# Material Selection for Spacecraft Radiation Control and Radiative Heat Transfer

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**During this series of experiments, we investigated the effects of radiation on materials and the potential of various materials to be used as thermal and radiation shielding. We determined that polished and brushed aluminum are more effective for maintaining cool temperatures due to their high reflectivity, and that white and black coatings are more effective for heat absorption, with black aluminum being the most absorptive material and white aluminum being almost as emissive as the black aluminum. Additionally, we determined that lead shielding is the most effective at reducing radiation from a point source per unit of thickness, at the cost of increased mass. Finally, we created a multi-layer insulation design that would theoretically be extremely effective, but remains to be tested in the vacuum chamber.**

## Nomenclature

$A$ = area, $m^2$

$c$ = specific heat, $J\ g^{-1}\ °C^{-1}$

$D$ = absorbed dose, mRad

$I$ = sunlight intensity, $W\ m^{-2}$

$m$ = mass, kg

$\dot{Q}$ = radiative heat transfer, W

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$T$ = temperature, K

$\sigma$ = Stephan-Boltzmann constant, W $m^{-2}$ $K^{-4}$

$\varepsilon$ = emissivity

*Subscripts*

ca = cross-sectional area

## I. Introduction

Radiation and thermal control is an essential aspect of spacecraft design, as thermal control is crucial to normal operations of the spacecraft components and protection against radiation ensures mission longevity and is especially critical for human spaceflight. Additionally, the sole method of heat dissipation into the environment in space is radiation itself, so different materials, methods, and coatings are used to manage this radiative heat transfer including paints, polishing of metal surfaces, and multi-layer insulation. However, radiation can also be a major source of damage to the spacecraft, leading to component failures ranging from single-bit effects on processor data to intense degradation of sensitive electronics and sensors [1]. Seeing this as a possible mission-ending effect, Aerospace Engineers have spent decades and enormous amounts of money and energy perfecting shielding and mitigating techniques.

To this day however, no actually perfect method exists to mitigate all radiation damage. The best options are also unfortunately the most costly. For instance, lead is particularly effective at blocking certain types of radiation but it is also very dense. This means a launch vehicle will have to be very large and carry a lot of fuel to carry up lead shielded craft into space. The larger launch vehicle and increased fuel consumption means more money is spent on the mission and this is often implausible for companies and governments alike. This is the same problem most solutions to radiation damage face. Thus, engineers walk the fine line between minimalistic budgets and sufficient radiation mitigation.

Our lab experiment has several segments, each with their own goals. We intend to explore the penetrating power of radiation, its ability to be absorbed by different materials/coatings, and the methods by which engineers can protect spacecraft.

## II. Methodology

This lab included several experiments covering multiple topics. For this report, we will address them in four distinct sections:

A. Radiative Heat Transfer and the Radiation Environment (Experiment 1)

B. Radiative Heat Transfer and the Radiation Environment (Experiment 2)

C. Ionizing Radiation & Radiation Shielding

D. Maintaining Temperature: MLI (Multi-Layer Insulation) Blankets

Our testing was done over the course of several weeks during March and April 2022. This will be important to note given our results' dependency on temperatures. The location for all these tests was also the same: the Space Environments Laboratory in building 41 at Cal Poly SLO.

<u>Experiment A: Radiative Heat Transfer Pt. 1</u>

Our plan for this part of the lab test was to explore the different effects of radiation on a variety of materials. The most effective types of data for this type of experiment are temperature recordings, electrical resistances, and radiation counts. These were respectively measured using temperature probes, ohmmeters, and radiation sensors. Specifically, the probes were inserted into several bottles made of different materials and set in the sun to collect radiated heat. Our ohmmeter was used by probing the sides of a cube enclosing a lightbulb (See fig. 1) with two leads to test the electrical resistance of the materials comprising the sides of the cube. While testing this, our radiation sensor could read the voltage difference across the materials to give us further clarification on the absorbed radiation. The different materials of the bottles were black body material, white body material, and aluminum. The sides of the cube were made of black body material, white body material, polished aluminum, and brushed aluminum.

Both of these experiments had periods where lab technician inputs were not necessary. In order for our cube experiment to yield useful results, we needed to wait about 45 minutes for the cube to heat to a requisite temperature. Our bottles did not need time to reach any specific threshold. However, we did need to record the temperature changes over the course of about 40 minutes.

Aside from the heating period, the cube experiment took little preparation. We only needed to turn the apparatus on and gather the needed sensors. Our bottles required more pre-recording work. For those we needed to download logging software compatible with our temperature probes and prepare the bottles for the test. The bottles were filled with 300 milliliters of cool water and sealed using tape with the temperature probes in the water. After this we left them in the sun while a computer logged the temperatures from the probes over the course of 40 minutes.

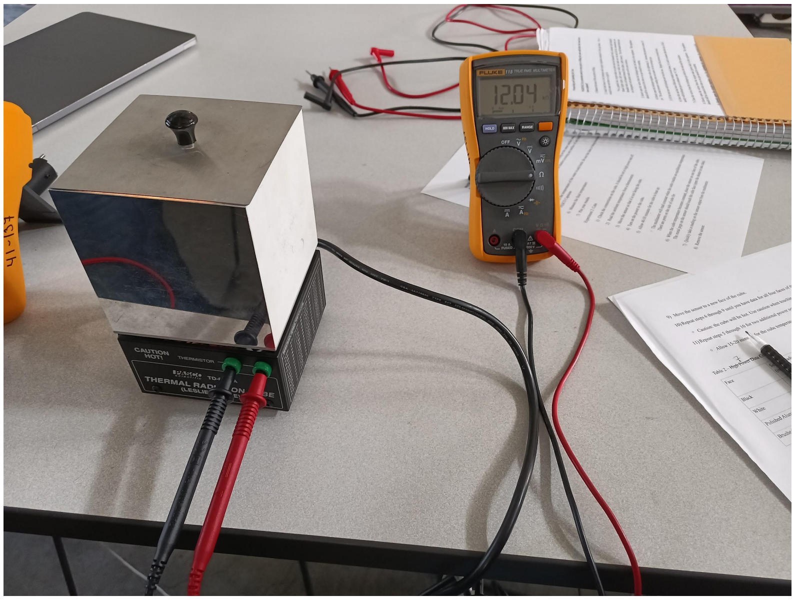

**Figure 1: Experiment A Thermal cube with thermal resistance probes. A lightbulb was lit inside the cube in order to radiate heat.**

Experiment B: Radiative Heat Transfer Pt. 2

This experiment was similar to that discussed in the previous section where we tested the change in heat of 3 bottles over the course of 40 minutes. For this lab we did a similar test using the same materials. The difference between that test and this is that for this test we used small solid cylinders of the materials (black body, white body, and aluminum) and we recorded the temperatures of the materials directly rather than an interior fluid.

Our apparatus (see fig. 2) was a stand which held the temperature probes on the ends of which we placed the cylinders. The cylinders had holes in which we could insert the probes for convenience. To best mitigate errors in our data, we tilted our probes to face directly at the sun so no sunlight could directly hit the sensors. Thus, most of the change in temperature was due to radiation absorbed by the cylinders on the ends of the probes. As with the previous experiment, we left the whole apparatus in the sunlight while a computer logged the temperature readings.

**Figure 2: Experiment B Temperature Probe Stand. The leads were connected to a logging device which was connected to a computer. [2]**

Experiment C: Ionizing Radiation & Radiation Shielding

This test was conducted to give us a more holistic view on the types of radiation a spacecraft can encounter in the radiation environment. In the previous two experiments, we looked at solar radiation. Here we were more interested in Ionizing Radiation and how deep its penetration can be felt.

Our procedure here required a simple setup. The materials needed were: a geiger counter, a test sample of the Cobalt 60 isotope, layers of shielding made of different materials, a caliper, and a ruler. For our setup, we placed our isotope sample against a vertical surface and then, between it and our geiger counter (oriented with the sensor side facing the radioactive sample), we set several layers of shielding (See fig. 3). The geiger counter required some inputs to record in the desired manner (Sampling period, testing mode, etc.). This was done alongside a ruler so we could measure the distance between the geiger counter and the sample. Our caliper was used to measure the thickness of the shielding. We estimated the thickness of individual layers by taking the shielding thickness and dividing by the number of layers.

The methodology for the test went as follows. We placed our geiger counter at various distances behind the shielding to test the effect distance has on radiation. Then we occasionally changed the material being used to shield the sensor and then continued measuring the radiation counts at different distances from the sample. We recorded the readings on a computer using logging software. At each location we let the geiger counter measure the radiation for 90 seconds.


**Figure 3: Experiment C Apparatus.**

Experiment D: Maintaining Temperature: MLI Blankets

This test was less defined by the Cal Poly faculty in that we had a choice in how we could construct our test sample. The goal of this experiment was to see the effect the space environment could have on radiation shielding. This was done by using the “Thing 1” vacuum chamber in the Space Environments lab and setting up an apparatus within that chamber. We placed two thermocouple sensors and an electronic strip-heater inside the chamber. The thermocouples were placed on the top and bottom surfaces of the MLI blanket constructed by the students (See below for MLI construction information). The strip heater was placed in an electric current which heated it and radiated heat towards the blanket. The amount of heat allowed to pass through the blanket determined its ability to shield a spacecraft from radiation. Data was only recorded while the vacuum was in place and thus heat could only be caused by radiation, not convection or conduction.

Students were allowed to build MLI blankets within their groups according to their own designs (One MLI blanket per group). Our group constructed a blanket however due to timing issues, we were unable to test our design. Given this issue, our professor has shared with us data corresponding to a similar MLI blanket. The main difference between our design was a decrease in layers of mylar for his design. Both of our designs utilized multiple layers of mylar with a kapton layer on the bottom face (nearest to the heater).

## III. Results and Discussion

Experiment A: Radiative Heat Transfer Pt. 1

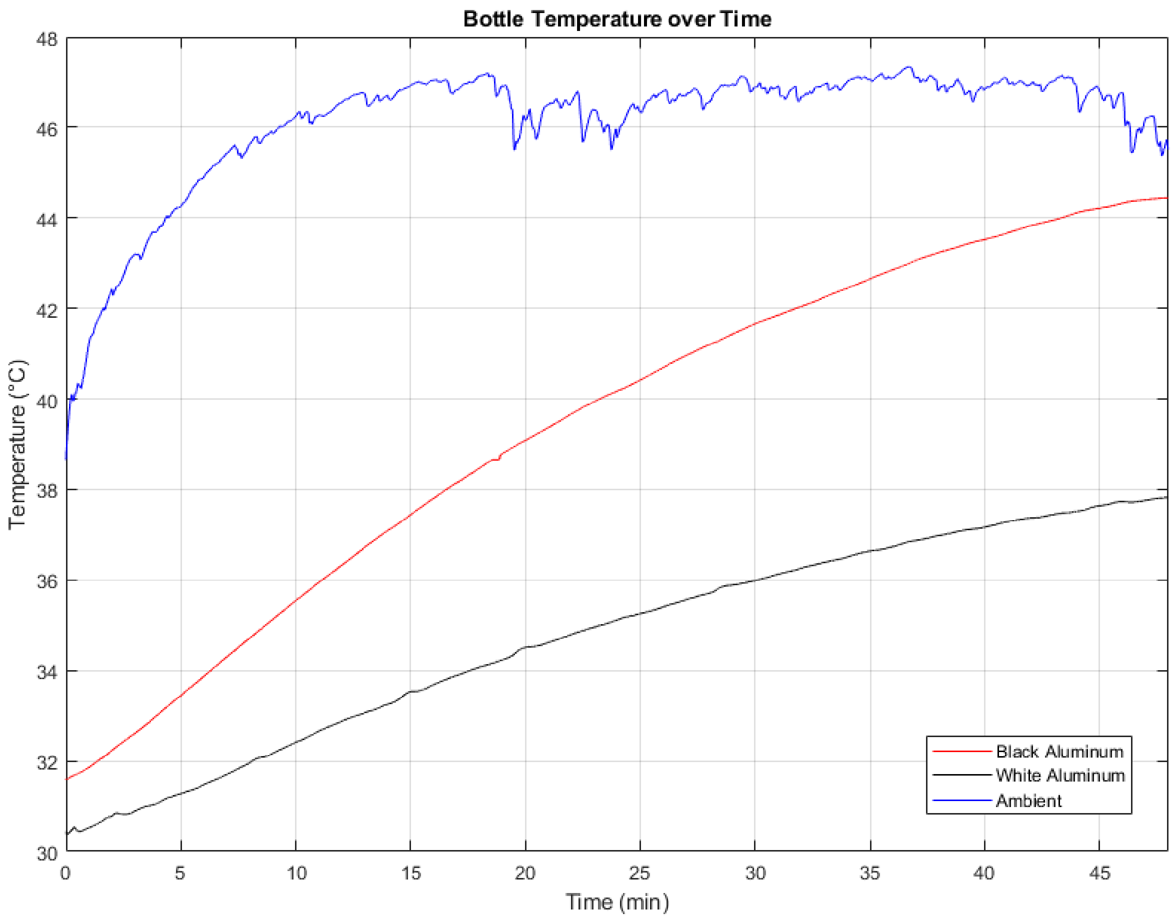


**Figure 4: Bottle temperature as a function of time**

The temperature of the bottles increased steadily until the black aluminum bottle approached the ambient temperature, thereafter leveling off. Unfortunately, the sensor for the brushed aluminum bottle failed to record data.

The results of the thermal cube experiment is displayed in Table 1 below:

| Setting | Face | Sensor Reading (mV) | Thermal Resistance (kΩ) | Temperature (°C) | Sensor Reading (mW) |
|---|---|---|---|---|---|
| 4 | Black | 4 | 40.75 | 46 | 0.182 |
| | White | 0 | 40.75 | 46 | 0.000 |
| | Polished Aluminum | 1 | 40.75 | 46 | 0.046 |
| | Brushed Aluminum | 1 | 40.75 | 46 | 0.046 |

| | | | | | |
|---|---|---|---|---|---|
| 7 | Black | 8.3 | 15.96 | 69 | 0.377 |
| | White | 8.1 | 15.96 | 69 | 0.368 |
| | Polished Aluminum | 0.6 | 15.96 | 69 | 0.027 |
| | Brushed Aluminum | 2.8 | 15.96 | 69 | 0.127 |
| 9 | Black | 11 | 10.71 | 80 | 0.500 |
| | White | 11 | 10.71 | 80 | 0.500 |
| | Polished Aluminum | 1 | 10.71 | 80 | 0.046 |
| | Brushed Aluminum | 4 | 10.71 | 80 | 0.182 |

**Table 1: Thermal cube readings**

When to use each type of material depends on the mission constraints. A polished aluminum finish would be more useful for its reflectivity being its primary advantage to brushed aluminum. Since the polished surface would reflect much of the external heat, the internal temperature the polished aluminum is surrounding would increase at a comparatively slower rate than the other materials that were tested. On the other hand, polishing aluminum smooths out the surface of the material and effectively reduces your surface area for heat dissipation. As such, brushed aluminum is an overall better material for heat dissipation while polished aluminum, while still decent in heat dissipation, is better if the heat source in question can be reflected (i.e. light). In general, the strictly black or white finish is less ideal than either polished or brushed aluminum, and as such should be used if aluminum would cause a corrosive action with another material, such as copper. In this event, settling for the overall less efficient options would be reasonable. White follows a similar idea to the polished aluminum in that it can reflect heat from a heat source. If black is used, it should be used for heat sink purposes as it will absorb heat due to its emissivity being equal (or approximately equal) to one.

Between the materials, the difference in emissivity is a driving factor in the difference in the heat transfer rates. Emissivity varies between zero (no heat transfer) and one (100% heat transfer). In general, lighter colored materials will have a lower emissivity than darker colored materials. This can also change due to the properties of some materials, such as the reflectivity of aluminum contributing to a lower overall emissivity. When determining a material for a spacecraft, the material chosen should generally have a lower emissivity unless the material has a significant issue that would be ill-suited for the particular mission. For example, a polished aluminum finish would have a lower emissivity, but the reflectance of the surface might prove detrimental to another system of the spacecraft and thus would be ineligible for being the chosen material.

Experiment B: Radiative Heat Transfer Pt. 2

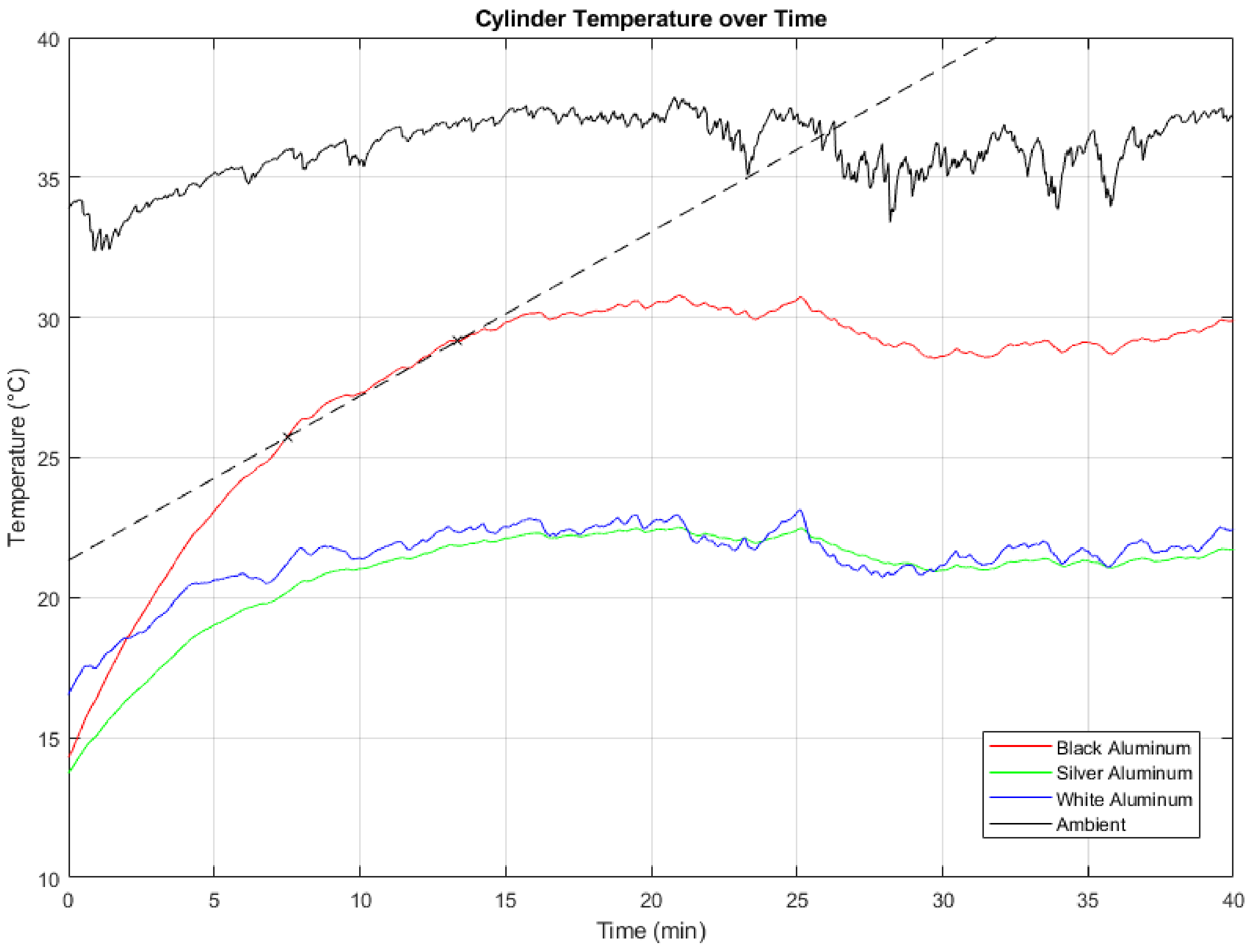


**Figure 5: Cylinder temperature as a function of time**

By performing a linear fit on the temperature of the black aluminum cylinder near its equilibrium temperature, we determined the rate of change of the temperature in this region to be

$$\frac{dT}{dt} = \frac{29.15\,°\mathrm{C} - 25.73\,°\mathrm{C}}{13.3325\ \mathrm{min} - 7.4992\ \mathrm{min}} = \frac{3.42\,°\mathrm{C}}{5.8333\ \mathrm{min}} = 0.5863\frac{°\mathrm{C}}{\mathrm{min}} = 0.009771\frac{°\mathrm{C}}{\mathrm{s}}$$

We used the provided value for the mass of the cylinder to be 0.029488 kg. Similarly, we used the provided dimensions of the cylinder, calculating the cross-sectional area to be

$$A_{ca} = ld = (0.0381\,\mathrm{m})(0.01905\,\mathrm{m}) = 7.2581 \cdot 10^{-4}\,\mathrm{m}^2$$

We used the specific heat of aluminum [5] to determine the solar intensity from the temperature rate of change:

$$I = \frac{mc\frac{dT}{dt}}{A_{ca}} = \frac{(29.488\,\mathrm{g})(0.8987\,\frac{\mathrm{J}}{\mathrm{g}\cdot{}^{\circ}\mathrm{C}})(0.009771\,\frac{{}^{\circ}\mathrm{C}}{\mathrm{s}})}{7.2581\cdot 10^{-4}\,\mathrm{m}^2} = 356.762\,\frac{\mathrm{W}}{\mathrm{m}^2}$$

We determined the error from the accepted value of the solar intensity [6] to be

$$error = \frac{1366\,\frac{\mathrm{W}}{\mathrm{m}^2} - 356.762\,\frac{\mathrm{W}}{\mathrm{m}^2}}{1366\,\frac{\mathrm{W}}{\mathrm{m}^2}} = 0.7388 = 73.88\,\%$$

While this error is relatively large, the actual value for the solar constant on the day we performed the experiment was likely slightly reduced by atmospheric and environmental factors, though it probably still exceeded 1000 W $m^{-2}$ as it was a clear and sunny day.

Experiment C: Ionizing Radiation & Radiation Shielding

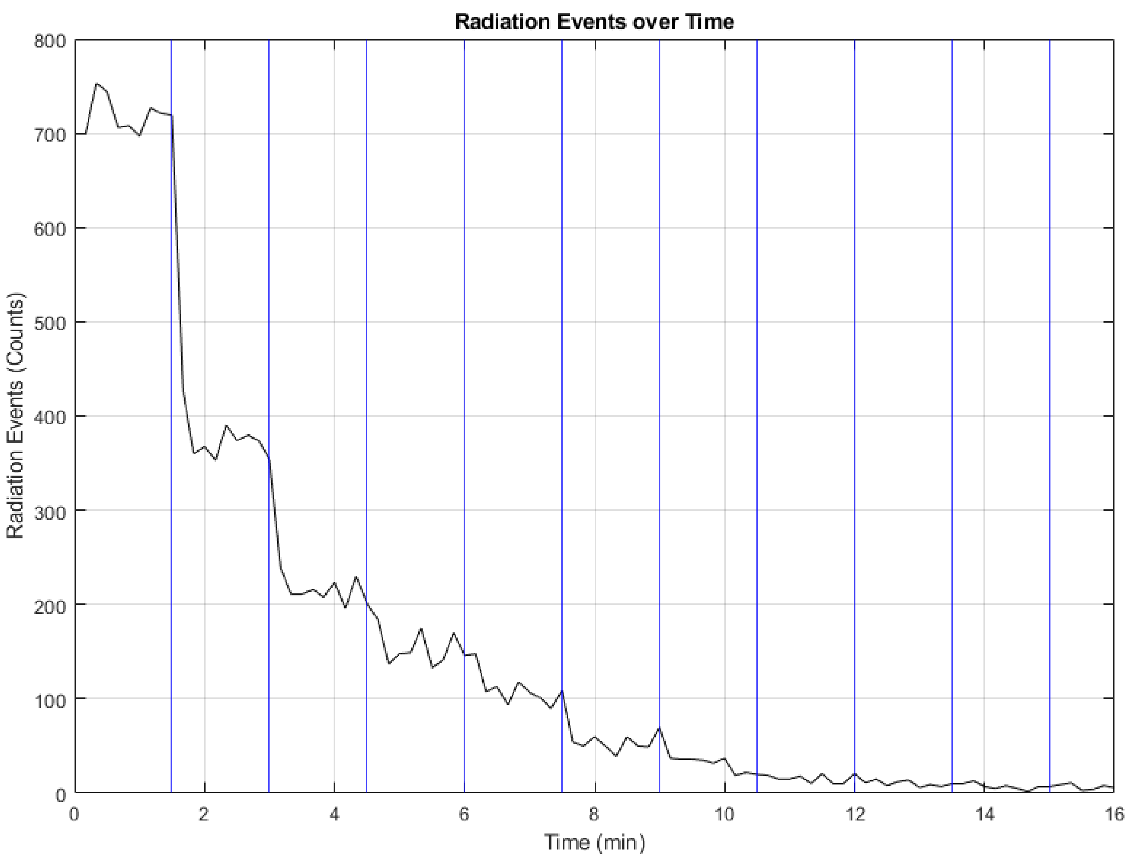


**Figure 6: Radiation events as a function of time**

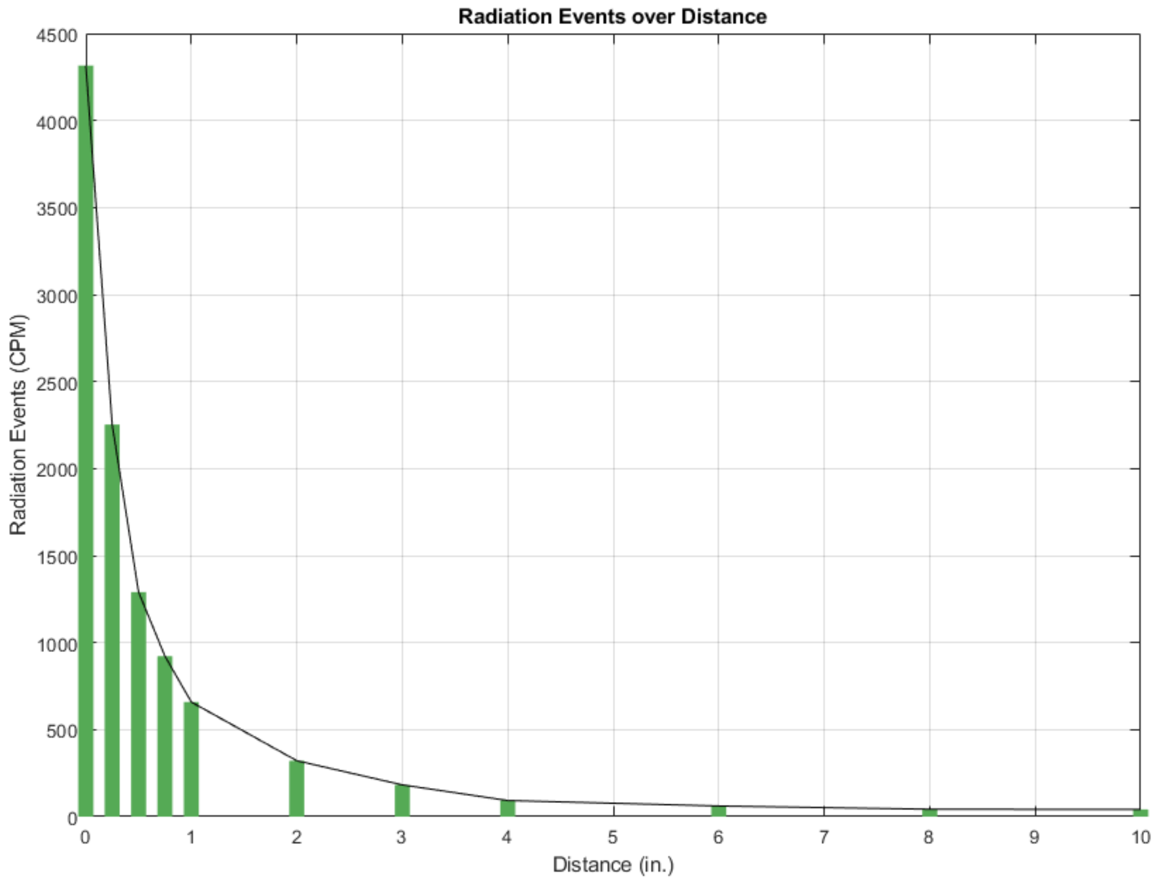


**Figure 7: Radiation events as a function of distance**

We determined that the radiation event counts per minute roughly followed the inverse-square law, dropping off proportionally to the square of the distance from the radiation source. At a distance of 3 inches, the absorbed dose from the radiation source would be

$$D_{3\text{ in.}} = (182.667\text{ CPM})\left(\frac{0.001\frac{\text{mR}}{\text{hr}}}{1\text{ CPM}}\right)\left(\frac{0.877\text{ rad}}{1\text{ R}}\right) = 0.1602\ \frac{\text{mrad}}{\text{hr}}$$

This dose is extremely minimal for any reasonable amount of time for the lab experiment, but could be detrimental if one experienced constant exposure to this radiation source, as the annual dose would be

$$D_{\text{annual}} = \left(0.1602\ \frac{\text{mrad}}{\text{hr}}\right)\left(\frac{8760\text{ hr}}{1\text{ yr}}\right)\left(\frac{0.01\text{ Sv}}{1\text{ rad}}\right) = 14.03\frac{\text{mSv}}{\text{yr}}$$

This is fairly substantial as it exceeds the average dose from background radiation on Earth, and is about 1.5 to 3 times higher than the absorbed dose from a single medical X-ray or CT scan [7].

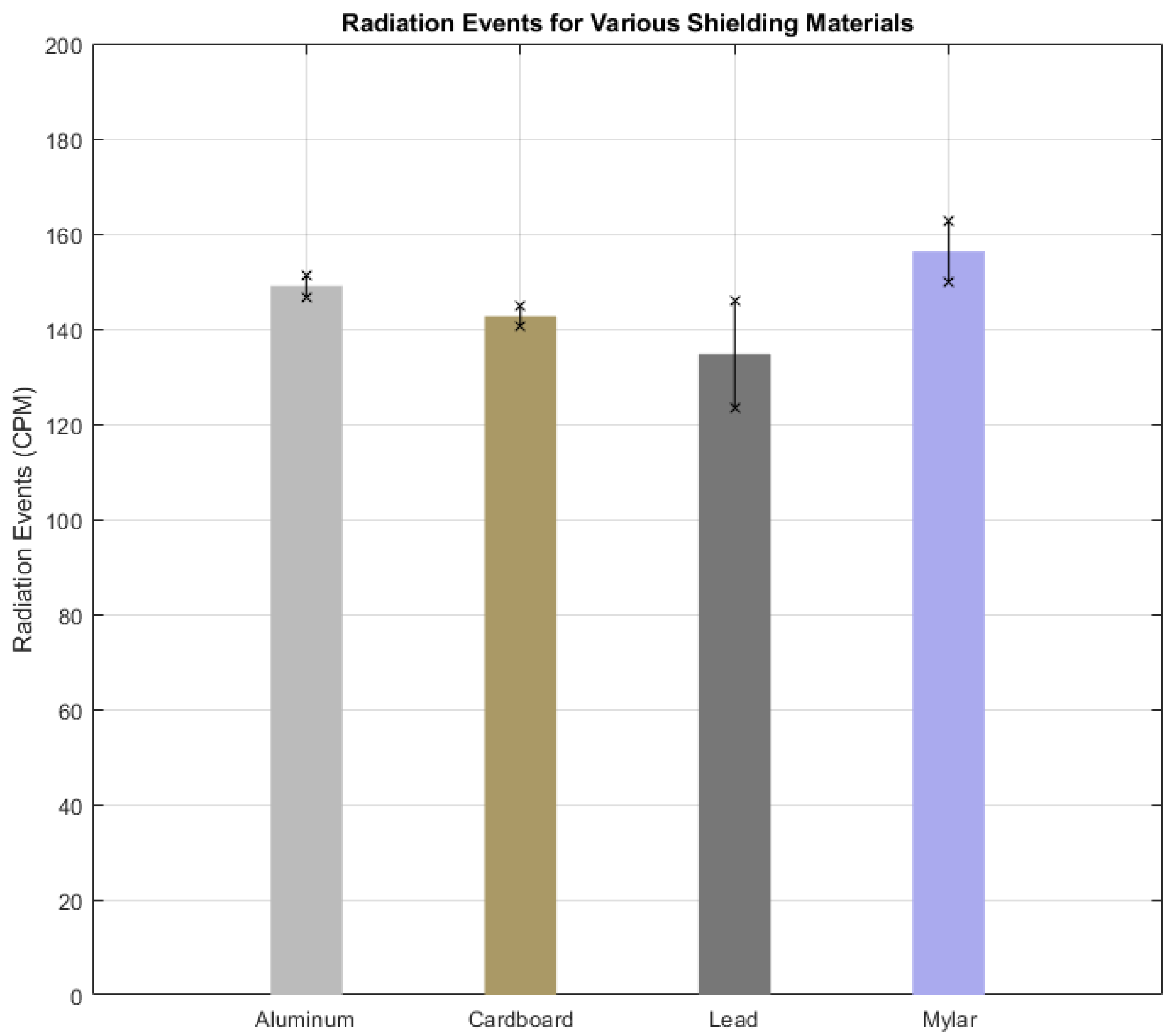


**Figure 8: Radiation events for each shielding material**

The radiation shielding materials performed mostly as expected, with the densest material, lead, being the most effective at reducing radiation events. Surprisingly, the cardboard shielding was the second most effective at reducing radiation events, but was also thicker than every other shielding material. When adjusted for thickness, the effectiveness of the lead shielding is much higher than the other three materials. However, it is also the most massive shielding due to its extremely high density. The mylar shielding is thicker than most of the other materials, but offers good performance per unit mass due to its extremely low density.

| Material | 3 Layer Thickness (in.) | 4 Layer Thickness (in.) |
|---|---|---|
| Aluminum | 0.293 | 0.395 |
| Cardboard | 0.317 | 0.422 |
| Lead | 0.169 | 0.212 |
| Mylar | 0.325 | 0.401 |

**Table 2: Radiation shielding thicknesses**

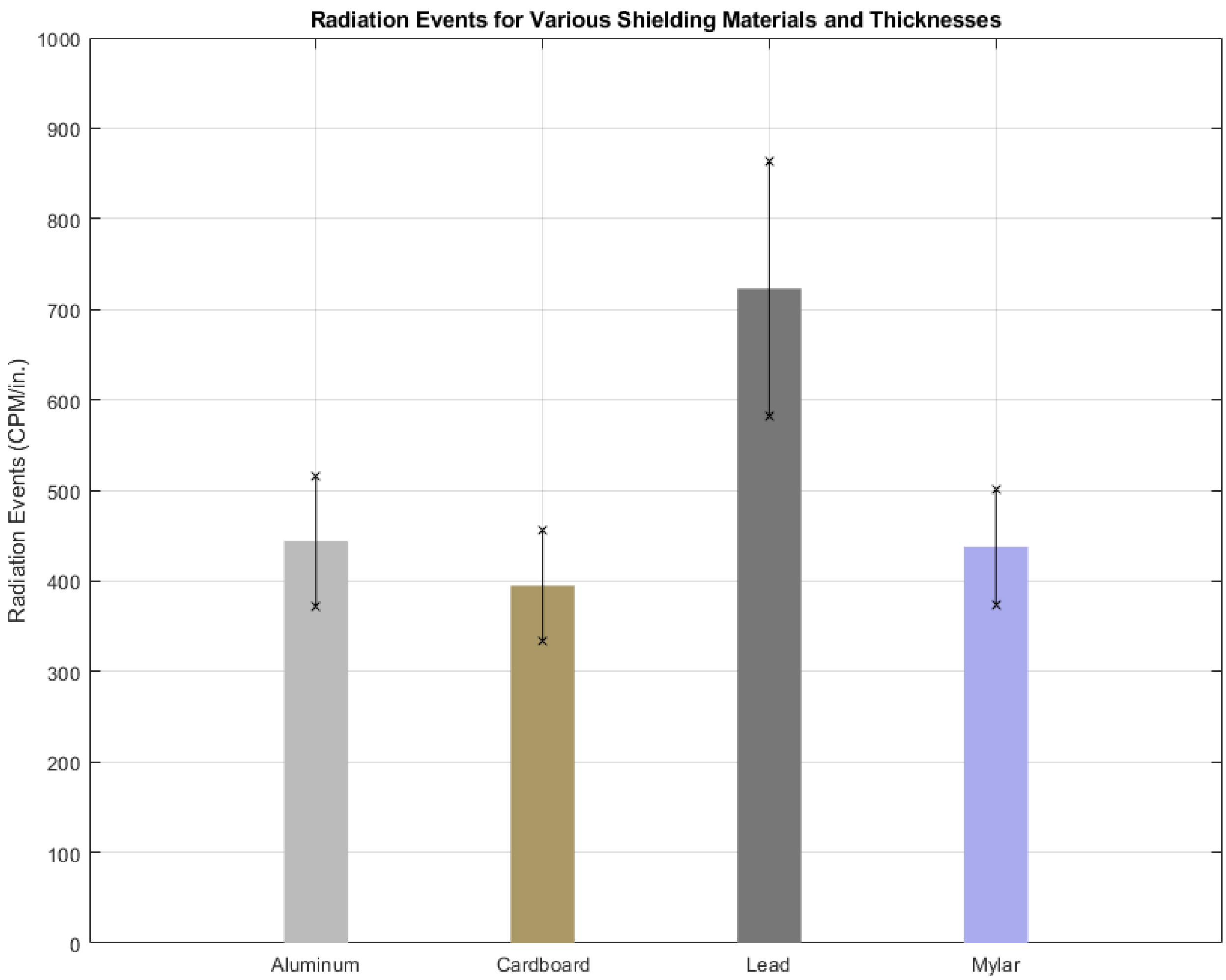


**Figure 9: Radiation events for each material, adjusted for the material thickness**

The aluminum shielding is only 10.03 mm thick for the 4 layer test, so the radiation dose in GEO would be around $10^6$ rad/day. This would result in intense damage to biological matter and electronics within a single day, with hydraulic systems and glass becoming susceptible shortly thereafter. At LEO, this thickness would result in a dose of around $10^{-2}$ rad/day, which is much less than the dose limits for astronauts. In fact, shielding of just a few millimeters would be sufficient to meet these dose limits [3].

Experiment D: Maintaining Temperature: MLI Blankets

The temperature variance for the provided multi-layer insulation design are presented in Table 2:

| Pressure (mTorr) | Time (s) | $T_1$ (°C) | $T_2$ (°C) |
|---|---|---|---|
| 48 | 0 | 23.1 | 26 |
| | 60 | 22.9 | 26.6 |
| | 120 | 22.9 | 29.5 |
| | 180 | 23 | 34 |
| | 240 | 22.9 | 42.1 |
| 54 | 300 | 22.9 | 52 |
| | 360 | 23 | 65.6 |
| 68 | 420 | 22.9 | 78.4 |
| | 480 | 23 | 91.2 |
| | 540 | 23.1 | 102.3 |
| 93 | 600 | 23.2 | 112.5 |

**Table 3: Multi-layer insulation performance**

The emissivity of the individual layers of insulation are as follows:

$$\epsilon_{mylar} = 0.76$$
$$\epsilon_{kapton} = 0.72$$

Using the equation for effective emissivity of multiple parallel layers of material, we determined the emissivity of both the multi-layer insulation that we constructed and the multi-layer insulation used in the provided test data, neglecting the nomex analogue and nomex spacers respectively:

$$\epsilon_{eff}=\frac{1}{\frac{2n}{\epsilon_{\text{int}}}-n-1+\frac{1}{\epsilon_i}+\frac{1}{\epsilon_o}}$$

$$\epsilon_{untested}=\frac{1}{\frac{2(9)}{0.76}-9-1+\frac{1}{0.72}+\frac{1}{0.76}}=0.061$$

$$\epsilon_{provided}=\frac{1}{\frac{2(2)}{0.76}-2-1+\frac{1}{0.72}+\frac{1}{0.76}}=0.201$$

Our multi-layer insulation design would have been less emissive than the provided test design, and thus would have been more effective at blocking thermal heat transfer per unit mass, as our MLI weighed only 1.12 g for the 3 $in^2$ sample compared to 2.85 g for the same 3 $in^2$ sample used for the provided data set. However, this relies on the assumption that the emissivity of our mylar analogue was the same as the reported emissivity for mylar, the thickness and geometry of the nomex analogue and actual nomex layers does not have any effect on the radiative heat transfer, and there is no conduction between insulation layers.

Assuming that the heater would have reached 110 °C during testing of our multi-layer insulation, and that the top side would have remained at 25 °C, we can compare the heat transfer from radiation of our design and the provided design:

$$\dot{Q}=\sigma\,\epsilon\,A\left(T_1^4-T_2^4\right)$$

$$\dot{Q}_{untested}=\left(5.67\cdot10^{-8}\frac{\mathrm{W}}{\mathrm{m}^2\mathrm{K}^4}\right)(0.061)(0.0508\,\mathrm{m})(0.0381\,\mathrm{m})\left((383\,K)^4-(298\,K)^4\right)=0.091\,\mathrm{W}$$

$$\dot{Q}_{provided}=\left(5.67\cdot10^{-8}\frac{\mathrm{W}}{\mathrm{m}^2\mathrm{K}^4}\right)(0.061)(0.0508\,\mathrm{m})(0.0381\,\mathrm{m})\left((385\,K)^4-(296\,K)^4\right)=0.315\,\mathrm{W}$$

Carrying all of the above assumptions, we determined that our multi-layer design would have been more effective at reducing radiative heat transfer than the provided multi-layer insulation design.

## IV. Conclusion

We were able to explore a number of interesting topics over the course of the several weeks when we ran these experiments. Given the expansive view of our lab work, our results and conclusions we drew from our findings were also diverse. Some of these results also stood contradictory to what we expected.

As anticipated our bottles and cylinders heated in the sunlight and we were able to do some calculations based off of that to find the intensity of the sunlight. We also were able to make informed predictions of the trend our bottle and cylinder temperatures would follow. It did seem the temperature followed an inversely exponential curve and eventually the temperatures plateaued or would have had we continued to experiment. Similarly, when exposed to sunlight, a spacecraft will have both a maximum and a minimum temperature when the rate of heat radiating into and out from the craft will be approximately equivalent.. It is up to the designers to create conditions where the vehicle will maintain a temperature best suited for its mission.

One interesting finding we had in our experiments was the possibility of an optimization technique where engineers can find an optimal ratio of emissivity in MLI blankets to their weight thus creating the best circumstances for a light yet shielded craft. This however is only useful in the event this shielding is effective enough to protect whatever electronic, biological, or mechanical cargo the craft may hold. In other words, there might be a perfect ratio of shielding effectiveness to weight but if the shielding is too light to be effective, then the spacecraft may fail in its objective.

Our understanding of how radiation works was enhanced by this lab. However, our assumptions made before this lab are still valid in that the effectiveness of shielding is typically enhanced by increased shielding mass which is not a viable option for some clients. The most effective way we found in our testing to get around this obstacle was to find materials which would provide maximum shielding for minimal mass trade offs. Materials such as mylar and kapton are therefore very useful in spacecraft at least in absorbing some types of radiation and different coatings may be helpful in maintaining optimal temperatures. It should be noted the actual application of these findings is always mission specific depending on the cargo, mission duration, optimal temperature of a mission, etc. In the future, other materials will hopefully be even lighter or more effective to improve the reliability and plausibility of space travel.

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