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# Design and Analysis of Liquid Hydrogen Storage Tank

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*Abstract:*

**The storage of liquid hydrogen presents a promising solution for harnessing the energy potential of hydrogen, but it also comes with unique properties and challenges. This mini project delves into the intricate realm of liquid hydrogen storage, with the primary objectives of reviewing existing technologies and proposing a novel design for enhanced performance, safety, and corrosion resistance. The investigation begins with an exploration of the distinct characteristics and challenges associated with liquid hydrogen, emphasizing the critical importance of maintaining extremely low temperatures and addressing issues related to insulation and boil-off rates. Subsequently, the project conducts an exhaustive review of existing technologies and solutions in the field of liquid hydrogen storage, examining their advantages and limitations. In response to the findings from the review, this project proposes a novel design that aims to not only optimize the performance of liquid hydrogen storage but also enhance its safety and resistance to corrosion. The design incorporates innovative materials, insulation techniques, and safety features, while considering the practical aspects of storage, transportation, and utilization of liquid hydrogen. By focusing on these objectives, this mini project contributes to the advancement of liquid hydrogen storage technology, potentially opening new avenues for the efficient and sustainable utilization of hydrogen as a clean energy source.**

*Keywords:* **Hydrogen, Storage system, AISI Stainless Steel, RPF**

## 1. INTRODUCTION:

In a world where the pursuit of cleaner and more efficient energy solutions is paramount, liquid hydrogen emerges as a beacon of promise. Renowned for its high energy density, this transparent and volatile substance holds the potential to revolutionize various industries, from space exploration to aerospace and transportation systems [1-3]. However, the realization of this potential hinges on one critical aspect: the efficient and secure storage of liquid hydrogen. Picture this project as a compass guiding us through the intricate terrain of designing and scrutinizing liquid hydrogen storage tanks [4-6]. Our mission is clear: to delve into the nuances of design, emphasizing paramount factors like safety, material compatibility, and insulation [3, 6-8]. These considerations aren't mere technical details; they form the bedrock of ensuring that liquid hydrogen, with all its potential, can be harnessed safely and effectively.

The heart of our endeavor lies in the meticulous exploration of design elements. We're not just building tanks; we're crafting vessels that can withstand the challenges posed by the unique nature of liquid hydrogen [5-9]. Through the marriage of numerical simulations and computer modeling, we aim to dissect the structural integrity of these storage tanks under various conditions. It's not just about functionality; it's about reliability and safety—the keystones that unlock the true potential of liquid hydrogen as a clean energy solution. So, buckle up as we embark on a journey into the world of liquid hydrogen storage, where innovation meets responsibility, and every design choice reverberates with the echoes of a cleaner, more sustainable future. [4] Liu et. al. Hydrogen as a renewable energy source has gained significant attention for its potential to address environmental challenges by producing zero emissions. However, the effective storage of hydrogen remains a critical technical challenge across various sectors. In this literature review, we explore the design and analysis process of hydrogen storage tanks and the materials used for their manufacturing [4, 10-13]. The design process of hydrogen storage tanks involves adhering to standard guidelines and codes. One such code is I.S. :2825-1969 “Code for Unfired Pressure Vessels," which provides essential specifications and safety requirements for pressure vessels used in hydrogen storage. Through this code, engineers can calculate the thickness of storage tanks and ensure compliance with safety standards. The analysis process is equally important to assess the structural integrity and performance of storage tanks. By subjecting the tank designs to numerical simulations and finite element analysis, engineers can identify stress points and evaluate the tank's ability to withstand internal and external pressures. The analysis also includes thermal assessments to ensure proper insulation and minimize heat losses, essential for maintaining the cryogenic conditions required for liquid hydrogen storage. Material selection plays a crucial role in the successful design of hydrogen storage tanks. Composites are emerging as promising materials for such applications due to their high strength-to-weight ratio and resistance to corrosion. Notably, the website “Add Composites" provides valuable insights into the materials used for manufacturing hydrogen storage tanks [7, 11-13]. Engineers

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can explore various composite materials and their properties at cryogenic temperatures to ensure compatibility with liquid hydrogen and maintain structural integrity. the literature review highlights the importance of the design and analysis process in developing efficient and safe hydrogen storage tanks. By adhering to standards like IS :2825-1969, engineers can ensure compliance with safety regulations [13]. Moreover, the use of composite materials, as explored through "Add Composites," offers potential solutions to address the unique challenges associated with hydrogen storage. As research and advancements continue in this field, innovative storage tank designs and materials will play a vital role in unlocking the full potential of hydrogen as a clean and sustainable energy source [11-15].

## 2. DESIGN OF METAL BARRIERS FOR STORAGE TANKS

Depending on the liquefied gas to be retained, type-C tanks are insulated cylindrical, bi-lobe or tri-lobe tanks that can be fully or partially pressurized. Because of the cylindrical shape that improves material utilization in relation to internal pressure, the construction looks similar to that of a pressure vessel.

### 2.1 Selection of Metal Barrier Materials

Austenite in stainless steel has an excellent plastic deformation ability and a face-centered cubic crystal structure. Austenitic stainless steel retains its outstanding ductility and low-temperature impact resistance as its strength rises with temperature. Austenitic stainless steel was used for the tank construction of Suiso Frontier, the first hydrogen transport ship in history. It is preferable to use corrosion-resistant materials in the maritime environment in which ships operate. For instance, Mo can be added to 316 L stainless steel to increase its ability to withstand the corrosion of chloride ions, making it appropriate for use in ocean environments with high concentrations of salt spray. Because of this, the primary material for the metal barrier in this study is AISI type 316 L stainless steel [14], and excess stress is removed through the annealing process. The specifications of AISI type 316 L stainless steel are displayed in Table 1.

### 2.2 Metal barrier thickness calculation

When designing the thickness of the tank wall for tanks with a specific internal pressure, care must be taken to ensure that the liquid cargo is safe and leak-free, while also managing the tank's weight and maintaining economy. The China Classification Society (CCS) specifications can be used to calculate the wall thickness of Type-C tanks used to transport cryogenic liquid cargo. These tanks must meet the following requirements.
Regarding the cylindrical barrier plate's thickness in equation 1.

$t \geq (P_{eq}*Di)/ (2\quad m - P_{eq})$ …………………..…… (Eq.1)

where C is the corrosion addition, mm; m is the allowable membrane stress, take 131.25 N/mm2; di is the inside diameter of the tank, 26,380 mm; $p_{eq}$ is the internal pressure of the tank, take 0.45 MPa; and t is the barrier thickness, mm. The corrosion increment will be disregarded because the tank's corrosion-prone areas will be treated with anti-rust measures; 4 is the welded joint efficiency facto, so take 0.95 in this case.
The following formula can be used to express the thickness of a spherical end plate Equation: 2.

$t \geq (P_{eq}*Di\ y)/(2\quad m\quad - 0.5P_{eq})$ …………………. (Eq.2)

where y is the form factor, which for a spherical end is usually assumed to be 0.55. In addition to fulfilling the prerequisites listed above, plates in any region must not be thinner than, Equation:3.

$t \geq 3+((D_i)/1500)$ …………………. (Eq.3)

Finally, the thickness of the primary barrier is calculated be 4mm.

### 2.3 The secondary barrier

Generally speaking, liquid cargo tanks with a cargo temperature of 218 K (about 55 C) at atmospheric pressure must have an independent secondary barrier installed, under the IGC Code (International Code for the Construction, 1986). Additionally, the cryogenic liquid cargo must be contained in the secondary barrier for 15 days in case the liquid-tight main barrier is breached and spills. Thus, this research uses the same AISI Type 316 L stainless steel as the main barrier and develops the secondary barrier with a thickness that is consistent with that of the primary barrier for liquid hydrogen delivered at 20 K (~253 ~C).

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**Table – 1 AISI type 316L stainless steel (annealed plate) related parameters**

| Parameter names | Values | Units |
|---|---|---|
| Density | 8 x 10$^3$ | Kg/m$^3$ |
| Hardness, Brinell | 146 | N/mm$^2$ |
| Tensile strength, Ultimate | 560 | Mpa |
| Tensile strength, Yield | 235 | Mpa |
| Elongation at Break | 55 | % |
| Modulus of elasticity | 193 | Gpa |
| Charpy impact | 103 | J |

### 2.4 Design of tank insulation layer

The insulation layer structure in a physical model
The transportation tank for liquid hydrogen is made up of an insulation layer and two layers of barriers. The VCS and RPF combo is put between the metal primary and secondary barriers to create insulation. A drawing of the liquid hydrogen transport tank under design is shown in Fig. 1.

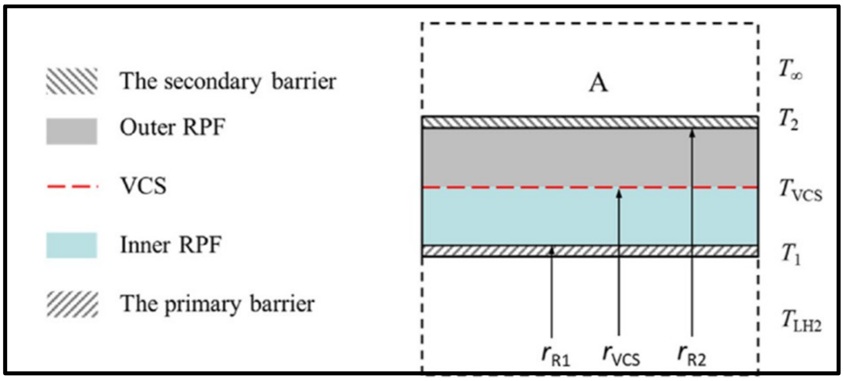

Fig – 1 Tank material used between the primary and the secondary barriers.

rR1 and rR2 are the radii of the cryogenic and hot boundaries of the insulation from the axis of the longitudinal axis of the tank; rVCS is the radii of the VCS heat exchanger tube in the insulation from the axis of the longitudinal axis of the tank; T1 and T2 are the surface temperatures of the cryogenic and hot boundaries of the insulation; Tin and Tout are the hydrogen temperatures of the inlet and outlet of the VCS heat exchanger tubes; The temperature of the VCS heat exchanger tube wall is denoted by VCS, whereas the surrounding air temperature is represented by T∞, which is 318 K.
The VCS heat exchanger tubes' material must be low temperature resistant and have strong thermal conductivity. AISI 316 L stainless steel heat exchanger tubes measuring 3 mm X 0.5 mm make up the VCS used in this study. There are 100 heat exchanger tubes in all, spaced and symmetrically distributed around the tank's longitudinal axis. To lessen heat transfer from the outer RPF, an insulating layer will grow on all of the tubes. The 3D schematic of the VCS heat exchanger tube layout is shown in Fig. 2. Because of the longer bending radius of the tube, which approximates a straight tube, the low-temperature hydrogen gas passes through the long, thin tubes.

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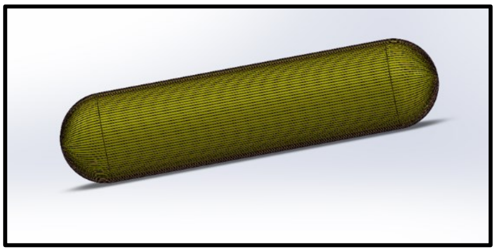


Fig – 2 3D schematic diagram of how the VCS heat exchanger tubes are laid.

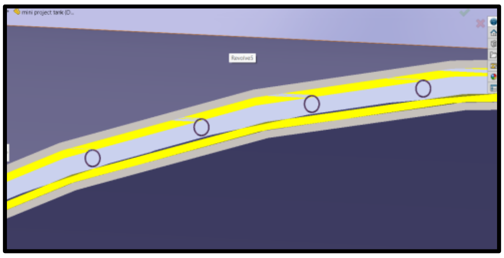


Fig – 3 the cross-sectional view of the tank

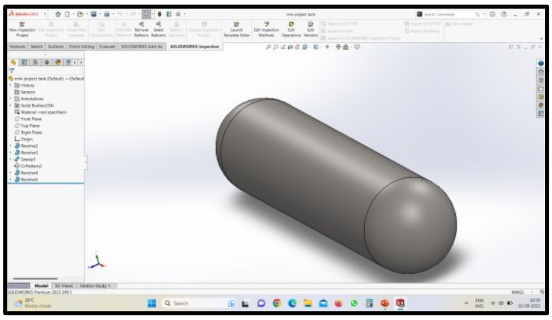


Fig – 4 the overall view of the tank

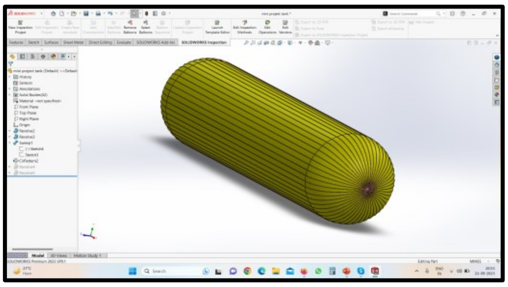
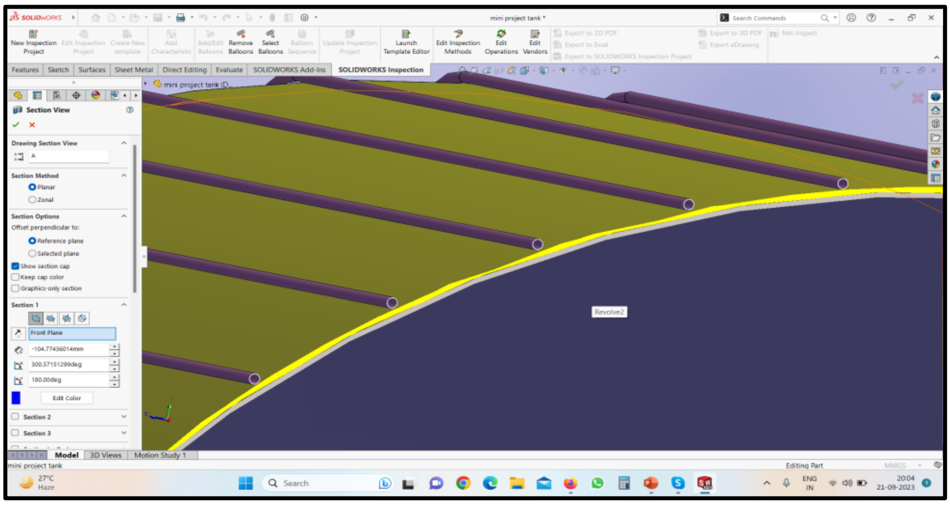


Fig – 5 3D schematic diagram of how the VCS heat exchanger tubes are laid in another orientation.



Section View

Drawing Section View: A

Section Method: ● Planar ○ Zonal

Section Options
Offset perpendicular to: ● Reference plane ○ Selected plane
☑ Show section cap
☐ Keep cap color
☐ Graphics-only section

Section 1: Front Plane
-104.77436014mm
300.57151299deg
180.00deg

☐ Section 2
☐ Section 3

Fig – 6 the 3 layers and cross sectional tank

## 3. ANALYSIS OF LIQUID HYDROGEN STORAGE TANK.

ANSYS Workbench can be used to analyses a liquid hydrogen storage tank in a number of processes, thus it's vital to divide the work into manageable chunks. An overview of the general actions you could take for a thorough study is provided below. Please be aware that the details may change depending on your design, the characteristics of the material, and other elements.

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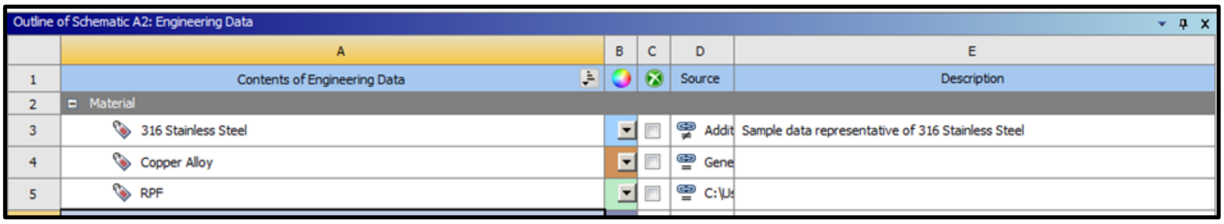
### 3.1. Material Adding:

In ANSYS Workbench, the process of incorporating materials into the Engineering Data section is a fundamental step in simulating the behavior of a liquid hydrogen storage tank. This involves defining material properties for each component, ensuring a comprehensive representation of the tank's construction. To begin, access the Engineering Data tab and create a new material by specifying its type, name, and basic properties such as density, thermal conductivity, and specific heat. Mechanical properties like Young's Modulus, Poisson's ratio, and yield strength are also defined, along with thermal expansion coefficients if applicable. Once the material is configured, it is assigned to the respective components within the model. It is essential to verify the accuracy of the assigned material properties and, if possible, validate them against reference data or experimental values. This meticulous process guarantees a robust foundation for subsequent analyses, providing a realistic simulation of the liquid hydrogen storage tank's performance under various conditions.



Outline of Schematic A2: Engineering Data

|  | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | Contents of Engineering Data |  |  | Source | Description |
| 2 | Material |  |  |  |  |
| 3 | 316 Stainless Steel |  | ☐ | Addit | Sample data representative of 316 Stainless Steel |
| 4 | Copper Alloy |  | ☐ | Gene |  |
| 5 | RPF |  | ☐ | C:\Us |  |

Fig – 7 Outline of Engineering Data

### 3.2. **Geometry and Meshing:**

#### 3.2.1.Import Geometry:

Importing the 3D model of a liquid hydrogen storage tank into ANSYS Workbench is a crucial initial step to ensure a reliable and accurate simulation. Within the ANSYS Workbench environment, access the geometry tab and either create or import the 3D model of the storage tank. It's imperative that the model faithfully represents the tank's physical structure, capturing all relevant details and intricacies. Check for any inconsistencies, such as gaps or overlaps in the geometry, and perform necessary clean-up to rectify any issues. The fidelity of the 3D model directly influences the precision of subsequent analyses, making it essential to invest attention to detail during this stage. Whether through CAD software integration or file import options, the goal is to establish a virtual representation that mirrors the real-world liquid hydrogen storage tank, ensuring the simulation results closely align with expected physical behaviour.

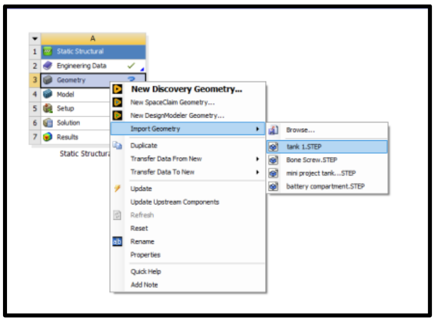


Fig – 8 Static structural

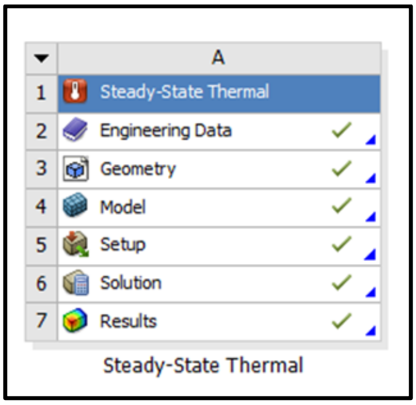


Fig – 9 Steady – state thermal analysis

#### 3.2.2. **Geometry cleanup:**

Inspect and clean up the 3D model in ANSYS Workbench to eliminate gaps or overlaps, ensuring an accurate representation of the liquid hydrogen storage tank's physical structure. Utilize geometry tools to identify and rectify inconsistencies, promoting the reliability of subsequent simulations. Carefully address regions impacting structural integrity or fluid dynamics. Confirm the resolution of all irregularities to guarantee a precise simulation outcome. This meticulous approach establishes a solid foundation for the analysis process.

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3.2.3. Meshing:

Create a high-quality mesh in ANSYS Workbench to accurately capture the geometry's features. Employ ANSYS Meshing tools to generate a refined mesh, particularly in areas requiring detailed representation. Ensure that the mesh density is appropriately adjusted to capture critical aspects of the liquid hydrogen storage tank's geometry. A fine mesh in key regions enhances the simulation's accuracy and resolution. Regularly review and optimize the mesh for an effective balance between computational efficiency and precision in the analysis.

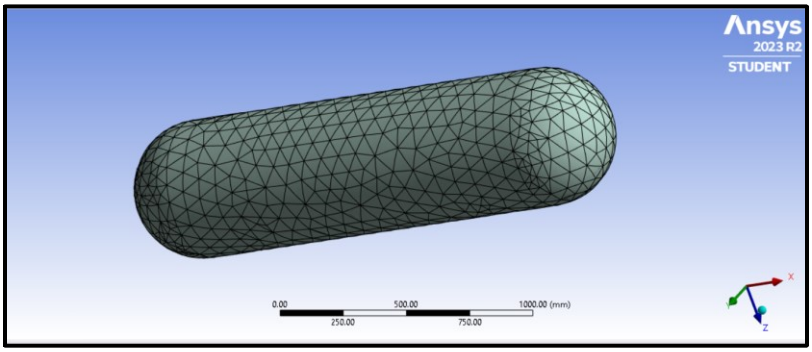


Fig – 10 Meshing of tank

The completion of body sizing with an 80mm element size and the selection of tetrahedral elements in ANSYS Workbench marks a crucial step in meshing the liquid hydrogen storage tank model. These choices impact the simulation's accuracy and computational efficiency, particularly in handling complex geometries. Validation through convergence testing and assessment of mesh quality, addressing distortions if any, is imperative. Additionally, ensure compatibility with the chosen solver and consider refinements like boundary layer meshing. This approach lays a solid groundwork for subsequent analyses, enhancing the reliability of simulation outcomes.

3.3. Material properties:

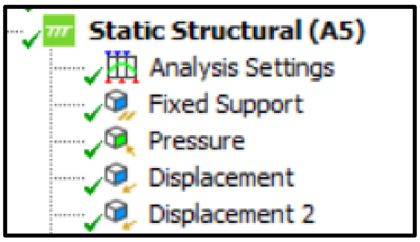
3.3.1. Define Materials**:**

Assigning material properties in ANSYS for the liquid hydrogen storage tank involves crucial considerations. Specifically, tailor parameters to reflect the cryogenic nature of liquid hydrogen, emphasizing low-temperature properties and thermal expansion characteristics. This meticulous approach ensures accurate representation in simulations, providing a foundation for reliable results.

3.4. Load and Boundary condition:

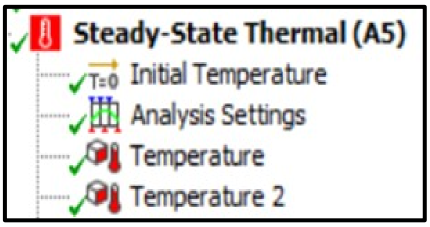
3.4.1. Apply loads :

In ANSYS, define the loads acting on the liquid hydrogen storage tank by specifying a pressure of 0.4 MPa exerted by the stored liquid hydrogen. Ensure accurate representation by considering the density and temperature of the liquid hydrogen. This load definition is essential for simulating the structural response of the tank, offering insights into its behaviour under the specific pressure conditions imposed by the stored substance.



**Static Structural (A5)**
- Analysis Settings
- Fixed Support
- Pressure
- Displacement
- Displacement 2

Fig – 11 loads applied in static structural



**Steady-State Thermal (A5)**
- Initial Temperature
- Analysis Settings
- Temperature
- Temperature 2

Fig – 12 loads applied in thermal analysis

3.4.2. Boundary conditions:

In ANSYS Workbench, establish constraints and supports to accurately represent the liquid hydrogen storage tank's interaction with its surroundings. Apply fixed constraints at one end to simulate structural anchoring. For thermal considerations, establish appropriate connections between different layers, ensuring realistic heat transfer behaviour.

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These constraints and supports play a crucial role in simulating the tank's structural response and thermal behaviour, providing insights into its performance under specified conditions and aiding in the assessment of safety and reliability.

### 3.5. Slover setup:

#### 3.5.1. Choose solver:

Choose the suitable solver, such as ANSYS Mechanical, in ANSYS Workbench based on the specific requirements of your analysis. ANSYS Mechanical is a robust solver for structural, thermal, and coupled-field simulations, offering a wide range of capabilities. Ensure compatibility with the chosen solver for your simulation type, allowing for accurate and efficient analysis of the liquid hydrogen storage tank's structural and thermal behaviour.

#### 3.5.2. Solver setting:

In ANSYS Workbench, configure solver settings for the liquid hydrogen storage tank analysis, specifying convergence criteria, time steps, and other parameters. This customization ensures accurate simulation results by controlling solution stability and temporal resolution. Optimal configuration enhances the reliability of structural and thermal behaviour predictions.

### 3.6. Analysis type:

#### 3.6.1. Steady state :

The liquid hydrogen storage tank underwent a steady-state analysis, accounting for internal pressure effects. This simulation focused on determining the structural response of the tank under constant conditions, providing insights into its stability and deformation characteristics.

#### 3.6.2. Thermal analysis:

In the thermal analysis of the liquid hydrogen storage tank, an internal temperature of -253 degrees Celsius was considered, reflecting the cryogenic nature of the stored substance. The external temperature was set at 30 degrees Celsius, mimicking real-world conditions. This thermal simulation aimed to assess how the tank responds to extreme temperature differentials, offering valuable data on its thermal behavior and potential thermal stresses.

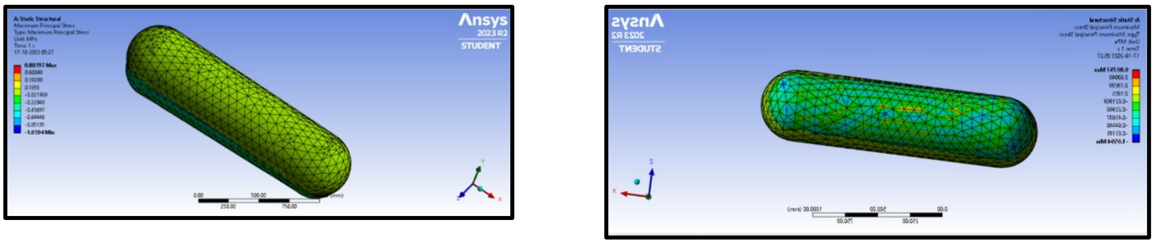
### 3.7. Solution:

#### 3.7.1. Run analysis:

Execute the analysis and monitor for convergence. Review results for any anomalies or unexpected behaviour.

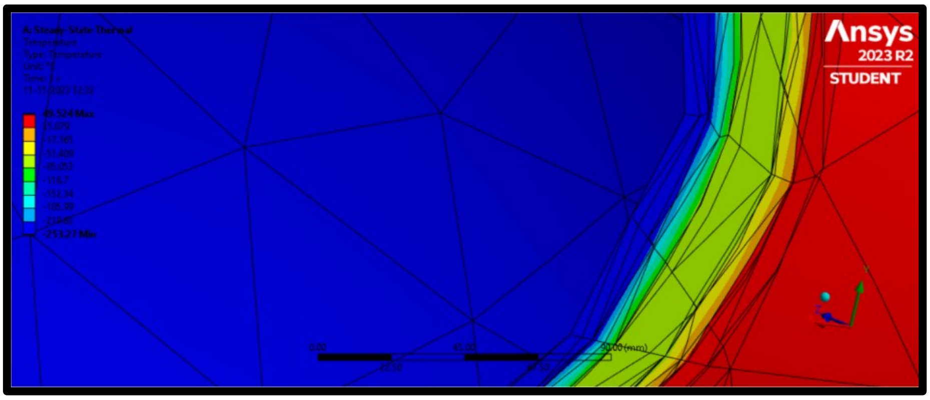
### 3.8. Post – Processing:

#### 3.8.1. Reviewing result:



(a) reviewing result of static structural

(b) reviewing result of static structural



(c) Fig – 13 (a) , (b) are reviewing result of static structural and (c) is reviewing result of steady – state thermal

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3.8.2. Generating results :

Static structural

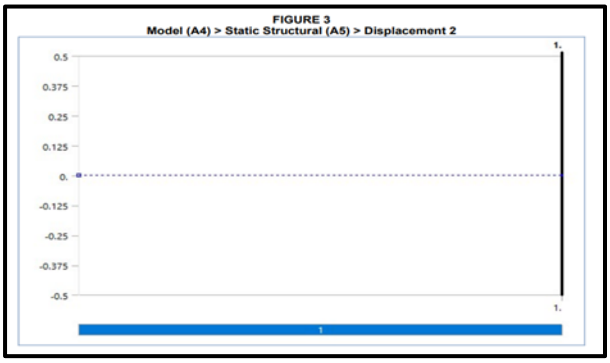


Fig – 14 Displacement graph

Solution :

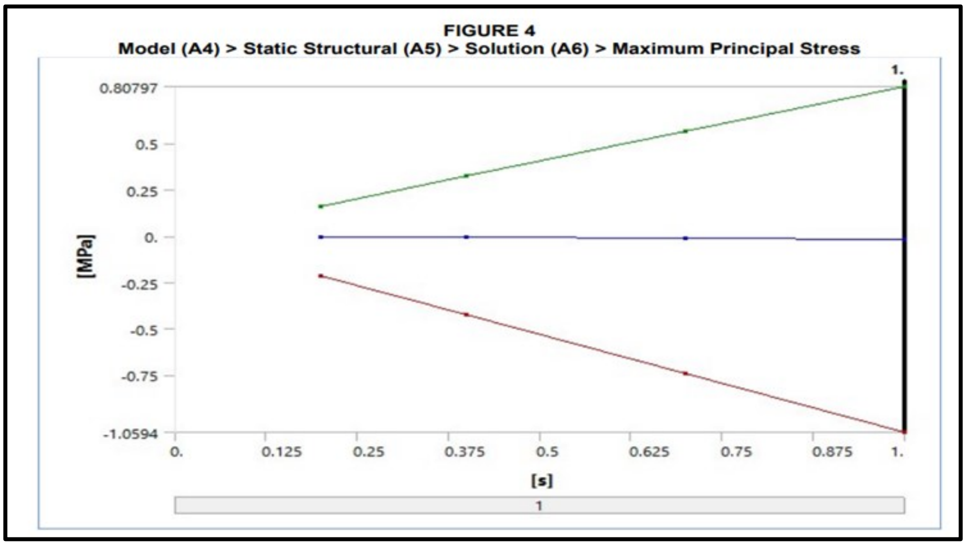
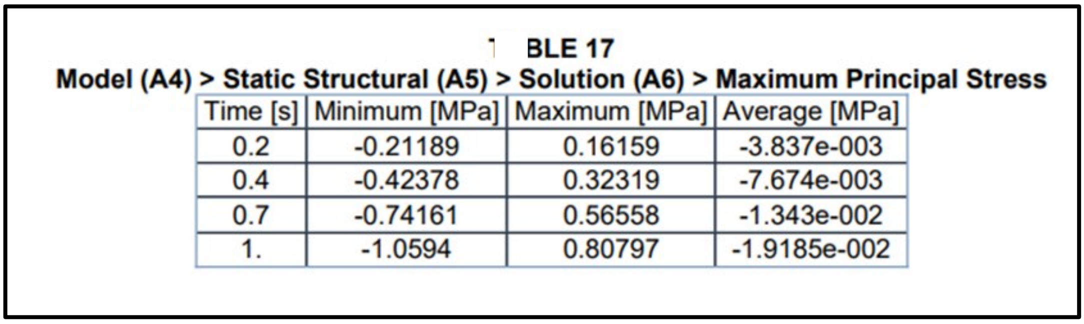


Fig – 15 Maximum principle stress  graph



BLE 17

Model (A4) > Static Structural (A5) > Solution (A6) > Maximum Principal Stress

| Time [s] | Minimum [MPa] | Maximum [MPa] | Average [MPa] |
|---|---|---|---|
| 0.2 | -0.21189 | 0.16159 | -3.837e-003 |
| 0.4 | -0.42378 | 0.32319 | -7.674e-003 |
| 0.7 | -0.74161 | 0.56558 | -1.343e-002 |
| 1. | -1.0594 | 0.80797 | -1.9185e-002 |

Table – 2 maximum principal stress results

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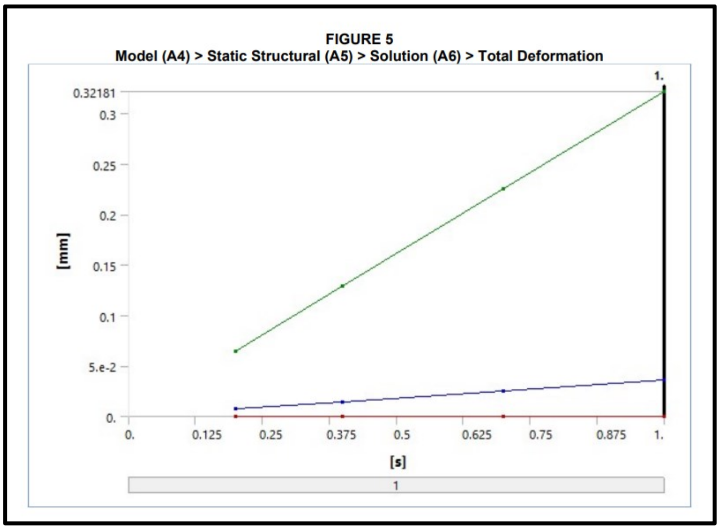
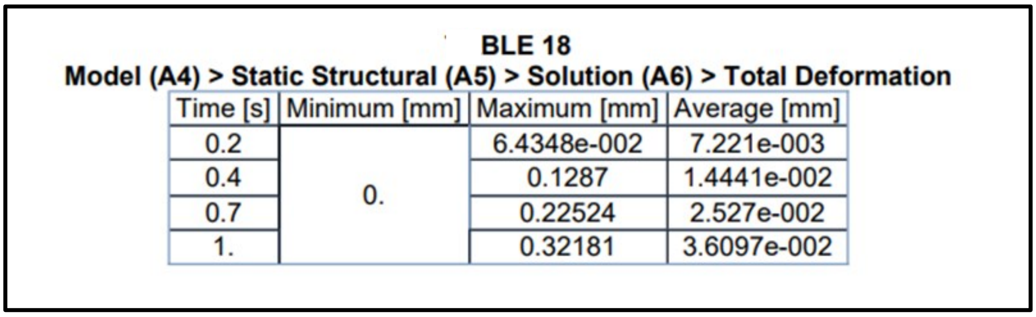


Fig -16 Total deformation graph



BLE 18

Model (A4) > Static Structural (A5) > Solution (A6) > Total Deformation

| Time [s] | Minimum [mm] | Maximum [mm] | Average [mm] |
|---|---|---|---|
| 0.2 | 0. | 6.4348e-002 | 7.221e-003 |
| 0.4 | | 0.1287 | 1.4441e-002 |
| 0.7 | | 0.22524 | 2.527e-002 |
| 1. | | 0.32181 | 3.6097e-002 |

Table – 3 total deformation result

**Thermal analysis:**

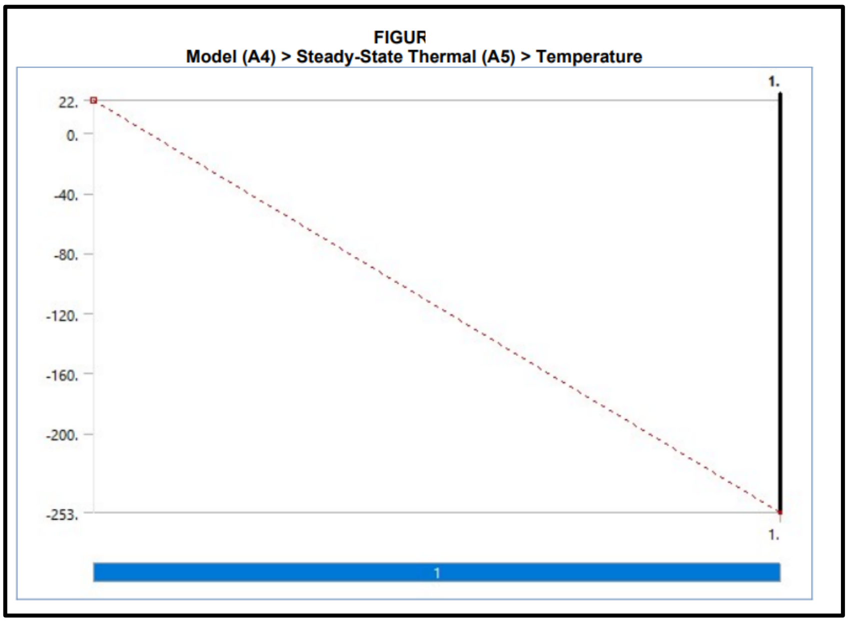


Fig – 17 Temperature graph

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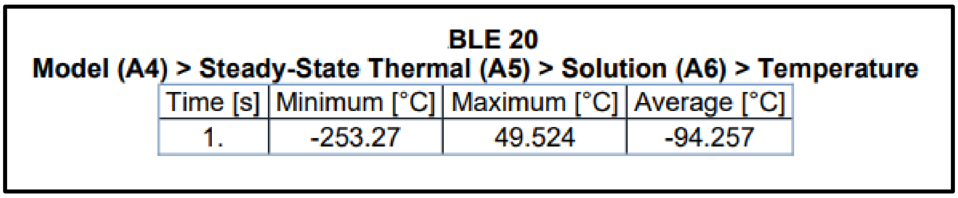

BLE 20
**Model (A4) > Steady-State Thermal (A5) > Solution (A6) > Temperature**

| Time [s] | Minimum [°C] | Maximum [°C] | Average [°C] |
|---|---|---|---|
| 1. | -253.27 | 49.524 | -94.257 |

Table – 5 Result

The figures and tables presented illustrate the results of the thermal analysis of the tank. Figure 14 shows that there is no displacement of the tank due to the high strength materials used in its construction. Figure 15 shows that the maximum principal stress induced in the tank is 0.807 MPa. Table 2 provides the values of maximum stress with respect to time intervals. Figure 16 shows that the deformation of the tank is very low, around 0.3 mm. Figure 17 shows the maximum and minimum temperatures of the tank surfaces (inner and outer). Table 3 summarizes the total deformation results. Table 4 presents the results of the thermal analysis, reflecting the heat transfer through the layers and the maximum and minimum temperature limits. The inner surface temperature is -253 oC, which is required for storing the liquid hydrogen. Table 5 provides the final result of the thermal analysis.

## 4. CONCLUSION:

The combined steady-state and thermal analyses conducted on the liquid hydrogen storage tank have furnished a comprehensive understanding of its structural and thermal characteristics. The steady-state analysis, focusing on internal pressure effects, has illuminated the tank's behaviour under constant conditions, shedding light on its stability and deformation tendencies.

In parallel, the thermal analysis, with an internal temperature of -253 degrees Celsius and an external temperature of 30 degrees Celsius, delved into the tank's response to extreme temperature disparities. This dual-pronged approach provides nuanced insights into the tank's performance spectrum, offering critical information for evaluating safety, reliability, and efficiency in managing liquid hydrogen across a range of operational scenarios.

The integration of these analyses underscores the significance of a holistic assessment in ensuring the tank's optimal functionality and robustness.

## LIST OF ABBREVATION

AISI – American Iron and Steel Institute

RPF – Rigid Polyurethane Foams

VCS – Vapor cooled shield

$P_{eq}$ – Equivalent Pressure

T – Temperature

$_{m}$ – Allowable stress

t – Thickness of barrier ,mm

– Weld joint efficiency

y – Shape factor

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