Conceptual Design and Selection

Team 15

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

Team Members:

Sebastian Bellini- Sab13j
Jason Carvalho- Jc12v
Michael Kiefer- Mbk13
Stephen Johnson- Ssj12

Faculty Advisor

Dr. Wei Guo

Sponsor

James Jim Martin

10/21/2016

Table of Contents

Table of Figures

Table of Tables

Abstract

Team 15, sponsored by the NASA Marshall Space Flight Center, is 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 that it maintain the MLI's structural integrity, minimize heat flow into the interstitial space, minimal power consumption and have a minimum response time of 1 second. The device will be tested from the atmospheric pressure range of 101 kPa (760 torr) to a pressure as low as 10^{-2} Pa (10^{-3} torr). 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: Sound Acoustic Wave Pressure Sensor, Piezoelectric Pressure Sensor and Fiber Optics Pressure sensor. Afterwards, a decision matrix was used to determine fiber optics as the most viable option.

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 spacer. 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 from the ranges of 101kPa to 10^{-2} Pa.
- 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 work from a range of 101 kPa to 10^-2 Pa (760 torr to 10^{-3} torr).

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.

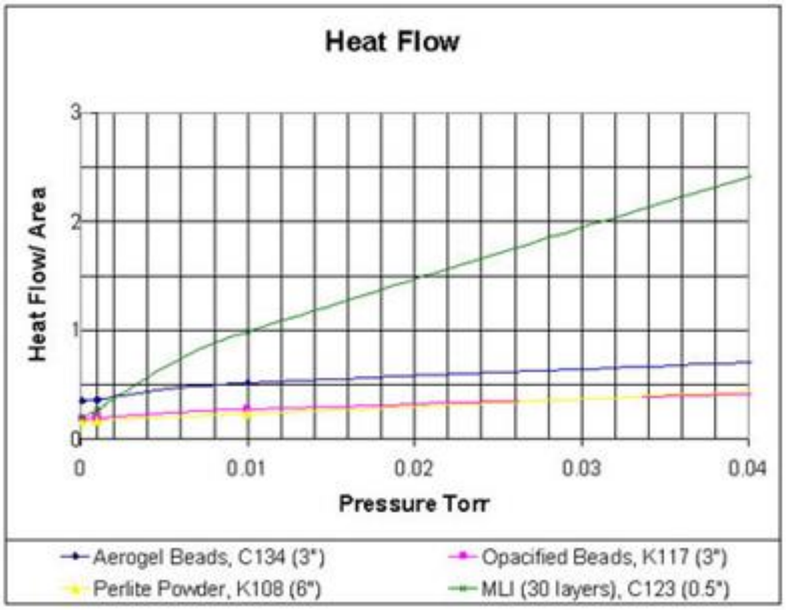


Figure 1 The Performance of Cryogenic Insulation systems at various interstitial pressures[1]

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.

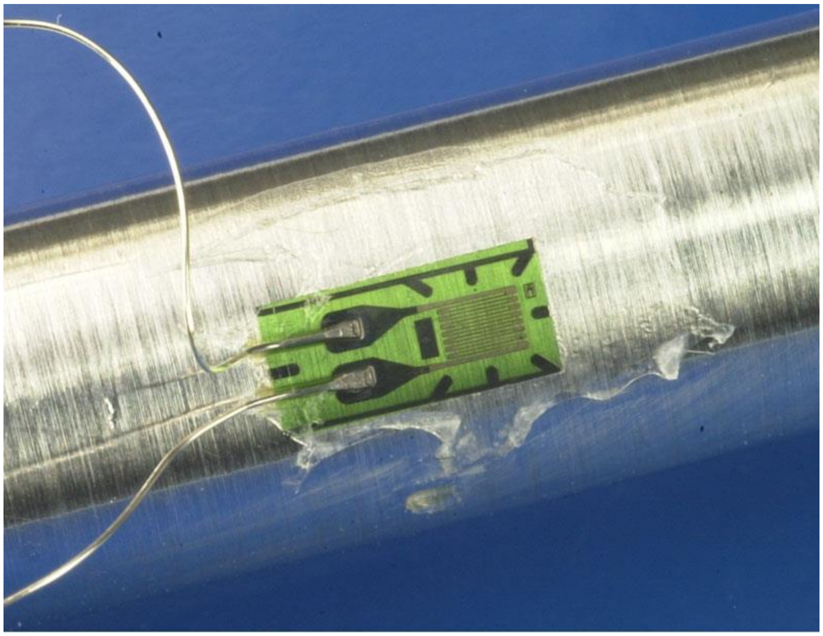


Figure 2 Strain gauge on a cylindrical object[5]

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.

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.

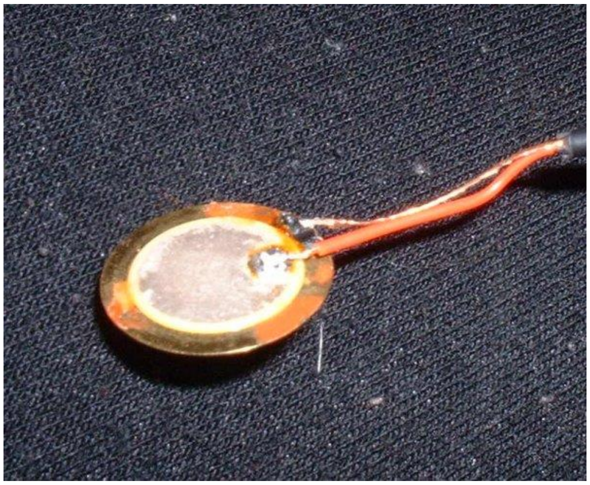


Figure 4 A piezoelectric transducer[7]

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%).[8]

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.[9]

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.[10]

2.5.3 Working Environment (Space)

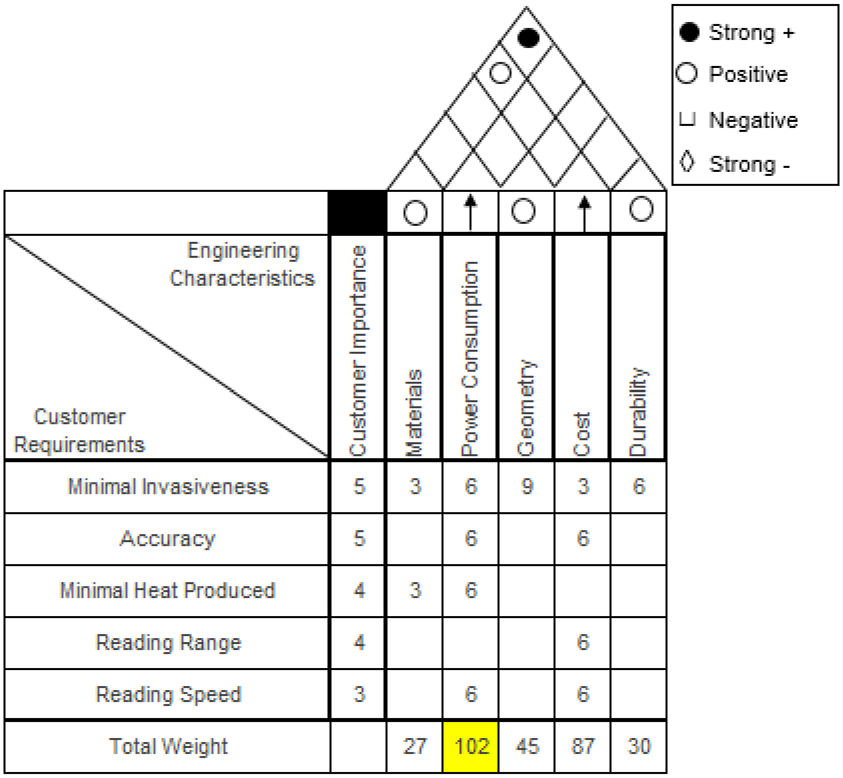
Space is the working environment of this project. Space is a vacuum therefore materials and laws act differently in space then they would on earth. In a vacuum, heat transfer doesn’t react the same way as it does on Earth. This is because since there is no air, convection cannot occur, which leaves radiation 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 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



Engineering Characteristics / Customer Requirements	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

3.2 Conceptual Design

3.2.1 Sound Acoustic Wave Pressure Sensor

In this design there are two main components: the transmitter and the receiver. As you can see from figure 5 below, the two main components fit in between the layers of the MLI. The transmitter sends a mechanical wave through the empty space to the receiver. The receiver measures the transmit time or a wave characteristic (wavelength, polarization, etc.) and correlates this value to get the pressure.

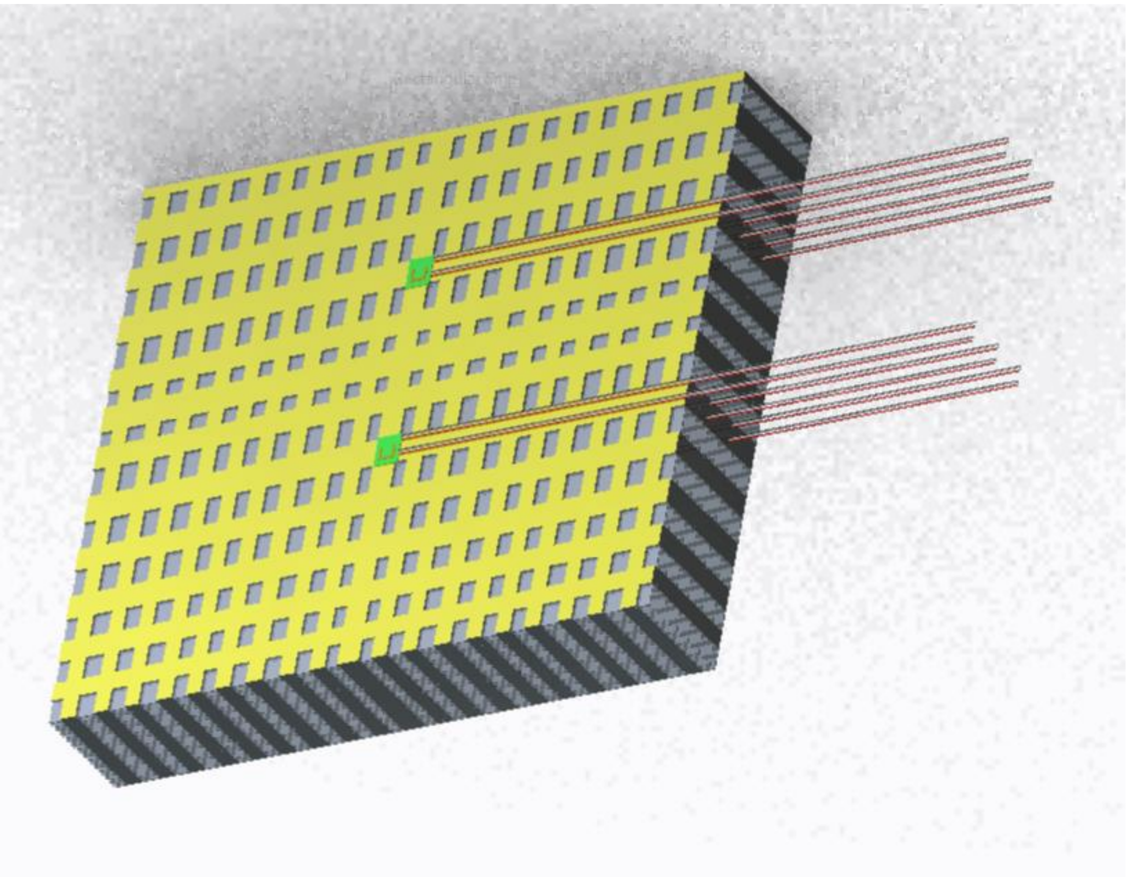


Figure 5 SAW placed within the MLI

3.2.2 Piezoelectric Pressure Sensor

In this design the piezoelectric sensor fits in between the layers as can be seen in figure 6 below. When the quartz crystal inside feels a stress it sends out an electrical signal which can be measured and correlated to pressure with the help of a microchip or computer.

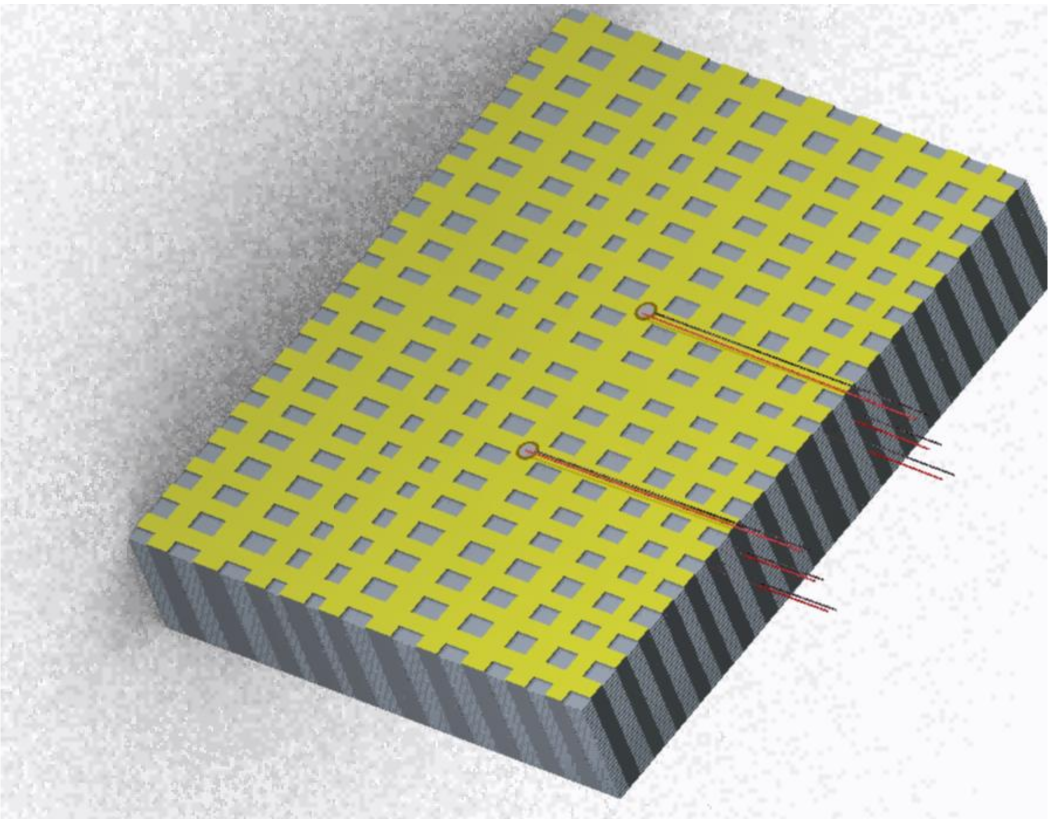


Figure 6 Piezoelectric pressure sensor on the MLI

3.2.3 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.

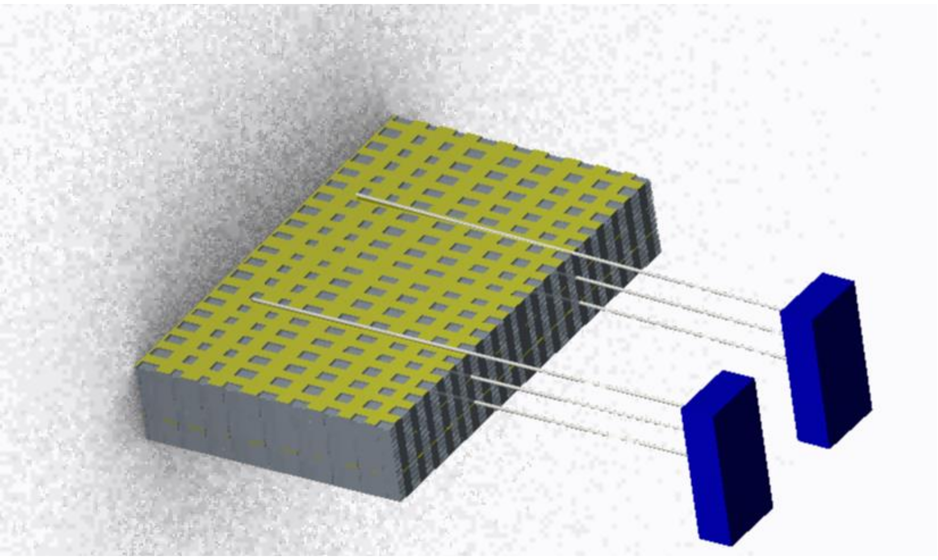


Figure 7 Fiber optics sensor embedded within the MLI

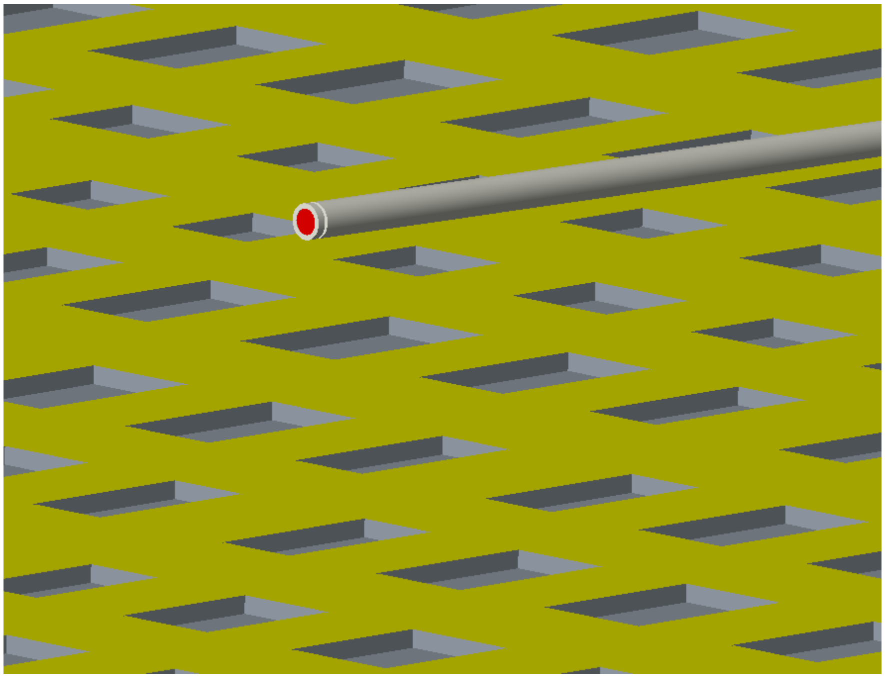


Figure 8 Close up on the end of a fiber optics cable

3.3 Design Specs

Table 2 Design specs for the different concepts

Sensor type	Size	Pressure Measuring Range	Operating Temperature Range	Stress allowed	Power
Piezoelectric	38.1 x 63.5 x 0.1905 mm	21 kPa - 100 Mpa	Varies With Design	Varies with Quartz geometry	N/A
Sound Acostic Wave IDT	0.1 x 0.1 x 0.002 mm	0 - 100 Mpa	-35 to 150 °C	5 MPa	9.5 V
Sound Acostic Wave Antenna	Base: D=5mm	1 - 100 Mpa	-35 to 150 °C	22 MPa	9.5 V
Fiber Optic	125 micometers	10^{-12} - 10^{12}Pa	-65 to 200 °C	690 Mpa	Varies

Based on the size of all three, each design could potentially work. However, the Sounds acoustic wave and the fiber optic would be more convenient because of their ability to bend into tight crevices. The pressure reading for the sound acoustic wave and the fiber optic sensor meet the requirements given by the sponsor (10^{-2} Pa to 101 kPa). However, the piezoelectric cannot get close to vacuum, practically eliminating this option. For the operating temperature range, the fiber optic is most desirable because it operates at a lower temperature and the sensor will be close to cryogens. The piezoelectric sensor operating temperature range varies because it depends on the geometry of the quartz crystal. In terms of durability the fiber optic cable still comes on top at 690 MPa. Once again the stress allowed depends on the geometry of the quartz crystal for the piezoelectric design. In terms of power consumption, the piezoelectric sensor would be the best. This is because no input power is required to operate since it runs of the piezoelectric effect (material stress to current). 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

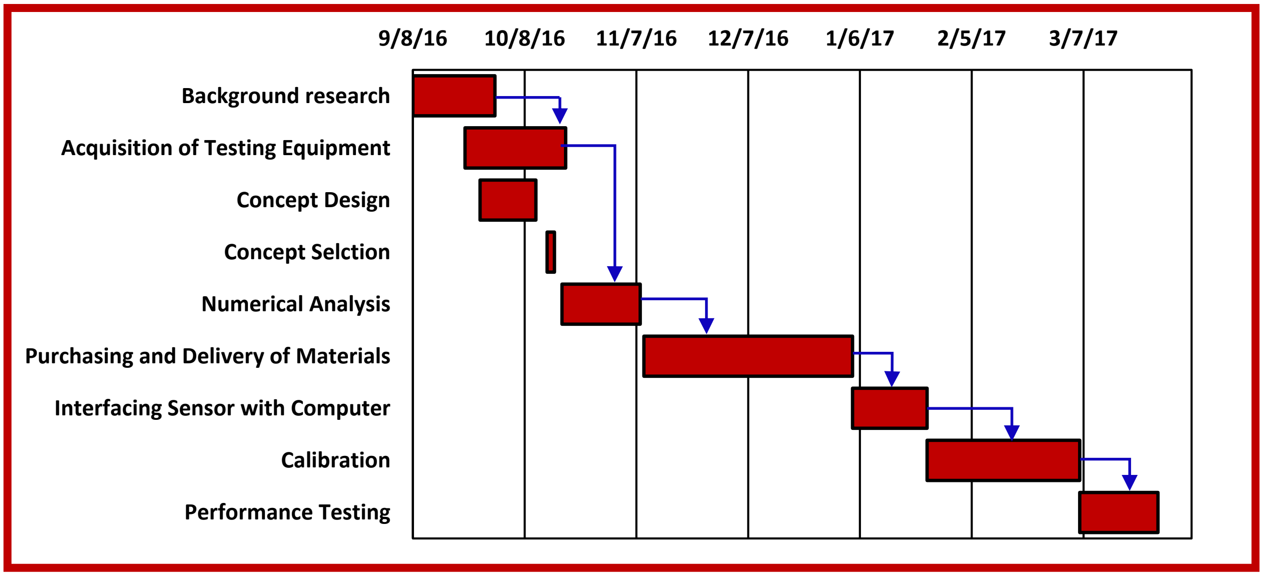
	SAW	**Fiber Optics**	**Piezoelectric**
Accuracy	0	1	-1
Minimal Invasiveness	0	1	-1
Heat Production	0	-1	0
Reading Range	0	1	-1
Reading Speed	0	0	0
Total	0	2	-3

After generating the three different designs a decision matrix was created in order to select one concept. The Sound Acoustic Wave (SAW) was selected to be the datum as can be seen in table 2 with the SAW scoring a 0. Piezoelectric scored worse than our datum with a score of -3. The piezoelectric sensor's accuracy varies depending on temperature and humidity, therefore the accuracy scored a -1. The piezoelectric sensor was the most invasive of the three designs and also had the smallest reading range. Fiber optics 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 and will work in any condition. Also the fiber optics sensor was the least invasive with a diameter of 125 µm (0.125mm). The reading range on the fiber optics sensor was larger than the SAW concept as well. 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 secondary concept would be the SAW and finally the third concept would be the piezoelectric sensor.

4. Methodology

4.1 Gantt Chart

Table 5 Gantt chart



As seen above in table 3, the Gantt chart contains the future planned time frames for the 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 were selected to have extra room in order to account for any delays that may occur. For a Gantt chart with more detailed dates, please refer to appendix A.

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 is tasked with creating and maintaining the website, as well as to assist the other team members when necessary. Stephen Johnson is the machine specialist. Mr. Johnson is currently tasked with computing the numerical analysis for the fiber optics design. Michael Kiefer is the lead financial advisor. Mr. Kiefer is currently tasked with assisting Mr. Johnson in the numerical analysis. Afterwards, Mr. Kiefer will tasked with creating a budget for the purchasing of materials necessary to develop a prototype. As a group the materials will be selected and purchased. Also as a group, the prototype will be assembled, calibrated and tested. Sebastian Bellini is 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. Conclusion

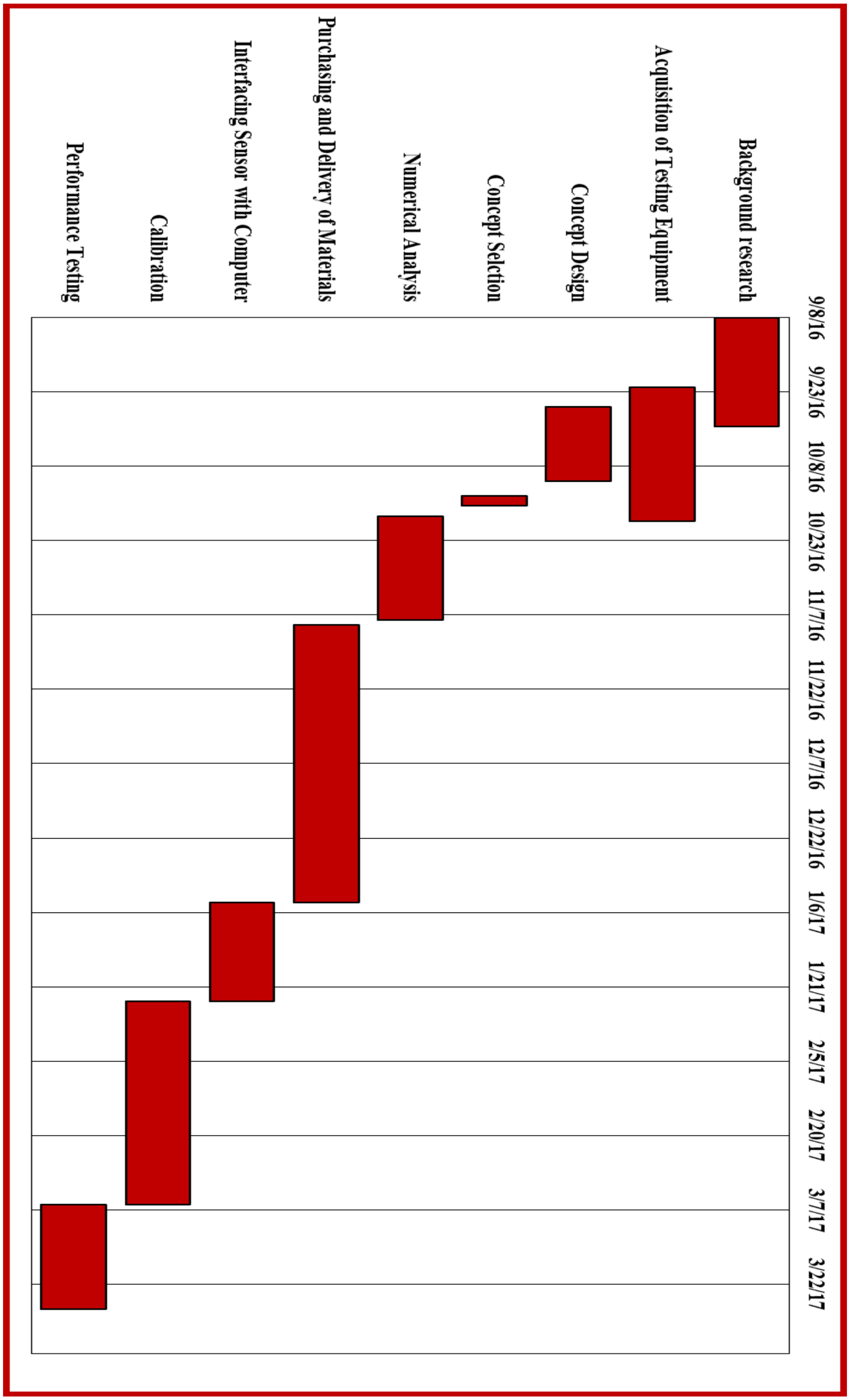
Multi-Layer Insulation, MLI for short, is a material that is used to reduce the amount of heat transfer in space. This material is wrapped around cryogenic propellant tanks in order to reduce the boil off rate of the fluids. There is only one form of heat transfer in a vacuum, which is radiation. It 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 less than 0.8mm 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 sound acoustic pressure sensor, piezoelectric 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.

The future steps are to compute the numerical analysis of the system and verify the design satisfies all customer needs. The materials will then be purchased and assembled to create a working prototype. Interfacing the sensor and calibrating the sensor will be the last steps before performing test of the system.

Appendix A


Background research
Acquisition of Testing Equipment
Concept Design
Concept Selection
Numerical Analysis
Purchasing and Delivery of Materials
Interfacing Sensor with Computer
Calibration
Performance Testing
9/8/16
9/23/16
10/8/16
10/23/16
11/7/16
11/22/16
12/7/16
12/22/16
1/6/17
1/21/17
2/5/17
2/20/17
3/7/17
3/22/17

Biography

Sebastian Bellini is a senior mechanical engineer studying at Florida State University. Sebastian is specializing in thermal 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 sciences but plans to pursue a career in the aeronautics track preferably working for NASA. After graduation, Jason plans to acquire a Masters in mechanical engineering and possibly study further. 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.