Impact of Coatings on the Heat Transfer and Thermal Transmittance of Materials for Space Applications

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Abstract

Spacecraft experience extreme heat changes making it important to study how materials are able to absorb heat and transmit thermal energy. For example, a light color may reflect more thermal radiation while a darker color is more likely to absorb it. In this study four materials were studied: aluminum 2024, aluminum 7075, steel 304, and a carbon fiber composite. The materials were tested under a 100-watt heat lamp for four hours, each without a coating and two separate trials with the addition of polyimide kapton tape and zinc oxide paint. The temperature was recorded every 30 minutes with Type K thermocouples placed on the top side (heat exposed) and back side. The results indicated that the coatings had an effect on the heat transfer, although with slight variation depending on the material used. Zinc oxide paint generally increased the heat transfer of the material while both coatings lowered the heat transfer for the carbon fiber composite. Both coatings lowered the thermal transmittance of the materials with the zinc oxide paint having the greatest effect. These findings suggest that surface coatings have a meaningful effect on the behavior of aerospace materials. Understanding these differences is important in order to select materials for aerospace applications depending on the purpose.

Introduction

In space, extreme temperature fluctuations make it important to choose a suitable material for aerospace applications. Due to thermal radiation and changing orbits, these materials must survive large temperature ranges from -250°F to 250°F, which can lead to component overheating/undercooling and material fatigue for some applications (Mobility Engineering, 2010). Depending on a material's properties, it can either reflect heat or absorb the heat, resulting in different temperatures. A material's reflectivity determines how much heat is absorbed vs. reflected, while a material's emissivity characterizes its propensity to re-emit thermal radiation absorbed; both of these properties contribute to the net heat flux, or energy flow through a given area, a material experiences. Thermal performance of materials for space is often measured as radiation, the emission of electromagnetic waves that are generated by heat.

Generally, darker materials tend to absorb and radiate more heat in comparison to lighter materials. An example of a system that keeps a component at a given temperature against this is reflective insulation or a multilayer insulation, which is used to minimize heat loss in the case of low temperatures. On the other hand, high-emissivity radiator paints are used to enhance emissivity in order to reflect heat in environments where thermal radiation may be too high, like close to the sun (Kodur et al., 2025). Many aerospace materials are primarily chosen for mass and structural integrity, but their surface characterization inevitably affects their thermal properties as well. Conventionally, heaters or coolers are also used to maintain the desired temperature of the spacecraft. Heaters are often used when the temperature drops below a safe operating rate and coolers are used to direct heat in a desired area, specifically away from sensitive components. Sometimes a design requires a certain metal or carbon fiber, but it is advantageous to change its surface properties to modulate its temperature. This can be done at low cost and without the mass and complexity of a full heating and cooling system. For this purpose, special coatings can be added to increase reflection of the sun, these include zinc oxide paint, silver or gold foils, or specialized tape. As such, this research both explores the properties of common base aerospace materials and the role of coatings in modifying thermal properties.

Common aerospace materials include a range of durable metals and more recently carbon fiber. This study analyzes aluminum 2024 (primary alloy of copper) and 7075 (primary alloy of zinc), stainless steel 304, and carbon fiber. Both aluminum 2024 and 7075 are commonly used for their high strength-to-weight ratio. Although aluminum 2024 has a high fatigue resistance, aluminum 7075 is more durable. While stainless steel is very durable and strong, it has downsides such as its weight. For this reason it is less popular than aluminum, although it is a highly reflective material. Carbon fiber is a more modern option for aerospace applications, primarily chosen for its lightweight benefits while still maintaining tensile strength.

Y. Sakumoto et al. (1996) studied the thermal expansion rate of steel for infrastructure purposes. The stress on the steel was also tested at high temperatures in order to determine its durability in a fire. They found that the heat transfer rate of SUS304, stainless steel 304, had a greater thermal expansion rate compared to a more conventional steel like SS400. The coefficient of thermal expansion for SUS304 is approximately 19–20 × 10^{-6} /°C while for SS400 it is approximately 14–15 × 10^{-6} /°C. The study by Y. Sakumoto et al. is important because of its

similar use of metal to this study but uses an electric furnace as the heat source. This study uses the sun as the primary source of heat.

L F S Carollo et al. (2012) presents a method for finding the thermal conductivity and volumetric heat capacity of different metals. By using a kapton heater and type K thermocouples they were able to identify that 304 and 316 stainless steel and grade 2 titanium thermal properties differed by less than 2% from previously published values. The test set up differs because it uses a heater attached to the kapton sample rather than heat from the sun. Although this study is important because it tests the same grade of steel.

D.J. Benford et al. (1999) studied the thermal conductivity of Kapton tape from a temperature range of 5 K to 300 K. By placing the Kapton tape between a heat sink stage and a thermally isolated heated stage they were able to determine that kapton tape has a low thermal conductivity. The measured conductivity was found to be about 1.75 $W \cdot m^{-1} \cdot K^{-1}$ while previous research found it to be around 2.7×10^{-3} T $W \cdot m^{-1} \cdot K^{-1}$. The methods used differ from this study because it will be analyzing the heat flux due to thermal radiation. However, the properties of Kapton tape found in this study are useful to compare to the following test.

Teodorescu (2007) studied the emissivity of metals at high temperatures including copper, aluminum, nickel, titanium, and zirconium. The emissivity was measured using a FTIR spectrometer and specialized infrared detectors finding that as the emissivity increased the oxidation on the metal surface did as well. This uses specialized equipment rather than a thermocouple and direct sunlight to measure emissivity. Similarly, it compares the emissivity of a variety of different metals.

Setién-Fernández et al. (2024) studied the emissivity of copper and nickel between 250°C and 900°C. Using a precision radiometer they were able to find that when temperature increased the emissivity increased, varying largely between the two metals. They directly measured the emissivity at high temperatures while this paper focuses on changes due to sunlight.

Prior studies have measured thermal properties of space-relevant materials at different temperatures and explored the relationship with emissivity and reflectivity. However, no one has surveyed the heat transfer and thermal transmittance of a large range of space materials and coatings simultaneously in one study. Therefore, this study will investigate the following research question: to what extent do different materials such as aluminum, carbon fiber, and steel, experience thermal changes in exposure to constant heat source, and how do the results change with the addition of a coating? This paper will discuss the methodology, the setup and execution of the test, the results, and conclusion, and the future implications of the results.

Methodology

For this study the emissivity, a material's ability to absorb heat was measured for four different materials. The materials selected were aluminum 2024 (90.75% to 94.7% aluminum, 3.8% to 4.9% copper, 1.2% to 1.8% magnesium and traces of other metals), aluminum 7075 (87.1% to 91.42% aluminum, 5.1% to 6.1% zinc, 2.1% to 2.9% magnesium, 1.2% to 2.0% copper, and traces of other metals), steel 304 (66.25% to 74.5% iron, 17.5% to 20% chromium, 8% to 10.5% nickel, and traces of other elements), and carbon fiber. The surface of the materials measured 6 x 6 inches and were 0.03125 ± 0.00125 inches thick. They are each commonly used in aerospace applications because of properties including their weight, durability, strength and thermal behaviors. In addition, two coatings were added to the material to determine if they had an effect on the material's ability to absorb heat from sunlight. This

made a total of three different trials for each material. The materials selected were a kapton tape and a white zinc coating because of their space-relevance and different emissivity values (i.e. white vs. orange/brown). Each of the four materials was first tested without the addition of a coating. One side of each of the materials was tested with kapton tape and then a third test was conducted with zinc paint on one side.

Before testing, the thickness of each of the materials was determined using calipers and weighed using a digital scale. The initial temperature was measured using a Type K thermocouple connected to a thermometer. One thermocouple connected to each side of the material, secured with two small pieces of kapton tape. Each of the samples were then placed 8 inches under a 100-watt heat lamp. Each test lasted a total of 4 hours, with the temperature recorded for the front and back every 30 minutes. This process was repeated for each material with each of the additional coatings.

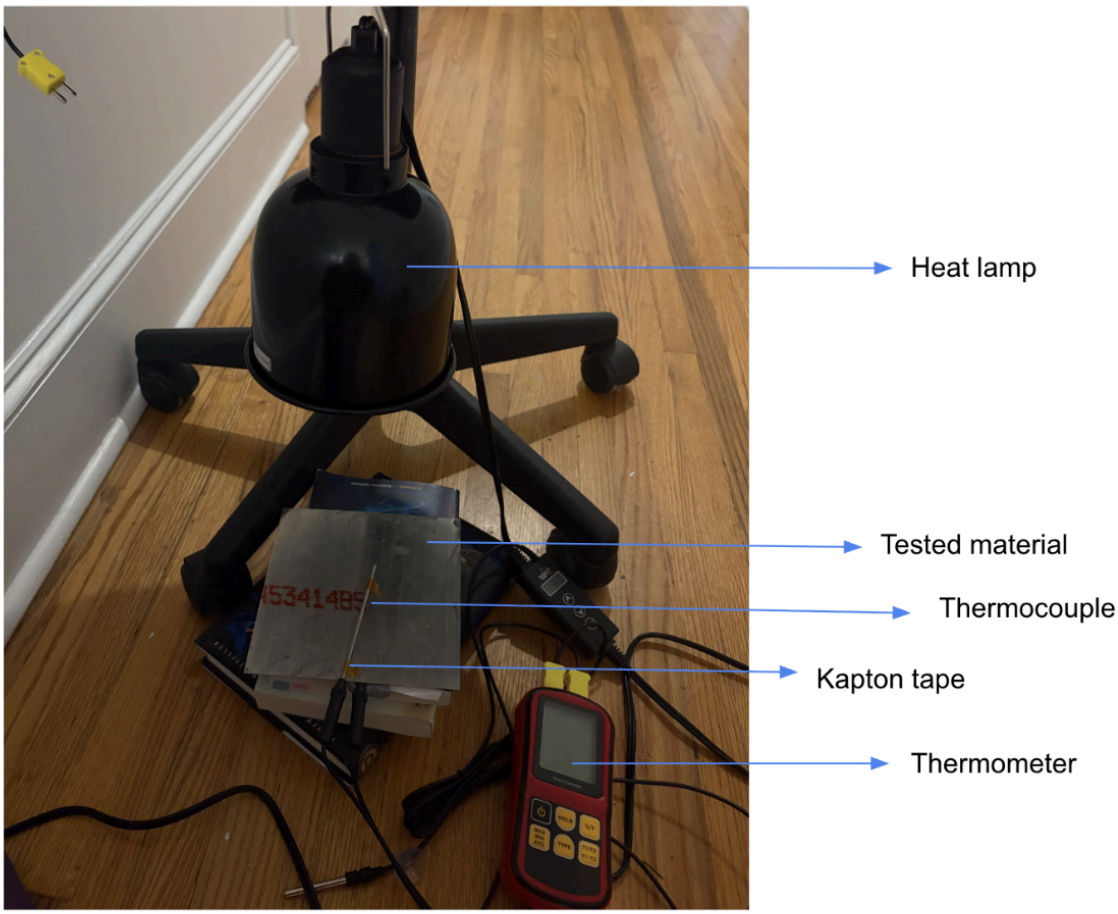


Figure 1. Heat lamp experimental set-up with material sample below. A Type K thermometer is taped to the surface for in-situ temperature measurements.

A bill of materials can be viewed below including the item, its purpose, and the brand and/or supplier.

Table 2. Bill of materials used in testing and sourcing

Material	Use	Source
Aluminum 2024 (6in x 6in)	Material tested	McMaster-Carr
Aluminum 7075 (6in x 6in)	Material tested	McMaster-Carr
Carbon Fiber (6in x 6in)	Material tested	McMaster-Carr
Steel 304 (6in x 6in)	Material tested	McMaster-Carr
Zinc Oxide-Based Paint	Material coating	ZincKote
Aluminized Polyimide (Kapton) Tape	Material coating	Uline
Calipers	Measurement	Sangabery
Type K thermocouple and thermometers	Heat measurement	JuviPerpric
Heat lamp	Heat	LUCKY HERP

The temperature change in the sample was determined by subtracting the initial temperature from the final temperature. This was then used to determine the energy in joules absorbed by each of the materials every 30 minutes using the equation:

$$Q = mC_p\triangle T \quad \text{(Equation 1)}$$

where C_p is the specific heat capacity, m is the mass in grams, $\triangle T$ is the change in temperature in °C, and Q is the energy (joules). The specific heat values were obtained from prior research rather than calculated.

Table 1. Specific heat capacity for materials

Material	Specific heat capacity (J/(g°C))	Source
Aluminum 2024	0.875	(MatWeb, n.d.)
Aluminum 7075	0.960	(MatWeb, n.d.)
Steel 304	0.500	(MatWeb, n.d.)
Carbon fiber	0.750	(Pan et al. 2019)

Zinc Paint	0.3898	(MatWeb, n.d.)
Kapton tape	0.261	(American Durafilm - KAPTON® Film - Physical Properties of KAPTON®, 2025)

The exact value for the specific heat capacity of zinc paint was not found. The paint is 96% zinc; therefore, the specific heat capacity of zinc was used instead.

With the values from the previous equation, the thermal conductivity, how heat travels through a substance, was also calculated for each material. The value was found using Fourier's law of heat conduction:

$$k = (Q)/[(L(T_1-T_2)] \quad \text{(Equation 2)}$$

where k is the thermal conductivity (W/m·K), Q is rate of heat transfer (W), A is the area perpendicular to heat flow (m^2), L is the thickness of the material (m), and $T_1 - T_2$ is the temperature difference across the material (°C). An important distinction is the data in this paper is presented in W/m^2-K, divided by area (A) instead of length (L), which is closely related to thermal conductivity but typically referred to as heat transfer coefficient (HTC) or thermal transmittance.

Results

Each graph shows the heat transfer of the materials over time in minutes for each material, carbon fiber, aluminum 2024, aluminum 7075, and steel 304. In each of the graphs, there is a heating rise when the material is initially heating up. It then plateaus as the material reaches steady state from a steady state heat source. It is important to note that the joules are not scaled the same on the y-axis of each graph.

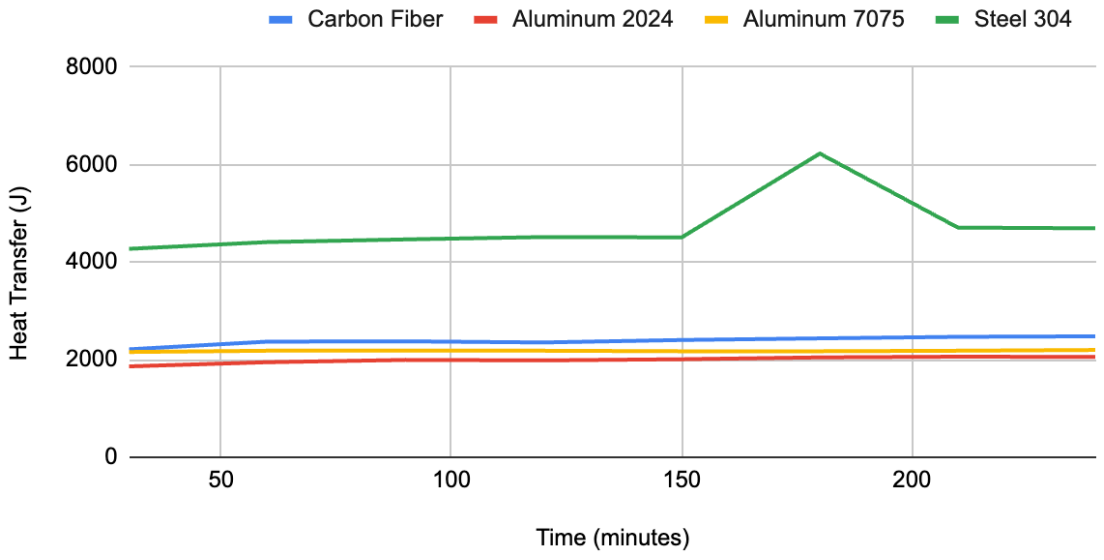


Figure 2. Heat transfer (J) for uncoated materials over time (minutes) under heat lamp exposure

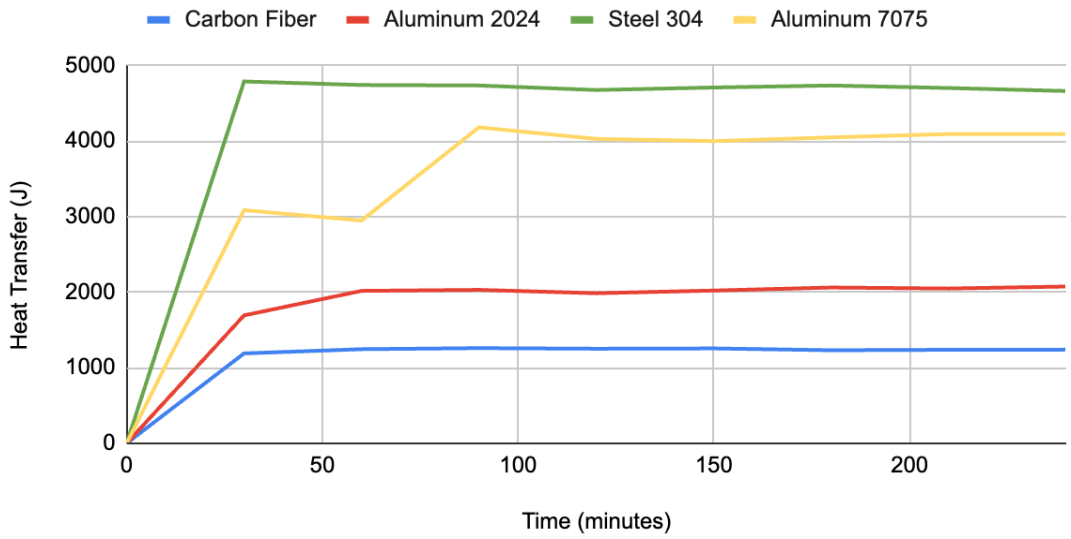


Figure 3. Heat transfer (J) for Kapton taped materials over time (minutes) under heat lamp exposure

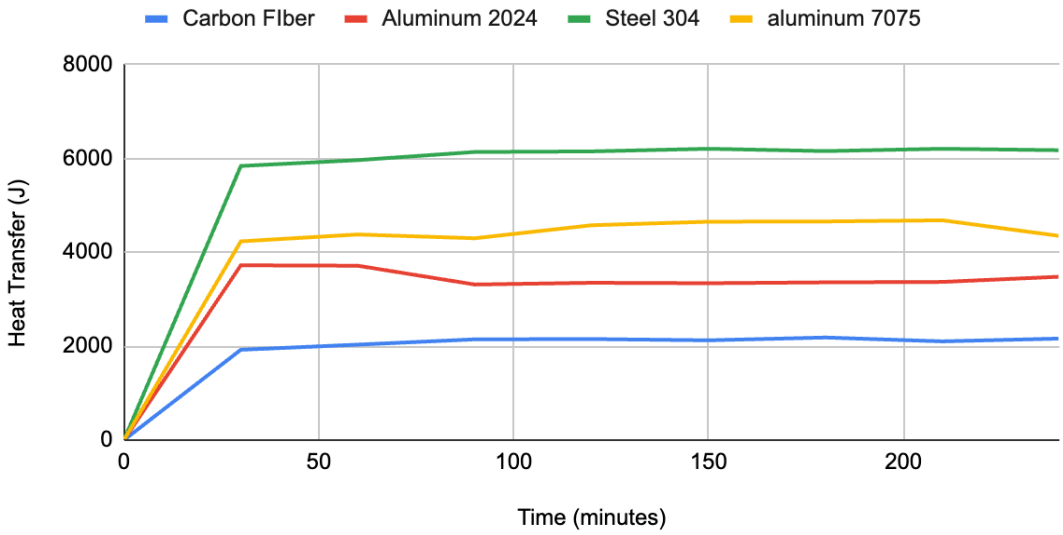


Figure 4. Heat transfer (J) for zinc oxide paint coated materials over time (minutes) under heat lamp exposure

The range of heat transfer for the materials with no coating is larger than the materials with either of the other coatings by roughly three orders of magnitude. This is due to steel 304 having a significantly larger thermal conductivity when compared to the other materials. This is due to the mobile electrons that carry energy throughout the material. The other three materials, carbon fiber, aluminum 2024, and aluminum 7075, all have a heat transfer of less than 3000 Joules, generally within the range of the materials with a coating. The zinc oxide paint has more of an effect on the heat transfer, the highest heat transfer being less than 4000 J. The highest heat transfer for the kapton tape was less than 5000 J while the lowest slightly greater than

1000 J. Similarly, the zinc oxide paint never reached below 1000 J for any of the materials after their steady state.

The differences between the materials have an effect on how energy is stored, absorbed, and transferred through electron movement, explaining differences observed in heating rates of materials. Stainless steel is made up of metallic bonds in an austenitic crystalline structure (*Categories, Grades and Product Forms - Worldstainless*, 2025). The carbon fiber is made up of carbon atoms held together by strong covalent bonds. These fibers are then woven together and usually combined with epoxy resin to form the material (Huang, 2009). Both aluminums are made of different alloys, primarily aluminum but also zinc, magnesium and copper, and while they also have the same metallic bonds as steel, they have different atomic arrangements and compositions (Cui et al., 2025).

The differences in the heat transfer with the addition of a coating can be explained by how coatings are able to modify the surface of the materials. For example, the zinc oxide particles are able to reflect and scatter incoming radiation having an effect on how the heat is absorbed into the material (Johnson et al., 2003). Kapton tape is made of a polyimide, long chains of covalently bonded atoms that make of the polymer. The additional layer is able to change how the heat moves through the surface of the material (Chowdhury et al., 2025). These differences explain why the zinc coating produced a greater increase in thermal energy materials, although the results differ between the materials used.

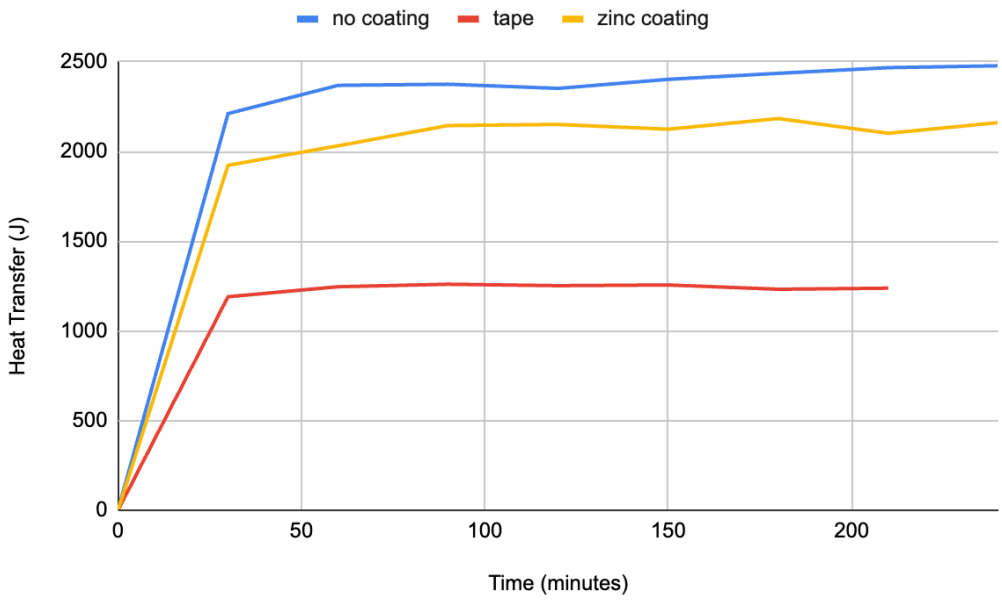


Figure 5. Heat transfer of carbon fiber with each of the coatings over time (minutes) under heat lamp exposure.

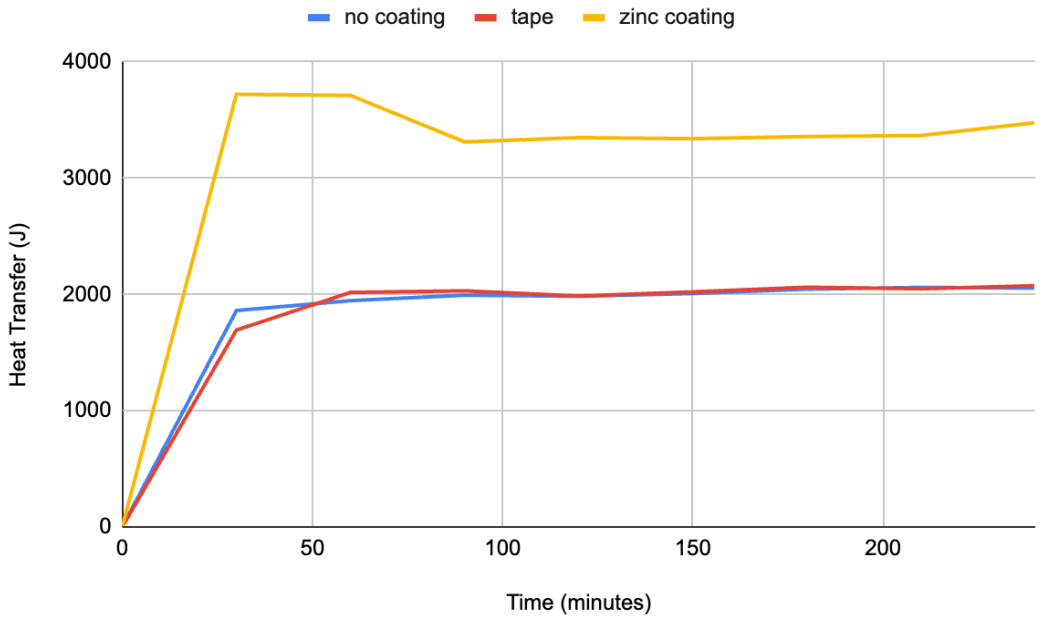


Figure 6. Heat transfer of aluminum 2024 with each of the coatings over time (minutes) under heat lamp exposure.

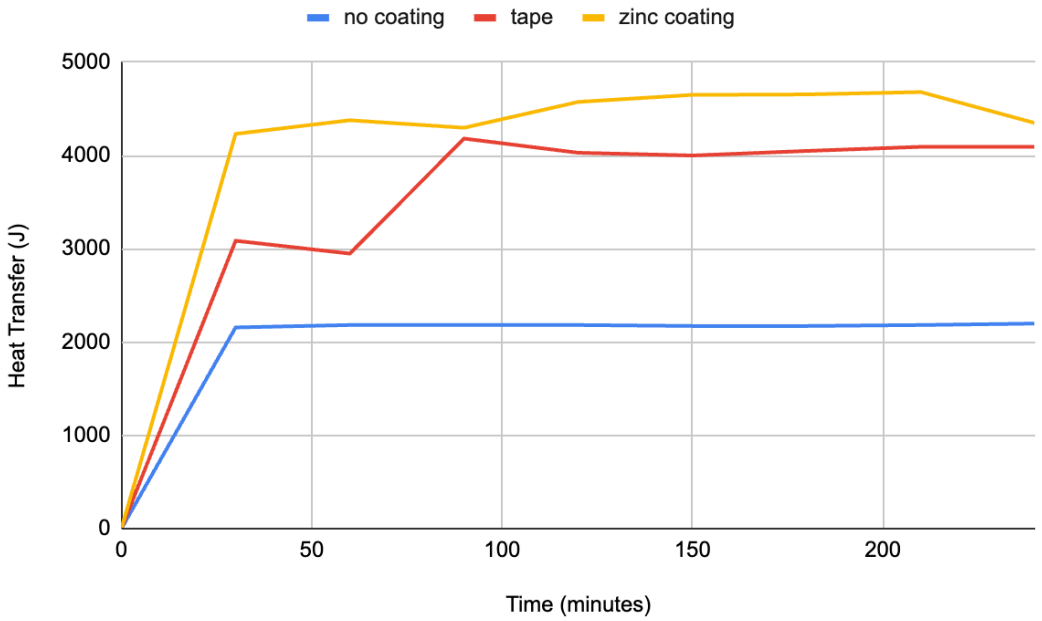


Figure 7. Heat transfer of aluminum 7075 with each of the coatings over time (minutes) under heat lamp exposure.

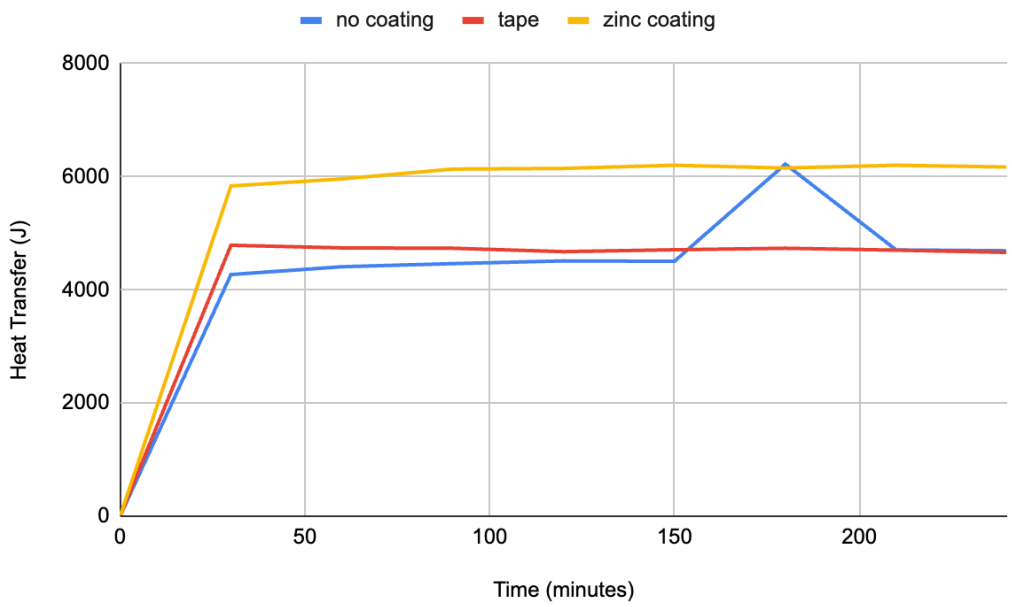


Figure 8. Heat transfer of steel 304 with each of the coatings over time (minutes) under heat lamp exposure.

In figure 5, the Kapton tape has the most effect on the heat transfer of the carbon fiber, lowering it by about 1500 J, while the zinc coating had little effect on lowering it. In figure 6, however, the zinc coating raised the heat transfer of aluminum 2024 and the Kapton tape had about the same heat transfer as the material with no coating. In figure 7, the zinc coating increased the heat transfer of aluminum 7075 by around 2500 Koules after the material reached its max temperature. The Kapton tape also significantly increased the heat transfer by around 2000 J from the material with no coating after the material reached a steady temperature. In figure 8, the zinc coating increased the heat transfer of the steel 304 by around 2000 J after it reached its max temperature; this is excluding an outlier in the data when the heat transfer significantly increased for steel 304 without coating at around 175 minutes. This is likely due to an experimental error.For example, the thermocouple could have moved when taking the measurement and not had good contact with the surface. Because the heat lamp was set to be constant and the heat transfer returned to the previous range, it is unlikely that there was a change in the materials' properties.

In figure 5, the heat transfer without the coating is higher than carbon fiber with either of the coatings, deviating from the general trend. Without any coating the material is black, which generally is able to absorb more radiation from the heat lamp than a lighter color. The zinc coating has a light grey surface which has the opposite effect, reflecting the radiation and lowering the heat transfer. The lower conductivity of the layer of polyimide kapton tape could lead to a lower calculated heat transfer. Due to these factors, this could explain why the heat transfer was highest for carbon fiber without a coating.

In figure 6, figure 7, and figure 8, the zinc coating raised the heat transfer for aluminum 2025, aluminum 7075, and steel 304. The coating had the opposite effect on carbon fiber in figure 5, decreasing the heat transfer. Kapton tape generally did not lower the heat transfer for any of the materials, this is excluding carbon fiber shown in figure 5. It remained within close

proximity of the material with no coating for both figures 6 and 8, while increasing heat transfer in figure 6.

Table 3. Thermal transmittance for each material at steady state heating

	No Coating (W/(m²·K))	**Kapton Tape** (W/(m²·K))	**Zinc Coating** (W/(m²·K))
Aluminum 2024	51.74	6.80	3.96
Aluminum 7075	17.19	9.02	3.59
Carbon Fiber	2.25	3.80	1.38
Steel 304	13.44	5.27	3.53

According to Li et al. (2022), the thermal transmittance for aluminum 2024 is 40 W/(m²·K). The recorded value found in this study with no coating is above this measurement, at 51.74 W/(m²·K). When the kapton tape is added, the thermal transmittance drops to 6.80 W/(m²·K), significantly below the published value. When the zinc coating is added it drops even further to 3.96 W/(m²·K), both materials having a significant effect on the thermal transmittance.

According to Saberi et al. (2022) the thermal transmittance for aluminum 7075 is 4 to 12 W/(m²·K). In this study the thermal transmittance for aluminum 7075 was found to be 17.19 W/(m²·K) which is above this published value. With the addition of the kapton tape (9.02 W/(m²·K)), the thermal transmittance falls within the published range. The zinc coating (3.59 W/(m²·K)), is just lower than the published range and significantly lower than the material with no coating.

The thermal transmittance reported by Schutzeichel et al. (2022) for carbon fiber 2.5 W/(m²·K) for free convection and 10–40 W/(m²·K) for forced convection. The value calculated for carbon fiber without a coating in this study, 2.25 W/(m²·K), is very similar to the published value for free convection while is low for forced convection. This makes sense because our test set-up had only free convection from ambient air, not any forced air flow. The calculated values with the kapton tape (3.80 W/(m²·K)) and zinc coating (1.38 W/(m²·K)) are both still low compared to the coerced convection range, while the kapton tape is increasingly higher than the free convection value and calculated value for carbon fiber without the coating. The zinc coating thermal transmittance is slightly lower than the thermal conductivity with no coating.

According to Lienhard V and Lienhard IV (2024), the thermal transmittance of stainless steel 304 is 6.7 W/(m²·K). The value calculated in this study for stainless steel with no coating was 13.44 W/(m²·K), about double the published value. The thermal transmittance with the kapton tape was closer in range at 5.27 W/(m²·K), the zinc coating even lower at 3.53 W/(m²·K).

In Table 3, the results showed a drop in thermal transmittance with the addition of either of the coatings. This is excluding carbon fiber when the kapton tape increases the thermal conductivity. The zinc coating had the most effect, with a thermal transmittance range around 1 to 4 W/(m²·K), having the smallest thermal conductivity for every material.

Conclusion

For each material, adding a coating had a significant effect, either lowering or raising the heat transfer. The zinc paint lowered the heat transfer for aluminum 2024, aluminum 7075, and steel 304. Both coatings on the carbon fiber lowered the heat transfer, the kapton tape more significantly.

With the addition of a coating, the thermal transmittance generally dropped significantly for each material. The zinc coating had more of an effect than the kapton tape with no greater than 4 $W/(m^2 \cdot K)$ for any of the materials. Without and with each of the coatings, carbon fiber had the smallest thermal transmittance, greatest with the kapton tape. Aluminum 2024 had the largest thermal conductivity without the coating and with the zinc coating while aluminum 7075 had the largest with the kapton tape.

Various limitations occurred during the experiment which could have had an effect on the accuracy of the results. When taking measurements of the material, heat was lost to the surrounding environment and materials supporting the materials, affecting the overall heat transfer. By not directly measuring the heat transferring through the materials, measuring only the front and back temperatures, the calculated values may not fully represent the actual thermal transmittance. While the thermocouple was taped onto the material, any movement or poor contact could have affected the temperature reading, as well as the kapton tape used. Realistically, the materials would be exposed to sunlight, but for this study the heat lamp was used to maintain continuity of heat with less external factors.

Spacecraft experience extreme temperature fluctuations, making it important to select the correct material that will maintain performance of the aircraft. When adding a coating to the material, it is important to select the right coating for the material and understand how it will operate along with it. This study suggests that the addition of a coating significantly impacts how the material absorbs or reflects heat. For example, Kapton tape lowers the heat transfer of carbon fiber but increases the heat transfer of aluminum 7075. This information is important to help engineers choose materials and coatings for their design based on its purpose. Further research could explore a wider variety of materials with coatings and used more advanced facilities to acquire more accurate results.

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