Europa Clipper Enclosure

Final Report

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ME 450 Section 005
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TABLE OF CONTENTS

I. EXECUTIVE SUMMARY

Design Problem Description: Recent advances and scientific evidence points to some remarkable conclusions: Europa, one of the four Galilean satellites of Jupiter likely has a global ocean of water. The presence of water indicates the possibility of life forms on Europa and for this reason NASA has made it one of its top priorities to investigate this moon through its Europa Clipper Mission. The Clipper Spacecraft will be carrying several instruments on board. Team 22's task (in association with the Space Physics Research Lab, University of Michigan) is to design an electronic enclosure that will house certain key components of an ice penetrating radar that will be carried to Europa, by the Clipper Spacecraft.

Specifications: The needs and specifications were provided to the team in a thorough and well defined manner. Several instrument electronic chassis and mechanical mounting requirements were provided to the team through the JPL D-80302_Europa_Clipper_Environmental_Requirements_Document-140529. Mass and volume requirements were set at 4.79 kg (allowing a contingency margin of 32%) and 0.01042 m^3 respectively. In addition to the enclosure requirements for operation and use, the structure must be able to survive the launch environment. This environment includes both depressurization, and load requirements. Structural load requirements were broken down into mass acceleration, random vibration, acoustic environment, and pyrotechnic shock requirements. For venting, all flight hardware must be designed with margin to survive without degradation a depressurization rate of -4.4kPa/s (-0.638 psi/s) during launch (bounding case for EELV is Atlas V).

Final Design: Our final design has been chosen and has the following design characteristics: 6 plates with step connections, six mounting flanges, a recessed lip design with vents, inserted EMI shielding, a use of helicoils and wedge-loks, and Aluminum 6061 T6 as the material.

Validation Testing and Protocol: Team 22 was not required to perform physical tests; therefore, we used software results to validate our proposed design. Due to the scope of the project, we were not required to manufacture the entire prototype for the spacecraft; it has been manufactured to only ensure its manufacturable viability. The final assembled design was physically inspected and its mass was measured to ensure it is within the constraints provided to us by our sponsors. Finite element analysis of the entire model was performed to test and verify the behavior of the various components under a variety of conditions. A vibrational test (to simulate launch and in flight vibrations) was performed using SolidWorks. A heat transfer analysis was also performed to ensure proper heat dissipation (with the newly included heat frames in our design). This confirmed the proper functioning of the cards held in the enclosure. The CAD model was tested under different loads to further demonstrate the structural rigidity. Venting adequacy was established by satisfying the following empirical rule: $(V/A) < 2000$ inches where V = the total internal "void" volume of the assembly in cubic inches and A is the total area of the vent hole(s) or path(s) in square inches. Radiation modelling was performed using the provided testing (Spenvis) for an aluminum spherical shell dose/depth for Trajectory 13-F7 (the trajectory similar to the one the Clipper Spacecraft will follow). The safety of the fasteners was verified by performing a theoretical modeling of the load on the fasteners. Team 22 will not perform other physical tests; instead we have provided testing manuals to provide a step-by-step description of how to use the shake table and the thermal vacuum chamber to test the manufactured prototype.

Conclusions: Through the team's computer-simulation and FEA-driven validation, it was discovered that some design requirements could not be met simultaneously with each other along with additional concerns resulting from a lack of information at this stage in the design process. The team did, however, meet many of the initial design requirements without problems. Wall connections utilizing stepped joints were determined to be unsuited for use on thin-walled enclosures when prioritizing mass as well as adding needless complication to enclosure design and assembly. The reduction of mass of a previously thick-walled radiation-reduction based enclosure resulted in unacceptable levels of deflection of the enclosure plates. Radiation reduction were determined to be unobtainable with the current mass restrictions, resulting in a need for spot-shielding of critical components as well as mass allocation for that purpose. EMI shielding utilizing a separate "card" was determined to needlessly add mass and reduce available space in the enclosure. The team recommends integrating the EMI shielding onto the heat frame of the sensitive card or emitting card. Fasteners smaller than M3 were determined to be too fragile, and helical inserts at that size are difficult to handle and install properly. The team recommends use of M4 and larger fasteners. Heat frame heat transfer and deflection reduction were inconclusive due to the lack of card layout detailing heat sources and mass distribution. Finally, the team determined that a new design iteration is needed at the conclusion of the team's work, having learned that the current design does not satisfy all sponsor requirements, but does provide some potential solutions.

II. EUROPA BACKGROUND AND MISSION INTRODUCTION

The ice-covered world Europa - one of the four large Galilean satellites of Jupiter - may be the best place in the solar system to look for currently existing life beyond Earth.
Europa is about the same size as Earth's Moon, but its surface is much more dynamic. Its young, bright, icy landscape is criss-crossed by a network of cracks and ridges, interrupted by smooth bands, disrupted chaotic terrain, and just a handful of large craters [1].

Several lines of scientific evidence [2] point to remarkable conclusions: Europa likely has a global ocean of liquid water under its icy surface, maintained by tidal flexing and heating due to its eccentric orbit about Jupiter, and that ocean could potentially be habitable by microorganisms.

For these reasons, future investigation of Europa is a top priority for planetary exploration, as emphasized in NASA's fiscal year 2015 proposed budget. NASA's Europa Clipper mission concept could enable a leap in scientific understanding of this unique part of the solar system.

With the preliminary data sets obtained from previous missions to and past Jupiter, it is clear that Europa's youthful surface, potential subsurface ocean, and ongoing tidal flexing suggest that it is probably geologically active today. However, data return from the Galileo mission (1989) was limited, and the mission was not designed to detect subsurface water, so many mysteries remain. [3]
Models for the formation of Europa's bizarre surface features are consistently maturing but remain inconclusive. Fundamentally, it is not yet known if Europa has sufficient energy sources to sustain a biosphere, nor is it known if life within the interior ocean of Europa ever existed or still exists.

Mission concept

A return mission to Europa is the only way to gather the critical data required to answer the highest-priority geophysical and astrobiological questions about this intriguing ocean world. Collecting a global data set in a systematic manner is the appropriate next step.

The Europa Clipper mission concept [4], currently in formulation by NASA, could meet the science requirements and engineering challenges of a mission to Europa by flying past the moon repeatedly and observing with a payload specifically designed to address potential habitability. "Habitability" as defined in a solar system exploration context refers to the potential ability for a planetary environment to support microorganisms analogous to known terrestrial ones [5].

By orbiting Jupiter rather than Europa directly, the Europa Clipper (Fig 1 and 2, p. 5) would spend most of its time outside of the high-radiation environment close to Jupiter (Jovian radiation) that can be damaging to electronics. On each orbital pass, it would swoop as low as 25−100 kilometers from Europa, employing its remote sensing instruments to study the surface and subsurface while detecting particles from Europa's tenuous atmosphere and the moon's gravitational and magnetic fields. After each close approach, the spacecraft would transmit its data back to Earth.

A key feature of the mission concept is that the Clipper would use gravitational perturbations from Europa and from the icy Galilean moons Ganymede and Callisto - to deflect its trajectory, allowing the spacecraft to return to a different close approach point with each flyby. The flyby paths would create an intersecting web allowing remote sensing instruments to scan most of the surface over time.

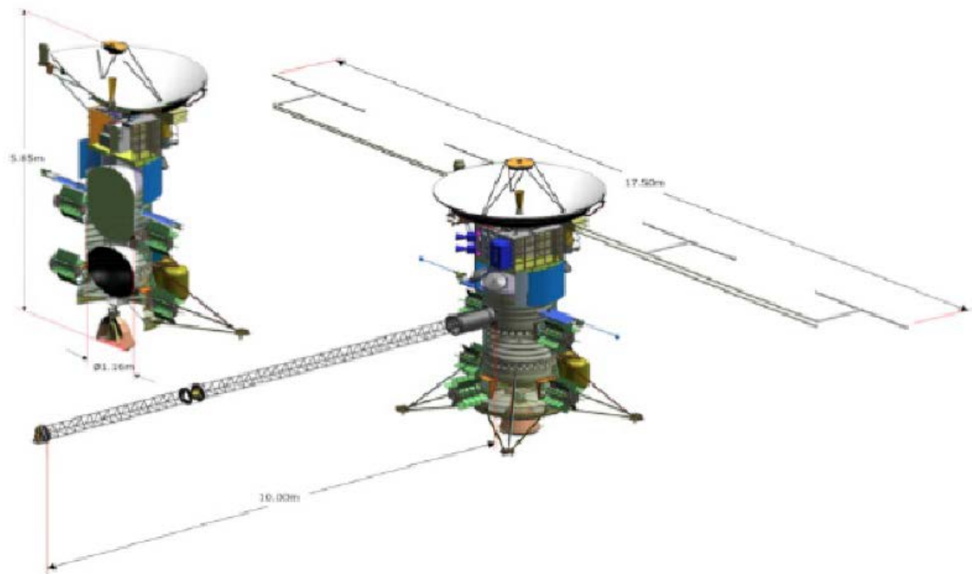

Figure 1. Overview of the Europa Clipper Spacecraft

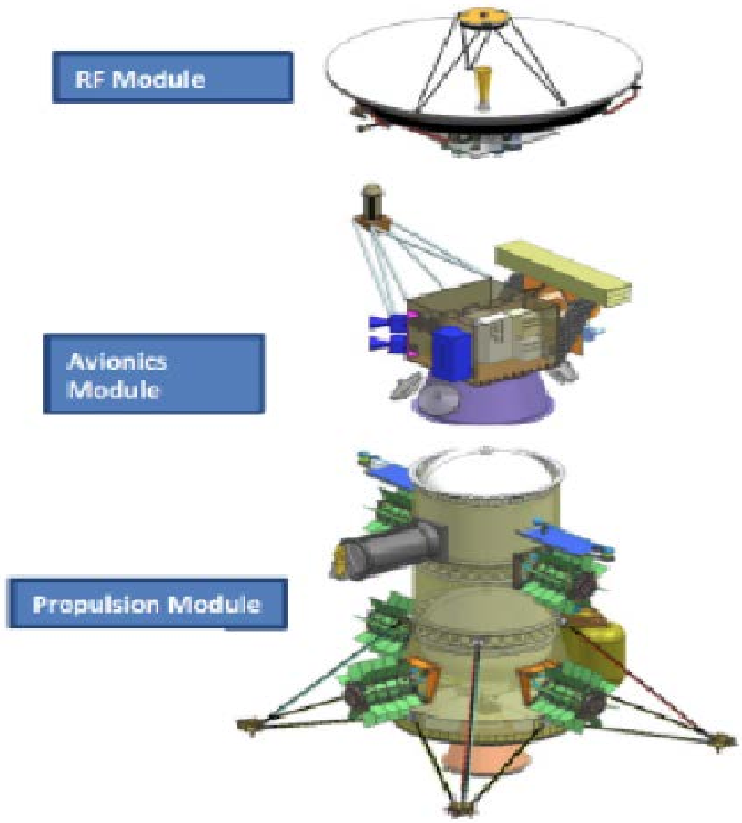

Figure 2. View of the main modules of the Europa Clipper concept: the RF module, avionics module and the propulsion module

Mission Goal: Test Europa for Habitability

The main science goal for the proposed mission is to explore Europa to investigate its habitability. Within this scope, three key science objectives involve investigating Europa's ice shell and ocean, composition, and geology. In turn, each objective has been mapped to example experiments and measurements that could realistically be performed by the Europa Clipper. These targets, in turn, helped the team of scientists and engineers conceptualizing the proposed spacecraft envision a sample set of instruments that would satisfy the science goal and objectives.

Questions that the Europa researchers hope to help answer include: Does the moon have an ocean, and if so, how thick is the ice above it? Is material exchanged between the surface and the ocean? What are the chemistry and origin of non-ice materials on the surface and in Europa's tenuous atmosphere? Are there areas of recent or current geological activity, and what are their morphology and topography?

The initial example science payload consists of an ice-penetrating radar to search for water in the subsurface, an infrared spectrometer to identify molecular compounds, a stereo camera for mapping and topography, a neutral mass spectrometer to identify atmospheric constituents, a magnetometer along with Langmuir probes to measure the induced magnetic field to constrain the salinity and thickness of the ocean, and the spacecraft's radio system to undertake gravity measurements. Such a payload would enable the Europa Clipper to seek evidence of subsurface water, chemistry compatible with habitability, and active geological processes driven by tidal flexing and heating. [6]

A team of scientists, engineers, and researchers from the University of Michigan and the University of Massachusetts Lowell have come together to design the proposed ice-penetrating radar assembly to place onboard the spacecraft (Fig 3, p. 7).

The primary objective of Team 22 was to design and fabricate the mechanical enclosure that will house the 5 6U form factor boards and other key components of the ice-penetrating radar. The primary constraints related to any equipment being developed for space flight are mass, volume, and radiation shielding, to name a few. Our objective was to successfully design this vault by April 2015, so as to have it ready for the instrument selection process (Phase A) of NASAs mission timeline.

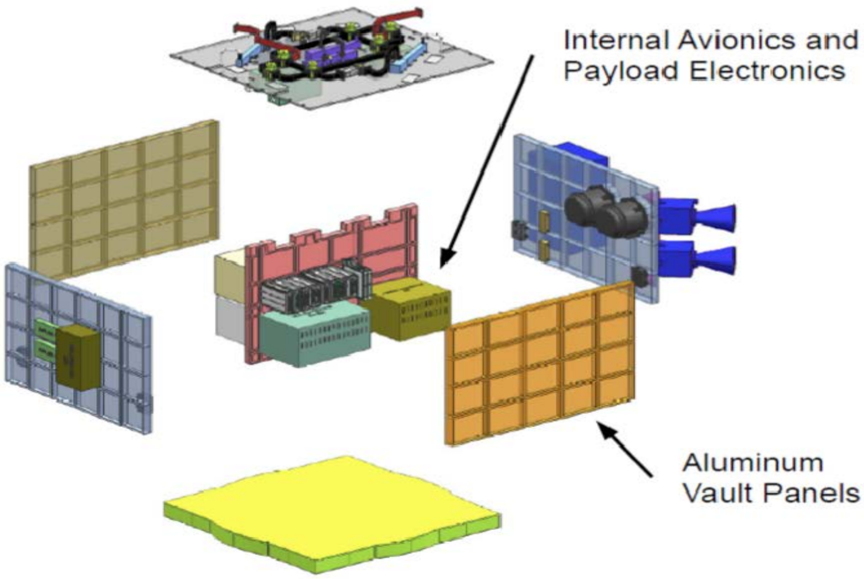

Figure 3. The position of the internal avionics and payload electronics enclosure (inside the vault) that Team 22 will be designing

For the enclosure, two types of instrument accommodations were expected: an instrument provided electronics chassis housed in the enclosure and hardware located outside the enclosure connected via harness. The chassis would be defined by the instruments and hosted within the vault. All instruments were to use a bolted interface. Where close thermal coupling is necessary, an appropriate thermal interface was to be implemented.

Mission Lifetime

The current baseline profile for the Europa Clipper mission concept is a launch aboard an Atlas V 551 rocket sometime in the first half of the coming decade. The transit time to Jupiter is about 6 years, using a Venus-Earth-Earth gravity assist (VEEGA) trajectory (Fig 4, p. 8). However, if it launched aboard NASA's in-development Space Launch System, Clipper could arrive at Jupiter on a direct trajectory in less than 3 years. A nuclear power source is tentatively planned (several Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs)), and the feasibility of a solar-powered spacecraft is also being evaluated.

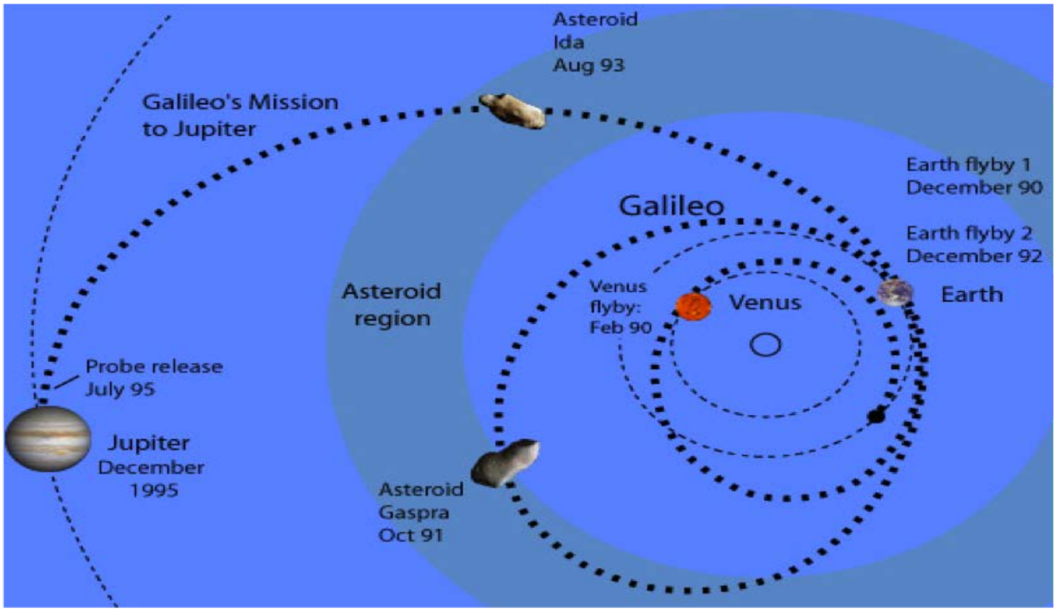

Figure 4. VEEGA trajectory as taken by the Cassini Spacecraft to Saturn; A similar trajectory will be followed by the Clipper Spacecraft

Upon arrival at Jupiter, encounters with Ganymede and Callisto would shape Clipper's orbit, placing it into a resonant orbit with Europa. Then it would make about 45 flybys of Europa over its proposed 3.5-year mission. Mission lifetime would be limited by radiation, but the mission radiation tolerance is designed to be twice the expected radiation dose to account for uncertainties; thus, survival of the spacecraft and instruments is expected well beyond the planned mission duration. The estimated cost of the entire Europa Clipper is around $2 billion.

III. BENCHMARKS

The team utilized the limited benchmarks available to it (due to International Traffic in Arms Regulations Restrictions). They are discussed below.

Benchmark: Juno Mission

In order to meet the design requirements of the electronics enclosure, we looked to NASA's storied past to find new ideas. Launched from Cape Canaveral in 2011, the Juno mission will arrive at the planet Jupiter by 2016. Once there, it is set to enter polar orbit and measure several qualities of the gas giant, gravitational field and magnetic field to name a few. Juno's mission will enter the radiation-heavy magnetosphere surrounding Jupiter, and so Juno became the first spacecraft to be fitted with an electronics enclosure to protect its vital electronics [7].

The electronics enclosure for Juno was constructed out of Titanium [8]. This is because Titanium provided the radiation-shielding needed and the structural integrity to withstand the flight environment while being low-density compared to many steels to meet mass specifications. Juno will be orbiting Jupiter for 15 months during which she will take the equivalent of 100 million dental x-rays in radiation exposure [9].

Like Europa Clipper, Juno will have a larger vault to reduce the radiation load on the electronics. However, the radiation environment is less severe for Juno than the Europa mission, meaning our design has to be ready to take a greater load.

Benchmark: Patent for Radiation Shield

Juno isn't the only benchmark design available for study. In order to gain a greater understanding of radiation shielding for electronics, we looked at old patents. US patent 20,070,184,285 discusses the pros and cons of different radiation shielding methods, "Tantalum, for example, provides adequate x-ray shielding but is a very heavy metal (density=16.7g/cc). Aluminum is lighter than tantalum by a factor of six, but does not adequately shield from x-rays." The solution to our problems should come from the manufacture of the enclosure itself, not a coating that has to be applied afterwards. Because of this, the inventors propose a cast zinc-alloy enclosure within a lightweight aluminum shell. "In the disclosed embodiment, the light-weight alloy body is of aluminum alloy. The zinc alloy is of zinc and aluminum and the finish metal layer is of nickel and gold. The zinc alloy film may be on the order of 100 microns thick. ...the electronics enclosure further comprises an interior layer of Ti/Pd/Ag to function as a hydrogen and moisture gatherer"[10]. The design in this patent tackles many of the same challenges as our Europa Clipper design has to. The proposed enclosure would be mechanically strong and well-shielded without incurring too much mass increase.

IV. USER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

After learning about our project and interviewing our sponsor, we were able to obtain the requirements needed for any of our solutions to be deemed successful. Since our project is an integral part of a much larger scale project, a satellite mission to Jupiter, not meeting any of these requirements is not an option. If we failed to meet any of the integral requirements, our project would be scrapped and a new design would have to be developed.

Instrument Electronics Chassis and Mechanical Mounting

Chassis and Mounting

The enclosure must be able to securely house instrument electronics. The enclosure has to contain five VPX boards [11] with 6U form factor [12], as well as pre-amplifiers and has to interface to other electronic instruments in the vault [17]. The boards must be shielded and sealed from EMI generated by the power amplifiers as per GSFC-733-HARN-01 and must be sealed with a resistance of less than 2 mΩ. The orientation of the VPX boards will be vertical and placed inside the enclosure in a stacked fashion. The enclosure must have through-holes for the following electronics connectors to pass: a Dsub26, a Subritec NDL-T 015112-500, a Dsub26, a Dsub15, two Connectronics 10406 and a UFF092F. Figure 5 below, shows the orientation of the VPX boards. Connectors should be at the top of the box as shown to support the integration needs inside the vault. The enclosure should use a bolted interface to attach to the vault base. The model payload assumes a maximum volume (box and connectors) of 0.0243 m^3 for the electronics in the vault, with a target volume of 0.01042 m^3. The electronics enclosure must have the volume to contain (5) 6U cards, with target dimensions of 255mm long by 214mm wide and a depth of 191mm. The maximum allowable mass is 3.02 kg with an allowable contingency margin of 18%. The target mass for the enclosure is 4.79 kg, which allows for an increased contingency margin of 32%. The engineering specifications and dimensions are defined by the Europa Clipper Proposal Information Package: Science and Reconnaissance Payload document, which utilized JPL and NASA requirements.

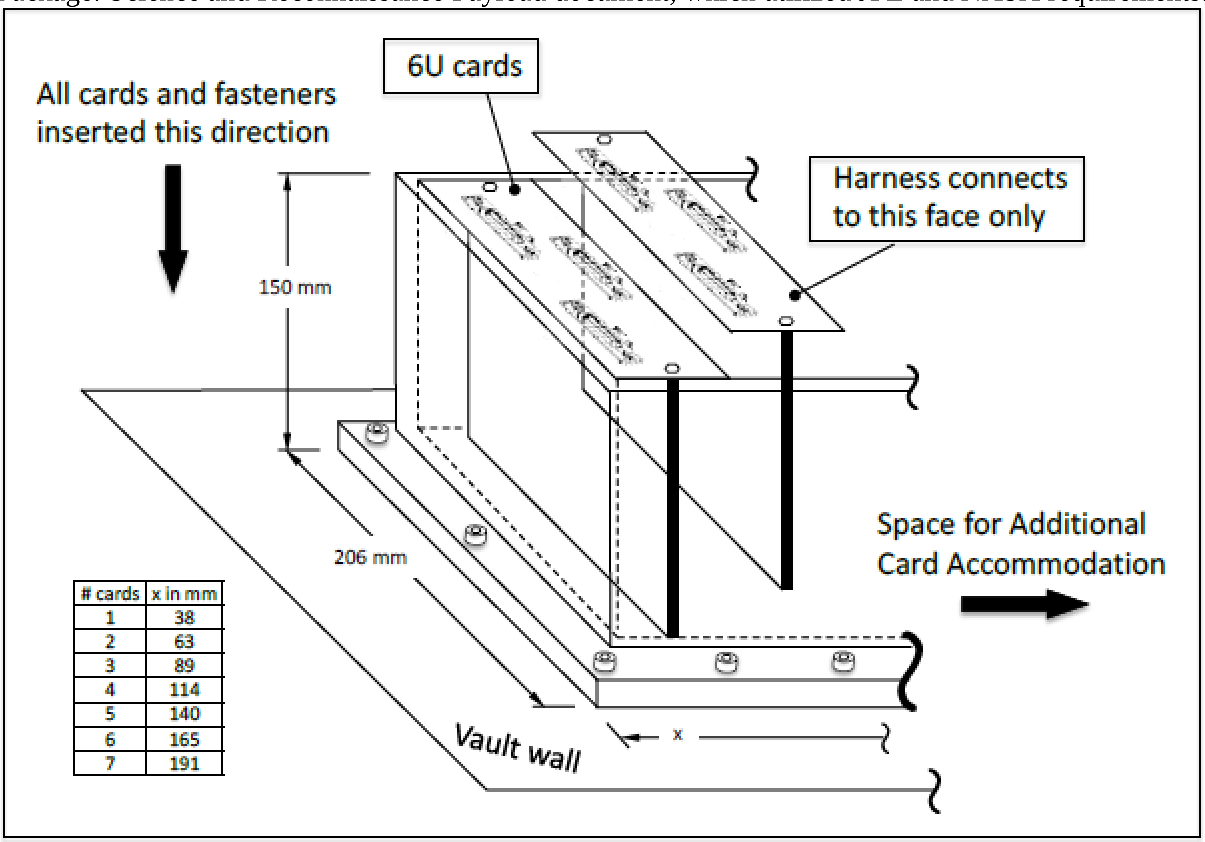

Figure 5. Instrument electronics enclosure and showing the orientation of the VPX boards

Any hardware must be designed to perform within specification, inside a vacuum, over thermal test limits [13]. The enclosure must be designed to survive without permanent degradation after exposure, inside a vacuum, to the non-operating thermal test limits of -35 C to 125 C [16]. These requirements were taken from the Europa Clipper Environmental Requirements Document provided by JPL. This also means that the 5 VPX boards inside the enclosure must be kept within the same temperature range, which will be thermally controlled by our enclosure design [14]. The chassis surface mounted to the vault wall will be a thermally controlled surface. The reasons for these requirements is to validate that our design will not fail in the known temperature conditions inside the vault during space flight [15]. The recommended thermal testing profile is shown in Figure 6 [16]. All specifications for thermal requirements are outlined in the Europa Clipper Environmental Requirements Document (JPL D-80302) as required by JPL and NASA standards.

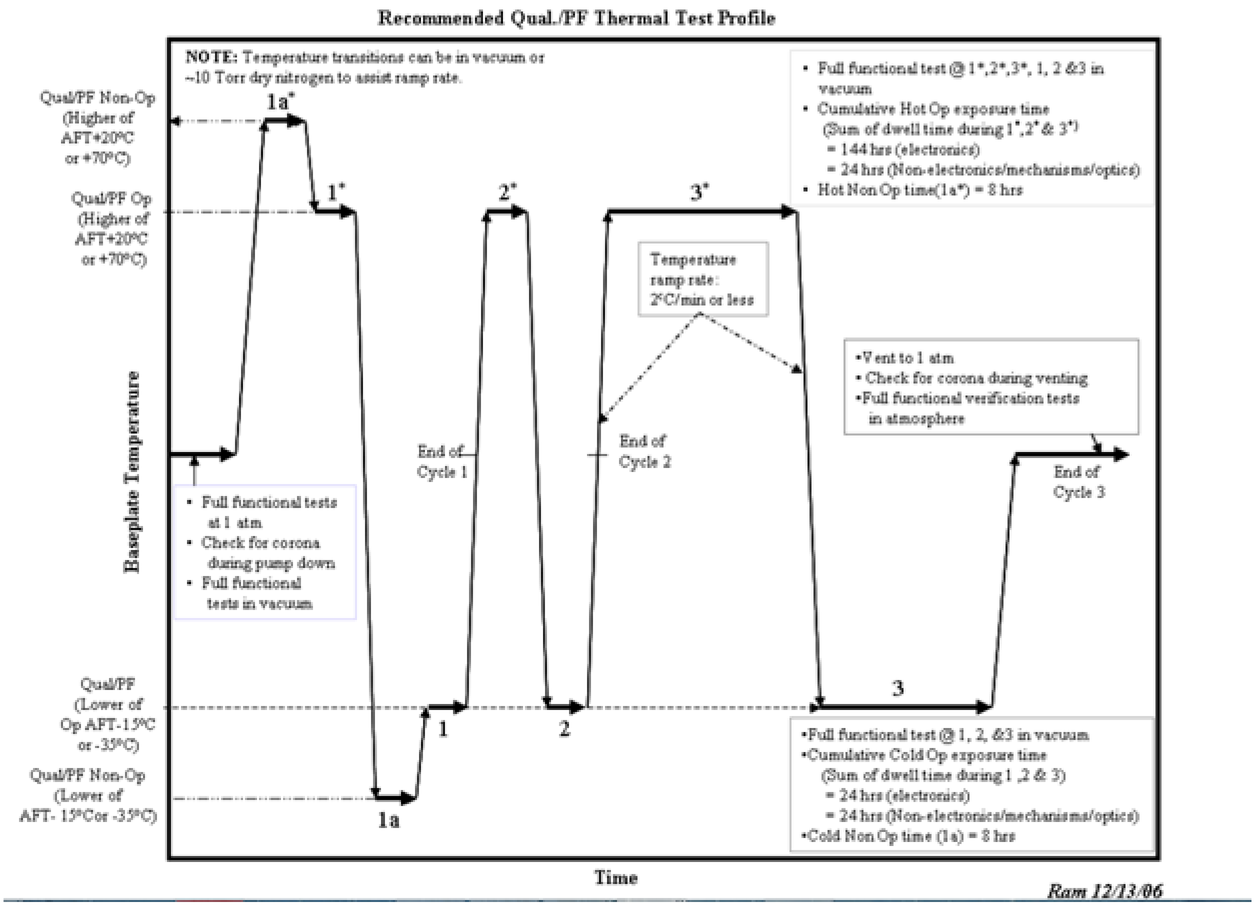

Figure 6. Example of Recommended Thermal Testing Profile [16].

Electrical Bonding of Structure, Housing, Cabling/Connectors/Shields, and Other Conductive Elements

The enclosure must be bonded to the spacecraft ground. A bond for electrical purposes is the conductive joining of two metallic assemblies. To ensure electrical continuity of the chassis and other metallic non-electrical/electronic hardware throughout the Flight System, bonding must meet the impedances indicated of less than 2.5 mΩ in Table 4.7-7 of JPL D-92256. The target impedance is 1 mΩ. All specifications for electrical requirements are outlined in the Europa Clipper Environmental Requirements Document (JPL D-80302) as required by JPL and NASA standards.

Internal Charging and Electrostatic Discharge (ESD)

It is assumed that there would be one or more enclosures of thick metal that would be used to protect most spacecraft hardware contained inside it from the effects of space radiation. The basic ESD requirement for hardware contained within the enclosure is that the electron flux must be below 0.1 pA/cm^2 average for any 20 hour period [Preliminary]. The target electron flux is to be below 0.05 pA/cm^2 average for any 20 hour period. All specifications for electrical requirements are outlined in the Europa Clipper Environmental Requirements Document (JPL D-80302) as required by JPL and NASA standards. [17]

Ionizing Radiation

The primary requirement of the enclosure is to protect electronics from the radiation environment it will be present in via shielding. The ionizing radiation exposure of Europa Clipper flight hardware will come primarily from the Jovian radiation belt environment, and secondarily from solar protons, solar and galactic cosmic rays, and Jovian heavy ions. The contribution from Jovian radiation belts is expected to dominate for all hardware. Flight System components and devices must be selected such that they operate within performance specification during and after the exposure to the radiation environment documented herein at a radiation design factor (RDF) of 2 times the level present at the location of the device. [17]

High Energy Radiation Environments

Europa Clipper mission radiation dose is based on solar protons and trapped Jovian protons and electrons through 59 Science Orbits. Within the vault, the total mission dose is not to exceed 150 krad (Si). The electronics enclosure must have a total mission dose of less than 100 krad (Si), with a target dose of 50 krad (Si) when using the RFD. The Radiation Design Factor (RDF) is defined as: RDF = Radiation-tolerance level of a part or component in a given application Radiation divided by environment present at the location of the part or component. The radiation-tolerance level of the electronics cards will allow the electronics to operate within the shielded enclosure at this mission dose. [17]

All general specifications for expected radiation environments are outlined in the Europa Clipper Environmental Requirements Document (JPL D-80302). The specific radiation doses for the proposed electronics enclosure are defined by the Europa Clipper Proposal Information Package Science and Reconnaissance Payload documentation (JPL D-92256).

Launch Environment

In addition to the enclosure requirements for operation and use, the structure must be able to survive the launch environment. This environment includes both depressurization and load requirements. All flight hardware must be able to survive structural loads occurring during the launch process. Structural load requirements are broken down into mass acceleration, random vibration, acoustic environment, and pyrotechnic shock requirements.

Venting

Flight hardware must be able to vent during launch. All flight hardware must be designed with margin to survive without degradation a depressurization rate of -4.4kPa/s (-0.638 psi/s) during launch (bounding case for EELV is Atlas V).

A 1.5x margin for analysis must be applied to this depressurization rate. Vent paths must be directed away from sensitive surfaces of the instruments. Venting adequacy can be established by satisfying the following empirical rule: (V/A) < 2000 inches where V = the total internal “void” volume of the assembly in cubic inches and A is the total area of the vent hole(s) or path(s) in square inches. If the assembly satisfies this rule, then no further venting analysis is necessary. [16]

Structural Loads Design and Verification Requirements

Mass Acceleration Curve

Quasi-static structural design loads represent the combined quasi-steady accelerations and the low frequency mechanically transmitted dynamic accelerations occurring during launch. The most conservative and earliest available design loads are from the Mass Acceleration Curve (MAC) defined in

Figure 7.

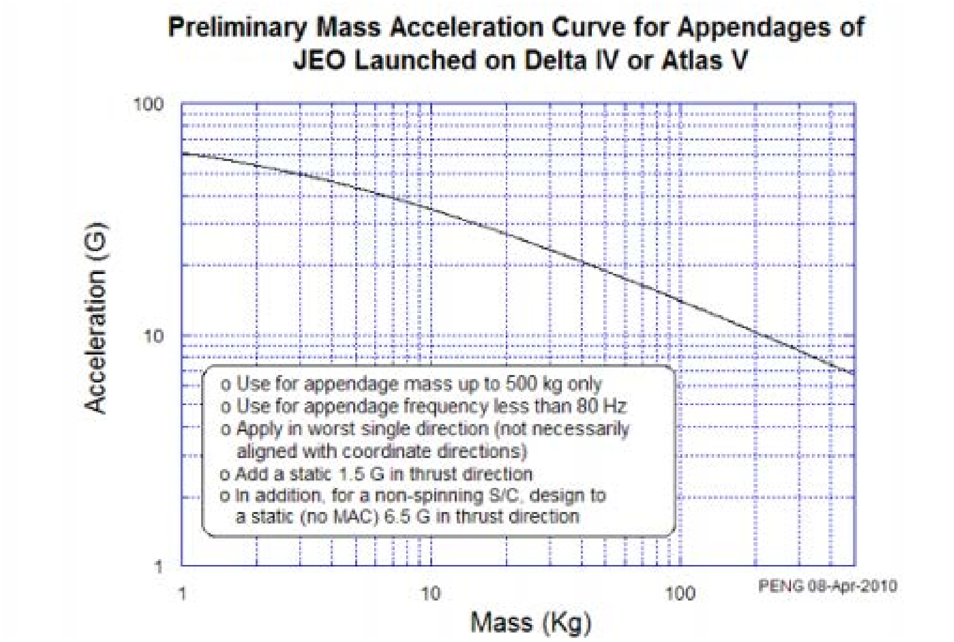

Figure 7. Preliminary Mass Acceleration Curve for the proposed Europa Clipper Mission

Load Condition (2)	Max. Lateral Case	Max. Axial Case
Thrust Axis Lateral Axes	+4.0/-1.1 g [(3)] ± 2.2 g	+6.5/-2.0 g [(3)] ±0.8 g

Notes:
(1) Loads are applicable at spacecraft C.G. and should be multiplied by appropriate safety factors to obtain structural design loads.
(2) Lateral and thrust axes loading may act simultaneously during any flight event.
(3) Plus indicates compression loads and minus indicates tension load.

Figure 8: Preliminary Spacecraft C.G. Limit Load Factors for Europa Clipper Launch on Candidate Evolved Expendable Launch Vehicles (Atlas-V)

This curve (Figure 7) must be used as preliminary design curve for all appendage structures (including primary structures other than the spacecraft core), secondary structures, support structures for equipment, and equipment structural attachments and housings. The MAC analysis was performed for JEO, as the Europa Clipper configuration is evolving. A final MAC curve for Europa Clipper would be produced prior to the System Requirements Review. The electronics enclosure must function without degradation when these loads are applied. [17]

Europa Clipper Flight System
Random Vibration
The Europa Clipper Flight System must be designed and tested to the random vibration requirements per Table 1. These vibrations are a result of launch operations. [17]

Frequency Hz	FA Acceleration Spectral Density	Qual/PF Acceleration Spectral Density
10 – 20	+ 3 dB/Octave	+ 3 dB/Octave
20 – 200	0.0075 g^2 / Hz	0.015 g^2 / Hz
Overall	1.19 Grms	1.68 Grms

Qual: 2 minutes in each of the three axes. PF/FA: 1 minute in each axis.

Table 1. Flight System Random Vibration Test Levels [Preliminary]

Flight System Acoustic Environment

The acoustic environment (Table 1) is the envelope of the acoustic environments for the candidate EELV launch vehicles (Atlas V and Delta IV Heavy). The SLS vehicle acoustic levels are expected to be bound by these levels. The maximum acoustic environment for the Europa Clipper Flight System would occur during lift-off and transonic flight. The environment is represented as a reverberant acoustic field with random incidence specified in 1/3 octave bands [20]

The Europa Clipper Flight System design must perform within specification after being subjected to acoustic test levels as defined in Table 2 and 3, page 15 [17].

Table 2: Acoustic Qual /Protoflight & Flight Acceptance Test Levels

Duration: Qual: 2 minutes; PF and FA: 1 minute

1/3 Octave Band Center Frequency	FA Sound Pressure Level	Qual/PF Sound Pressure Level	Test Tolerances
(Hz)	(dB ref. 20 μPa)	(dB ref. 20 μPa)	
31.5	123.5	126.5	+5, -3
40	127.5	130.5	+5, -3
50	130.0	133.0	+5, -3
63	131.5	134.5	± 3
80	132.5	135.5	± 3
100	133.0	136.0	± 3
125	133.0	136.0	± 3
160	133.0	136.0	± 3
200	133.0	136.0	± 3
250	133.0	136.0	± 3
315	133.0	136.0	± 3
400	131.0	134.0	± 3
500	129.0	132.0	± 3
630	126.5	129.5	± 3
800	124.5	127.5	± 3
1000	122.5	125.5	± 3
1250	120.7	123.7	± 3
1600	118.3	121.3	± 3
2000	118.0	121.0	± 3
2500	115.0	118.0	± 3
3150	114.5	117.5	± 3
4000	112.5	115.5	as close as possible
5000	111.5	114.5	as close as possible
6300	111.0	114.0	as close as possible
8000	111.0	114.0	as close as possible
10000	112.0	115.0	as close as possible

1/3 Octave Band Center Frequency	FA Sound Pressure Level	Qual/PF Sound Pressure Level	Test Tolerances
Overall	143.1	146.1	± 1

Table 3. Acoustic environment test levels

Flight System Pyrotechnic Shock

The Flight System would experience a shock due to the firing of pyrotechnic or other devices during payload separation. For reference, Table 5 contains maximum predicted shock levels at the Flight System interface due to payload separation from the PAF. At the Flight System, verification would be performed by activating twice each shock-producing device that is the dominant shock source for any potentially shock susceptible hardware [19]. All other shock producing devices must each be activated once. The Flight System must be designed to survive without degradation and to function safely during deployment events when subjected to shock environments shown in Table 4 [17] [18].

Table 4. Sinusoidal Microphonic Environment for Instrument Deck

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Frequency (Hz)	Requirement
10-1000	0.1 g, 0-to-Peak

1 g = standard acceleration due to gravity = 9.81 m/s^2
Test sweep rate: 2 octave/minute (upsweep only) in each of three orthogonal directions.

Table 5. Maximum Flight Level Pyroshock Environment at the Launch Vehicle Interface [Preliminary]

Frequency, Hz	MEFL SRS (Q=10)
100	150 g
1000	5000 g
10,000	5000 g

All specifications for launch requirements are outlined in the Europa Clipper Environmental Requirements Document (JPL D-80302) as required by JPL and NASA standards.

V. CONCEPT GENERATION

To begin generating concepts, our team first began researching the overall design of previous spacecraft electronic enclosures. These included images from press releases, product data sheets we requested from companies as well as spacecraft prototypes with relevant components on display at the university. Our research in this area was severely hampered by ITAR (International Traffic in Arms Regulations) restrictions, limiting the information available to us. A CAD model our sponsor had intended for us to utilize was not available for us due to this reason. Through analysis of previous spacecraft, we were able to determine several overall designs of electronics enclosures common throughout spacecraft, particularly those intended to survive radiation environments. As a result of restricted access to CAD models, to gain an understanding of the designs of previous spacecraft, we reverse engineered images by using known dimensions to scale components to create detailed drawings.

From these common designs, we were able to individually brainstorm overall enclosures we felt would meet our requirements. Due to the restrictive requirements for the enclosure, well felt it was better to decompose the functional aspects of each design, by category. Once these categories had been defined, we were able to better differentiate concepts that are key to the construction and performance of our enclosure. These categories were: the method of joining the plates that the enclosure is composed of, methods for weight reduction of the plates, the method for attaching the base plate to the vault wall of the spacecraft, methods for protecting vents with the “lid” or top plate, venting methods, EMI shielding integration, fastener threading techniques and overall material. Additionally, a baseline concept was developed consisting of a milled block of solid aluminum for later use in our concept selection process. A complete collection of our initial design concepts, including explanations, can be seen in Appendix A.

Reference Terminology

For reference, the following terminology will be used throughout the report (Figure 9). The uppermost plate along the x-axis is the Top Plate. The two plates parallel to y-axis are the two identical Side Plates. The two plates parallel to the z-axis are the identical Front and Back Plates. The Front Plate is in the Positive y-direction and the Back Plate in the negative y-direction. The Base Plate is the lowermost plate in the z-direction, and may be extruded as a method of attaching the enclosure to the vault wall of the spacecraft.

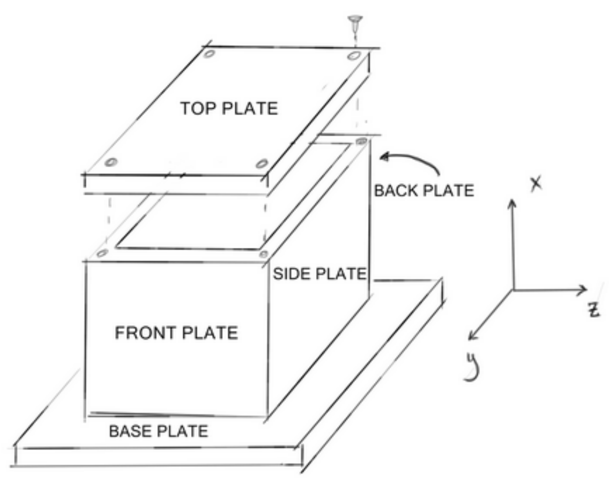

Figure 9. Concept reference terminology and geometry.

Plate Joining
The methods for joining the plates composing the enclosure included a baseline of making the plates a solid, milled enclosure, utilizing a flat connection with fasteners, and finally improving on this design and utilizing a stepped connection with fasteners. The three connection types are pictured below (Figure 10).

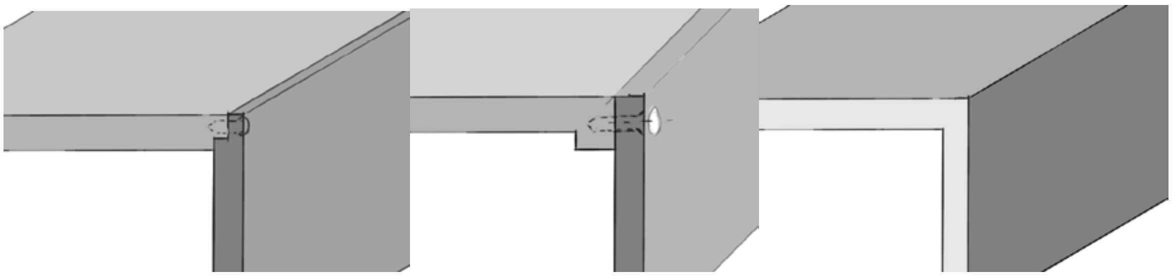

Figure 10. Plate Joining Methods: stepped, flat and solid joints.

Mass Reduction
The methods for weight reduction of the plates included a baseline with no reduction, rectangular reduction designs, triangular reduction designs, and a hybrid reduction design that is commonly utilized on CubeSats. These are pictured below (Figure 11).

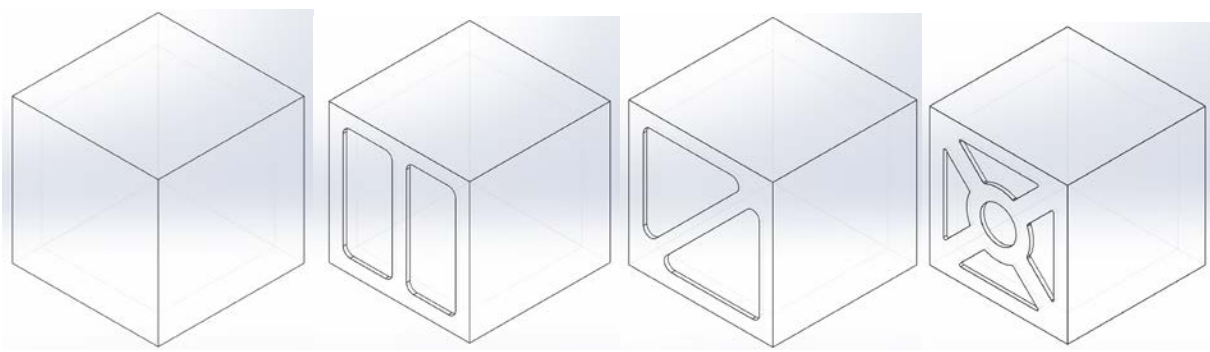

Figure 11. Mass Reduction: Reference, rectangular, triangular and hybrid (cubesat) reduction geometries.

Base Mounting
The method of securing the enclosure to the vault wall of the spacecraft included an extended baseplate on two and four sides, mounting flanges on two and four sides, and a unique enclosure shape allowing for fasteners to be placed in the corners. These concepts are shown below (Figure 12).

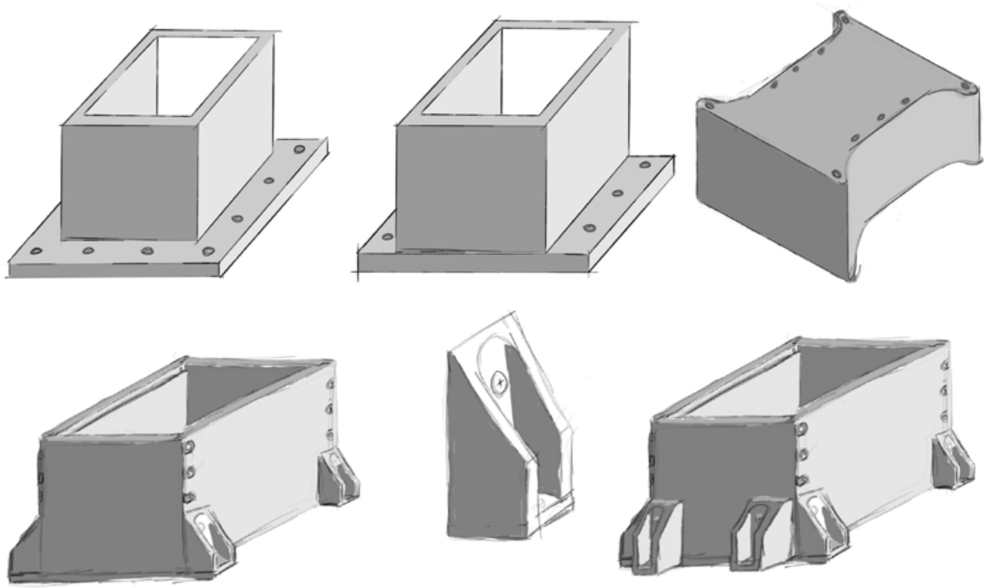

Figure 12. Base Mounting: Extended base on four sides, extended base on two sides, hybrid corner connection, mounting flanges on two sides, example mounting flange, mounting flanges on four sides.

Top Plate Design

The methods for protecting vents with the placement of the top plate included a flush Top Plate, a Top Plate that overhung the Side Plates with an outside "lip," and a recessed Top Plate that sat inside the Side Plates. These concepts are shown below (Figure 13).

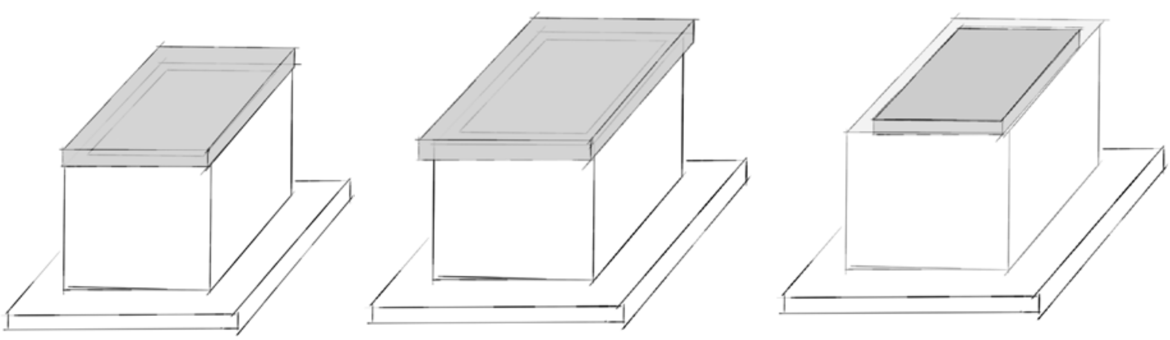

Figure 13. Top Plate Designs: Flush, overhung, and recessed top plates.

Venting

The methods for venting atmosphere during launch included a Top Plate based recess for venting as well as a Side Plate based "wall" vent. These concepts are shown below (Figure14).

Figure 14. Venting methods: Top Plate venting and Side Plate venting.

EMI Shielding

The methods for EMI shielding integration between the cards included treating the EMI shielding as a "card" to be placed in a slot and integrating the shielding into the structure of the enclosure (Figure 15).

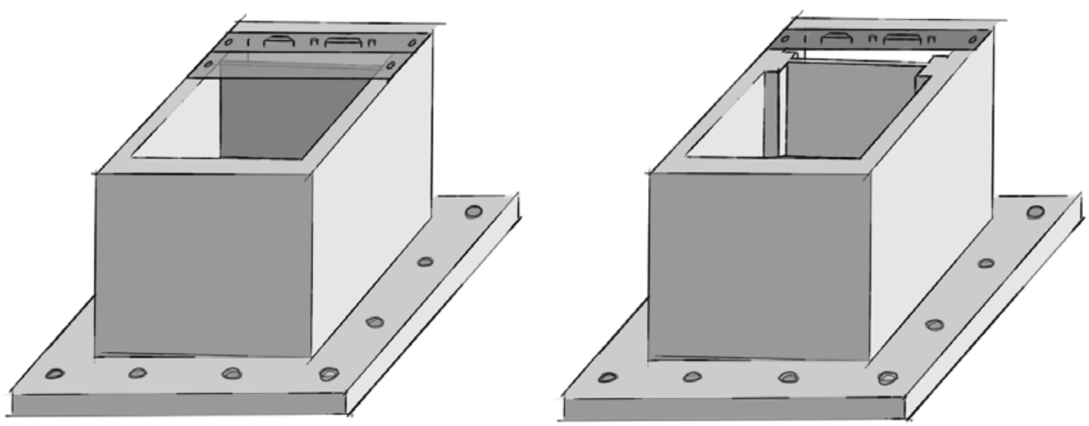

Figure 15. EMI shielding Integration: card based shielding and structure-integrated shielding.

Fastener Threading

The two fastener threading techniques investigated included threading directly into the enclosure material and inserting helicoil type inserts into the enclosure material. A helicoil is shown below (Figure 16).

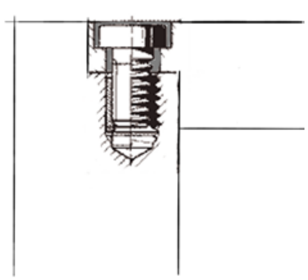

Figure 16: Helicoil fastener insert.

Material Selection

The overall materials considered for the construction of the enclosure included Aluminum 6061 T6 and grade 5 Titanium. Both materials are commonly used in spacecraft applications, are lightweight, and provided some radiation protection.

VI. CONCEPT SELECTION

Apart from the sponsor requirements and engineering specifications of our project, we had to take into account some assessment of the feasibility of each concept. This included the financial, temporal, and technical constraints of ME450 and the resources we have access to. All of our design concepts are feasible and within our given constraints except for the final material selection of our design. Space grade titanium (Grade 5), although it might be the best possible solution for our design, will be too expensive and unable to be manufactured with the resources available to us.

After generating more than 20 concepts of our design, we needed to systematically select the design that best meets our requirements. To do this we made a Pugh chart that compared each design to a datum design, a 1 cm thick aluminum block with our desired dimensions, in various criteria which are the following: mass, thermal management, manufacturability, radiation shielding, structural rigidity, volume, and launch protection. We allocated each criteria a weight (1-5), depending on the importance of the criteria (5 being the most important, 1 is least important). Table 6 shows each criteria and their allocated mass. Our pugh charts for each design category are in Appendix B.

Table 6. The criteria used in our Pugh chart with their weight and description

Criteria	Weight	Description
Mass	5	Mass of the design; minimized
Thermal Management	4	Effectiveness of heat transfer of the design; maximized
Manufacturability	2	The degree of difficulty of manufacturing our design; minimized
Radiation Shielding	5	Amount of radiation shielding our design provides; maximized
Structural Rigidity	3	Ability to survive launch environment; maximized
Launch Protection	2	Ability to protect internal components during launch; maximized
Volume	1	Volume of our design; minimized
Venting Area	2	Surface area where air can escape enclosure; maximized

Chosen Design

After completing the Pugh chart, we were able to select the tentative final design of each category, pending further tests for radiation, mass, and rigidity. Our final design is shown in Figure 17.

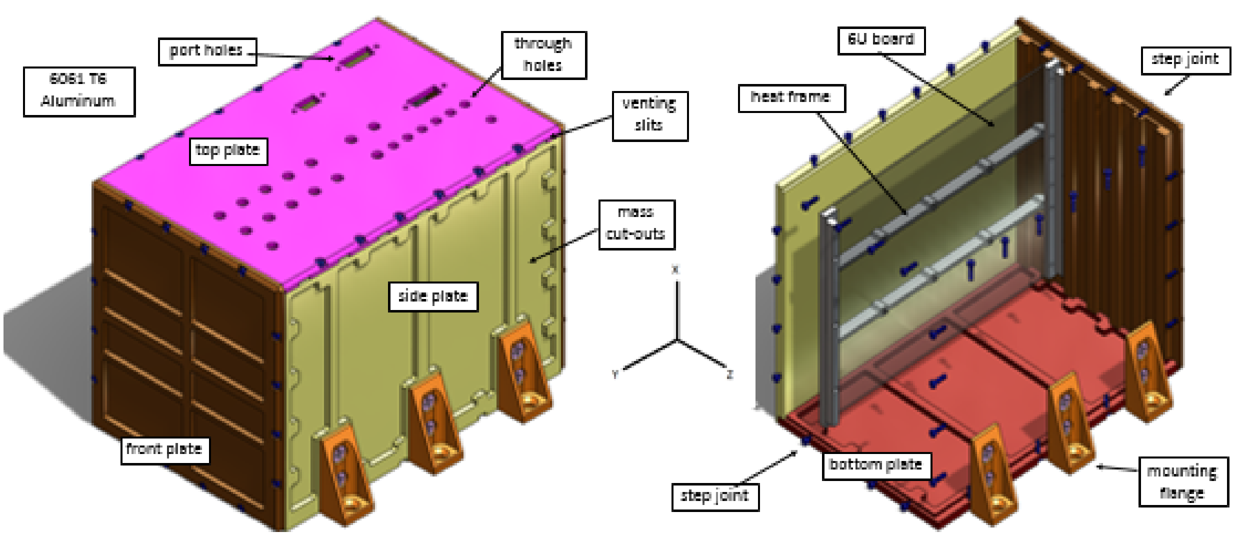

Figure 17: Final design concept CAD model with and without the Top, Front and Side plates.

Wall Connection: To connect our 6 plates together, we chose to have a step connection for each wall. The advantage of having a step connection over our other options is the added structural rigidity of our design. Another advantage of having a design that utilizes 6 separate walls instead of a single piece of material is the manufacturability. A design that is comprised of six, relatively simple, components will be much easier and more feasible to manufacture than a single block of the chosen material. The disadvantage of this design compared to a solid piece material is the added weight and management.

Wall Mass Reduction: To reduce the mass of our system, we chose to have square cutouts on the four side plates. The advantage of this design is that it will reduce the most mass, compared to our other design options. Also this design will be easier to manufacture than our other cut-out designs. A disadvantage to removing wall mass, compared to having a flat plate, is the added difficulty in manufacturing.

Base Mounting: To connect our enclosure to the vault of the spacecraft, we chose to have a mounting flange that would mount the enclosure to the vault. The advantage of this design compared to our other design options is the reduction in mass of the design. Another advantage of this design is the higher structural rigidity and launch protection of the housed electronic components. There is a slight reduction in thermal management when compared with our other design options due to the decrease in contact surface area to the vault wall. Also it will be more difficult to manufacture this chosen design.

Lid Design: To enclose our enclosure, we chose to have a recessed lip lid to cover and seal our enclosure. The advantage of this design is that it required the least mass of all our design options. Another advantage of this design is that it minimized the final volume of our enclosure compared to other design options. The disadvantage to this design is that it will be more difficult to manufacture.

Venting: In order to let air escape our enclosure during launch, we chose to have a vent integrated in our lid. The advantage of this design, compared to having a vent in our enclosure walls, is the reduction in mass. This design will also be easier to design and manufacture. Another advantage of this design is that it has the largest venting area, which ensures that we will meet the venting requirements of the enclosure. A disadvantage to our chosen design is that it will decrease the structural rigidity of the enclosure.

EMI Shielding: To incorporate an electromagnetic interference (EMI) shield in our design, we chose to design to allow for the EMI shield to be inserted into our enclosure. The advantage of an inserted EMI shield versus an incorporated shield is the manufacturability of the design. Both designs are similar in shield effectiveness, thermal management, and mass. The disadvantage of including an EMI shield is the added mass, due to the increased volume needed to house the shield, compared to not including an EMI shield. Even though an EMI shield will increase the mass of our enclosure significantly, it is a requirement from our sponsor.

Fastener Design: To connect our enclosure walls together, we chose to use helicoils as our fasteners. The advantage of this design, compared to using threaded fasteners, is the added structural rigidity of our enclosure and the added protection of the housed electronics during launch. The disadvantage of using helicoils is that it is more difficult to manufacture and has slightly more mass compared to our other design concepts. However, threaded fasteners are much weaker, and will compromise the structural rigidity of our enclosure, possibly causing our walls to disconnect.

Material Selection: The material selection for our final design is still undecided. We are currently deciding between two different materials, Aluminum 6061 T6 and Titanium (Grade 5). We would need to run various computer software simulations of thermal and radiation tests to determine our material selection. Aluminum has the following advantages over titanium: less mass, easier to manufacture, costs less, and better thermal management. The advantages of titanium are the following: greater radiation shielding and greater structural rigidity.

VII. KEY DESIGN DRIVERS

In order to meet the sponsor requirements and the engineering specifications of the project, we chose our final design as shown in Figure 17, p 22. As discussed in our Concept Selection we chose to move forward with a design that not only meets our sponsor's requirements, but also meets our design and manufacturing capabilities. The key parameters we centered our design around, were mass, thermal management, manufacturability, radiation shielding, structural rigidity, volume, and launch protection. Of these parameters, mass constraints and radiation shielding were the primary design concerns. After satisfying these two requirements, we continued our design generation process, taking into accounting the structural rigidity needs and manufacturability of the prototype. Our simplest competent model is a 6061 T6 aluminum enclosure (1 cm thick) that is composed of 6 aluminum plates (a front plate, a back plate, two side plates, a flush fit top plate and a base plate). These plates are attached using a solid (milled) joint. The wall design in the simplest model was designed based on existing reference models. The enclosure is mounted to the vault wall using four flange mounts, two on either side of the enclosure. This model achieves the thermal management, manufacturability, radiation shielding, structural rigidity, volume, and launch requirements. It does not meet the mass requirements and was used as a model to make mass and radiation optimizations, amongst other optimizations.

After generating all the concepts, the team narrowed down on a final design concept. We realized that each concept had its trade-offs, and we chose a final design that would satisfy all the requirements, to the best of our abilities. Further testing via computer software simulations would be needed to finalize our design, before entering the manufacturing stage.

VIII. CHALLENGES

Here we discuss some of the challenges our team faced, in successfully designing and manufacturing the enclosure, required for the Europa Clipper Spacecraft.

Radiation simulation

One major consideration for our design is the added radiation shielding capabilities it must have. As mechanical engineers, our team did not have prior experience with any radiation shielding testing. We were advised to use SPENVIS (Space Environment Information System), a radiation simulation software. Learning and successfully using this software to test our design's capabilities to shield for radiation was a challenge, more so, because of the short time period we had.

Material selection and Titanium usage

One possible material that was being considered in our design is Titanium (Grade 5). Although titanium is a common material used in spacecraft design, it is not very easy to manufacture. While we did not have to manufacture the final design of the enclosure for the Europa Clipper Spacecraft, we did have to manufacture a prototype as per the ME450 requirements. Titanium is extremely costly and procurement would have been a challenge. While aluminum is soft, ductile and easy to manufacture, titanium is 60% denser and has double the strength of aluminum. While titanium does possess its advantages over aluminum, it does have its own drawbacks and challenges associated with it.

Manufacturability

A key design driver for our project was manufacturability. Many of our design concepts and final design selection decisions have been based on the 'ease of manufacturing' aspect. While it did not rank high in our Concept Selection Pugh Chart, manufacturability remains a vital parameter. Since we are in Pre-Phase A of the Clipper Mission, and we are only making a prototype of the enclosure, we will not be required to meet NASA manufacturing standards. However, we decided to have tolerances that are extremely close to, if not identical, to NASA standards. Using the tools and machines we have at our disposal, it was a challenge to do so. Technical assistance and some special equipment would have been needed if we were to achieve the set NASA protocols.

Validating correctness of our solution

ME450 is a senior design course with open ended problems. There is no right or wrong solution and therefore, we thought, that validating the correctness of our solution would be a challenge. Our project has some very strict constraints and design requirements, but even within these constraints, there is some design flexibility, as seen in our design Concept Generation section. Meeting our sponsor's requirements, and the extensive engineering specifications with a valid and exceptional design was challenging. Given these engineering specifications and requirements, we could only validate our design with computer software testing. We proposed two empirical tests: a thermal heat chamber to validate our heat transfer analysis, and a vibration table test to validate our structural vibration analysis. However, our sponsor said that with the scope of our project, being in the very early design proposal stages of the NASA mission timeline, these empirical tests were deemed too costly and would not be needed for our project. Our sponsor stated that simulation software testing will be enough for our project, and would not need to be validated by empirical tests.

Final Design Concept

Generating a final design concept was a major challenge for our team. We were working with other teams of engineers and scientists from across the country and could not finalize our design, before they determined their final requirements. We knew that we must have a detailed engineering design of our prototype, and meeting this task requirement seemed to be an uphill task, primarily because of the number of people involved in this project and the amount of coordination required between everybody.

IX. CONCEPT DESCRIPTION

As a result of our engineering analysis and sponsor requests, significant alterations were made to our design concept, on multiple occasions. Our final design is shown in Figure 19 below. This design in decomposed into several key features in order to meet our design drivers.

Reference Terminology

For reference, the following terminology (which is used throughout the report) is shown here again (Figure 18). The uppermost plate along the x-axis is the Top Plate. The two plates parallel to y-axis are the two identical Side Plates. The two plates parallel to the z-axis are the identical Front and Back Plates. The Front Plate is in the Positive y-direction and the Back Plate in the negative y-direction. The Base Plate is the lowermost plate in the z-direction.

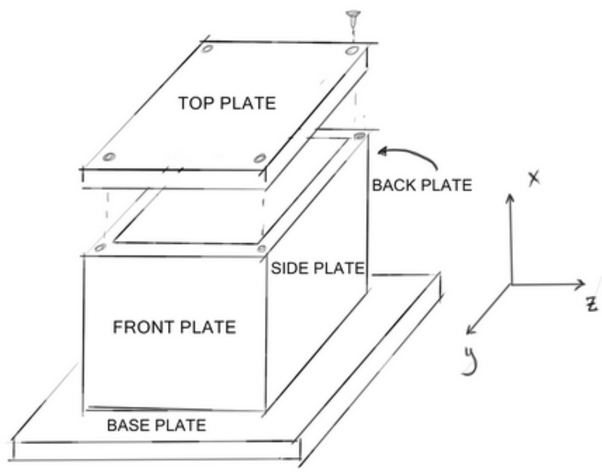

Figure 18. Concept reference terminology and geometry.

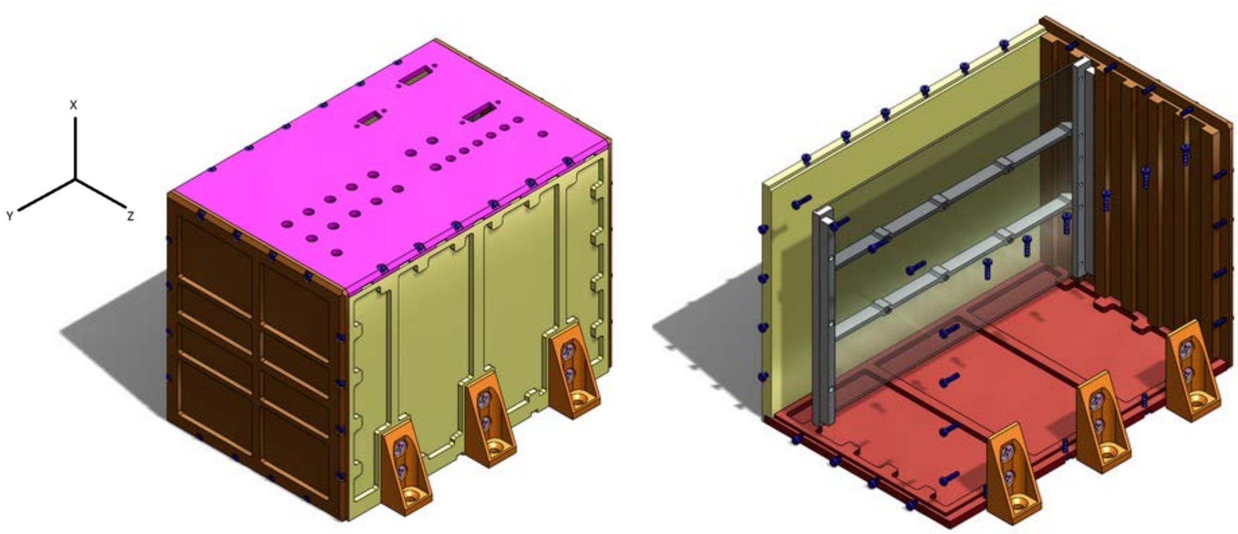

Figure 19. Final design concept CAD model with and without the Top, Front and Side plates.

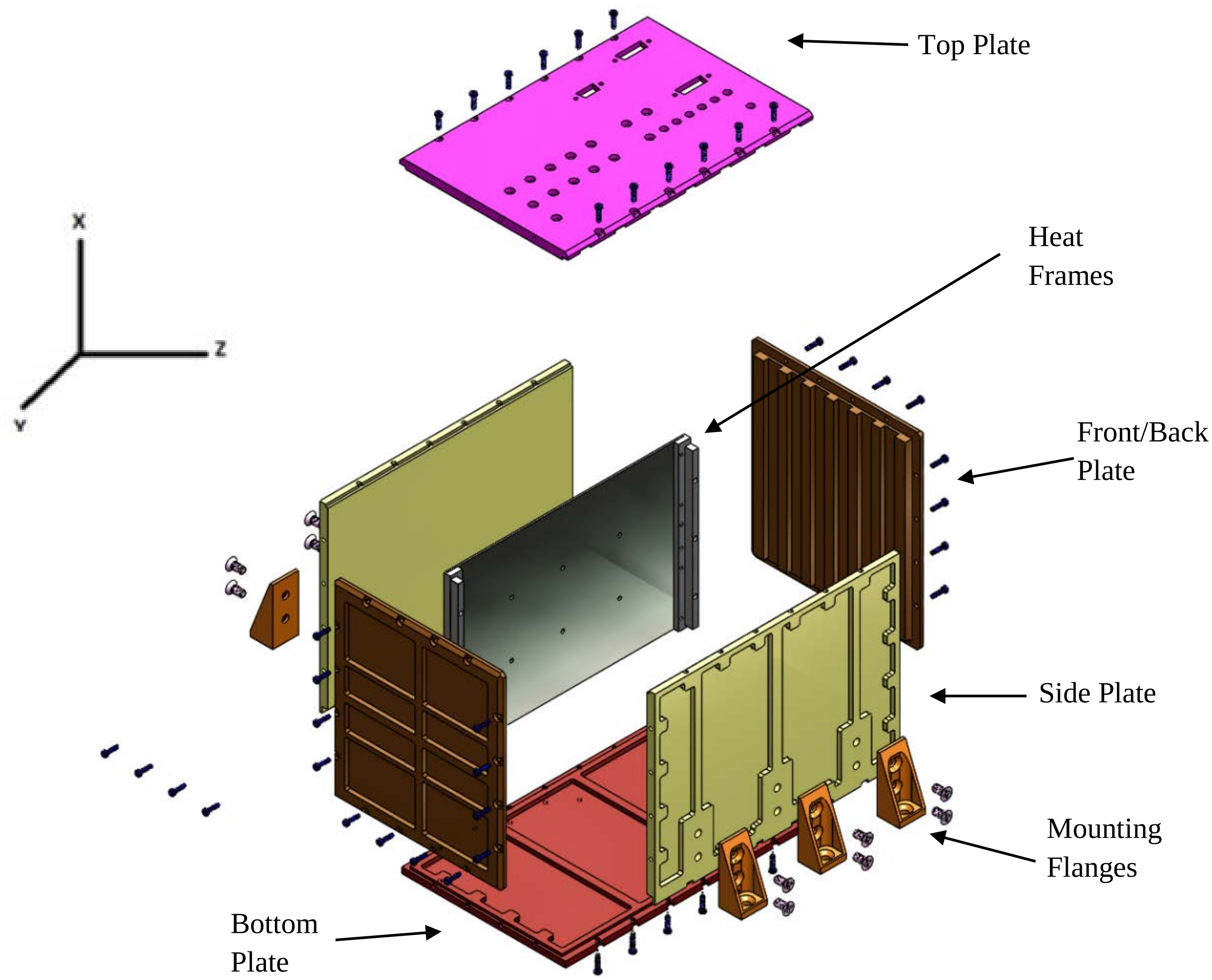

Figure 20. Exploded view of our final design with parts labeled.

Plate Connection: To connect our 6 plates together, we chose to utilize a stepped connection for each plate. The advantage of having a step connection over our other options is the added structural rigidity of our design. Another advantage of having a design that utilizes 6 separate plates instead of a single piece of material is the manufacturability. A design that is comprised of six, relatively simple, components will be much easier and more feasible to manufacture than a single block of the chosen material. The Steps also prevent any line-of-sight for radiation or EMI interference to enter the enclosure. The plates are joined by 2.5mm (2.5M 45) 316 stainless steel socket head cap metric fasteners. The fasteners are inserted into 316 stainless steel screw-lock helical insets.

Plate Mass Reduction: To reduce the mass of our system, have chosen a plate thickness close to the minimum required to achieve the required radiation exposure. All plates, for radiation shielding purposes, are a maximum of 8mm thick. Due to radiation exposure concerns, the inclusion of mass reducing cutouts was not possible.

Mounting Flanges: To connect our enclosure to the vault of the spacecraft, we chose to have a mounting flange that would mount the enclosure to the vault. The advantage of this design compared to our other design options is the reduction in mass of the design, only having a mass of about .08kg each. Another advantage of this design is the higher structural rigidity and launch protection of the housed electronic components. As a result of our engineering analysis, we have determined the number of mounting flanges required to be 6 instead of the previous 4. The mounting flanges are secured to the Side Plates of the enclosure and the Vault Wall of the spacecraft using 6mm (M6) 316 stainless steel socket head cap metric fasteners. The fasteners inserted into the Side Plates are inserted into 316 stainless steel screw-lock helical insets.

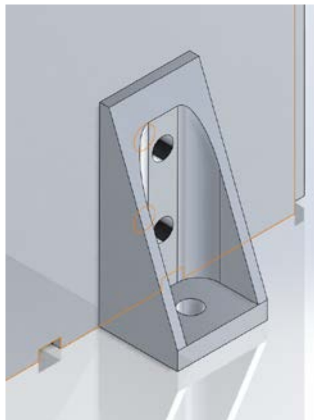

Figure 21. Mounting Flange Detail.

Lid Design: The lid now incorporates thru-holes for the required connectors in the required order, spaced according to their respective card's location. The connectors are: 2x Dsub26, Subritec NDL-T 01511-500, Dsub15, Connectronics 10406, and 2x UFF092F.

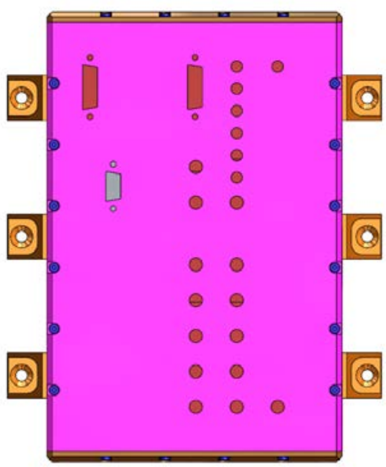

Figure 22. Lid Detail.

Venting: In order to let air escape our enclosure during launch, we chose to have a vent integrated in our lid. The advantage of this design, compared to having a vent in our enclosure walls, is the reduction in mass. This design will also be easier to design and manufacture. Another advantage of this design is that it has the largest venting area, which ensures that we will meet the venting requirements of the enclosure. A disadvantage to our chosen design is that it will decrease the structural rigidity of the enclosure.

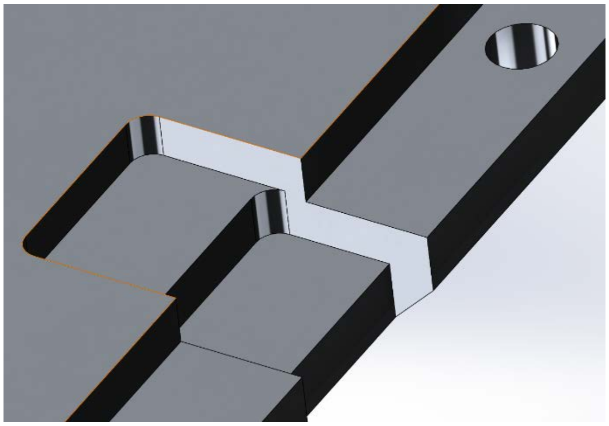

Figure 23. Venting Detail.

EMI Shielding: To incorporate an electromagnetic interference (EMI) shield in our design, we chose to design to allow for the EMI shield to be inserted into our enclosure. The advantage of an inserted EMI shield versus an incorporated shield is the manufacturability of the design. Both designs are similar in shield effectiveness, thermal management, and mass. The disadvantage of including an EMI shield is the added mass, due to the increased volume needed to house the shield, compared to not including an EMI shield. Even though an EMI shield will increase the mass of our enclosure significantly, it is a requirement from our sponsor.

Card Side Anchors: Card side anchors are included in order to provide structural support for the cards as well as to provide a contact surface to act as a heat sink. The side anchors are currently utilizing the maximum space our enclosure can make use of without input from the team designing the cards.

Figure 24. Stepped joints and card anchors.

Material Selection: The material selected for our concept was Aluminum 6061 T6. Aluminum has the following advantages over titanium: less mass, easier to manufacture, costs less, and better thermal management. The limits of the resources available to our project resulted in aluminum being the only feasible candidate.

X. ENGINEERING ANALYSIS

Here, the team has presented its analyses for the electronic enclosure of the Europa Clipper Spacecraft.

Theoretical Modeling of Radiation Environment

The radiation environment encountered by the enclosure in unique to the spacecraft's expected flight path. There are three contributing factors to the radiation environment; high energy electrons and protons from Jupiter's radiation belts and solar photons. Using the radiation exposure data for an aluminum sphere from JPL D-92256 for trajectory 12-F7, we were able to create a plot of the experimental data points provided by the mission proposal document (Figure 25 shown below). From this data, were able to exponentially interpolate the thicknesses for the radiation doses (Equation 1, shown below) and determined enclosure thicknesses required beyond that provided the outer vault wall to limit radiation exposure to certain values (Table 7, p 31). The interpolation equation had an error of 1mm to known data points.

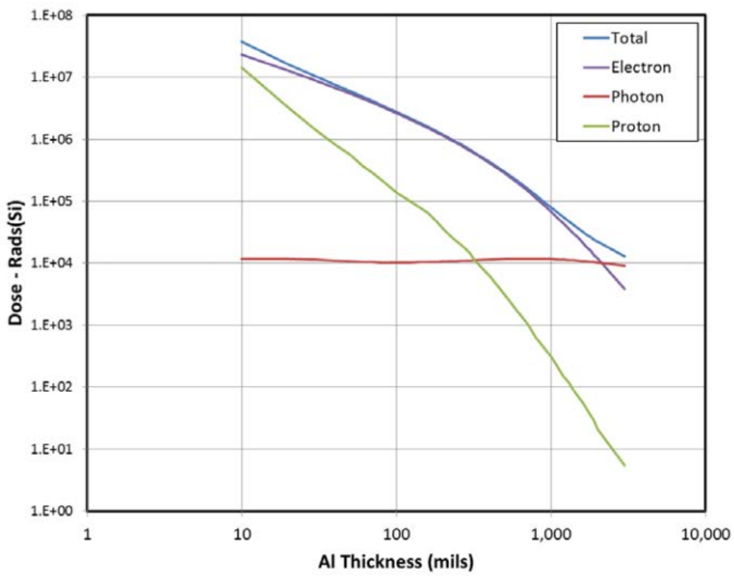

Figure 25. Aluminum Spherical Shell Dose/Depth Curve for Trajectory 13-F7

Equation 1. Required thickness in mm to shield from *x* radiation (in rads) for Trajectory 13-F7.

$$\boldsymbol{Required\ Thickness\ (in\ mm) = 8466.7x^{-0.514}}$$

Figure 26. Aluminum thickness versus Radiation Dose Curve

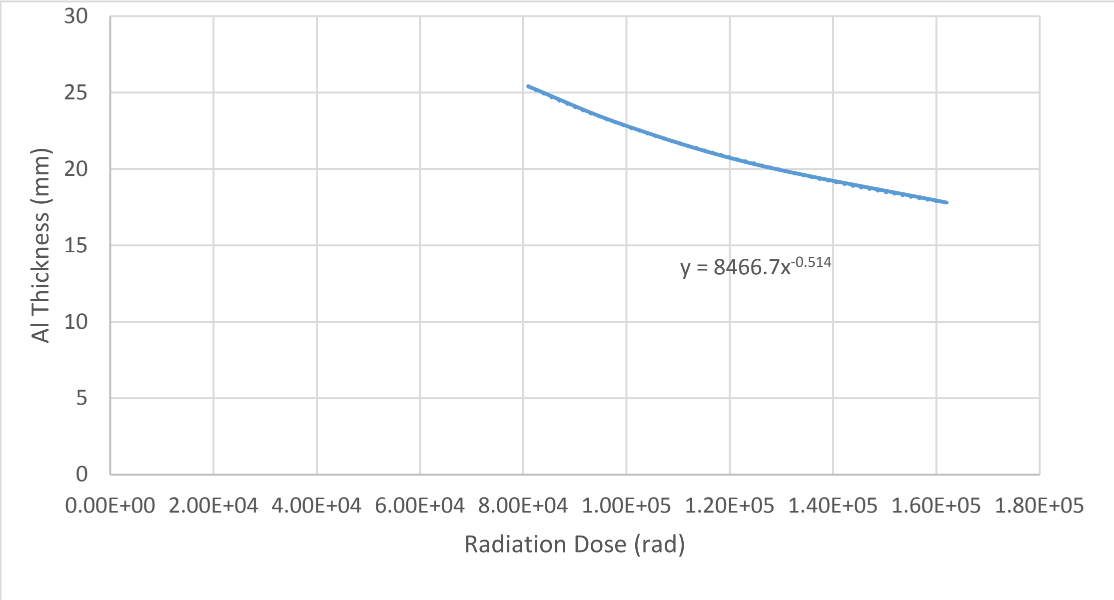

Table 7. Interpolated Aluminum Thicknesses

Radiation Dose (krad)	Total Al Thickness Required (mm)	Enclosure Thickness Required (mm)
150	18.5013	0
100	22.784	4.2827
75	**26.42**	**7.9187**
50	32.542	14.0407

The results of this analysis showed that to achieve a radiation design factor of 2, with 50 krad total exposure would require a prohibitively thick enclosure. For this reason it was decided to use a radiation design factor of 1.5 with 75 krad exposure, and to have 8mm thick enclosure walls.

Theoretical Modeling of Venting

Venting adequacy can be established by satisfying the following empirical rule, as established by JPL D-80302:

$$\frac{V}{A} < 2000\ inches$$

Where *V* = the total internal "void" volume of the assembly in cubic inches and *A* is the total area of the vent hole(s) or path(s) in square inches. If the assembly satisfies this rule, then no further venting analysis is necessary.

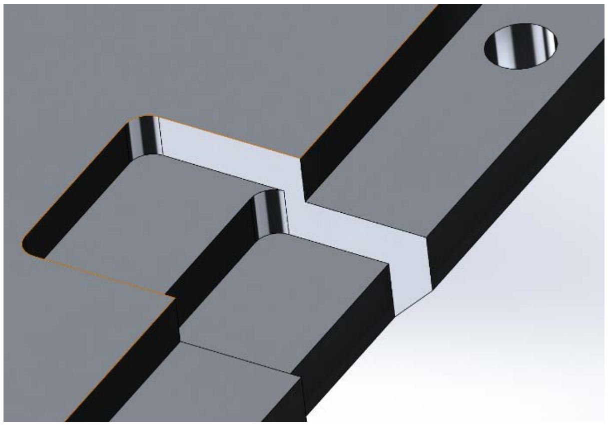

Figure 27. Vent Design Detail.

Our design utilizes 14, 2.25mm by 8mm vents, for a total venting area of .3906 in^2, while our enclosure has maximum dimensions of 239mm by 170mm by 153.5 mm, for a total volume of 380.59 in^3. The resulting V/A is 974.4 inches, which is less than the maximum of 2000 inches, proving our venting is adequate.

Theoretical Modeling of Fastener Load

The theoretical maximum load on the enclosure is determined by the following equation:

$$L = sf * M * K * g$$

Where L is the maximum load (N), sf is the safety factor (1.4 for our calculations), M is the mass of the entire enclosure including the internal components (kg), K is the maximum amount of g-force on an object during flight (function of mass as seen in Figure 5), and g is $9.81\frac{m}{s^2}$. The mass of our enclosure is 26 kg which gives us a $K = 50$. Using the above equation we get maximum load $L = 17.85\ kN$.

The fasteners used for joining our plates is rated at a minimum tensile strength of 2.4 kN. There will be 12 of these fasteners on each plate which give us a total tensile strength of 28.4 kN which is above the maximum load of 17.85 kN. Therefore we are confident that our plate fasteners will not fail due to fracture.

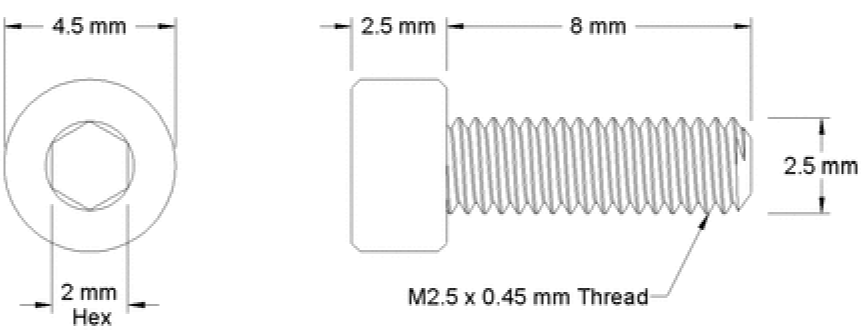

Figure 28. Type 316 Stainless Steel Socket Head Cap Screw used to join our plates.

The fasteners used to join our flanges to the vault base is rated at a minimum tensile strength of 13.6 kN. There will be 4 of these fasteners on each side, which give us a total tensile strength of 108 kN which is above the maximum load of 17.85 kN. Therefore we are confident that our flange fasteners will not fail due to fracture.

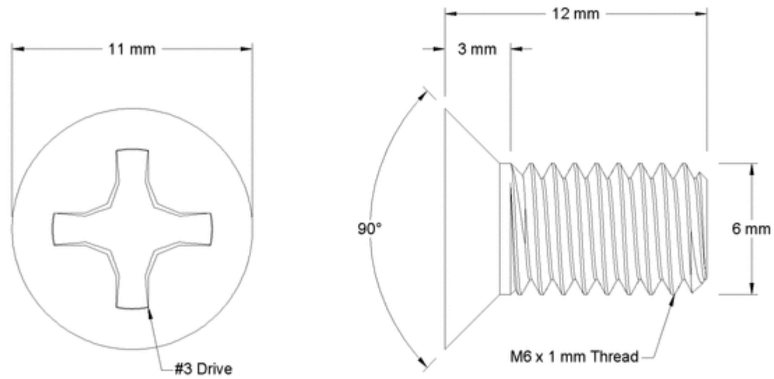

Figure 29. Metric 18-8 Stainless Steel Flat Head Phillips Machine Screw used to join our flange to the vault base.

Empirical Testing of Heat Transfer

The thermal engineering requirements of our design specify keeping the cards contained within the enclosure. The base plate of the enclosure can be assumed to be thermally coupled to the thermal loop with in the vault that ranges between 10°C and 50°C. The deep-space environment was defined as a vacuum at 2.7K. Engineering specifications require the design to keep the cards in the enclosure in the temperature range of -25°C to 125°C, both during peak and minimum power usage.

Experiment setup:

The CAD model of the enclosure was loaded into SolidWorks simulation and a steady state thermal analysis was conducted. The two analysis conducted were a peak power usage analysis worst case scenario and a minimum power usage worst case scenario. The card order is defined below. The electronics cards were assumed to have the properties of silicon, with an emissivity (ε) of 0.83 and a thermal resistance of 500 $W/m^2\ ^oK$. All contact points between aluminum card anchors and the cards were defined with this thermal contact resistance, and all exposed card faces were defined with this emissivity. The aluminum plates composing the enclosure and EMI shield were given an emissivity (ε) of 0.11 and a thermal contact resistance of 2200 $W/m^2\ ^oK$. All contact points between aluminum plates and mounting flanges were defined with this thermal contact resistance, and all exposed faces were defined with this emissivity.

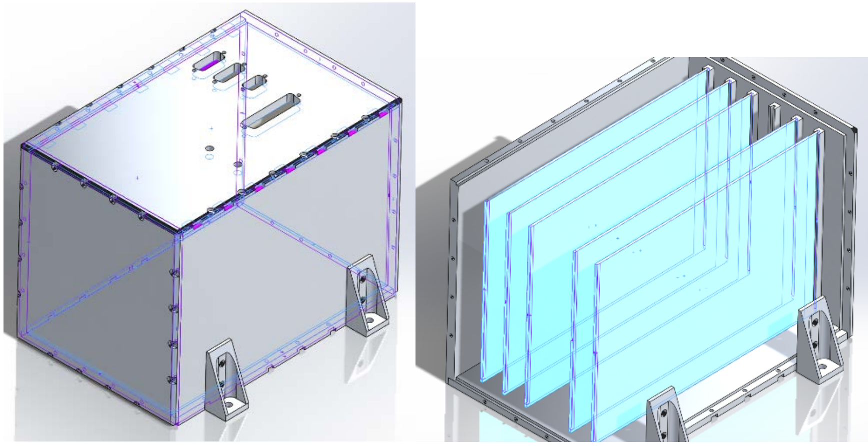

Figure 30. Creating contact sets for aluminum-aluminum and aluminum-silicon connections

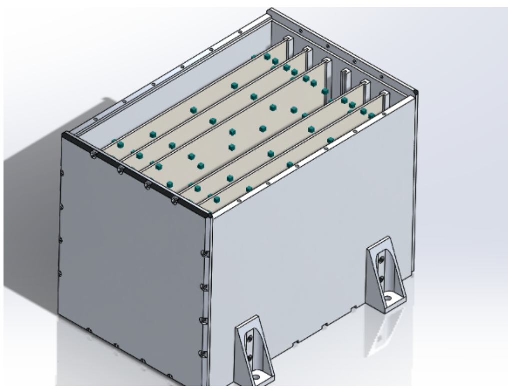

Figure 31. Setting exposed card face radiation

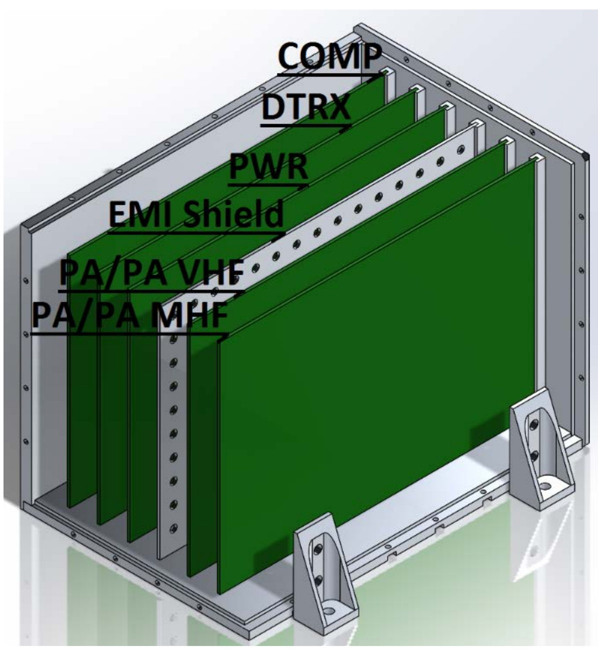

Figure 32: Card Order

Peak power usage:
During peak power usage, the worst case scenario requires the base plate thermal coupling be heated to a constant 50°C.

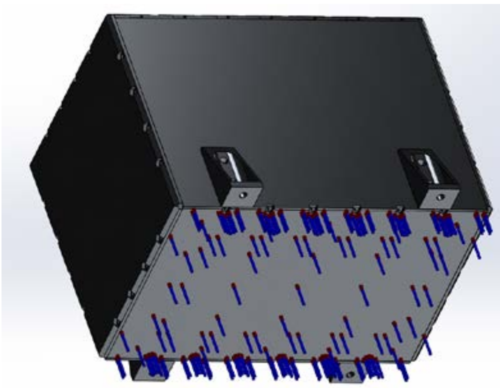

Figure 33. Setting bottom face of base plate to 50°C.

During peak power usage, the following heat powers were applied to the respective cards. Although knowing where on the card the heat power is generated would be more useful, that information was not available to us.

Table 8. Maximum Card Heat Power

Card	Heat Power
COMP	20W
DTRX	14W
PWR	5.3W
PA/PA VHF	160W
PA/PA MHF	160W

Minimum power usage:
During minimum power usage, the worst case scenario requires the base plate thermal coupling be heated to a constant 10°C.

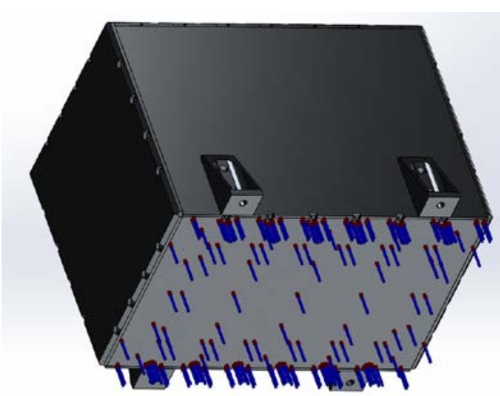

Figure 34. Setting bottom face of base plate to 10°C.

During minimum power usage, the following heat powers were applied to the respective cards. Although knowing where on the card the heat power is generated would be more useful, that information was not available to us.

Table 9. Minimum Card Heat Power

Card	Heat Power
COMP	8W
DTRX	0W
PWR	1.14W
PA/PA VHF	0W
PA/PA MHF	0W

Results:

High Power Analysis:

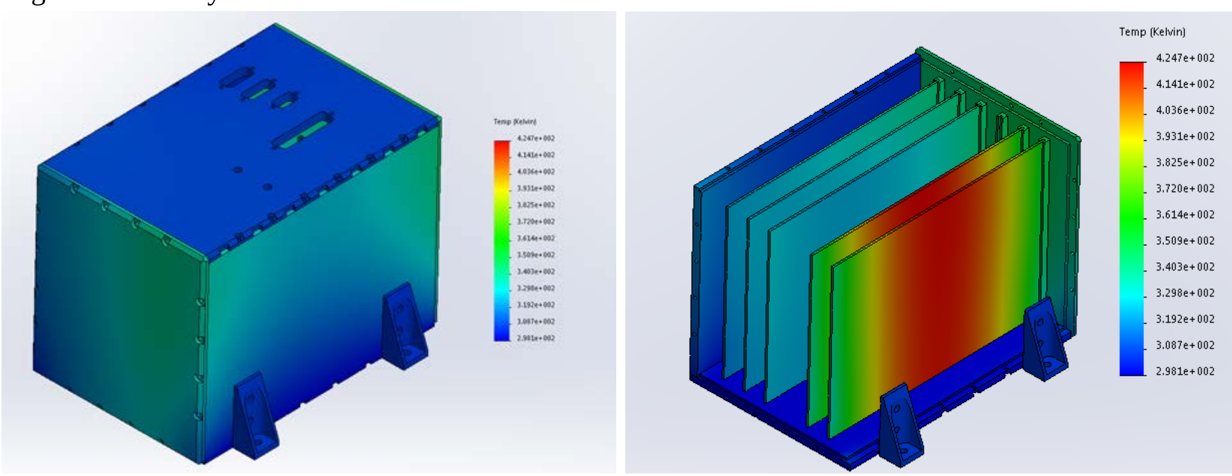

Figure 35. Results of High power consumption steady state analysis.

The results of the maxiumum card heat power showed the cards reached a maximum temperature of 151.6°C, unacceptably high. Of particular note is the two failing boards are the PA/PA boards, which have the largest heat power during peak usage.

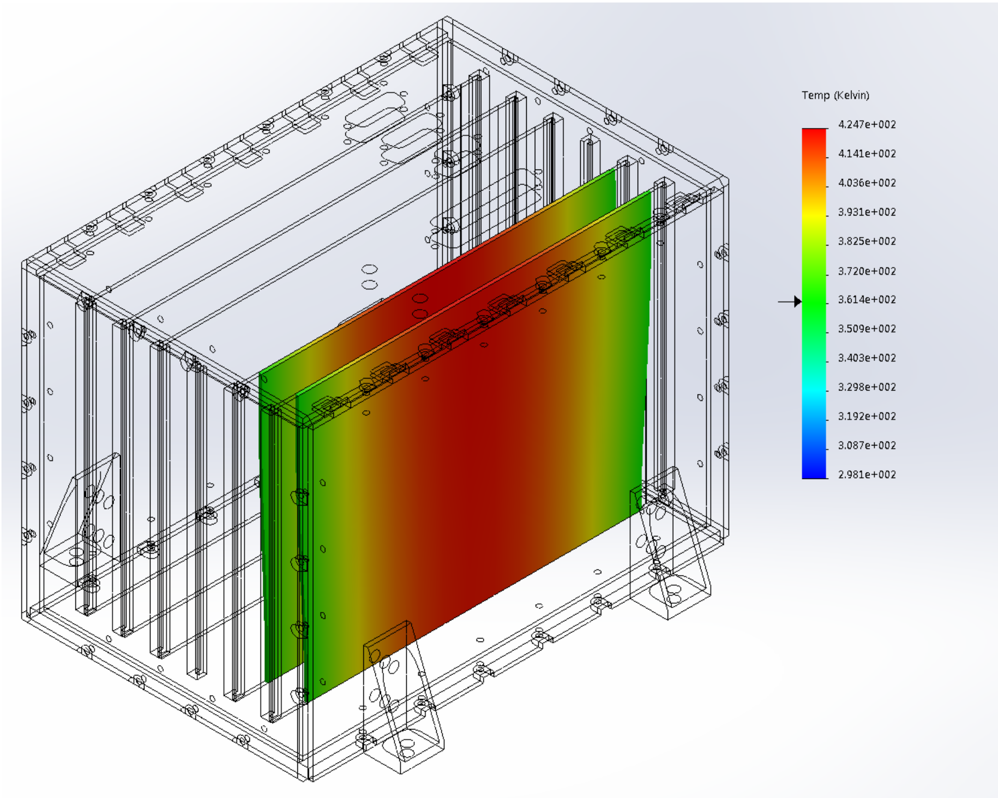

Figure 36. Board Locations over maximum temperature, both PA/PA boards.

Minimum Power:
The results of the minimum card heat power showed the cards reached a minimum temperature of -13.75C, an acceptable temperature. Of particular note is the two coldest boards are the PA/PA boards, strengthening the case to increase the heat sink contact area for them.

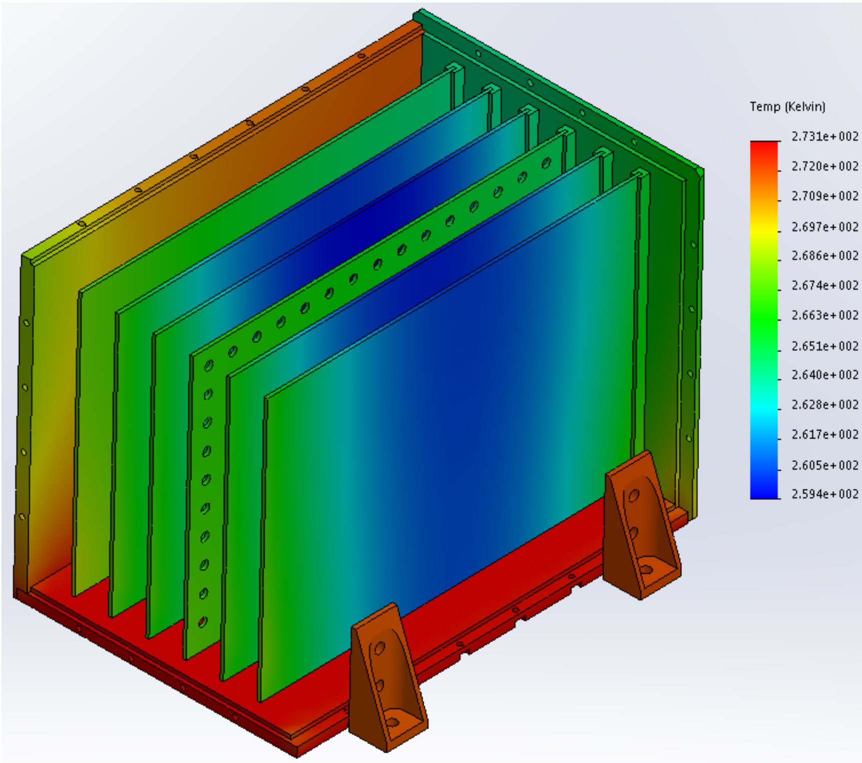

Figure 37. Results of minimum power consumption steady state analysis.

Empirical Testing of Launch Environment

During the launch of the spacecraft, the enclosure must endure varying vibrations as defined by JPL D-80302. In order to detect modes of vibration that may be harmful to the enclosure or the cards it contains, a body resonance study was conducted in SolidWorks. To begin, the fastener locations were all fixed to each other to join the enclosure and the cards were fixed in their respective anchor points. The Mounting flanges were fixed to the Side Plates of the enclosure and assumed to be solidly fixed to the vault wall. The base of the enclosure was assumed to have a roller-joint like interface with the vault wall.

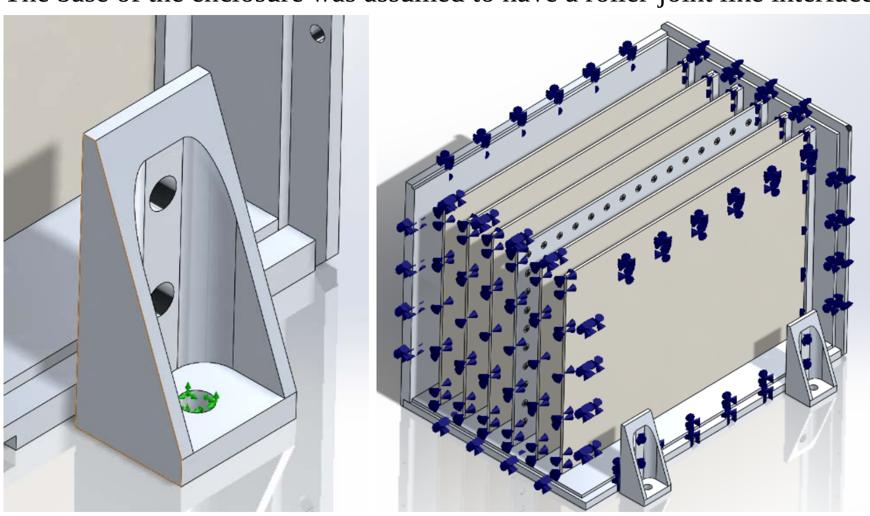

Figure 38. Fixed mounting flanges, fixed cards/card anchors, and joined fasteners.

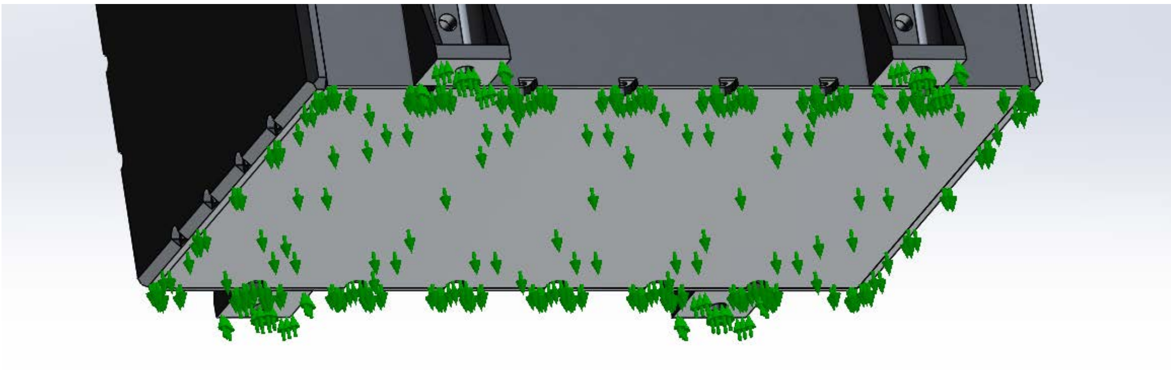

Figure 39. Roller joint simulation of vault wall and enclosure base.

Results:
For the analysis, the modes in which the frequency created the most deflection were found. The largest deflections were considered the most dangerous. These were found for the enclosure plates, the electronics cards and the EMI shield.

Table 10. Maximum deflection of components.

Component	Mode Frequency	Maximum Deflection
Enclosure Plates	2067.7Hz	1.459mm
Electronic Cards	300.72Hz	4.075mm
EMI Shield	194.63 Hz	4.005mm

The maximum deflection of the EMI shield is a concern at 4mm, and future design iterations will have to add structural supports in order to reduce this deflection. The Maximum deflection of the electronics cards is a major concern, and this will have to be addressed by the use stiffeners or additional anchor points by the team designing the electronics cards. Ideally, the cards should deflect no more than 1mm. The maximum deflection of the enclosure plates, at 1mm overall, is the least concerning, and other physical properties will create displacements more severe than this. The location of the displacement is also of a lesser concern, with no card anchors or fasteners located near it on the side plate. This lack of displacement allowed us to further justify the reduction of mounting flanges from 6 to 4.

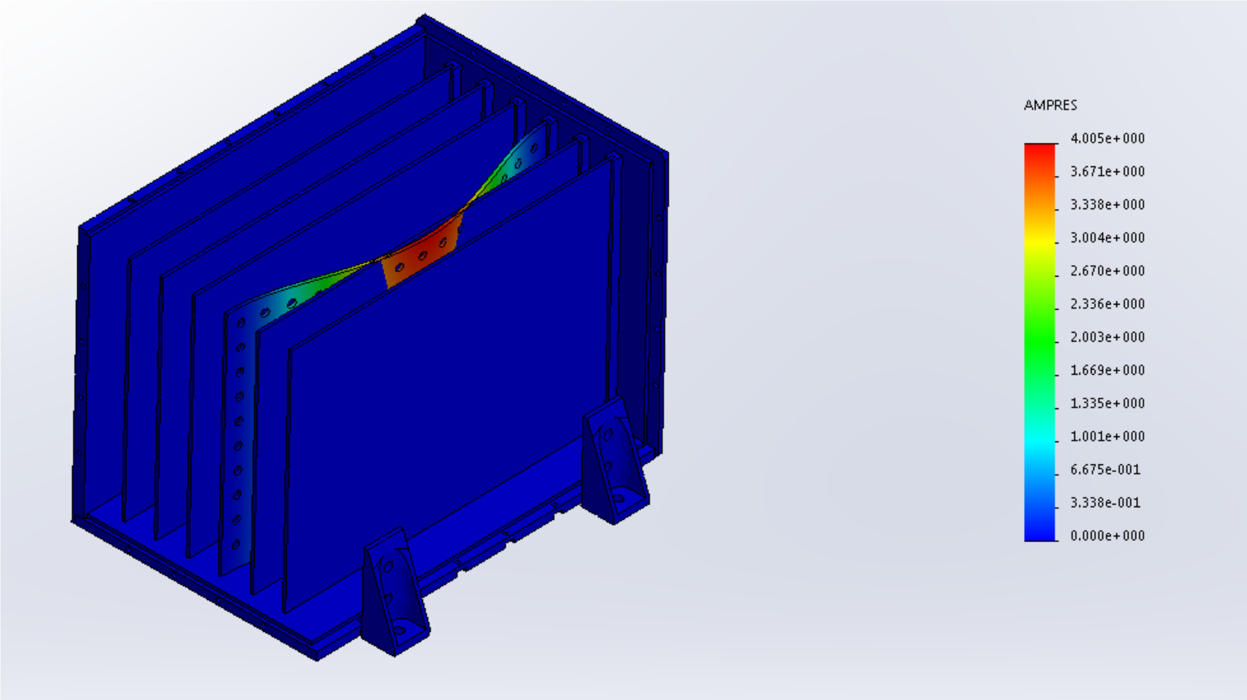

Figure 40. Exaggerated deflection of EMI shield (in mm)

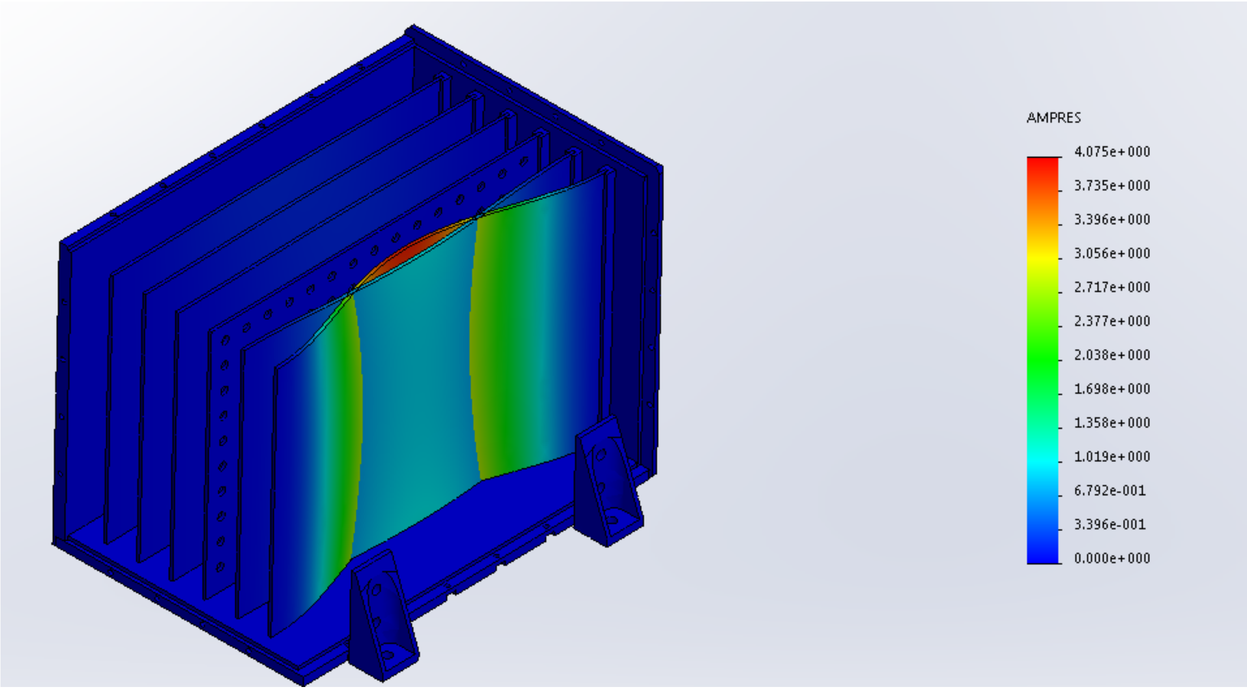

Figure 41. Exaggerated deflection of electronics card (in mm)

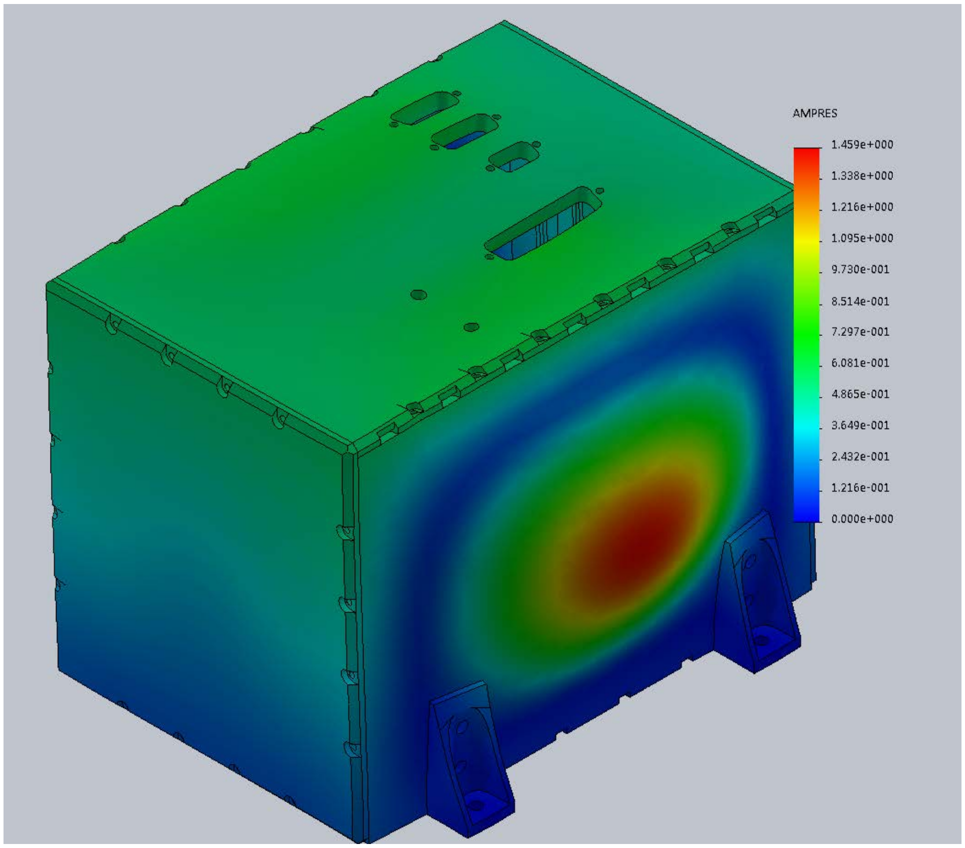

Figure 42. Exaggerated deflection of Enclosure Plates (in mm).

Mockup Construction Testing of Structural Interferences

In order to ensure our enclosure design could be manufactured and assembled, an interference check was performed in SolidWorks to simulate assembly. As shown in the figure below, several minor interference locations were detected in our earlier design. These interferences between the side card anchors and the Base Plate were removed by slightly reducing the length of the anchors by 1mm. The current model has no interferences present that would prevent assembly.

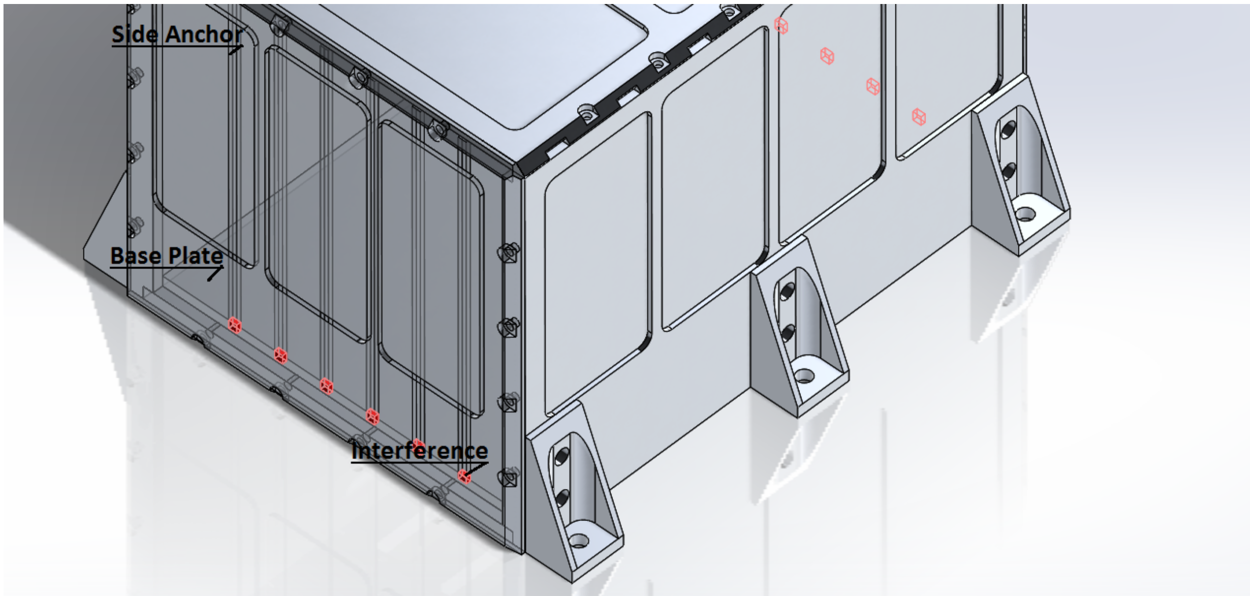

Figure 43. Assembly interferences between card anchors and mounting flanges.

Failure Mode and Effects Analysis

We performed a failure mode and effects analysis to determine any potential modes of failure and risks associated with them. We have seven design components with each component having multiple functions and potential failure modes associated with the function. Our FMEA is shown in table zz1.

Table 11. Failure Mode and Effects Analysis of enclosure.

									Action Results			
	Potential Failure Mode	Potential Effect(s) of Failure	Potential Cause(s) / Mechanism(s) of	SEV	Occ	Det	R.P.N.	Actions Taken	SEV	Occ	Det	R.P.N.
Side Plate												
Provides radiation shielding	thickness of plate below rated radiation shielding	Internal computer will fail and not operate	Incorrect design calculations and testing for plate thickness	8	3	2	48	Design for a safety factor of 1.5 of rated radiation	8	1	2	16
Provides support for flanges	stripping of threading	Detaches the enclosure from vault, causes enclosure to freely move w/in the vault.	Vibration caused from launch environment	10	3	2	60	Use helicoils	10	1	2	20
Provides protection of the internal components	plate deflection	physically break the internal components	Vibration caused from launch environment	8	2	2	32	Design step joints and additional fasteners	8	1	2	16
Front/Back Plate												
Provides radiation shielding	thickness of plate below rated radiation shielding	Internal computer will fail and not operate	Incorrect design calculations and testing for plate thickness	8	3	2	48	Design for a safety factor of 1.5 of rated radiation	8	1	2	16
Provide card anchors for thermal contact and card support	warping of anchors	physically break the internal components	Vibration caused from launch environment	8	2	2	32	Design step joints and additional fasteners	8	1	2	16
Provides structural protection of the internal components	plate deflection	physically break the internal components	Vibration caused from launch environment	8	2	2	32	Design step joints and additional fasteners	8	1	2	16

									Action Results			
	Potential Failure Mode	Potential Effect(s) of Failure	Potential Cause(s) / Mechanism(s) of	SEV	Occ	Det	R.P.N.	Actions Taken	SEV	Occ	Det	R.P.N.
Top Plate												
Provides radiation shielding	thickness of plate below rated radiation shielding	Internal computer will fail and not operate	Incorrect design calculations and testing for plate thickness	8	3	2	48	Design for a safety factor of 1.5 of rated radiation	8	1	2	16
Allows for electronics ports to pass through to internal cards	plate deflection	breaks the electronics connectors by stripping screws	Vibration caused from launch environment	6	1	1	6	Design step joints and additional fasteners	6	1	1	6
Provides structural protection of the internal components	plate deflection	physically break the internal components	Vibration caused from launch environment	8	2	2	32	Design step joints and additional fasteners	8	1	2	16
Base Plate												
Provides radiation shielding	thickness of plate below rated radiation shielding	Internal computer will fail and not operate	Incorrect design calculations and testing for plate thickness	8	3	2	48	Design for a safety factor of 1.5 of rated radiation	8	1	2	16
Provides support for passive back plane	plate deflection	Breaks passive back plane	Vibration caused from launch environment	10	2	1	20	Design step joints and additional fasteners	10	1	2	20
Flanges												
Attaches the enclosure to the vault wall	flanges fracture	Detaches the enclosure from vault, causes enclosure to freely move w/in the vault.	Vibration caused from launch environment	10	2	1	20	Increase thickness of flange walls, if mass allows	10	1	1	10
Fasteners												
Attaches plates together	one fastener breaks	fastener would freely move w/in the vault, potentially causing damage to other components	Vibration caused from launch environment	6	2	2	24	Increase diameter of fastener from M2.2 to M2.5	6	1	2	12
Attaches plates together	multiple fastener breaks	detaches plates, causing the enclosure to open to radiation	Vibration caused from launch environment	7	1	1	7	Increase diameter of fastener from M2.2 to M2.5	7	1	1	7
Attaches enclosure to the vault wall	fastener breaks	Detaches the enclosure from vault, causes enclosure to freely move w/in the vault.	Vibration caused from launch environment	10	2	1	20	Increase length of fastener by 1 mm and diameter of M5 to M6	10	1	1	10
EMI Shield												
provides EMI shielding to internal components	Gaskets sealing the shield fail	EMI gets to components, causing electrical components to not operate	Vibration caused from launch environment	8	3	1	24		8	3	1	24
	EMI shield detaches from the enclosure	short other electronic boards inside the enclosure	Vibration caused from launch environment	8	2	1	16	Use additional fasteners to attach to enclosure	8	1	1	8

The aspect of our design with the highest risk is the mounting of our flanges to the side plates. If the connection of the side plates to the mounts fails, or the enclosure becomes detached from the mounting flange, our enclosure will be freely translating inside the vault, damaging almost all the instruments inside the vault. The failure mode is the side plate thread stripping due to the forces caused by the vibrations of launch environment. To reduce the occurrence of this potential failure mode, we will use helicoils in our fastener design connecting the flanges to the side plate. The use of helicoils greatly reduces the change of thread stripping. The overall risk associated with this design is now at “acceptable” levels. Similar design changes were implemented to reduce the occurrence of the potential failure mode for different design aspects, such as implementing step joints to reduce plate deflection. All of our designs are now at “acceptable” levels.

XI. DISCUSSION
Design Critique

Through the team's computer-simulation and FEA-driven validation, the team revealed that some design requirements could not be met simultaneously with each other along with additional concerns resulting from a lack of information at this stage in the design process. The team did, however, meet many of the initial design requirements without problems.

Wall Connection/Step Joints

The design of the wall connections was initially made for thick-walled, in this case greater than 8mm thick, enclosures intended to meet the radiation requirement. At this thickness, utilizing separate plates for each side of the enclosure was relatively simple to design and easy to join with fasteners. However, with the change from a thicker enclosure to a thinner on with a focus on mass, connecting the walls with fasteners became less ideal, and a solid enclosure with one or two separate plates would be ideal. The limitations of the team's manufacturing ability and time restrictions prevented this from being pursued. Additionally, the design contains what can now be seen as an excessive amount of step joints, complicating how the plate is joined with fasteners. These step joints can be seen as artifacts present from the initial thick-plate emphasis, and greatly complicated design changes. For future work, stepped joints should be added only once other features of the enclosure are finalized. These steps also complicated assembly to some degree, requiring parts to mate perfectly in order to be joined.

Mass Reduction and Deflection of Enclosure Plates

The initial, 8mm "thick-plate" design had acceptable deflection limits of the enclosure plate, close to 1mm maximum, and in unimportant areas where it did not affect the PCB cards. With the addition of mass reductions, these plates began to deflect to potentially harmful levels, at times around 5-7mm. With the design development path the team took, there was little to retroactively do to alleviate this beyond optimization of the material thickness in critical areas, a time consuming process that also added to the mass of the enclosure. In the future when designing mass constrained enclosures, the team recommends allocating mass to plate stiffeners and other necessary mass restrictions, and then determining the mass remaining to specify the shielding thickness. As the project was at first shielding-focused, the team was unable to pursue this design path.

Radiation Protection

The team's analysis mid-way through the design process determined the requirements for radiation and mass were unable to be simultaneously met. It would take far too great of thickness, and thus mass of aluminum to shield to the specified requirement. As a result, the team's design only protects to approximately 104 krad exposure, allowing far more than the 50 krad limit. As a result, our team recommends pursuing spot-shielding of PCB card requiring additional protection. Mass allocated for this shielding must be reduced from the enclosure mass, which would be placed over mass requirements if such shielding was added at the moment. This reduction would most likely have to be sourced from redesign of the enclosure plates.

Base Connection Method

The team's design for connection of the enclosure to the interior of the vault of the spacecraft was initially (4) mounting flanges attached to the side plates via fasteners. Through discussions on other projects, it was determined that for safety, the total number of mounting flanges should be raised to (6). The use of fastener-secured mounting flanges was originally derived from past thick-plated designs and driven by the team's lack of manufacturing capabilities. The team recommends these flanges be machined out of the side plates they are attached to in future designs as it improves their structural integrity greatly.

Lid Design and Venting

The lid design of the enclosure was changing throughout the design process due to the changing order of the PCB cards. Although all features excluding thru-holes for ports and cables were finalized early on, additional changes may cause problems in the future if quick changes are needed. Moving to a top-plate sectioned into pieces for covering each card may alleviate this in the future. The team's vent design used on the enclosure wasn't based upon any previous missions, but did appear to meet all NASA design document specifications and is recommended for future designs.

Materials

The use of 6061-T6 aluminum by the team was driven primarily by the team's limiting factors of machining ability and cost. Aluminum plates were ideally suited for the thick plated initial design, having a radiation protection level and density that allowed for fastener insertion into the side of plates while still protecting from radiation and having a lower mass. However, with the switch to a mass focused design, neither titanium of aluminum could satisfy both requirements. The team recommends investigating composites for future designs, but also notes that dimensional restrictions may prevent their use.

EMI Shielding

The EMI shielding design the team pursued was recommended by the sponsor to be a card-like design inserted into a channel and secured in the same manner as a PCB card to separate sensitive cards from EMI producing ones. The team determined that this approach needlessly wastes mass on additional enclosure width as well as on an additional heat frame and stiffener to prevent deflection. The team recommends attaching the EMI shield plate to the heat frame of the PCB card to be protected and sealing it with conductive gaskets. This change would reduce the mass and the size of the enclosure.

Fasteners and Helical Inserts

The initial thick plated design the team pursued allowed for insertion of fasteners into the sides of the enclosure plates due to their relative thickness. With the move to a mass focused design, the team was required to redesign complicated features in order to allow for fastener threading in these plates, which consumed mass. Additionally, due to using helical inserts for fastener retention, the maximum fastener size used was M3. In the assembly process, the team found this fastener and its associated helical insert difficult to install. M3 interior diameter helical inserts are easy to damage on installation and M3 fasteners may deflect while tightening or assembling the enclosure. For these reasons, the team recommends utilizing no smaller than M3 fasteners on load-bearing connections, and prefers M4 size or above when using helical insets. The team did not experience these problems when installing the M6 sized inserts or fasteners. Additionally, as mentioned above, the team recommends future designs machine the enclosure out of (3) or fewer plates to reduce the need for fasteners and increase its strength.

Heat Frames and Deflection of PCB Cards

The requirement for a method to remove heat from the PCB cards in a more effective manner became apparent to the team after the initially performed analysis. As the heat generated on the cards couldn't dissipate fast enough through the PCB itself, a heat sink was required. As the exact location of the heat generated was unknown, the team was unable to conclusively show their heat frame cross bars are effective at keeping the entire card within temperature limits. Initial analysis also showed deflection of the PCB card to be an issue, but again without mass locations known, the team was unable to conclusively show the heat frame stiffened the cards adequately. As the team's requirement of stiffening the PCB cards and providing additional heat transfer was discovered relatively late in the design process, the additional mass required to accomplish these tasks would place the enclosure over the mass limit, as their mass is considered part of the enclosure. Future iterations of the enclosure must reduce the mass of the heat frames as well as allocate mass from the enclosure to allow for them. The team recommends utilizing larger wedge-loks to aid with this, as a wedge-lok's density is much lower than the aluminum heat frame's. Additionally, to improve stiffness and if the length requirement allows it (which it currently does not allow for additional length), the team recommends the heat frame crossbars be mounted directly onto the heat frame side bars to allow for better rigidity and heat transfer.

Future Work

At the team's current stage in the design process, our mass-reduced, thick walled enclosure is unsatisfactory to complete all new and discovered requirements found through the team's analysis and PCB card layout changes. A new enclosure iteration, designing from the inside (PBC card and heat-frame) to the outside of the enclosure (plate thickness and mounting) would be the next step the team recommends. This new enclosure iteration would use the lessons learned attempting to focus on a thicker enclosure with cutouts to design a thin-plated but stiffened enclosure. This enclosure would most likely consist of a separate top plate and an enclosure body machined from a solid piece of aluminum. Once heat and mass locations are determined by the team designing the PCB cards, the team recommends complete prototype fabrication of the new design for the purposes of physical prototype validation of thermal and vibration requirements.

An example of such an enclosure is provided below. The mass of the example future iteration of the enclosure (with top plate) was 3108.60 grams.

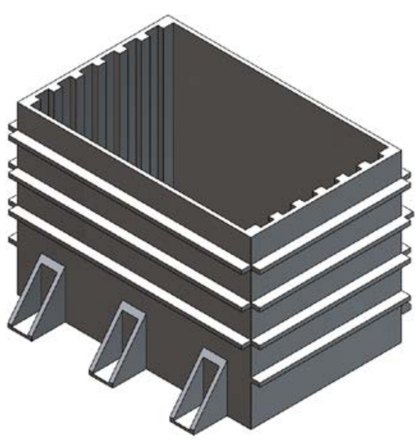

Figure 44: Stiffener examples are visible on the exterior of the example iteration enclosure.

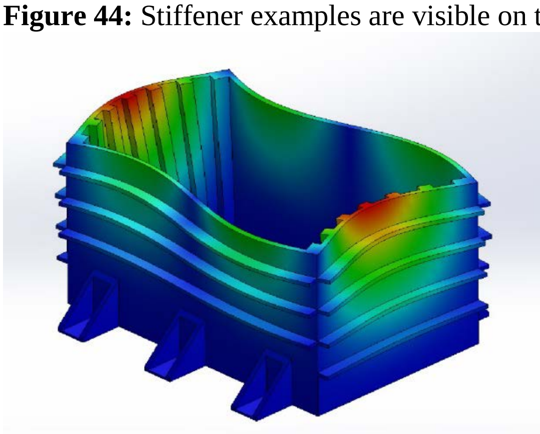

Figure 45: The most dangerous mode of vibration caused the enclosure to deflect 2.45 mm and occurred at 1198.91 Hz.

Mass

The team was unable to perform mass validation of the enclosure plates as a result of the team's limited manufacturing capabilities, which prevented the key mass cutouts from being implemented. Mass Was instead validated using standard density of 2700 kg/m^3 for 6061 T6 aluminum enclosure plates and 8070 kg/m^3 for the 316 stainless steel fasteners and helical inserts. The result was an estimated enclosure mass of 3497.93 grams. Each heat frame, placing the overall enclosure over the mass limit, had a mass of 101.67 grams, including the wedge-loks.

Construction and Assembly

The construction of the enclosure and its assembly was also investigated by the team. In order to ensure ease of assembly and accessibility of all parts, an assembly manual was produced and followed. Through construction and assembly of the enclosure, the team determined that M3 helical inserts were potentially too fragile for reliable insertion without cleaning thoroughly lubricating tapped holes, leaving residue. M3 fasteners also had a tendency to deflect when inserted due to their narrow diameter and the close tolerances of the stepped joints. The team's recommendation is that fasteners no smaller than M4 be used in the future. The team also encountered difficulties assembling the enclosure in an order other than the instruction manual provides due to the double step joint present on some plates, and recommends reducing or removing some steps.

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XIII. APPENDIX A

MANUFACTURING PLANS

We have developed a manufacturing plan to build our prototype. Milling was chosen because we were only asked to produce a single assembly of our box. We believe milling will give us the necessary tolerances on the machined aluminum. The drawback of using the mill is that it can be time-consuming to remove so much material. CNC mill is recommended to produce both the mounting flanges and the top plate due to complex features. Forging is too costly for a single prototype and 3D printing does not allow us to work with the Aluminum alloy we desire.

Manufacturing Plan

Name: Falconer

Part Number: 1

Part Name: Top Plate

Material: 3/8" 6061 T6 Al Sheet

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed***
1	CNC Mill This				
2	Insert Helicoils				
3					
4					
5					
6					
7					
8					
12					
13					
14					
15					
16					
17					
18					
19					
20					

Manufacturing Plan

Name: Falconer

Part Number: 2

Part Name: Front Plate

Material: 9/16" inch 6061 T6 Al

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed***
1	cut to approximate area dimensions 6.54 x 7.32"	bandsaw			275
2	square and end mill edges	mill		end milll	1000
3	zero mill using edge finder	mill		edge finder	1000
4	using 4 flute facing mill take material off until a thickness of .54" is achieved	mill		4 flute	1000
5	setting a depth of .31", cut into the material up to .31" and cut around THREE edges. The remaining edge will only need a cut-in of .23"	mill		end milll	1000
6	turn the plate over and re-establish the datum	mill		edgefinder	1000
7	using a .12" radius end mill, cut fastener depressions into all four sides centered at positions shown	mill		end milll 1/4" DIAMETER	1000
8	using .13" dia drill bit drill through holes at the centers of the depressions made in step 7	mill		9/64 drill bit	875
12	CNC mill the card holders	CNC mill			
13	45 degree 3mm chamfer on all 4 top edges				

Manufacturing Plan

Name: Falconer

Part Number: 3

Part Name: Side Plate

Material: 3/8" 6061 T6 Al Sheet

Step #	*Process Description*	*Machine*	*Fixtures*	*Tool(s)*	*Speed*
1	Cut stock to roughly 9.6" by 7.1"	bandsaw			375
2	square and bring stock to dimension spec	mill		edgefinder, end mill	1000
3	using 4 flute, cut whole plate to thickness of .31"	mill		4 flute	875
4	make .09" lip and .23" lip on opposite sides. Depth is the same as above.	mill		end mill	1000
5	zero mill using edgefinder	mill		edgefinder, end mill	1000
6	measure and center drill at hole locations	mill		center drill	1000
7	drill through holes using 5/16 drill bit	mill		5/16" drill bit	1000
8	cut weight out of remaining face	mill		end mill	875
12	rotate stock, center drill holes at locations shown on ALL FOUR SIDES	mill		center drill	1000
13	drill to a depth of .314" at center locations	mill		.12" dia drill bit	1000
14	insert helicoils				

Manufacturing Plan

Name: Falconer

Part Number: 4

Part Name: base plate

Material: .3/8" 6061 T6 Al Sheet

Step #	Process Description	Machine	Fixtures	Tool(s)	Speed
1	cut stock to roughly 6.4" by 9.5"	bandsaw			375
2	square edges and zero mill	mill	square	edgefinder	1000
3	using edge mill make cutouts for fasteners at locations	mill		.25" dia end mill	1000
4	center drill at these locations.11" from edge	mill		center drill	1000
5	drill through holes at centers	mill		9/64 bit	1000
6	mill whole plate down to thickness of .31inches	mill		4 flute end mill	1000
7	cut weight channels at locations using end mill	mill		.25" end mill	875
8	create .09" lip and .23" lip using edge finder and end mill	mill		edge finder/end mill	1000
12	rotate plate to view thin edge, center drill at locations shown on drawing	mill		smaller center drill	1000
13	drill a depth of .364" into the sides at each location using centers	mill		9/64 drill bit	1000
14	repeat for other side of thin edge				
15	insert helicoils				

Manufacturing Plan

Name: Falconer

Part Number: 5

Part Name: mounting flange

Material: 1X1 inch Aluminum 6061 square stock

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed***
1	Cut the stock to 2.2" length	bandsaw			375
2	face one edge down to .88" width, bring length down to 2.18" as in spec	mill		.25" end mill	1000
3	measure .11" in from top and score. Measure .2" up from base and score			calipers	
4	cut diagonally on bandsaw between the two scored lines	bandsaw			375
5	square part in the mill and zero mill using edge finder	mill	square	edge finder	1000
6	.2" up from the base and .1" in from the side, take material out to make the rounded channel	mill		.25" radius end mill	875
7	measure .5" from side and .31" from adjacent side and center drill at location	mill		center drill	1000
8	countersink hole using .5" diameter	mill		.5" dia. Countersink bit	1000
12	drill through hole at center location	mill		9/32 drill bit	1000
13	rotate part to second view on drawing				
14	after zeroing the mill, measure .5" down and center drill at .59 and 1.38 from left edge	mill		center drill	1000
15	countersink hole using .5" diameter			.5" dia. Countersink bit	
16	drill through hole at center location			9/32 drill bit	
17	clean up diagonal edge with end mill	mill			

Manufacturing Plan

Name: Falconer

Part Number: 6

Part Name: heat frame

Material: .25" 6061 T6 Al Sheet

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed***
1	Water Jet Part				
2	Mill edges for smoothness	mill		end mill	
3	tap holes to M2.5			M2.5	

BILL OF MATERIALS

Part	*Quantity*	*Supplier*	*Part #*	*Cost per($)*	*Material*
3mm radius Helicoil Inserts	56	McMaster	91990A407	0.45	Stainless Steel
6mm radius Helicoil Inserts	8	McMaster	91630A251	0.48	Stainless Steel
3mm radius fastener	56	McMaster	92290A058	0.11	Stainless Steel
6mm radius fastener	14	McMaster	92010A424	0.152	Stainless Steel
Top Plate	1	Alro		TBD	.5" 6061 Al
Side Plate	2	Alro		TBD	.5" 6061 Al
Front Plate	2	Alro		TBD	.5" 6061 Al
Bottom Plate	1	Alro		TBD	.5" 6061 Al
Mounting Flange	4	Alro		TBD	1 X 2 X 1.5" 6061 Al
EMI Shield	1	n/a	n/a	n/a	n/a

XIV. APPENDIX B
Assembly manual

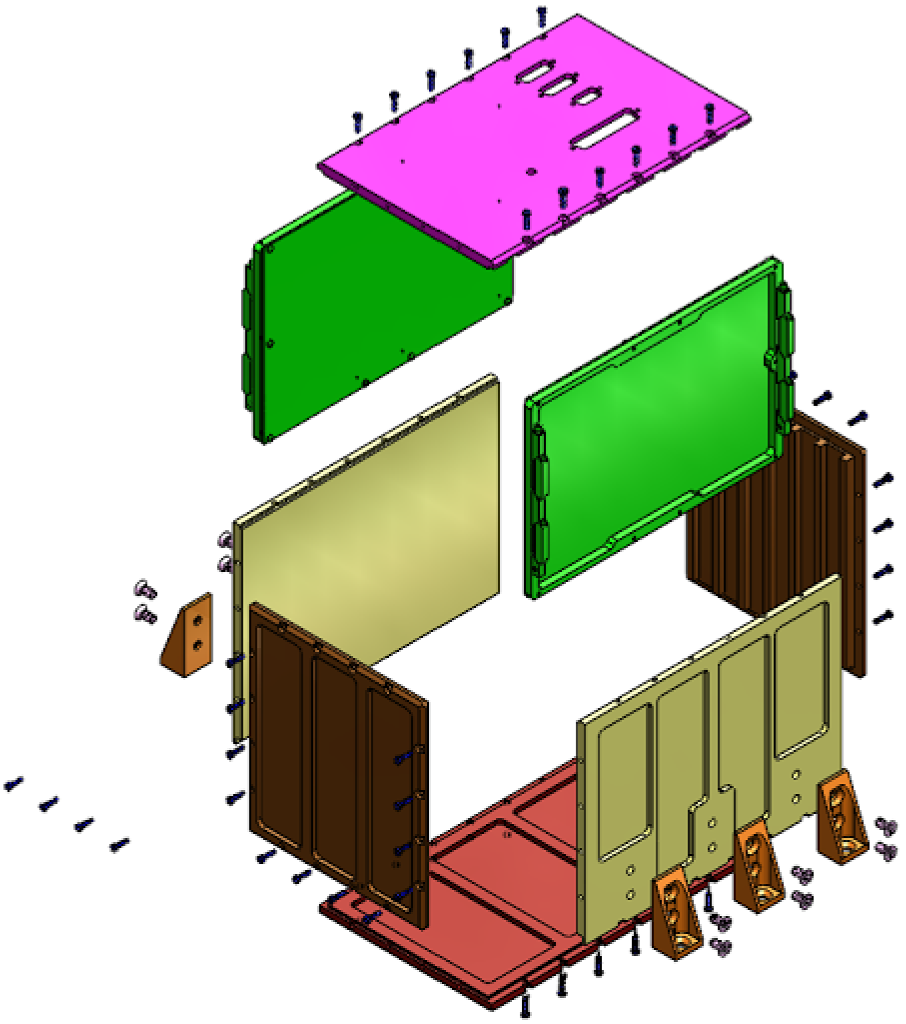


Figure 1B. Exploded view of final assembly

Assembly Instructions:

Step	Reference Figures	Instructions
1	EA 1-2	Secure Mounting Flanges (Orange) to Side Plates (Yellow) using (6) M6 8mm Fasteners (Pink) using torque wrench at 1280 N*cm. Repeat for both plates.
2	EA 3-4	Attach Side Plates (Yellow) to Side Walls (Red) using (12) M3 12mm Fasteners (Blue) using torque wrench at 78 N*cm.
3	EA 5-6	Attach Front Plate and Back Plate (Red) to Side Plates (Yellow) and Base Plate (Red) using (12) M3 12mm Fasteners (Blue) using torque wrench at 78 N*cm. Repeat for both plates.

4	EA 7-9	Insert Card Assemblies (Green) into Enclosure slots. Secure Card Assemblies by tightening Wedge-lok fasteners to 50 N*cm using torque wrench.
5	10-11	Plug connector extenders into their respective ports on cards. (Tentative step until card port location is known).
6	12-16	Secure Top Plate to Side Plates, Front Plate and Rear plate using (20) M3 12mm Fasteners (Blue) using torque wrench at 78 N*cm.

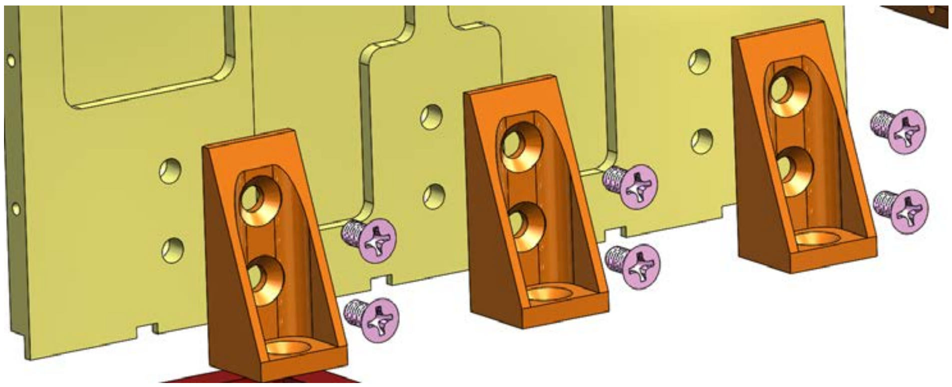


Figure 2B. Attachment of Mounting Flanges (Orange)

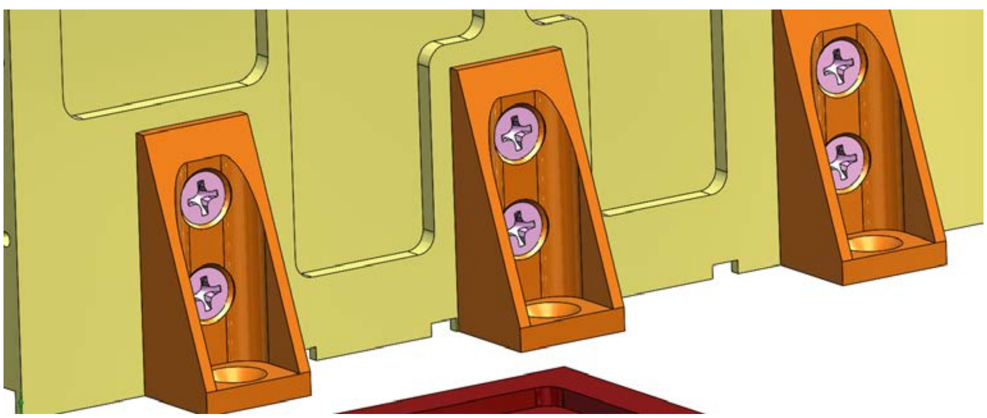


Figure 3B. Attachment of Mounting Flanges (Orange)

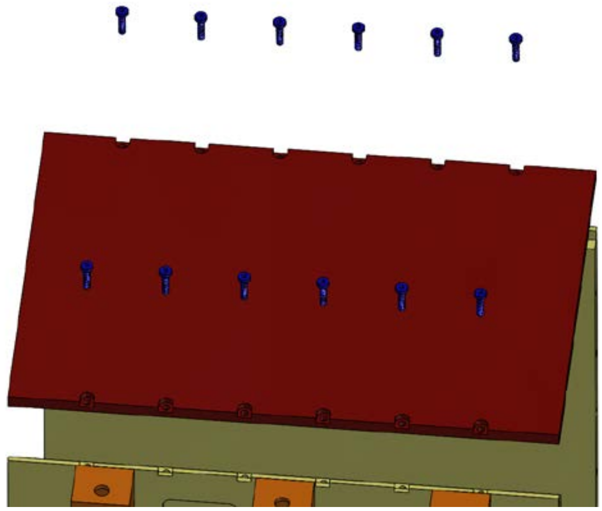


Figure 4B. Attachment of Base Plate (Red)

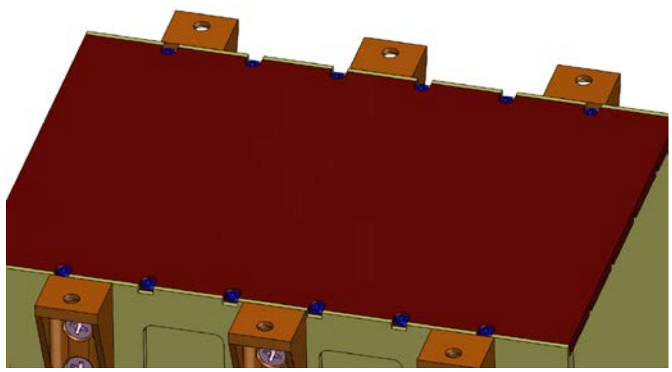


Figure 5B. Attachment of Base Plate (Red)

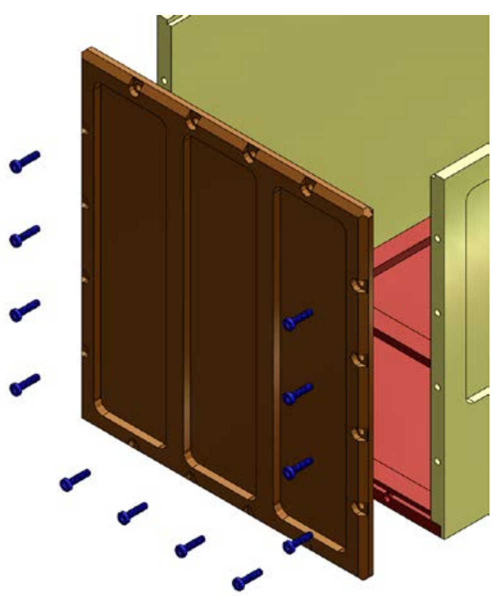


Figure 6B. Attachment of Front Plate (Orange)

Figure 7B. Attachment of Front Plate (orange)

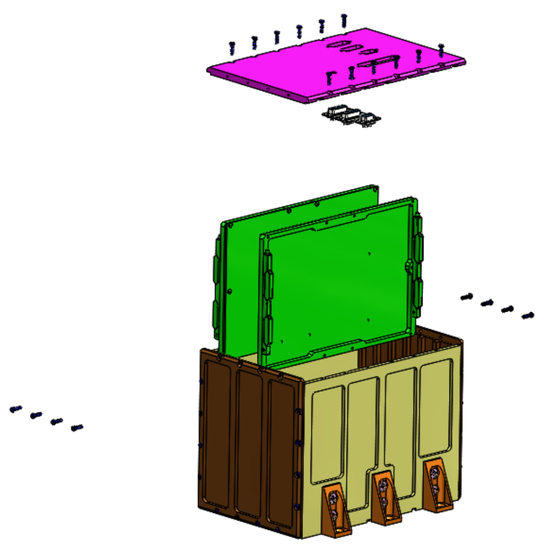


Figure 8B. Assembly of Heat Frames (Green), and Top Plate (Purple)

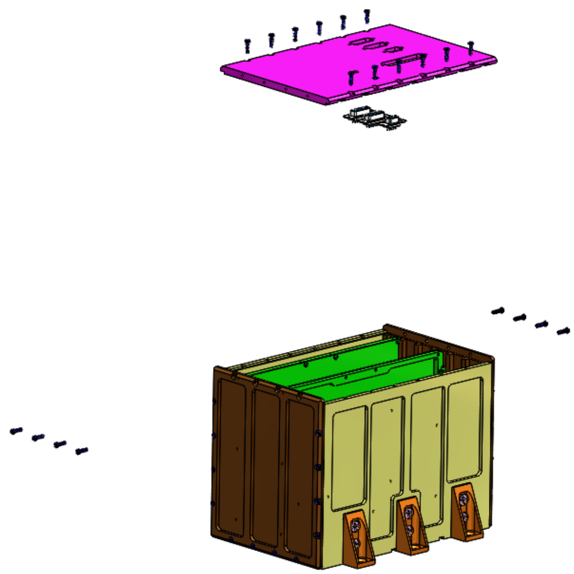


Figure 9B. Assembly of Heat Frames (Green, and Top Plate (Purple)

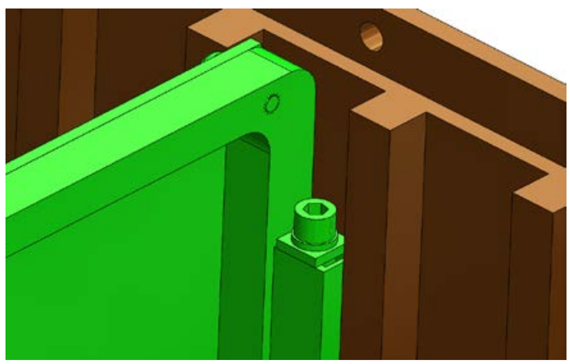


Figure 10B. Heat Frames (Green) attached inside the enclosure.

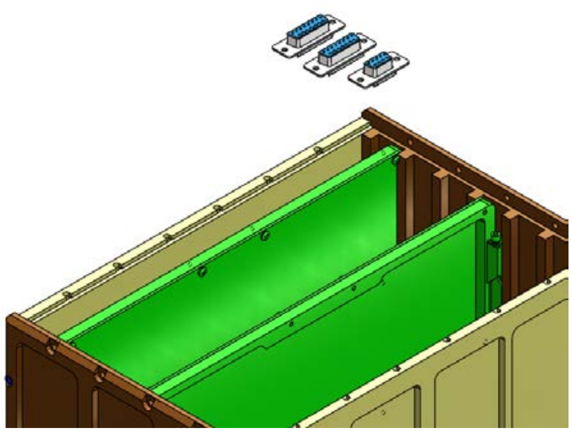


Figure 11B. Port Connectors location undetermined.

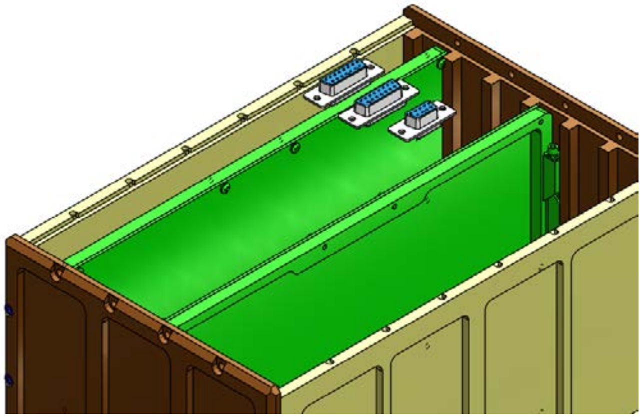


Figure 12B. Port connector location, exact position undetermined

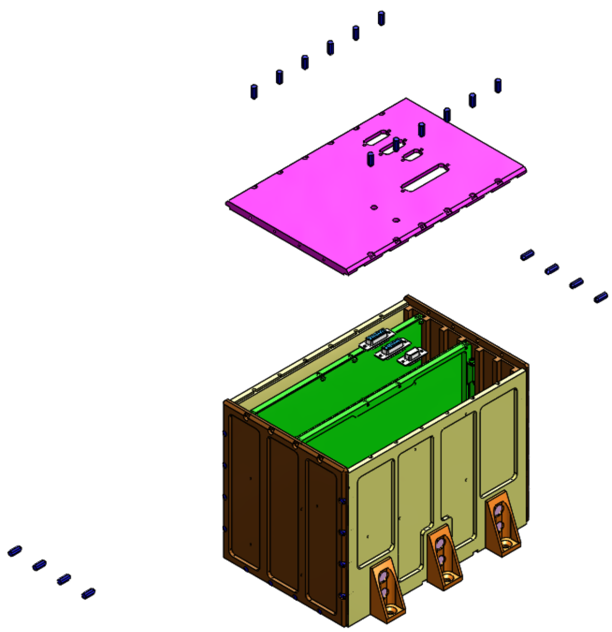


Figure 13B: Assembly of Top Plate (Purple)

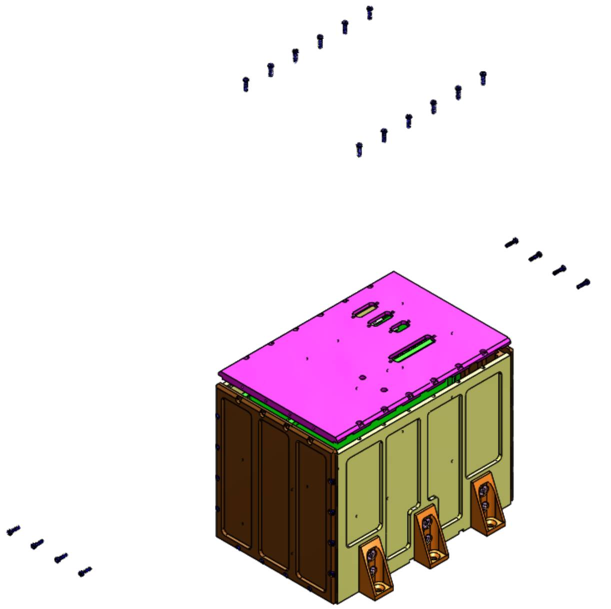


Figure 14B. Assembly of Top Plate (Purple)

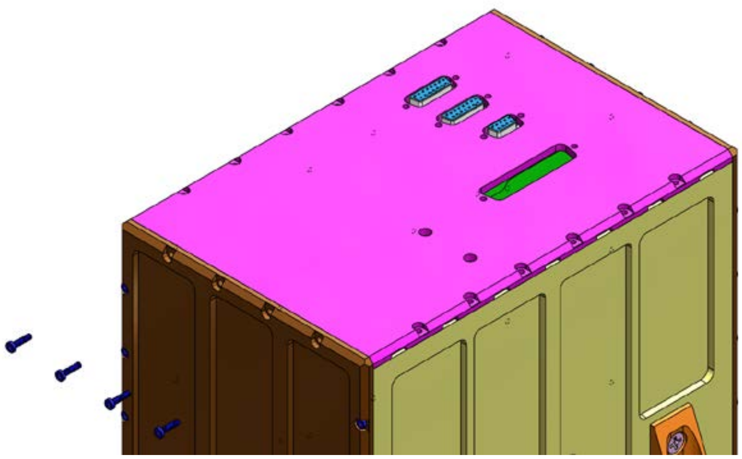


Figure 15B. Front Plate (Orange) and Top Plate (Purple) connection by M3 12mm Fasteners (Blue).

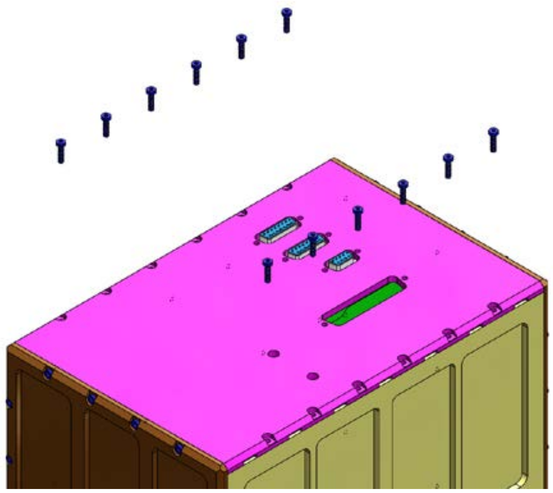


Figure 16B. Side Plate (Yellow) and Top Plate (Purple) connection by M3 12mm Fasteners (Blue).

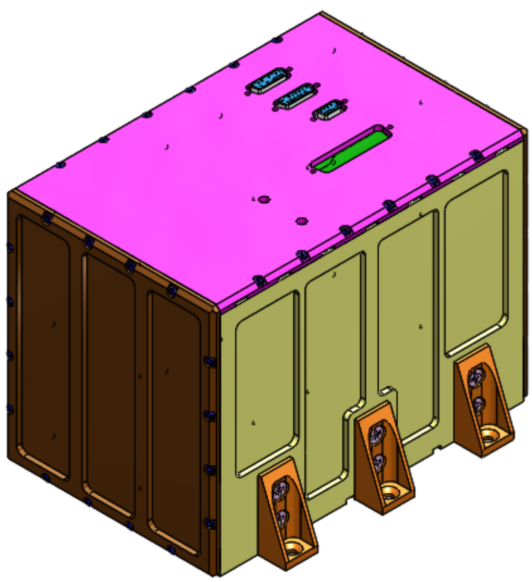


Figure 17B. Final Assembly of Enclosure

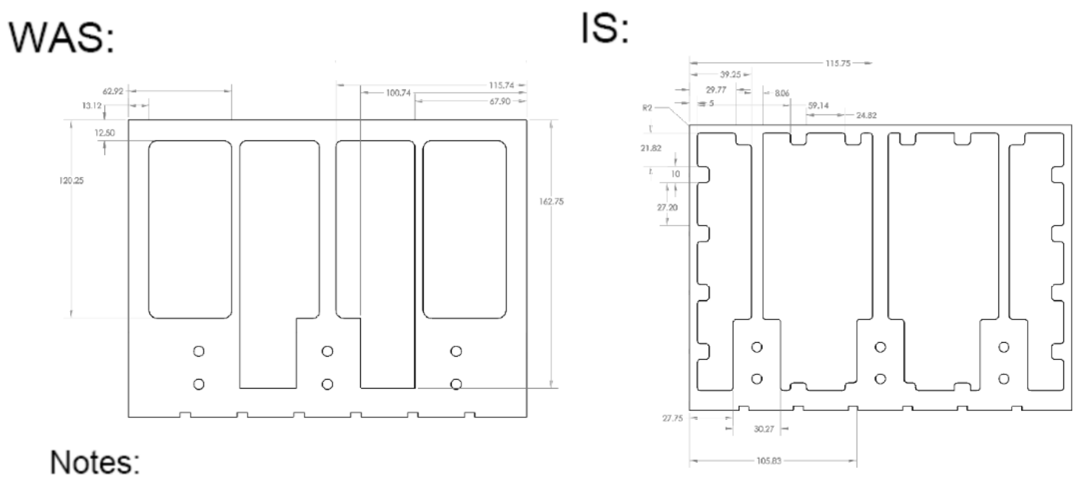
XV. APPENDIX C – ENGINEERING CHANGE NOTICES

The following changes have been made to our design since DR4. Engineering Change Notice Documents are located in the Appendix, and include drawings detailing each change.

Side Plate

The Side Plates design required geometry changes in order to reduce the overall mass of the plates. Because there are two plates used in the enclosure, mass reductions on these plates have a significant impact. This iteration reduced the width of the remaining material on the edges of the plate to 5mm from 12.5mm and 13.2mm widths. The locations where fasteners were inserted had to remain at length for their threading and helical inserts. The end result was a mass reduction from 648.59 to 587.98g for a total of 60.61g reduction per plate.

Engineering Change Notice



Notes:

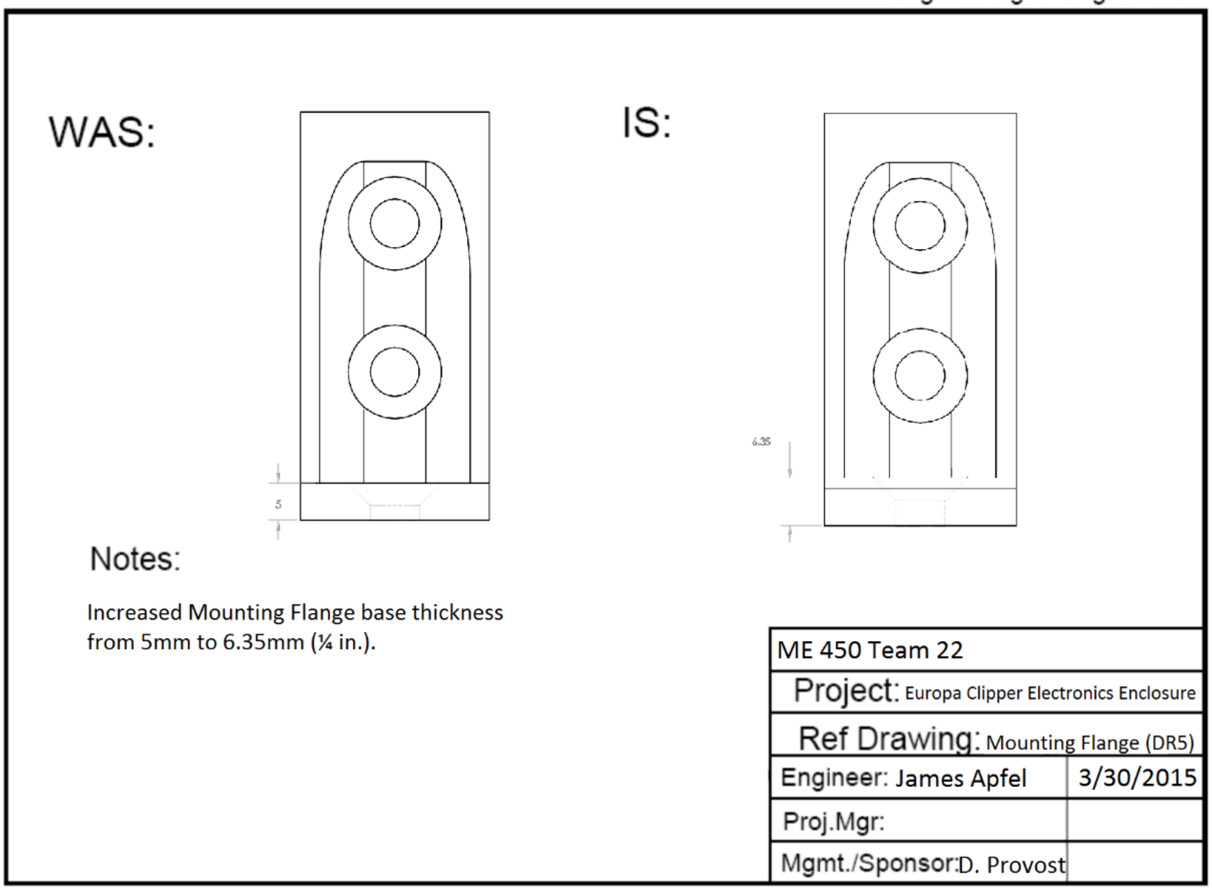
Reduction in mass of Side Plate from 648.59g to 587.98g (60.61g per plate).

ME 450 Team 22	
Project: Europa Clipper Electronics Enclosure	
Ref Drawing: Side Plate (DR 5)	
Engineer: James Apfel	3/30/2015
Proj.Mgr:	
Mgmt./Sponsor: D. Provost	

Mounting Flange

The mounting flanges used to connect the Side Plates of the enclosure to the interior of the vault wall underwent a geometry change to reinforce the connection with the vault wall at the recommendation of our sponsor. Previous mounting brackets had experienced failure during testing they conducted recently. The thickness of base of the Mounting Flange was increased from 5mm to 6.35mm (¼ in.).

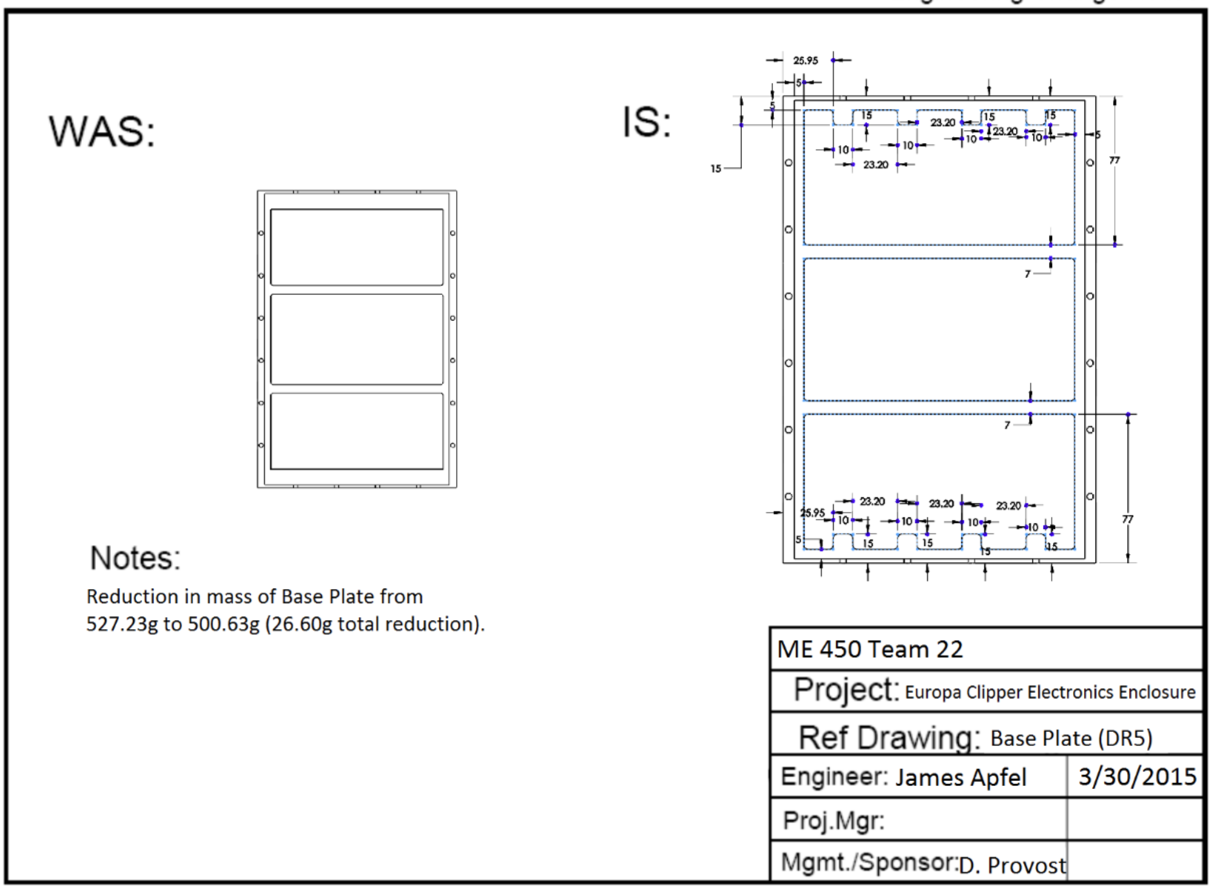
Engineering Change Notice



Base Plate

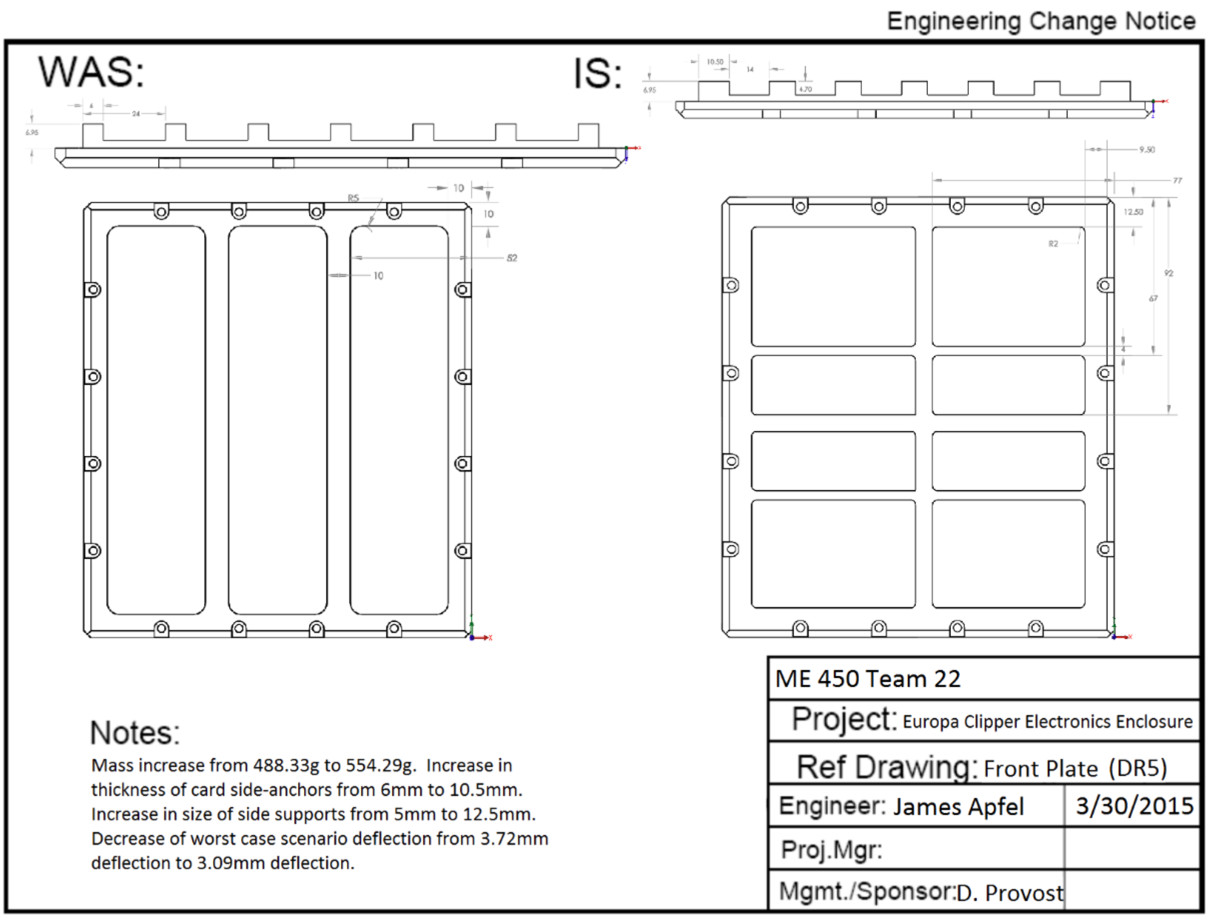
The Base Plates design required geometry changes in order to reduce the overall mass of the plates. The new reductions made to the Base Plate are similar to those already made to the Top Plate. This iteration reduced the width of the remaining material on the edges of the plate to 5mm from 15mm. The locations where fasteners were inserted had to remain at length for their threading and helical inserts. The end result was a mass reduction from 527.23g to 500.63g (26.60g).

Engineering Change Notice



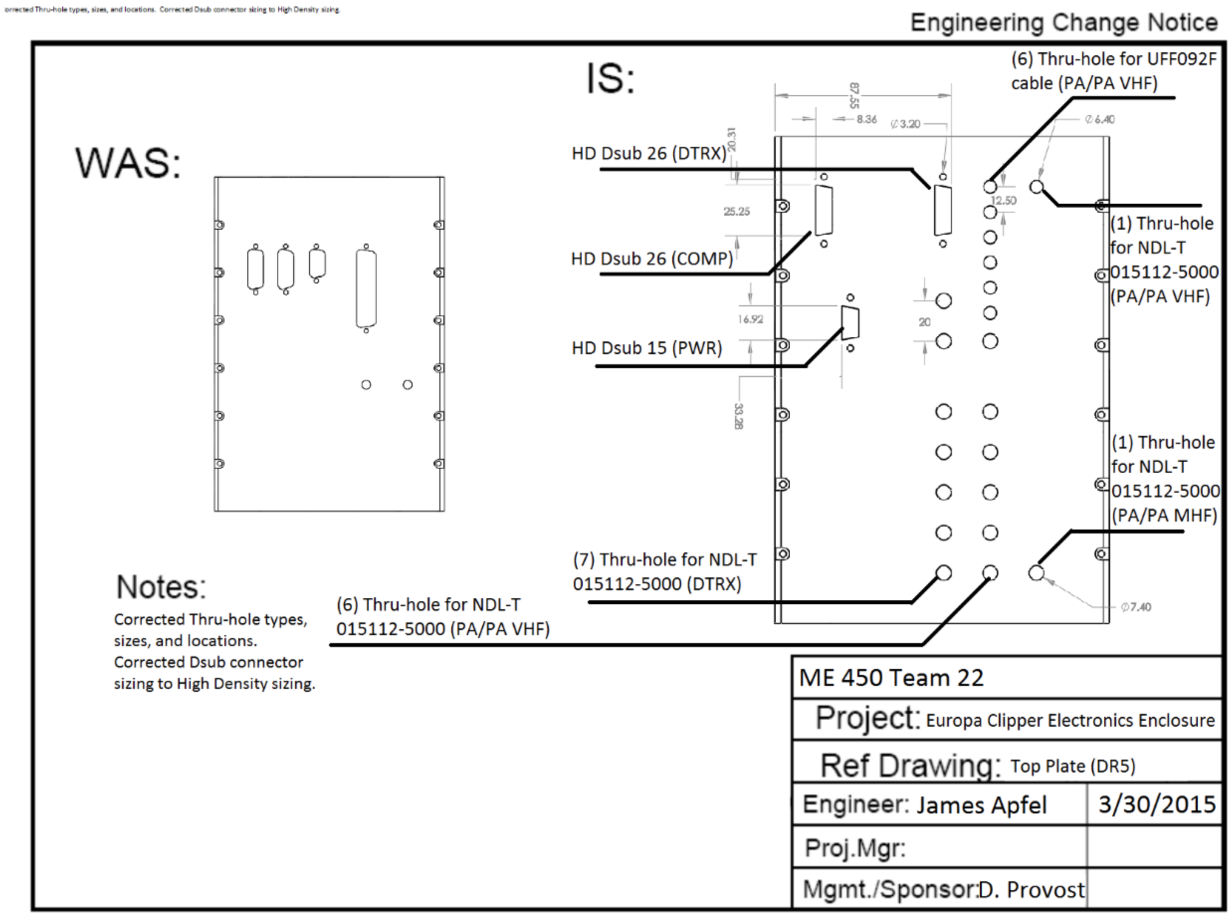
Front Plate

The Front Plate Design required changes to the reinforcement of the mass cutout sections to reduce deflection under launch conditions as well as changes to the spacing and size of the card side-anchors to accommodate the wedge-loks we selected. The card side-anchors increased in thickness from 6mm to 10.5mm. The spacing of the side-anchors decreased from 20mm to 14mm. The reinforcing material on the edges of the plate's width increased from 5mm to 12.5mm. This resulted in a decrease of worst case scenario deflection from 3.72mm deflection to 3.09mm deflection. This also increased the thickness of a key plate connection from 2mm to 5mm. As a result of all of these changes, the mass of each plate increase from 488.33g to 554.29g.



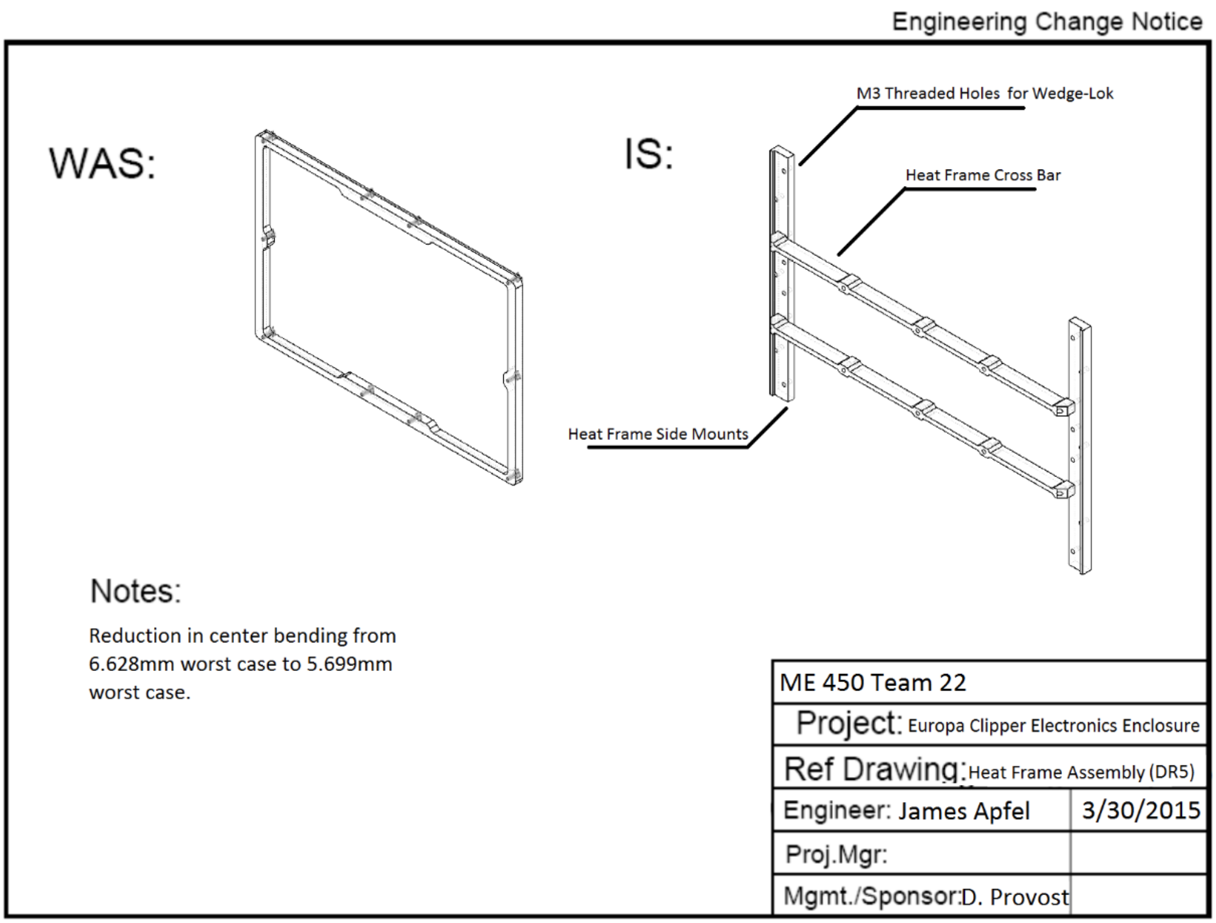
Top Plate

The Top Plate required revision of the type and location of thru-holes for connectors. Due to changing sponsor requirements, the order of the underlying boards also changed to the following: COMP, PWR, EMI Shield, DTRX, PA/PA VHF, and PA/PA MHF boards. This resulted in changes to the order of the ports, as detailed in the Engineering Change Notice. The size of the High Density Dsub connectors also changed as a result of obtaining the manufacturer’s exact dimensions, which are thinner than standard connectors.



Heat Frame

The Heat Frame underwent drastic geometric re-design following input from UMass project collaborators designing the electronics boards. As a result, the Heat Frame Assembly now consists of four sub-components: two Heat Frame Side Mounts and two Heat Frame Cross Bars. The Cross Bars were adapted from the top and bottom of the past heat frame design, but are now adjustable (separated, additional drilling and threading would have to be done) and have mass reductions. The Side Mounts are adapted from the sides of the past heat frame design and now include threaded 3M holes for attaching Wedge-loks. These changes were primarily driven by a need to stiffen the cards, which can have a mass of up to 4kg. The result was a reduction of worst case center bending from 6.628mm to 5.699mm. Although this does not resolve the deflection issue, the unknown distribution of the mass reduces our ability solve the issue completely.



XVI. APPENDIX D - VALIDATION PROTOCOL

In order to validate that our prototype meets or fails to meet our engineering specifications, we will have to conduct multiple experiments to test our prototype. However, due to the time and cost constraints of our project, our group will not be able to conduct these tests. The steps to do so are still given in the following:

Vibration Testing

A. What is measured: Structural rigidity of enclosure during launch
B. What equipment will be used:
    1. Shake table
    2. Accelerometers
    3. Labview
C. What are the basic steps to follow to acquire data:
    1. Attach accelerometers at standard locations
    2. Attach enclosure to shake table
    3. Turn on computer
    4. Unlock power and turn power on wall
    5. Start vibration view and input specifications
    6. Run at standard frequencies for each dimension (x, y, z axis)
    7. Record data throughout
    8. Turn off system
D. How to process the data to find useful and significant results: Analyze the deflection profile of each plate at each tested frequencies to either confirm or fail to confirm that the enclosure meets the launch environment specifications.

Thermal Chamber Testing

A. What is measured: Temperature inside the enclosure
B. What equipment will be used:
    1. Thermal Vacuum Chamber
    2. Thermocouples
    3. Thermocouple controllers
    4. National Instruments Series modules
    5. Labview
    6. Power supplies
C. What are the basic steps to follow to acquire data:
    1. Mount Thermocouples at standard locations
    2. Wire heaters to connectors
    3. Close Chamber
    4. Pump down chamber per standard procedure
    5. Turn on each heater circuit and confirm operation
    6. Start data acquisition
    7. Set thermo vacuum shroud to follow the temperature test profile
    8. Record until profile is finished
    9. Turn off all power
D. How to process the data to find useful and significant results: Analyze the temperature profile of the interior of the enclosure that is recorded in Labview to either confirm or fail to confirm that the enclosure meets the temperature specifications.

XVII. APPENDIX E

Ethical Design Statements

James Apfel: The primary ethical concerns our team encountered with our project centered on our competence with engineering fundamentals in fields other than our own that this project encompassed, safety of the materials we utilize, and finally, the immense overall cost the eventual mission risks. These three ethical concerns were derived from the ASME Code of Ethics and drove our development towards our final design. Our primary ethical challenge was validating designs and results relating to areas outside of the mechanical engineering curriculum. Many aerospace and electrical engineering requirements were present for our project that we were unable to interpret. To ensure thorough understanding, we checked our interpretations of requirement with our sponsor and discussed validation methods. For designing elements we were unfamiliar with the construction of, we met with our sponsor, other project collaborators, and outside experts. In one case I personally met with SSSFL students who had experience with mounting electrical components in order to discuss validation on our design so far, mounting methods they were familiar with, and additional validation methods they use or encounter. Our secondary ethical concern was health and safety, as most aerospace electrical enclosures have chemical films applied that contain large amounts of cadmium, a carcinogen. It was decided that our project, in its current phase, does not require this coating. Additionally, we avoided buying parts with this coating, such as the wedge-loks. The prototype model will be handled by various people throughout design reviews and expo who do not have the proper safety equipment to handle cadmium coated materials, and as such it is not feasible to coat the prototype safely. Finally, the final ethical concern was the eventual cost and risks of the final Europa Clipper mission. Our team delivers data that helps guide other teams in the development of their modules and perhaps the eventual electronics enclosure design. To provide incorrect data or designs that may result in an eventual failure of a far more expensive prototype or mission launch could be catastrophic. The overall mission cost for the Europa Clipper is projected at 2 billion dollars, and one failing fastener could jeopardize timely launch or the entire mission down the line. As such, we are only providing data and designs we have verified to the best of our ability and consulted with our sponsors and others along each step of the design process. To conclude, the risks of our project are very small at the present, with cadmium health risks easily avoided, but as the project progresses a failure could be catastrophic not just for our design team, but for the mission.

Joseph Cho: Our team of engineers applied the code of ethics throughout the entire design process of the Europa Clipper project. We held paramount the safety, health and welfare of the public by developing a safety plan of our manufacturing process and strictly following the safety procedures. Because our group composed of engineering students, we all have background in design and manufacturing, structural rigidity, thermodynamics, and heat transfer which are the core areas our project encompasses. However, our group did not know the specific government regulations and mandates that our design would have to follow, and thus we did much research regarding those specifications very early in our project. Our group always acted professionally both during the weekly meetings held with our sponsors and professor, and during the design review presentations held throughout the semester. The main conflict of interest was the confidential information given to us about the engineering specifications of our project and how we can report them to our classmates and professors without jeopardizing the confidentiality. We avoided this conflict by reporting false engineering specifications which our classmates and professors knew were false. Our group only associated with other University of Michigan engineering students and professors, a Space Research team at the University of Michigan and at the University of Massachusetts. These persons and organizations are very reputable. All of our reports and presentations to our peers were truthful and objective. Our group also considered the environmental impact of our project, and made an effort to reduce as much materials used in our project.

William Falconer: Our team has taken the code of ethics and applied it to our design. All analyses were done honestly and with the best interest of our sponsor in mind. Each student only worked on areas in which they were knowledgeable. Our main ethical concern, however, was ITAR. ITAR is the set of regulations guiding exchange of government engineering ideas. Our team has addressed these concerns by keeping our design specifications hidden. Our sponsor has repeatedly expressed that we must keep our mass and dimensions hidden. In order to do this, we have reported false numbers or left numbers out of our reports completely. Our device does not interact heavily with human users so we did not have any real safety concerns as far as the design. However, we encouraged the highest level of safety during the manufacture of the enclosure by wearing safety glasses, close-toed shoes, and using safe machine shop etiquette.

Vivek Merchant: Team 22 has abided by the Code of Ethics of Engineers. We have used our knowledge in the field of mechanical engineering, to the best of our abilities, to design the enclosure for the Europa Clipper Spacecraft. We have been honest with our clients and not withheld any information about our analyses from them. This specifically refers to the team's discovery of the impossibility of meeting the radiation and mass specifications of the project.
We have tried to ensure maximum safety over the course of this semester, while dealing with our project. All manufacturing has been carried out after receiving all required approvals. Machine shop etiquette has been followed and all necessary precautions have been taken into account (wearing the necessary safety gear and appropriate apparel). The team members worked on those aspects of the project that they were the best at, in order to design a competent and safe model; thus, not jeopardizing anybody's safety or the quality of our project.
Our project does have certain ITAR (International Traffic in Arms Regulations) restrictions that we must abide by. Due to the nature of our project, we were forbidden from reporting certain values and measurements of our final design. The team has ensured no confidential information has been compromised, by modifying the reported numbers in reports and presentations.

Environmental Impact Statements

James Apfel: The environmental impact of our proposed solution is almost entirely concentrated in the transportation of the electronics enclosure to space. The launch vehicle materials and fuel expended during launch vastly outweigh the impact of the aluminum utilized to construct the prototype and eventual launch enclosure. Aluminum production in the US, although still energy intensive, draws its energy from a much cleaner grid than other country's supplies of aluminum, such as China, who relies on coal for much of their electricity mix. Only a few kilograms of aluminum are being utilized for construction, and that further minimizes it. The eventual launch enclosure will feature a cadmium-based chemical coating in order to prevent outgassing in space. Although the process for applying the coating generates toxic byproducts, the quantity and scale of a one-off enclosure reduces this impact greatly. Overall, an Atlas V Rocket costs about $21,000-$100,00 per payload pound to launch, depending on the destination. The overall launch will consume around 284,089 pounds of rocket fuel (kerosene and oxidizer), with our enclosure accounting for a small, but still significant fraction of that. Every fraction of a pound saved saves tens of thousands of dollars' worth of rocket fuel cost, both in mission price and environmental. Kerosene fueled rocket launches release HLC high in the atmosphere, where it is more ozone depleting. The shuttle program alone was responsible for 0.016% of annual halocarbons, per launch. Finally, at the end of the enclosure's life, the spacecraft is deorbited into Jupiter or collided with Ganymede to avoid polluting Europa's ice and ocean with external life or toxins. The material composing the enclosure in not recycled, so that potential energy saving is not recovered. The cadmium and other toxins in the chemical coating are not disposed of on Earth, and disintegrating in a gas planet's atmosphere or hitting the moon Ganymede might be the safest disposal of a material possible for it to no longer harm Earth's environment. Overall, the enclosure's environmental impact is that of transporting it to space, taking thousands of pounds of fuel for the enclosure alone. This in turn requires the manufacture of the rocket, and the release of the rocket's exhaust. The rocket's exhaust is ozone depleting and delivered directly to the sensitive portions of the atmosphere.

Joseph Cho: Our team did consider the environmental impact of our design, however it was not the top most priority, due to the small scale of our project. Since our design will not be massed produced, or duplicated, we did not think the environmental impact of our designs were significant. The major environmental impacts of our design were the amount of raw materials used to manufacture the product, and the final mass of the product. Since we are designing an enclosure that will be sent out of the earth's atmosphere, reducing the mass of our enclosure would thus reduce the amount of rocket fuel needed to launch. Our major design goal was to reduce the mass of enclosure, and this coincided with reducing the environmental impact. The materials used in our design was mostly aluminum. Manufacturing aluminum does have an environmental impact due to the extraction, forging, transportation, and finally machining. Having the environmental impact in mind, we tried to buy the least amount of aluminum needed to build our prototype. At the end of life of our product, given that NASA does choose our sponsor's proposal, our product will be thrown into Europa, disintegrating our product.

William Falconer: The *Europa Clipper* electronics enclosure has a large environmental impact that our team has tried to minimize in several ways. Because the enclosure is being constructed from aluminum there are concerns about where the aluminum is sourced and how much is used. We recommend getting aluminum from US producers instead of overseas producers in China or elsewhere because the impact from US aluminum is smaller. We also planned to reduce scrap by cutting our pieces out in a compact form factor. A lot of aluminum is wasted during the milling process, so we recommend that that be recycled. Our device's impact will be lessened by the fact that it is not planning to be mass produced. At the end of its life, our enclosure will be slammed into Ganymede, a moon of Jupiter. Our prototype will be recycled by the SPRL or kept on display. A lot of energy and water are used in the milling and water-jetting processes and so we have made every effort to reduce our time on both of those machines.

Vivek Merchant: Most of our project has involved computer software use and running simulations to test the models. Since our project is a space related project, the environmental impact considerations are minimal, and all the emphasis is placed on obtaining the best quality design, manufacturing and ultimately, the completion of a mission successfully. This implies that cost is also not a factor, which our sponsors told us from the first meeting itself. However, as Team 22, we have tried to minimize our environmental footprint. The material we are using is 6061 T6 aluminum, a commonly available material. Instead of ordering the material, we went ourselves to pick it up from the nearest hardware store in Ann Arbor, with a final bill of materials, to avoid multiple trips. We have been machining the prototype using the materials purchased in an optimal manner, to avoid scraps and wastes. Some amount of material is always wasted, but since it is aluminum (a common material), it can be reused in the machine shop itself. The Space Physics Research Lab at the University of Michigan will retain the prototype we are building, and therefore, there will be no wastes there. We realized a majority of the energy being consumed by our team was while using computers and while machining our prototype. Minimizing this energy consumption was almost not possible. The bigger picture, which involves the entire spacecraft that NASA will be launching, includes smashing the spacecraft into Ganymede, one of Jupiter's moons. We of course, have no say as to what happens there.

XVIII. APPENDIX F – AUTHORS
AUTHORS

James Apfel is a junior in Mechanical Engineering at the University of Michigan. He is a member of a Multidisciplinary Design Project team working on production line optimization at Detroit Manufacturing Systems. He is a cadet enrolled in the Army Reserve Officers' Training Corps, and intends to commission as a second lieutenant in the US Army upon graduation in the winter of 2016.

Joseph Cho is a senior at the University of Michigan studying mechanical engineering. His concentration is in sustainable engineering/alternative energies and system and controls engineering. He is currently interning at the Environmental Protection Agency where he is helping with the development of tools for various teams at the EPA for application development projects. After graduation, he will work for General Motors in their Battery Algorithms and Software group.

Vivek Merchant hails from Mumbai, India and is a senior in Mechanical Engineering at the University of Michigan. As a member of the College of Engineering Honors Program, he is minoring in Computer Science and is pursuing a Program in Sustainable Engineering. He interned at Ami Tech (India) Pvt. Ltd in the summer of 2014, where he analyzed the potential for smart grid systems in India. After graduation, he wants to pursue an MBA, after gaining a few years of work experience.