Structural Tensegrity for Optimized Retention in Microgravity – (S.T.O.R.M.)

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Course: MAE 434W

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Abstract:

Cryogenic storage systems are essential components in aerospace applications to store propellants like liquid hydrogen (LH2) and liquid oxygen (LO2) at extremely low temperatures, maximizing thrust upon combustion. While current metal-based structures provide necessary strength and stability, they often compromise thermal performance, leading to significant boil-off losses. This project explores the integration of tensegrity structures into cryogenic tank support systems to minimize thermal bridges and optimize load distribution. By replacing traditional metal structures with lightweight, high-strength synthetic fibers and composites, we aim to minimize conductive heat transfer while maintaining structural integrity. This innovative design offers the potential to significantly reduce boil-off losses and improve the overall efficiency of cryogenic storage systems. A scaled model will validate the design through thermal and mechanical testing, aligning with NASA's objectives for long-term cryogenic storage solutions.

1 Introduction:

Cryogenic propellants, such as liquid hydrogen (LH2) and liquid oxygen (LOX), are integral to NASA's future space exploration missions, particularly for long-duration storage and transfer in space-based depots. LH2 is typically stored at a temperature of approximately -253°C (-423°F), while LOX is stored at around -183°C (-297°F). Maintaining these extremely low temperatures is critical to keeping these propellants in their liquid state and presents significant engineering challenges in thermal management and structural design [1]

Structural supports for cryogenic tanks must balance two conflicting requirements: providing sufficient mechanical strength to stabilize the tank under dynamic forces while minimizing conductive heat transfer to reduce boil-off losses. Conventional strut-based designs are robust but introduce significant thermal bridges, creating inefficiencies in long-term storage systems [2] .

To address these limitations, the S.T.O.R.M. (Structural Tensegrity for Optimized Retention in Microgravity) team is developing a novel cryogenic storage solution based on tensegrity principles. Tensegrity structures offer a promising alternative by minimizing contact points between the tank and its support system. Composed of tension-only members and isolated compression elements, these systems significantly reduce thermal bridges while maintaining structural stability in microgravity environments [3]. Moreover, their lightweight and modular nature makes them particularly suited for space aligning with NASA's goals for scalable and efficient designs for lunar and cislunar exploration [4].

This project focuses on developing a tensegrity-based structural support system for a space-based cryogenic propellant depot. The use of advanced materials such as Kevlar 49 and Graphite Carbon Fiber Reinforced Polymer (CFRP) to optimize thermal resistance, mechanical strength, and mass efficiency [5]. The goal is to demonstrate a significant reduction in thermal ingress compared to conventional designs, supporting NASA's objectives for Zero Boil-Off (ZBO) storage in space-based operations [6].

Figure 1-I Single Launch, Dual-Fluid Propellant Depot. Credit [1]

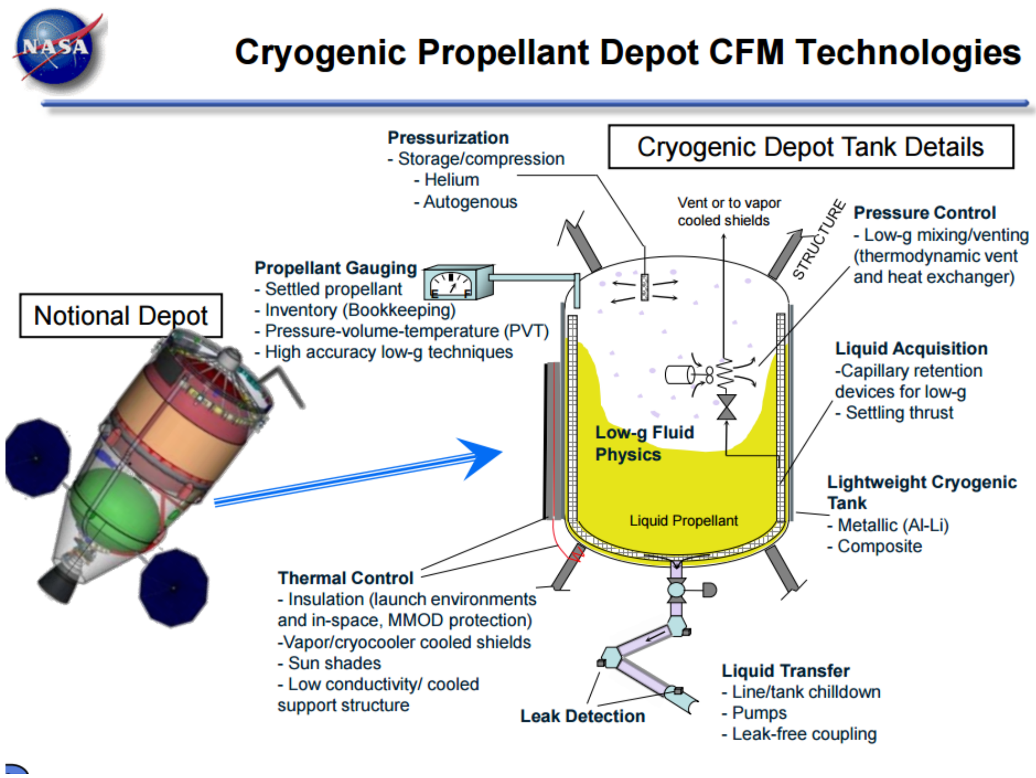
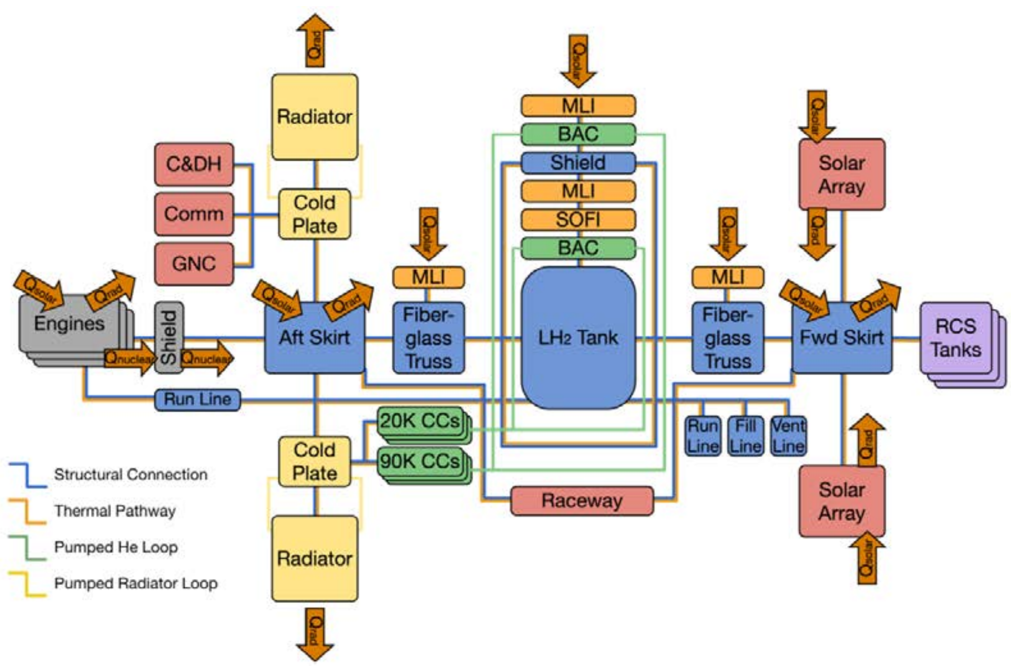


Figure 1-II Thermal Diagram of Core Stage showing heat pathways [7]



2 Completed Methods

2.1 Literature Review of Cryogenic Systems

A thorough review of cryogenic storage systems and materials was conducted to establish a foundation for the project. Key areas of focus included environmental challenges, material suitability, and existing tank designs.

2.1.1 Environmental and operational challenges

Thermal and Mechanical Requirements:

- Propellant depots must maintain temperatures of ~20 K for Liquid Hydrogen (LH2) and ~90 K for Liquid Oxygen (LOX) while exposed to heat sources such as solar radiation and Earth albedo [6].
- Structural supports are a primary source of thermal ingress, which contributes to propellant boil-off and reduces the efficiency of multi-layer insulation (MLI) systems [2].

2.1.2 Structural Challenges

Cryogenic tanks must withstand forces across all mission phases [2]:

- **Ground Testing**: Supporting the full weight of the tank and its contents under 1-g conditions.
- **Launch Thrust**: Withstanding axial loads and vibrations during ascent.
- **Orbital Maneuvers**: Ensuring stability in microgravity while counteracting dynamic forces.
- **Landing Engine Thrust**: Absorbing deceleration forces and potential uneven loads during surface landing.

Heat Transfer through Structural Penetrations:

- Structural penetrations through insulation layers act as thermal bridges, contributing to parasitic heat transfer and increasing boil-off rates.

2.1.3 Materials Evaluation

Advanced materials were evaluated based on their thermal resistance, mechanical properties, and compatibility with cryogenic temperatures. A summary of selected materials are presented in Table 2.1

Table 2.-1 Material Properties and Applications [5]

Material	Density (g/cm^3)	Young's Modulus (GPa)	Tensile Strength (MPa)	Thermal Conductivity (W/m·K)	Applications
Kevlar 49	1.44	112	3000	Very Low	Tension-only members in tensegrity supports
Graphlite CFRP	1.55	134	2340	Low	Hybrid tension-compression applications
Vespel SCP-5050	1.76	8.9	172	Very Low	Insulative components for structural joints
Al-Li Alloys	~2.7	76–80	440–600	Moderate	Compression members and tank walls

2.1.4 Thermal Management:

Multi-layer Insulation (MLI):

- A critical passive thermal control system that reduces radiative heat transfer from external sources such as solar and lunar radiation [1], [4].

Thermal Bridges (shorts):

- Traditional designs prioritize loads, rather than conductivity

Building on this foundation, the team has developed preliminary concepts for a tension-based support system that integrates cryogenic tanks with the lander's structural skirt. This approach aims to:

- Minimize conductive heat transfer by reducing the number of contact points.

- Maintain load-bearing capacity during high-acceleration conditions while ensuring thermal efficiency.

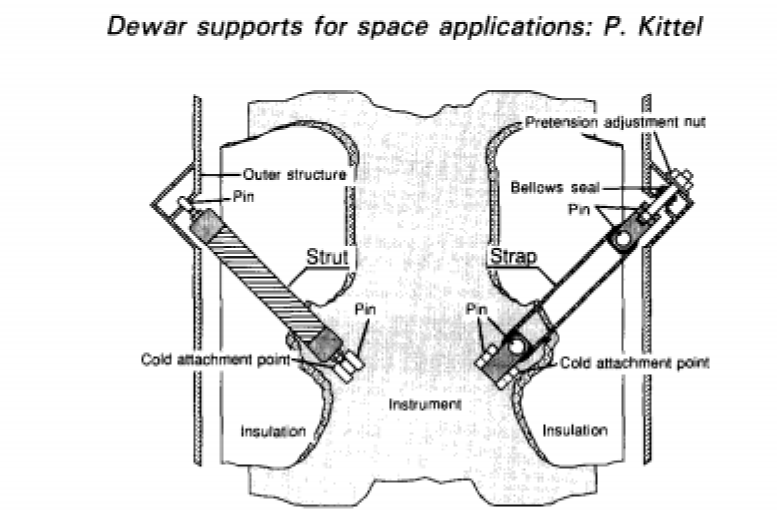


Figure 2-I A Schematic of Strut Vs Strap Supports [8]

3 Proposed Methods

3.1 Tensegrity-Based Structural Support Design

The proposed method focuses on developing a tension-based support system for cryogenic tanks, leveraging the unique properties of tensegrity structures. This design aims to overcome the challenges of conventional strut-based supports by minimizing thermal ingress and maintaining structural stability.

3.1.1 Design Objectives:

Thermal Management:

- Minimize conductive heat transfer by reducing the number and size of contact points between the tank and supports.

- Minimize or eliminate penetrations of high-performance insulation materials (e.g., MLI) with the support structure for enhanced thermal resistance.

Structural Integrity:

- Ensure load-bearing capacity during high-acceleration phases such as launch thrust and landing forces.
- Maintain stability during microgravity conditions while reducing weight to optimize the mass-to-volume ratio.

3.1.2 Design Process:

- Develop CAD models to visualize and analyze the tensegrity structure's geometry and performance.
- Select materials (e.g., Kevlar 49, Graphlite CFRP) based on their thermal and mechanical properties as identified in **Table 2.1**.

3.2 Finite Element Analysis

To validate the proposed design, simulations to be conducted using Patran due to its capability to define tension-only members and analyze complex structures by defining mesh nodes.

3.2.1 Thermal Analysis:

- Evaluate heat transfer through the tensegrity supports, focusing on minimizing thermal ingress across structural bridges [6].
- Simulate the impact of external heat sources, including solar and lunar radiation, on the integrated system.

3.2.2 Structural Analysis:

- Assess the performance of tension-only members under dynamic loading conditions, including launch thrust and landing forces [3].
- Ensure stability and load distribution under static and dynamic operational scenarios.

3.3 Model Fabrication and Testing

To support design validation, a physical model of the tensegrity-based support structure will be constructed. This model will serve to demonstrate key design principles and provide insight into potential challenges.

3.3.1 *Model Fabrication*:

- Construct a scaled-down physical model using lightweight materials to replicate the geometry and load-bearing characteristics of the proposed design.
- Include simplified representations of insulation layers (e.g., MLI) and attachment points to simulate interactions with the tank.

3.3.2 *Testing Environment*:

- Perform qualitative testing to evaluate the model's mechanical behavior under representative load conditions.
- Demonstrate the conceptual advantages of tensegrity structures in reducing thermal bridges and supporting dynamic loads.

3.4 Key Performance Metrics

The success of the proposed design will be evaluated based on:

3.4.1 *Thermal Performance*:

- 20% Reduction in thermal ingress compared to conventional designs [2].
- Conceptual demonstration of zero-boil-off (ZBO) capability during simulated storage.

3.4.2 *Structural Integrity*:

- Qualitative assessment of the model's ability to simulate load-bearing behavior under dynamic conditions.

3.4.3 *Design Feasibility*:

- Evidence of reduced thermal bridges and improved load distribution, aligning with the objectives outlined in **3.1**.

4 Discussion

The integration of tensegrity principles into cryogenic tank support systems presents a promising avenue for enhancing thermal performance and structural efficiency. Traditional metal-based supports, while robust, often compromise thermal performance due to high thermal conductivity. Structural penetrations in conventional designs, which act as significant thermal bridges, contribute to propellant boil-off and system inefficiency. The proposed design minimizes these thermal bridges by reducing the number and size of contact points between the tank and its supports, while maintaining load-bearing capacity during dynamic mission phases. The proposed use of tensegrity with advanced materials for cryogenic tank support leverages the unique properties of tension and low thermal conductivity to potentially alleviate the limitations of traditional metal-based designs.

While the potential benefits of tensegrity are significant, practical challenges must be addressed. One primary concern is maintaining uniform tension within the structure, which is crucial for its integrity. Any significant deviations, particularly during dynamic events like vehicle launches, could lead to structural failure. Additionally, the selection of suitable materials is critical. These materials must possess low thermal conductivity to minimize heat transfer, maintain high performance in extreme cold, and be readily available for manufacturing. While Table 2.1 presents promising materials, the absence of rigorous laboratory testing limits our ability to assess their suitability for this application. Further research and experimentation are necessary to validate the performance of these materials under cryogenic conditions and dynamic loads.

Our team will continue our research through rigorous prototype testing, focusing on materials like Kevlar 49 and Graphlite CFRP. This testing will encompass thermal conductivity, fatigue resistance, and environmental durability assessments. While constructing a full-scale cryogenic tank prototype is impractical, we will create a scaled-down model to validate our tensegrity design principles. The data collected from this model will be enhanced with computer modeling & simulations to approximate the performance of a full-scale system as a proof of concept.

4.1 Limitations

The current approach has several limitations that constrain its immediate applicability:

- The physical model represents a conceptual demonstration rather than a functional prototype. It does not account for all real-world conditions, such as microgravity effects and prolonged exposure to cryogenic temperatures.
- While finite element analysis provides valuable insights into thermal and structural performance, discrepancies between simulation results and real-world behavior are possible, particularly in dynamic environments such as launch or landing.
- Material properties, particularly at cryogenic temperatures, can vary from simulated assumptions. Experimental validation will be essential to confirm theoretical predictions.

4.2 Future Work

Future work will focus on addressing the limitations identified and advancing the proposed design:

- Perform iterative testing of the scaled model under simulated space conditions, including vacuum and cryogenic temperatures.
- Explore additional materials, such as aerogels, carbon nanotubes or other composites, to enhance thermal resistance.
- Refine finite element models to incorporate dynamic factors, including vibrations and transient thermal loads.
- Engage with NASA and industry partners to validate the scalability and operational feasibility of the design.

5 Appendices:

5.1 Budget:

Table 5-1 Hulc Budget Progress As of 12-24

Phase	Labor Hours	Labor Cost ($)	Material Cost ($)	Travel Cost ($)	Total Cost ($)	CBC	% Complete	CEV	CAC	CPI	CV	TCPI
NOI Submission	18	450	0	0	450	450	100%	450	450	1	0	1.00
Q&A Session & Prep	12	300	0	0	300	750	100%	750	750	1	0	1.00
Literature Review	35	875	0	0	875	1625	100%	1625	1875	0.87	-250	1.05
Material Selection	20	700	0	0	700	2325	100%	2325	2375	0.98	-50	1.01
Conceptual Design	60	1200	100	0	1300	3625	0%	0	2375			0.00
Structural Analysis	20	950	0	0	950	4575	0%	0	2375			0.00
Proposal Preparation	40	400	0	0	400	4975	0%	0	2375			0.00
Prototype Development	45	1125	500	0	1625	6600	0%	0	2375			0.00
Travel and Final Prep	16	400	100	3000	3500	10100	0%	0	2375			0.00

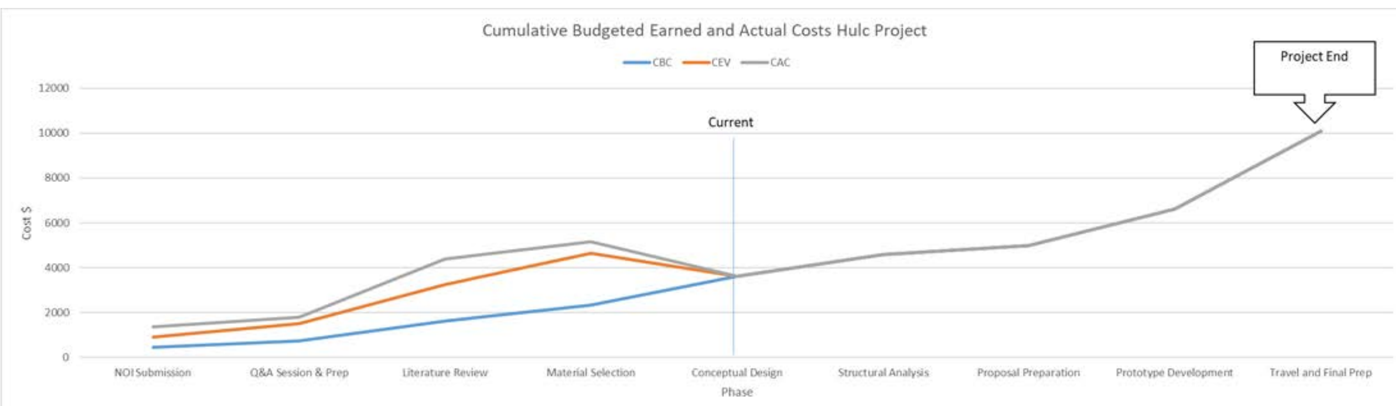


Figure 5-I Cumulative Budget Graph as of 12-24

5.1.1 Question 1 Are you on track with your budget?

Based on the **Cost Performance Index (CPI = 0.94)** and **Cost Variance (CV = -200)**:

- **CPI < 1:** Indicates that the project is slightly **over budget**, earning $0.94 of value for every $1.00 spent.
- **CV = -200:** A negative cost variance shows that the project has spent $200 more than the value of work completed so far.

Labor and Materials:

- **Labor Costs:** The total labor budget is progressing as planned, but actual spending on conceptual design has exceeded the value earned, which is driving the CPI below 1. This is likely due to underestimated labor hours.

- **Materials Costs:** No overspending has occurred on materials so far; the total budget for materials ($500) has been allocated appropriately, with no unexpected costs.

Adjustments Needed:

- **Increase Labor Efficiency:**
  - Focus on allocating time more effectively for tasks like **conceptual design** and **structural analysis** to avoid unnecessary hours and overspending.
- **Prioritize Critical Tasks:**
  - Delay or streamline non-critical tasks to maintain budget alignment while focusing on deliverables for the **proposal submission**.
- **Reassess Remaining Hours:**
  - Identify areas where labor hours can be reduced or shifted without compromising quality, particularly for low-completion tasks.

5.1.2 Question 2: How do you plan to remain on track (or get back on track) for MAE 435?

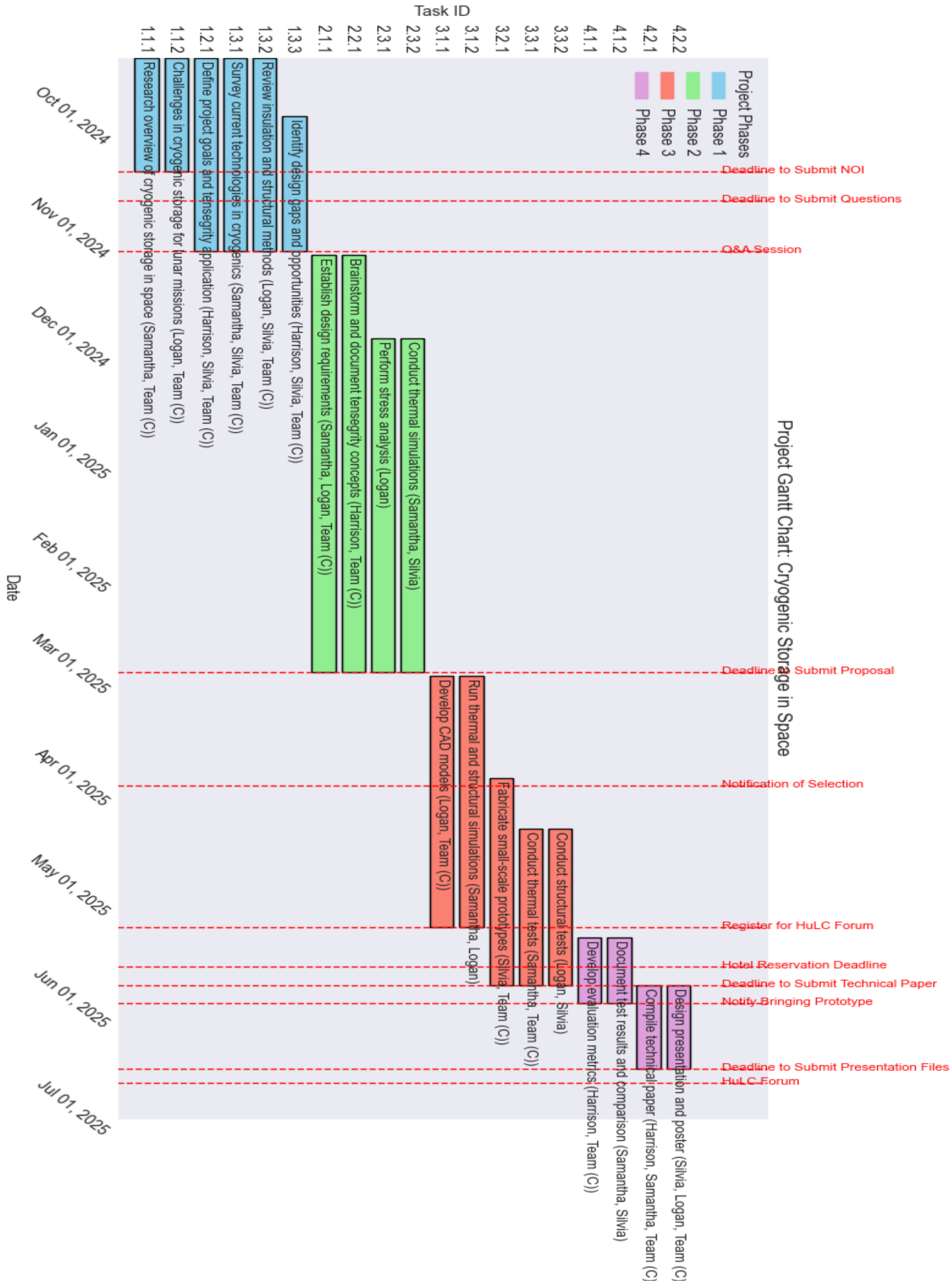
- **Regular Monitoring:**
  - Conduct weekly reviews of **CEV**, **CAC**, and **CPI** to ensure spending aligns with project progress. Update the budget and earned value calculations after every major milestone.
- **Focus on High-Value Tasks:**
  - Emphasize tasks with high completion percentages (e.g., material selection and proposal preparation) while ensuring adequate resources for the **prototype phase** during MAE 435.
- **Optimize Labor Allocation:**
  - Reevaluate the time spent on tasks. For MAE 435, aim to adhere to the suggested **6–10 hours per week per team member** to complete remaining work efficiently.
- **Budget Reallocation:**
  - If future phases (like travel or prototyping) show overspending risks, reallocate funds from non-critical categories.

5.2 Responsibility Assignment Matrix (RAM)

Table 5-2 P: RAM - Primary / S: Secondary / C: Collaboration

WBS Task ID	Task Description	Harrison	Samantha	Logan	Silvia	Collab	Due Date
Phase 1: Plan and Research							
1.1.1	Research and define the overview of cryogenic storage in space	S	S		S	C	October 16, 2024 (NOI)
1.1.2	Explain the importance and current challenges of cryogenics in lunar missions	S	S		S	C	October 16, 2024 (NOI)
1.2.1	Define the project's specific goals and focus on tensegrity-based supports	P	S	S	S	C	November 7, 2024 (Q&A)
1.3.1	Survey current technologies in cryogenic storage	P	S	S	S	C	November 7, 2024 (Q&A)
1.3.2	Review thermal insulation methods and structural integrity solutions	S	S	P	S	C	November 7, 2024 (Q&A)
1.3.3	Identify design gaps and opportunities for innovation	P	S	S	S	C	November 7, 2024 (Q&A)
Phase 2: Concept Development							
2.1.1	Establish thermal insulation and structural stability criteria	P	S	S	S	C	March 3, 2025 (Proposal)
2.1.2	Set material selection parameters (thermal conductivity, strength)	S	P	P	S		March 3, 2025 (Proposal)
2.2.1	Brainstorm and document potential design concepts for the tensegrity framework	S	S	P	S	C	March 3, 2025 (Proposal)
2.3.1	Perform stress analysis for structural integrity under lunar conditions	P		S	S		March 3, 2025 (Proposal)
2.3.2	Conduct thermal simulations to evaluate heat transfer reduction	P		S	S		March 3, 2025 (Proposal)
Phase 3: Design and Prototyping							
3.1.1	Develop CAD models for chosen design concepts	P	S	S		C	May 12, 2025 (Registration)
3.1.2	Run simulations for thermal and structural performance	P	S	S	S		May 12, 2025 (Registration)
3.2.1	Fabricate small-scale prototypes based on simulation outcomes	TBD- Depends on #				C	May 28, 2025 (Tech Paper)

5.3 Project Timeline – Gantt Chart



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