# Launch Vehicle Structure

# UC Irvine Rocket Project

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# 1. Problem Definition

## 1.1 Problem Statement Introduction

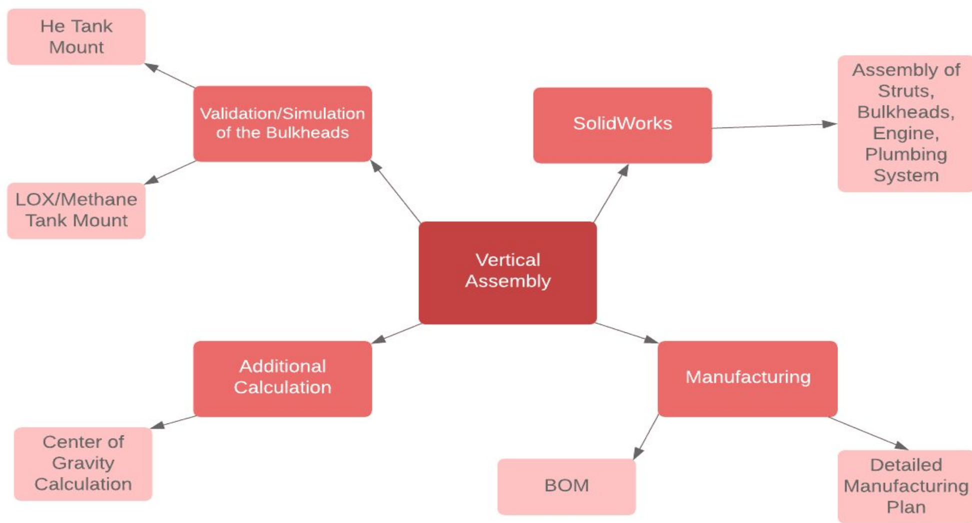
With the finalized strut and tank bulkhead designs and a complete layout of the plumbing system for PTR Launch Vehicle, the LV needs to integrate all of the sub-assemblies of the rocket to model a complete assembly of the vehicle. An accurate assembly of the system is necessary to perform flight load simulation and determining the center of gravity is essential for taking the next steps in designing the planform of fins.

As a vertical assembly engineer, simulate and determine the distribution of flight loads in the main structure given the parameters of PTR flight dynamics to test for the stability of the rocket. Then, present a vertical assembly of the rocket with all of the sub-assemblies integrated.

## 1.2 Primary/Secondary Research

1. Contacted Noah Yim who worked on tank mounts last quarter and obtained design reviews and requirements that were considered for the tank mount design
    - FOS must be at least 1.3 (requirement obtained from George from Winter 2020 Propulsion Team and modeled off of industrial FOS)
    - Buckling must be higher than 1.3 to account for drag forces on the skin
2. Talked to Srinath and Caitlyn to analyze the distribution of loads during flight
    - He tank force, LOX/Methane tank force, weight due to the plumbing system, weight of the structure, acceleration due to thrust, drag force (TBD)
3. Contacted Mariam to obtain an estimate of the weight of plumbing system
    - Obtained a BOM of the plumbing system made by Ananth from the Propulsion Team
4. Talked to Arthur and Cliff about mass updates on fins, nosecone, and propellants
    - Propellants:
        i. LNG: 8.97 → 16.41 lb
        ii. LOX: 26.04 → 47.59 lb
    - Fins: 3 lb
    - Nosecone: 12.65 lb
5. Contacted Collin Sledge from 195 Check-in about center of gravity calculation
    - Obtained an example of center of gravity calculation for aircraft on excel

### 1.2.1 Mind Map

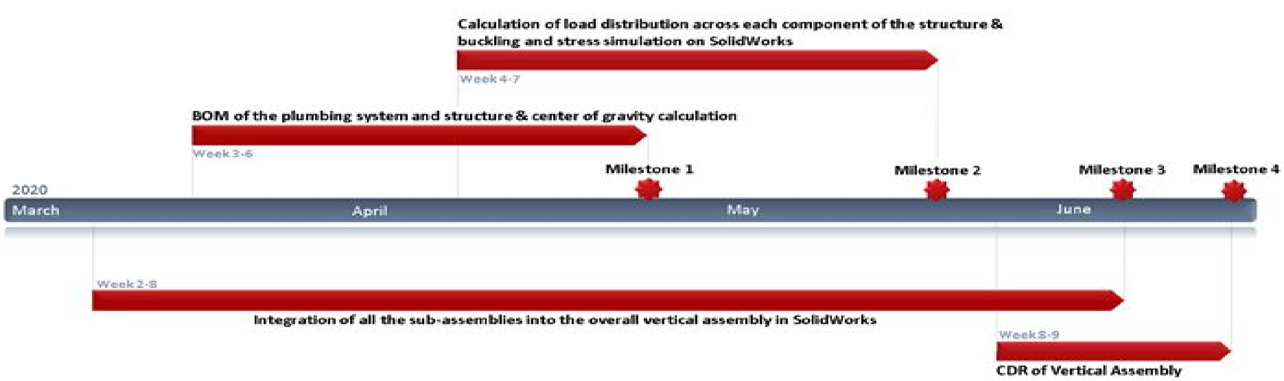



(*Figure 1: Brainstorm map of Vertical Assembly*)

## 1.3 Final Problem Statement

Starting Fall of 2019, the Launch Vehicle team has been making progress towards bulkhead and strut designs and completed the final design of the bulkhead and strut assembly by the end of 2020. To continue with the vertical assembly of PTR, the vertical assembly engineer needs to calculate the load distribution of the rocket across each component of the structure, in which the bucking and stress simulation on SolidWorks should have at least a factor of safety of 1.3. Furthermore, the final vertical assembly of the rocket must include all of the sub-assemblies and satisfy the following parameters: Rocket Skin ID: 12.75" inner diameter for the rocket skin, 12.75" outer diameter for vertical assembly and bulkheads, and around 22-24 ft for the overall height of the rocket.

### 1.3.1 Project Milestones

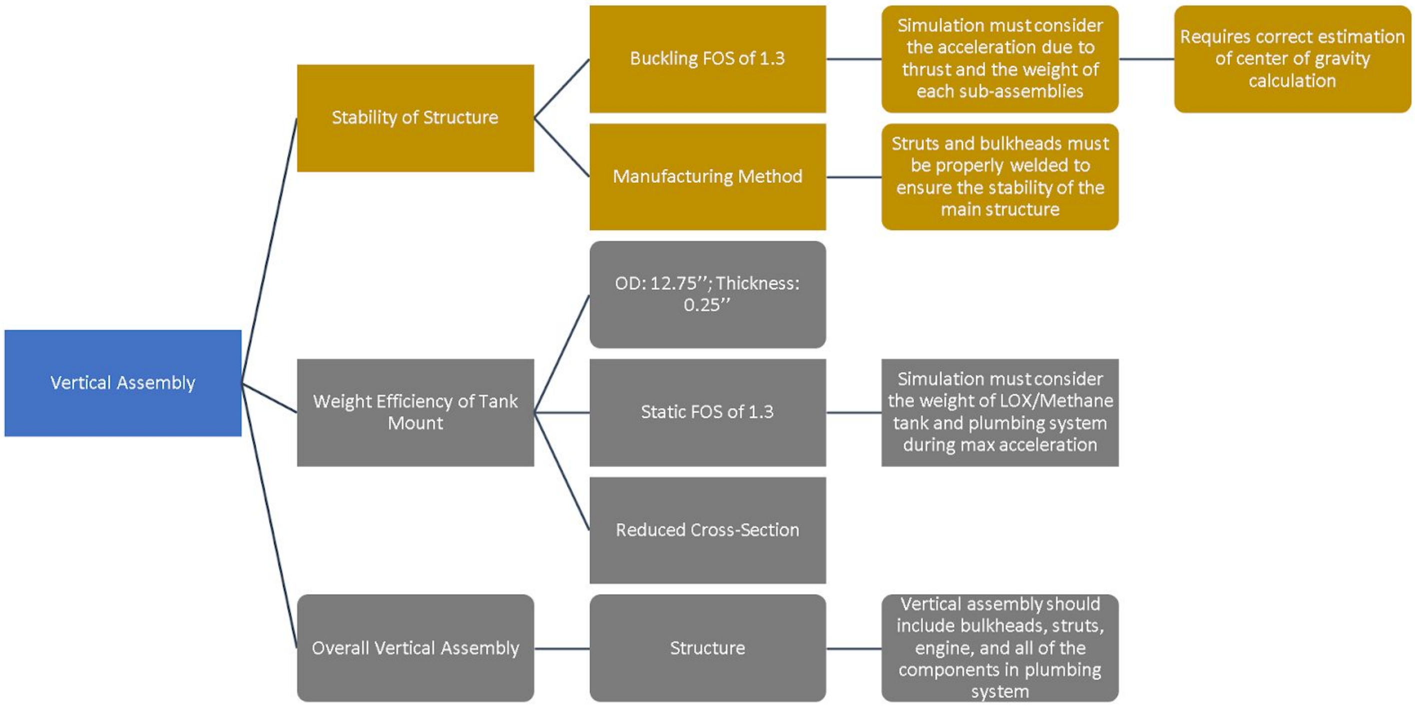



(*Figure 2: Project milestones diagram for Vertical Assembly*)

## 1.4 Design Attributes Table

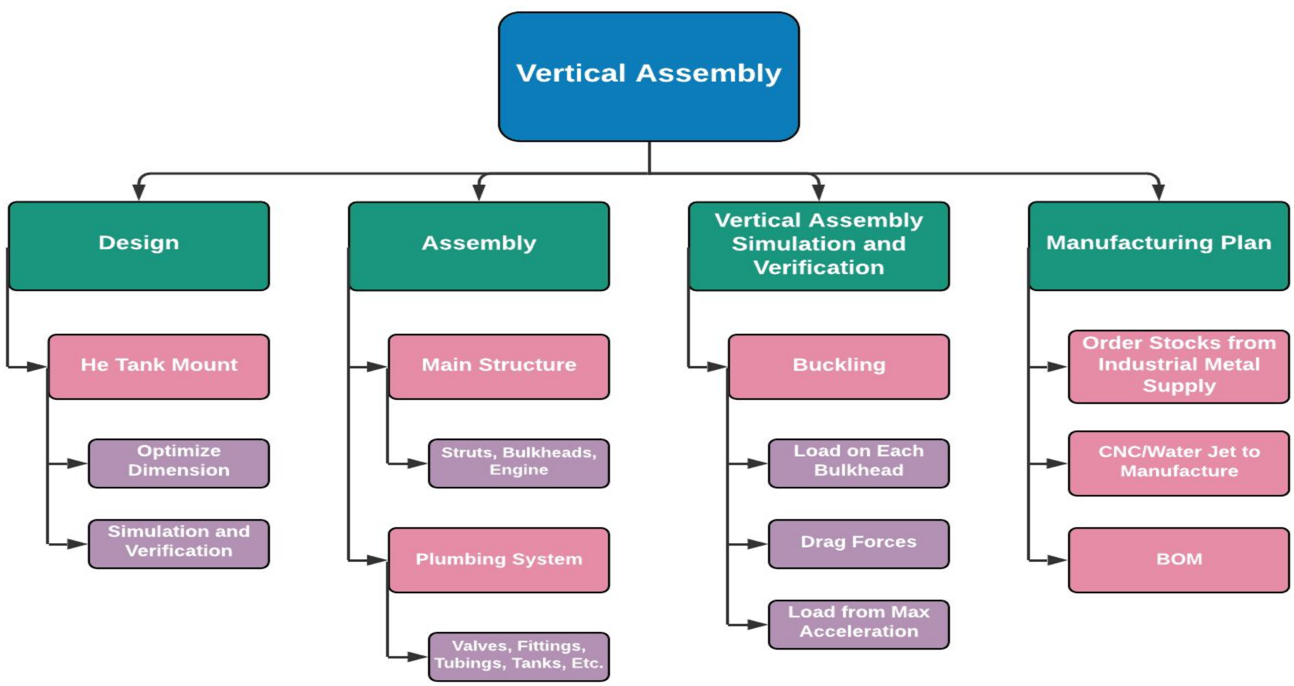
| A list of Vertical Assembly Attributes (O = Objectives; C = Constraints; F = Functions; M = Means) | | | | |
|---|---|---|---|---|
| **Characteristics** | **O** | **C** | **F** | **M** |
| Rocket Skin ID: 12.75" | | ✔ | | |
| Vertical Assembly/Bulkheads/etc. OD: 12.75" | | ✔ | | |
| Length Estimate: ~22-24 ft | | ✔ | | |
| Bulkheads FOS of 1.3 | | ✔ | | |
| Vertical Assembly Bucking FOS of 1.3 | | ✔ | | |
| All of the sub-assemblies in the Vertical Assembly should be securely mounted | ✔ | | | |
| Vertical Assembly should be weight efficient | ✔ | | | |
| The bulkheads and struts are 6061-T6 Aluminum | | ✔ | | |
| The weight of engine mount can be more efficient by reducing cross-section of the bulkhead | | | | ✔ |
| The structure of PTR should be stable during the flight | ✔ | | | |
| The bulkheads must support the weight of the tank and the plumbing system | | | ✔ | |
| The propellants must be secured to the tank mounts | ✔ | | | |
| The top bulkheads can be welded after securing the propellants to the bottom mount to provide extra support | | | | ✔ |
| Vertical Assembly should be cost efficient | ✔ | | | |

## 1.5 Objectives-Requirements Tree



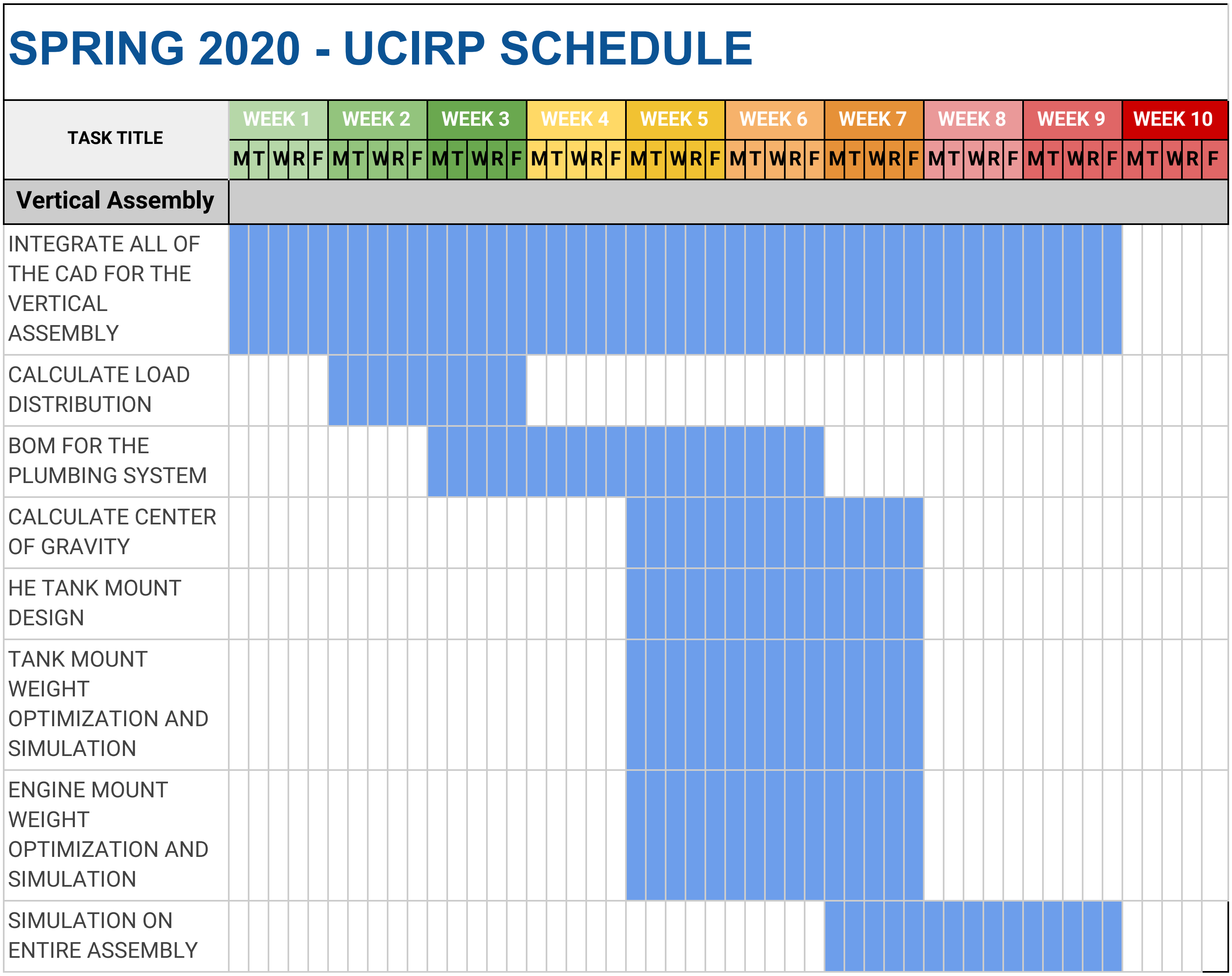

(*Figure 3: Preliminary objective-requirements tree*)

## 1.6 Work Breakdown Structure




(*Figure 4: Preliminary WBS*)

## 1.7 Gantt Chart



# 2. Preliminary Design

## 2.1 Concept Development

One of the main components of the Vertical Assembly is tank mount. Initial development of the tank mount with a critical design was produced by Noah Yim in the Winter of 2019 (see Appendix A). The dimensions of the tank mount were later changed in the Spring of 2020 from OD of 10.75” to 12.75”. The design of tank mount created by Noah was suitable for LOX as it needed to withstand the most amount of force from LOX and the plumbing weight, but the design was later modified for Helium and Methane bulkheads as the forces applied on these tank mounts were significantly lower than that of the LOX bulkhead. Therefore, preliminary designs for the Helium and Methane tank mounts were created as a placeholder before performing buckling analysis on the structure. A more extensive research for weight and geometry optimization can be done in the future.

## 2.2 Selection Process

Before performing buckling analysis on the structure, the dimensions of the rocket needed to be finalized. I had to work with the leads and complete a weight analysis on different dimensions of the following components: struts, tank mounts, and engine mounts. In the end, the leads decided the length of the rocket is around 22-24 ft with an OD of 12.75’’ as mentioned in the previous section.

| Mass (lb) | | | | |
|---|---|---|---|---|
| | Diameter (in) | | | |
| Length (ft) | | 10.75’’ | 11.41’’ | 12.75’’ |
| | 24’ | 50.95 | 55.75 | 66.25 |
| | 20’ | 46.12 | 50.92 | 61.42 |
| | 18’ | 43.72 | 48.52 | 59.02 |
| | 16’ | 41.32 | 46.12 | 56.62 |

(*Figure 5: Weight analysis on different bulkhead OD and strut length* )

## 2.3 Design Documentation

A structural analysis of the rocket is subjected to three major forces: weight, thrust, and drag. Thrust estimation was finalized with the selection of the rocket’s engine. However, weight and drag are dependent on other subsystems and due to these subsystems still in progress with design and verification, a rough estimation of 250 lbm was made for the ideal max rocket. The estimation includes the following subsystems: the plumbing system (134.92 lbm), struts and bulkheads (56.25 lbm), skins (23 lbm), chamber (20 lbm), nosecone (12.5 lbm), and payload (2lb). The drag is neglected for now due to incomplete fins and nosecone design. See Appendix B for the subsystems.

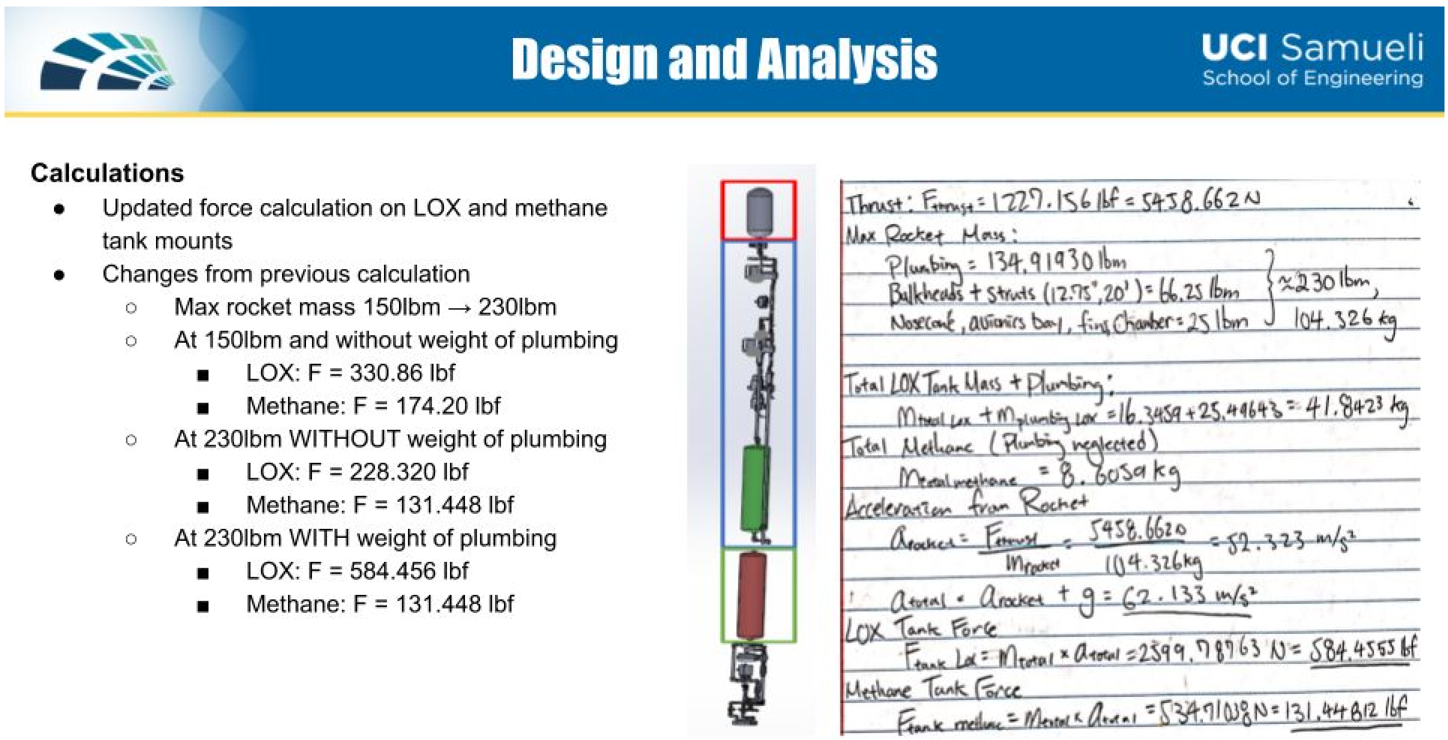
## 2.4 Design Development Summary

With updated dimensions, following the weight analysis of the rocket's structure, all of the subsystems were redesigned to have an OD of 12.75'' and length of 22-24 ft. A new estimation of the rocket's max weight of 230 lbm was then made to help define the parameters that are needed to perform buckling analysis on Vertical Assembly.

# 3. Detailed Design

## 3.1 Detailed Design Development

As mentioned in previous sections above, the dimensions of the overall rocket were updated, which affected the overall weight, acceleration, and distribution of weight of subsystems on each tank mount. This required a new calculation of the forces applied on Helium, LOX, and Methane tank mounts.

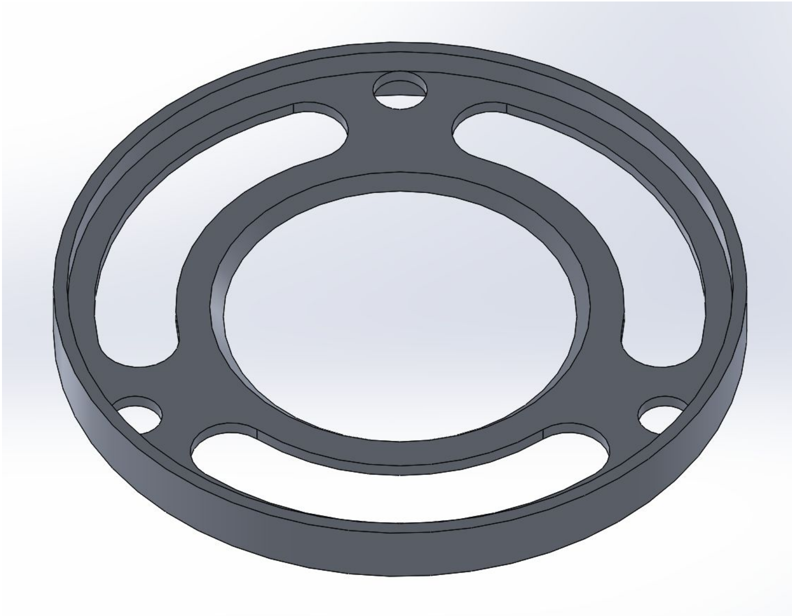



(*Figure 6: Preliminary acceleration and force calculation for Vertical Assembly*)

The original assumption of the max rocket mass 150 lbm increased to 230 lbm, which decreased acceleration from 90.082 m/s$^2$ to 62.133 m/s$^2$. Moreover, accounting the distribution of the weight of plumbing resting on top of each propellant increased the forces applied on LOX and Methane tank mounts. In the end, the force applied on LOX and Methane tank mounts came out to be 584.5 lbf and 131.4 lbf respectively.
A new estimation of the maximum rocket mass shifted the center of gravity. The center of gravity calculation of the plumbing system can be found in Appendix C. The weight of nosecone, fins, chamber, skins, and payload will be added before running the buckling analysis to account for the overall weight of the rocket and the location in which the load is applied at.

As shown in the force calculation for each tank, the Methane and Helium tank mounts are subjected to considerably smaller magnitude of forces than the LOX tank force. This allows for removal of excess weight on

Methane and Helium tank mounts. Although a more extensive research on designs can be made for maximum weight optimization, there was not enough time to finalize the designs. Therefore, a design concept shown below, which was mentioned in one of the design concepts for the tank mount in the Winter 2019, will be used as a placeholder in order to run bucklin analysis by the end of Spring 2020. The design removed about 0.65 lbm for each tank mount, resulting in a total weight loss of 2.6 lbm.



(*Figure 7: Version 2 of modified LOX/LNG/He bulkhead*)

## 3.2 Updated Detailed Design Development

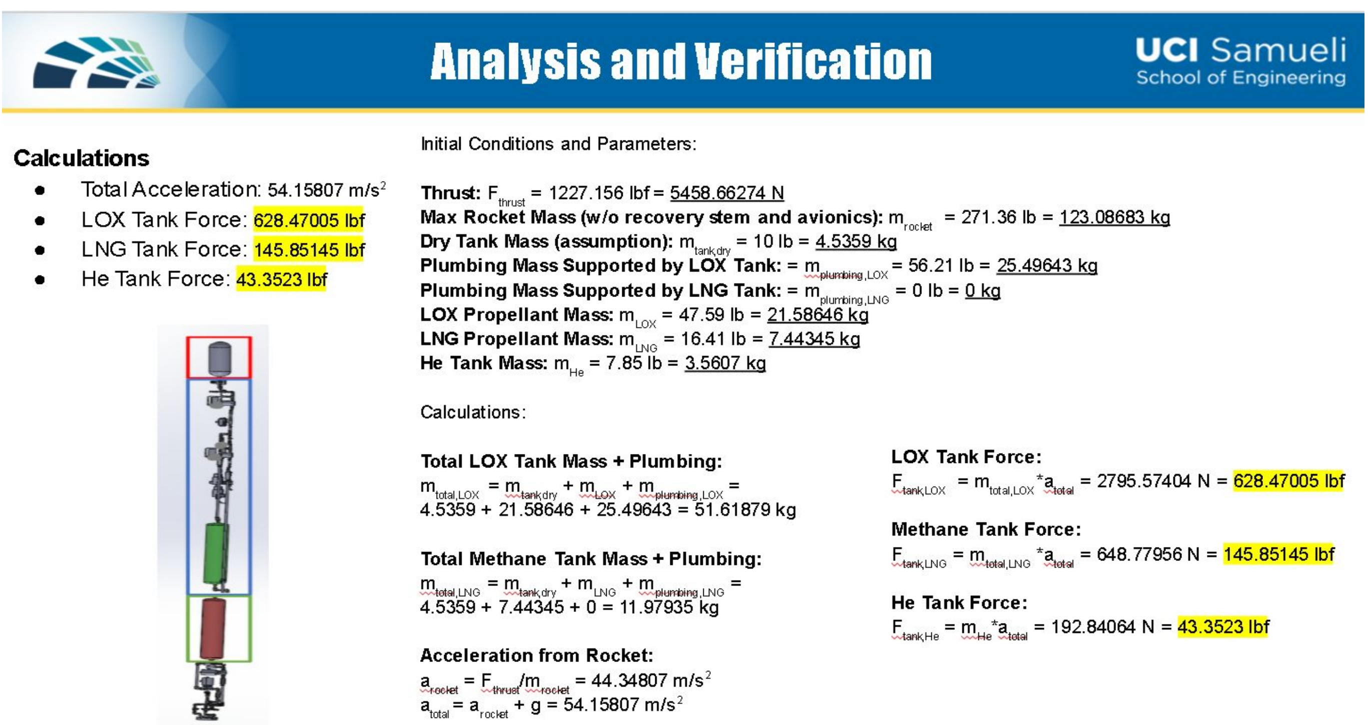
From my check-in in W8 leading up to my CDR in W10, there was some new information from Arthur, Cliff, and Sebastian regarding mass updates on propellants, fins, and nosecone. A breakdown of the mass of each subsystem is shown below.

| Components/ Subsystems | Mass (lbm) | Comment |
|---|---|---|
| Plumbing w/ Dry Tank | 99.91 | Plumbing system with dry tank (10lb each) only |
| Propellants | 64 | Estimation from Sebastian (16.41lb from LNG and 47.59 from LOX) |
| He Tank | 7.85 | Estimation from Overall plumbing - 12.75in diameter on GrabCAD |
| Struts | 26.55 | length of 22' |
| LOX Tank Mount | 5.32 | Top and bottom tank mount (total of 2 bulkheads) |

| | | |
|---|---|---|
| LNG Tank Mount | 4.3 | Top and bottom tank mount (total of 2 bulkheads) |
| He Tank Mount | 3.78 | Top and bottom tank mount (total of 2 bulkheads) |
| Chamber | 20 | Estimation from Kaylee |
| Skins | 22 | Weight proportional to strut length |
| Nosecone | 12.65 | Max weight of nosecone from Cliff |
| Payload | 2 | Estimation from Kaylee |
| Fins | 3 | Estimation from Arthur |
| Recovery | N/A | |
| Avionics Bay | N/A | |
| | | |
| Total Dry Mass | 207.36 | |
| Total Wet Mass | 271.36 | |

(*Figure 8: Updated weight calculation of PTR*)

Due to these mass changes, a new set of calculations had to be done to approximate the acceleration of the rocket and the forces applied on each tank mount. Furthermore, the tank mounts had to be modified to comply with these new calculations.




(*Figure 9: Final acceleration and force calculation for Vertical Assembly*)

## Selected Design with Changes

**LOX Tank Mount**
- OD: 12.75''
- 0.25" thick flange with 1.25" height
- 6.5" inner hole with 45° chamfer
- Mass: 2.66 lb

**LNG Tank Mount**
- OD: 12.75''
- 0.25" thick flange with 1.25" height
- 6.5" inner hole with 45° chamfer
- Mass: 2.15 lb

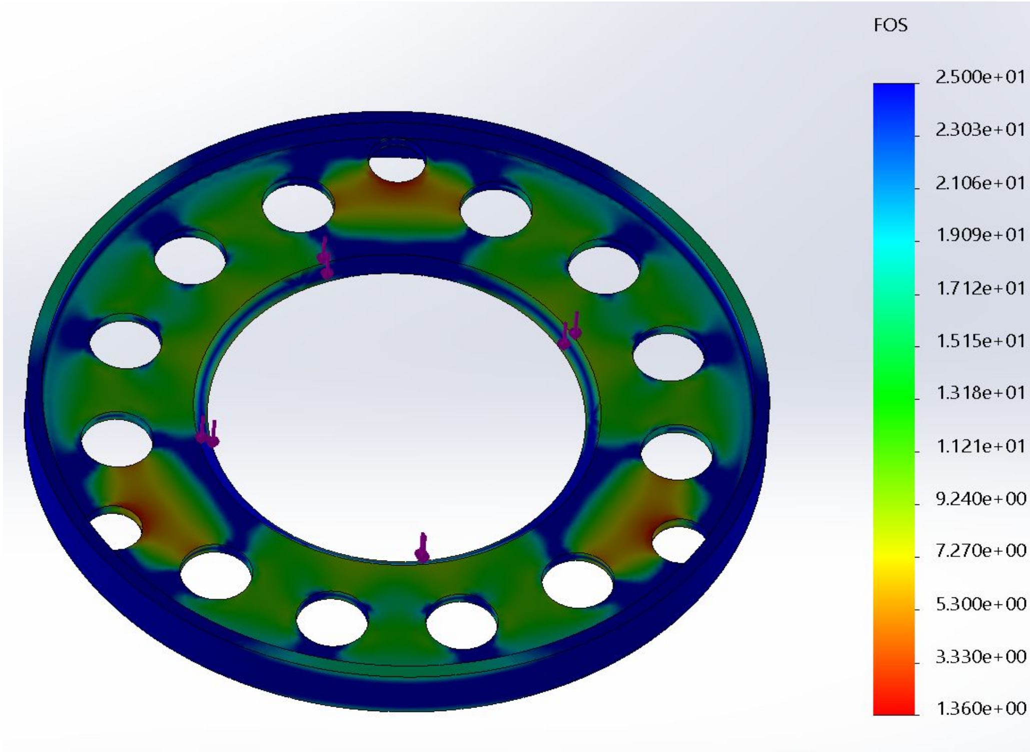
**He Tank Mount**
- OD: 12.75''
- 0.25" thick flange with 1.25" height
- 6.2 inner hole with 45° chamfer
- Mass: 1.89 lb

(*Figure 10: Final LOX, LNG, He bulkhead designs*)

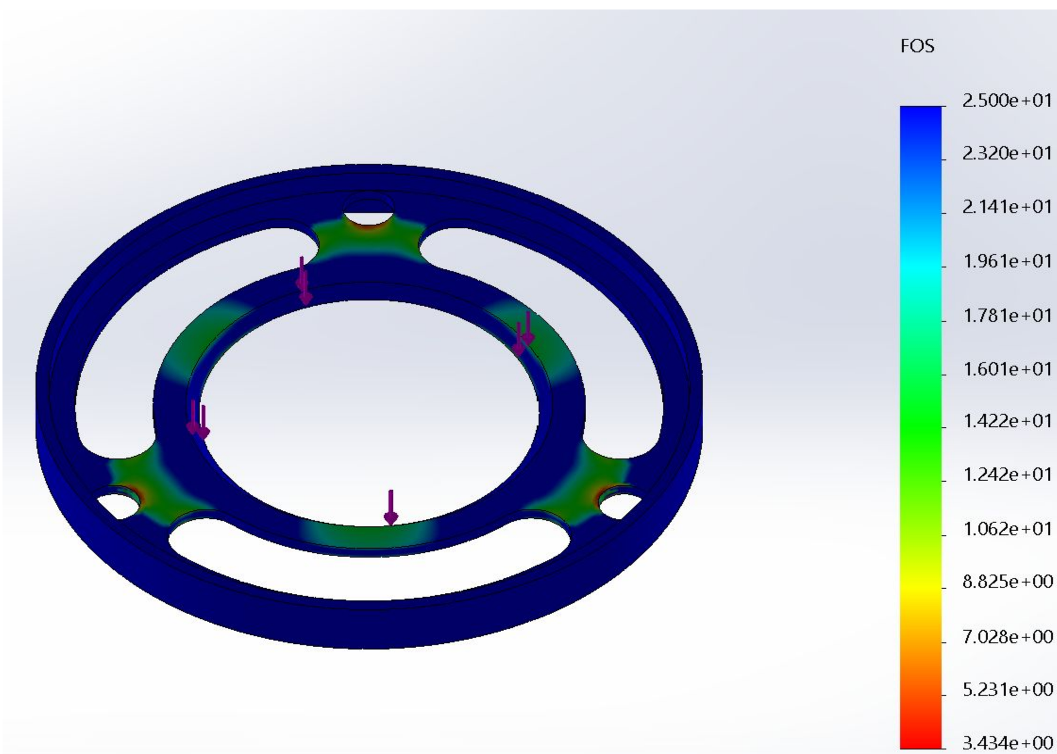
Compared to the previous calculations, the acceleration of the rocket decreased from 62.133 m/s^2 to 54.158 m/s^2 and the mass increased from 230 lbm to 270 lbm. The updated weight calculation of the rocket now includes fins, nosecone, and the updated propellants. The applied force and mass of each tank mount have also been updated, which are shown in the figures above.

## 3.3 Detailed Engineering Analysis

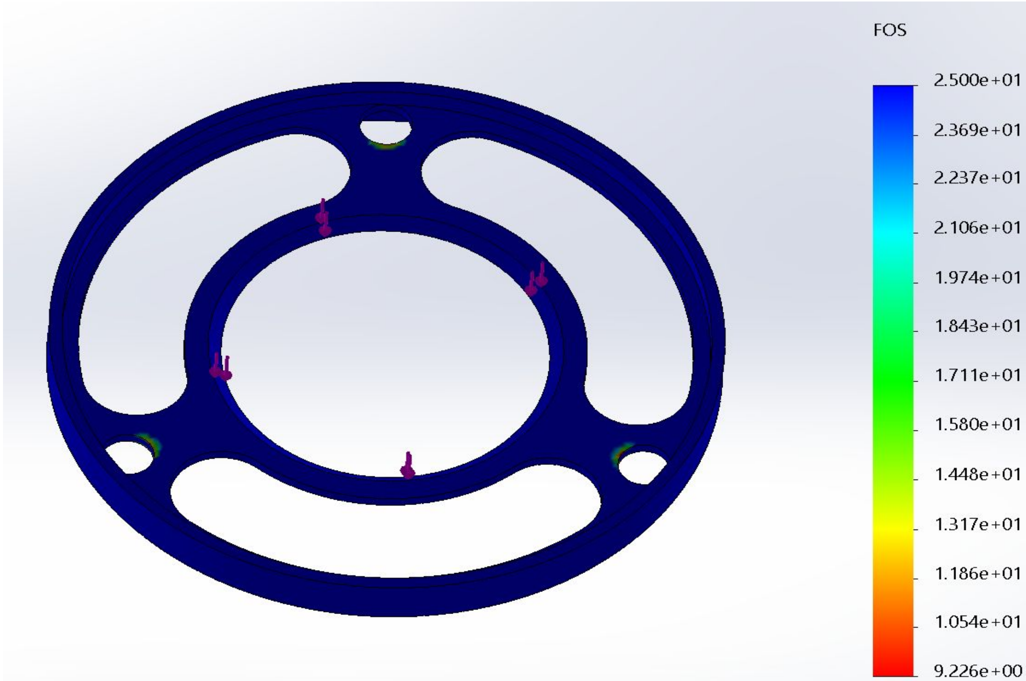
The simulations shown below had the LOX, Methane, and Helium tank mounts restrained with a fixed geometry along the edges of the three outer circular holes where the struts will be welded. The loads were applied perpendicular from the face of the bulkhead pointing down along the edges of the top and bottom inner hole, where the tank will be placed.




(*Figure 11: Static stress/ FOS of 1.4 - LOX tank mount*)

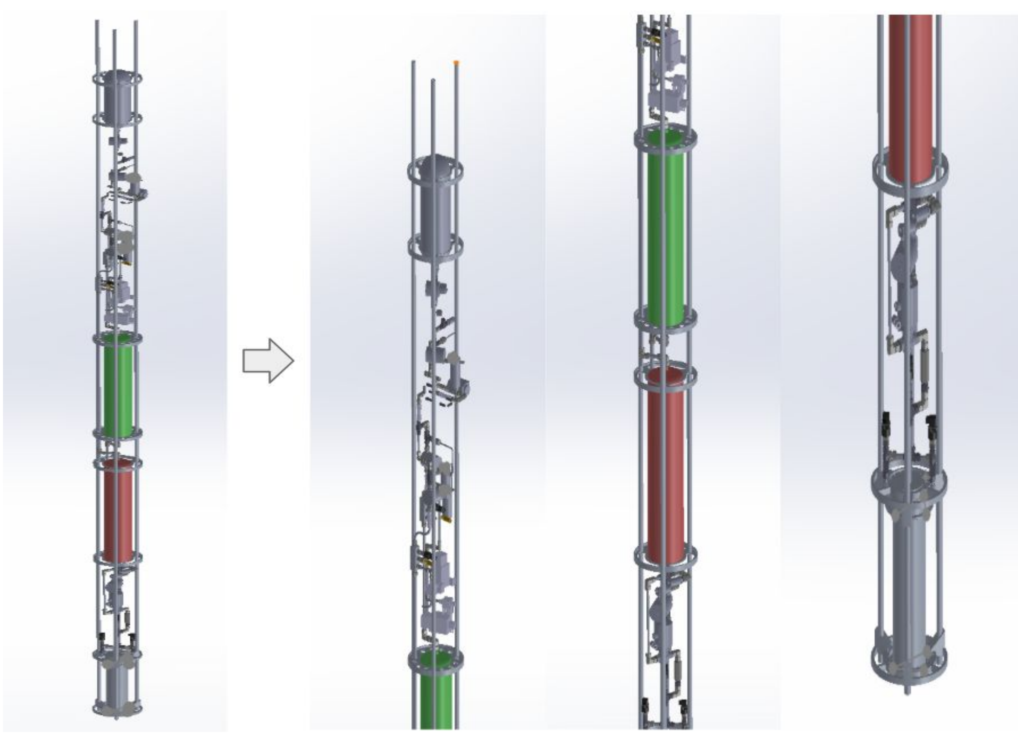



(*Figure 12: Static stress/ FOS of 3.4 - LNG tank mount*)

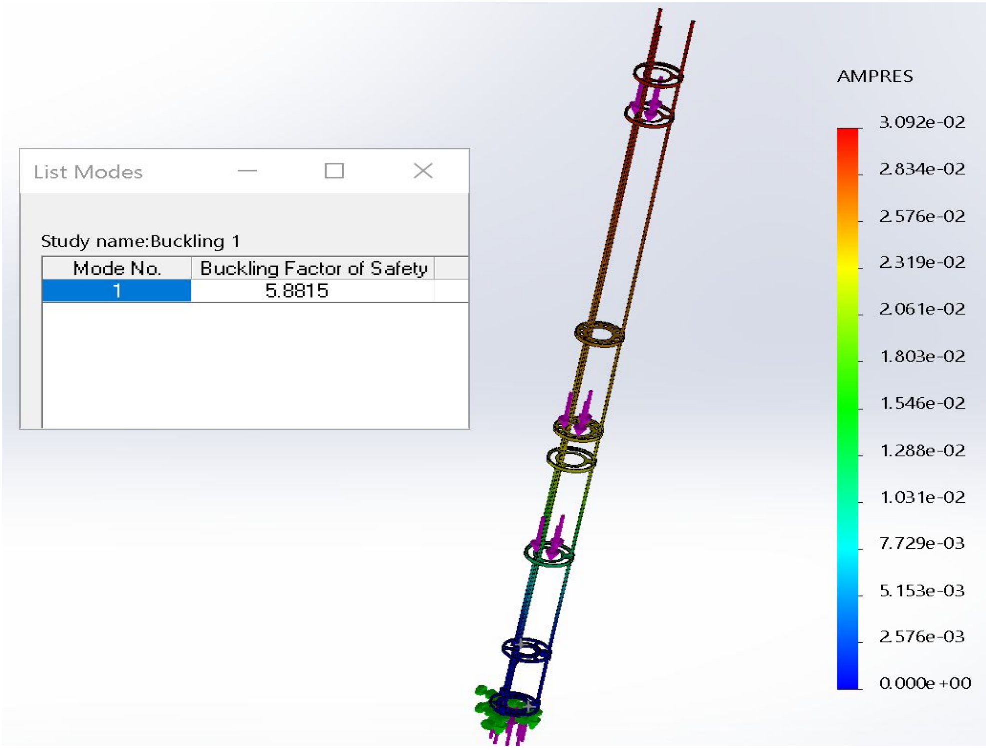



(*Figure 13: Static stress/ FOS of 9.2 - He tank mount*)

Because all three tank mounts had a FOS above 1.3, a buckling simulation for the Vertical Assembly was conducted to test if the three 1 inch struts were sufficient enough to withstand the forces with a FOS of 1.3 or higher. The buckling test simulated the LOX, LNG, and He forces applied perpendicular to the bottom tank mounts' fillet around the inner circle and the thrust force applied on the bottom face of the lower engine mount.



(*Figure 14: Updated Vertical Assembly with close-up screenshots*)




(*Figure: 15 Vertical Assembly buckling simulation*)

Figure 14 shows the most up-to-date Vertical Assembly of the rocket. The following are the components shown in the Vertical Assembly: plumbing system, LOX/LNG/He bulkheads, engine mount, chamber, struts, and injector. The assembly does not include skins, nosecone, fins, recovery, and avionics. Some of the subsystems listed are not included because the CAD files are incomplete, but there was also a problem with the plumbing system assembly that the Propulsion team provided that prevented me from adding the skins on to the rocket. Most of the subassemblies in the plumbing system assembly were off-centered with each other, which restrained me from mating the struts with three outer holes of all bulkheads. This problem has been notified and is currently work in progress. Figure 15 shows that the three 1inch struts are sufficient enough to withstand the forces. The Vertical Assembly has a FOS of 5.9, which is well above the minimum FOS. The buckling simulation does not take drag forces into consideration, but the calculated FOS far exceeds the minimum FOS, and therefore, leaves room for additional forces, such as drag, that will later be added in the simulation once the nosecone and fins are finalized.

## 3.4 Design Verification

| Requirement | C/NC (Compliant/Non-Compliant) | Verification | Notes |
|---|---|---|---|
| OD: 12.75’’ | C | | |
| Bulkhead Thickness: | C | | |

| | | | |
|---|---|---|---|
| 0.25’’ | | | |
| LOX Bulkhead Withstanding 628.47 lbf with FOS of 1.3 or Higher | C | | |
| LNG Bulkhead Withstanding 145.85 lbf with FOS of 1.3 or Higher | C | | |
| He Bulkhead Withstanding 43.35 lbf with FOS of 1.3 or Higher | C | | |
| Vertical Assembly Buckling FOS of 1.3 or higher | C | | |
| Three 1 inch Struts Passing Buckling Simulation with FOS of 1.3 or higher | C | | |
| Finalized LOX/LNG/He Bulkhead Designs | NC | | Incomplete weight optimization on LOX/LNG/He Bulkhead designs; can remove more excess weight |

(*Figure 16: Compliance table for Vertical Assembly*)

## 3.5 Detailed Design Review

Link to the Vertical Assembly Final Check-in

# 4. Final Design

## 4.1 Risk Assessment

| Likelihood \ Consequence | Trivial | Minor | Moderate | High | Critical |
|---|---|---|---|---|---|
| Rare | A1 | B1 | C1 | D1 | E1 |
| Unlikely | A2 | B2 | C2 | D2 | E2 |
| Moderate | A3 | B3 | C3 | D3 | E3 |
| Probable | A4 | B4 | C4 | D4 | E4 |
| Very Likely | A5 | B5 | C5 | D5 | E5 |

(*Figure 17: Risk assessment matrix*)

| Failure Modes | Causes | Effects | Severity & Likelihood | Mitigations |
|---|---|---|---|---|
| Bulkhead Failure | Unable to withstand forces | Major damages to plumbing system and potential damages to other subsystems | D2 | Proper verification of each bulkhead and have FOS above 1.3. |
| Detachment of Bulkhead from Struts | Improper welding | Major damage to plumbing system and potential damages to other subsystems | E2 | Receiving assistance from an experienced welder. |
| Vibration Fatigue in Propellant Tank and Bulkheads | Significant spacing between propellant and bulkheads | Chattering. Damage to propellant tank and bulkheads. | C3 | Secure the tanks between the bulkheads while welding. Add sponge-like material between the bulkhead and tank. Possible additional clamping mechanism |

## 4.2 Critical Design Review

[Link to the Vertical Assembly Critical Design Review]

# 5. Validation and Closure

## 5.1 Summary of Validation Results

The LOX, LNG, and He bulkheads as well as the three 1 inch struts satisfied the minimum static and buckling FOS requirement. A force of 628.47 lbf was applied on the LOX bulkhead and it had a FOS of 1.4. 145.85 lbf was applied on the LNG bulkhead and it had a FOS of 3.4. 43.35 lbf was applied on the He bulkhead and it had a FOS of 9.2. All three sets of bulkheads had an OD of 12.75'' and a thickness of 0.25''with different designs to remove excess weight accordingly. Furthermore, an overall assembly of the subsystems was made to estimate the strut's length and the locations of the tank and engine mounts in respect to the Vertical Assembly. This process was required in order to perform the buckling simulation in correct locations. The simulation accounted for thrust and three different applied forces on the bulkheads, which had a FOS of 5.8815.

## 5.2 Accomplishments and Future Design Refinements

Unlike other design process reports, my tasks centered around analysis and verification of preexisting designs. Adding onto last quarter's work pertaining to the bulkhead design and Vertical Assembly, there was a considerable amount of progress that was made with the LOX, LNG, and He tank mounts simulations and the Vertical Assembly. Running weight analysis for different dimensions and determining the center of gravity for various subsystems were necessary in order to calculate the applied forces on the bottom tank mounts during the acceleration. In addition, the information obtained from the calculations were used to determine if the bulkhead designs were compatible with PTR's requirements. After multiple iterations of design modification, all three bulkheads met the minimum FOS requirement. Once the bulkheads were completed, a vertical assembly of the rocket containing the struts, bulkheads, plumbing system, engine mounts, chamber, and injector was made. The buckling simulation was, then, performed and it had a FOS of 5.8815. The simulation did not account drag force and the weight of some of the subsystems.

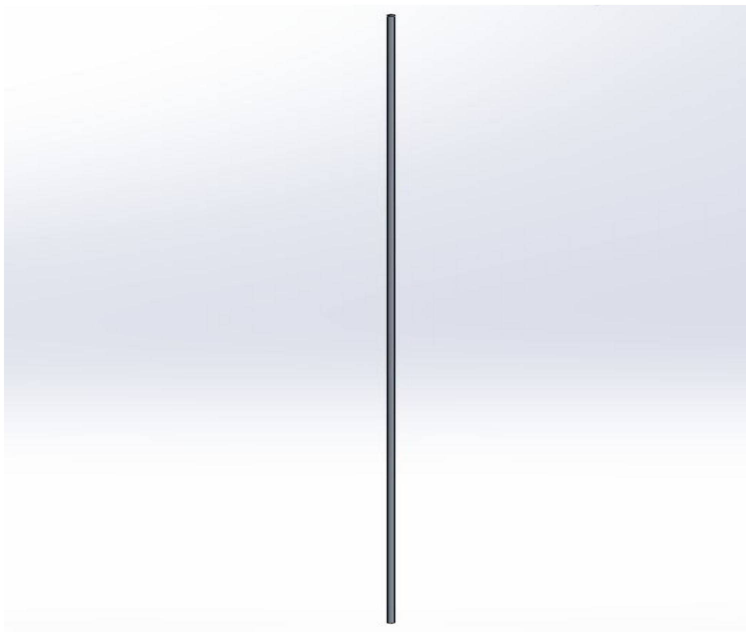
The lack of time on this project prevented me from running a more in-depth analysis of the bulkhead designs, especially LNG and He tank mounts. Both tank mounts had a FOS much higher than 1.3 and they can be optimized by removing more excess weight. For the Vertical Assembly, the assembly CAD file can be updated in the future with the completed fins, nosecone, recovery, and avionics bay. The buckling simulation can also reflect these changes with the known drag force.

# Appendices

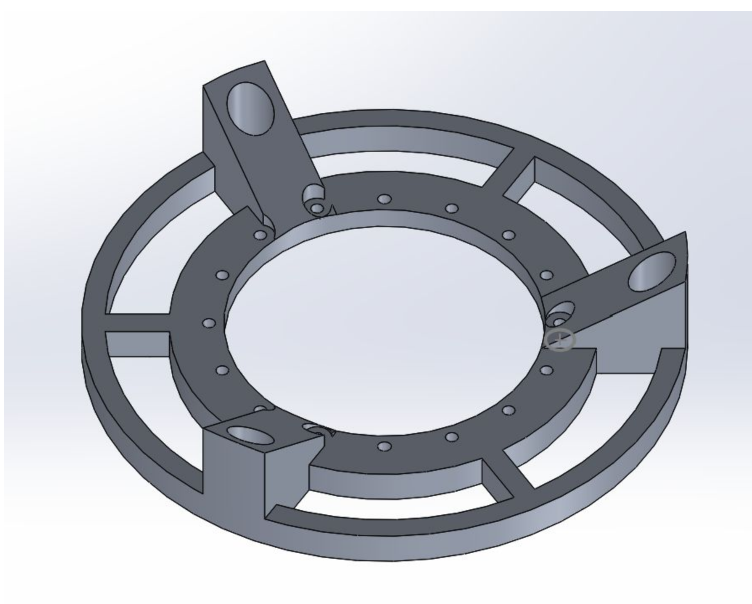
## Appendix A

Link to Winter 2020 Bulkhead Critical Design Review

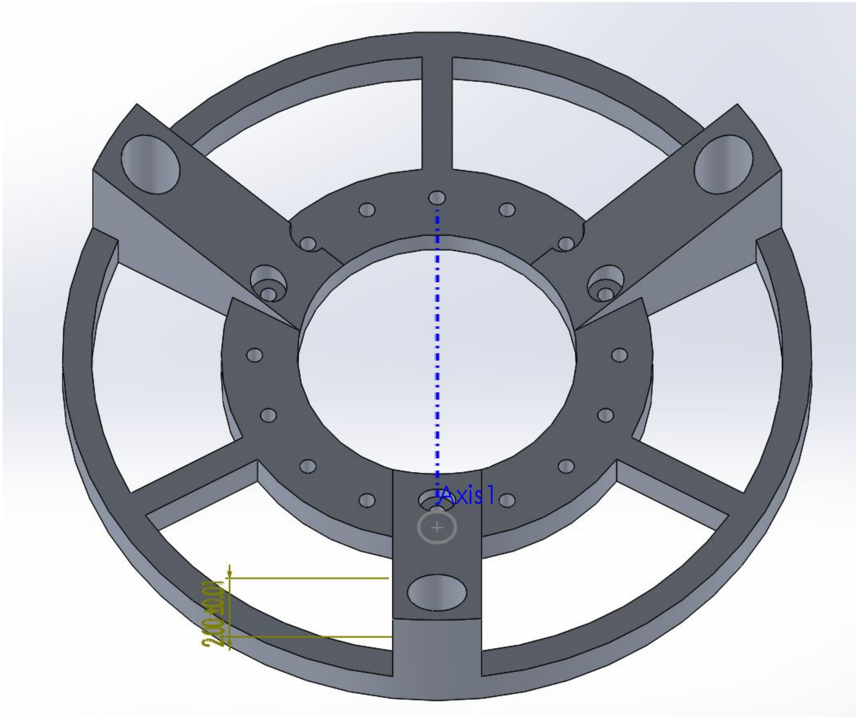
## Appendix B



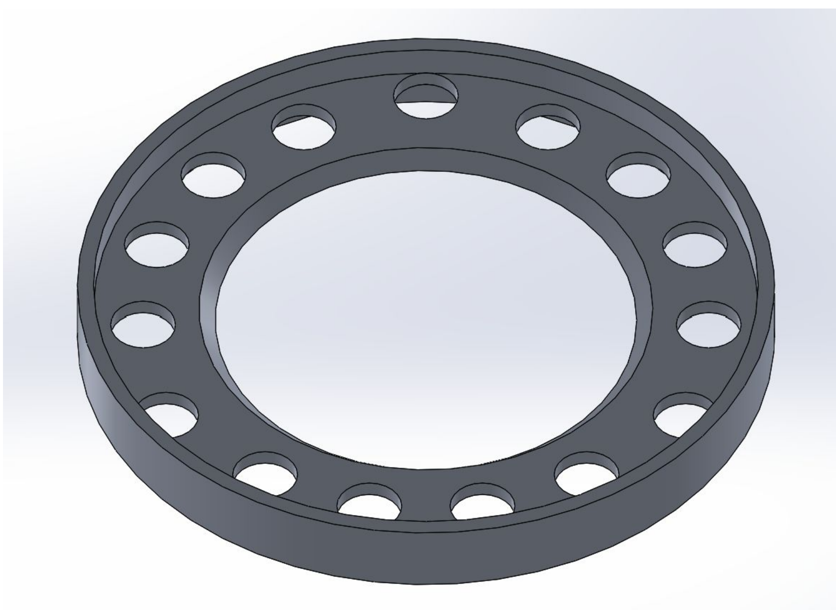
(*Strut - OD: 1'', Thickness: ⅛''*)



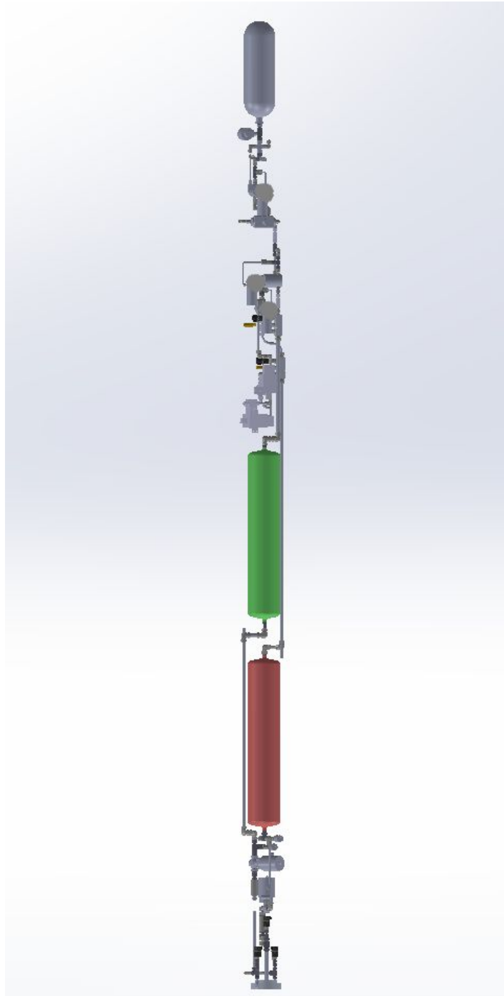
(*Lower engine mount created by Wes*)




(*Upper engine mount created by Wes*)



(*Winter 2020 LOX, LNG, He Bulkhead*)



(*Plumbing assembly created by Mariam*)

## Appendix C

| (origin - bottom of injector) | Component | weight | x (original origin) | x (mod origin) | x-mom |
|---|---|---|---|---|---|
| Tanks to injector with LOX | 10-02-0003-01 | 1.62 | 76.15 | 0.66742 | 1.0812204 |
| | 10-02-0002-01 | 1.7 | 76.3 | 0.51742 | 0.879614 |
| | 10-02-0001-00 | 1.65 | 75.15 | 1.66742 | 2.751243 |
| | A | 3.11 | 68.11 | 8.70742 | 27.0800762 |
| | B | 7.58 | 51.93 | 24.88742 | 188.6466436 |
| | Tank (methane) | 18.9727618 | 19.19 | 57.62742 | 1093.351313 |
| | Tank (LOX) | 36.03654091 | -28.61 | 105.42742 | 3799.239534 |
| | C | 0.19 | -5.75 | 82.56742 | 15.6878098 |
| | | | | | |
| | Total Weight | 70.85930271 | | | |

| | | | | | |
|---|---|---|---|---|---|
| | CG | 72.37888686 | | | |
| | | | | | |
| (origin - bottom of injector) | | | | | |
| Vertical - He to tank | D | 2.14 | 27.57 | 236.72902 | 506.6001028 |
| | E | 9.7 | -0.35 | 208.80902 | 2025.447494 |
| | F | 41.25 | -25.83 | 183.32902 | 7562.322075 |
| | | | | | |
| | Total Weight | 53.09 | | | |
| | CG | 190.1369311 | | | |
| | | | | | |
| (origin - bottom of injector) | | | | | |
| HE COPV Manifold Assembly | He COPV | 7.85 | 29.56 | 169.34374 | 1329.348359 |
| | G | 1.18 | 13.92 | 184.98374 | 218.2808132 |
| | | | | | |
| | Total Weight | 9.03 | | | |
| | CG | 171.3875052 | | | |
| | | | | | |
| (origin - bottom of injector) | H | 0.66 | 74.29 | 142.02159 | 93.7342494 |
| | I | 1.28 | 102.18 | 114.13159 | 146.0884352 |
| | | | | | |
| | Total Weight | 1.94 | | | |
| | CG | 123.6199405 | | | |
| | | | | | |
| | Final Plumbing Weight | 134.9193027 | | | |
| | FInal Plumbing CG | 126.0793574 | | | |
| | | | | | |
| (origin- bottom of injector) | Bottom LNG tank mount | 2.79 | | 39.57739 | 110.4209181 |
| | Upper LNG tank mount | 2.79 | | 75.56665 | 210.8309535 |
| | Bottom LOX tank mount | 2.79 | | 87.35759 | 243.7276761 |
| | Upper LOX tank mount | 2.79 | | 123.34685 | 344.1377115 |
| | Bottom He tank mount | 2.79 | | 220.82527 | 616.1025033 |

| | | | | | |
|---|---|---|---|---|---|
| | Upper He tank mount | 2.79 | | 236.02526 | 658.5104754 |
| | Struts (3) | 29.95 | | 95.47523 | 2859.483139 |
| | | | | | |
| | Final Structure Weight | 46.69 | | | |
| | Final Structure CG | 108.0148506 | | | |
| | | | | | |
| | Final (plumbing and structure) Weight | 181.6093027 | | | |
| | Final (plumbing and structure) CG | 121.4351469 | | | |