Project Prometheus: Design and Analysis of a Modular Aerostructure for a Small Launch Vehicle

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Project Prometheus is a sub-team of the Alabama Rocket Engineering System (ARES) project, which has been in development for about four years. This system is a bi-propellant pressure-fed rocket meant to prove new technology and launch to about 30,000 ft. Project Prometheus is the structural and integration sub-team of Project ARES. The team has worked since August 2020, moving from concept, through preliminary and critical design, and then onto analysis and testing validation and manufacturing. This paper walks through the main requirements, design decisions with rationale, analysis proving the validity of the design, and highlights the important features and the transferability of the concept to other small launch vehicle applications.

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I. Introduction

PRoject Prometheus is a part of the development efforts of the Alabama Rocketry Association (ARA) for the Mars or Bust Initiative. This project has been in development over the past several years and has included several subteams, all working on the first-generation liquid-propelled launch vehicle. The ultimate goal of this initiative is to have a launch vehicle carry observational instruments to the Moon for scientific research in the lunar lava tubes. The goal for the initial stage of the Mars or Bust initiative is to prove the concept and technology by launching a 6U CubeSat to Low Earth Orbit and recovering the launch vehicle. For this first-generation vehicle, the objective is to launch to at least 45,000 ft, have successful data collection and analysis, and recover the rocket for future iterations and improvements.

II. Purpose and Scope

The ARES VI Aerostructures team is currently focusing on the mission objectives for the first-generation ARES launch vehicle. The main objective of the team is to successfully demonstrate a functioning liquid engine rocket launched to 45,000 ft and be recovered. Project Prometheus is the name given to the ARES VI: Aerostructures team, who will develop a resilient internal structure with an external shell that can support the subsystems previously designed and developed for this vehicle. This includes managing the thermal conditions of the liquid engine, securing the 3 tanks within the rocket, and properly installing the avionics and the recovery system. This structure is one of the final pieces required to make this vehicle viable and ready to launch upon the procurement of all necessary hardware. The aerostructures team is working in tandem with the powerhead team, who is finishing the work from last year's group; the test stand team, which will allow us to test our liquid engine before integration; and the propulsion team, who is finalizing details of the system which was disrupted last year due to the COVID-19 shutdown. To ensure a successful flight of the rocket, the aerostructure team must be able to build and validate the robustness of the structure and then fully integrate the remaining subsystems.

III. Mission Objectives

The ultimate goal of the Alabama Rocketry Association and the ARES team is to support the Mars or Bust Mission. The Mars or Bust (MoB) mission is intended to support NASA in the continuation of human exploration with a focus on developing a gateway on the Moon. This will enable the development of necessary technologies and resources needed for interplanetary travel, specifically to Mars. MoB is tasked with "[Identifying] and [developing] key technologies need to colonize Mars". Each team within AEM 402 senior design contributes student innovation and fresh ideas for technology needed for the advancement of the Deep Space Gateway. The focus of the 2020-2021 teams is to fully develop engineering models of the launch vehicle and CubeSat to be used for technical proof of concept and further iterations of space-worthy systems. The ultimate goal of these space-faring vehicles is to study the Marius Hills skylight on the Moon and search for data on the lunar lava tubes.

The specific mission objectives of the ARES VI: Aerostructures team are as follows:

- The rocket shall reach an apogee of at least 45,000 ft but no greater than 60,000 ft.
- The rocket shall operate within any additional operating limitations imposed by the FAA on the operator's approved Certificate of Waiver.
- The rocket shall operate within the operating limitations for Class 3 - Advanced High-Power Rockets.
- The rocket shall maintain structural integrity throughout the flight and through recovery.
- The rocket shall be able to be tracked and successfully recovered after apogee and parachute deployment.
- The rocket shall use a pressure-fed propellant system.
- The rocket and ground equipment shall perform all functions needed to safely start the propulsion system and release the rocket for liftoff.
- The rocket shall perform any system monitoring and control functions needed to achieve and maintain thrust necessary to reach mission apogee.
- The rocket shall be able to be assembled and integrated and then disassembled after launch without causing irreparable damage to the structure or subsystems inside.

The main objective of this structure is to fully integrate the propulsion, powerhead, and avionics subsystems into a structurally sound vehicle. The fall semester will be focused on developing a design concept and analyzing the feasibility of it with finite element analysis and other detailed simulations. The major milestones for this year are the Preliminary Design Review (PDR) and the Critical Design Review (CDR). Both of these will occur in the fall semester. PDR will occur during the first full week of October 2020, and CDR will occur the first week of December. The feedback from these design presentations will be used to direct the hardware assembly and testing of the final structure. Manufacturing, procurement, and assembly will begin in November 2020 and continue through March 2021. The complete structure must be tested for static, vibrational, and thermal loading the vehicle will experience during flight. By the end of April 2021, the materials and components shall be machined and assembled. All available subsystems shall be integrated into the vehicle to prove sizing and compatibility.

IV. Program Success Criteria

The main goal of the ARES team as of September 2020 year is to launch and recover a fully functional and tested vehicle within the next year. However, several obstacles may make this goal unattainable, specifically budget constraints and lab accessibility due to COVID-19 restrictions. To ensure Project Prometheus has realistic and attainable success criteria for this year, some adjustments have been made to define success outside of a full test and launch of the system.

The 2020-2021 Project Success Criteria Include:

- Functional design and assembly of an internal skeleton structure to support all subsystems.
- Full integration of the internal skeleton and all completed subsystems.
- Successful pass of all possible static load testing for the aerostructure components and subassemblies.
- Completed finite element analysis demonstrating necessary strength and resilience of the structure of the integrated vehicle.
- Successful hardware in-loop testing of the integrated system.
- Successful completion of these criteria by April 2021.

V. Technical Summary

A. System Baseline Description

1. Concept of Operations

The goal of the ARES VI Team is to design, test, and build a liquid propellant rocket capable of reaching an altitude of 45,000 ft. Therefore, this team must ensure the rocket's aerostructure functions optimally in the lower atmosphere, specifically the Troposphere. We must consider the expected changes in temperature, pressure, and air density as the rocket gains altitude. We must also consider the environmental conditions of our prospective launch site. (These locations have been narrowed to Tuscaloosa, AL, test/launch sites in Florida, and arid regions in the southwest United States.) Until we know where we will be launching from, we must account for a wide variety of different environmental conditions at launch.

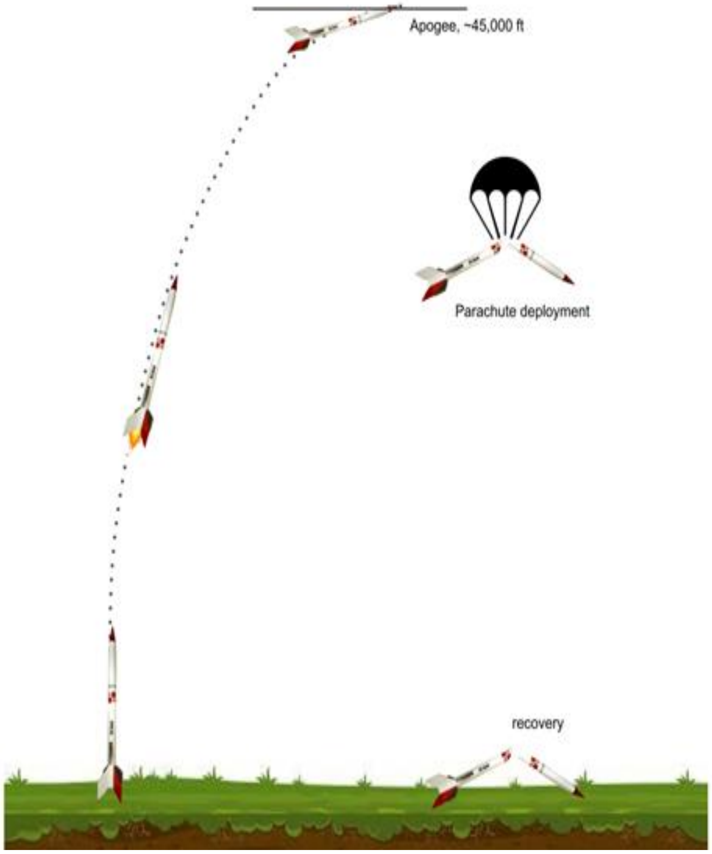


Figure 1. ARES VI Concept of Operations

2. Main Structural Components

a) Body Tubes

The external structure of the launch vehicle must withstand all in-flight loads, protect the internal hardware, and provide aerodynamic stability. It must also attach to the internal structure and remain attached during assembly and through flight.

b) Internal Structure

The main load-bearing structure is on the inside of the launch vehicle. The structure is a network of metal bulk plates, rods, nuts, bolts, and other fasteners that make up the structure and support the subsystems. This structure must also distribute the mechanical and dynamic loads from the propulsion system. Trade studies and finite element analysis have helped determine the optimal structure for the vehicle. The thrust structure is specifically designed to dissipate the heat generated from combustion and distribute the thrust force from the nozzle to the entire rocket body. The support structure is designed specifically to withstand and distribute the thrust force generated from the propulsion system. The main structure will also have structural elements that directly support subsystem interfaces. These elements specifically include valves, controllers, the injector, actuators, and other essential control elements.

Steel Rods

Steel rods are one of the main structural supports of the system. Rods will run up and down the structure connecting sections that support each tank and the avionics and recovery systems. The rods are ¼” diameter steel alloy. They will be threaded at each end and attached to each bulk plate with nuts and washers. The steel rods must withstand buckling loads and twisting and vibrating of the vehicle during flight. The rods have undergone extensive analysis to verify that they can withstand the weight and load of the vehicle.

Bulk Plates

Bulk plates are the main structural elements that interface with the internal subsystems. The bulk plates also separate each unique subsystem, including the engine, each tank, the controllers and valves, the avionics, and the recovery system. The plates will match the internal diameter of the body tube and be machined to accommodate any through components, particularly cabling and feed lines. The bulk plates will also interface directly with the body tube structure. L-brackets and bolts will be the connection points between the plates and the body tube. The bulk plates must support the weight of the subsystem components between them, as well as the dissipated loads from the threaded rods. Like the steel rods, the bulk plates have undergone extensive analysis to verify that they can withstand the weight and load of the vehicle.

Supporting Rings

The supporting rings will connect all rods in each subsection and help mitigate displacement from any buckling loads. They will be manufactured out of thin sheet metal and attached with some sort of friction mechanism. These were added to the design after simulations indicated large displacement of the rods under the load of the thrust force.

Bolts, Nuts, and Washers

Bolts, nuts, and washers are the main fasteners and connection mechanisms for the entire structure. Nuts and washers secure the rods to the bulk plates. Nuts and bolts are also used to connect the internal structure to the outer skin. The bolts must withstand the bending moments caused by the weight of the internal subsystems and shear forces traveling up the rods from the thrust force.

L-bracket connectors

L-brackets are the main connectors between the bulk plates and the external skin. The l-brackets will be attached to the inner diameter of the tube with epoxy or another adhesive. The other leg of the bracket will be attached to the bulk plate with a nut and bolt. There will be at least four L-brackets per bulk plate.

*Tank Support*s

The tank supports each interface with a bulk plate and the dome of one of the tanks. The support structure is cage-like to allow ports and lines to move outside its footprint. The dimensions of each support are custom to the distance that the specific tank is from each bulk plate. The support will use friction and compression to stabilize the tanks and will use a few bolts to connect to the respective bulk plates. The piece will be welded of three distinct aluminum pieces. There will be six tank supports for the entire vehicle, two for each tank.

Thrust Control Assembly

The thrust control assembly is a unique section design that will attach directly to the combustion engine. This structure must withstand additional loads and more harsh conditions. This structure must survive the harsh temperature gradient of cryogenic fluids and of combustion. This section features partially threaded rods ½" in diameter. It also features a custom aluminum plate that use heat-treated bolts to connect the engine and the rods. The rods will be joined at the top to provide stability and rigidity to the structure and help distribute the loads from the engine.

c) Vehicle Sizing

The actual diameter and height of the launch vehicle shall be such that all subsystems can be accommodated, and the appropriate mass constraints can be met. The vehicle will have an inner diameter of 14 inches and will be no more than 20 ft tall.

Project Prometheus is a crucial step on for the ultimate Mars or Bust mission. This project is developing the first structural support system for a launch vehicle by a University of Alabama student team. The ARES VI: Aerostructure system requires multiple trade studies to fully evaluate the design options for an effective system. These trades include the support selection, material selection, number of compartments and sections, section interfaces, fin attachment, and body tube attachment. These trade studies will affect the whole integration of the system and its final size and weight.

Aspects of the vehicle that require trade studies are:

1. Internal Support System (the design approach for the structure)
2. Primary Structural Materials

3. Body Tube Material
4. Configuration of the Vehicle around the subsystems
5. Fin Attachment Method
6. Fin Material
7. Body Tube Attachment Mechanisms

The primary aspects important to the design are:

1. Feasibility
2. Manufacturability
3. Cost
4. Weight
5. Complexity
6. Ease of Access
7. Safety

The main concerns for this design are cost, weight, and complexity. The Aerostructure team has a deadline for a test launch by Summer 2021. To meet this ambitious goal, the structure must be simplified as much as possible. With limited financial resources for the team, the same article that is used for testing will also complete the first test launch. Therefore, the components must be resilient and the structure robust. Consequently, manufacturability and ease of access to inside components are secondary factors to the overall design and vehicle configuration.

3. Mission Objective

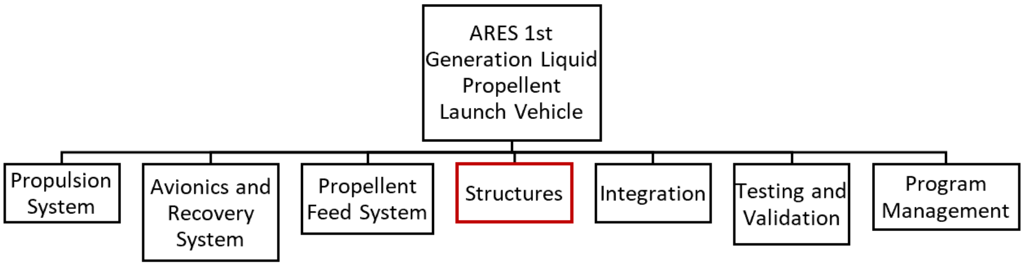


Figure 2. ARES Organizational Breakdown

The propulsion, avionics, and propellant feed system were worked on last year by the ARES V team. The Avionics and Recovery system is largely complete with some hardware assembly and software upgrades required before it can be fully integrated into the system. The propulsion system is still under development and testing within the Alabama Rocketry Association (ARA) but is working outside of the senior design course structure. The propellant feed system was designed and acquired last year and still requires assembly, test, and integration. This team will be working in parallel to the aerostructures team as a continued senior design project. Efforts to ensure readiness for subsystem and system testing and validation are underway by the Test Stand team, also known as Project Atlas. This team is looking to build a stand that can be used for static fire testing of a liquid rocket engine by the end of this year. Project Prometheus is focused on the structure and aeroshell of the launch vehicle. We will be designing around the current subsystems to accommodate and protect sensitive components from structural, dynamic, and thermal loads. In this design process, our team will also be focused on integration of all sub-systems. In order to minimize the need for costly design changes, a systems-level design approach will be taken to developing this model and structure.

B. Design Solution Justification

A series of trade studies were conducted to determine the ideal approach and configuration of various aspects of the design. Each of these trades is outlined in a table and the decision behind each score is explained below that table. The main design criteria that were evaluated with a trade study were:

- The main structure design concept

- Body Tube Materials
- Body tube attachment method

As the design progressed and was analyzed, additional features were added to increase strength and stability of the structure and the total system. Weight, Ease of Integration, and Cost were the three most significant factors considered for each trade study because they most directly affect our ability to carry out the mission objectives. The scoring criteria for each trade study is:

1 = challenging/very weak

2 = difficult/moderately weak

3 = maybe/could be strong or weak

4 = likely/moderately strong

5 = highly likely/very strong

1. Main Structure Design Concept

Table 1. Trade Study for Main Structural Design Concept

Design Options				
Criteria	***Weight***	***Truss/Spars and Webbing Design***	***Threaded Rod Design***	***Skin-Based Design***
Relative Weight	20%	**2**	**4**	4
Manufacturability	20%	**3**	**5**	2
Ease of Integration	15%	**5**	**3**	3
Ease of Subsystem Access	15%	**5**	**2**	1
Cost	30%	**2**	**3**	4
Feasibility		**1**	**1**	0
Total Score	**100%**	**3.1**	**3.45**	**0**

For the main structural design, three different approaches were considered. Originally, the team had looked at pursuing a truss-based design, but after additional system constraints were defined, we re-evaluated and selected a threaded rod design. Threaded rods provide high strength solution at a lower weight than the truss-based design. The team also looked at a skin-based design that would've meant all structural elements came from the body tube but decided that it was not feasible based on our current capabilities and ultimate goals for the project.

2. Body Tube Materials

Table 2. Trade Study on Body Tube Materials

Design Options					
Criteria	***Weight***	***Carbon Fiber***	***Fiberglass***	***Aluminum***	***Steel, A287***
Density	15%	5	4	4	1
Shear Modulus	10%	2	3	3	5
Strength to Weight Ratio	20%	5	4	3	1
Coefficient of Thermal	10%	4	2	1	2

Expansion					
Manufacturability	25%	3	2	3	2
Cost	20%	2	3	4	5
Feasibility		1	1	1	1
Total Score	100%	3.50	3.00	3.15	2.55

The team considered four different materials for the external body tube. The main criteria for this component were weight, the overall strength of the material, and the ability to attach it to the internal structure. The steel option has far too low of a strength to weight ratio to meet our design intent. Alabama Rocketry Association and the Aerostructure team preferred the composite material options of Carbon Fiber or Fiberglass, however, this trade study indicated that Aluminum could be an acceptable substitute if composite tubes were not available. Based on this trade study, carbon fiber is the preferred material for the body tube. However, after completing this trade the team learned that the previously designed Avionics system was only compatible with a fiberglass body tube.

3. Body Tube Attachment Method

Table 3. Trade Study on Body Tube Attachment Mechanism

Design Options				
Criteria	*Weight*	*Epoxy*	*Nuts and Bolts*	*Welding*
Complexity	10%	3	4	2
Weight	15%	5	3	4
Ease of Access	30%	1	5	1
Ease of Assembly	25%	3	4	2
Cost	20%	4	3	2
Feasibility		1	1	1
Total Score	100%	2.9	3.95	2

The results of this trade study determined the mechanism that would be used to connect the internal structure to the body tube. A key criterion of this structure is that it must have the ability to be assembled and disassembled easily and in multiple environments. The methods of welding and epoxy assembly are both permanent assembly methods. This does not meet the overall objectives of the structure design. Thus, nuts and bolts, along with brackets and supports were chosen as the method to integrate and assemble all components.

C. System Assembly and Implementation

The process of integration and assembly is the most critical aspect to our system design after the structural resilience is proven. The overall goal of this design is that it could be transported in piece parts and assembled at any location with simple tools such as a torque wrench and screwdriver. All components have been designed so that they are compatible with each other and with standard tools. The structure overall is also compatible with the powerhead system and the propulsion system which were both developed by previous ARES teams. The vehicle will be assembled horizontally, working from the nose cone down to the engine. The structure will be assembled one 'compartment' at a time and will be supported with 3D printed pieces that hold the main structural components in place during the assembly process. The figure below shows the order of integration for one of the compartments and all of the components and supports that would be contained within that section.

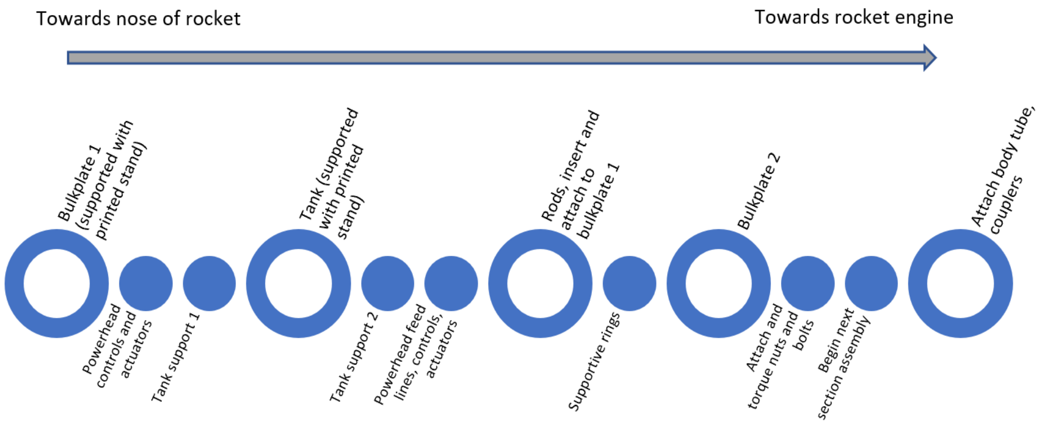


Figure 3. Integration Method and Order of Assembly

VI. Testing and Verification

Since several of the internal subsystems have not procured all of the designed hardware for integration, it is necessary to use other analysis methods to verify and validate the structural and system-level requirements of the assembly. Given the size of the structure relative to the size of the available laboratories at The University of Alabama, most of the testing and verification will have to be done analytically and with finite element analysis by simulation.

A. Assumptions and Limitations

Given the current state of hardware procured and the assembly progress of the other internal subsystems, the entire system cannot be assembled and tested in the way a large launch vehicle testing campaign should be performed. Additionally, some assumptions must be made to make the analysis feasible. These include the assumption that the weight of all components is known from the ARES V parts and designs, the assumption that all previously designed subsystems meet system requirements and will survive the flight environment, and the assumption that the structural raw materials have uniform mechanical properties. Some limitations of the test campaign include the lack of physical testing facilities for a structure of this size at The University of Alabama, and the lack of internal subsystem components to fully validate the integration of hardware into the structure.

B. Hardware Testing

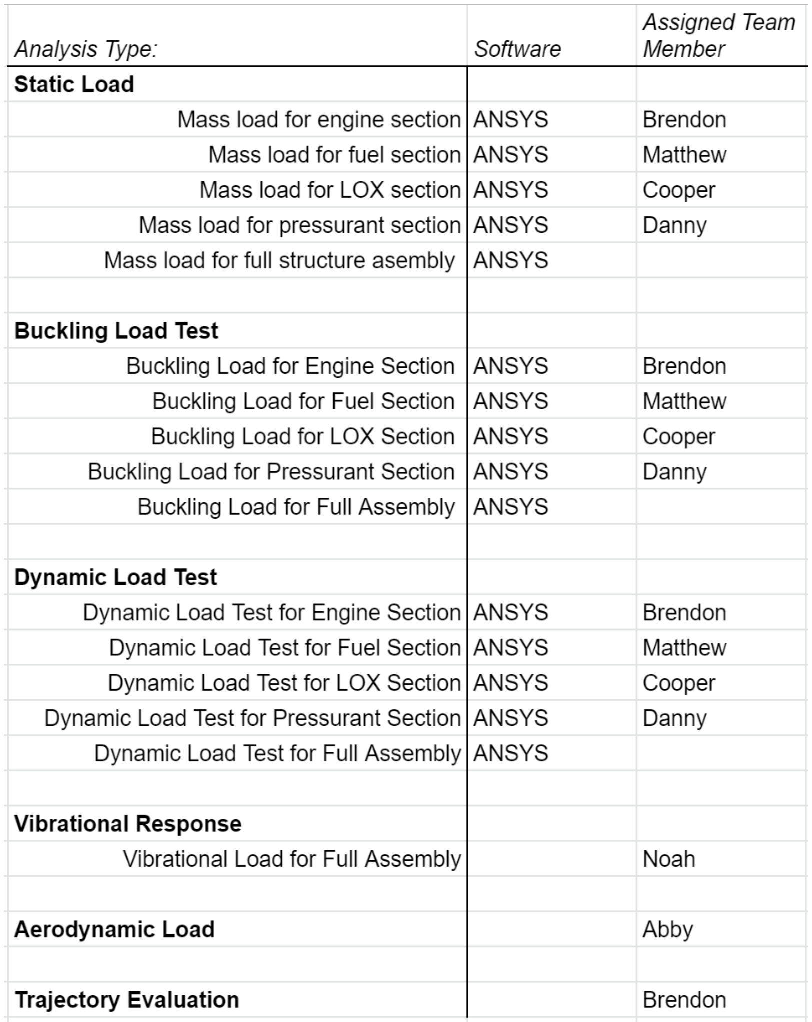
However, given these limitations, some physical tests can be conducted. These tests will be conducted before April 2021 in the ARA Laboratory.

- Static weight test: weights will be attached to the assembled structure of rods and bulk plates to ensure that they can withstand the anticipated maximum applied load, plus a 10% margin, without experiencing mechanical failure.
- L-bracket load testing: attach the L-brackets used for connecting the structure and the body tube to an unused tube in the ARA lab. Apply epoxy and load the mechanism sub-assembly with the anticipated bending load from the anticipated mass of the structure.
- Integration testing: attach and assemble all manufactured pieces of the structure to ensure that they integrate together properly with appropriate tolerances.

C. Analysis Testing and Verification

As discussed earlier, a majority of the requirements for this system will initially be validated using finite element analysis as varying levels of detail on the CAD model of the structure. The analysis will be performed in ANSYS Structural, and the campaign will include static loading, dynamic loading, buckling loading, and vibrational response.

The analysis campaign will also include trajectory analysis and aerodynamic loading or stability analysis. The campaign matrix is outlined in detail in Figure 4 below, where each part of the assembly is assigned to a specific team member.



Analysis Type:	*Software*	*Assigned Team Member*
Static Load		
Mass load for engine section	ANSYS	Brendon
Mass load for fuel section	ANSYS	Matthew
Mass load for LOX section	ANSYS	Cooper
Mass load for pressurant section	ANSYS	Danny
Mass load for full structure asembly	ANSYS	
Buckling Load Test		
Buckling Load for Engine Section	ANSYS	Brendon
Buckling Load for Fuel Section	ANSYS	Matthew
Buckling Load for LOX Section	ANSYS	Cooper
Buckling Load for Pressurant Section	ANSYS	Danny
Buckling Load for Full Assembly	ANSYS	
Dynamic Load Test		
Dynamic Load Test for Engine Section	ANSYS	Brendon
Dynamic Load Test for Fuel Section	ANSYS	Matthew
Dynamic Load Test for LOX Section	ANSYS	Cooper
Dynamic Load Test for Pressurant Section	ANSYS	Danny
Dynamic Load Test for Full Assembly	ANSYS	
Vibrational Response		
Vibrational Load for Full Assembly		Noah
Aerodynamic Load		Abby
Trajectory Evaluation		Brendon

Figure 4. Analysis Testing and Verification Matrix

VII. Next Steps

Project ARES faces significant financial challenges moving forward with the program. Additionally, several of the subsystems that were initially designed under ARES IV and ARES V will no longer be used for the final vehicle. At this time, there is a narrow path for the future of the project unless more funding is secured. At this point, Project Prometheus plans to complete all analysis and testing we are able to before the end of the 2020-2021 academic year. The results will be compiled along with the official designs and files and then archived and passed along to the next team that will work to fully integrate the vehicle.

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All ARES teams, past and present

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