Needs Assessment

Team 15

Compact Pressure Sensing Device for Measuring Multi-Layer Insulation (MLI) Interstitial Vacuum

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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 760 torr to a pressure as low as 10^{-3} torr. The team hopes to approach this design challenge by researching current pressure sensing technologies with rapid response times, and develop a compact pressure sensor capable of being embedded in the MLI.

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 Definition

2.1 Need 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 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 Background Research

2.2.1 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.

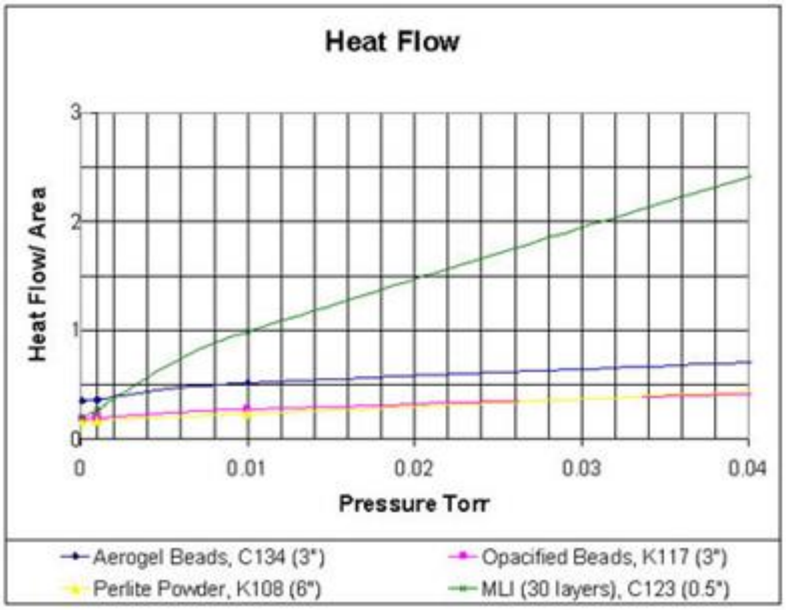


Figure 1 The Performance of Cryogenic Insulation systems at various interstitial pressures[1]

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.

2.2.2 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.

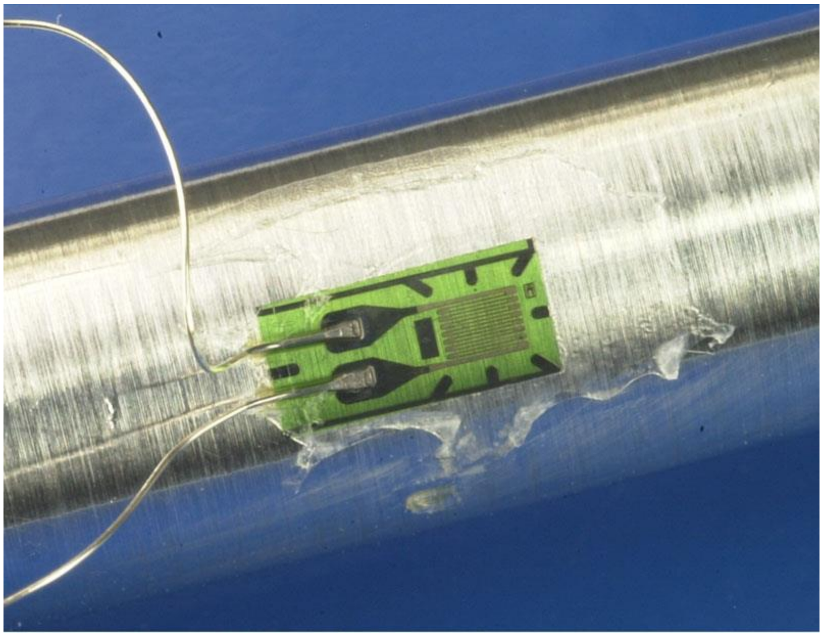


Figure 2 Strain gauge on a cylindrical object[5]

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.

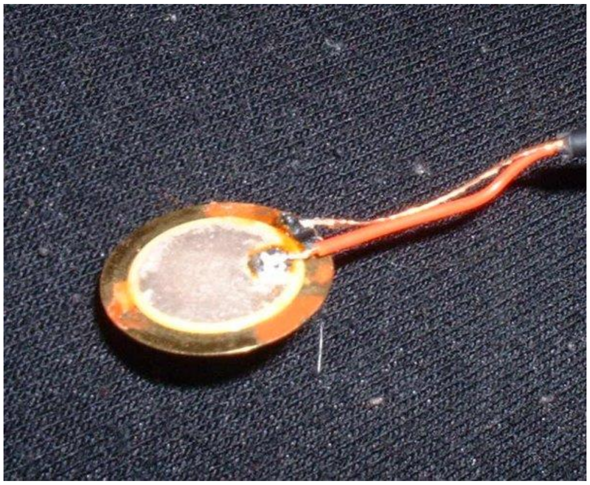


Figure 4 A piezoelectric transducer[7]

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]

2.2.3 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.

2.3 Goal Statement and 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 760 torr to 10^{-3} torr or better if capable.
- Minimize heat produced
- Reliable and able to work in space.
- Minimize power consumption.
- Minimize size in order to be as noninvasive as possible.

2.4 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 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.

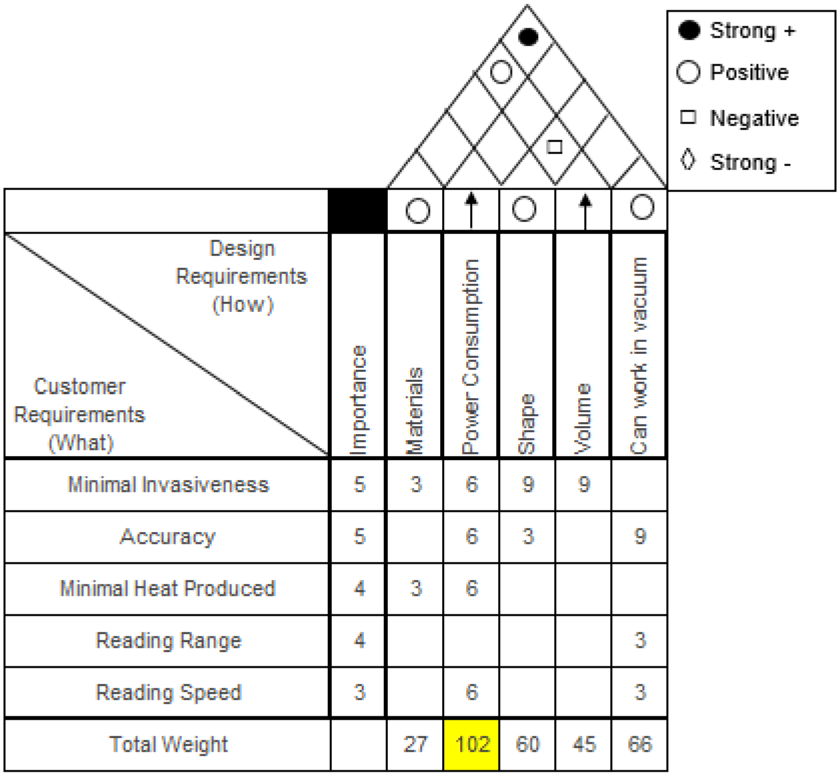
Out-gassing is caused by the release of gasses trapped inside of spacecraft materials. Out-gassing can coat the lenses used by sensors, and also allow electrical components to arc, destroying them. In order to combat out-gassing, the aircraft and components are "baked" before the flight in a thermal 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.

3. Methodology

3.1 House of Quality



Design Requirements (How) / Customer Requirements (What)	Importance	Materials	Power Consumption	Shape	Volume	Can work in vacuum
		○	↑	○	↑	○
Minimal Invasiveness	5	3	6	9	9	
Accuracy	5		6	3		9
Minimal Heat Produced	4	3	6			
Reading Range	4					3
Reading Speed	3		6			3
Total Weight		27	102	60	45	66

Figure 5 House of qualities

Figure 5 above represents the house of qualities, HOQ. This is a matrix that helps compare the customer's needs with the design requirements. From the HOQ, there is one noticeable design requirement with more importance than the others. That requirement is power consumption.

The reason power consumption scored so high on the HOQ is because suppling power to the sensor will generate heat, and this heat will not be able to dissipate. Also depending on how much power is used, the power lines can be too invasive and potentially damage the MLI during travel. Also power consumption has a direct correlation with reading speed as the more readings that are taken, the more power it will draw.

3.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. These obstacles must be taken into consideration during the design phase.

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