COLLEGE OF ENGINEERING
MECHANICAL ENGINEERING
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Packaging of Planetary Exploration Organic Composition Analyzer for NASA's Europa Mission

Final Report

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EXECUTIVE SUMMARY

Our team has designed a spaceflight packaging structure for a micro gas chromatograph (GC), an organic compound analysis instrument currently being developed by Prof. Kurabayashi at the University of Michigan for NASA's proposed lander mission to Europa, one of Jupiter's moons. As the development of the GC continues, our stakeholders need a more robust structure to package the device and simulate the space environment. Using the design framework and methodologies learned in ME 450, our team has created and verified a solution to meet our stakeholder's current needs. This report documents Team 33's solution design process.

Based on our interviews with Prof. Kurabayashi, we identified three main problems that the new packaging structure needed to address: securely housing the GC components, withstanding mechanical shocks and vibrations to be expected on the mission, and managing internal thermal fluctuations. Using data from the stakeholder and the Mars 2020 rover test flight, we translated these needs into engineering specifications, including standard factors of safety used by NASA.

In the concept exploration phase, divergent thinking, a morphological chart, and design iterations were used to fully expand the solution space. The three main design requirements were then each evaluated using Pugh charts and engineering principles, narrowing down the solution space to one design. This preliminary solution consisted of a two-layer, rectangular box made of a T7075 aluminum alloy. Between the inner and outer layer would be an array of springs, which were later removed in the solution development phase. A high-performance elastomer called Sorbothane was chosen to surround the inner components, and the synthetic insulator Aerogel would manage the thermal fluctuations of the GC's analytical column and preconcentrator.

To develop this preliminary solution, a full CAD model of the package was created and analyzed in ANSYS and COMSOL. In ANSYS, two shock tests were used to examine the deformation under force, and one vibration test estimated the resonant frequency. Using guidance from our stakeholders, failure points for the axial and lateral shock tests were identified as maximum deformations of 1 mm and 2 mm, respectively. Under 222 kN of force, the model deformed only 0.81 mm and 1.26 mm. The vibration test confirmed that the structure would not resonate between the bandwidth of 5-200 Hz at 3G's. The three tests showed that the design met all of our shock and vibration specifications. In COMSOL, the sequence of thermal fluctuations in the GC were modeled to test Aerogel's insulation properties. The team found that 6x5x1 cm of Aerogel would be able to fully isolate the analytical column and preconcentrator from other components.

The final solution contained several design flaws, such as the overall manufacturability and the integration methods for wiring. The team also did not test the reliability of adhesives, which were integral to the design. However, despite these pitfalls and several others, we have verified with our stakeholder that this solution succeeded in meeting all of their current needs.

PROBLEM DEFINITION

Space Exploration, Europa, and NASA's Mission

NASA and JPL (Jet Propulsion Lab) have proposed a mission to Europa, one of Jupiter's 79 moons. The project is currently still in the proposed phase but the plan is to send a Lander to Europa in 2027 to examine the icy surface for signs of life. There is believed to be a salty, global ocean on the moon. Professional opinion is that if life did exist on Europa they would be in the form of biosignatures that make their way to the surface where they could be detected. Europa has no atmosphere, causing us to neglect atmospheric effects in this project. The Europa Lander would be equipped with a variety of analytical tools to collect and characterize samples from the surface, including a gas chromatography system being developed at the Microsystems Technology and Science Lab (MSTS) at the University of Michigan.

Micro-Electromechanical System Gas Chromatograph Device (MEMS GC)

Led by Professor Kurabayashi, the MSTS Lab is developing a Micro-Electromechanical system (MEMS) gas chromatograph (GC), shown in Figure 1. A GC is an analytical instrument that vaporizes a sample compound and separates it through a long, narrow tube, called the Analytical Column, into its constituent elements for analysis. A micro GC redesigned for space flight and the associated extreme conditions could potentially enhance the capabilities of the already-onboard mass spectrometer for planetary exploration (MASPEX), developed by the Southwest Research Institute (SWRI) for NASA on the Europa Mission. In order to test the viability of this new GC system coupling, the MSTS Lab will need a packaging structure for the GC system so they can model the space flight environment. The current prototype of the GC system is being tested in Professor Sherman Fan's Lab at the University of Michigan. The system is currently packaged inside a SH300-YL Seahorse Case, however, this temporary packaging will be replaced with our team's ultimate design. The GC system is still being developed and is subject to change as the MEMS and GC technology evolve and more detailed parameters of the mission are released.

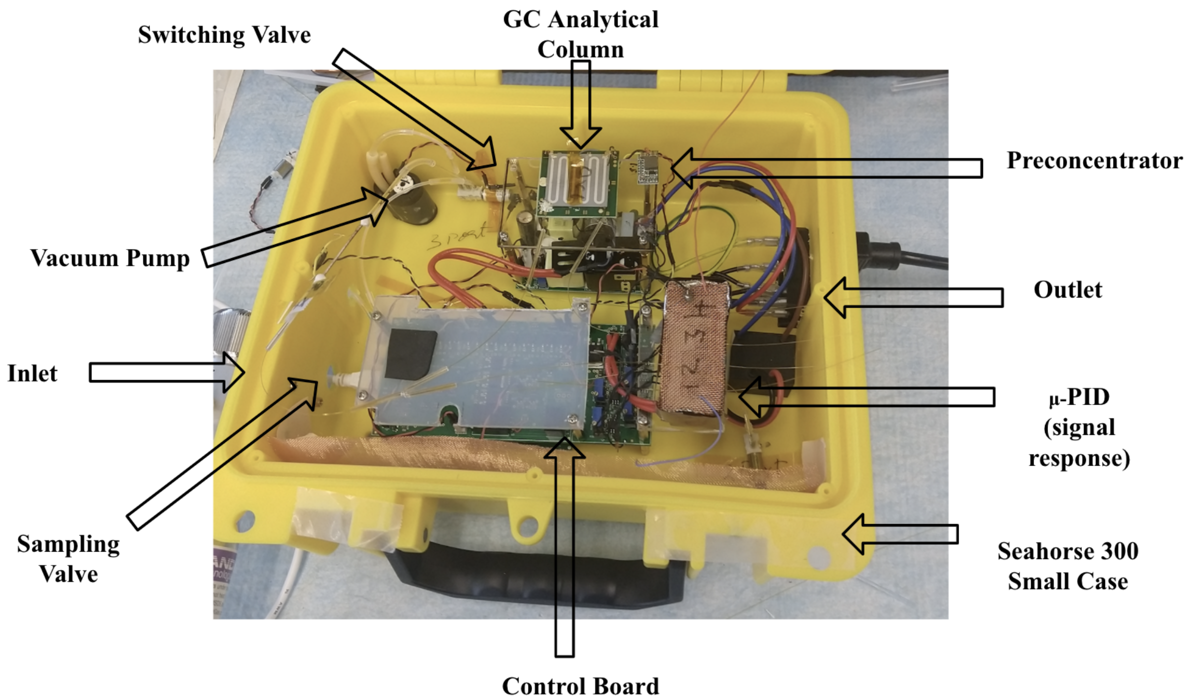


Figure 1. MEMS GC in current packaging case with major components labeled.

Problem Description

To support future testing of the GC system designed by Prof. Kurabayashi and the Southwest Research Institute, our team designed and simulated tests for a packaging structure to secure the system and withstand the expected environmental conditions of the Europa Lander mission. Through our initial interviews with Prof. Kurabayashi, we defined three problems that the packaging must solve (Figure 2). First, it must dampen the mechanical shocks and vibrations to be expected on the mission in order to protect the hardware. Second, the packaging must optimize thermal management to prevent the heat produced by the preconcentrator from reaching sensitive electronics in low-atmospheric conditions. Third, it must securely hold all components of the MEMS GC.

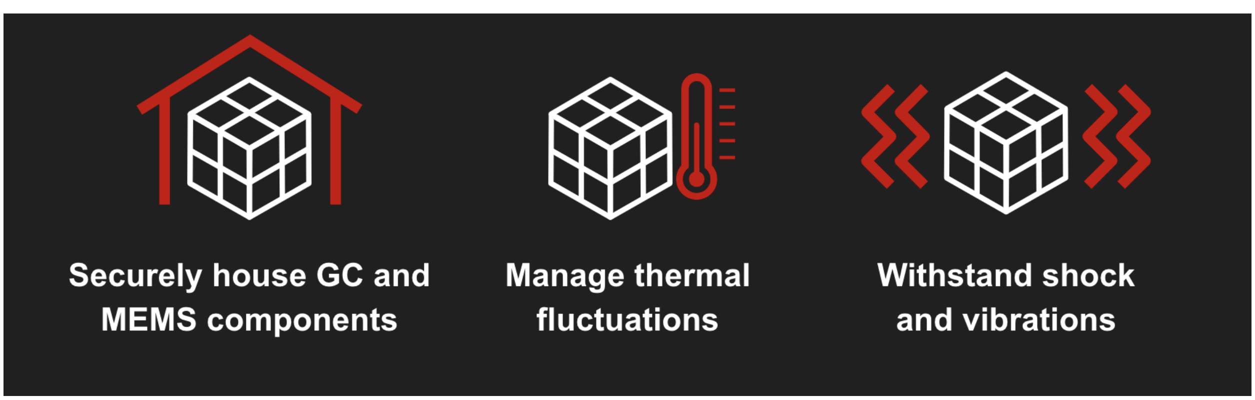


Figure 2. The Three problems addressed in designing the packaging structure for the MEMS GC.

Mars 2020 - Maximum Load Design Benchmark

The environmental conditions of spaceflight pose major technical challenges for engineers designing MEMS packaging. MEMS devices are subjected to heavy shock and vibration during liftoff and landing, and they endure temperature extremes while operating in a vacuum. It is often difficult to simulate the environments that these sensitive and expensive devices will endure, but using previous missions as benchmarks for future missions has proven to be quite useful. To better understand the mechanical conditions of spaceflight, our team leveraged NASA's Mars 2020 test flight data for the Entry, Decent, and Landing (EDL) phase of the mission as a benchmark for mechanical shock conditions.

The 2020 Mars Rover mission has many important similarities to the proposed 2027 Europa Lander mission. First, both missions utilize a Sky Crane sequence for the final stage of EDL. Both landers are also composed of four separate stages: the Carrier Stage, the Deorbit Stage, the Descent Stage, and the Lander. By understanding and capitalizing on these similarities, we were able to create engineering specifications derived from measured data (Figure 3).

We determined that the maximum force the MEMS GC system will experience will be during the Descent Stage. This was obtained from the data collected during the ASPIRE test flights conducted with a representative payload meant to simulate the force that the Lander will experience during the EDL procedure on Mars. During these tests, it was shown that the maximum load experienced by the payload was the instant the parachute was deployed. We concluded that since the Europa EDL sequence did not involve a parachute, using the peak value would be unnecessary as the Europa payload will not experience that extreme of a sudden load. This is due to Europa not having an atmosphere nearly as dense as Mars, rendering a parachute useless in that situation. Thus, the mission is planning to use 4 thrusters for an extended powered descent on Europa (as opposed to a combination of powered descent and parachuting like the Mars 2020 mission).

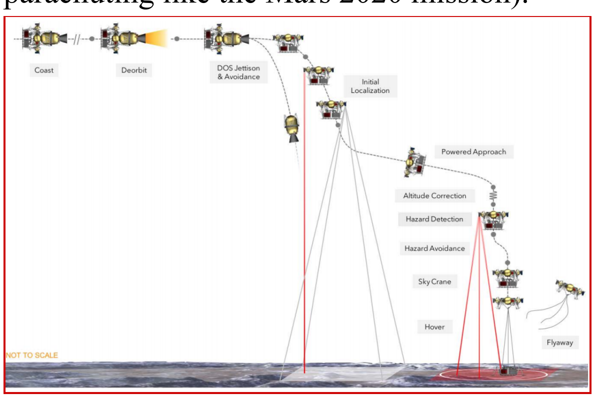


Figure 3a. 2027 Europa Lander EDL proposal

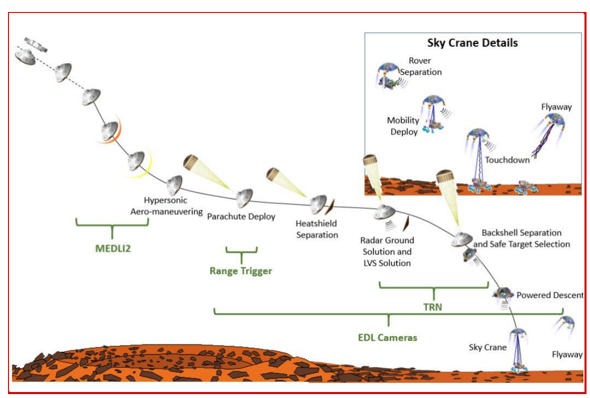


Figure 3b 2013 Mars Lander EDL

So we instead used the start (i.e. maximum) of the steady-state decline in load as our benchmark, making the assumption that the powered descent of the Europa Lander will try to roughly adhere to the load of the Mars Lander after the initial deployment of the parachute.

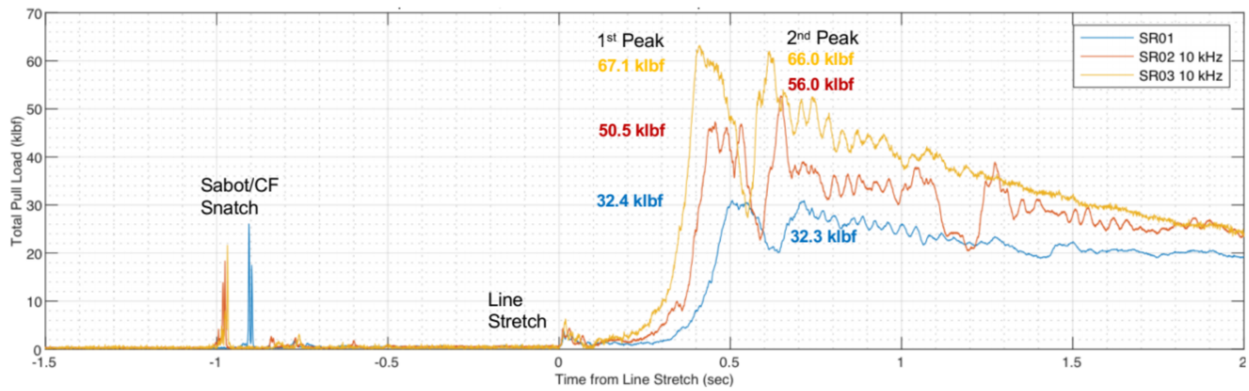


Figure 4. Measured inflation pull loads for each of the three ASPIRE flights. Note that the bold numbers are for total parachute force which accounts for the mass of the parachute and high deceleration environment.

From the three test flights shown in Figure 4, we concluded that the start of the steady-state decline in load was about 0.7 seconds after Line Stretch (roughly 0.1 seconds after the 2nd peak). This results in forces of about 50, 38, and 30 klbf of force for each test flight. We made the decision of keeping all units in metric, thus giving us forces of about 222, 169, and 133 kN of force that the payload will experience. To arrive at a single number for our engineering specification, we took the average of these 3 flights to arrive at a load of 175 kN that we will test our packaging structure against.

NASA Standards - Vibration Design Benchmark

For our vibration requirement, we determined that the maximum vibration load that the Lander will experience during the Europa mission will be during takeoff when the rocket is initially launched. NASA has extensive research on testing conditions for payloads during takeoff, so it was relatively straightforward to come up with a clear specification of 3Gs of force at a frequency of 5-200 Hz.

It was also important to consider safety factors when choosing our specifications since a margin of error is critical for spaceflight. We used the General Environmental Verification Standard (GEVS) to determine these safety factors: 1.4 and 1.25 for mechanical shock and vibration, respectively.

Requirements and Engineering Specifications

Stakeholder needs were synthesized between Prof. Kurabayashi from the Microsystems Technology and Science Lab at U-M, Dr. Blase from the Southwest Research Institute (SWRI), and Dr. Venkatasubramanian from Prof. Fan's testing lab at U-M. The relative importance of these needs has shifted slightly over time based on continuing stakeholder feedback; they are listed in order of importance in Table 1 below.

Table 1. Summary of the stakeholder requirements, associated specifications, and design justifications.

Stakeholder Requirement	Engineering Specification	Justification
Protect all internal components from onboard mechanical shocks and vibrations	1. Shock: 175 kN[3] (x 1.4 SF)[2] 2. Vib: Force of 3G's at 5-200 Hz[4] (x 1.25 SF)[2]	For force experienced, we used the Mars 2020 EDL test flight data as a benchmark since Europa EDL procedure is very similar. Maximum vibration is anticipated during rocket launch, for which we used NASA mission standards.
Regulate internal temperature range	Internal temp 330°C → 25°C within 24 hours[1]	The GC system heats the mass sample to 330°C to vaporize it and carry it through the analytical column. Lack of atmosphere on Europa will effectively eliminate surface conduction, slowing down the cooling process. The GC system needs to be cooled back down to 25°C within 24 hours (estimate time between samples) to perform daily measurements at nominal temperatures.
Allow for gas flow in and out of the packaging	1. Two inlets (Carrier gas + sample) 2. One outlet (Mass Spectrometer)[1]	A GC requires a carrier gas to ensure sample moves through the system, helium in this case. The second inlet is the sample itself that will be obtained from just below the surface of Europa. The sample, once separated, will then be fed to a mass spectrometer (MS) for analysis.
Easy access to components	Easily removable panel (1 tool < 2min)	The packaging system needs to be opened to examine the components of the GC system for damage after shock vibration and thermal tests.
Prevent against electromagnetic interference on device	< 5% data corruption w/ hand 1cm from device	Due to sensitivity of the system, testing will be prone to error due to electromagnetic interference, particularly from humans. Minimizing this will increase the reliability of data collected both during tests and the mission.
Minimize internal volume	Internal volume < 4723 cm^3 [6] (24.13 x 18.80 x 10.41 cm)	The internal volume should be minimized to save space on the Europa Mission, while securely housing the components of the GC system. Currently they are using the Seahorse 300 small case as a temporary packaging which has an internal volume of 4723 cm^3.
Minimize weight	Total weight of package < 5.4 kg[1]	Available mass for instruments on the Europa Lander is tightly constrained. Payload suballocations must not exceed 5.4 kg [7].
Within budget	Cost < $3000	A budget of $3,000 was specified by the sponsor.

CONCEPT EXPLORATION

Concept Generation

For concept generation, we scheduled a ninety-minute session to brainstorm solutions for our specifications. The specifications we generated solutions for were: Shock and Vibration, Electromagnetic Interference, Easy Access to Components, and the materials used to minimize the weight. These functional groups were derived directly from the requirements and specifications in Table 1, representative of each full-length specification. The specifications were also mutually exclusive, meaning we could generate ideas for each one individually, without worrying about how they would affect the feasibility of the other specifications. The team went through each specification, giving about twenty minutes to develop as many solutions as we could, resulting in the mind map in Figure 5. The entire list from the brainstorming session can be found in Appendix A. At the end of the session, each team member picked a specification to research in greater detail in order to fully flesh out the solution space and develop a better idea of the best design concepts.

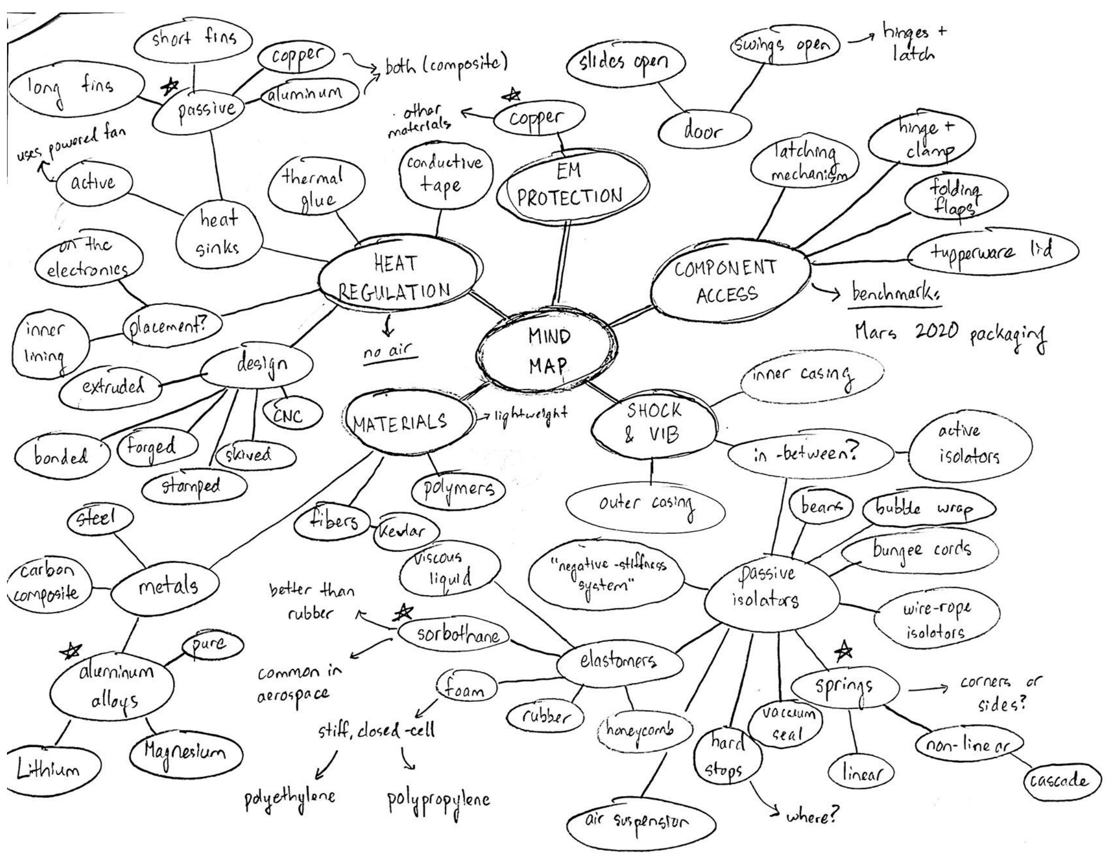


Figure 5. The mind map created during the brainstorming session. Four branches represent the specifications we were addressing, with the fifth branch used for noting potential materials we could build the system with. The most promising ideas from the mind map were carried onto the concept development phase for further exploration.

Concept Development

In the concept development phase, our ideas from concept generation were organized in order to better understand the solution space. Some of the ideas were also taken a step further and explored through several design iterations in order to fully investigate the ideas.

Morphological Chart

For the concept development component of our concept exploration, we elected to use a morphological chart as a method to organize ideas in an analytical and systematic manner. The functional categories of the system, which represented the requirements and specifications in Table 1, are displayed in the left column of the chart and the potential solutions are displayed next to each of them. The solutions for each function represent the ideas from the concept exploration phase that were passed on to concept evaluation for screening. The morphological chart is shown in Figure 6 below:

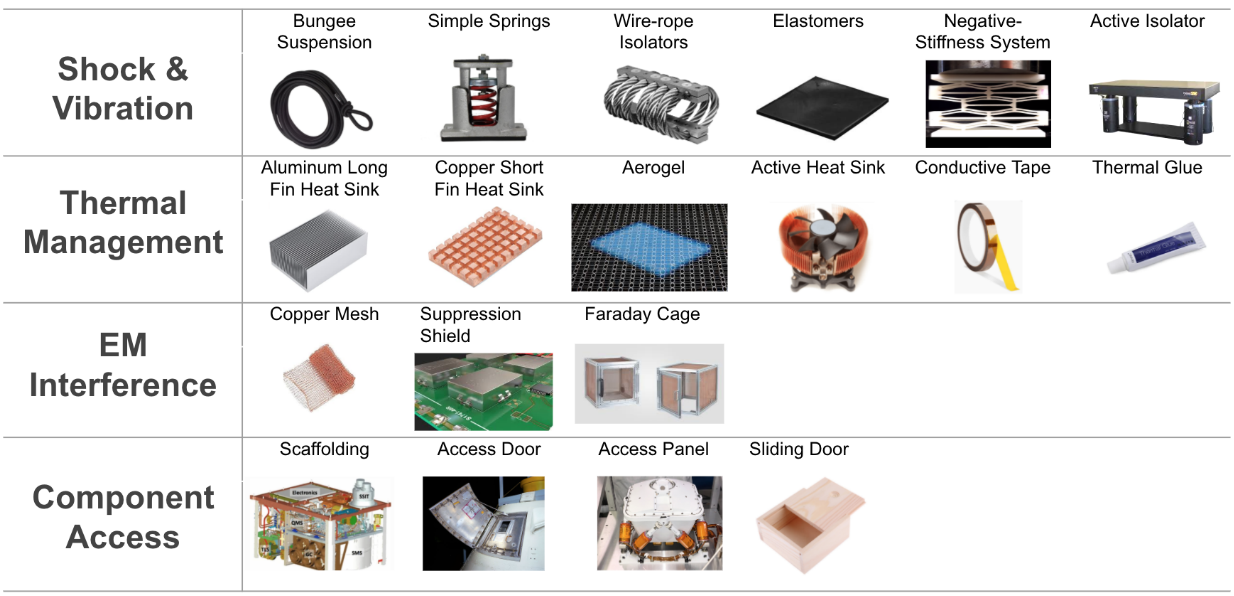


Figure 6. Morphological chart composed of the main functions on the left and possible solutions on the right. The solutions in the chart include the ideas that were passed on from concept generation to concept evaluation.

Design Iterations for Shock and Vibration

Effectively mitigating the shock and vibration for the packaging structure was one of the most critical requirements for our stakeholders. Among the solutions shown in Figure 5, there were also several variations for each. As an additional step to broaden our concept development, our team explored several iterations of some of the most promising solutions for these functions.

Elastomers. Elastomers are polymers with visco-elastic properties, which make them excellent shock absorbers. They also help to passively isolate vibrations by suppressing resonance in a system. The different variations of elastomers we considered included closed-cell foams (polyethylene as well as polypropylene), rubber, and a proprietary elastomer called Sorbothane.

Springs. Springs are another solution for shock and vibration mitigation. High-stiffness springs can absorb considerable shock and can also be fine-tuned for vibration isolation — an essential packaging technique used to protect MEMS devices. Not only can the stiffness of a spring be carefully selected to meet a designer's needs, but many types of springs also exist. These include linear springs, non-linear springs, and cascaded systems of springs. Examples of these can be found in Figure 3 below. Additionally, the springs can be integrated in the box either via the corners or the sides.

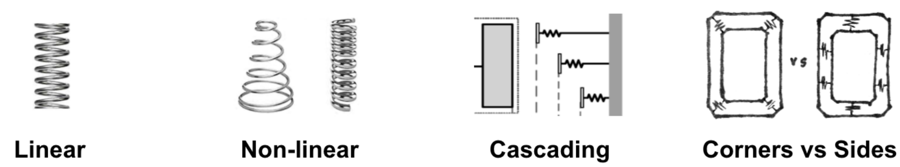


Figure 7. Different variations of springs.

Wire-rope Isolators. Similar to springs, wire-rope isolators provide another form of passive isolation. They are small, relatively easy to install, require no power, and highly durable. They can be fine-tuned for a wide range of shock and vibration needs, making them a common choice for aerospace and industrial applications. Wire-rope isolators come in many different forms; these can be seen below in Figure 4.

Figure 8. Different variations of wire-rope isolators.

Design Iterations for Component Housing
The design of the component housing has implications for stakeholder requirements 1, 2, 4, 5, 6 and 7. As a result, the architecture and materials used in the design of the component housing were investigated in Figure 6.

Component Access. Stakeholder requirement 5 requires the ability to open the package to examine the components of the GC system for damage after shock, vibration, and thermal tests. The stakeholder specifies the package must be opened using one tool in less than two minutes. To investigate the solution space, four different modes of entry were iterated during the morphological analysis.

Figure 9. Different variations of component access. Scaffolding, Hinged Door, Sliding Door, Screwed down access panel (Left to Right)

Housing Materials. Stakeholder requirement 5 restricts the weight of the component housing. The stakeholder specifies a weight of less than 5.4 kg. To investigate the solution space, different materials were considered in the analysis of component housing.

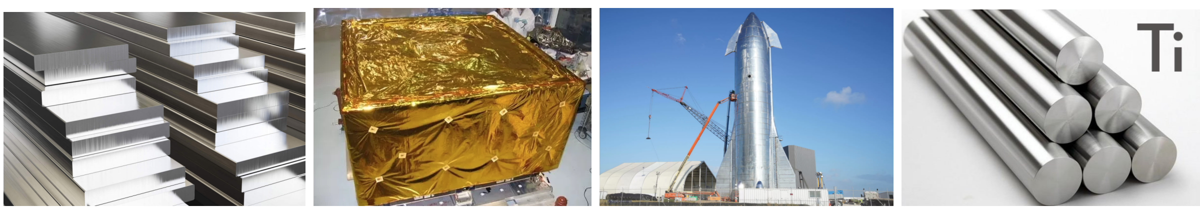


Figure 10. Different variations of component housing materials. Aluminum, Gold Plating, Stainless Steel, and Titanium (Left to Right)

Concept Evaluation

The concept evaluation phase was meant to narrow down our large number of ideas from the concept generation phase to a few potential candidates for our final design and to thoroughly examine which one(s) best meet our stakeholder requirements and engineering specifications.

Shock and Vibration

To narrow down our solutions for the shock and vibration specifications, we used a structured approach composed of several stages. These included a pugh chart to initially screen out ideas, engineering principles to motivate selections, and performance metrics to inform final decisions.

Pugh Chart. The ideas from the morphological chart were initially passed through a pugh chart to screen out the unfavorable concepts. This can be seen below in Table 2.

Table 2. The Shock and Vibration Pugh Chart is a weighted matrix of functional requirements and various solutions.

	Bungee Suspension	Active Isolation System	Air Suspension System	Negative Stiffness System	Springs	Wire-Rope Isolators	**Elastomers**
Volume	1	-3	-2	-3	2	2	**3**
Durability	2	1	1	2	2	1	**2**
Precision	-2	2	-1	1	1	2	**2**
Power Usage	2	-3	-2	2	2	2	**2**
Total	3	-3	-4	2	7	7	**9**

As can be seen in Table 2, many of the ideas from concept generation were able to be screened out on the basis of volume usage, durability, precision, and power usage. Active isolation systems and air suspension systems both require power sources and take up too much volume, which penalized those concepts severely. While bungee suspension and negative-stiffness systems are both highly durable passive isolation systems (meaning no power required), they both have their own pitfalls. Bungee cords are difficult to precisely calibrate to aerospace standards, and negative-stiffness systems also take up too much volume. This narrows down the potential solutions to springs, wire-rope isolators, and elastomers.

Application of Engineering Principles. To further narrow down our remaining concepts for shock and vibration management, we took into consideration the basic engineering theory for impact shock and resonance. For impact shock, we can reference Equation 1:

$$F = \frac{\delta}{\Delta t} \tag{1}$$

where δ is the shock amplitude and Δt is the contact time. With this in mind, we know that we should choose designs that maximize contact time and/or minimize the shock amplitude.

On the vibrations side, basic theory says that in order to suppress resonance, the natural frequency of the system should be separated as far as possible from the forcing frequency acting on the system. The natural frequency of a given body is generally defined as:

$$\omega_n = \sqrt{\frac{k}{m}} \tag{2}$$

where k is stiffness and m is mass. Therefore, in order to shift the natural frequency of the packaging system, we can adjust the stiffness or mass as needed.

Performance Metrics. As mentioned in the concept development section, springs, elastomers, and wire-rope isolators each have many variations. Among the elastomers, we considered the closed-cell foams polypropylene and polyethylene, as well as neoprene rubber and a proprietary material called Sorbothane, which is frequently used in aerospace applications. Figure 11 below shows how Sorbothane performs compared to other commonly used elastomers.

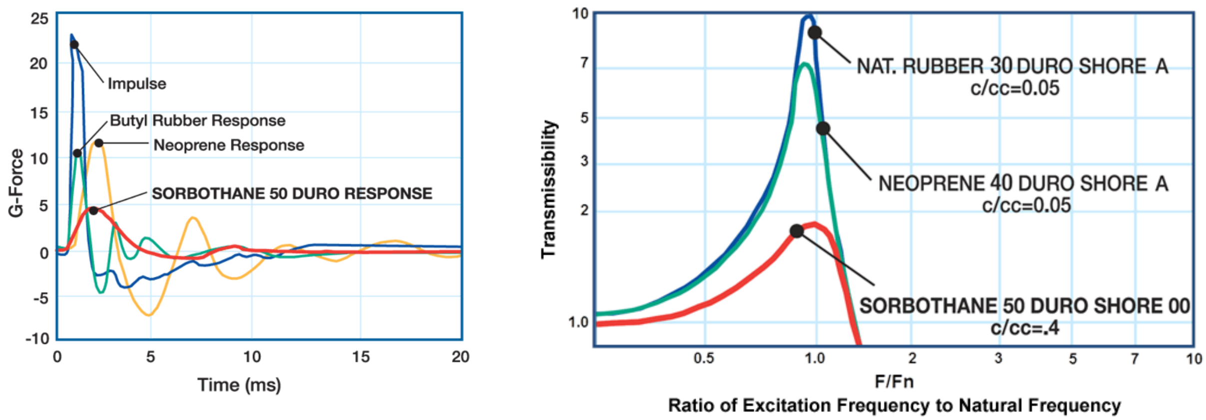


Figure 11. Sorbothane performance (red line) for both shock mitigation (left) and vibrations (right).

Looking at the data in Figure 11, it was clear to us that Sorbothane was the best choice of elastomer. It performs exceptionally well at mitigating impact shock and also reducing transmissibility, a measure of vibration isolation, at low frequencies.However, Sorbothane is in and of itself a material, and its properties can not be changed. For this reason, we are skeptical that it can meet the full bandwidth of our vibration specification, which requires us to suppress resonance from 5-200 Hz. To solve this problem, we introduce springs and wire-rope isolators. While both of these passive isolators are also good at reducing impact shock, we can use them to bolster the vibration isolation capabilities of Sorbothane. Scanning through the wide catalogues of datasheets for springs and wire-rope isolators available at Isotech, Vibro/Dynamics, Isolation Dynamics Corp., and McMaster-Carr, we are confident that either of these will work for vibration isolation. Thus, for our preliminary design, we plan to use a combination of these solutions — Sorbothane for impact shock, in tandem with wire-rope isolators or springs for vibration — in order to leverage the strengths of each.

Thermal Management

Table 3. The Thermal Management Pugh Chart is a weighted matrix of functional requirements and thermal management materials.

	Weight	Copper Passive Long Fins	Aluminum Passive Long Fin	Active Heat Sink	Thermal Tape	**Aerogel**
Mass	1	-1	1	-1	4	**3**
Conductivity	4	-1	1	-1	1	**3**
Shape	3	1	1	-1	1	**2**
Power Usage	2	1	1	-1	1	**1**
Design Integration	2	-1	-1	-3	-1	**1**
Total		-2	8	-16	11	**25**

We decided to evaluate six potential ideas for thermal management within the GC system, and selected 5 design features that we felt would be key to meeting the relevant specification of protecting the analytical column from the preconcentrator: conductivity (how well can it dissipate heat?), shape (will it fit within our packaging?), power usage (does this method need power to work?), design integration (is it compatible with the rest of the components in the system and packaging?), and mass. After weighting these features, we were able to evaluate the 6 ideas in a comprehensive way and choose the one that would work best for our design.

After evaluating it against our existing ideas, it was clear that Aerogel would be the best to move forward with. Passive heat sinks rely mostly on air convection to dissipate heat, of which will not be of concern in a vacuum environment such as the one on Europa, while thermal tape is used mostly to manage consistent high temperatures in electronics such as motherboards and computer processors.

Aerogel was selected as our heat management system because it is a synthetic material that is lightweight, an extremely good insulator (it won't allow heat to spread to other components in the GC system), and moldable into nearly any shape. It is also quite cheap for small applications like our project ($1 per cubic centimeter). Our sponsors initially brought this material to our attention, citing its use in many previous spaceflight missions as an ideal thermal insulator. After evaluating it against our existing ideas, it was clear that it would be the best to move forward with. Passive heat sinks rely mostly on air convection to dissipate heat, of which will not be of concern in a vacuum environment such as the one on Europa, while thermal tape is used mostly to manage consistent high temperatures in electronics such as motherboards and computer processors.

Component Access

Table 4. The Component Access Pugh Chart is a weighted matrix of functional requirements and modes of access.

	Weight	**Scaffolding with one access plane**	Scaffolding with two access planes	Scaffolding with three access planes	Scaffolding with four access planes	Sliding Door with latch	Swinging Door with latch
Ease of access	4	**2**	2	2	2	4	4
Access Planes	2	**1**	2	3	4	1	1
Structural Integrity	4	**4**	3	2	1	-1	-1
Thermal Properties	4	**4**	3	2	1	2	2
Cost	2	**1**	2	3	4	-1	-1
Total		**44**	40	36	32	19	19

Stakeholder requirement 5 specifies the package must provide "easy access" to the GC system. The stakeholder anticipates the need to test individual components of the GC after it is placed inside the packaging. He specified the package must include a mode of access which can be used with a maximum of 1 tool in less than 2 minutes.

To address the requirement, we evaluated 6 designs. The first four designs include a rectangular prism composed of an interior scaffolding and exterior panels. The interior scaffolding exists to organize the individual components of the GC. The exterior panels exist to enclose and protect the system. The design was benchmarked off a GC system named "MOMA" launched by the European Space Agency in September 2020.

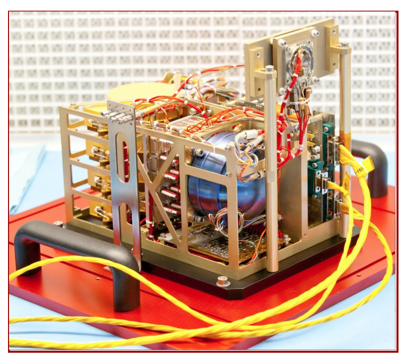


Figure 12. The Gas Chromatograph built for the MS-GC instrument MOMA (Mars Organic Molecule Analyzer) launched on the Rosalind Franklin Rover. A T7075 Aluminum Alloy interior scaffolding organizes the GC system and supports exterior panels.

All six package designs are rectangular prisms as specified by the NASA Europa Lander mission proposal. Designs 1 through 4 are rectangular prisms which differ in the number of exterior panels which can be removed. The fifth design is a rectangular prism which includes a sliding door to provide component access. The sixth design is a rectangular prism which includes a hinged door to provide component access.

The six designs were evaluated in Table 4 against five functional requirements: ease of access (measuring the minutes required to open the package), number of access planes, structural integrity (measuring the potential points of failure), thermal properties (measuring the number of breaks in the seal of the package), and cost minimization. Each design was given a score from -4 to 4 based upon its ability to fulfill the functional requirement. Each functional requirement was given a weight based upon its relationship to the stakeholder's needs. Functional requirements "ease of access", "structural integrity", and "thermal properties" were given the highest weights in the decision matrix because they directly reflect stakeholder requirements 1, 4, and 5.

Design 1 was selected as the component access design for our package. The design is a rectangular prism with an interior scaffolding to organize GC components and one removable exterior access panel. The exterior access panel will be secured to the prism with socket head cap screws and removed using a drill or hex key.

Table 5. The Structural Materials Pugh Chart is a weighted matrix functional requirements and material types.

	Weight	**T7075 aluminum alloy Scaffolding + Gold Plated Panels with Structural Webbing**	Titanium Scaffolding + Gold Plated Panels with Structural Webbing	Stainless Steel Scaffolding + Gold Plated Panels with Structural Webbing
Ease of Manufacturing	2	**4**	-2	3
Strength to Weight Ratio	4	**3**	3	1
Thermal Properties	4	**1**	3	3
Cost	1	**1**	-2	0
Total		**25**	18	22

Stakeholder requirement one specifies the package must protect all internal components from onboard mechanical vibrations and shocks. To fulfill this requirement, the structural material of the package was investigated using the decision matrix above.

To address the requirement, we evaluated three materials. T7075 aluminum alloy was evaluated because of its use on ESA's Rosalind Franklin Rover. Next, Titanium was evaluated because of its excellent strength to weight ratio and high melting point. Finally, stainless steel was evaluated because of its high melting point and use in Space-X's Starship design.

The three materials were evaluated against four functional requirements: ease of manufacturing, strength to weight ratio, thermal properties, and cost minimization.

Table 6. Material Properties of T7075 Aluminum Alloy.

Density	Tensile Strength	Yield Strength	Modulus of Elasticity	Coefficient of Thermal Expansion	Thermal Conductivity	Melting Point	Machinability Percentage	Cost
2.81 g/cc	572 MPa	503 MPa	71.1 GPa	23.4 $\mu m/m - C^{\circ}$	0.0960 $J/g - C^{\circ}$	477-635 C°	70%	$1.80/kg

T7075 Aluminum alloy was selected as the structural material for the package design. 7075 aluminum is an aluminum-zinc alloy with 1%-8% zinc in addition to small amounts of magnesium and small quantities of copper and chromium. This alloy is precipitation hardened to very high strength levels and used in airframe structures and other highly stressed components.. The typical strength in the T6 temper is higher than most steels at $\frac{1}{3}$ of their weight. Although it has high strength, 7075 offers lower corrosion resistance than other aluminum alloys and does not offer the same levels of machinability or weldability. At the same time, 7075 was flight tested on two Mars rovers and offers stress and strain resistance acceptable for the Europa mission.

In addition to T7075 aluminum alloy, gold plated mylar sheets will be used as a structural material. Gold plating provides low emittance as a thermal coating and stability against flaking at high temperature. The material is used regularly on the exterior surfaces of NASA instruments and satellites.

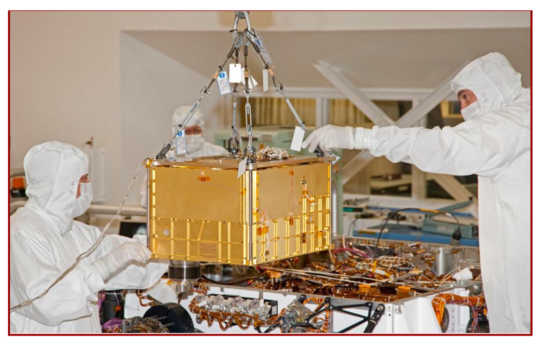


Figure 13. The Sample Analysis at Mars (SAM) suite built for the Mars Curiosity Rover. The instrument was packaged in a rectangular prism with a gold plated exterior. The instrument consisted of a mass spectrometer, gas chromatograph, and tunable laser spectrometer.

Preliminary Design Solution

Figure 14 shows a sketch of our packaging structure with all requirements and specifications taken into account. The outside consists of 2 layers of T7075 Aluminum walls held together by cascading springs (we were thinking of incorporating nonlinear springs as well as multiple springs with different stiffnesses) to address the vibration specification. We then further organize the GC system by separating each subsystem into sections. Each compartment is lined with sorbothane for shock protection, and the compartment that houses the analytical column and preconcentrator (i.e. where the heat generation will take place when samples are collected) will be also lined with the aerogel for thermal insulation, thus allowing us to isolate the heat source from the other sensitive electronics. Additionally, we leave space for the inlet and outlets holes on the left and right of the system, respectively. It is also noteworthy that this is a top down view of the system, and the copper mesh will most likely line the top panel of the package, so it is not shown.

This initial design concept was presented to both Prof. Kurabayashi and Dr. Blase in a stakeholder meeting before the Design Review presentations. They expressed their interest in seeing this design be further explored in detail, and our team planned to progress with 3D models as well as COMSOL simulations in the following weeks to see if this structure is a feasible solution to the task.

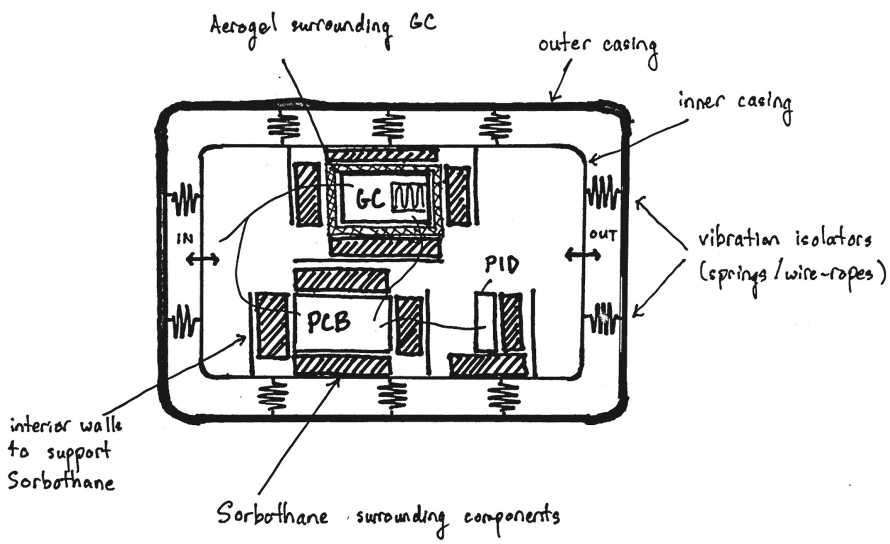


Figure 14. The first integrated design concept that was presented to our sponsors.

Coming out of Concept Exploration and beginning our engineering analysis, our team learned that having springs between an inner and outer casing is not a feasible design choice for several reasons. To begin, the springs would not be able to withstand the amount of shock and vibration experienced during the takeoff and EDL phase of the lander mission. The springs will have to be small enough to fit on the MEMS device, which in turn limits the load that the springs can handle. There would need to be more small springs attached to the packaging device than the packaging device has room for (we calculated a need for nearly 500 individual springs on each plane). Additionally, our team developed worries that having so many different small springs may leave more room for individual resonant frequencies to be reached. This would overwhelm the already weak spring system and potentially lead to failure of the packaging structure. Due to the amount of small springs that would be needed and the inability for them to handle the necessary shock and vibration, it was decided to remove the outer casing and springs from the packaging structure and focus more on the internal components. Henceforth, we hypothesized that the Sorbothane by itself would be able to solve for both our mechanical shocks and vibration specifications. We have validated these capabilities as well as the thermal properties of Aerogel here in solution development.

SOLUTION DEVELOPMENT AND VERIFICATION

Final Design Solution

After developing several iterations of our design in 3-D, our team has come to a final design solution for modeling the packaging structure. The 3-D model was produced using SolidWorks. Screenshots of the final CAD are shown below in Figure 15:

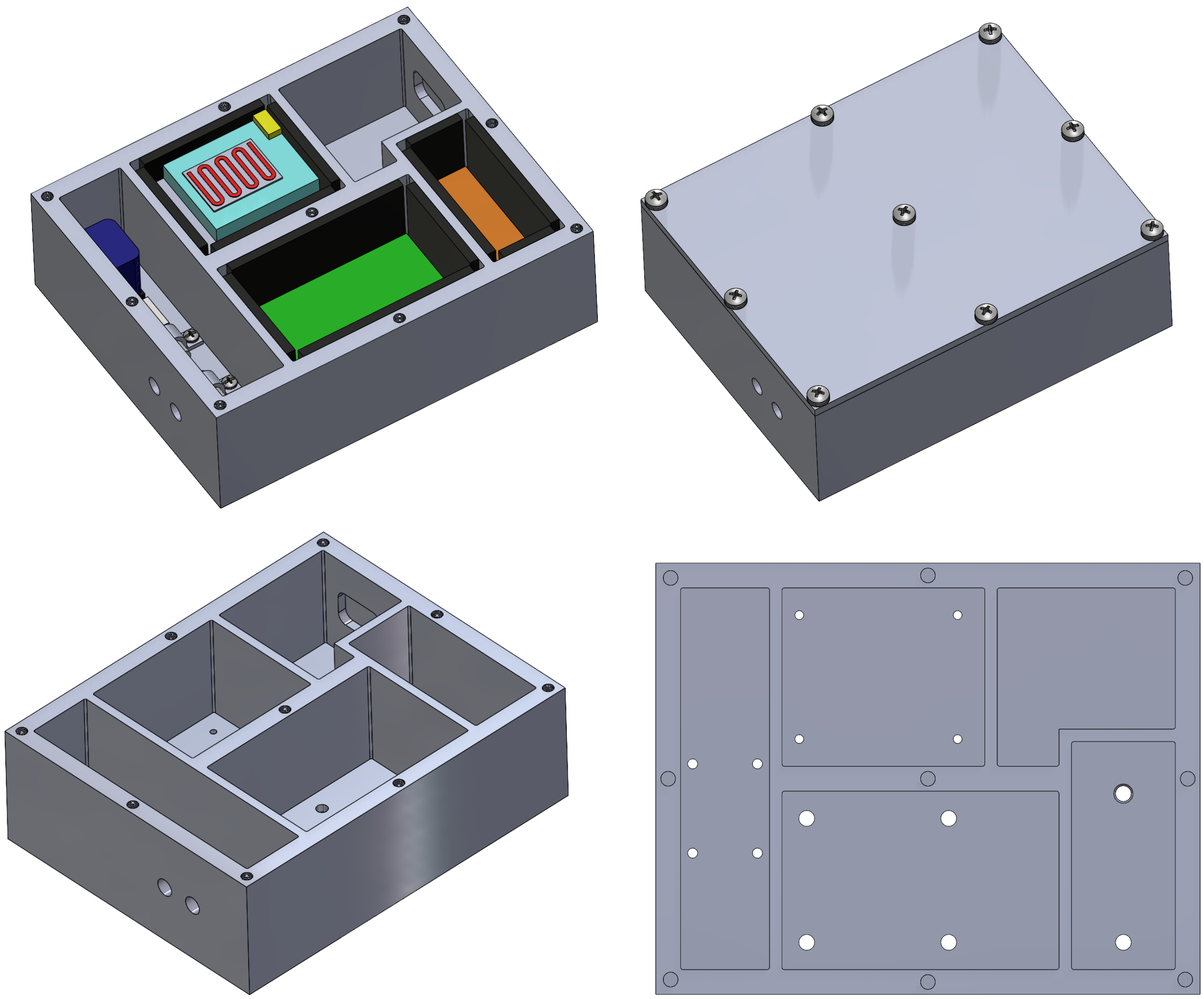


Figure 15. Screenshots of packaging structure with and without major MEMS GC components and lid.

Table 7. Properties of the packaging structure

Part	Dimensions (X x Y x Z, mm)	Weight (kg)
Inner Structure	220 x 174 x 70	2.8
With Lid	220 x 174 x 75	3.33
With Components	220 x 174 x 70	3.1
With Lid and Components	220 x 174 x 75	3.63

The packaging structure is made up of 7075 Aluminum alloy. There are several compartments in the box structure meant to house the various components needed for the functioning of the MEMS GC system. Figure 16 shows a birds eye view of the box structure and its major components:

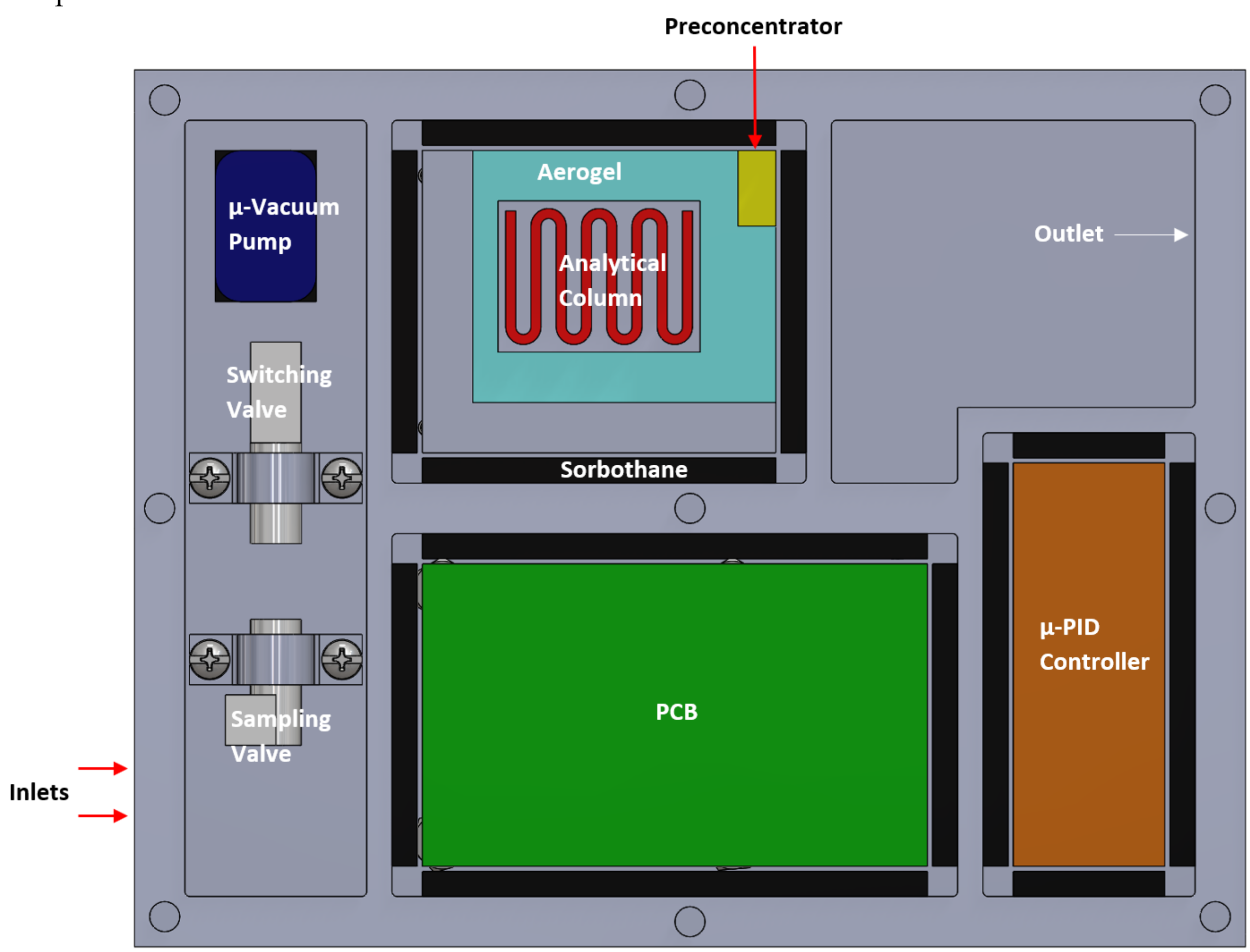


Figure 16. Bird's eye view of MEMS GC system in the packing

Each of the major components are developed and named by the stakeholders of this project. For each individual compartment that houses a major component, an elastomer called sorbothane will line the walls to absorb the external shock and vibration. The sorbothane will be secured to the walls and floor underneath each major component by Pressure Sensitive Adhesive (PSA) developed specifically for the application of sorbothane.

To regulate the internal temperature range of the packaging structure, a synthetic, ultralight material called Aerogel will be placed between the preconcentrator and the analytical column. The heat generated by the preconcentrator will be absorbed by the Aerogel and prevent overheating of any other components in the system. A close up of the preconcentrator-analytical column arrangement is provided in Figure 17 below:

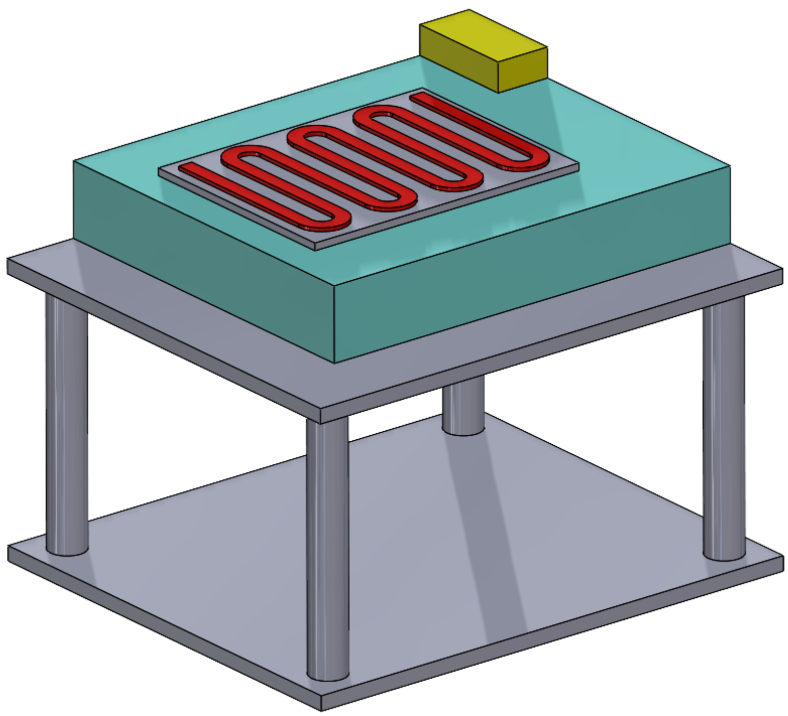


Figure 17. Subassembly of the Aerogel, analytical column, and preconcentrator. The bottom surface will support sensitive electronics that control the temperature fluctuations of the preconcentrator and analytical column, necessitating the use of a thermal barrier under the top components.

The PCB, PID controller, and Analytical column subassembly will be fastened to the packaging structure using Thread-Locking Hex Drive Flat Head Screws secured by High-Strength Steel Thin Hex Nuts. Two different views of the CAD displaying the nut and screw system is provided in Figure 18 below:

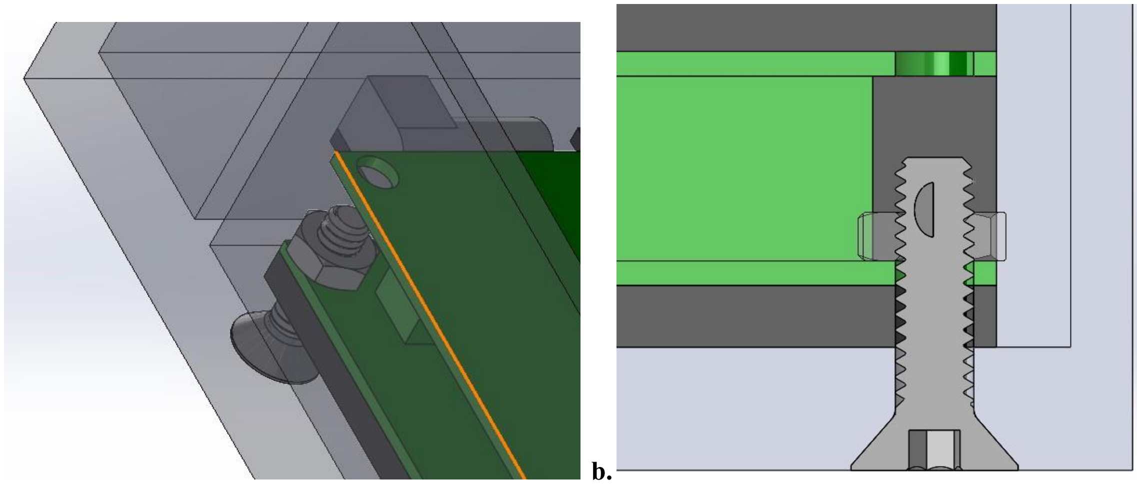
a.  b.

Figure 18 a. Orthogonal View and **b.** Section view of our strategy for fasteners.

The valves in the inlet compartment will also sit atop a thin layer of sorbothane and secured with brackets, which are in turn attached to the package via a screw in a threaded hole. Using m4 Pan Head Screws, the valves will be strapped to the floor of the packaging structure. This is shown in Figure 19 below:

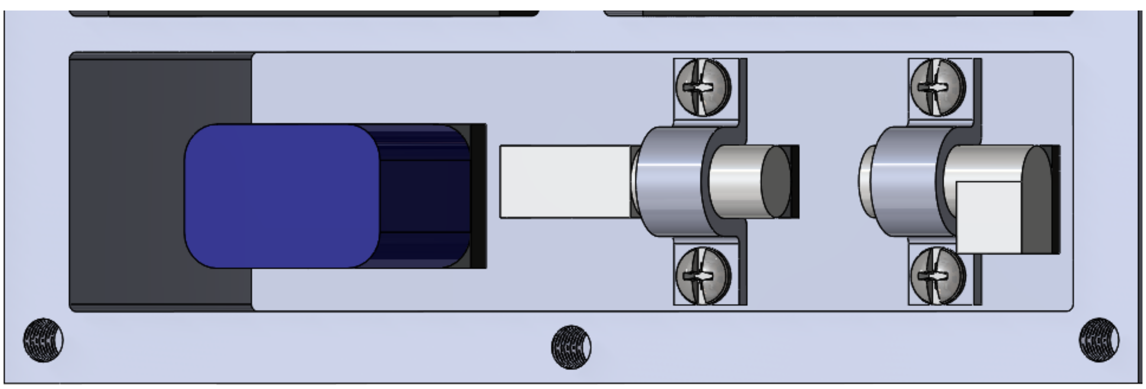


Figure 19. Close-Up of inlet compartment showing fastening strategy for the sampling and switching valves.

There are two inlet holes placed in the compartment housing the valves. One inlet hole will take in the sample material from Europa and the other will transport the carrier gas that will advance the sample through the system once it has been vaporized. There are gaps between the sorbothane-lined walls in each compartment to allow for the passage of any wiring or tubes (we were not asked to include these minor components in our model of the packaging structure). The outlet interface will be in an empty compartment to allow the separated sample to move to the Mass Spectrometer for analysis. A lid made up of the same 7075 Aluminum material as the box structure will seal the packaging structure. The lid is screwed into the box structure using M6 Vibration-resistant Pan Head screws, which will allow for easy removal using a single tool as well as resistance to coming loose from vibrations incurred during spaceflight. Figure 20 below displays the setup of the lid:

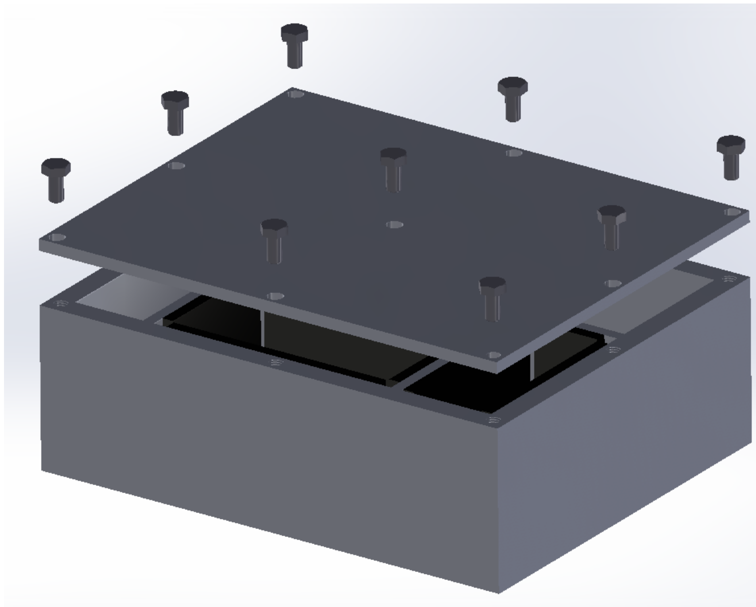


Figure 20. Exploded view of the lid and fasteners.

The most stark difference between our team's initial design and the final design solution is the elimination of an outer structure. Originally, the packaging structure was going to consist of our current box structure design with another outer structure connected to the inner box structure via springs. This design was meant to absorb shock and vibration first in the outer structure while providing minimal shock and vibration to the inner box structure that houses the major components of the MEMS GC structure. Coming out of Concept Exploration and beginning our engineering analysis, our team learned that having springs between an inner and outer casing is not a feasible design choice for several reasons. To begin, the springs would not be able to withstand the amount of shock and vibration experienced during the takeoff and EDL phase of the lander mission. The springs will have to be small enough to fit on the MEMS device, which in turn limits the load that the springs can handle. There would need to be more small springs attached to the packaging device than the packaging device has room for (we calculated a need for nearly 500 individual springs on each plane). Additionally, our team developed worries that having so many different small springs may leave more room for individual resonant frequencies to be reached. This would overwhelm the already weak spring system and potentially lead to failure of the packaging structure. Due to the amount of small springs that would be needed and the inability for them to handle the necessary shock and vibration, it was decided to remove the outer casing and springs from the packaging structure and focus more on the internal components. Henceforth, we hypothesized that the sorbothane by itself would be able to solve for both our mechanical shocks and vibration specifications. We validated these capabilities as well as the thermal properties of Aerogel in the solution verification phase.

Shock and Vibration Analysis in ANSYS

We simulated our shock and vibration scenarios in ANSYS Discovery to get an idea of how well our design meets requirement 1. We ran 3 simulations to test the response to these forces of both the structure as a whole and a section cutout meant to represent the response near where the fasteners would experience the greatest stress and strain (as well as estimating the structure's response to forces in the X- and Y-axis).

The results for these 3 simulations showed that our packaging structure meets the relevant specifications under the conditions we specified. The first simulation, shown in Figure 21, was a measure of the deformation of the Aluminum T7075 packaging in response to a force of 175 kN in the +z direction. We defined failure as a deformation of more than 1 mm since that was the point we, along with our sponsors, agreed that the sensitive electronics in the MEMS system would start to experience critical damage; the PCB board and analytical column, specifically, contain sensitive materials that are not meant to bend in any significant way. This test proved successful as the maximum deformation experienced was 0.64 mm. With the safety factor of 1.4 included, the packaging was still able to retain its structural integrity, deforming 0.81 mm at its most vulnerable point.

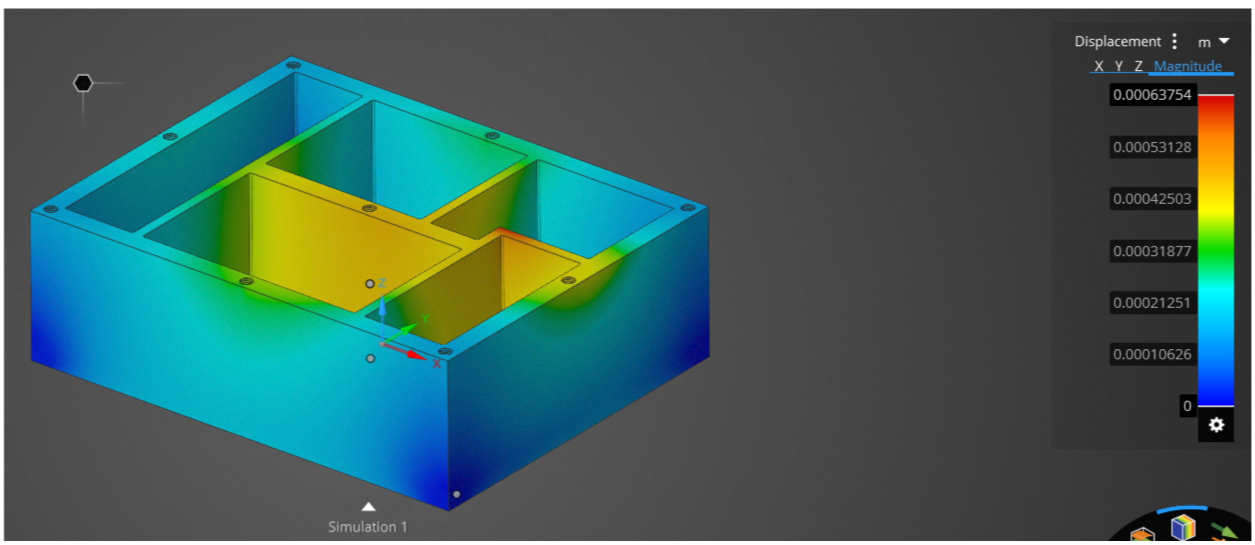


Figure 21. Simulation results for Z shock.

The second simulation, shown in Figure 22, was meant to measure the deformation of a side wall near where an electronic component, such as the PCB board, was secured with fasteners under a force in either the x or y directions. The magnitude of the force was determined by finding the fraction of the wall cutout area divided by the total side wall area multiplied by 222 kN: $\frac{area\ of\ wall\ cutout}{total\ area\ of\ side\ wall} * 222\ kN$. Failure here was defined as a deformation of more than 2 mm since there is a 1 mm gap between the component and the Sorbothane lining the walls of each compartment. Again. We were able to validate our design as this test resulted in a maximum deformation of 1.26 mm.

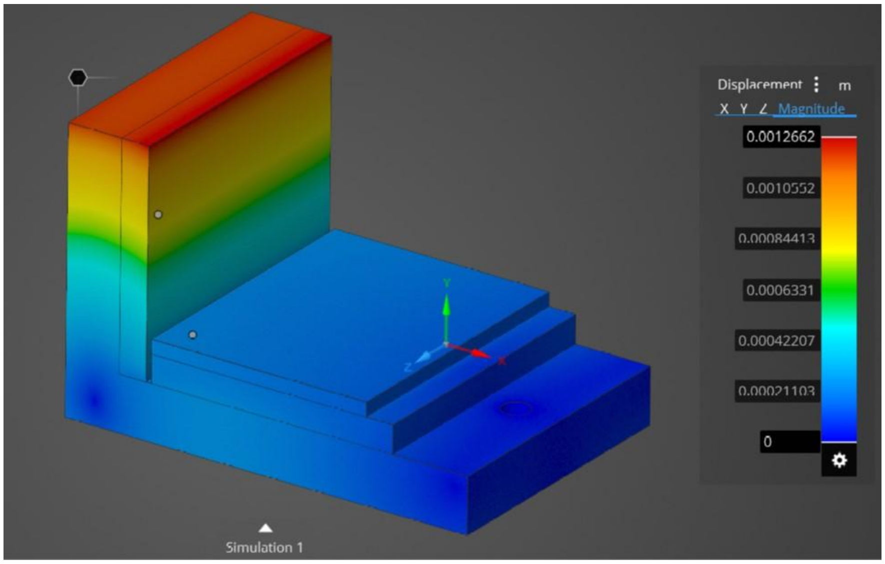


Figure 22. Section simulation results for X/Y shock.

The 3rd simulation was a vibration test with the weight of the GC system and the lid approximated, shown below in Figure 23. Our goal with this test was to estimate the resonant frequency of the packaging structure under a 3G load, and the results from Discovery showed the first resonant frequency to be 1791.8 Hz which is good news for us since NASA standards recommend testing at a frequency of 5-200 Hz. This would indicate to us that our design would not be in excessive danger of damage from the vibrations experienced in spaceflight.

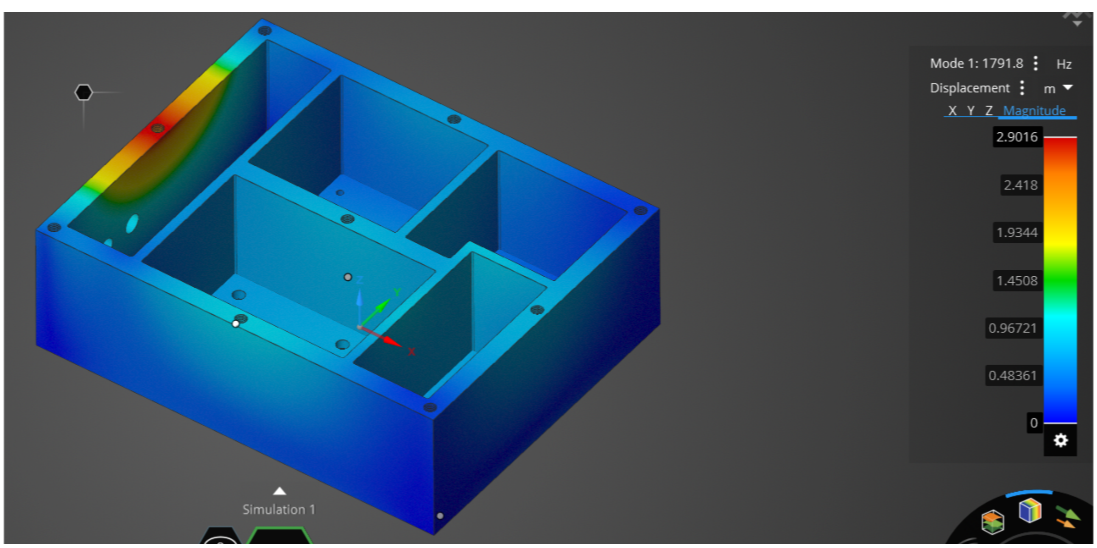


Figure 23. Simulation results for vibration.

Thermal Analysis in COMSOL

A thermal analysis was performed to evaluate the final design with regards to Stakeholder Requirement & Specification 2: Decrease the internal temperature of the instrument from $330^{\circ}C$ to $25^{\circ}C$ every 24 hours.

We began the analysis by identifying the thermal events which create waste heat within the packaging. The thermal events were obtained from the paper: *Experimental Coupling of a MEMS Gas Chromatograph and Mass Spectrometer for Organic Analysis in Space Environments*, written by Ryan C. Blase and Katsuo Kurabayashi. The thermal events are displayed in Table 8. and proceed as follows: “The preconcentrator was rapidly heated with a high-voltage pulse for a duration of 0.8 s to approximately $250-300^{\circ}C$ and then held at that temperature with a second, lower-voltage pulse for 8 s. The initial high-voltage pulse of the preconcentrator defines the injection start time of the analytes onto the analytical column. The column temperature profile was isothermal at $17.5^{\circ}C$for the first 75 s after injection and then heated at a rate of approximately $14.7^{\circ}C\ min^{-1}$ from 75 to 130 s and $10.3^{\circ}Cmin^{-1}$ from 130 to 300 “ [1].

Table 8. Summary of the temperature events experienced by the preconcentrator and analytical column

Time	Component	Temperature	Event
(0, 0.8)	Preconcentrator	300°C	Heated with a high voltage pulse
(0.8, 8)	Preconcentrator	300°C	Held at constant temperature with a lower voltage pulse
(0, 75)	Analytical Column	17.5°C	Isothermal Profile
(75, 130)	Analytical Column	14.7°C / min	Heat Rate
(130, 300)	Analytical Column	10.3°C / min	Heat Rate

A thermal simulation was performed using COMSOL Multiphysics Software to evaluate the volume of Aerogel needed to minimize conductive heat transfer below the analytical column and preconcentrator. We began with a layer of Aerogel underneath both of the components in question with dimensions 6 x 5 x 1 cm. We next performed a transient temperature distribution simulation for the first 300 secs of thermal activity.

The transient temperature distribution simulation required three assumptions with regards to heat transfer methods, material properties, and initial conditions. First, we assumed convective heat transfer to be negligible. The assumption was made because Europa lacks a robust atmosphere, meaning heat is mainly dissipated through conductive and radiative heat transfer. Second, we assumed the material properties listed in Table 9. The material properties were gathered from the websites of part suppliers listed in the BOM [B] and the COMSOL Material's Library. Third, we assumed the ambient temperature on Europa to be 140K and that each component had an initial temperature of 140K.

Table 9. Summary of material properties for components studied in thermal testing. The material properties for aerogel were obtained from the product information of Pyrogel XTE, manufactured by Aspen Aerogel Inc. [29]. All other material properties were obtained from the COMSOL Multiphysics material properties library.

Component	Material	Density $(\frac{kg}{m^3})$	Surface Emissivity(1)	Thermal Conductivity $(\frac{W}{m \cdot K})$	Heat Capacity $(\frac{J}{kg \cdot K})$
Thermal Shield	Aerogel	200.24	0.9	0.022	2300
Preconcentrator & Analytical Column	Silicon	2329	0.68	131	700
Analytical Column	Glass	2210	0.82	1.4	730
Stand	Acrylic Plastic	1190	0.94	0.18	1470

The transient temperature distribution simulation is displayed in Figure 24. The simulation demonstrates that the aerogel thermal shield was successful in stopping conductive heat transfer below the preconcentrator and analytical column. The top surface of the stand remained at 140 K for the entire duration of the 300 sec test.

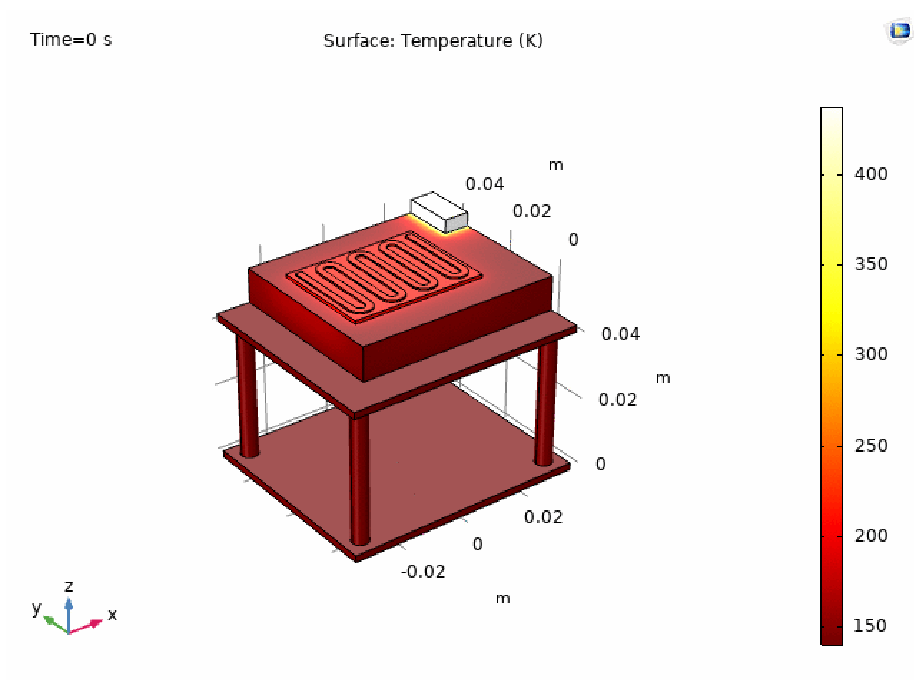


Figure 24. A COMSOL multiphysics animation of the temperature distribution during the first 300 secs of use. The bottom boundary of the Aerogel remained below 298 K for the duration of the simulation, thereby fulfilling Requirement and Specification 2.

Figures 25 and 26 present the isothermal profiles within the aerogel for the times at which the preconcentrator and analytical column were at their maximum temperatures. The preconcentrator reached a maximum temperature of 573.15 K at 8 sec and the analytical column reached a maximum temperature of 588.96 K at 300 sec.

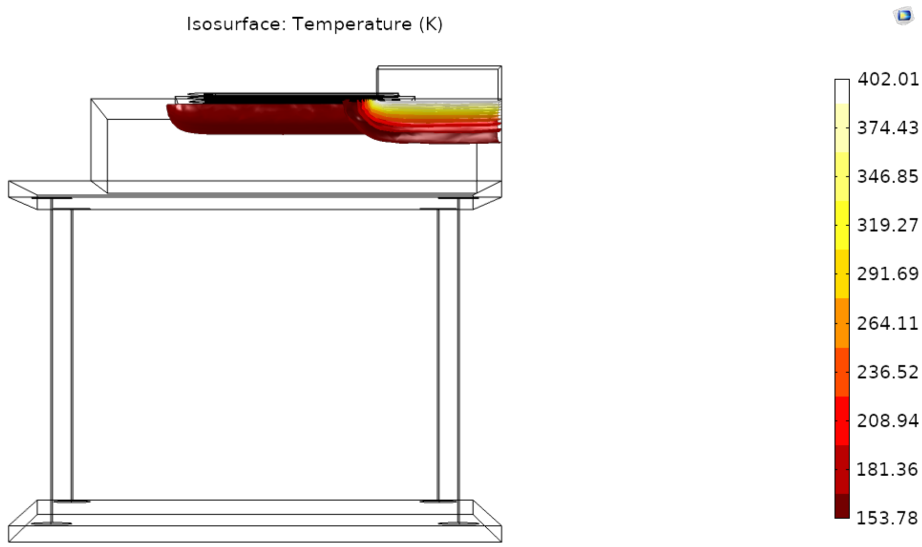


Figure 25. The aerogel cross sectional isothermal contours for when the preconcentrator reaches its maximum temperature at 8 seconds.

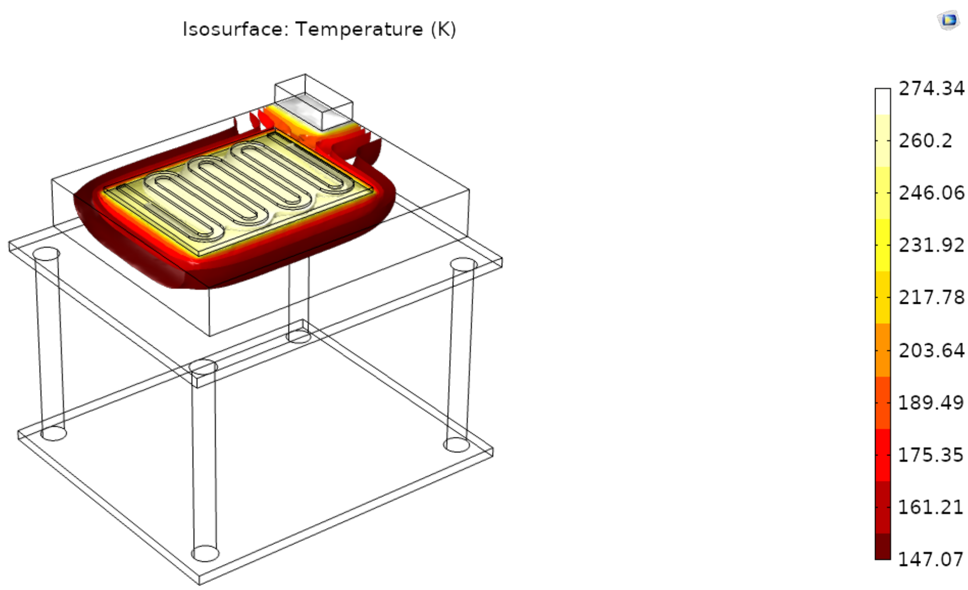


Figure 26. The aerogel isothermal contours for when the analytical column reaches its maximum temperature at 300 seconds.

Based on the data from Figures 24, 25, and 26, our team has concluded that an aerogel of dimensions (6cm x 5cm x 1cm) and material properties of the Pyrogel XTE will be sufficient to regulate the internal temperature of the packaging structure below $25^{\circ}C$ every 24 hrs, and ensure the heat from the preconcentrator and analytical column does not affect the functionality of the other design components.

Assumptions and Risks

In order to perform these initial simulations, we had to make a few assumptions and approximations about our design and simulation setup.

As mentioned before, we were using deformation as a benchmark for electronic failure and estimating the mass of the electronic components for the vibrations test. We also had to approximate the dimensions of the components included in our model since our sponsors do not have existing 3D models of the system as it currently stands. For the shock test, we assumed that the force in the +z direction would not damage the screws, leading to us only testing horizontal force in the simulation of the section cutout. Another important note with this analysis is that we did not consider the effects of fatigue, crack failure, or any other mode of structural damage that the package may experience in spaceflight. Additionally, we did not consider the mounting strategy for the packaging structure to the rest of the Lander. This would have an effect on how our design will experience shock and vibrations in actual spaceflight, since the stresses will largely concentrate around the fasteners involved with securing the packaging to Lander. Also not considered was some of the smaller electronics involved in the complicated MEMS GC system, such as wires and capillaries. All of these assumptions and estimations were discussed with our sponsors prior to running our simulations and given approval for moving on with our engineering analysis.

For the thermal simulation, we made three assumptions regarding heat transfer methods, material properties, and initial conditions. For each assumption made, we believed it was important to consider the risks the assumption may have introduced to the simulation. First, we assumed there to be no convective heat transfer on Europa. In reality, Europa has a tenuous atmosphere composed of primarily of oxygen, with a surface pressure of $0.1\ \mu Pa$. Second, we assumed the material properties of the aerogel to be equal to Aspen Aerogel Inc's. Pyrogel Xte. Aerogel thermal properties can range significantly based on its intended application and manufacturer. If the stakeholder decides to source the aerogel from a different manufacturer the thermal simulations must be re-done. Third, we assumed the ambient surface temperature of Europa to be 140 K and the initial temperature of each component within the simulation to be 140 K. In reality, the surface temperature of Europa can range from 110 K at the equator to 50 K at the poles. 140 K was chosen as a safety factor.

While our team is satisfied with the results of the shock, vibration, and thermal simulations, we recommend updating the simulations when the testing specifications of the Europa mission are determined by NASA and the material suppliers of the packaging design are selected.

DISCUSSION AND RECOMMENDATIONS

Design Shortfalls

While our team is confident in our final design solution, there are still some shortcomings that come with the design. One of these shortcomings is the manufacturability of the packaging structure. To manufacture the box structure and successfully implement the housing compartments, a large subtractive manufacturing process must be performed. Each of the housing compartments must be machined into a block of aluminum that is the dimensions of the entire packaging structure. Additionally, the fasteners will be difficult to install due to the small size of the MEMS GC device system and the crowdedness within the packaging structure.

Another pitfall encountered by this design is that the dimensions of each of the housing compartments are not directly related to the size of the major components of the system. This is due to the fact that the component dimensions were not provided to the team, so each of the housing compartments were not developed to exactly fit the major components of the system. In terms of the connections between components, our final design solution slo does not model the wires, tubes and capillaries running through the structure, as this was not tasked for this project. There are gaps in between the sorbothane-lined walls of each compartment for our stakeholders to potentially use for connection between components, if they choose to do so. Additionally, there is no current connection strategy for attachment of the packaging structure to the rest of the Europa lander; nor is there a design verification for the adhesives being used in the structure. Despite all of the shortcomings we have brought forth, our design has still been approved by our stakeholders and has met their current needs.

Ongoing Difficulties

In terms of the issues that the overall project still has, there are several ongoing difficulties. To start, the overall project is actually still in the proposal phase as many of the other aspects of the mission have not yet been defined. Additionally, the micro GC system that has been discussed extensively throughout this report is not finished. The major components have not been finalized and design changes are still ongoing.

Throughout this project we have used the Mars 2020 explorer as a benchmark, but this poses another ongoing challenge as the accuracy and applicability of this trip is not yet determined. This project also has been disturbed by the COVID-19 pandemic, which has disrupted many of the plans our team had in place. Teammates got sick during the semester and our team could not meet with our professor in person. Many of the struggles brought about by the pandemic ultimately led to the decision to not build a physical prototype and only build 3-D models that can be tested through computer simulations.

Recommendations

As a result of the ME 450 course project, we have created a design solution that meets all of our stakeholders' primary goals. These include housing the GC components, withstanding expected shock and vibrations of the Europa Lander mission, and managing thermal regulation of the internal components. Due to the current status of the GC device, our team was not tasked with prototyping the full package. In lieu of this, we ran computer simulations to verify the success of a potential physical design. If this design were to ever be actually fabricated, there are certain design changes, assumptions, and next steps that our team finds important.

There are a few critical design changes that would alter the geometry of the package. First, each compartment inside the package needs to be specifically sized to the GC component it holds. This is important for the Sorbothane to perform appropriately. Since the GC components were being replaced over the course of the semester, it is critical that these compartment dimensions are checked against the latest component sizes. In addition to this, we decided early in the project in agreement with our stakeholders that wiring would be out of scope of the design. For this reason, there is currently limited space to run wires between each of the compartments. We recommend either using the corners in between each of the Sorbothane pieces to run wires, or shortening the lengths of the Sorbothane pieces and adding slots to the compartment walls. Finally, the thickness of each of the design components is subject to change. Although we have demonstrated that the thicknesses of the Sorbothane and interior walls are successful in our current final design, the stakeholder may want to change these design choices as they wish.

Another important aspect of this design are the elements that were neglected for the purpose of testing. These include any and all fragile capillary tubes holding the gas, electronic components of the PCB's, and adhesives. In the ANSYS and COMSOL simulations, these elements were considered out of scope. For physical prototyping, however, they could be of greater importance. We recommend first taking a closer look at the electronic soldering, as well as the adhesive options for Sorbothane. For the Sorbothane to stay stationary, it would have to be attached to the interior walls of the compartments. Leaving the elastomer loose could potentially undermine its shock absorption capabilities. Since we did not test the effectiveness of Sorbothane adhesives, this would be an important place to investigate. The company that manufactures Sorbothane provides recommendations on their website for possible adhesives.

Finally, our team recognizes that the simulations run for this project relied on several assumptions and did not model every piece of the GC system. Knowing that a physical prototype is most likely of ultimate interest for the stakeholder, we recommend following several next steps, after the aforementioned redesign changes. These steps include proper vibration testing using the provided test instruments at SWRI, performing a classic drop test for mechanical shock, and performing physical tests to verify the effectiveness of Aerogel. With these next steps, we are confident that the physical solution would solve all of the stakeholder needs.

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And, finally, thank you to the University of Michigan Mechanical Engineering Department for making this project possible.

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APPENDIX

[A] Concept Generation Team 33

Concept Generation

Sponsor Update: Next Friday, 2/19
Deliverable 1: Mind Map
Deliverable 2: Morphological Chart + Heuristic Cards

- Protect all internal components from onboard mechanical vibrations and shocks
    - Outer casing
        - Passive Isolators
            - [3] The most used family is the family of passive isolators which uses specific properties of non-linear materials to isolate for high frequency excitation with a sufficient stiffness at low frequencies to sustain launcher typical dynamic loads.
        - Active Isolators
            - [3] active isolators which impose an active response to reduce shock excitation but which is not widely used in space industry due to lack of efficiency and technology maturity
        - Small Dampers
            - [3] A damper is defined as a device that removes continuously energy from a moving system to control its response. The damper material has resilient properties allowing him absorbing energy when it is deformed elastically
        - Shock Absorber
            - [3] A shock absorber is defined as a device that absorbs a maximum amount of kinetic energy, and brings a moving mass to a stop with minimal force. In the space industry, the stop can be generated by a crushable material like honeycomb. Honeycomb crush absorber is an efficient solution for attenuation shock due to impact against the end stop of a highly preloaded system.
        - Dampening materials
        - Foam
    - Inner components (holding them in place)
        - Dampers
            - Springs
            - Rubber
            - Dampeners
            - Foam
    - Vacuum seal
    - Packing peanuts
        - could squish or become displaced

- Air bags
    - could pop
- Liquid metal
- Spring shock absorbers
- Pistons
    - Valid shock absorbers, but they struggle with high amplitude vibrations
- Zero gravity box
- Surround the box in viscous liquid / gel
- Gyroscope
- Beans (like bean bags)
    - again could become displaced
- Bubble wrap
    - would surely pop
- Suspension system with air
- Tennis racket shock absorber
- Suspended by the corners with ropes/bungee cords
    - could be hard to calibrate precisely
- Stoppers

- Allow for gas flow in and out of packaging
    - Holes for tubing
        - Rubber ring to seal around tube
    - Need connection blueprint for MS

- Prevent against interference on device
    - **Copper mesh**
    - cotton /linen fabric in solution
    - Lead mesh
    - brass mesh
    - Nickel mesh
    - Steel mesh
    - Tin mesh

- Regulated internal temperature
- NASA Technology Roadmap Thermal Management: https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_14_thermal_management_final.pdf
    - PS5 cooling system
    - Thermal glue
    - **Thermal conductive tape**
        - **Extra protection of electronics**
        - **Transfer heat from source to sink**
    - **Active vs Passive heat sink**
        - Passive does not rely on airflow

- **Lining of inner compartment can be heat sink**
- **Copper heat sink**
- Aluminum heat sink
- **Custom designed**
  - Extruded
  - Bonded
  - CNC machined
  - Stamped
  - Forged
  - Skived
- Refrigeration (liquid coolant)

- <u>Easy Access to components</u>
  - Door (swings open with hinges and latch)
  - Door (slides open)
  - Latching mechanism
  - Screws/Dowels
  - Hinge w/ clamp
  - Tupperware type lid
  - Folding flaps
  -

- <u>Materials</u>
  - Titanium - low thermal expansion
  - Inconel Steel
  - Kevlar
    - Incredibly lightweight and strong
  - Aluminum
    - Aluminum alloys are strong and lightweight enough to be functional in space.
      - [1] The lower density of Aluminum-Lithium alloys, coupled with their somewhat increased stiffness, could provide immediate weight savings of 7 to 20%.
      - Aluminum - Lithium alloys and Magnesium - Aluminum - Lithium alloys show increased toughness in cryogenic temperatures.
    - Most used material for flight structures.
  - Polymer Matrix Composites
    - Subject to environmental degradation effects in space.
  - Metal Matrix Composites
  - Carbon-Carbon Composites

  - Careful with:
    - radiation
    - too lightweight can resonate and break
    - temperature changes

Source

[1] https://www.nap.edu/read/2351/chapter/7#45
[2] https://spaceworkshop.fi/assets/presentations/FSW2018_nevalainen.pdf
[3] http://www.vibrationdata.com/tutorials2/ECSS-E-HB-32-25A(14July2015).pdf
[4] https://www.gabrian.com/6-heat-sink-types/

2/14
Concept Dev

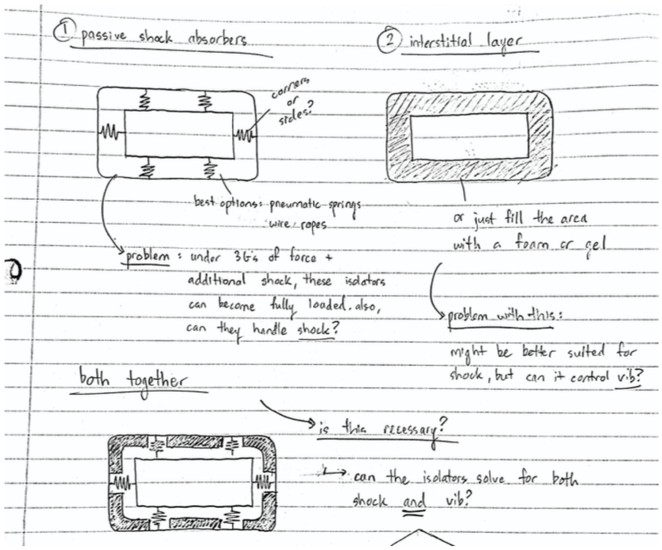
<u>shock & vib</u>

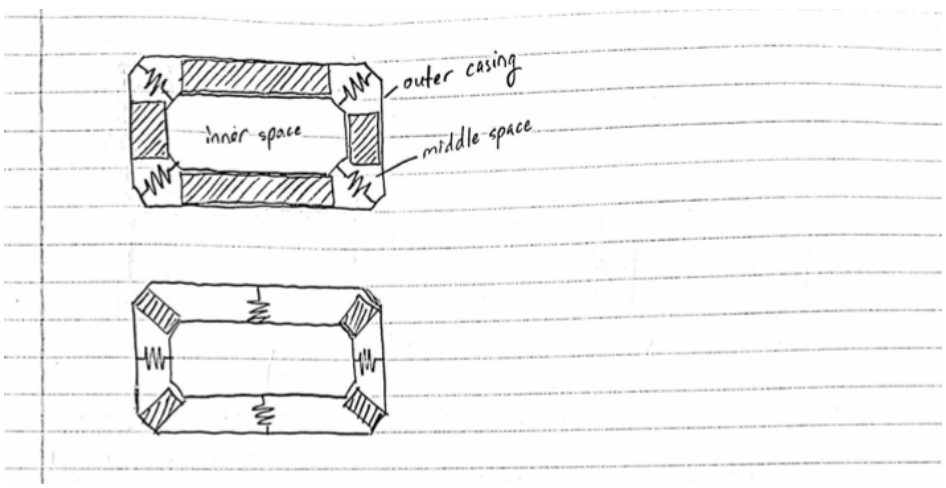
- **outer and inner casings**
    - no real requirements at this phase
    - ideally: cheap, lightweight, **high stiffness** for vibrations, high **yield strength**, high **toughness** for freezing temperatures, high deformation temperature for 330ºC, radiation-resistant
    - needs copper mesh somewhere
    - might need protective shock absorbent layer somewhere
        - **sorbothane** is a really good polymeric solid that absorbs 94.7% of shock
        - **polyethylene** or **polypropylene closed-cell foam** is also good

- **connection between casings**
    1. interstitial material
        - gel, foam, rubber, honeycomb (material?)
            - maybe as a failsafe, but none of these would fully constrain the inner box in the center position. would be "floating" more or less
            - gel, foam, rubber, and crush-absorbers like honeycomb could all also deteriorate over time
    2. shock absorbers
        - springs, struts, telescopes
        - active vibration isolators:
            - slightly higher transmissibility, but expensive and more complex
            - usually used for high-precision electron microscopes and such
        - **passive vibration isolators**
            - 3-part system of isolated mass, spring, and damper
            - excellent for high-freq vibrations, but they resonate at 1-10 Hz
            - different kinds
                - **<u>springs</u>**: simple and the most reliable. pneumatic springs are often used due to low res freq characteristics
                - **<u>wire-rope isolators</u>**
                - <u>elastomers</u>: non-isotropic
                - <u>air tables</u>: not applicable (no air, no level, too big of vibs)
                - <u>negative-stiffness systems</u>: not designed for aircraft applications. more suited for microscopic experiments

- basic theory of vibration isolation
    - #1 - make the natural frequency of the system as far from the forced frequency + noise as possible. The bigger the gap the better the isolation
    - #2 - suppress resonance at the natural frequency. Since w=sqrt(k/m), change k and m as necessary

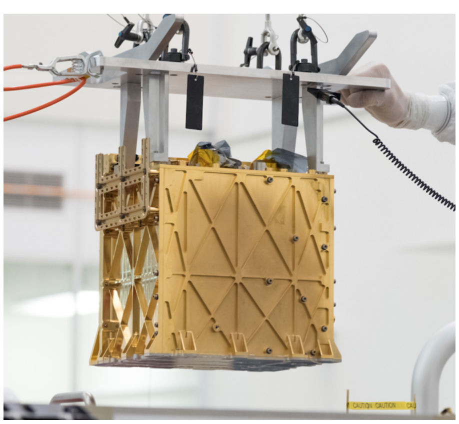
- general shock & vib notes:
    - challenges with vib: 1) insane variability in the vibrations (see chugging and screaming on pg. 104, or pogo vibrations). 2) how do we design against resonance without knowing the natural frequency of our own system? (can be solved with modal impact hammer test) (→ found a solution, see section on "shock fragility as the starting point") 3) absorbers might need to be stronger in one direction than others
    - challenges with shock: 1) passive isolators may not be enough for vibrations and our shock specs. they could bottom out under enough Gs or shock alone. sorbothane/foam layer may work for that. 2) if we go with a soft layer like sorbothane, where would we put it

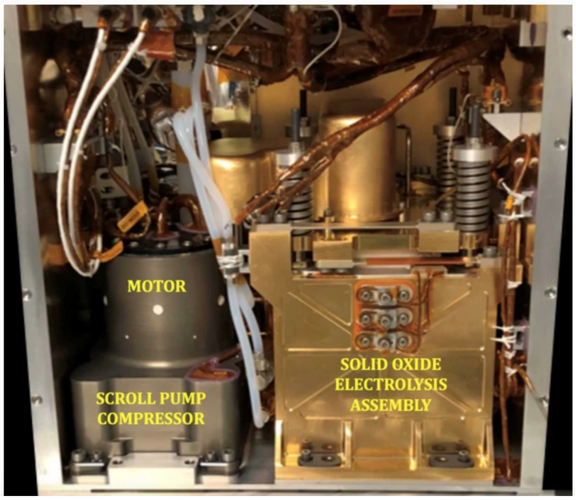


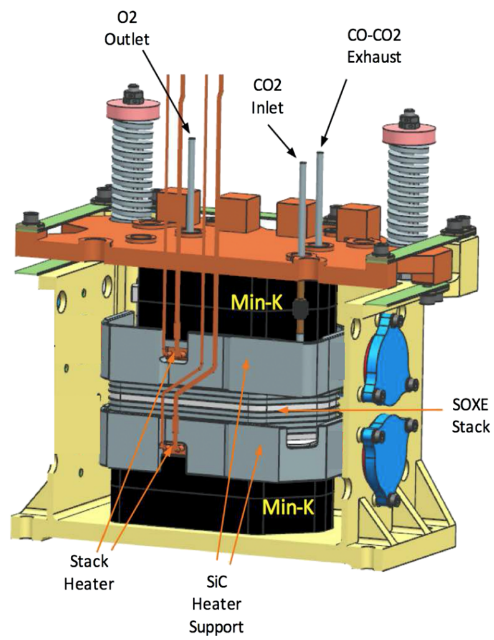


Benchmark Instrument Packaging

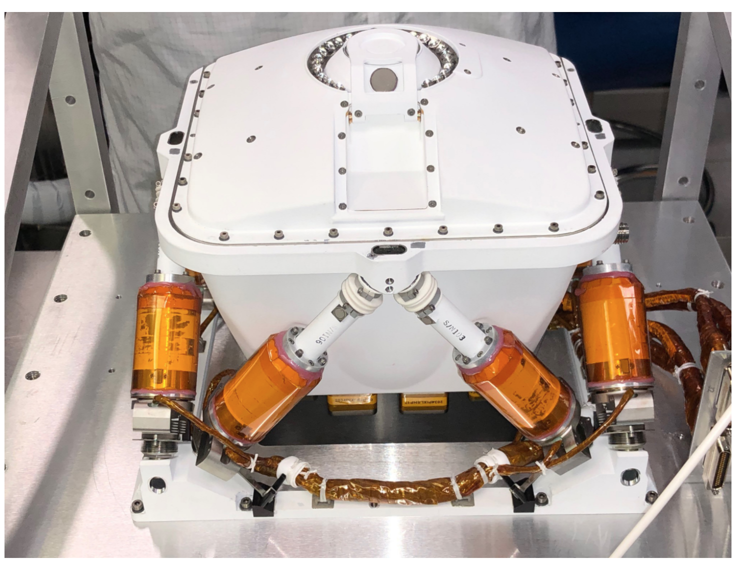
- MARS 2020 Perseverance
  - MOXIE: https://link.springer.com/article/10.1007/s11214-020-00782-8



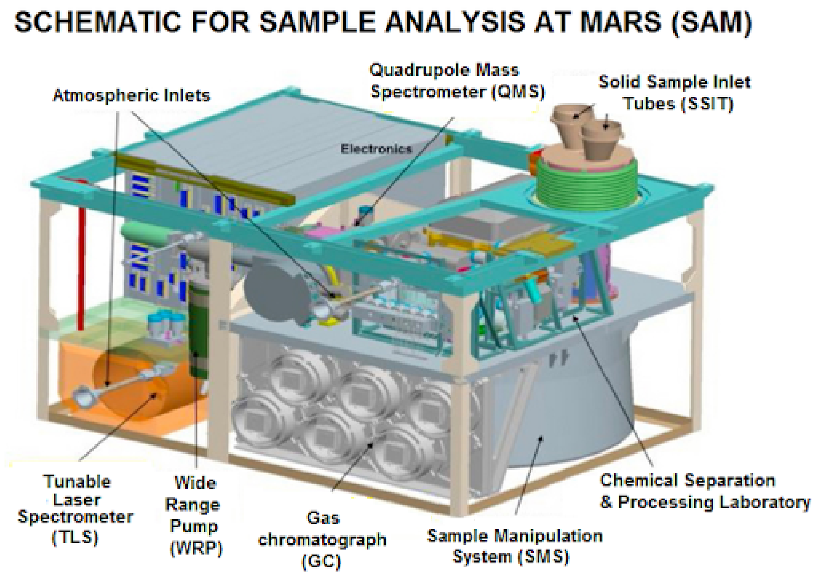


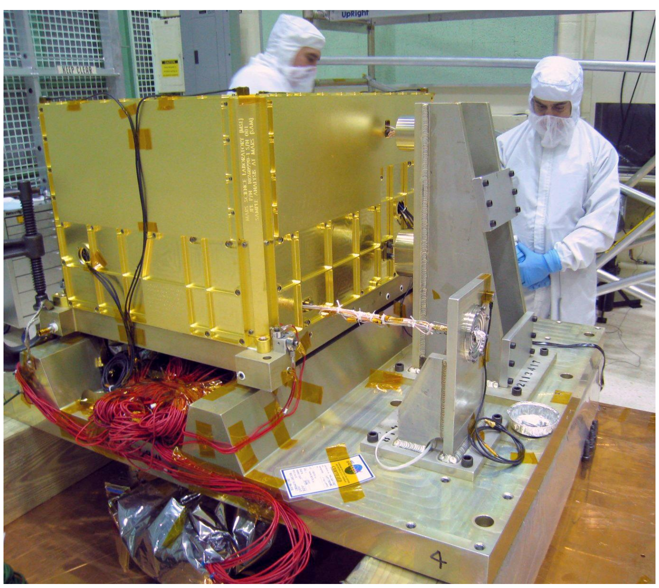


1. Thermal Insulation:
    a. "Thermal insulating layer consisting of a combination of aerogel in unstressed locations and Min-K™ elements (ceramic) that bear the compressive force of the springs."
2. Heat Carriers
    a. "A trade study of heater carrier materials favored Inconel 600 over silicon carbide, which performed well thermally but was prone to cracking, and over pure chromium, which performed well thermally and mechanically but was determined to be sensitive to small impurities that were not consistently characterized by the vendors. Even though Inconel 600 has poor thermal conductivity, its mechanical and thermal robustness made it the favored choice."
3. Mechanical Compression Apparatus: "Four Springs
    - PIXL



- MARS Curiosity Rover
  - SAM (Sample Analysis at Mars) https://link.springer.com/article/10.1007/s11214-012-9879-z





Thermal Management:

"Since SAM is mounted within the interior of the rover, no survival heaters are required. SAM and the other components mounted to the RAMP are largely enclosed within the rover chassis and are shielded from Martian wind and dust. CO2 gas gaps between the outer walls of the rover chassis and SAM provide further insulation from the cold surface environment."

“Several power-dissipating components within SAM require contact with a good thermal sink (i.e. the RAMP). These include the Main Electronics Box, RF Electronics, the two WRP’s, the TLS TEC’s, the HC-trap TEC’s, and the GC injection trap TEC’s. The MEB and HC-trap TEC baseplate are in direct contact with the RAMP, and an RTV thermal interface filler (NuSil CV-2942) is applied during SAM installation to ensure a high quality thermal contact. The RF Electronics is thermally connected to the RAMP via an encapsulated annealed pyrolytic graphite (APG) strap. Heat pipes transport heat from the four remaining components (TLS, WRP1, WRP2, GC TEC’s). On the surface of Mars, these ammonia-charged heat pipes will operate in gravity-assisted (reflux) mode.”

Mechanical Structure
“The SAM structure is fabricated primarily from high strength T7075 aluminum alloy optimized for high strength to weight ratio. Gold plating was applied to the structure, which provides low emittance as a good thermal coating and good stability against flaking at high temperature. Structural webs on the panels were typically 0.035″ thick with non-structural areas as thin as 0.010″; this required high-precision machining with the mill under vacuum to provide stability and maintain flatness.”

Systems engineering processes are mandated by NASA/GSFC in the development and implementation of spaceflight hardware. Reference Documents.

1. NPR 7120.5, the NASA Space Flight Program and Project Management Requirements
2. NPR 7123.1; NASA Systems Engineering Processes and Requirements
3. GSFC-STD-7000; General Environmental Verification Standard (GEVS)
4. GSFC-STD-1000; Rules for the Design, Development, Verification, and Operation of Flight Systems (GOLD Rules)

ESA MOMA Websites
http://www.lisa.u-pec.fr/fr/actualites/264-prototype-moma-gc
http://moma.projet.latmos.ipsl.fr/MOMA-GC_Instrument.html

[B] Bill of Materials Team 33

Part	Part Name	Material	Dimensions	Supplier	Quantity	Price
1	Box Structure	7075 Aluminum	22 x 18 x 10 cm	American Steel and Aluminum LLC	1	$523
2	Lid	7075 Aluminum	22 x 18 x 0.5 cm	American Steel and Aluminum LLC	1	$194
3	Elastomers	Sorbothane with PSA	15.24 x 30.48 x 0.5 cm	Sorbothane Inc.	5	$125
4	Thermal Shield	Aerogel	6 x 5 x 1 cm	Aspen Aerogel Inc.	1	$490
5	E&M Shield	Copper Mesh	22 x 18 cm	McMaster	1	$3
6	PCB, AC, PID screws	Thread-Locking Hex Drive Flat Head Screws	¼”-20	McMaster	10	$10.50
7	Nuts	High-Strength Steel Thin Hex Nuts-Grade 8	¼”-20	McMaster	10	$2
8	Valve Screws	Metric Stainless Steel Pan Head Combination Phillips/Slotted Screws	M4 x 0.7	McMaster	4	$7
9	Lid Screws	Metric Stainless Steel Pan Head Screws with Internal-Tooth Lock Washer	M6 x 1.0	McMaster	9	$8

REQUIRED SUPPLEMENTAL APPENDIX

Engineering Standards

For this project, identifying the engineering standards that we needed to meet was a critical part of developing the final solution. This was an interesting challenge to tackle with our stakeholders, due to the early-phase nature of the project. On one hand, our team wanted to create an aerospace-grade design, suitable for shipment to Europa itself. On the other hand, since the device was still in its prototyping phase and evolving constantly, one could argue that the device, and specifically the packaging of the device, did not require extreme engineering rigor just yet. This became an important point of discussion with our stakeholders in the very beginning of the project. Ultimately, we were able to find a solution that allowed us to use relevant engineering standards to space flight missions, without necessarily having the full, comprehensive system tests that are typically run before missions.

The engineering standards that our team used for this project are mainly documented in the GEVS, the General Environmental Verification Standard, by NASA's Goddard Space Flight Center (GSFC). This 200-page document, last updated in 2018 and signed by a Chief Engineer, a Dir. of Applied Engineering and Technology, a Dir. of Flight Projects, and a Dir. of Safety and Mission Assurance at GSFC, contains extensive literature describing the performance standards that NASA adheres to for its mission instruments. Not only does it outline all of the factors of safety for various failure modes as well as testing and diagnostic methods, but it also includes specific sections for mechanical shock and vibrations on space missions, to which we were glad that our stakeholders pointed us to. We were able to leverage these sections to directly define our engineering specifications. This document helped us to define the factors of safety, as well as sufficient performance metrics for onboard instruments. In addition to the GEVS, we also used test flight data from the Mars 2020 and Mars 2013 rovers to help set standard benchmarks for our solution. Between the two of these sources, we were able to set forth relevant, and achievable engineering standards for the project.

Engineering Inclusivity

In the engineering industry, many of the useful inventions developed across the world are skewed in terms of who stands to benefit from this new technology as well as who stands at a disadvantage. The important questions raised from this issue are: What is the social impact of the technical decisions made by engineers? Who stands to benefit from their technology? Who has been overlooked or intentionally excluded by the design decisions made? To help think systematically through these issues, two important concepts are used: social identities and social power.

Social identities are our "memberships" in socially constructed groups (Deaux 2001; Wetherell and Mohanty 2010; Oyserman, Elmore & Smith 2011). Examples of social identities include categories such as race, gender expression, religious affiliation, or socioeconomic status. Our social identities are inseparable from our roles as engineers because they inform the point-of-view each of us brings to our design projects and the ways we interact with our teammates, our users, and other stakeholders. Understanding how our own identities may be influencing our work is the first step toward more inclusive interactions and decisions.

Social power can be defined as the ability to influence an outcome (Aye, 2017). Power is inherent in all design projects as the final result is the solution to a problem. Engineering technology always has an effect on the lives of users and other stakeholders. These effects can have intentional or unintentional consequences. Being aware of the different expressions of power, both explicit and subtle, can provide inclusivity in the engineering world.

In terms of the development of our final design for the packaging structure of a planetary exploration organic compound analyzer, it has been concluded that this project successfully contributes to engineering inclusivity. The best way to describe why this is so is to look at the stakeholders—both visible and invisible. The stakeholders directly affected are Professor Kurabayashi, Dr. Blase of the Southwest Research Institute, and Dr. Venkatasubramanian of the University of Michigan. The different social identities and powers that each of these stakeholders has provides diversity and inclusion amongst the Europa lander project needs assessment. Furthermore, larger, more invisible stakeholders are companies like NASA, who have a huge stake in the impacts that life on an interplanetary basis would provide.

In fact, this design for a packaging structure may have consequences that impact the human race as we know it. Discovering life on another planet would open up possibilities of humans living on another planet. This could provide societies with the opportunity to find a better life for themselves on another planet. While this concept is far reaching, and much more needs to be done to get humans off Earth after finding life on other planets, it is still the main goal of this project. The design of this packaging structure ensures that the MEMS GC system stays safe during exploration and can analyze the surface of Europa for potential signs of life.

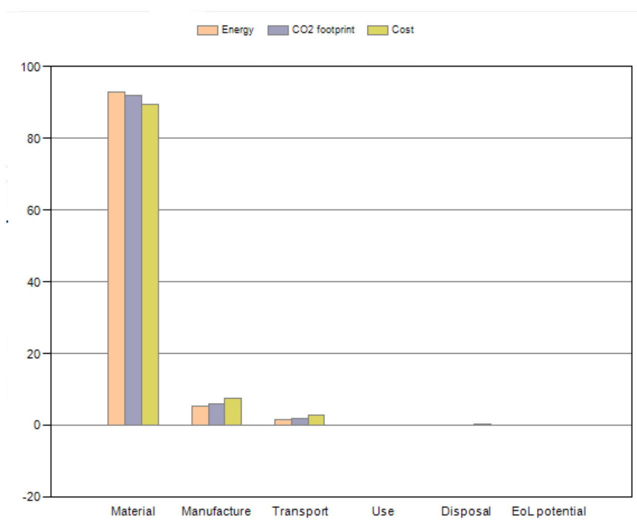
With this comes a potential unexpected consequence that would leave poor societies in worse condition if interplanetary living becomes normal. Interplanetary living would likely be expensive and only feasible to the rich, while Earth may begin to be seen as an inferior location to live while climate change continues to threaten the existence of human life on Earth. This would develop an even larger social gap between communities.

Environmental Context Assessment

A technology is determined to be sustainable if it fulfills the environmental, social, and economic triple bottom line of sustainability. As engineers, we can evaluate the sustainability of our final design by asking ourselves the following questions: 1. Does the system make significant progress towards an unmet and important or social challenge? 2. Is there potential for the system to lead to undesirable consequences in its lifecycle that overshadow the environmental/social benefits?

First, our team concluded that the final design does make significant progress towards an important social challenge by supporting the exploration of Jupiter's moon Europa. Specifically, the packaging will safely secure the MASPEX (mass spectrometer gas chromatograph) during liftoff, EDL, and use on the 2025 Europa Lander. The packaging is designed to protect the instrument from shock forces of $175\ kN$and vibrational forces of $3G's$ at $5 - 200\ Hz$. The package will also regulate the internal temperature of the instrument from $330^{\circ}C \rightarrow 25^{\circ}C$ within 24 hrs of use. In total, the design allows for the gathering of critical information on the composition of Europa's surface, which will lead to new insights on the origin, evolution, and habitability of Europa. The mission objective is in agreement with the UN's Sustainable Development Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.

Second, our team concluded that it is unlikely for the system to lead to undesirable consequences in its lifecycle which will overshadow its benefits. After performing an Eco-Audit using GRANTA EduPack 2020, we concluded that the largest energy and CO_2 contributions resulted from the product's material. 91% of the product's energy use and 91.6% of product's CO_2 footprint was contributed from the sourcing of aluminum T7075. Our team concludes that as long as we source aluminum T7075 from a sustainable supplier, the design can be considered sustainable.



Phase	Energy (kcal)	Energy (%)	CO2 footprint (lb)	CO2 footprint (%)	Cost (USD)	Cost (%)
Material	7.98e+05	92.8	493	92.1	148	89.5
Manufacture	4.69e+04	5.5	32.7	6.1	12.5	7.56
Transport	1.47e+04	1.7	9.75	1.8	4.69	2.84
Use	0	0.0	0	0.0	0	0
Disposal	0	0.0	0	0.0	0.117	0.0707
Total (for first life)	**8.6e+05**	**100**	**535**	**100**	**165**	**100**
End of life potential	0		0			

Social Context Assessment

Considering the social context of space exploration was interesting, given the small actual impact of the Europa Mission versus the magnitude of its potential significance. Right now the stakeholder map is relatively small, as few groups are actually impacted by the mission. The Primary stakeholders for our individual part of the project for the Europa Mission would be Prof. Kurabayashi and the MSTS Lab, Dr. Blase and the SWRI. Secondary stakeholders include NASA and JPL, and the government funded programs involved in the actual Europa Mission. Finally the tertiary stakeholders are Prof. Saitou and the ME450 team, as they were not impacted but had the ability to affect the success of the project. Things become more complex if the MEMS GC on the mission were to detect signs of life on Europa, as that could open up an entire universe of stakeholders.

When considering the lifecycle cost of the packaging structure you can neglect the multiple use aspects as the structure will only be used once. Since its lifetime is only one use, and cost is already extremely high its lifetime cost is very large. This raises the question of whether the cost is worth undertaking the project at all. However, considering the total budget of the mission of 195 millions USD and our lifetime cost of 3000 USD is relatively cheap, justifying the use of the MEMS GC and packaging structure. The entirety of our cost can be contributed to materials and manufacturing as other aspects of the mission account for transportation, acquisition, inventory, maintenance, operating and environmental/health costs. The actual cost falls on the taxpayers as NASA is a publicly funded government agency. The public cost goes further then just the financial aspect as the impact of discovering life would be huge on the public. Furthermore the cost can be justified by the advancement it makes in the field of space exploration, the technologies developed here will help make space exploration cheaper and more feasible going forward.

Ethical Decision Making

Throughout the semester and development of our project, we had ethics and ethical decision making in mind, especially after it was reaffirmed through the ME 450 learning block. Both as a team and individually, we made conscious decisions to ensure that our solution, the materials it used, and the processes we recommended to make it were adhering to a just code of ethics. As engineers, and as human citizens, we all believe that we can use our skill sets to leave a lasting positive impact on the world.

The nature of our solution is very much a positive development for humanity. Space exploration, and the people behind the technology that allows for it to happen, is by far one of the greatest achievements in the history of humanity, and it is always ongoing. There are very few things that bring people together as much as the curiosity for what else is out there in our solar system and beyond. We feel that the development and implementation of our solution on the Europa lander mission will have minimal negative social, societal, economic, or environmental impacts, making the ethical justification for this technology quite easy.

In order to do our due ethical diligence, we went beyond the scope of our project to ensure that the companies and materials that we were planning to work with had ethical standards that aligned with our own. For one, the companies that produce and sell Sorbothane and Aerogel have defined sustainable manufacturing processes that they use in order to minimize their negative impacts on the world. We also found that these two companies work regularly with NASA and other governmental agencies to provide for their space exploration needs, and we know that the standards for working in the public sector tend to be higher and more strictly regulated than the private sector. NASA is the world leader in space exploration, so we know that the people and companies they work with are of the highest caliber.