Spring 2017 Final Report

Team 15

Design of a Compact Pressure Sensor for Multi-Layer Insulation Inside a Vacuum Environment

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Table of Contents

Table of Figures

Table of Tables

Abstract

Team 15, sponsored by the NASA Marshall Space Flight Center, was tasked with developing a compact pressure sensing device that is capable of measuring the interstitial vacuum pressure between layers of Multi-Layer Insulation (MLI). The additional requirements for the pressure sensor are maintain the MLI's structural integrity, minimize heat flow into the interstitial space, use minimal power consumption and must record at least one measurement per second. The device must be able to read pressure as low as 10^{-2} Pa (10^{-3} torr) and would be beneficial if it can measure up to atmospheric pressures. From a house of qualities, the most important engineering characteristics in respect to customer requirements was determined and considered in designing the concepts. Three main concepts were designed: single stage capacitor pressure sensor, multi-stage capacitor pressure sensor and fiber optics pressure sensor. Afterwards, a decision matrix was used to determine fiber optics as the most viable option with the second design being the multi-stage capacitor. Fiber Optics design is commercially available to purchase from FISO, so team 15 pursued creating the single stage capacitor design. It is not viable to pursued the multi-stage capacitor before verifying the single stage capacitor will function, so the single-stage capacitor advanced to the prototype phase. The manufacturing process for a scaled prototype and actual size prototype was developed. Unfortunately, the single stage capacitor could not be fully developed as the UV polymer necessary to adhere the silicon diaphragm to the base exceeded the budget. The budget for the project was $500 while the polymer was $600.

1. Introduction

Cryogenic fluids are stored in space by applying MLI to the external surface of cryogenic propellant tanks. Determining an accurate heat transfer will help calculate the boil off rate of the cryogenic fluid. The only heat transfer that occurs naturally in space is radiation, therefore the MLI material has a very low emissivity. Occasionally, air will be trapped between the mesh like layers of the MLI. This can pose a problem as the trapped air will allow convection to occur throughout the pockets of air. The more heat transfer that occurs, the faster the boil off of the cryogenic fluid. The pressure sensors placed on, or in, the MLI material will determine if there is trapped air present.

Due to the compactness of the MLI, placing a sensor within the MLI can pose a problem. If the sensor is too large, then it deforms the shape of the MLI which can lead to increased heat transfer, or the pressure sensor can tear the material during its travel into space. Another current issue with pressure sensors is the production of heat. In space, since it is a vacuum, heat cannot dissipate causing any heat that is produced by the sensor to stay in that area. This will then transfer heat into the tank causing the boil off rate of the cryogenic material to increase. Designing a sensor to not be invasive or increase the boil off rate of the material will be key throughout the project.

2. Project Overview

2.1 Project Statement

The customer's need can be summarized as follows:

"Due to their size, current pressure sensing devices are unable to measure the interstitial vacuum pressure between layers of multi-layer insulation (MLI) and generate excess heat and power while in operation"

To design and develop a compact device best suited to measure pressure within multilayer insulation.

2.2 Project Scope

Design a minimally invasive pressure sensor to determine the interstitial pressure. The sensor must take one sample per second and have a range from 10^{-2} Pa to 101 kPa. Due to space being a vacuum, heat cannot dissipate similar to earth therefore the sensor must produce minimal heat.

2.3 Project Objectives

Design a pressure sensing device that can be embedded within the layers of MLI for NASA. Objectives:

- Sensor must be able to read pressures as low as 10^{-2} Pa (if possible, read range from 10^{-2}-101kPa)
- Minimize heat produced
- Reliable and able to work in space.
- Minimize power consumption.
- Minimize size in order to be as minimally invasive as possible.

2.4 Project Constraints

The constraints in this project are determined by the MLI, pressure sensors and the working environment of space. The primary constraint caused by the MLI layers is due to the thinness of layers, less than 0.8mm per layer. The interlayer spacing should be able to accommodate the sensor with as little invasiveness possible.

The pressure sensors constraints are constraints only affect the pressure sensors themselves. The sensor must be able to take one measurement per second. Also the pressure sensor should be able to measure pressures as low as 10^{-2} Pa (if possible, read range of 10^{-2} Pa- 101 kPa).

The constraints previously mentioned are minor compared to the last constraint. This constraint in the working environment of space. Not only will the pressure sensor have to work in the normal conditions of Earth's atmosphere, but it will also have to work in the harsh environment of space. Space is quite the unforgiving environment. Any factors that could cause failure must be addressed, and precautions should be established to avoid failure.

Acknowledging the gravitational change in space relative to the Earth is important depending on the type of pressure sensor chosen. Gravity will alter any air molecules and the pressures associated with these molecules, and the pressures determined from the sensor will have to account for the current gravitational acceleration that is exerted on it in order to accurately determine the pressure within the layers.

The most prominent feature of space, and the trait that will pose the biggest threat, is the vacuum of space. The vacuum of space generates issues that need to be designed around in order to integrate the pressure sensor with the MLI. These problems include out-gassing, cold welding, and heat transfer.Out-gassing is caused by the release of gasses trapped inside of spacecraft materials. Out-gassing can coat the lenses used by sensors, and also allow electrical components to arc, destroying them. In order to combat out-gassing, the aircraft and components are "baked" before the flight in a thermal vacuum chamber in order to eliminate as much gas from the aircraft and materials as possible. Heat transfer, or rather the lack of, is vital to the MLI's role. Implementation of the pressure sensing device will have to account for the change of heat transfer through the material with the sensor embedded. Because the heat transfer will be radiation soaked from space, it is crucial to ensure that implementing the pressure sensor does not degrade the ability of the MLI material to insulate against thermal energy transfer.

As stated above, radiation is the major form of energy transfer in space. Prolonged exposure to Ultraviolet radiation can cause spacecraft coating to degrade. This degeneration of materials and coatings will prove important, when choosing a design for a pressure sensor that may come into contact with radiation being soaked by the MLI material.

2.5 Background Research

2.5.1 Multi-Layer Insulation

Multi-Layer Insulation, MLI, or Super Insulation is a special type of high-performance thermal insulation that is comprised of alternating layers of a reflective polymer film such as Teflon or Mylar and a webbed spacer material like Dacron (commonly known as Polyethylene Terephthalate)[1]. Initially, when processed, the polymer film is surrounded with a metallic coating through a vapor - deposition process[2]. Metalizing the film increases its reflectivity, making it an effective radiation shield since materials with high reflectivity have a low absorptivity and transmissivity[3]. However, if all the films were stacked together, a thermal short circuit would occur, enhancing conduction heat transfer and destroying the purpose of the MLI. The spacer material, with a netting pattern, resolves this issue due to its low thermal conductivity which prevents heat from penetrating the MLI. The film and spacer layers are carefully held together by tape with low outgassing properties[4]. The multilayer films reduce incident radiant energy with each successive layer and reflect back almost 95% to 99% of incident solar radiation. MLI is also anisotropic and sensitive to edge effects and mechanical compression, stressing the need for proper installation[4].

Since radiation is the dominant mode of heat transfer in a vacuum, MLI is frequently utilized in conjunction with an external vacuum environment. Additionally, the interstitial space between film layers is also evacuated. The thermal performance of MLI is dependent on the vacuum level and pressure in this interstitial region. At a pressure of about 10^{-4} torr, convective heat transfer becomes negligible while conductive heat transfer is reduced due to the high order of the vacuum and the Dacron spacers [5]. If the interstitial pressure were to increase beyond 10^{-4} torr due to phenomena like outgassing, conduction and convection heat transfer would take over and rapidly transfer energy between reflective film layers. Figure 1 below illustrates the difference between various cryogenic insulation systems in certain pressure ranges. The chart shows how MLI is suitable at very low pressures but starts to become ineffective at higher pressures.

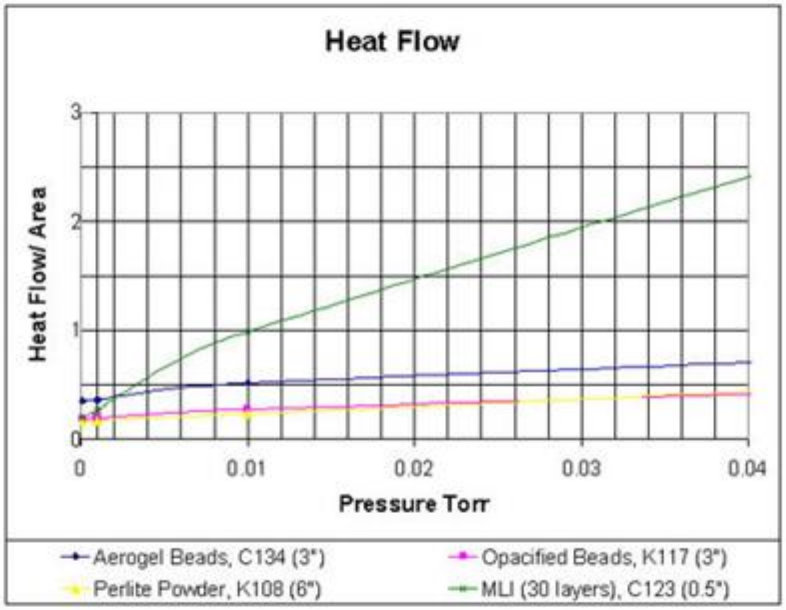


Figure 1 The Performance of Cryogenic Insulation systems at various interstitial pressures[1]

The thickness of Multi-Layer Insulation can range from 30 layers per inch to the standard 60 layers per inch depending on the application, storage duration and environmental conditions [Project Description Reference]; the thickness of the MLI sample determines the spacing between layers and is an important factor to consider. Although MLI is used to protect sensitive instrumentation on spacecraft (like the Huygens Probe), its application extends to the shielding of cryogenic liquid propellant tanks. For this project, Double Aluminized Mylar was used as the material for the radiation shields and the spacers were constructed from Dacron or PET.

2.5.2 Pressure Sensors

There are many different pressure measuring techniques and devices. However, there are five types in particular that stand out. These include strain, capacitance, Piezoelectric, fiber optic, and surface acoustic wave type pressure transducers.

Plainly put, strain transducers operate by converting material elongation due to a force into the corresponding resistance (R), inductance (L), and/or capacitance (C). A photo of a strain transducer can be seen below in figure 2.

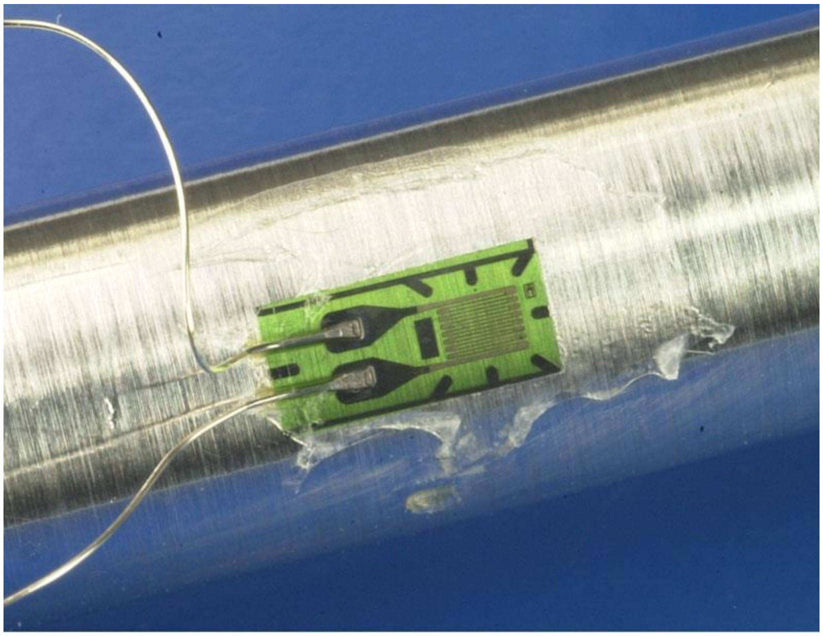


Figure 2 Strain gauge on a cylindrical object[5]

More specifically, these transducers work by setting a thin wire where the pressure needs to be measured. When this wire feels a force, it stretches creating a resistance change. Since strain is proportional to the resistance, the resistance can easily be found with the help of a wheatstone bridge. Advantages of this type include size versatility and relative cheapness. Some disadvantages of this type include major temperature errors and minor humidity errors.

Capacitance transducers operate by noting that dielectric constant of solids, liquids, and gases change with differing pressure. An image of a capacitance gauge can be seen below in figure 3.

Figure 3 A capacitance gauge[6]

The change in the dielectric constant is measured using a resonance circuit. One big advantage to this type of transducer is its ability to accurately measure both static and dynamic measurements. The dielectric constant only varies slightly with large pressure changes, 0.5% for a pressure change of roughly 10 MPa, meaning this device is only suitable for measuring very large pressure changes.

A capacitor is a passive, two – terminal circuit element that stores energy in an electric field. It consists of conductive plates separated by a dielectric material like Air, Mica or Ceramic[7]. When connected in series with a battery or other power source, the plates accumulate charge until the capacitor is at the power source voltage. If the power source were removed, the capacitor would discharge at a rapid rate[8]. Although mainly used for energy storage, capacitors are also desirable due to their ability to filter out high frequency noise from a lower frequency signal[9]. The capacitance of a material describes its ability to store charge. It is defined according to the following equation

$$C=QV$$ Eq. 1[10]

where C is the capacitance, typically measured in microfarads, Q is the charge stored on each plate, and V is the voltage applied to the plates. Parallel plate capacitors are separated by a distance, d, that is used to determine the capacitance according to Equation 2.

$$C=\epsilon 0Ad \quad \text{Eq. 2}$$ [10]

Where ε_0 is the permittivity of free space and A is the area of a single plate. A diagram of a parallel plate capacitor is depicted in Figure 1.

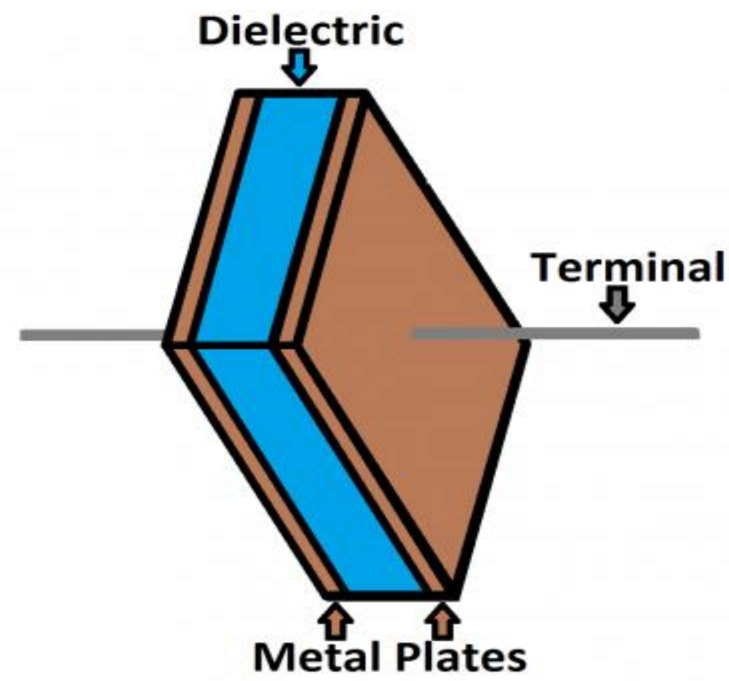


Figure 4 Parallel Plate Capacitor[8]

If the top plate of a capacitor was a flexible diaphragm and the bottom plate and plate area were fixed, the capacitance would essentially depend on the separation between plates. This distance is affected by the ambient pressure, which can be expressed in terms of the force exerted by the environment on the plates and the area of the plates. Force can then be calculated according to Hooke's Law given below.

$$F= -kx \quad \text{Eq. 3}$$

where x would be the variable separations between the capacitors plates. Solving Equation 2 for the distance between plates and inserting that into Hooke's law yields an expression for the force in terms of the capacitance[11].

$$F= -k\epsilon 0AC \qquad \text{Eq.4}$$

If Equation 4 was divided by the area of the plates, an empirical expression relating pressure to capacitance would be known. Since the capacitance or distance between plates is measured, pressure readings can easily be obtained.

Piezoelectric transducers work with the help of a specifically cut quartz crystal and a surrounding circuit. An image of a piezoelectric transducer can be seen in figure 4.

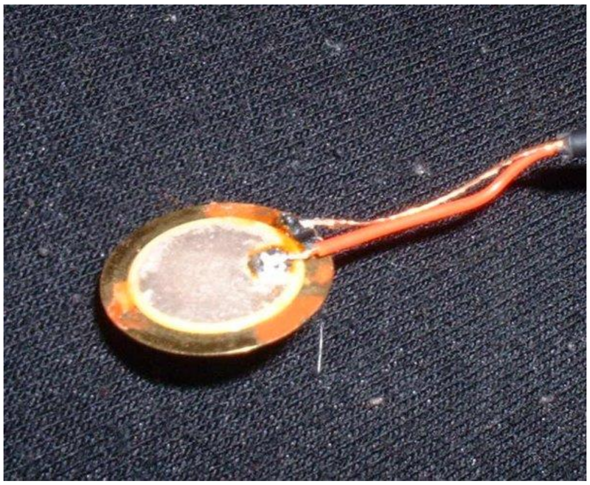


Figure 5 A piezoelectric transducer[12]

When the quartz crystal feels a force, an electrical charge is produced on the crystal surface. This electrical charge is known as piezoelectricity. Some advantages of this transducer include a high frequency response, self-generating power source (piezoelectricity), small dimensions, and large measuring ranges. Some disadvantages include errors based on the crystal temperature and humidity (H>85% & H<35%).[13]

Fiber optic transducers are very complicated. The optical fibers are used to measure phase, polarization, and wavelength and in turn convert this input value(s) to pressure. Fiber optics pressure sensors benefit from being able to withstand harsh conditions such as high vibration, extreme heat, noisy, wet, corrosive, and explosive environments. Additionally, fiber optics are very ductile allowing bend. This allows fiber optic sensors to be placed in confined areas. Some disadvantages include high cost and limited long-term stability.[14]

Surface acoustic wave transducers use a combination of the piezoelectric effect and surface acoustic waves (SAW) to measure pressure. These work by sending a mechanical or acoustic wave on the surface of a material. The time it takes the wave to meet the end of its path, as well as the phase characteristics, are then measured. Once measured, these values can finally be correlated to pressure.[15]

2.5.3 Working Environment (Space)

Space is the working environment of this project. Space is a vacuum therefore materials and laws act differently in space then they would on earth. In a vacuum, heat transfer doesn't react the same way as it does on Earth. This is because since there is no air, convection cannot occur, which leaves radiation as the primary source of heat transfer. Systems that typically generates heat on earth will not be able to dissipate it. This could potentially cause a problem. Working in space also can cause cold welding. Cold welding is common among mechanical parts with very tight tolerances. On Earth, air is generally found between the spaces of parts, such as bearings or revolute joints. This air can create miniscule pockets, which allow the part to move. However, in the vacuum of space the air pocket is removed. This can cause the part to lock up, or "cold weld" together.

3. Concept Design & Analysis

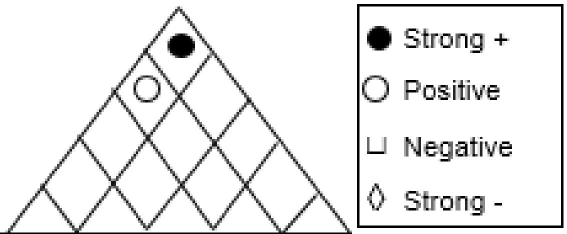
3.1 Reiteration of Design Phase

Team 15 revisited the design phase. They believed the Sound Acoustic Wave design and piezoelectric design were not going to be viable options. As a result, the team felt it was necessary to visit the design phase once again in order to generate two additional concepts. During this time, further research into capacitors was done. This research lead to development of two different capacitor designs, which will be discussed soon.

3.2 House of Qualities

Table 1 contains a house of qualities and is used in order to determine which engineering characteristics are most valuable in relation to the customer requirements. As can be seen, minimal invasiveness and accuracy are the most important customer requirements. Once the engineering characteristics and customer requirements have been related, the total weight of the engineering characteristics can be determined. As seen in table 1, Power consumption is the most important characteristic scoring a total of 102 points. Power consumption has a direct correlation with minimal invasiveness because as the power consumption increase the size of the wires supplying the power must increase as well. The more power that is consumed the more heat that will be produced. The more rapid and accurate the pressure readings are the more power that will be consumed. The second most important engineering characteristic is cost scoring a total of 87 points. Even though power consumption and cost scored vastly better than the other engineering characteristics, every engineering characteristic will still be taken into consideration with an emphasis in power consumption and cost.

Table 1 House of Qualities



Customer Requirements \ Engineering Characteristics	Customer Importance	Materials	Power Consumption	Geometry	Cost	Durability
		○	↑	○	↑	○
Minimal Invasiveness	5	3	6	9	3	6
Accuracy	5		6		6	
Minimal Heat Produced	4	3	6			
Reading Range	4				6	
Reading Speed	3		6		6	
Total Weight		27	102	45	87	30

3.3 Conceptual Designs

3.3.1 Capacitor Pressure Sensor

The single stage capacitor pressure sensor design was created in order to tackle the value of the interrogation equipment needed to analyze the fiber optic pressure sensor's light. The capacitance sensor begins with a solid cylindrical silica base as seen in figure 5 (yellow plate on the bottom), which is reduced down in size to the required length. Next, a rigid capacitor plate, made of either a thin metal, or a thick silica plate Nano-coated in metallic particles, is applied to one end of the cylindrical silica core by either a thermal fusion process, or using UV-set polymers. Next, a cavity will have to be formed in order to allow for a vacuum pressure to reside within the sensor as a gauge pressure. This cavity is formed by using HF acid to etch a parabolic cavity into the pure silica. This cavity etching process has been shown to be easily repeatable and highly accurate, as long as the material properties of the silica cores and the acidic properties of the HF acid stay consistent. Next, the flexible pressure sensing diaphragm will need to be created. The diaphragm consists of a pure silica outer rim, with a germanium doped silica core as seen in figure 5 (top yellow plate). The diaphragm is sized down to an approximate thickness, and is prepared for its final etching process. When HF acid is introduced onto the diaphragm, the germanium doped inner core etches faster than the pure silica outer rim. This allows the diaphragm to be etched down to the appropriate thickness, as well as to allow the raised pure silica outer rim to protect the diaphragm against any obtrusions that might damage the sensor. Finally, the flexible diaphragm is attached to the cylindrical silica core on the etched cavity side. This process, however, has to occur inside of a vacuum chamber in order to seal the pressure sensor with a vacuum pressure inside. This final diaphragm attachment can once again use either a thermal fusion process, or the UV-set polymers.

The thickness of the diaphragm will dictate the pressure ranges the sensor can adequately sense. A thinner diaphragm will result in decreased stiffness, making it more susceptible to pressure ranges. However, due to the yield point of the material, over deflecting the material too far will ensure it will not return back to its equilibrium. This concern means that the cavity length for the single-stage capacitor will have to be determined to ensure that the diaphragm will rest on the cylindrical silica core far before the diaphragm material reaches its yield point. This will ensure that the capacitor will be able to repeat pressure readings, without damaging the diaphragm.

The major downfall of the single stage capacitor design is that its pressure reading range is limited by the thickness of the diaphragm. In order to read the low pressure ranges, it will require a thinner diaphragm, which will deflect more with low pressures. However, the diaphragm will "bottom out" on the silica core after a small pressure range, and its sensing capabilities will be nonexistent, until the pressure returns to within the small range of the capacitance sensor. The sponsor for this project, NASA, relayed to team 15 how it would be beneficial to create a sensor that would be able to read both the low pressure ranges of 10^{-2} as well as reading atmospheric pressures. This suggestion led our team to create a second design, using a multistage capacitance sensor to read more than just one diaphragms' adequate range.

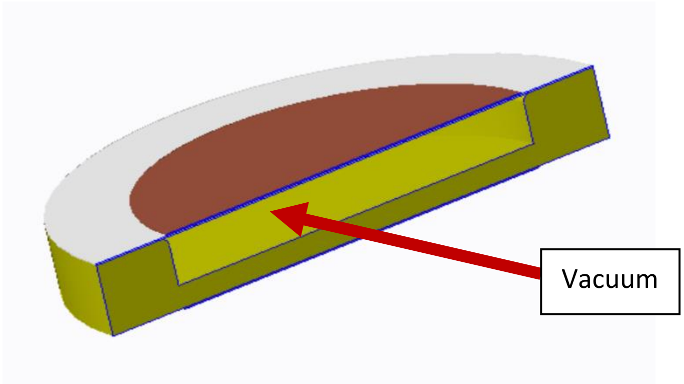


Figure 6 Cross sectional view of capacitor sensor displaying the layers and vacuum chamber.

3.3.2 Multi-Stage Capacitor Pressure Sensor

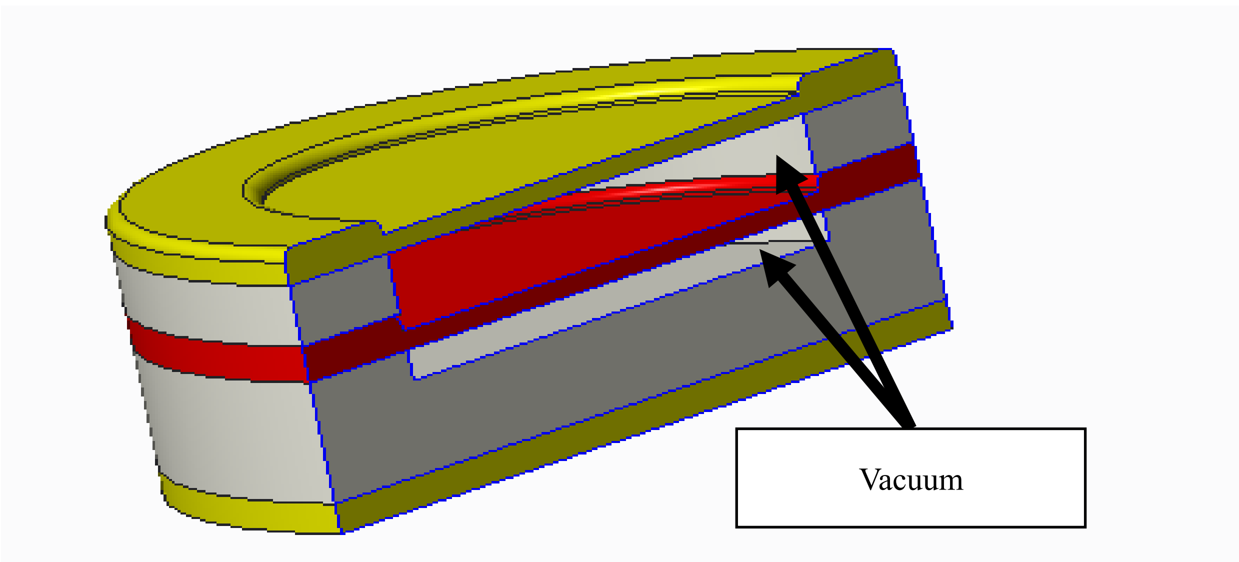


Figure 7 Cross sectional view of multi-stage capacitor sensor displaying the layers and two vacuum chambers.

In order to tackle the pressure range requirement that NASA has implemented, a multistage capacitor design was needed. The multistage only differs from the single stage capacitor by the amount of diaphragms in parallel as seen in figure 6. By stacking the diaphragms on top of each other, with the lowest stiffness diaphragm on the outside of the pressure sensor, it enables multiple reading ranges to occur. When the more flexible diaphragm on the outside finishes its reading range in its cavity, it will begin to touch the second diaphragm, whose stiffness is greater. These two diaphragms stiffness will add in parallel, and allow for a second higher pressure reading range to occur. However, it is important to remind ourselves of the yield point constraint as described earlier. The more flexible outer diaphragm will no longer deflect only in its cavity, but will also will traverse through the second cavity during the second reading range. It is important to ensure that the distance the first diaphragm will travel when in contact with the second diaphragm in the second cavity is still underneath the yield point stress of the material chosen. Special consideration of cavity lengths and diaphragm thicknesses will need to be taken to ensure proper functionality and repeatability of the sensor.

3.3.3 Fiber Optics Pressure Sensor

For the fiber optic design, fiber optic cables in the micrometer range are placed through the layers of the MLI as see in figure 7. Figure 8 is a close up of the fiber optics. An external power source sends a pulse of light through the fiber optic and hits a germanium doped silicon core membrane. This membrane is deflected due to the ambient pressure which is exerted on it, and sends the light back with different wave qualities. The qualities of this new wave, polarization, wavelength, and light intensity, or mainly transmit time can be measured with a sensor and correlated to pressure.

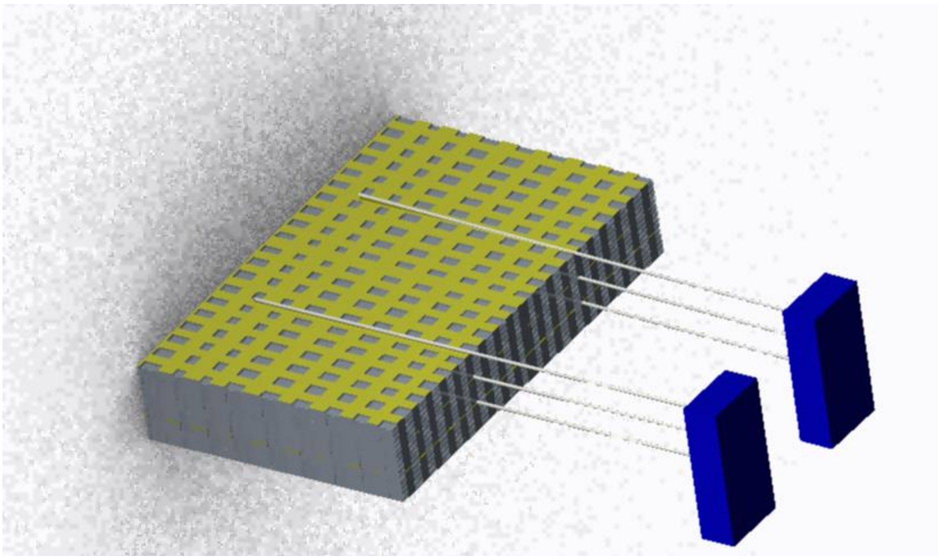


Figure 8 Fiber optics sensor embedded within the MLI

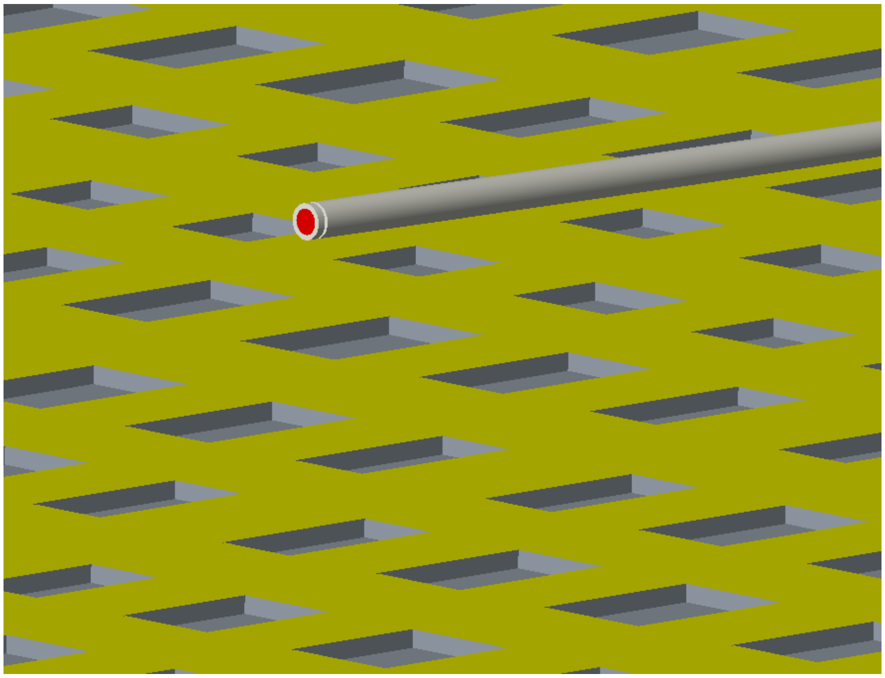


Figure 9 Close up on the end of a fiber optics cable

3.4 Design Specs

Table 2 Design specs for the different concepts

Sensor Type	Size (Diameter)	Pressure Measuring Range	Stress Allowed	Operating temperature Range	Power
Single Stage Capacitor	125 micrometers	$10^{-2} – 10^{2}$	600 kPa	-65°C- 200°C	2V
Multi-Stage Capacitor	125 micrometers	10^{-2}—101 kPa	Varies	-65°C- 200°C	2V
Fiber Optics Sensor	125 micrometers	$10^{-12} – 10^{12}$ Pa	690 MPa	-65°C- 200°C	Varies

The design specs for the three concepts are very similar, as seen in table 2, due to most of the parameters being dependent on the diaphragm, which is the currently the same for the three concepts (with the exception of the second layer on the multi-stage capacitor). The size of both capacitor design can vary in area depending on the final material thickness in order to increase the curvature of deflection. The pressure ranges is where the designs vary vastly due to the different layers as well as the method on how the sensors work. The Fiber optic power input varies based on how many fiber are within the fiber optic, type of fiber optic, and the current being run through the system.

3.4 Pugh Matrix

Table 3 Decision matrix

	Capacitor	**Fiber Optics**	**Multi-Stage Capacitor**
Accuracy	0	1	0
Minimal Invasiveness	0	0	0
Heat Production	0	-1	0
Reading Range	0	2	1
Reading Speed	0	0	0
Total	0	2	1

After generating the three different designs a decision matrix was created in order to select one concept. The single stage capacitor pressure sensor was selected to be the datum as can be seen in table 2 with the SAW scoring a 0. Multi-stage capacitor pressure sensor scored better than our datum with a score of 1. The Multi-stage capacitor sensor only scored better than the datum on the reading range. As the two sensors are very similar in design all the requirements scored the same as well. Fiber optics sensor scored the best with a score of 2 points. The fiber optics sense score 1 point in accuracy as it is the most accurate sensor. The reading range on the fiber optics sensor was larger than the other two concepts those scoring a 2. The only area the fiber optics senor lack was in heat production. Due to the fiber optics sense working by sending a beam of light through the optic cable, this will cause this design to have the largest heat production from the three designs. Once the three designs' points were assigned, the fiber optics sensor was selected

as the primary concept. The fiber optics design can be bought from the private market, from FISO, so team 15 pursued creating the single stage capacitor design. It is not viable to pursued the multi-stage capacitor before verifying the single stage capacitor will function, so the single-stage capacitor advanced to the prototype phase.

4. Parameters of Single Stage Capacitor

Table 4 Dimensions of the prototype and actual sensor

	Diaphragm Diameter	**Min. Thickness (@150 kPa)**	**Design Thickness**	**Safety Factor**	**Critical Diaphragm Pressure**	**Maximum Deflection (@150kPa)**	**Shell Thickness**	**Critical Body Pressure**
Prototype	25 mm	0.05 mm	0.10 mm	2.00	600 kPa	5.60 mm	5 mm	20 MPa
Actual Sensor	125 µm	0.25 µm	0.50 µm	2.00	600 kPa	28.0 µm	20 µm	400 MPa

The maximum pressure the sensor would experience is 150 kPa. The pressure sensor will only experience this pressure during take-off at roughly 13km to 14km of altitude. The dimension of the sensors were determined by using three sets of equations. The first parameter calculated was the minimum thickness of the diaphragm using equation 5.

$$h = \sqrt{\frac{3r^2 \Delta P}{4\sigma_y}} \qquad \text{Eq. 5}$$

Where r is the radius of the diaphragm, ΔP is the difference in pressure, and σ_y is the yield stress of the diaphragm.

Once the minimum thickness was determined, it was possible to determine the maximum defection of the diaphragm using equation 6.

$$W_{max} = \frac{-3\Delta P r^4\left[\left(\frac{1}{\nu}\right)^2 - 1\right]}{16E\left(\frac{1}{\nu}\right)^2 h^3} \qquad \text{Eq. 6}$$

Where ΔP is the difference in pressure, r is the radius of the diaphragm, ν Poisson ratio, E young's modulus, and h can be seen in equation 5.

It is vital to determine the maximum body pressure in order to determine the correct epoxy, for the prototype, or shell thickness for the sensor. This can be determined by using equation 7 below.

$$p = \frac{0.855}{(1-\nu^2)^{\frac{3}{4}}} * \frac{E\sqrt{\gamma}}{\left(\frac{r}{t}\right)^{\frac{5}{2}} * \frac{l}{r}} \qquad \text{Eq. 7}$$

Where ν is Poisson's ration, E is Young's modulus, r is the radius of the diaphragm, l is the sensor length, t is the shell thickness, and γ can be seen in equation 8.

$$\gamma = 1 - 0.901(1 - e^{-\phi}) \qquad \text{Eq. 8}$$

Where ϕ can be seen in equation 9.

$$\phi = \frac{1}{16}\sqrt{\frac{r}{t}} \qquad \text{Eq. 9}$$

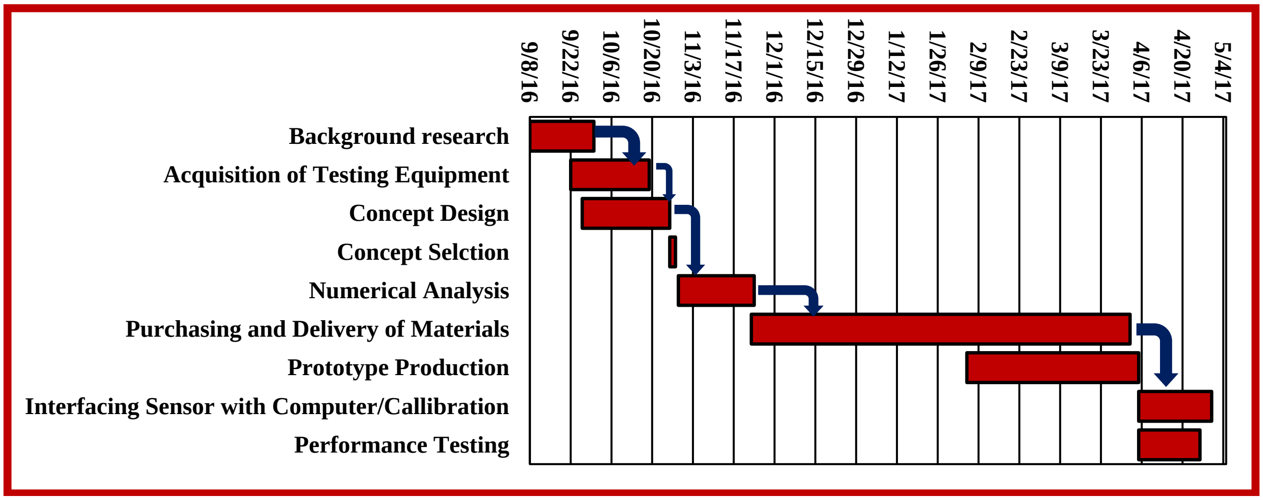
Where r is the diaphragm radius, and t is the shell thickness.

4. Methodology

4.1 Gantt Chart

As seen in table 5, the finalized Gantt chart contains the schedule of project task. The Gantt chart contains blue arrows to signify the critical path. This is the minimal amount of time to complete the project, which is roughly 208 days. These dates changed from the initial dates. Most of the task were accomplished on time except for numerical analysis and delivery of material. Both of these task took longer than initially expected.

Table 5 Gantt chart



4.2 Resource Allocation

There are multiple resources that will used throughout the course of this project by team 15. The primary resource is the internet as this is where majority of information is found. Another resource team 15 has been using and will continue to use is the faculty advisor, Dr. Wei Guo. Dr. Guo's knowledge on the topic has proven to be essential in preliminary analysis of the system and will continue to be essential. A more physical resource being used is the cryostat vacuum chamber as this is where majority of testing will be conducted.

Jason Carvalho is the webmaster, and Mr. Carvalho was tasked with creating and maintaining the website, as well as assisting the other team members when necessary. Stephen Johnson is the machine specialist. Mr. Johnson was tasked with computing the numerical analysis for all of the design. Michael Kiefer is the lead financial advisor. Mr. Kiefer assisted Mr. Johnson in the numerical analysis. Afterwards, Mr. Kiefer was tasked with creating a budget for the purchasing of materials necessary to develop a prototype. As a group, the materials were selected and purchased. Also as a group, the prototype was assembled. Sebastian Bellini was tasked with assisting the other team members with their objective, as well as maintain contact with the sponsor (James Martin) and faculty advisor (Dr. Guo).

5.0 Design for Manufacturing

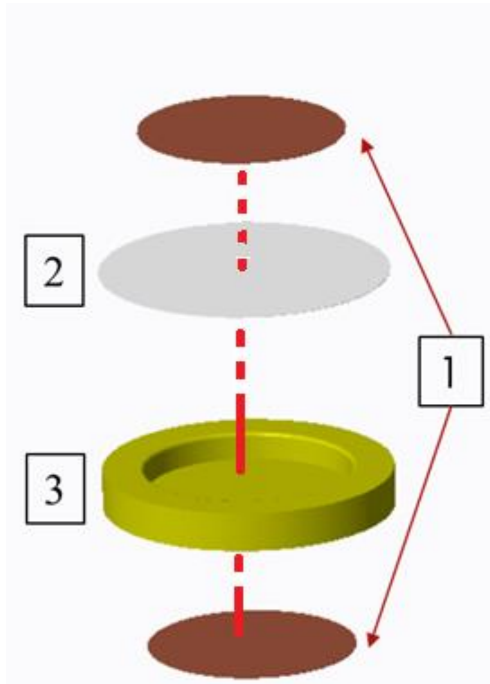


Figure 10 (1) Palladium-Gold sputtered tracts. (2) 0.50 µm thickness Silicone diaphragm. (3) Germanium doped silica base

Figure 10 shows an exploded view of the capacitor pressure sensor. Part 1 in figure 10 is the Palladium- Gold sputtered tracts, part 2 is the silicone diaphragm and part 3 is the silica core or epoxy core for scaled prototype.

5.1 Necessary Supplies for Scaled Prototype Manufacturing

1. HIPs Filament
2. 3D Printer
3. Fibre Glast 2000 Epoxy resin
4. Fibre Glast 2000 Epoxy cure
5. Stirring stick
6. D-limonene
7. UV10 silicone epoxy by MasterBond
8. Vacuum chamber
9. Moveable platform capable of fitting and operating inside the vacuum chamber
10. UV light
11. Silicone sheet 0.1mm

12. High grit sand paper
13. Low grit sand paper
14. Sputtering Machine
15. Palladium-Gold sputtering material
16. Solder gun
17. Solder material
18. 2- Resisters of known resistance
19. 1- Variable resistance resistor
20. 2- Capacitors of known capacitance
21. Low temperature oven (not necessary)
22. Electric drill (not necessary)
23. Shaft (not necessary)
24. 3D Printed Mixing Propeller (not necessary)
25. Tape (not necessary)
26. Aluminum Foil (not necessary)

5.2 Steps to Manufacture Scaled Prototype

Using a 3D printer, upload the .obj file of the upper the sensor mold, seen in figure 11, into a 3D printer. Select the necessary options to begin the print.

Figure 11 HIPS bottom mold

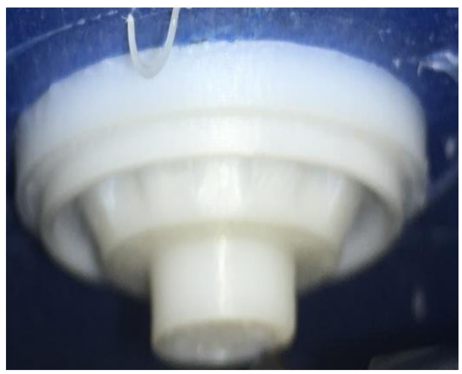


Figure 12 HIPS top mold

Once the print has finished, remove the mold and begin to print the lower part of the mold shown in figure 12. The time to print the mold depends on the quality of the 3D printer. Once the molds have been printed, the Fibre Glast 2000 epoxy resin and Fibre Glast 2000 epoxy cure should be mixed in the prescribed directions. After thoroughly mixing the resin, allow 5 to 10 minutes for the bubbles to rise. This step is crucial as any bubbles that form in epoxy will decrease the sensors strength. Once the bubbles have risen, pour the epoxy into the bottom mold slowly to not allow any bubbles to be trapped under the epoxy. If any bubbles have been trapped or remain in the epoxy, then allow it to sit for roughly 2-5 minutes. Place the top part of the mold in to the bottom part slowly. Once the mold is assembled, allow 18-24 hours for the epoxy to cure due to the minimal heat exposer. This step can be accelerated by placing the assembled mold into the oven at a very low temperature (maximum temp allowed is 175°F), but allow the epoxy to cure for 10-15 minutes before placing in the oven. This will prevent any bubbles from forming while inside the oven. The time for the epoxy to cures varies on the temperature of the oven. Once the epoxy has hardened completely, place the mold into the D-limonene bath and allow for the HIPS plastic to dissolve. The time for this process varies vastly. The dissolving process can take up to 13 hours and thus it is recommended to enhance the dissolving rate. This can be done with a few different methods. The method selected by team 15 was to create a circulating current inside the D-Limonene bath. This was achieved by attaching a 3D printed mixing propeller, as shown in figure 13, to a shaft. This shaft was then placed inside of a 12-volt electric drill. The propeller was placed on the surface of the D-Limonene bath, and the electric drill was held in the on position by holding the button with tape as shown in figure 14.

Figure 13 3D printed mixing propeller in bath

Figure 14 Electric drill being used to create a current

This allows for the fluid to circulate decreasing the dissolving time to roughly 3-4 hours. If the circulating current is not created inside the D-limonene bath, then it is highly recommended to constantly check every 20 to 30 minutes, and remove the lose dissolving HIPS from the surface as this will decrease the dissolving time by a couple of hours. It is acceptable to simply allow the

HIPS mold to dissolve in the D-limonene bath without assisting it, but the dissolving time could take more than 12 hours. Remove the sensor base from the D-Limonene and begin to sand any uneven or rough edges with the low grit sand paper, then use the high grit sand paper to give the mold a smooth and even finish. Clean any powder that may remain on the sensor after sanding. Cut a 2”x2” square of silicone. Place small moving platform inside the vacuum chamber with the silicone on the platform. Place the sensor base into the vacuum chamber directly underneath the platform. Place the UV10 epoxy on rim of the sensor base. Turn on the vacuum chamber and allow for all the air to be removed. Lower the platform onto the sensor and hold in place. Place the UV lights above the vacuum chamber and allow for the resin to cure. UV10 can take roughly 60 seconds to cure depending on the amount of UV light being used. It is recommended to use a UV light of wavelength 320-365 nm and energy output as low as 20-40 milliwatts/cm^2. If a UV light of different ratings is used the UV epoxy could take several minutes to cure. If a UV light of different ratings is used it is highly recommended to surround the entire structure in Aluminum foil. This will reflect any UV light amplifying the process. Once the resin is set, remove the sensor and trim excess silicone. Using the sputtering machine, sputter the top diaphragm and bottom surfaces using Pallidum-Gold for 15 minutes per surface. The rate of sputtering can be increased to increase the electric conductivity of the sensor. Solder the lead wires to the capacitor, and build a Schering bridge.

5.3 Time to manufacture scaled prototype

Table 6 Time to manufacture the sensor

Step	3D printing mold	Setting epoxy in mold	Dissolving HIPS mold	Sanding sensor	Attaching diaphragm to sensor	Sputtering	Soldering lead wires	Schering Bridge	Total Time
Time (Minutes)	80	1440	720	10	15	40	20	30	2,355

The process to manufacturing the sensor was roughly 2,355 minutes (39 hours and 15 minutes) as seen in table 6. The manufacturing process took slightly longer than expected during the setting of the epoxy in the mold and dissolving of the HIPS. This was taken into consideration during the next batches of sensors manufactured. The manufacturing time was then reduced by introducing additions to certain process as previously mentioned in section 2. The mold for the sensor was also redesigned to allow for more surface area in the dissolving process. The reduced manufacturing time can be seen in table 7. The reduced total time to manufacture the sensor is 490 minutes (8 hours and 10 minutes), which was roughly half the time from the initial manufacturing process.

Table 7 Reduced time to manufacture the sensor

Step	3D printing mold	Setting epoxy in mold	Dissolving HIPS mold	Sanding sensor	Attaching diaphragm to sensor	Sputtering	Soldering lead wires	Schering Bridge	Total Time
Time (Minutes)	75	120	180	10	15	40	20	30	490

5.4 Necessary Supplies for Nano-Scaled Prototype Manufacturing

1. Electron Microscope
2. Germanium doped Silica fiber (165 μm diameter)
3. Hydrofluoric Acid (HF)
4. UV10 silicone epoxy by MasterBond
5. Moveable platform capable of fitting and operating inside the vacuum chamber
6. Sputtering Machine
7. Palladium-Gold sputtering material
8. Solder gun
9. Solder material
10. 2- Resisters of known resistance
11. 1- Variable resistance resistor
12. 2- Capacitors of known capacitance
13. UV lights
14. Silicone sheet (0.5µm)
15. Vacuum Chamber

5.5 Steps to Manufacture Nano- Scaled Prototype

A solid germanium doped silica fiber, roughly 165 μm in diameter, is prepared for an acidic etching solution with hydrofluoric acid. Acid is applied to the face of the silica, and allowed to etch downwards in a parabolic fashion into the germanium doped silica. Special consideration will need to be taken to ensure the cavity diameter created from the etching process is consistent with the diameter requested. A silicone diaphragm is then to be prepared at the correct thickness, 0.50

μm. UV10 polymer is applied to the rim of the silica fiber where the etching occurred. The sensor is then to be placed into a robotic arm that holds the sensor underneath the diaphragm. Once the air pressure is fully lowered below 10^{-2} Pa, the sensor is raised to the diaphragm until contact between the UV10 and diaphragm has occurred. Next, the UV light is turned on to set the UV polymer, and thusly seal the vacuum inside of the sensor. The sensor can now be taken out of the vacuum chamber. The sensor is then taken to a sputtering machine, so that Palladium-Gold tracts can be sputtered on both the hard silica bottom, and the top of the diaphragm on the opposite side. Next, wires need to be adhered to each respective capacitance plate, and the Shearing Bridge is constructed.

5.6 Time to manufacture Nano-scaled prototype

The etching process at the beginning will take roughly 15-20 minutes, depending on the depth of the cavity that we would like to create. The etching process could be shortened, if a stronger acid is used or a more reactive substrate is chosen. Shaving the silicone diaphragm to the correct thickness is a slow process, and not meant to be accomplished hastily. This is approximated to take roughly 30-45 minutes, depending on the available equipment. The application of UV polymer glue at the Nano-scale is an arduous task, and could take the longest out of most of the steps. This process would have to occur under an electron microscope, and many factors can cause trouble. One big issue is the viscosity of the polymer. On a Nano-scale, viscous fluids need to be controlled slowly, as the misplacement of the sticky polymer could ruin the entire sensor. This is approximated to take roughly 20-30 minutes. Both bringing the vacuum down and setting the UV polymer is one of the easier steps, with the vacuum taking roughly 10 minutes to set to equilibrium, and the UV polymer activation taking 2 minutes to finish. The sputtering of the sensor, due to the small Nano-layers that would be needed, will only take 10 minutes at most to accomplish the desired tracts. The full sensor manufacturing can take roughly 4-5 hours, with very little room for optimization due to the issues faced at the Nano-scale.

All times for the Nano-scaled prototype are a rough estimate due to not being able to build the sensor and can be seen in table 8. The Nano-scaled sensor would have to be outsourced to a third party company to manufacture.

Table 8 Time to manufacture Nano scale Prototype

Step	Etching Silica core	Silicone thickness face cut	Setting UV polymer	Attaching diaphragm to sensor	UV curing	Sputtering	Soldering lead wires	Schering Bridge	Total Time
Time (Minutes)	20	40	30	10	2	10	40	30	182

5.7 Complexity of the design

There are only 3 main components in the manufactured sensor. Those parts consist of the Palladium-Gold sputtering, silicone diaphragm and the silica base (or epoxy for the scaled prototype). The design cannot be simplified as these are the minimum parts necessary to create the sensor. The only section of our design that can be changed would be the Schering Bridge. The addition of a network analyzer to replace the Schering Bridge will allow the pressure to still be read without the complexity or additional parts necessary for the Schering Bridge. The network analyzer would be more useful when conducting experiments in lab, while the Schering Bridge would be more useful in its application in outer space.

6.0 Design for Reliability

The prototype should work just as well the first time as it does the 10,000 time. This is because there are not many moving parts with this sensor since it is mostly electrical. The far more probable chance of failure is if the senor breaks from damage incurred during the lift off or flight. The main reliability concern is if the seal breaks within the sensors measuring cavity. If this problem did occur, it could only be fixed at a lab able to reseal the seal under a vacuum chamber. An FMEA on the capacitor sensor can be seen in appendix A-1.

7.0 Design for Economics

The total budget set aside for this project was $500, but these funds weren't physically allocated to Team 15. It is expected out-of-pocket costs spent on the project will be reimbursed. Taking $500 as the minimum for the expected allocated budget, the total cost of the project was roughly $160. Thus, 32% of the total budget was exhausted. Figure 15 has the percentage of costs for each component.

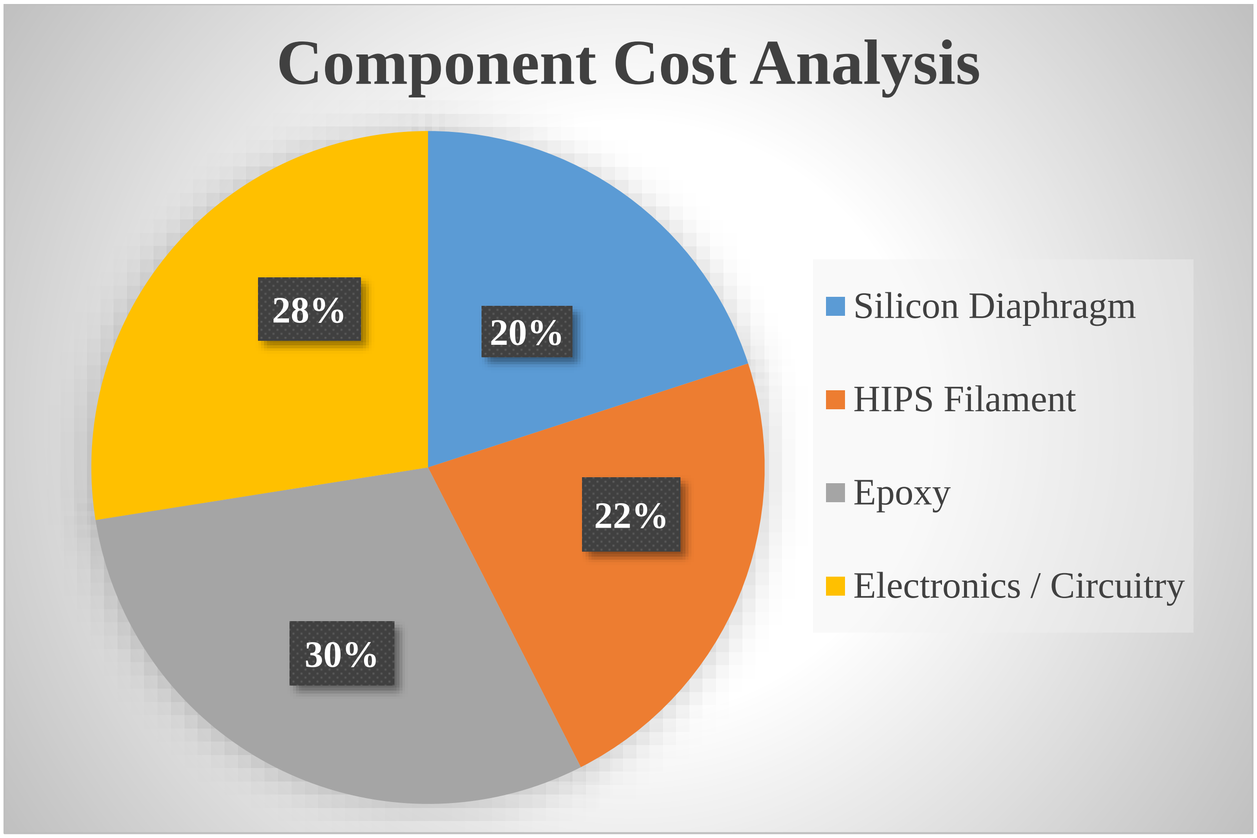


Figure 15 A pie chart depicting the breakdown of funds spent on the project as a number and a total percentage

Approximately 20%, $40, was spent on purchasing sheets of silicon for the top diaphragm. 30%, $60, was spent on purchasing several different epoxies that were used to create the capacitor base shell. The circuitry, 28% or $55, comprised of a significant chunk of the budget as expected. $340 or 68% of the $500 was unused. Since the price of the capacitance tracts is an estimate, a good price range for the pressure sensor is expected to be $145 – 160. It is difficult to compare the original, Nano scale pressure sensor to other competitors on the market. Most pressure sensors aren't built to be accommodated into the interstitial space (0.42mm) between the Multi-Layer Insulation.

8.0 Functional Analysis

The capacitor sensor will determine pressure as a function of distance between the parallel plates. This distance will vary depending on the pressure being exerted onto the top diaphragm. Due to the vacuum in the system as shown in figure 16, the top diaphragm will deflect as a function of pressure.

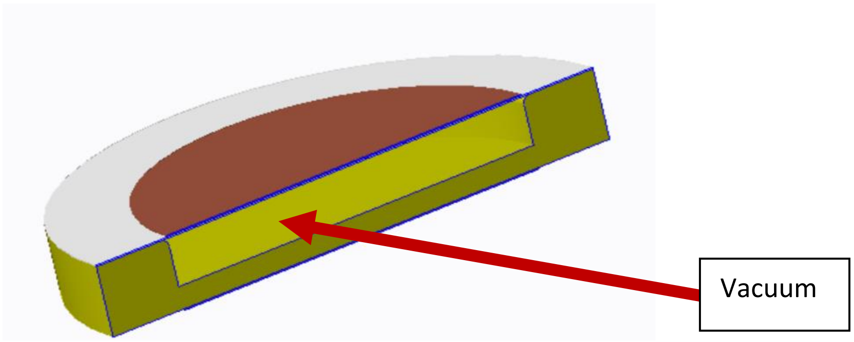


Figure 16 Capacitor pressure sensor with a vacuum chamber

The capacitor is placed in a Schering Bridge circuit as shown in figure 17 below. In the Schering Bridge, R_1, R_2, R_3, C_1 and C_2 are known, while C_3 is the project's capacitor sensor. In between nodes A and B, a voltmeter is attached to measure the voltage.

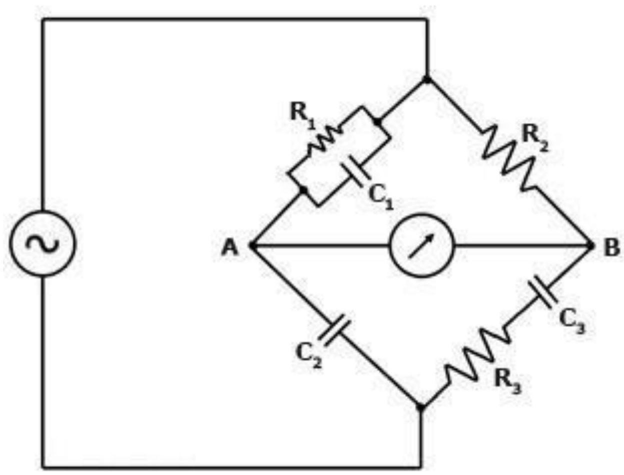


Figure 17 Schering Bridge

The microcontroller will then determine the capacitance of C_3, by adjusting C_1 and R_1 till the voltmeter reads 0 zero. When this occurs, the voltage at node A and node B are equal, thus the bridge is considered balanced. Once the bridge is balanced, the microcontroller will then use equation 10 determine the capacitance.

$$C_1 = \frac{R_1 * C_2}{R_2} \qquad \text{Eq. 10}$$

The microcontroller will then use equation 11 to determine the distance between the two parallel capacitance plates.

$$d = \frac{\varepsilon A_{S,c}}{C} \qquad \text{Eq. 11}$$

Where ε is the permittivity of the dielectric, $A_{s,c}$ is the surface area of the capacitor plate, C is the capacitance. Pressure can then be related to the change in distance using equation 12.

$$d = \frac{-3\Delta P r^4\left[\left(\frac{1}{\nu}\right)^2 - 1\right]}{16E\left(\frac{1}{\nu}\right)^2 h^3} \qquad \text{Eq. 12}$$

Where ΔP is the difference in pressure, r is the radius of the diaphragm, ν Poisson ratio, E young's modulus, and h can be seen in equation 13.

$$h = \sqrt{\frac{3r^2\Delta P}{4\sigma_y}} \qquad \text{Eq. 13}$$

where r is the radius of the diaphragm, ΔP is the difference in pressure, and σ_y is the yield stress of the diaphragm.

9.0 Operation Instruction

Assemble a Schering bridge as show in figure 1. In the Schering Bridge, R_1, R_2, R_3, C_1 and C_2 are known, while C_3 is the project's capacitor sensor. In between nodes A and B, a voltmeter is attached to measure the voltage. Once the Schering Bridge is assembled, place the capacitor sensor in the environment that is being measured. Turn on the microcontroller when ready to measure pressure. The micro controller will calculate the pressure based off the deflection of the diaphragm and display it on the screen.

9.1 Troubleshooting

There are three issues that are of concern. The first being that the seal keeping the vacuum cavity breaks making the sensor inoperable. Since this seal must be created in a lab with a vacuum chamber, immediate repair cannot be done and must be fixed in a lab. However, a second sensor can be stored so that the entire sensor can be replaced instead of fixing one component. Another problem is if the integrated circuit breaks or malfunctions. This can be fixed if certain individual components of the circuit break. However, if something such as outgassing occurs the circuit must be replaced. Another issue that could occur is if the sputtering faded away with time. If this happens the sputtered surface must be re-doped.

9.2 Project Assembly

Figure 18 shows an exploded view of the capacitor pressure sensor. Part 1 in figure 3 is the Palladium- Gold sputtered tracts, part 2 is the silicone diaphragm and part 3 is the silica core or epoxy core for scaled prototype. A Schering bridge as shown in figure 17. In the Schering Bridge, R_1, R_2, R_3, C_1 and C_2 are known, while C_3 is the project's capacitor sensor. In between nodes A and B, a voltmeter is attached to measure the voltage.

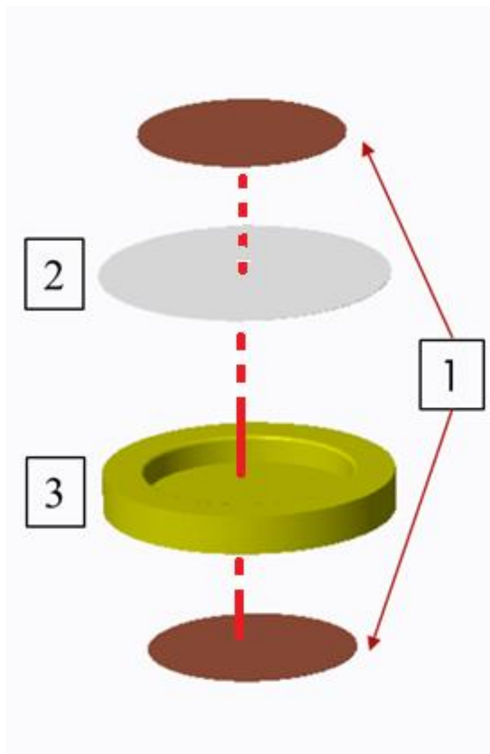


Figure 18 (1) Palladium-Gold sputtered tracts. (2) 0.50 μm thickness Silicone diaphragm. (3) Germanium doped silica base

10.0 Obstacles

When sealing the vacuum inside of the sensor, an adhesive must be used to attach the diaphragm to the sensor base. However, most adhesives will begin to set thermally, or via oxidation, within a few minutes. Evacuating the air from a vacuum chamber takes time, and there is no ability to touch the sensor under these conditions. The evacuation time can range between 5-10 minutes, depending on the vacuum pump being used. Due to the inability to touch the sensor in the vacuum, the adhesive polymer which connects the diaphragm to the base must be placed on the sensor rim before it is brought down into vacuum. Accounting for the time needed to bring the vacuum down, it was evident that most all adhesives would self-cure before the diaphragm was ready to be attached. This issue pushed our team to do research into adhesives that can be externally cured from the vacuum chamber at a designated time. The vacuum chamber we had access to, had a clear thick acrylic lid, where light can easily be able to passed through. With this knowledge, UV-set polymers seemed like the best alternative, as the polymers were used in the fiber optic sensor production research papers we encountered.

During the production of the prototype, our team encountered an issue with the UV reactive polymer chosen to adhere the silicone diaphragm to the epoxy base. When reading the product data sheet, it ensured a strong bond to rubbers. The real result however was abysmal. There was some tact to the polymer, and it adhered great to the epoxy base, yet it would not form a tight enough seal on the silicone to adequately seal the vacuum inside the sensor. The only other UV curable polymer solution was extremely out of the budget, $600 pint, due to the polymer being a proprietary formula. Attempts were made to negotiate the price with the company since it would be for a school project, but Masterbond would not negotiate due to the formula being proprietary. To have continued with the sensor production, a new diaphragm would need to be chosen. However, upon doing research, we could not find an alternative which had similar elastic characteristics and working temperature. Due to these reasons, the prototype production came to a halt and was not able to be completed.

11.0 Conclusion

Multi-Layer Insulation, MLI for short, is a material that is used to reduce the amount of heat transfer in space. This material is wrapped around cryogenic propellant tanks in order to reduce the boil off rate of the fluids. There is only one form of heat transfer in a vacuum, which is radiation. It is possible for convection to occur if air is trapped in the mesh like spacers of the MLI. If air is present, the heat transfer will increase which will in turn increase the boil off rate. Using a pressure sensor, one can determine the amount of air trapped within the layers in order to have a more accurately calculated the heat transfer through the MLI.

One of the major obstacles for this project is the working conditions. MLI is very thin with a spacing of roughly 0.42mm per layer. This poses a problem as large pressure sensors can deform and potentially damage the MLI when entering space. Space presents another problem as working in a vacuum prevents the movement of heat. Any heat that is produced by the sensor will not dissipate and can affect the boil off of the fluids. Also some materials act differently in space then on earth and should be avoided.

A house of quality was used to determine the relation between customer needs and engineering requirements. From the HOQ, it was determine that power consumption was the most important engineering characteristic. All engineering characteristics was used during conceptual design phase, but power consumption was heavily considered when creating the design. Three different concepts were designed. The three designs are single stage capacitor pressure sensor, multi-stage capacitor pressure sensor and fiber optic pressure sensor. With the use of a decision matrix, the fiber optics design was determined to be the most ideal concept followed by the multi-stage capacitor pressure sensor. The fiber optics design can be bought from the private market, from FISO, so team 15 pursued creating the single stage capacitor design. It is not viable to pursued the multi-stage capacitor before verifying the single stage capacitor will function, so the single-stage capacitor advanced to the prototype phase.

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Appendix

Key Part	Potential Failure Mode	Potential Failure Effects	Severity	Potential Causes	Occurance	Current Control	Key Part	Potential Failure Mode
Palladium Gold Sputtered Capacitance Plate	Doping Surafce Wears Off	Renders Sensor Inoperable	10	Wore Down by the Sun	1	Check Sensor Every Three Months	9	5
	Surface Breaks	Renders Sensor Inoperable	10	Damage by Collision or Enviromental Effects	1	Check Sensor Every Three Months	8	5
Silicone Diaphram	Diaphram Ruptures	Renders Sensor Inoperable	10	In a High Pressure Enivroment	1	Ensure Control of the Pressure of the Enviroment	6	5
Silica Capacitor Plate	Plate Cracks	Renders Sensor Inoperable	10	Enviroment	1	Check Sensor Every Three Months	9	5
Integrated Circuit	Circuit Breaks or Cracks	Cannot View Measurement	9	Outgassing	3	Check Several Times Before Launch that Circuit Has Been Expelled of All Gas	10	8
	Circuit Malfunctions	Cannot View Measurement	9	Coponent Breaks	2	Test Circuit Before Launch	9	3

Acknowledgements

We would like to thank James Martin, and NASA Marshall Space Flight Center, for their continued assistance throughout the project. His timely responses have helped us proceed in a quickly manner. We would also like to thank Dr. Guo for his guidance throughout the entire project especially during the brainstorming process.

Biography

Sebastian Bellini is a senior mechanical engineer studying at Florida State University. Sebastian is specializing in thermo fluids. He enjoys reverse engineering designs and enjoys understanding how it works. He is hoping to pursue a career in design and test of products.

Jason Carvalho is a senior mechanical engineer at Florida State University. He has an interest in thermal-fluid science and plans to pursue a career in that track preferably with NASA. Some of his hobbies include playing chess and reading.

Michael Kiefer is a senior mechanical engineer at Florida State University. Michael specialized in materials and thermal fluids. He particular enjoy thermal fluid design. Michael is currently a member of the Florida Army National Guard and loves serving his country. He is looking forward to entering the workforce and navigating all the challenges associated with it.

Stephen Johnson is a senior mechanical engineer studying at Florida State University. He is specializing in robotics. He enjoys designing concepts and bring the design to life. Stephen is skilled in 3-D printing and creates designs to print as a hobby. He is looking to pursue a career in robotics.

Constants

$tensile\_modulus\_epoxy := 16827\ psi$

$length\_cylinder := 3.5\ mm$

$diameter\_diaphragm := 25\ mm$

$radius\_diaphragm := \frac{diameter\_diaphragm}{2}$

$radius\_diaphragm = 12.5\ mm$

$\mu := 0.35$

http://cdn.fibreglast.com/downloads/00343-A.pdf

http://www.montana.edu/composites/documents/3D%20Static%20Property%20Report.pdf

https://shellbuckling.com/papers/classicNASAReports/NASASP-8007.pdf

http://www.colorado.edu/engineering/CAS/courses.d/Structures.d/IAST.Lect03.d/IAST.Lect03.pdf

Initial Guess of Thickness for Cylinder Shell

$shell\_thickness := 5\ mm$

$outer\_radius := radius\_diaphragm + shell\_thickness$

$outer\_radius = 17.5\ mm$

$outer\_diameter := outer\_radius \cdot 2 = 35\ mm$

Determining Critical Pressure via Buckling/Bending

$$\phi := \frac{1}{16}\left(\sqrt{\frac{outer\_radius}{shell\_thickness}}\right)$$

$\phi = 0.117$

$\gamma := 1 - 0.731\left(1 - e^{-\phi}\right)$

$\gamma = 0.919$

$$Pressure\_critical := \frac{0.855}{\left(1-\mu^2\right)^{\frac{3}{4}}} \frac{tensile\_modulus\_epoxy \cdot \sqrt{\gamma}}{\left(\frac{outer\_radius}{shell\_thickness}\right)^{\frac{5}{2}} \cdot \left(\frac{length\_cylinder}{outer\_radius}\right)}$$

$Pressure\_critical = 22.887\ MPa$

For SCALED DOWN model

Constants

$young\_modulus\_silica := 70\ GPa$

$length\_cylinder := 300\ \mu m$

$diameter\_diaphragm := 125\ \mu m$

$$radius\_diaphragm := \frac{diameter\_diaphragm}{2}$$

$radius\_diaphragm = 62.5\ \mu m$

$\mu := 0.17$

Initial Guess of Thickness for Cylinder Shell

$shell\_thickness := 20\ \mu m$

$outer\_radius := radius\_diaphragm + shell\_thickness$

$outer\_radius = 82.5\ \mu m$

$outer\_diameter := outer\_radius \cdot 2 = 165\ \mu m$

Determining Critical Pressure via Buckling/Bending

$$\phi := \frac{1}{16}\left(\sqrt{\frac{outer\_radius}{shell\_thickness}}\right)$$

$\phi = 0.127$

$$\gamma := 1 - 0.731\left(1 - e^{-\phi}\right)$$

$\gamma = 0.913$

$$Pressure\_critical := \frac{0.855}{\left(1-\mu^2\right)^{\frac{3}{4}}} \frac{young\_modulus\_silica \cdot \sqrt{\gamma}}{\left(\frac{outer\_radius}{shell\_thickness}\right)^{\frac{5}{2}} \cdot \left(\frac{length\_cylinder}{outer\_radius}\right)}$$

$Pressure\_critical = 465.147\ MPa$