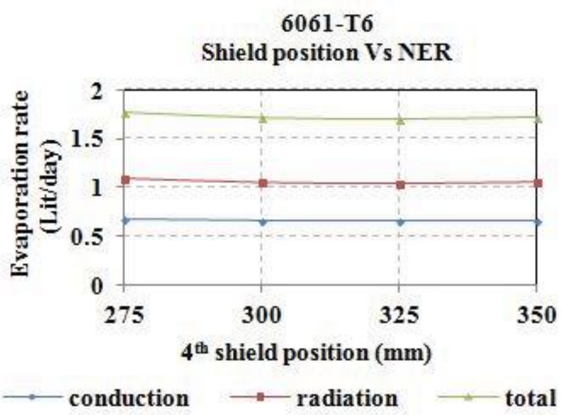

Figure 13: Heat in-Leak to LHe Dewar

For initial phase cooling Savings of weight and cryogen required

For calculating the weight and cryogen required for initial phase cooling we need to calculate the surface area of vessel

Surface area of Vessel= Surface area of Head + Surface Area of shell

$$\text{Surface area of head} = \frac{\pi \times (blank\ diameter)^2}{4}$$

Table 8 comparison of SS304 and Al-alloy Based Dewar w.r.t. Weight and Initial Phase Cooling

	SS304	Al alloy based
Volume (m3)	0.01144	0.01494
Mass (Kg)	92	40.5
Helium required for initial phase cooling (litres)	5.40	5.33

$$\%\ \text{of weight savings} = \frac{mass\ of\ SS304\ based\ dewar - mass\ Al\ alloy\ based\ dewar}{mass\ of\ SS304\ based\ dewar}$$

% of weight savings = 55.98 %

Cryogen required for initial phase cooling from room temperature to helium temperature is calculated as follow

$$\text{Cryogen required for initial phase cooling} = \frac{mc_p\Delta T}{h_{fg}}$$

CONCLUSION

The model is further extended to explore the range of minimum and maximum performance that could be theoretically claimed. Having completed it successfully, the model is finally utilized for aluminium alloy based Dewar. Other than reduction in weight by 56 % as compared to SS304 based dewar, The total heat in-leak is found to be reduced 50% to 60% less than that of SS304 based Dewar keeping number of thermal shield, positions of shield and number of superinsulation layers same. The shield positions are also ideally optimized by keeping all other geometrical and operating parameters constant. In addition to the thermal design of Dewar vessel, enough emphasis is given to the mechanical design as well. It is also seen that the amount of cryogen required for initial cool down is unaffected. Based on the above, it is observed that the NER and required number of MLI are significantly reduced compared to SS304 based helium Dewar of similar capacity.

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