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Heat Transfer of Sunscreens: Investigation into the Conductive Properties of Sunscreen

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Abstract

Sunscreen is a major preventative product very commonly used for protection against ultraviolet (UV) radiation and the skin cancers associated with extended exposure. There is minimal research into the conductive properties of sunscreen as the major research focus is on radiation effects, but it is still important to understand the impact of sunscreen on the body's natural heat transfer to the external environment through the skin and extremities, a necessary process to ensure homeostasis. Our research group investigated the conductive properties of sunscreens over two experiments. The first analysed the effect of increasing the thickness of sunscreen on its conductive heat transfer. The results showed that as thickness increased, heat transfer decreased and allowed us to calculate the conduction coefficient (k) for this specific sunscreen sample to be 0.43 W/mK. The second experiment analysed what the impact of combining multiple sunscreens which varied in ingredients, sun protection factor (SPF) and being water or oil based was on their heat transfer. The results allowed us to calculate the thermal conductivity constant (k) for each sunscreen and their mixtures, with Sunscreen B (Brand name Bondi Sands©) having the highest at k=1.34 W/mK, and Sunscreen A (Brand name LeTan©) the least at k=0.27 W/mK. Further, it was found that combining different sunscreens in a 1:1 ratio roughly portrayed that the conductive properties of the mixture was the average of the sunscreen's properties on their own (For example mixture AB had a conduction coefficient of k=0.70 W/mK). With an understanding of the conductive properties of sunscreen, we can see how exactly its application impacts heat transfer and evaluate if its effects in general are significant, or whether some sunscreens are better for different applications (i.e. ensuring insulative or conductive properties of different sunscreens are used for correct applications).

Keywords: *conduction, sunscreen, conductive heat flux (q''), thermal conductivity constant (k), ultraviolet (UV) radiation*

1. Introduction

1.1 Motivation and Aim

1.1.1 General problem

In Australia, sunscreen is an essential resource in providing protection against the relatively large proportion of UV radiation we experience in everyday life. It is one of the most effective preventative measures against skin cancers such as basal cell carcinoma, squamous cell carcinoma and melanoma, making it vital in ensuring the longevity of our lives. Due to this the prevalence of sunscreen use is at an all-time high, but since the focus is on its benefits in radiation prevention, there is minimal research into its conductive properties. The human body relies on heat transfer between the extremities and skin against the external environment as a way to ensure thermal homeostasis [1]. For the body's continued effective function, core temperature must remain approximately between 36.5 to 37.5 degrees Celsius, as this allows for the correct and optimized function of enzymes and other conditions of various bodily systems.

1.1.2 Scope and objective

In this study, we researched into the conductive properties of various brands of sunscreen, with different ingredients and Sun Protection Factor (SPF) ratings. Our research was conducted over two experimental investigations with the following questions:

What is the effect of increasing the thickness of sunscreen on its conductive ability to allow heat transfer?

This allowed us to analyse the conductive properties of sunscreen as an implication to its effect on the body's heat transfer.

What is the impact of applying different types and/or a combination of different sunscreens on their heat transfer?

It is quite often that when we apply sunscreens, we use different or multiple sunscreens with different protection ratings and ingredients. This experiment analysed the different conductive properties of different brand sunscreens (Appendix M), and what the impact of applying multiple sunscreens in a mixture is on its heat transfer properties.

For both these experiments, we simulated heat transfer using a hot plate as our heat generation source and measured the temperature of our sunscreen samples over a controlled period of time using thermal imaging cameras. From this experimental data, we used theory such as Fourier's law to calculate the conductive heat transfer coefficient (k), heat flux and other conductive properties of our samples. Through the trends in the data, we analysed our research questions and discussed if the application of sunscreen has a significant impact on the body's overall heat transfer. It is important to note that there were some significant assumptions made during this investigation, primarily that were was negligible heat loss the surroundings and there was only 1D conduction. This was primarily justified through the methodology and data collected and the experimental set-up. With the measured temperature being taken directly from the hot plate and the surface of the sunscreen sample, heat flux lost to the surroundings through the sides of the sample and other dimensions would have negligible impact due to relatively small height of the samples compared to the radius, leading to minimal heat loss. This was true in both investigations.

1.2 Previous studies

There has been minimal study into the conductive properties of sunscreen as all studies predominantly analyse its UV radiation protection properties. With that said some relevant trends can be seen as a result of studying different applications (although there was more qualitative analysis rather than quantitative measurement of convection). Some relevant trends were seen in the following studies:

'*Effects of sunscreen use during exercise in the heat'*, *T.D. Wells* – In this study, it was found that sunscreen worn in hot, dry conditions significantly increased skin temperature (i.e. less heat was transferred from the boundary between the body and bulk air) [2].

'Sunscreen Use and Sweat Production in Men and Women' J. Aburto-Corona – In this study, the application of sunscreen decreased perspiration, which could be a result of sunscreens impact on heat transfer between the body and external environment [3].

The lack of information on these conductive properties of sunscreen is part of our motivation to partake in this study, as it is important to understand the underlying effects such a commonly applied product has on maintaining health and wellbeing.

2. Methodology

2.1 General setup of the equipment used

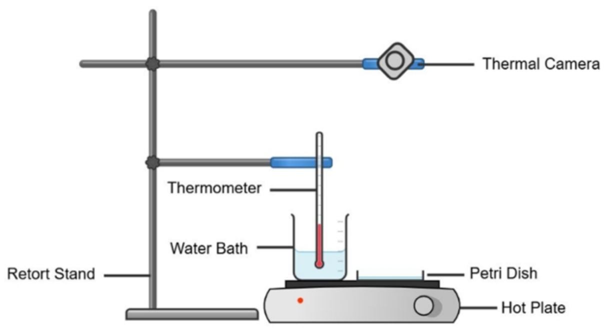

Figure 1: Experimental diagram testing varying combinations of sunscreen samples for both investigations 1 and 2.

The same experimental setup was used for throughout the investigation, which is shown in Figure 1. A thermometer was clamped to a retort stand and placed in a 50 mL beaker water bath to continually measure the temperature of the hot plate (37°C). The sunscreen sample tested was put inside petri dish case made of PET (polyethylene terephthalate) plastic with thickness of approximately 0.5mm. An InfiRay Pro 2 thermal camera was connected to a laptop via a cable and placed above the hot plate and the sunscreen surface. The thermal camera was fixed on an angle above the hot plate surface, in order to increase the reliability and the accuracy of the temperature recorded. The major challenges of this methodology involved getting consistent temperature readings from the thermal camera, due to unsteady camera angles as they were originally held by hand. This was addressed by attaching the camera to the retort stand to ensure consistent readings between measurements, improving accuracy and lowering error. Additionally, pre-mixing the sunscreen samples before application aided homogeneity of samples. More impactful challenges for the equipment and methodology that had a significant effect on the investigation have been discussed in section 3.3.2. Aside from this, the experimental set-up and methodology worked effectively.

2.2 Investigation 1: Effect of Sunscreen Thickness on Conductive Heat Flux

The petri dish was filled with sunscreen of various thicknesses. There was a total of 5 samples used with thicknesses ranging between 2 mm to 10 mm in increments of 2 mm. The thickness of the sunscreen was measured by dipping a metal plate into the petri dish, then measure the length of the plate that was covered by the sunscreen. The surface temperature of both the sunscreen and the hot plate was measured every 1 minute and up to three minutes after placing the samples on the heat plate. For each reading the temperature was recorded at three different points on the surface area for each sample, as shown in Figure 2. This was done in order to increase the reliability and account for the slight uncertainty of the thickness across the sunscreen sample.

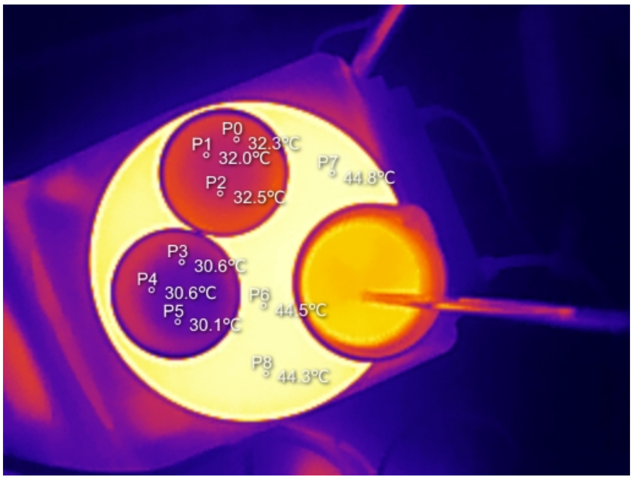

Figure 2. Screenshot of the thermal scan taken for thickness sample 6 and 8 mm, at third minute. Notice 3 measurements were done for each sample in order to account for variation of the thickness across the surface.

2.3 Investigation 2 - Effect of Sunscreen Mixture on Conductive Heat Flux

1 g of sunscreens A, B, and C were evenly distributed on separate plastic petri dishes. Mixtures AB and AC were composed of an evenly mixed 1:1 ratio of each sunscreen (0.5 g each). They were placed on the hot plate and temperatures were recorded every minute for six minutes. A temperature time plot was then produced. The overall method was very similar to the general methodology, with variations of mixture composition rather than thickness.

3. Investigation 1 - Effect of Sunscreen Thickness on Conductive Heat Flux

3.1 Hypothesis

The rate of the heat transferred from the hot plate to the surface of the sunscreen can be determined by the Fourier's law of thermal conduction for plane wall.

$$q'' = -k \frac{(T_{Plate} - T_{Surface})}{L_{(Sunscreen\ Thickness)}} \qquad \text{Eq (1)}$$

Where q'' is the conductive heat flux through the sunscreen (W/m^2), k is the thermal conductivity constant (W/mK), T_{plate} and $T_{surface}$ refer to the temperature of the heat plate and sunscreen surface respectively and L refers to the sunscreen thickness (m). As shown in Equation 1 above, the characteristic length of the plane (L) is inversely proportional to the heat flux (q"). Therefore, an increase in the thickness of the sunscreen is expected to decrease the rate of conduction. However, it is important to mention that some simplifications have been applied to this hypothesis. Firstly, heat conduction through the plastic container was assumed to be negligible (i.e., the measurement of the heat flux assumes that the sunscreen is directly in contact with the hot plate). Under temperatures between 20°C and 80°C, the thermal conductivity (k) of PET is around 0.2 W/m·K [4]. Considering that the approximate *k* value of the sunscreen is 0.43 W/m·K, the plastic would function as an insulator. However, the thickness of the plastic is approximately 0.5 mm, which is very thin. Therefore, the assumption is made that the temperature gradient throughout the plastic container will stabilise relatively quickly, and it would not affect the overall trend in the change of heat conduction, given that the temperatures are measured every 60 seconds. The inclusion of conduction through the plastic container increases the complexity of the heat conduction estimation significantly, as the plastic container also covers the sides of the sunscreen.

The second major predicted trend is that the heat flux will decrease with time. Again, using Fourier's law of conduction (Equation 1), the heat transfer rate is proportional to the temperature difference between the surface of the hot plate and the sunscreen. With this, as natural convection is the only factor for convective heat transfer from the sunscreen to the ambient air, it is reasonable to assume that the rate of heat transfer into the sunscreen is greater than the amount going out due to convection (i.e., energy is being stored in the sunscreen over time). Therefore, it is appropriate to consider that the temperature of the sunscreen surface will increase over time, and hence the temperature difference will decrease. Consequently, the heat transfer rate will decrease over time as well.

3.2 Results

3.2.1 Calculations for k

The thermal conductivity constant for the sunscreen in the thickness investigation was found through researching current literature on the composition of general sunscreens. Current literature indicated the base of sunscreens typically consist of water and oils with other active ingredients acting as UV filters and blockers [5]. Generally, sunscreen foundations consist of approximately 50-70% water [6] and 10-30% mineral, silicone and plant-based oils, with the rest being smaller constituents and active ingredients. The thermal conductivity constants for water and generic oils can be found and from this a thermal conductivity constant was estimated by using a weighted average approach, assuming the sunscreen was 60% water, 30% oils and 10% active ingredients. Water is known to have a conductivity constant of approximately 0.61 W/mK [7] at room temperature (300K). The thermal conductivity constant of the oil mixture was estimated to be approximately 0.15 W/mK by averaging generic values of mineral, silicone and plant-based oils [8] [9] [10]. The only active ingredient specific to the sunscreen used in this investigation that had an accessible conductivity constant was octyl salicylate with a value of 0.15 W/mK [11]. From this, the generic thermal conductivity constant was calculated to be 0.43 W/mK (Appendix G). This is a fair value based upon known thermal conductivities of the key components of common sunscreens.

3.2.2 Main Results

The data collected across the five trials of thickness at three repeats indicate two major trends, with high R^2 values for all trend lines. The first is the expected behaviour of the heat flux via conduction through the sunscreen decreasing with greater thickness due to a more protective and insulated character. Analysis of experimental data as seen in Figure 3 shows that the heat flux dropped from its initial values from approximately 84.1% to 90.2% when the thickness increased from 2mm to 10mm (Appendix H). Another trend identified was that the decrease in heat flux as thickness increased seemed to taper off, resulting in diminishingly lower heat fluxes as the results stayed relatively stable beyond 6mm of thickness. Analysis shows that the heat flux drops were greatest in the 2mm to 6mm range, with drops of between 43% to 57% approximately, with the least significant thickness increments being in the 6mm to 10mm range, with heat flux drops as low as 13% (Appendix I).

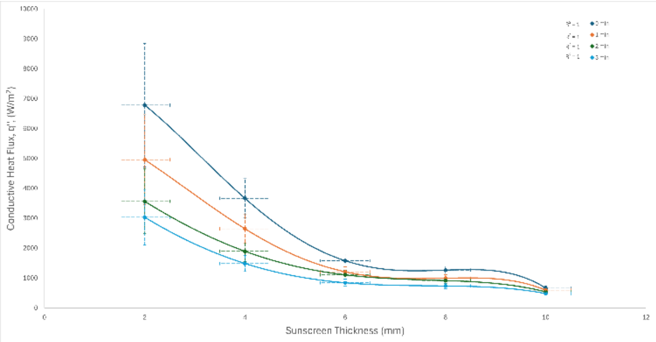

Figure 3: Graphed results of thickness investigation against conductive heat flux with error bars and uncertainty shown. The full tabulated experimental and calculated results can be found in Appendix B and C. A larger graph can be found in Appendix N.

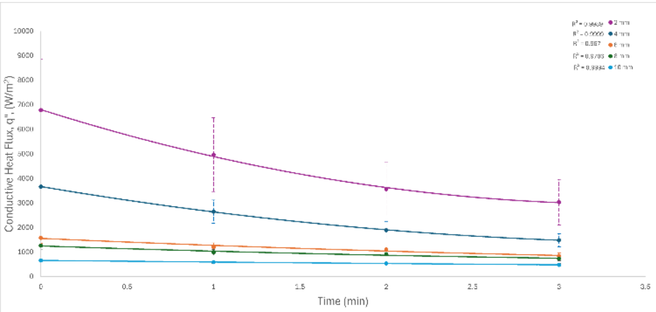

Figure 4: Graphed results of time against conductive heat flux with error bars and uncertainty shown. A larger graph can be found in Appendix N.

The other major series of trends found relate to how the heat flux varied with time in this investigation. Firstly, the drop in heat flux remained relatively constant (between 90.1% to 84.1%) as thickness increased at different time periods of the investigation, indicating that the sunscreen's conductive properties were unaffected by time exposure and supports the ability of sunscreen to limit conductive heat transfer at longer periods of time. However, the difference between the heat fluxes at the same thickness greatly varied with time at smaller thicknesses, from drops of up to 59% at 2mm and 4mm to only 27% at 10mm (Appendix J). This can be best seen in Figure 4, where the largest drops in the early time periods of the investigation can be seen in the 2mm and 4mm series. This indicates that while the properties of the sunscreen samples remained relatively constant throughout the investigation period and exposure to heat transfer, the effect of initial conductive heat transfer is most significant with minimal sunscreen applied; with a greater thickness the effects of longer exposure are mostly mitigated, demonstrated by the 10mm measurements being very closely grouped by comparison. This mirrors the trends found above of increasing thickness having a diminishing effect upon decreasing conductive heat flux, with increasing the thickness also having an effect upon the effects of time exposure.

3.3 Discussion

3.3.1 Interpretation of trends.

Examining the overall trend of how the conductive heat flux decreased with increasing sunscreen thickness, this is something that is generally expected as a thicker material results in improvements to the insulative characteristics of the material and larger resistance, resulting in lower heat flux via conduction with an inverse relationship [12]. This can also be examined through Fourier's law, (Equation 1), which states that the heat flux is inversely proportional to material thickness, given all other conditions remain constant. This is quite strongly reflected in the experimental data, with the sunscreen thickness increasing by five times resulting in a heat flux decrease of approximately 80% to 90%. Another important trend found was that after 6mm, increasing the thickness had a diminishing effect on lowering the heat flux through the sunscreen. This is generally attributed to how a material may reach a point where additional layers contribute minimally to heat transfer due to the limited temperature gradient across them [13]. However, this may have also been caused by an equipment fault of poor hotplate calibration resulting in inconsistent temperature differences between trials, which is discussed in more detail below. These are important observations in terms of applying this investigation to a practical scenario and investigating the aim of this investigation, as it shows how sunscreen can be used as a protective/insulative barrier to conduction. While it is unlikely that an individual would put any more than 1mm or 2mm of sunscreen, it demonstrates the overall trend of how heat flux can be minimized by applying the correct thickness of sunscreen as well as the optimal thickness of sunscreen to minimize heat flux while using the minimum amount required. While the experimental set-up did not properly mimic human tissue or everyday conditions, it still demonstrates the underlying principles and trends that are relevant in practice.

Another major trend found was how the thermal insulation and heat flux drop remained constant with increasing thickness regardless of the time period of the investigation, indicating the conductive and thermal properties of sunscreen were unaffected by the time and thermal exposure, indicating they were able to maintain their protective characteristics over the course of the investigation. This is somewhat contradictory to known literature, as the protective qualities of sunscreen are only expected to decrease with time due to photodegradation [14] of active components and environmental wearing [15]. However, given the limited length of time exposure (three minutes) and the fact that most of these degradations are primarily related to UV radiation, the findings in this investigation are not really in conflict with known literature. This is an important finding in terms of practical applications as it suggests that sunscreen can maintain its conductive protection over longer time periods, though the limited time scope of this investigation needs to be considered. The other major trend found was that with less thin sunscreen samples, there was a far larger and impactful difference in between the start and end of the time period. This is important in terms of a practical application of this investigation as it indicates that given longer time periods of exposure, applying a thicker layer of sunscreen is more important for stronger heat flux protection.

3.3.2 Limitations and Future Work

- *Thermal Conductivity Constant*

One of the major limitations of this report was that a specific value of the thermal conductivity constant was not able to be readily accessible, and so a generic value was calculated from approximate value of major components of sunscreen. This is a significant issue as it does not allow for certainty in numerical value of heat flux and questions the accuracy and validity of the results. However, it is important to note that regardless of the value of this constant, relative comparisons are still completely valid, and numerical calculations of differences between trend lines are still applicable as simple scalar multiples.

- *Uncertainty*

Considering uncertainty, it can be seen in Appendix C and Figures 3 and 4 that there was a significant effect of uncertainty, with final fractional uncertainties between 0.11 and 0.30. Most of the results had uncertainty values of between 0.11 and 0.18 which are impactful, but still mostly acceptable, with the 2mm trial having significantly larger uncertainty due to the larger fractional uncertainty of sunscreen thickness. This resulted in a significant uncertainty for the 2mm trials, resulting in overlapping values (which can be seen in Figure 3) primarily caused by the large thickness uncertainty. While this is significant, the overall trends found are still readily apparent and repeatable. Additionally, it is important to consider how the validity of the uncertainty calculations was limited by the lack of information of the thermal conductivity constant. A value of 5% was chosen for this, through it is difficult to evaluate if this is a fair value and is important to critically examine.

- *Equipment Error and Calibration*

A problem with the equipment was with the hot plate calibration that resulted in random variation of temperatures during and between trials as the temperature probe was placed in a beaker of water. Since the heat capacity of water is significantly higher than that of sunscreen, and since there was more water in the beaker, this control beaker was far less responsive to temperature changes than the sunscreen samples, meaning that small changes in the water temperature resulted in large temperature changes in the samples. This resulted in random variation between trials at certain points lowering accuracy. This is also important in the practical application of data as it meant that the experimental set up was unable to properly mimic human tissue due to significantly higher hot plate temperature than intended (around 40^{o}C-65^{o}C rather than the intended 37^{o}C) reducing the practical applicability of this investigation.

Another problem was that it was difficult to accurately record and ensure even distribution of sunscreen in the petri dish. While parallax error was accounted for by dipping a small stick into the dish and measuring the height, the choice of measuring equipment was not ideal resulting in significant uncertainties compared to the size of the samples, increasing inaccuracy and random variation. Additionally, it was difficult to ensure even distribution of sunscreen and a piece of equipment such as a tamper could have helped to ensure even distribution. The uneven distribution of sunscreen had a non-negligible effect resulting in variations of temperature across the sample surface. This was accounted for by taking three measurements for each individual measurement and averaging them to account for this variation. Another small point that created some systematic error came from the thickness of the petri dish. While this investigation assumed that the surface temperature of the hot plate was the temperature of the lower sunscreen, this would not be true due to some heat loss through the thickness of the base of the petri dish, leading to a small systematic error increasing the heat flux results from the true value. This is a limitation but isn't all that significant as this investigation cannot be directly applied to practical scenarios (due to the unrealistic temperatures and thicknesses) and still allows for strong comparison between trends and series. Additionally, the heat flux through the petri dish base would be insignificant compared to the sunscreen heat flux.

- *Practicality*

To improve the applicability of this investigation, the ranges of the thickness of sunscreen should be expanded to thinner values, as it is unlikely that an individual would apply more than two or so millimetres of sunscreen. Likewise, the time period could be expanded to better investigate if the conductive properties of sunscreen remain constant over longer periods that are more likely to be relevant to practical scenarios (such as up to an hour), and the experimental set-up could be more reflective of human tissue through the replacement of the petri dish with synthetic skin and tissue to mimic the thermal character of humans more accurately. In reality, there would be some form of uncontrolled convection, while in the investigation the effects of convection were minimal due to the walls of the petri dish blocking air flow. While this aided to isolate the effects of conduction, it limits the direct applicability of this investigation and convection would also have a significant effect of the behaviour and effectiveness of sunscreen. Additionally, a second thermal camera could be position horizontal to the sunscreen sample to measure the temperature gradient of the sample to gather more information on the conductive properties of the substance.

4. Investigation 2 - Effect of Different Sunscreen Material Composition and Combination on Heat Conduction.

4.1 Hypothesis

This experiment aimed to investigate the difference in heat transfer due to active ingredients of different brand sunscreens. The thermal conductivity (k) values of our sunscreens A, B, and C were 0.19, 1.34, and 0.27 respectively. It is known that mineral oils used in cosmetics, biomedicine, and food processes possess k values that range from 0.12-0.14 W/mK [8]. This is due to their physical structure, as oils contain weak intermolecular bonds that cannot absorb heat well. Studies show that starch water gels, at temperatures of 10, 50, and 80 degrees Celsius, possess k values of 0.364, 0.386, and 0.388 W/mK [18]. This demonstrates the difference in intermolecular bond strength between water and oil. It is predicted that mineral sunscreens that contain zinc oxide, such as sunscreen C, will exhibit the least heat transfer due to their low thermal conductivities. This is because of its properties as a physical blocker, forming a barrier on top of our skin to scatter and reflect UVA and UVB rays [16]. This is compared to chemical sunscreens which absorb into the skin, producing heat, rather than reflecting it [17].

4.2 Results

Table 1: Temperature increase of Sunscreens over 5 minutes

Mixture	ΔT (°C)
A	0.733
B	2.47
AB	2.17
C	0.967
AC	0.867

Table 2: Calculated K values of each individual type of Sunscreen

Sunscreen	Cp	q	K
A	2.81	2.06	0.19
B	3.10	7.65	1.34
C	2.84	2.75	0.27
AC	2.83	2.45	0.24
AB	2.97	6.43	0.70

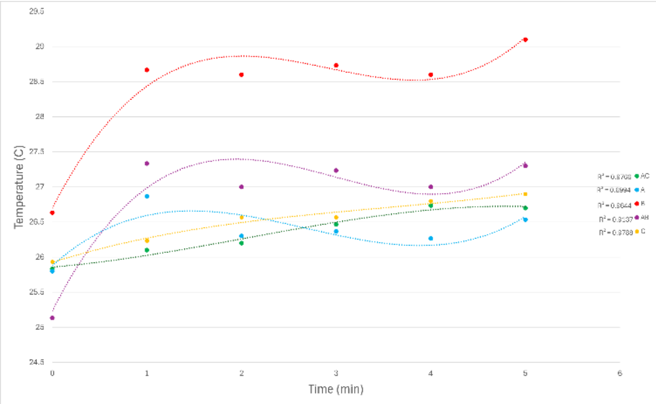

Figure 5: *Average temperatures of Sunscreen mixtures over 5 mins. A larger graph can be found in Appendix N.*

4.3 Discussion

4.3.1 Interpretation of results

The results collected measuring the temperature difference among mixtures of sunscreen indicated that the Sunscreen B (Bondi Sands) had the highest temperature increase of 2.47°C whereas the Sunscreen A (LeTan coconut Sunscreen) had the lowest of 0.73°C increase across 5 minutes. It was also found that the mixtures containing a 1:1 ratio of two designated sunscreens contained temperature increases that were approximately the average of their individual sunscreen tests. For example, Sunscreen A and Sunscreen C had a temperature increase of 0.73°C and 0.96°C respectively, and mixture AC was found to be 0.87°C, approximately the average of Sunscreen A and Sunscreen C's values with an error of only 2%. However, this trend was not fully consistent, as mixture AB's temperature increase was between the range of A and B but had a 35% error from the average. This observation would be mainly accounted by how uniform and how well the two sunscreens mix.

With this, there are 2 types of trends for the temperature change over time, depending on the type of sample used which are shown in Figure 5. For the sunscreen samples A, B and AB, the temperature tended to increase rapidly at the beginning, however it plateaus towards the end. For example, the surface temperature of the sunscreen for sample B had increased by 2.1°C after 1 minute from initial temperature of 26.6°C to 28.7°C, however the temperature fluctuates at around 28.7°C between 1 to 5 minutes. The samples C and AC displayed a linear trend, since the temperature increased consistently throughout the experiment. This is clearly shown in the two straight lines coloured in yellow (Sample C) and green (Sample AC). This can be attributed to Fourier's law of conduction as initially the Sunscreen is around room temperature whereas the hot plate was 32°C. Thus, the first minute has the largest temperature difference between the two surfaces resulting in higher heat transfer in the system initially. In some cases, the sunscreen may not behave linearly due to the decomposition of the active ingredients within the emulsifier [21].

4.3.2 Analysis of mixtures

Instead of being evenly distributed within the emulsion, the active ingredients end up clustering, leaving gaps within the emulsion and allowing the heat to pass through unaffected. This means that at higher temperatures, the effectiveness of the sunscreen is compromised. Another possible explanation is that the mixture may not be entirely homogeneous. Some sunscreens may be more polar than others resulting in insolubility when mixing. Polar molecules tend to favour other polar molecules, hence introducing the phrase, "like dissolves like". Without an amphiphilic emulsifier, the two sunscreens simply produce a biphasic mixture with droplets of each sunscreen surrounding each other. Studies show that mixing chemical sunscreens with zinc oxide may significantly reduce its effectiveness. Research of mixing a non-mineral SPF 15 chemical sunscreen with and without zinc oxide was conducted [19]. It was found that the sunscreen with the zinc oxide reduced in effectiveness by 84.3-91.8% whilst the lone sunscreen exhibited a decrease of only 15.8%.

4.3.3 Analysis of materials and polarities

Sunscreens are generally divided into two groups being oil based, and water based. Sunscreen B mainly contains compounds such as benzyl alcohol and phenoxyethanol which are low molecular mass and polar solvents that would have better thermal conduction. Polar solvents are generally more able to transfer heat than non-polar counterparts purely due the stronger intermolecular forces allowing for effective energy transfer between molecules. Polarity can be compared through the Reichardt's ET (30) Polarity scale which compares the polarity a molecule to water [20]. The ET (30) scale of polarity is units of kcal/mol representing the energy between intermolecular bonds. However relative polarity is a ratio between waters polarity of 63.1kcal/mol (Saini) - 2023.

$$Relative\ Polarity = \frac{Polarirty_{\ molecule}}{63.1kcal/mol}\quad Eq(2)$$

Benzyl alcohol and phenoxyethanol have relative polarities of 0.608 and 0.81. For comparison methanol which is a highly polar organic molecule has a relative polarity of 0.762 which indicates that molecules have strong hydrogen bonding allowing for more efficient heat conduction. Sunscreen A states it is water resistant, indicating the solution must mainly consist of oils to create a hydrophobic barrier. Oils are generally worse at transferring heat due to their lower densities and weak intermolecular forces. For example, Sunscreen B has Octocrylene as one of the ingredients providing the hydrophobic barrier. Since its chemical formula is $C_{24}H_{27}NO_2$ it can be assumed that its relative polarity would extremely low due being slightly higher than benzene's value of 0.009 due to majority of the molecule being nonpolar. Although all sunscreens do have common preservatives since Sunscreen C contains more nonpolar substances such as Octocrylene than Sunscreens A and B. With a lower molecular polarity, a large portion of the ingredients in Sunscreen C relies on weaker intermolecular bonds such as dispersion forces which limits the molecules' ability to have strong interactions resulting in inefficient energy transfer. Furthermore, high molecular weight molecules reduce molecular mobility, lowering thermal conductivity. Octocrylene, with a molar mass of approximately 361.5 g/mol is significantly heavier than the alcohol molar mass of 108.1 g/mol. This results in Octocrylene requiring more energy to move in a system and transfer energy than a Benzyl Alcohol molecule, resulting in less efficient conduction in comparison. Another key point is the ingredient of zinc oxide within sunscreen c. Zinc oxide is mainly used to absorb UV waves however it does have the zinc oxide do contain nanostructures which are spread across the sunscreen dispersing and limiting the heat conducted [22] explaining why it had the second lowest temperature increase.

4.3.4 Calculations for conduction coefficient

Through the ingredient descriptions of each sunscreen, their heat capacities were estimated as seen in Table 3. The ingredient descriptions mainly consisted of alcohols, oils and water as the main solvent in sunscreens. The heat capacity of oils is around 1.7J/gK and alcohols are around 2.5J/gK [23], and so these values were assumed for calculation. Combing these values with the percentage compositions of ingredients in each sunscreen, the heat capacity value was calculated. Sunscreen A contained 25% mass zinc oxide which has a heat capacity of 0.494 [24]. See Appendix E for calculations for estimated heat capacity values. The conduction coefficient was calculated using the specific heat capacity formula (Eq 3) and Fourier's Law (Eq 4):

$$q = mc\Delta T \quad (Eq\ 3)$$

$$q = -kA\frac{\left(T_{Plate} - T_{Surface}\right)}{L_{(Sunscreen\ Thickness)}} \quad (Eq\ 4)$$

Equation 2 is the specific heat capacity formula where q is defined as the energy transferred (Joules), m being the mass of the sunscreen (1g) and c representing the approximated heat capacity of each mixture. For this formula ΔT represents the temperature increase the sunscreen experienced over the 5 minutes of their respective trial. Equation 2 was equated to equation 3 being Fourier's conduction formula multiplied by Area. The hot plate temperature remained constant at 32°C to simulate the skin temperature, which is used for all calculations for *k (conduction coefficient)* for the different sunscreens. $T_{surface}$ represents the temperature of sunscreen at 5 minutes. *A* represents the total area of the sunscreen which was found considering the diameter of petri dish was 5cm. However, for these calculations' assumptions were considered to ensure values could be calculated. Minor assumptions were that the sunscreen was evenly spread among the total area of the petri dish where some areas may have had a larger thickness. The calculation method for the conduction coefficient assumes that there is only 1D conduction between the sunscreen and the hotplate. Future more in the experiment the conduction of the petri dish was assumed to be negligible considering it had a very low thickness allowing for majority of the energy to travel through the material to the sunscreen. See Appendix F for sample calculations of K.

The thermal conductivity values that were calculated in Appendix F and shown in Table 3 for the different sunscreen mixtures reveal distinct trends in heat transfer efficiency. Sunscreen B had the highest *k* value of 1.34 W/(mK), indicating the greatest thermal conductivity, consistent with its high heat absorption. In contrast, Sunscreen A exhibited the lowest conductivity suggesting stronger insulating properties which was consistent with the temperature observations. However, the *k* values for AB and AC closely align with the average *k* value between the individual samples. AB has 8% difference, and AC has a 4% difference only. This supports the assumption that thermal conductivity behaves approximately linearly with respect to the component proportions. The mixtures contain approximately the average conduction between two different types of sunscreens.

4.3.5 Limitations and Future Work

Although the experimental results were able to display clear trends between each sunscreen mixture there were several limitations throughout the experiment that hindered the validity and accuracy of the experiment.

- *Limitations in mixing procedures*

The first limitation in the validity of the result was caused by the possible lack of through mixing of the sunscreen samples. During the experiment, the two types of the samples were weighed on a petri dish and then mixed manually using a glass rod. This may have caused uneven distribution of the samples, as it is visually difficult to determine if the samples have been completely mixed or not. Having inhomogeneous mixtures can impact the result, as the surface of the sunscreen which the temperature was measured could have had different ratio of sunscreen compared to intended ratio. As shown in the result, the greatest error value was 4% obtained by the sample AB, and most of the other results have had low values ranging between 0 to 1% (Appendix D). Based on the results, it is appropriate to consider that the sunscreen samples were mixtures sufficiently, although there are few improvements that could be implemented as a future work.

A possible improvement would be to use a centrifugal mixer into order ensure that the two samples of sunscreen have been homogenous. Additionally, the use of centrifugal mixer means that it is likely that greater amount of sunscreen would be required compared to 0.5 grams per sample (i.e. mix 10 grams of sample A and B, instead of 0.5 gram each). This would improve the validity further as using greater amounts of sunscreen to prepare testing sample would decrease the uncertainty of the mass ratio.

- *Improvements for Accuracy*

In terms of the accuracy of the experiment, this could have been improved by testing larger variations of samples for example extra for CB and possibility 33% mixture of ABC could have been conducted. As this can allow for further comparison on whether applying different mixtures of sunscreen is more or less effective than just 1 type. Additionally, the R^2 value for the A sample was far lower than all other samples, indicating a higher degree of random error.

- *Potential Improvements for Materials*

Also, the plastic petri dish is a poor conductor of heat compared to human skin, and its insulating properties likely reduced the rate of heat transfer from the hot plate to the sunscreen. As a result, the measured temperature changes may not accurately reflect how the sunscreen would behave on actual skin. To improve validity, future experiments could use synthetic skin pads or gelatine-based materials to match skin thermal properties providing a more realistic approximation of how heat flows through skin in contact with sunscreen.

5. Conclusion

5.1 Investigation 1

In conclusion, the first investigation with the aim of investigating how the thickness of sunscreen affects the conductive heat flux through the samples was successful. Clear trends were found supporting the hypothesis of an inverse relationship between thickness and heat flux, with valuable secondary trends established such as the diminishing effect of extensive thickness application and the conductive performance with prolonged exposure. While there were some limitations around the experimental equipment, literature values and uncertainty, there were still clear trends established that effectively addressed the aim of this investigation with strong applicability to a practical scenario.

5.2 Investigation 2

In conclusion, the second investigation, with the aim of understanding the impact of mixing sunscreens of different active ingredients on thermal conductivity, was successful in identifying trends in relation to thermal conductivity for both material composition and effect of mixture. The hypothesis that that Sunscreen C would exhibit the lowest temperature change was somewhat supported. However, this does not suggest that the study did not possess several limitations which included improper and evenly distributed mixing which impacted the ratio of sunscreen at certain spots, small sample sizes and a possible three-way mixture, and the use of a petri dish which fails to mimic human skin in its ability to conduct heat due to its insulating properties.

5.3 Summary

In conclusion, this investigation was successful in finding characteristics that influence the conductive heat flux and heat transfer through different sunscreens, investigating both the effect of sample thickness, their compositional makeup and the effect of mixing different sunscreens. Identifying and improving some experimental limitations, such as assumptions of negligible heat loss to the surroundings, 1D conduction and limited convection could improve experimental accuracy and reliability in additional studies. Further improvements to the investigation would focus on improving the direct applicability of data to practical scenarios.

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Appendix

Appendix A: Sample valculations for Investigation 1:

Note that all sample calculations shown are for the 0 minute, 2mm trial 1:

- Heat flux:

$$q'' = -k\frac{dT}{dx} = -0.43\,\frac{W}{mK}\cdot\frac{66.5^{o}\,C - 35.4^{o}\,C}{0.002\,m} = 6690\,W$$

The values of the three repeats were then averaged for the tabulated value.

- Uncertainty for heat flux:

$$\frac{\delta T_h}{T_h} + \frac{\delta T_c}{T_c} + \frac{\delta x}{x} + \frac{\delta k}{k} = \frac{0.1^{o}\,C}{66.5^{o}\,C} + \frac{0.1^{o}\,C}{35.4^{o}\,C} + \frac{0.0005}{0.002} + 0.05 = 0.304$$

The uncertainty for the average heat flux for each trial was calculated through the sum of square errors merhod:

$$\sqrt{\frac{\sum\left(\frac{\delta q''}{q''}\right)^2}{3}} = \sqrt{\frac{(0.30)^2 + (0.30)^2 + (0.30)^2}{3}} = 0.30$$

From this the absolute uncertainty of the final value was found:

$$\delta q''_{avg} = \frac{\delta q''_{avg}}{q''_{avg}}\cdot q''_{avg} = 0.30\cdot 6790\,W = \pm\ 2070\,W$$

Appendix B: Full table of experimental and calcualted results for Investigation 1:

Thickness (mm)		Temperature (ºC) 0 min	1 min	2 min	3 min
2	Trial 1	35.4	39.1	40.7	40.1
	Plate	66.5	60.3	57.5	54.7
	Trial 2	35.5	38.4	42.3	40
	Plate	66.5	60.4	57.4	54.8
	Trial 3	33.8	34.2	39.5	41.8
	Plate	66.4	60.2	57.4	54.8
4	Trial 1	32.7	33.7	39.9	40.6
	Plate	66.5	60.3	57.5	54.7
	Trial 2	32.5	37.1	39.9	41.3
	Plate	66.5	60.4	57.4	54.8
	Trial 3	31.8	36.1	39.5	40.8
	Plate	66.4	60.2	57.4	54.8
6	Trial 1	27.8	30.2	30.4	32.2
	Plate	50	47.7	45.9	44
	Trial 2	27.9	30.2	30.2	32.1
	Plate	50	46.3	45.8	44
	Trial 3	28.1	30.6	30.5	32.5
	Plate	50.1	47.8	45.9	44.2
8	Trial 1	26.3	28.8	28.9	30.6
	Plate	50	47.7	45.9	44
	Trial 2	26.4	28.7	28.8	30.5
	Plate	50	46.3	45.8	44
	Trial 3	26.6	28.6	28.6	29.8
	Plate	50.1	47.8	45.9	44.2
10	Trial 1	27	26.8	27.8	28.2
	Plate	42.7	40.7	40.2	39.2
	Trial 2	26.9	26.4	27.5	27.7
	Plate	42.4	40.1	40.2	39
	Trial 3	27.1	26.7	27.4	27.4
	Plate	42.4	40.8	40.1	38.9

		Heat Flux, q'', through the suncreen (W/mK)			
Thickness (mm)		0 min	1 min	2 min	3 min
2	Trial 1	6687	4558	3612	3139
	Trial 2	6665	4730	3247	3182
	Trial 3	7009	5590	3849	2795
	Average	6787	4959	3569	3039
4	Trial 1	3634	2860	1892	1516
	Trial 2	3655	2505	1881	1451
	Trial 3	3720	2591	1924	1505
	Average	3669	2652	1899	1491
6	Trial 1	1591	1254	1111	846
	Trial 2	1584	1154	1118	853
	Trial 3	1577	1233	1104	839
	Average	1584	1214	1111	846
8	Trial 1	1274	1016	914	720
	Trial 2	1269	946	914	726
	Trial 3	1263	1032	930	774
	Average	1269	998	919	740

10	Trial 1	675	598	533	473
	Trial 2	667	589	546	486
	Trial 3	658	606	546	495
	Average	667	598	542	484

Appendix C: Full table of calculated fractional uncertinty and asbsolute uncertainty for Investigation 1:

		Heat Transfer , q, through the suncreen (W)			
Thickness (mm)		0 min	1 min	2 min	3 min
2	Trial 1	0.30	0.30	0.30	0.30
	Trial 2	0.30	0.30	0.30	0.30
	Trial 3	0.30	0.30	0.30	0.30
	Average	0.30	0.30	0.30	0.30
4	Trial 1	0.18	0.18	0.18	0.18
	Trial 2	0.18	0.18	0.18	0.18
	Trial 3	0.18	0.18	0.18	0.18
	Average	0.18	0.18	0.18	0.18
6	Trial 1	0.14	0.14	0.14	0.14

	Trial 2	0.14	0.14	0.14	0.14
	Trial 3	0.14	0.14	0.14	0.14
	Average	0.14	0.14	0.14	0.14
8	Trial 1	0.12	0.12	0.12	0.12
	Trial 2	0.12	0.12	0.12	0.12
	Trial 3	0.12	0.12	0.12	0.12
	Average	0.12	0.12	0.12	0.12
10	Trial 1	0.11	0.11	0.11	0.11
	Trial 2	0.11	0.11	0.11	0.11
	Trial 3	0.11	0.11	0.11	0.11
	Average	0.11	0.11	0.11	0.11

Absolute Uncertainty (W/mK)				
Thickness	**0min**	**1min**	**2min**	**3min**
2	2066	1509	1086	925
4	659	476	340	267
6	220	168	154	117
8	150	118	109	87
10	70.7	63.5	57.5	51.4

Appendix D: Absolute and percentage errors of inestigation 2

Mixture	Time(min)	0	1	2	3	4	5
A	Absolute error	1.136	0.569	0.300	0.208	0.503	0.379
	percentage error	4%	2%	1%	1%	2%	1%
B	Absolute error	0.379	0.404	0.436	0.289	0.265	0.100
	percentage error	1%	1%	2%	1%	1%	0%

AB	Absolute error	0.416	0.850	0.964	1.097	0.872	0.781
	percentage error	2%	3%	4%	4%	3%	3%
C	Absolute error	0.306	0.404	0.153	0.058	*0.173*	0.200
	percentage error	1%	2%	1%	0%	1%	1%
AC	Absolute error	0.153	0.300	0.100	0.115	0.058	0.100
	percentage error	1%	1%	0%	0%	0%	0%

Appendix E: Compostion and Heat capacity assumptions

Sunscreen	Compostion	Cp
A	40% water, 45% oil ,15% alchohols	2.81
B	50% water 30% oils 20% alchols	3.10
C	25% Zinc Oxide., 50% water 25% alchols	2.84
AB	50% A and 50% B	2.83
AC	50% A and 50% C	2.97

Sample calculation

$$Cp_A = 0.4 \times 4.18 + 0.15 \times 2.5 + 0.45 \times 1.7 = 2.81$$

Appendix F: Sample calculation of k value in investigation 2

$$q_B = 1g \times 3.1 J/g \cdot K \times (29.1 - 26.63)℃ = 7.65J$$

$$7.65J = -k\left(0.025^2\pi\right)\frac{(29.1-32)}{0.001}\; k = 1.34 W/(m \cdot K)$$

Appendix G: Calculation of the k value in investigation 1:

$$k = \frac{0.61\frac{W}{mK}}{60} + \frac{0.15\frac{W}{mK}}{30} + \frac{0.15\frac{W}{mK}}{10} = 0.43\ \frac{W}{mK}$$

Appendix H: % Drop in Heat flux with Increasing Thickness from 2mm to 10mm and Sample Calculation

Time	**% Drop in Heat flux with Increasing Thickness from 2mm to 10mm**
0 min	90.2%
1 min	87.9%
2 min	84.8%
3 min	84.1%

Sample Calculation: $\frac{q''_{2mm,\,0min} - q''_{10mm,\,0min}}{q''_{2mm,\,0min}} = \frac{6787\frac{W}{mK} - 667\frac{W}{mK}}{6787\frac{W}{mK}} = 90.2\%$

Appendix I: % Drop in Heat flux with Increasing Thickness in 2mm Increments and Sample Calculation

	% Drop in Heat flux with Increasing Thickness in 2mm Increments			
Thickness Step	**0 min**	**1 min**	**2 min**	**3 min**

2mm to 4mm	45.9%	46.5%	46.8%	50.9%
4mm to 6 mm	56.8%	54.2%	41.5%	43.3%
6mm to 8mm	19.9%	17.8%	17.3%	12.5%
8mm to 10mm	47.5%	40.1%	41.1%	34.5%

Sample Calculation: $\frac{q''_{2mm,\ 0min} - q''_{4mm,\ 0min}}{q''_{2mm,\ 0min}} = \frac{6787\ \frac{W}{mK} - 3669\ \frac{W}{mK}}{6787\ \frac{W}{mK}} = 45.9\%$

Appendix J: % Drop in Heat flux with Increasing Time at Set Thickness and Sample Calculation

Thickness	**% Drop in Heat flux with Increasing Time at Set Thickness**
2mm	55.2%
4mm	59.4%
6mm	46.6%
8mm	41.7%
10mm	27.3%

Sample Calculation: $\frac{q''_{2mm,\ 0min} - q''_{2mm,\ 3min}}{q''_{2mm,\ 0min}} = \frac{6787\ \frac{W}{mK} - 3039\ \frac{W}{mK}}{6787\ \frac{W}{mK}} = 55.2\%$

Appendix K: Raw results of Tempreture increases of sunscreen mixtures over 5 mineutes

	Time (min)					
Mixture	**0**	**1**	**2**	**3**	**4**	**5**
A	27.1	27.5	26.6	26.6	26.8	26.8
A	25	26.4	26	26.2	25.8	26.1
A	25.3	26.7	26.3	26.3	26.2	26.7
B	26.2	28.2	28.1	28.4	28.3	29
B	26.9	28.9	28.8	28.9	28.7	29.2
B	26.8	28.9	28.9	28.9	28.8	29.1
AB	25	26.7	26.3	26.6	26.4	26.8
AB	24.8	27	26.6	26.6	26.6	26.9
AB	25.6	28.3	28.1	28.5	28	28.2
C	26	26.3	26.6	26.6	26.9	27.1
C	26.2	26.6	26.7	26.6	26.9	26.9
C	25.6	25.8	26.4	26.5	26.6	26.7
AC	25.7	25.8	26.2	26.6	26.8	26.8
AC	26	26.4	26.1	26.4	26.7	26.7
AC	25.8	26.1	26.3	26.4	26.7	26.6

Appendix L: Average Results of Appendix K

Mixture	**0**	**1**	**2**	**3**	**4**	**5**
A	25.8	26.86667	26.3	26.36666667	26.26667	26.53333

B	26.63333333	28.66667	28.6	28.73333333	28.6	29.1
AB	25.13333333	27.33333	27	27.23333333	27	27.3
C	25.93333333	26.23333	26.56666667	26.56666667	26.8	26.9
AC	25.83333333	26.1	26.2	26.46666667	26.73333	26.7

Appendix M: Investigation 2 conduction coefficient (K) values of each sunscreen mixtures.

Sunscreen	**Cp**	**q**	**K**
A	2.81	2.06	0.19
B	3.10	7.65	1.34
C	2.84	2.75	0.27
AC	2.83	2.45	0.24
AB	2.97	6.43	0.70

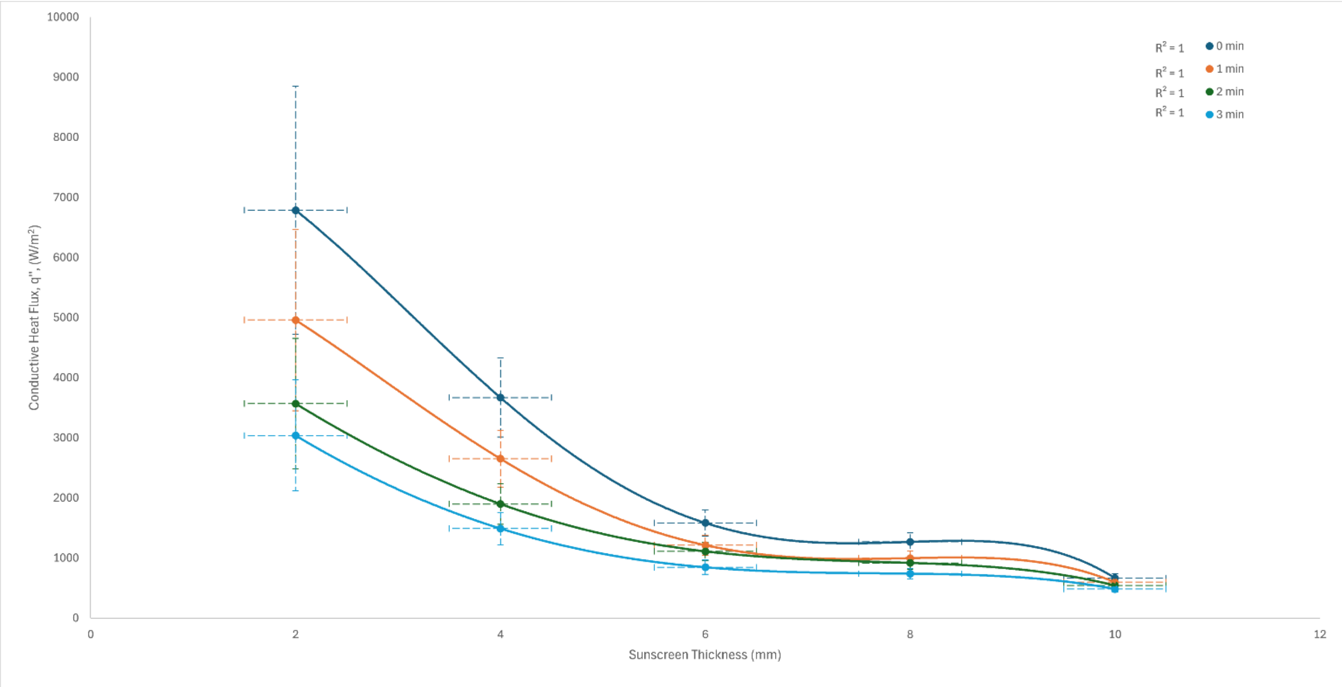
Appendix M: Sunscreens used in Investigation 2

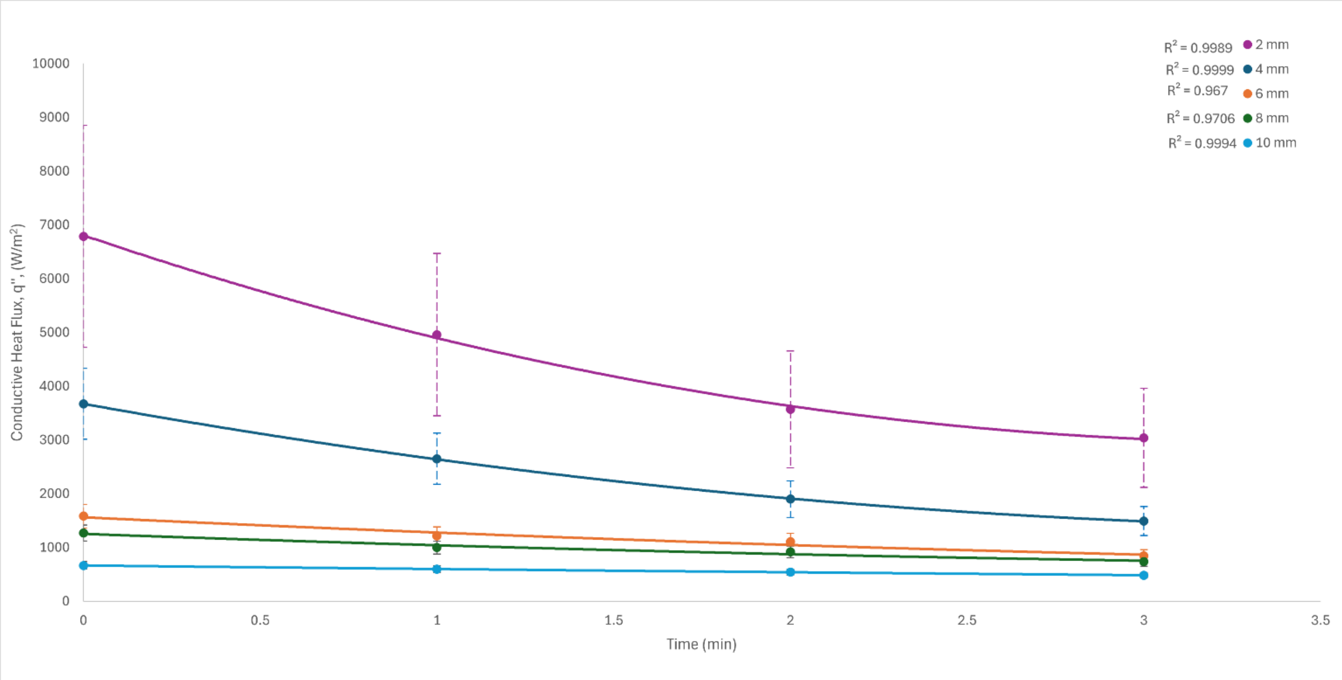
Sunscreen A (Letan coconut suncream 15spf) https://www.chemistwarehouse.com.au/buy/64759/le-tan-spf-15-coconut-sunscreen-lotion-125ml

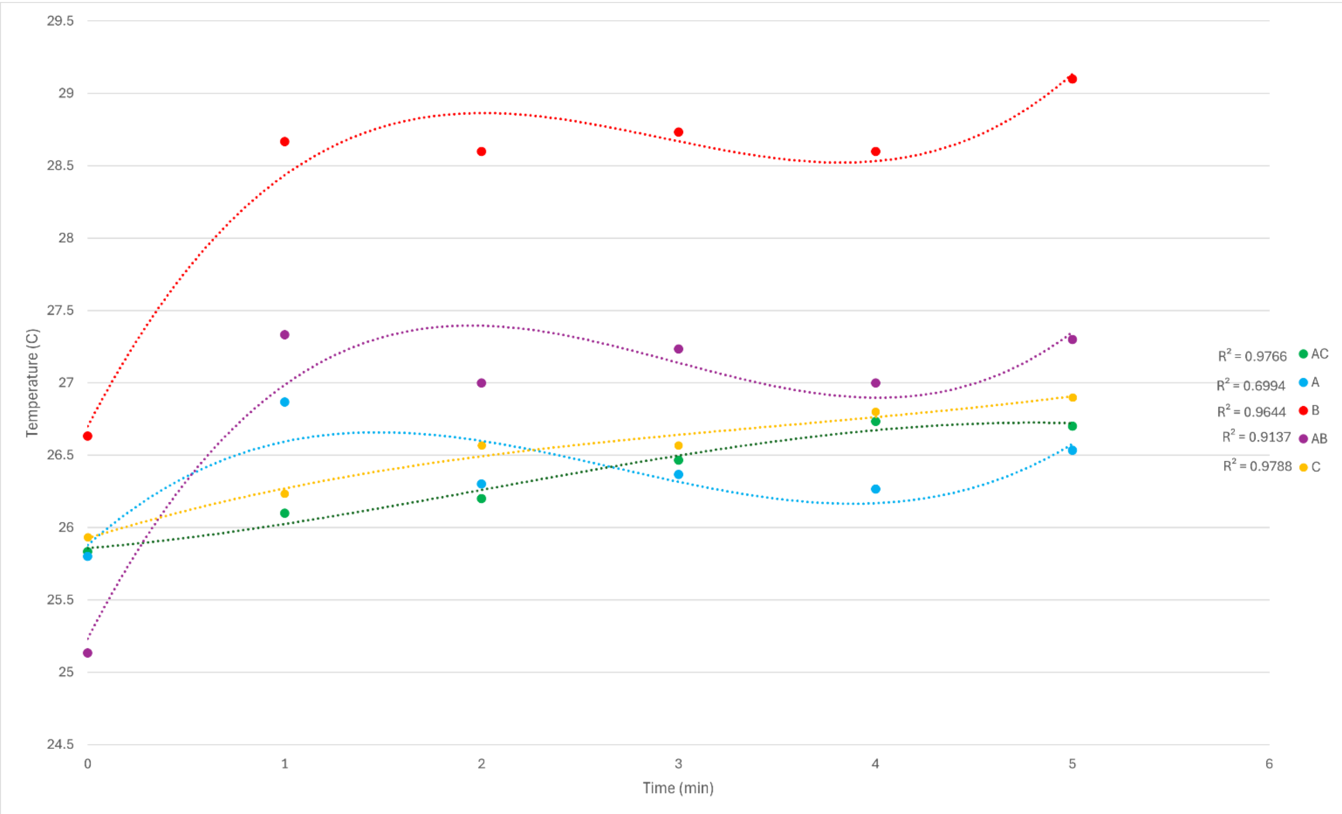
Sunscreen B (Bondi sands 50spf) https://incidecoder.com/products/bondi-sands-sunscreen-lotion-face-spf50

Sunscreen C (Banna boat baby zinc spf 50) https://www.chemistwarehouse.com.au/buy/131277/banana-boat-baby-zinc-spf-50-100g

Appendix N: Larger Graphs of Figures 3, 4 and 5




R² = 0.9989 2 mm
R² = 0.9999 4 mm
R² = 0.967 6 mm
R² = 0.9706 8 mm
R² = 0.9994 10 mm
Conductive Heat Flux, q'', (W/m²)
Time (min)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.5
1
1.5
2
2.5
3
3.5


R² = 0.9766 AC
R² = 0.6994 A
R² = 0.9644 B
R² = 0.9137 AB
R² = 0.9788 C
Temperature (C)
Time (min)
29.5
29
28.5
28
27.5
27
26.5
26
25.5
25
24.5
0
1
2
3
4
5
6

