Determining the Emissivity of Roofing Samples: Asphalt, Ceramic and Coated Cedar

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The goal is to perform heat measurements examine of selected roofing material samples. Those roofing materials are asphalt shingles, ceramics, and cedar. It's important to understand the concept of heat transfer, which consists of conduction, convection, and radiation. Research work was reviewed on different infrared devices to see which one would be suitable for conducting my experiment. In this experiment, the main focus was on a specific property of radiation. That property is the emissivity, which is the amount of heat a material is able to radiate compared to a blackbody. An infrared measuring device, such as the infrared camera was used to determine the emissivity of each sample by using a measurement formula consisting of certain equations. These equations account for the emissivity, transmittance of heat through the atmosphere and temperatures of the samples, atmosphere and background. The experiment verifies how reasonable the data is compared to values in the emissivity table. A blackbody method such as electrical black tape was applied to help generate the correct data. With this data obtained, the emissivity was examined to understand what factors and parameters affect this property of the materials. This experiment was conducted using a suitable heat source to heat up the material samples to high temperature. The measurements were taken during the experiment and displayed by the IR camera. The IR images show the behavior of surface temperatures being distributed throughout the different materials. The main challenge was to determine the most accurate emissivity values for all material samples. The results obtained by the IR camera were displayed in figures and tables at different distances, which was between the heap lamp and materials. The materials exhibited different behaviors in temperature and emissivity at certain

distances. The emissivity of each material varied with different temperatures. The results led to suggestions of certain materials that could be beneficial and disadvantageous in energy and cost savings during cold and hot seasons of the year. Also this led to some uncertainties in the data generated. Overall, this can support in exploring other ideas to increase energy and cost saving consistently during both season by using a material that can change its color and density based on a high or low temperature.

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CHAPTER 1

INTRODUCTION

1.1 Objective

The objective of the research work is to execute precise measurements to determine the emissivity of roofing materials: asphalt shingles, ceramics and cedar, using an IR camera FLIR A40. The main focus of the experiments was to examine the emissivity and determine what factors and parameters affect this property of the materials. Emissivity tables can be helpful when trying to perform heat measurements. However, the values from the emissivity table may raise some questions, such as: are the values from the table accurate? How are the values obtained? And are values the same at every temperature measured for that specific material. The purpose of this experiment is not only to determine the emissivity of the roofing sample, but also to check the values from the table are reasonable.

1.2 Factor

There are several types of roofing systems that can make houses more energy efficient. The efficiency of a house is affected by the materials used to build the roof. These materials have particular properties that can help calculate the heat transfer. The major factors for determining the heat transfer of roofing materials are: thermal conductivity, convection heat coefficient, emissivity, absorptivity, transmittance, reflectivity, and temperature of the surface and environment (ambient). These properties reflect how energy efficient buildings: residential, industrial and commercial can be.

CHAPTER 2

BACKGROUND

2.1 Heat Transfer

Heat transfer is the amount of heat energy that travels when there is a difference in temperature between a solid, liquid, gas, or a combination of one of the three. There are three modes of heat transfer: conduction, convection, and radiation (Incropera & Dewitt, 2007).

2.1.1 Conduction

Conduction is the transfer of heat energy due to the difference in temperature that occurs within a solid or stagnant liquid. Conduction over an area is called the heat flux. The equation used to determine heat loss is $q'' = -\frac{\gamma \nabla T}{L}$ known as Fourier's Law. (γ) is the thermal conductivity of the material. (L) is the thickness or the length of the substance. $\Delta T = (T_{s1} - T_{s2})$ is the temperature difference in the same substance. To measure the heat loss through the roof, it is needed to determine the U value, which is the reciprocal of the thermal resistance. The thickness (L) of the material divided by the thermal conductivity (γ) and the thermal resistance is (R) (Incropera & Dewitt, 2007). For example, a simple correlation, $L/\gamma = R$, shows how each property affects one another. Constructing a roofing system using a solid material with a larger thickness increases the thermal resistance. Thermal resistance shows how good of an insulator your material is. To combat low ambient temperatures, a thick insulation is desirable to reduce conductive heat loss. Therefore, materials with high R-values used in roofing designs would be better for colder climates than it would be for hotter climates

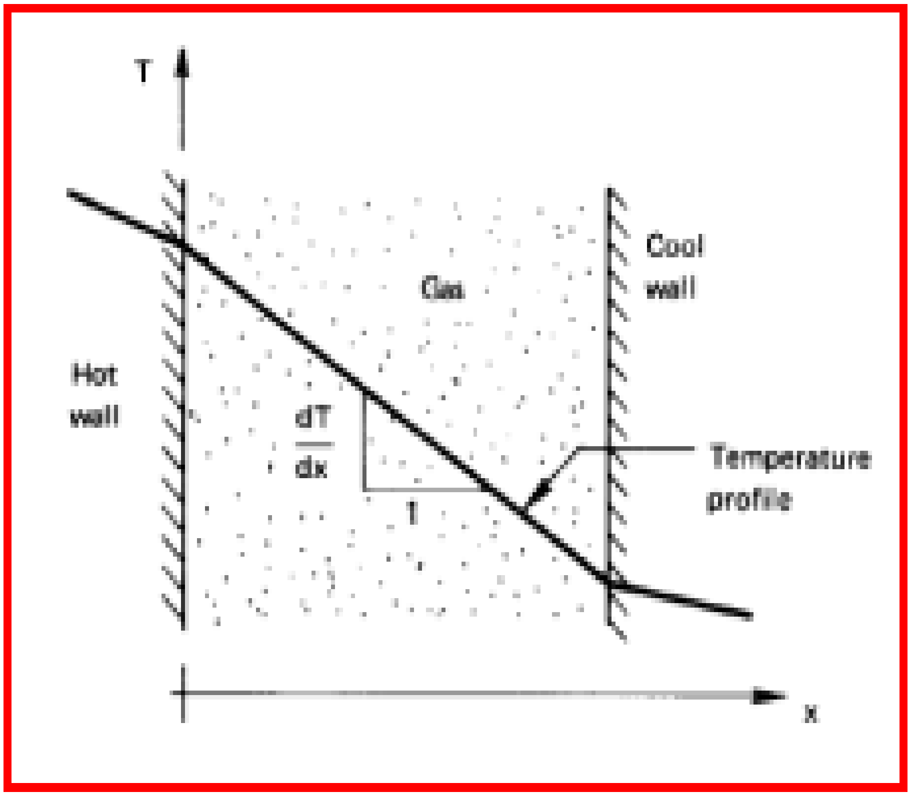

Figure 1 Heat conduction through two walls sepearted by a gas (Consigny, 2012)

2.1.2 Convection

Convection is the transfer of energy between a solid object and moving liquid or air. q ($\frac{W}{m^2}$) is the heat flux and h ($\frac{W}{m^2K}$) the heat transfer coefficient. The same concept for the energy transfer is applied. There needs to be a temperature difference for the energy transfer to occur where the liquid or solid object has a temperature higher or lower than the other. The equation that was used to determine the convection heat flux is $q" = (T_{Surf} - T_{amb})h$. T_{surf} is the temperature of the material surface and $T_{amb}$is the temperature of the surrounding or environment (Incropera & Dewitt, 2007).

When it comes to finding the energy performance of a solid object, the convection heat transfer is neglected Most of the experiments need to be conducted in a vacuum space becuase prevents natural convection.. (Incropera & Dewitt, 2007).

2.1.3 Radiation

Radiation is the energy released or emitted by matter: solid, gas, liquid, or plasma in the form of electromagnetic waves. The equation used to determine the radiation emitted by a blackbody is

$Q_{emit} = \varepsilon\sigma T_s^4$ [Watts/m^2] (Incropera & Dewitt, 2007)

ε is the emissivity, $\sigma = 5.67 \times 10^{-8}\ {}^{W}/_{m^2K^4}$ is the Stefan-Boltzmann constant, and T_s is the temperature of the material's surface. Graybody radiators use the same equation but it is referred to as the Stefan-Boltzmann formula. If the value of emissivity is equal to 1, the total radiation emissive heat flux (Q_{emit}) for a blackbody is obtained as: $Q_{emit} = \sigma T^4$ [Watts/m^2] (Incropera & Dewitt, 2007)

The emissive power of radiation from every object is able to be simply calculated by multiplying the blackbody radiation with the emissivity. The equation that is used to determine the rate at which the surface absorbs radiation is $Q_{abs} = \alpha Q_{incident} = \alpha\sigma T_{surr}^4$ where $Q_{incident}$ is the rate at which the radiation is incident on the surface. That means that the heat energy from the sun is being emitted into the surface to be absorbed. To determine the rate at which the surface reflectance radiation is $Q_{ref} = (1-\alpha)\alpha\sigma T_{surr}^4$. α is the absorptivity and T_{surr} is the ambient temperature. The emissivity is the property to provide measure of how efficiently a surface material radiates energy relative to a blackbody.

The absorptivity is the amount of radiant energy a material can absorb. For the materials that are assumed to be gray surfaces the emissivity and absorptivity are equal to one another. Therefore, the equation for the net rate of radiation heat transfer from the surface is obtained as $q''_{rad} = \frac{q}{A} = \varepsilon E_b(T_s) - \alpha G = \varepsilon\sigma(T_s^4 - T_{sur}^4)$. This equation represents the difference between thermal energy that is released due to emitted radiation emission and that which is gained due to absorb radiation. $q_{conv} = h_r A(T_s - T_{sur})$ is the radiation heat due to convection. $h_r = \varepsilon\sigma(T_s + T_{sur})(T_s^4 + T_{sur}^4)$ is radiation heat transfer coefficient. Therefore, the total radiation heat transfer is Q=Qconv+Qrad (Incropera & Dewitt, 2007)

2.2 Blackbody

The BlackBody is an ideal material that emits 100 percent of the heat energy received from the sun. It is referred to as a perfect emitter, therefore there is not an object that is capable of emitting the same amount as a blackbody at the same given temperature. The radiation characteristics of a hole where light can pass through in an isotherm cavity are composed of an opaque absorbing material. This will display approximately some specific blackbody properties. Any radiation that gets through the opening of the cavity is dispersed and absorbed by reoccurring reflections, therefore, only a small fraction can perhaps get away. The blackness captured at the opening is approximately equal to a blackbody and just about perfect with all wavelengths. A cavity radiator is an isothermal cavity that is provided with an appropriate heating source.

The isothermal cavity heated by an appropriate heat source to a consistent temperature produces blackbody radiation. Certain properties of the isothermal cavity can be found only by the temperature (FLIR, 2009).

2.3 Emissivity

The emissivity is a fraction of the quantity of emitted radiation an object can radiate compared to the quantity of radiation actually emitted by a blackbody at an equivalent temperature.

$$\varepsilon = \frac{\varepsilon_{object}(T)}{\varepsilon_{blackbody}(T)}.$$

A material usually has an emissivity ranging from 0.01 to 0.98. The value 0.01 represents a shiny material that is highly reflective, and 0.98 represents a material that is highly emissive almost like a blackbody. Materials that are non-metals: plastic, concrete, rubber, wood, rock, or organic materials, have a slight reflectance. They have high emissivities ranging between 0.8 and 0.95 (Gruner, 2003).

When using the IR camera to obtain heat measurements of metals, the data generated is difficult to understand and evaluate. The IR camera is not capable of distinguishing whether the energy is being reflected or emitted from the material. Non-oxidized metallic objects that are not transparent and highly reflective do not fluctuate much in wavelength. As a result, metals have values of emissivity that are small as the temperature rises and non-metals or graybodies have values of emissivity that are high as temperature is diminishing (FLIR, 2009).

2.4 Electromagnetic Spectrum

The electromagnetic spectrum is part and relates to all forms of radiation. The electromagnetic spectrum is composed of visible light, radio waves, microwaves, ultraviolent light, infrared light, Gamma-rays, and X-rays. Visible light is light that one can look at to help distinguish materials by shape and color. Radiowaves pertain to devices that transmit waves that have frequencies that allow people to hear what is going on such radar, walkie talkies, or cell phones. Microwaves relate to the microwave using radiation to heat up food. Ultraviolet pertains to heat energy released by the sun like a person's skin getting darker. Infrared is the heat produced from human skin or any object that can be seen with night vision goggles. Gamma rays pertains to gamma ray instruments like a PET scan (generates pictures to examine the inside a person's body). X-rays relate to CAT scans (used to observe the inside of a person's body). (NASA).

Electromagnetic waves pass through clear space. They are generated by electrically charged particles. Waves are irregular disruptions that maintain their shapes while traveling through in space as a function of time. The electromagnetic field is separated into a quantity wavelength intermissions referred to as bands. They're differentiated by developed techniques used to generate and identify the radiation. There is no difference among the radiation with different bands, the differences only is based on certain wavelengths (FLIR, 2009)

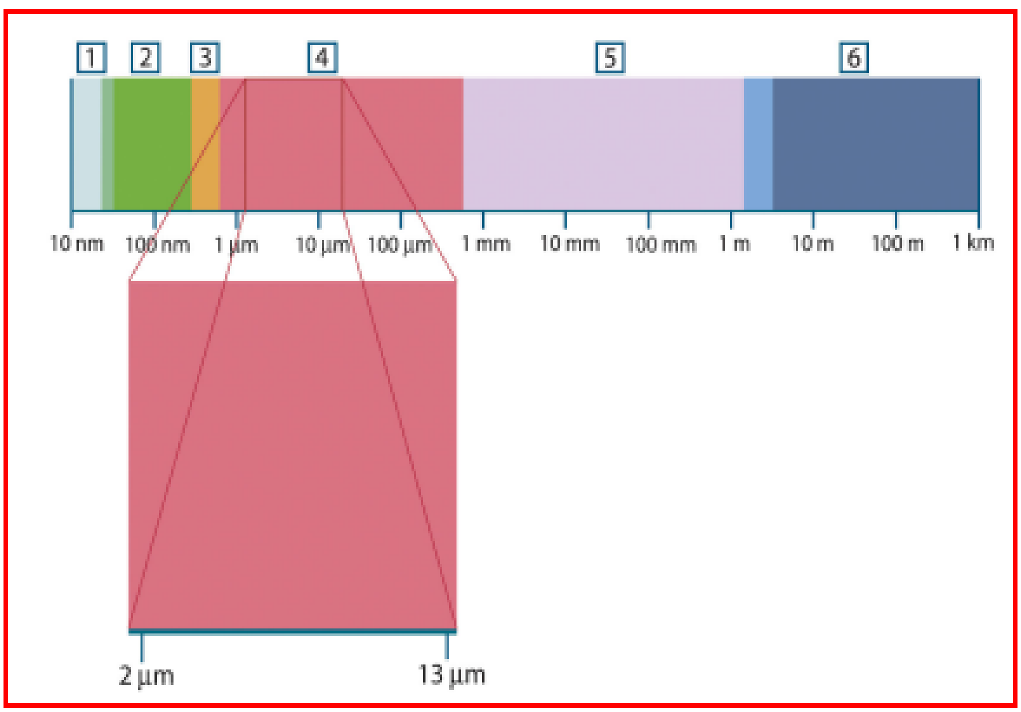

Figure 2 The Electromagnetic Spectrum: 1: X-Ray; 2: UV; 3: Visible 4; 5: IR; 6: Radiowaves (FLIR, 2009)

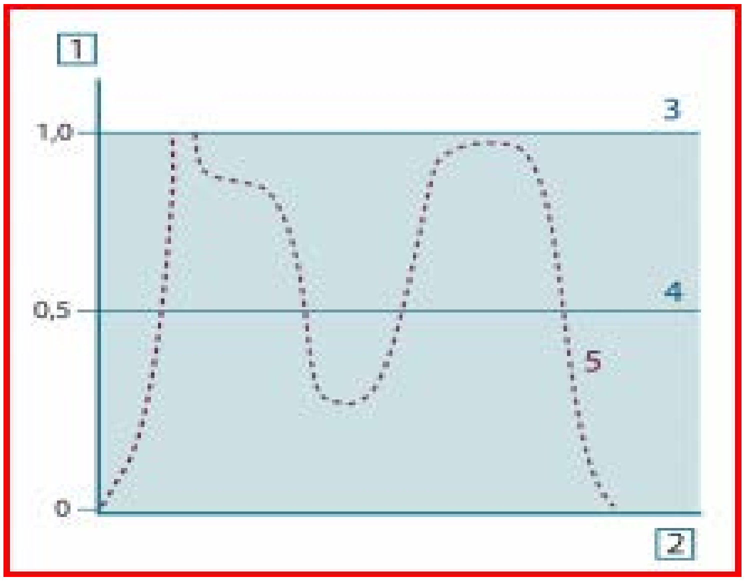

Figure 3 Spectral radiant emittance of three types of radiators 1: Spectral emissivity 2: Wavelength 3. Blackbody 4: Selective Radiator 5: Graybody (FLIR, 2009)

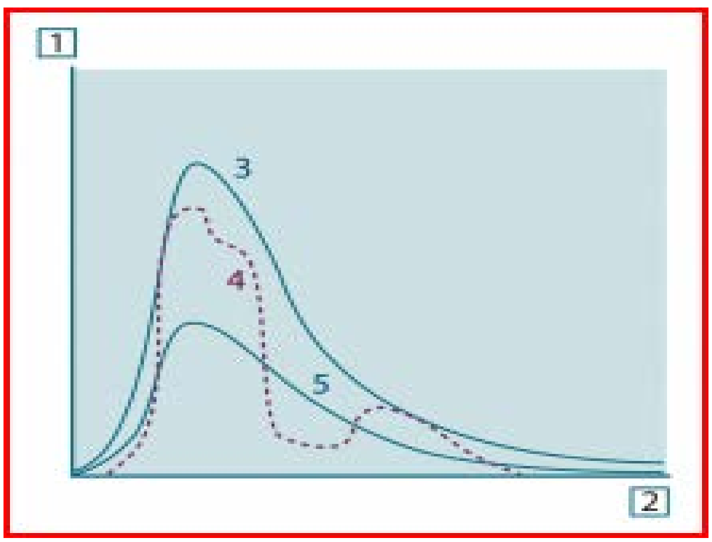

Figure 4 Spectral radiant emittance of three types of radiators 1: Spectral emissivity 2: Wavelength 3: Blackbody 4: Graybody 5: Selective Radiator (FLIR, 2009)

2.5 Energy Balance

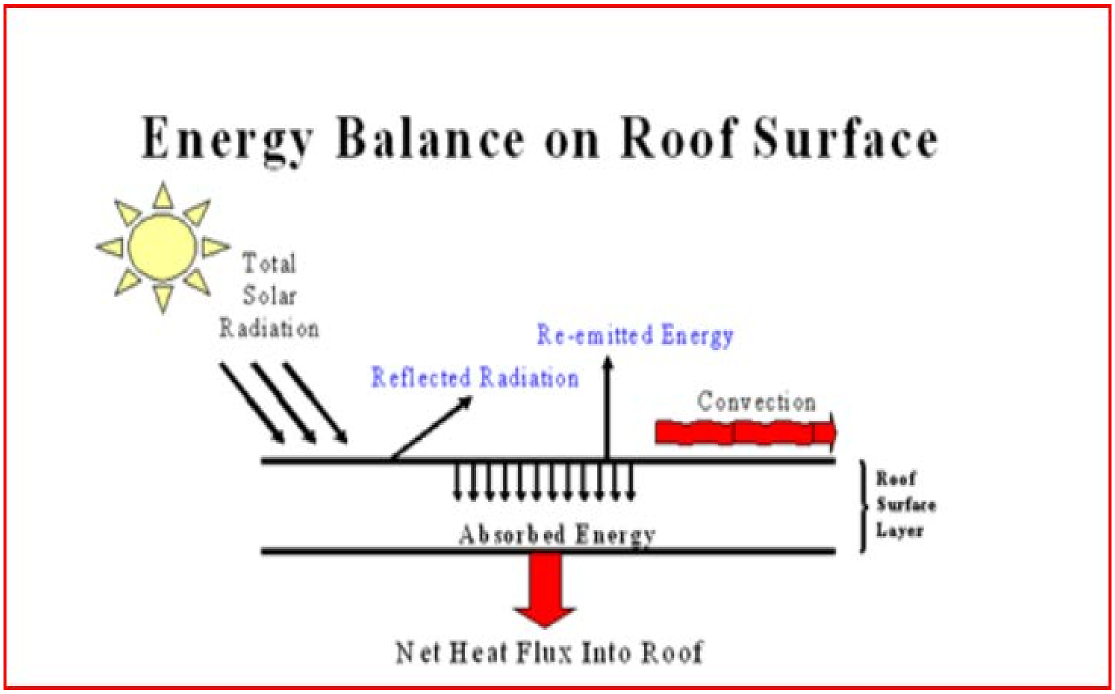

Figure 5 Energy balance on roof surface (Bush, Miller, & Kriner, 2010)

Figure 5 shows the energy balance of the roof's surface involving all three modes of heat transfer during the process of irradiation. The heat source is the sun emitting heat energy directly onto the roof's surface. This process is known as total solar radiation. The roof will reflect a portion of the energy but absorb most of it. The energy absorbed through the layers is the process of conduction heat transfer. The roof will also emit heat energy (the emissive power), which part of the total radiation is based on this equation $q_{conv} = \varepsilon\sigma(T_s + T_{sur})(T_s^4 + T_{sur}^4)A(T_s - T_{sur})$ found in section 2.1.3. The exterior of the roof will have a greater temperature than the underside of the roof because it's exposed to the heat emitted by the sun. The roof, whether it is reflective or absorbent, will emit some heat energy. Convention heat transfer will occur due to the current of ambient air.

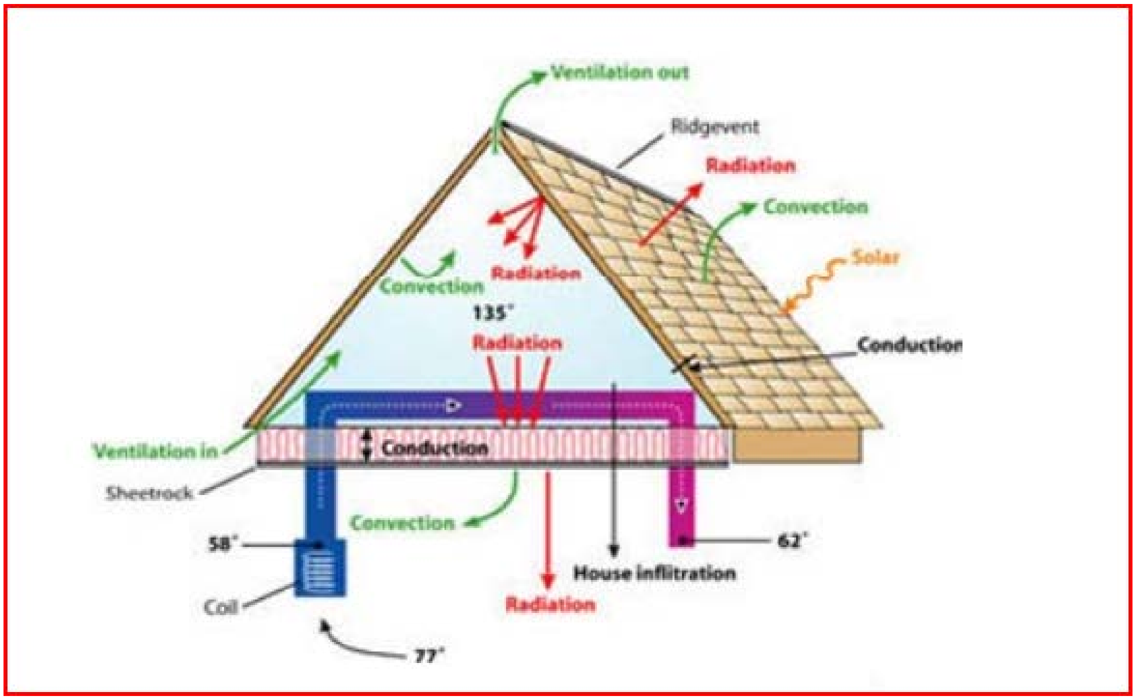

Figure 6 Heat transfer mechanisms for standard vented attic (Parker, Shewin, & Anello, 2001)

Figure 6 shows all three modes of heat transfer occurring on the attic.

2.6 Thermography

Thermography is the study of heat characteristics by observing the radiation from all materials through heat measurements. An Infrared device such as the IR camera is used to execute precise heat measurements. The data from this IR device is obtained and can be examined for further analysis.

2.6.1 Formulas

2.6.1.1 Radiation Measurement Formula

The IR camera identifies and reads infrared energy emitted from the material back to the camera. In order to do that, the camera uses an algorithm to determine the surface temperature as well as the emissivity. The object that is the target for measurement is going to emit a certain amount of heat energy. That energy emitted is represented by the following equation:

εV_{obj}, where ε is the emittance of the object and V_{obj} represents the target being measured at temperature T_{obj}.

The target will reflect some heat energy as well towards the camera, which is represented by this equation: $(1-\varepsilon)V_{ref}$, where $(1-\varepsilon)$ is the reflectance of the target and V_{ref} represents the ambient conditions that is at temperature T_{amb}. The heat energy that is emitted and reflected by the target passes through the air before it reaches the camera. So the transmittance τ and atmospheric temperature T_{atm} has to be considered. Therefore, this equation $\varepsilon\tau V_{obj}$ represents the emitted energy from the target passing through the air to reach the camera's lens. This equation $(1-\varepsilon)\tau V_{ref}$ represents the reflected heat energy from the object passing through the air to reach the IR camera's lens.

The heat energy emitted by the atmosphere is represented by this equation$(1-\tau)V_{atm}$, where $(1-\tau)$ is the emittance of the air and V_{atm} represents the atmosphere at a temperatureT_{atm}. The incident radiation is equal to the sum of all equations which is

$V_{tot} = \varepsilon\tau V_{obj} + (1-\varepsilon)\tau V_{ref} + (1-\tau)V_{atm}$. The term V_{tot} represents the total incoming radiation converted into the output voltage by the camera's core detector. The detectors of the infrared camera allows it to convert the incoming radiation into electrical signals. V_{tot} is a function of temperature T_{obj}. The equation $V_s = CW(T_S)$, where $T_S$is the blackbody temperature and the temperature of the object. To determine the temperature of the object, the value of the emissivity and transmittance needs to be set to 1.

Then the equation $V_{tot} = \varepsilon\tau V_{obj} + (1-\varepsilon)\tau V_{ref} + (1-\tau)V_{atm}$ simplifies to $V_{tot} = V_{obj}$. The same equation is used, however, the emissivity in the object parameters needs to be set to 0.95 which is the value of black tape. $T_{refl} = T_{atm} = 20°C = 68\ F$ and the transmittance is equal 1 and these are the fixed values in the object parameters. $V_{obj} = \frac{1}{\varepsilon\tau}V_{tot} - \frac{1-\varepsilon}{\varepsilon}V_{refl} - \frac{1-\tau}{\varepsilon\tau}V_{atm}$ is the equation used to find the object temperature. This equation: $V2_{obj} = \frac{1}{\varepsilon}V_{tot} - \frac{1-\varepsilon}{\varepsilon}V2_{refl}$ determines the temperature for the portion of the object applied without black tape. This equation: $V3_{obj} = \frac{1}{\varepsilon}V_{tot} - \frac{1-\varepsilon}{\varepsilon}V3_{refl}$ determines the temperature of the section of the object with black tape applied. This represents the actual temperature of the object when the IR camera converts the voltage ($V3_{obj}$) to temperature ($T3_{obj}$). To find the emissivity, the emissivity calculator solves for ε using those previous equations thus comparing the energy emitting at ($T2_{obj}$) to the energy emitted at ($T3_{obj}$). (FLIR, 2009).

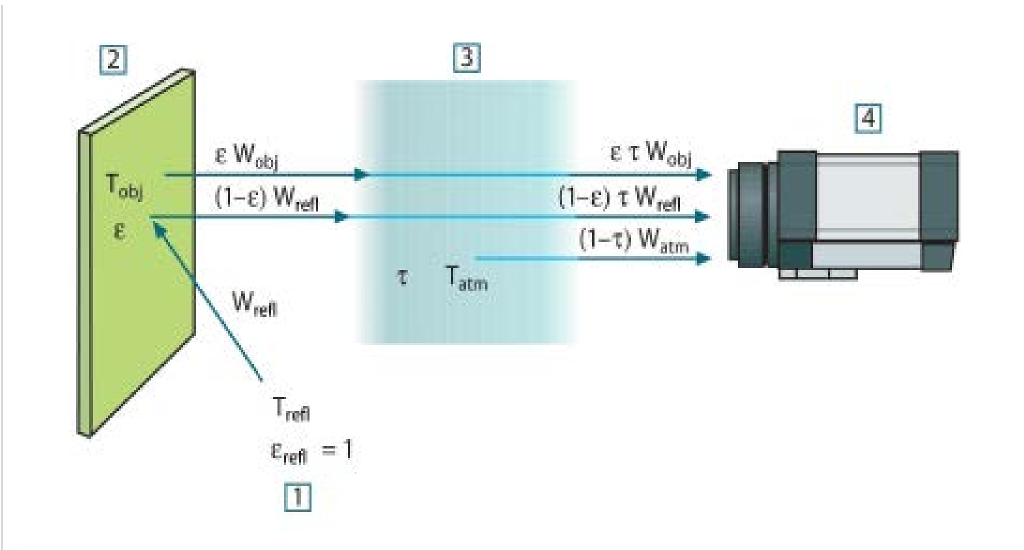

Figure 7 A schematic representation of the general thermo graphic measurement situation 1: Environment 2: Object 3: Atmosphere 4: Camera (FLIR, 2009)

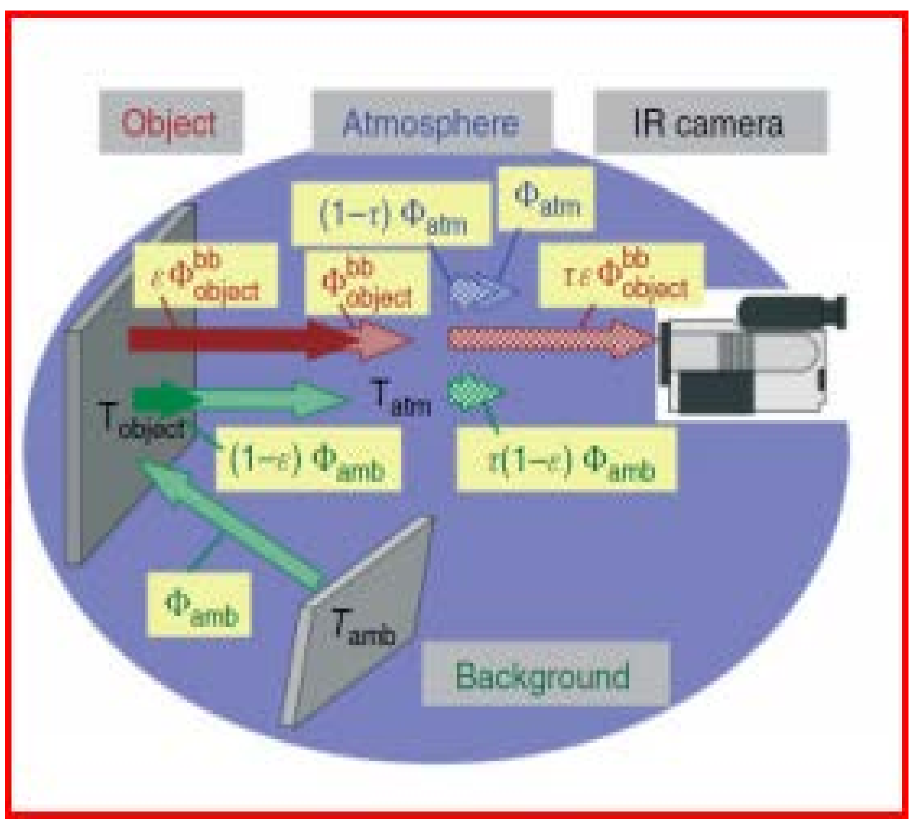

Figure 8 A schematic representation of the general thermo graphic measurement situation 1: Environment 2: Object 3: Atmosphere 4: Camera (Cosigny, 2012)

The IR Camera from FLIR Systems Camera depends on cavity radiators for corrections and adjustments for heat experiments. Things that are visible to the eye occur when the temperature rises higher than 525 °C (977 °F) (FLIR, 2009). Colors are used to assist in heat measurements when it comes to finding the surface temperature of the target. In Figure 9 below, the color starts form blue, changes to purple then yellow, and finally orange as temperature rises. Figure 9 shows the spot temperature on the portion of the high emissivity black tape for each material. SP01: Ceramic grey, SP02: Cedar coated with Aluminum paint: SP03: Cedar coated with paint, SP04: Ceramic brown, SP05: Cedar coated with black paint, SP06: Asphalt

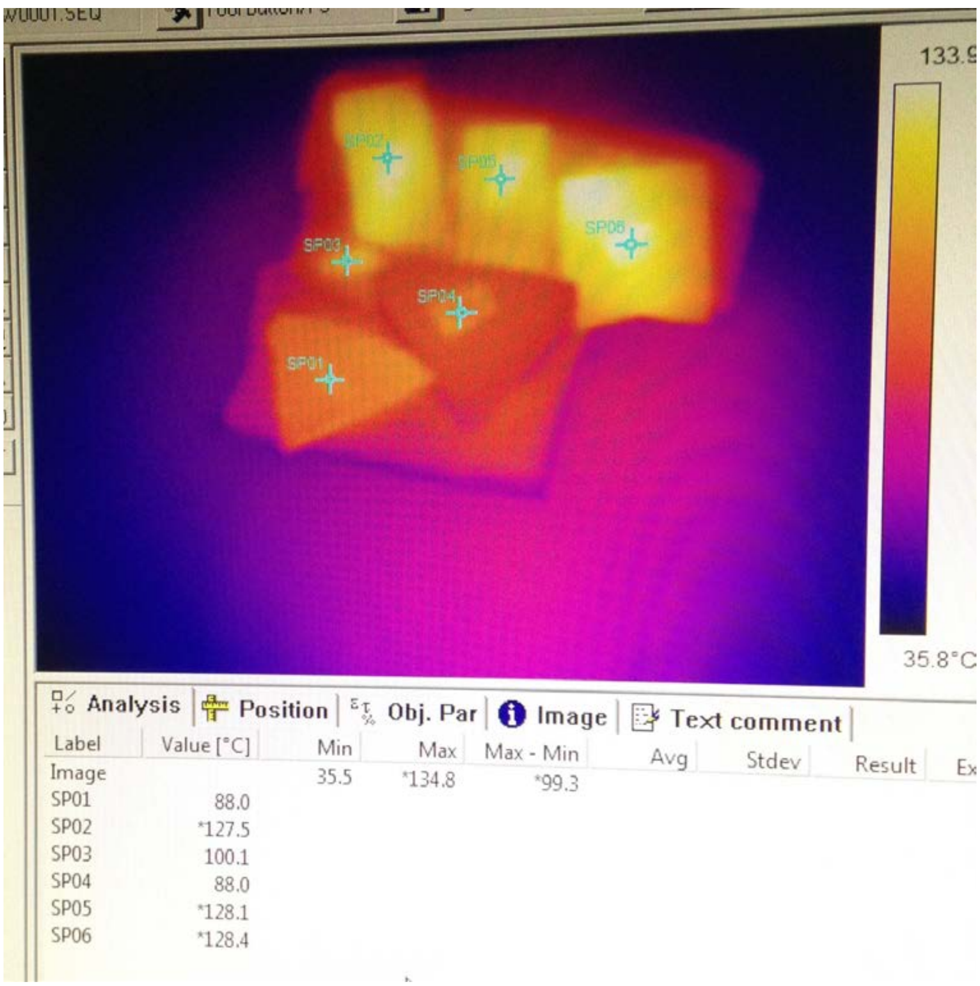

Figure 9 Color distinctions for low and high temperatures

2.6.1.2 Planck's Formula

Max Planck (1858-1947) created a formula to illustrate the spectral distribution of the radiation of a blackbody with the follow formula: $W_{\lambda b} = \frac{2\pi hc^2}{\lambda^5(e^{hc/\lambda kT}-1)} \times 10^{-6}[Watt/m^2, \mu m]$.

Where $W_{\lambda b}$ is blackbody spectral radiant emittance at wavelength λ.

C (3×10^8/s) is the speed of light in a vacuum. h (6.6×10^{34} Joules) is the Planck's Constant. k is (1.4×10^{-23} Joule/K) Boltzmann's Constant. T (K) is the blackbody's absolute temperature. λ(μm) is the wavelength (μm) (FLIR, 2009) (Incropera & Dewitt, 2007). 10^{-6} is the factor applied since spectral emittance in the curves is expressed in Watt/m^2, μm. When variation of temperatures are graphed and plotted, the Planck's formula generates several curves. In relation to every specific Planck curve, the spectral emittance is zero at λ=0, then rises quickly to a highest wavelength which is λ_{max}. Once the spectral emittance exceeds λ_{max}, it will decrease until it reaches zero at extremely extensive wavelengths (FLIR, 2009)

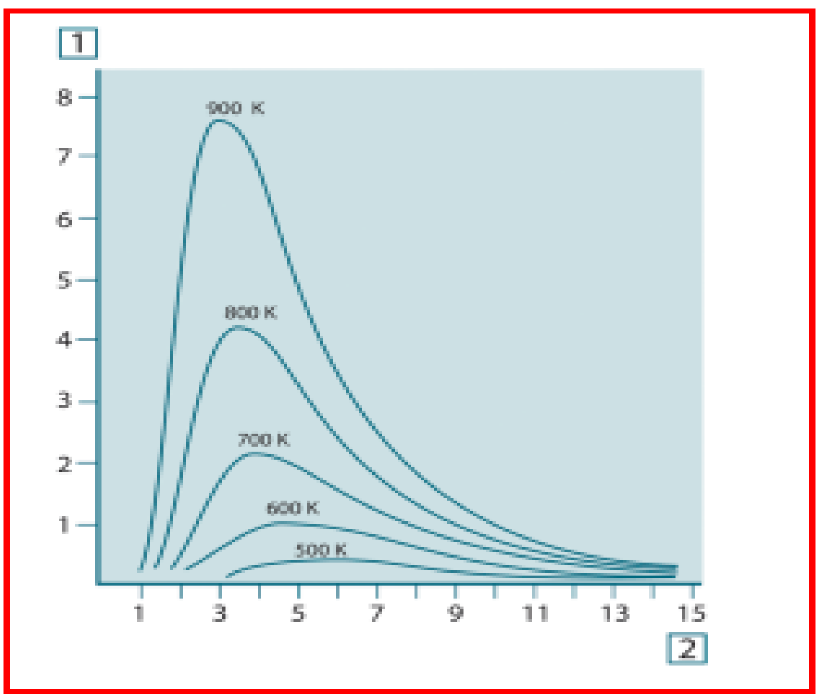

Figure 10 Blackbody spectral radiant emittance based on Planck's law plotted for a series of the absolute temperature (FLIR, 2009)

By deriving Planck's formula in relation to λ, and detecting the maximum, we obtain: $\lambda_{max} = \frac{2898}{T}$ [μm]. Planck's Formula comments on some key points: 1) Radiation emitted changes constantly with wavelength; 2) Radiation emitted increases with while temperature increases; 3) Increasing temperatures results in smaller wavelengths at which the maximum of a curve can be generated; and 4) A small portion of emitted radiation from a blackbody with a temperature about 5800K lies in the visible region of the spectrum and the emission where the temperature is less than 800k is in the infrared spectrum that is visible for the eye to see (Incropera & Dewitt, 2007).

2.6.1.3 Wein's Formula

Wein's formula demonstrates the general perception that colors change from violet to red or orange to yellow as the thermal radiation's temperature rises. The wavelength of the color and the wavelength calculated for $\lambda_{max}$are identical. Using the rule-of-thumb 3000/T μm leads to an estimated value of λ_{max}, which represents the known temperature of a blackbody.
Different objects have different wavelengths at certain temperatures. For example, the sun has a temperature of 6000K. The wavelength value is approximately 0.5 μm. The color of wavelength would be found between the ultraviolet and infrared section of the spectrum (FLIR, 2009). At the highest point on the infrared section, liquid nitrogen has the smallest wavelength value (38 μm) (FLIR, 2009).

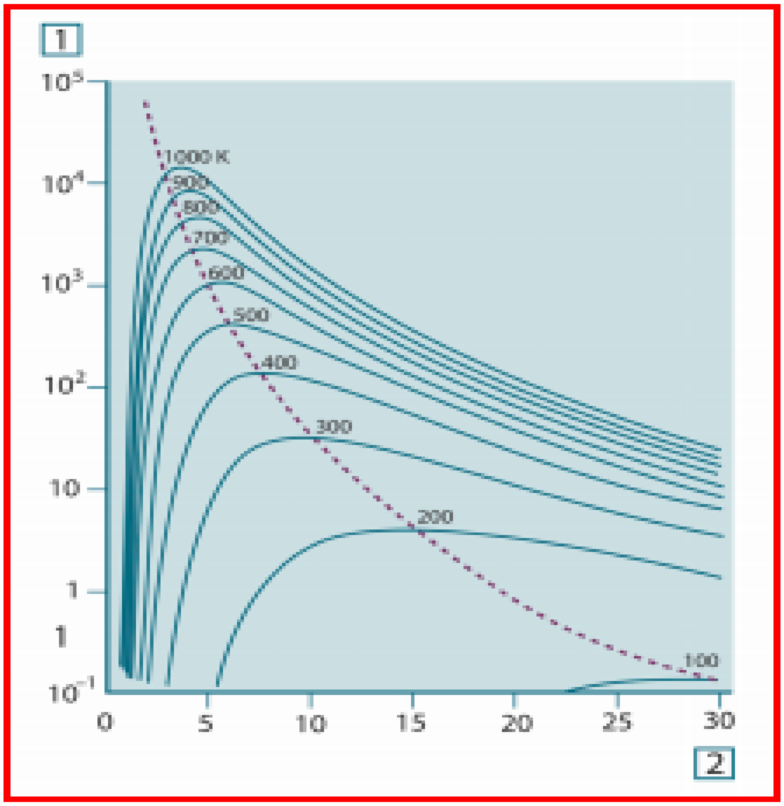

Figure 11: Planckian curves plotted on semi-log scales form 100K to 1000K. The dotted line represents the locus of maximum radiant emittance at each temperature as illustrated by Wien's displacement law (FLIR, 2009)

2.7 Roofing Materials

The most common roofing systems currently used are roof shingles. Roof shingles are square shaped tiles composed of many different materials. They interlock and extend over one another so that they stream water off a steeped roof. The slope of the roof allows it to remove water into a gutter system (Wise Geek, 2003). Roof shingles can help aid in saving energy. Adding a high reflectance coating to a roof can be essential to make homes more energy efficient as well. There are different types of roofing shingles. The ones that will be discussed are asphalt, cedar, and ceramic.

2.7.1 Asphalt

Asphalt is a roofing material and is available in two types: organic or fiberglass. Both of these types of asphalts are formed with a base that is a mat of substrate. There are some differences between organic shingles and fiberglass shingles. Organic shingles are composed of many different fibers of cellulose, which are recycled waste paper and wood fibers. The fiberglass shingles are composed completely of glass fibers with varying orientations and lengths. It also has better fire rating and longer warranty than organic shingles (Kaufman). Both of these types are soaked with a particular type of asphalt coating and covered with mineral granules that make the asphalt durable enough to endure harsh temperatures and weather conditions. They are inexpensive and easy to purchase. Repair and maintenance is rarely necessary. It can be incorporated into many different roofing designs. They are also fire resistant (Asphalt Roofing Manufacturers Association, 2015).

2.7.2 Cedar

Cedar is a light weight porous wood material that comes from a cedar tree. This material has a high R-value that is great for siding and fencing houses. The advantage of cedar wood shingles is that they are able to block out most outside sounds. Because of the high R-value, they can prevent heat loss when it comes to conduction heat transfer. That means it will prevent heat from escaping when using the heater in the winter season and it will prevent cold air from escaping when using the air condition in the summer season. It can withstand exposure to moisture and the material's dimension is unaffected by weather, humidity, or temperature conditions. Cedar can be coated with paint and still maintain it grain structure (Street Directory, 2015).

2.7.3 Ceramic

Ceramic is an inorganic and non-metal solid material. They are composed of non-metallic and metallic elements. There are two major categories of ceramics: traditional and advanced. The difference is that traditional ceramics involve clay products. Examples are dishes, flowerpots, roof, and wall tiles. The clay is heated at high temperatures to make the material hard and fragile, a little porous, and a coarse material. They are also corrosion-resistant, good insulators and can endure exposure to high temperatures. This material prevents heat from coming in homes during the summer season and cold air from coming in during the winter season. Advanced ceramic involve carbides such as silicon carbide SiC; oxides such as aluminum oxide, Al_2O_3 (Chemistry Explained Foundations and Applications, 2015).

2.8 Infrared Training Examples

2.8.1 Color and Emissivity

The object's color doesn't affect the objects ability to emit radiation energy. When it comes to observing objects in the infrared world, color is arbitrary. The emissivity deals with what the object or material is composed of. Here are some examples. We have a cup that is full of hot water and there are plastic tapes that have five different colors: blue, red, green, yellow, and black arranged from top to bottom as you can see in Figure 12.

Figure 12: A cup applied with different colors of tape (Orlove, 2002)

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From Figure 13, it is seen that in the infrared image, the five different colored tapes have the same emissivity because they have almost the same bright glow (Infrared Training , 2002).

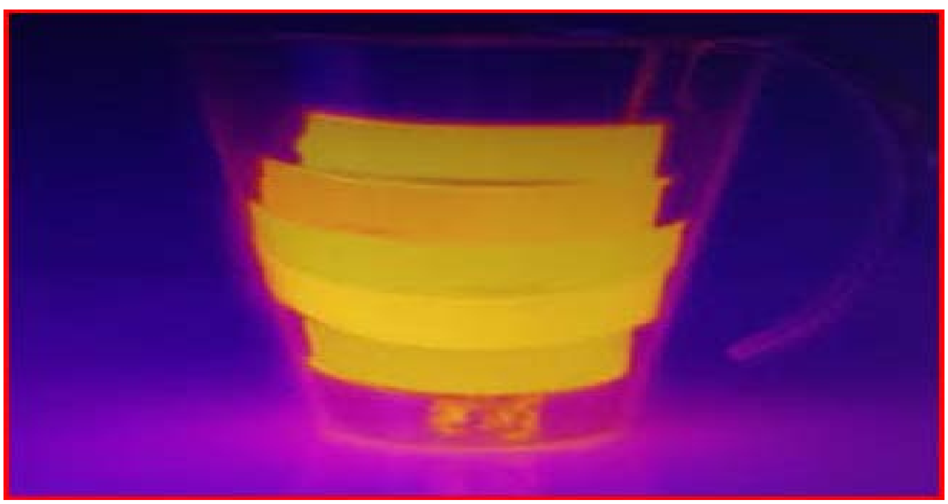

Figure 13: A cup applied with different colors of tape seen in the infrared (Infrared Training , 2002)

2.8.2 Temperature Verification

In another example in Figure 15, there is a flat aluminum plate and the right side is anodized black and the left side is left the way it is. The plate is heated on an electric heat source. A thermocouple is attached to the top of left side of the plate to measure the temperature of the plate. The temperature of the plate is 231 °F, or 110.55 °C, which is why thermocouples are used to assist in heat measurements to determine the exact temperature of specific objects. When used correctly, the thermocouples can display the correct surface temperature because they are not affected by the reflectivity of objects (Infrared Training , 2002).

Figure 14: Thermocouple reading 231 °F (Infrared Training , 2002)

Figure 15: The Aluminum plate (Infrared Training , 2002)

If the infrared image is displayed by the infrared camera in Figure 16, it shows that the temperature of the left side is 82°F and the right side of the plate is 230 °F. Therefore, the correct temperature of this plate was obtained, while the measurement would be inaccurate. The reason is because the IR camera is not able to distinguish the difference between the reflected and emitted temperature of the material (Infrared Training , 2002).

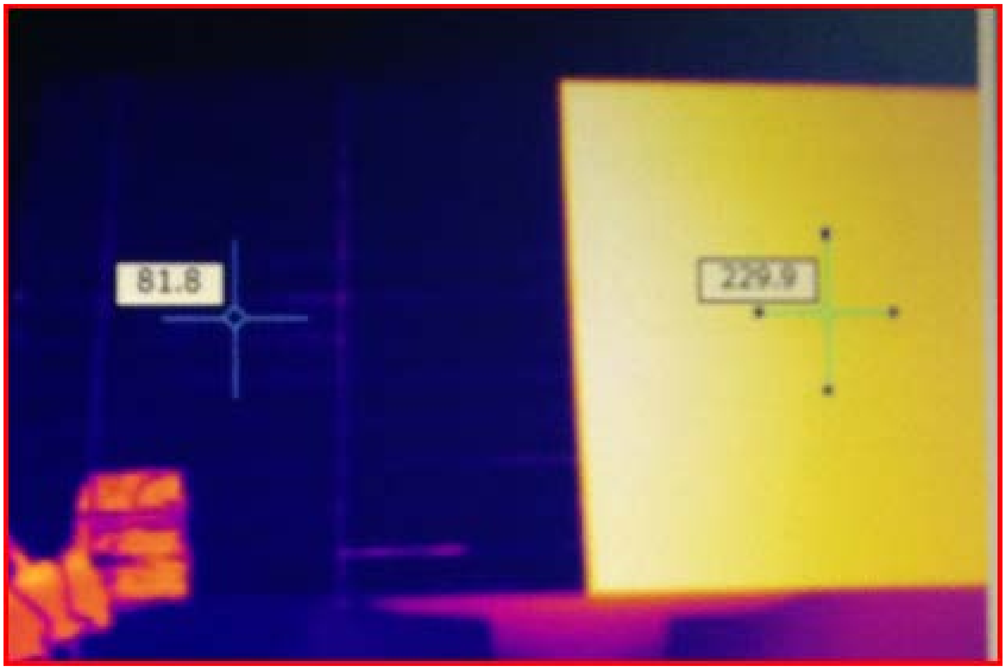

Figure 16: The Aluminum plate seen in the infrared (Infrared Training , 2002)

2.9 Conservation of Energy

The conservation of energy theory necessitates that every radiation directed and diffused to any object is reflected, absorbed, or transmitted through the object. This brings to equation 2.7 where ρ, t, and α correspondingly designate the portion of reflected, transmitted and absorbed radiation (Consigny, 2012).

2.9.1 Kirchoff's Law

The total energy that is absorbed, reflected, and transmitted is added up to equal 1 brings to this: $1 = \alpha(\lambda, T) + \tau(\lambda, T) + \rho(\lambda, T)$. According to Kirchoff's law, an object that absorbs the quantity of radiation is the same as the object that emits the quantity of radiation and that is typically written in the form $\alpha = \varepsilon$. This applies to materials that are graybodies. Therefore, the equation becomes: $1 = \varepsilon(\lambda, T) + \tau(\lambda, T) + \rho(\lambda, T)$.

τ =0 means that objects are nontransparent. Therefore, the equation is simplified to $1 = \alpha(\lambda, T) + \rho(\lambda, T)$. Extremely reflective materials, such as metals have extremely low emissivity values typically less or equal to 0.2. Therefore, for a shiny object, such as metals that are high in reflectance, this equation $1 = \varepsilon(\lambda, T) + \tau(\lambda, T) + \rho(\lambda, T)$ is simplified to ρ=1 because ε or α is approaching 0. Metals have a reflectance greater than their emittance which makes taking heat measurements of them very difficult since the IR can't distinguish one from the other (Consigny, 2012)

CHAPTER 3

LITERTURE REVIEW

Based on research and experiments done on determining emissivity, it is found that there are different IR instruments and thermographic techniques that are applied to obtain emissivity values of the object being measured. The best way to obtain these measurements is to use IR thermometers that do not require direct contact with materials.

3.1 Benefits of Noncontact Thermometers

These non-contact thermometers offer several benefits for measuring surface temperature and emissivity. 1) They are very quick at taking measurements. 2) The non-contact perspective makes it easier to take measurements of moving objects. 3) They are capable of getting measurements of harmful or physically untouchable material from a distance. 4) These thermometers take measurements of materials exhibiting high surface temperatures higher than 1300°C. 5) There is no distortion in measurements. However, the following needs to be assured: visibility of the object must be present to the IR camera; The environment must be clear of any particulate matter or air pollutants; The optics must be protected from any dust and condensing liquids in the air; High surface temperatures must be measured with varying emissivities of different material surfaces.

The ambient temperature must not be greater than the temperature being measured by the IR camera. The object must be protected from the surroundings or compensated if the temperature of the object is less than the ambient. (Gruner, 2003).

3.2 Selective Emitters

Figure 17 shows the spectral emissivities of a BlackBody, a graybody, and a selective emitter for a known temperature. The figures below show the behaviors of a blackbody, graybodies (non-metals), and selective emitters (non-graybodies). Selective emitters are materials that are affected by the wavelength that display a reflectance, transmittance or both. Those materials would be metals, plastics and glass.

Figures 17 and 18 show the behaviors these materials and if the emissivity is affected by the wavelength. The emissivity of a blackbody stays constant at a value of 1, which is unaffected by the wavelength. The emissivity of a graybody stays constant at a value of 0.7, which is unaffected by the wavelength (Figure 18). Most values of emissivity for graybody materials should be around or close to 0.9 depending on the temperature. However, the average of all graybody materials is around 0.7. Figures 17 and 18 illustrate that the emissivity of non-graybody materials changes with variation in wavelength.

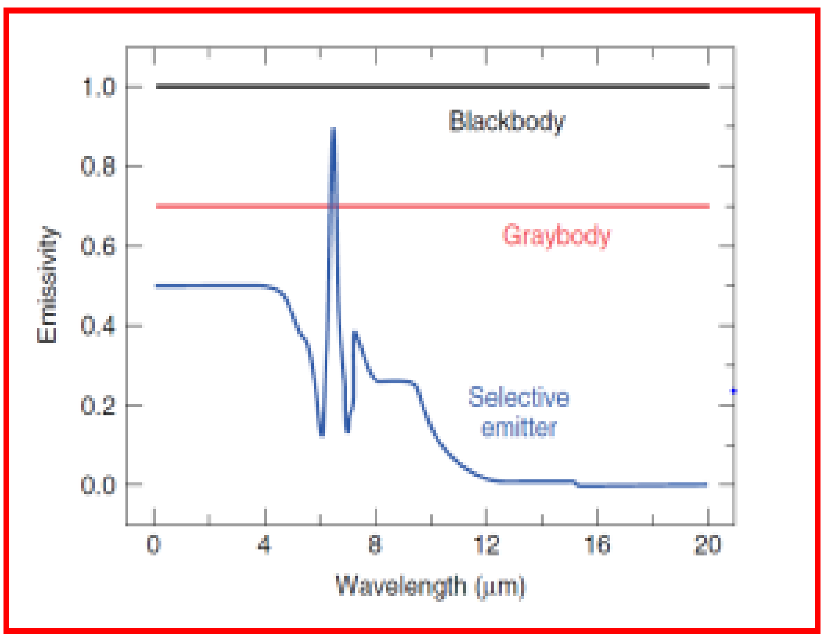

Figure 17 Spectral emissivties of a blackbody, a gray body, and a selective emitter (Consigny; 2012)

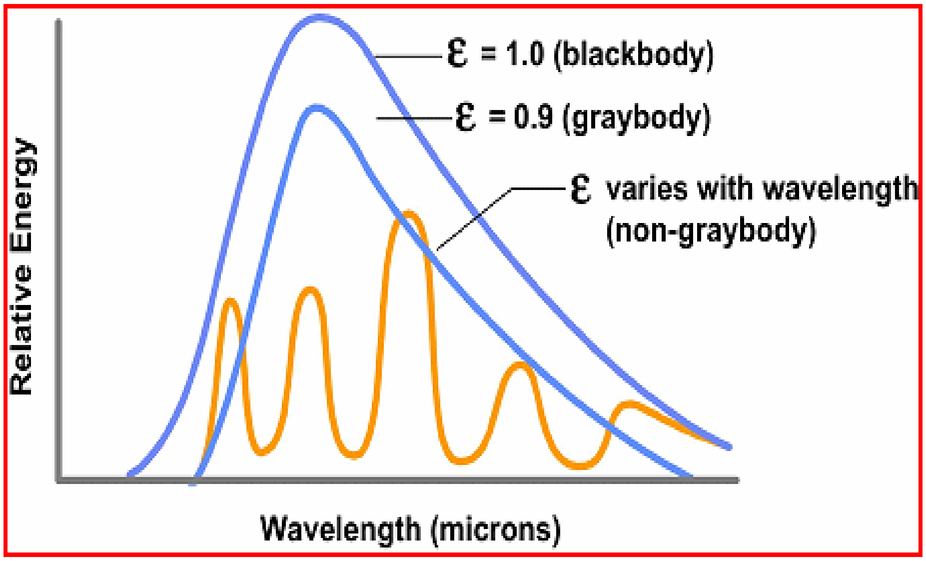

Figure 18: Diagram of emissivity vs. wavelength displays the spectral distribution of different emissivities (Gruner, 2003)

3.3 Measurement Procedures

The best way to check if measurements are valid is to use a material with a known emissivity to measure the temperature of the surface. Aluminum foil is not the best material for this purpose unless the material that is shiny. The reason is that foil is a shiny material that is highly reflective. It has an emissivity of 0.04, which means it is only emitting 4 percent of the heat absorbed from the sun. Shiny materials are like mirrors so the IR camera only sees itself or views object's reflections. Shiny materials are reflecting the heat that is emitted by the sun. There is an emissivity table shown in Figure 19 that can assist you in determining the right wavelength range for a known material and suitable measuring device.

When measuring metals, it needs to take into account that emissivity relies on the wavelength and temperature. Metals frequently reflect so ratio pyrometers are better devices for obtaining precise measurements.

When measuring plastics, it needs to take into account that emissivity relies on the wavelength and thickness. Plastics have transmittance relative to the thickness so an infrared device where a wavelength can be chosen would be essential for measuring the temperature.

When measuring glass, it needs to take into account wavelength, temperature, and thickness. An IR device is a great measuring device because it can accurately choose the right wavelength. It also has an adjusted emissivity setting capability to offset the reflectance. Since glass is an awful conductor of heat, an IR device has a short response time to combat the fast varying in surface temperature (Gruner, 2003).

Emissivity

Material	Emissivity (ϵ)
Aluminum alloy-oxided	0.40
Aluminum-highly polished	0.04-0.06
Aluminum-oxidized	0.11-0.31
Aluminum-Anodized sheet	0.55
Brass-Oxidized	0.60
Brass-polished	0.03
Chromium-polished	0.10-0.38
Copper-polished	0.02-0.05
Copper-heated at 600°C	0.57
Gold-pure, highly polished	0.02
Iron-polished	0.21
Iron-oxidized	0.94
rusted iron plate	0.65
Iron-rough steel plate	0.94-0.97
Lead-gray and oxidized	0.28
Mercury	0.09-0.12
Nickel-polished	0.12
Nickel-oxidized	0.37-0.85
Platinum-pure polished plate	0.05-0.10
Platinum-wire	0.06-0.16
Silver-pure and polished	0.02-0.03
Stainless steel-polished	0.16
Stainless steel-oxidized	0.74-0.87
Tin-bright	0.07-0.08
Tungsten-filament	0.32-0.39
Zinc-polished commercial pure	0.05
Zinc-galvanized sheet	0.23

METALS

Emissivity

Material	Emissivity (ϵ)
Asbestos Board	0.96
Asphalt, tar, pitch	0.90-0.98
Brick-red and rough	0.93
Brick-fireclay	0.75
Carbon-filament	0.53
Carbon-lampblack	0.96
Cement	0.54
Ceramic	0.90-0.94
Concrete	0.92-0.97
Frost crystals	0.98
Glass	0.80-0.95
Human skin	0.98
Ice	0.96-0.98
Marble-polished light gray	0.90
Paints, lacquers, varnishes Black	0.90-0.95
Paints, lacquers, varnishes aluminum paints	0.55
Paints, lacquers, varnishes flat black lacquer	0.96-0.98
Paints, lacquers, varnishes white lacquer	0.95
Paper	0.94
Plastic	0.84-0.94
Porcelain-glazed	0.92
Propellant-Liquid rocket engine	0.90
P.V.C.	0.91-0.93
Quartz-opaque	0.75
Rubber	0.95-0.97
Sand	0.90
Snorw	0.96-1.00
Soil	0.92-0.95
Tape-Masking	0.92-0.95
Wallpaper	0.85-0.90
Water	0.95-0.96
Wood-planed oak	0.82-0.89

NONMETALS

Figure 19: Emissivity Table (King)

3.3.1 Distance and Spot Ratio

The optics lens of an infrared thermometer pinpoints the emitted energy from a measurement spot and aims it on the detector. The object needs to absolutely fill the spot or be an identical size of the sensor in order to be measured or else there will be marginal errors will occur. The spot of the sensor should not overlap the objects that are being measured unless a ratio pyrometer is used. The distance from how far the object is from the spot diameter of the sensor is very important to obtain good measurements. The distance is known as the optic resolution, which is the Distance to Spot diameter ratio: (D:S) = $\frac{\text{Distance}}{\text{Spot Diameter}}$.

The larger value for this ratio means improved optic resolution for the measuring instrument. The use of lenses solely depends on a certain range in wavelength because of the lenses' material range of wavelength. Another factor is using optic lens at the specific wavelength range (Gruner, Principles of Non-Contact Temperature Measurement).

3.3.2 Methods for Determining Emissivity

If the emissivity of a material needs to be determined, an infrared measurement instrument with an adjusted emissivity setting needs to be used, which will make the measurement accurate. There are different procedures that need to be followed before determining the emissivity of the material. 1) Use a heating source such as a heating plate or furnace to heat the sample of the object to a known temperature. 2) Place a piece of black tape that has a high emissivity of approximately 0.95. 3) Use an infrared measuring instrument to measure the temperature of the surface modifier. 5) Determine the surface temperature of the material sample without the surface modifier. 6) Adjust emissivity until the surface temperature of the material sample matches the section applied with the surface modifier.

3.3.3 Preventing Reflections

When using a hot plate as your heat source, the experiment needs to be in a vacuum space. While the sample is being heated it should be totally covered by some type of containment. The inside of the containment should be covered with a black material or substance that has a high emissivity around 0.95. (Moghaddam, Lawler, & McCaffery, 2005). The hot plate should be coated with a black paint with a matte finish due to its high emissivity.
For example 3-M Black is a black paint that can be obtained from "Senotherm form Weilburger Lackfabrk or Minnesota Mining Company and will approximately have an emissivity value of 0.95 (FLIR, 2009).

This would prevent any reflectivity from the plate since its metal. Due to a high reflectivity of metals, they need to be reduced or prevented so that measurements can be accurate when using the IR camera. A furnace is a good heat source as well but has its downfalls. If the walls of the furnace are hotter than the material sample itself, it can result in error in the measurement (Gruner, 2003). Thermal radiation needs to be considered so the IR device can compensate for that by setting the emissivity value.

3.4 Infrared Devices and Measurements

There are many different infrared devices capable of obtaining heats measurements for many objects. All these devices function differently from one another. These devices have one of the followings: a setting that needs to be adjusted, have to be calibrated, can only determine specific variables, and can only be used for specific purposes. However, one common thing all these devices have is that they all pertain to a temperature. It means that these devices are used to determine a temperature value or uses the value of temperature to determine another property or variable.

3.4.1 Thermocouples

A thermocouple is a direct contact thermometer that is composed of two metals. Thermocouples are used for measuring the surface temperature of a material. A voltage is produced from the temperature difference between the hot junction and cold junction.
This is known as the Seeback Affect (Evanczuk, 2011). This device is rendered useless unless the thermocouple is embedded in the material. For example the thermocouple is probe shaped like a sphere that makes it uniform. The probe needs to be exposed to the entire surface of the material where the thermocouple can measure the temperature of the material evenly. Measuring the surface temperature of the material with the thermocouple attached to the top leads to an ineffective measurement. Inaccuracy in temperature occurs because the probe is not exposed to the entire surface. The bottom half of the probe is exposed to the top of the material and the top half is exposed to the tape. The black tape is used to hold down the thermocouple to the material creates two different temperature readings. To obtain a valid measurement the thermocouple must have great contact with the target. The challenge with measuring the target occurs when there is shaking and mobility. There are some conditions where the target is exposed to an extreme magnetic field. For instance a thermocouple cannot make direct contact with a target that is heated by an induction heat source, so a non-contact measurement device would be required in this case (Consigny, 2012).

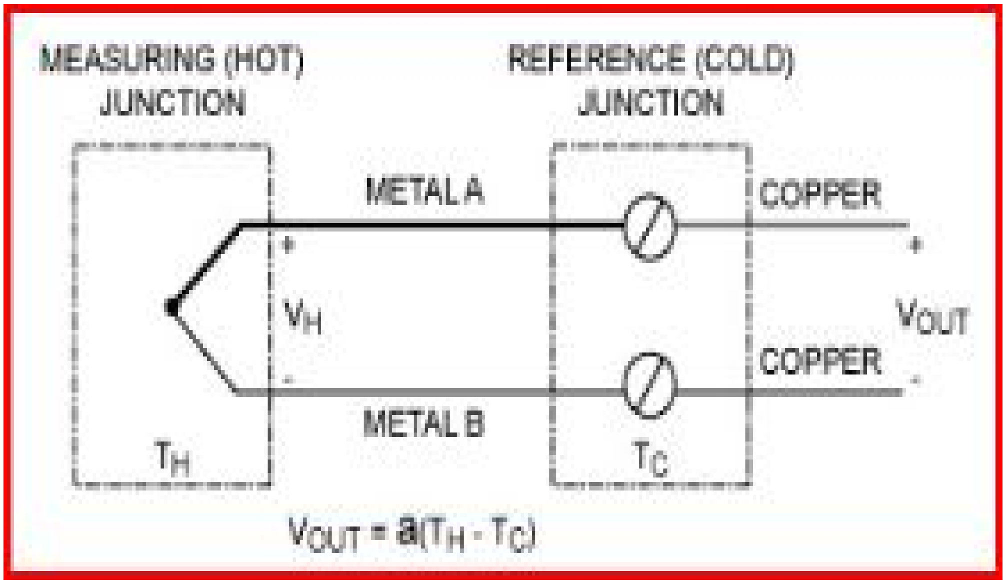

Figure 20: A voltage produced by the thermocouple by the temperatures of the Hot (measurement) Junction and Cold (reference) Junction (Evanczuk, 2011).

Thermocouples needs some form of temperature reference to compensate for the cold junctions. Now there are two circumstances in order to apply the cold junction method. First the junction of the two metals must be maintained at the same temperature. Second there must be a precise measurement of the temperature of junction of the two metals. The precision of the cold junction measurement is really essential since the error contributes to the temperature difference and once the error occurs, it is unable to be corrected (Texas Instruments, 2014)

3.4.2 Pyrometer

A pyrometer is an infrared device that is a non-contact thermometer. The device operates very much like an IR camera. The difference is that a pyrometer pays particular attention to a small section of the target and does not display an IR picture. Only the surface temperature of the target is displayed. The disadvantage of using a one color pyrometer is that it cannot obtain the object's emissivity since the object's emissivity value is required to be entered as an input constraint for this instrument to display the accurate temperature value (Consigny, 2012).

3.4.2.1 Fiber-optic Pyrometer

Fiber-optic pyrometers are used when disturbance in electrical or magnetic fields are present. These devices can be used when it involves heating an object with induction heat source. With the use of this device, the functioning temperature can be sufficiently increased without the required cooling (Gruner, 2003).

3.4.2.2 Ratio Pyrometer

The ratio pyrometer (also referred to as two-color pyrometers) has a better advantage. The difference is that it explores the radiation emitted by an object at different wavelengths (two colors) versus one wavelength. This enables the instrument to obtain the objects' temperature without the required known emissivity of the object. This device contains two channels of measurement, which are optical and electrical, and both are matching in formation (Gruner, 2003) p. Considering Eq. 2.10 for two different wavelengths give:

$$\emptyset_{det}(\text{det}(\lambda_1) = \tau\varepsilon_1 \emptyset_{object}^{bb}(T_{obj,} \lambda_1) + \tau(1\text{-}\varepsilon_1)\emptyset_{amb}(T_{amb}, \lambda_1) + (1-\tau)\emptyset_{amb}(T_{atm}, \lambda_1)$$

$$\emptyset_{det}(\text{det}(\lambda_2) = \tau\varepsilon_2 \emptyset_{object}^{bb}(T_{obj,} \lambda_2) + \tau(1\text{-}\varepsilon_2)\emptyset_{amb}(T_{amb}, \lambda_2) + (1-\tau)\emptyset_{amb}(T_{atm}, \lambda_2)$$

It is understood that the reflected section of the radiation is unimportant in front of the radiate portion even if the emissivity of the target is high or if the temperature of the target is high in front of the surrounding temperature, the latest formula can be rewritten as :

$$\frac{\emptyset_{det}(\lambda_1)}{\emptyset_{det}(\lambda_2)} = \frac{\varepsilon_1 \emptyset_{object}^{bb}(T_{obj,} \lambda_1)}{\varepsilon_2 \emptyset_{object}^{bb}(T_{obj,} \lambda_2)}$$

In regards to Planck's law, Eq. 2.4. Writing $c_1 = 2\pi hc^2$ and $c_2 = \frac{hc}{k}$ and assuming $e^{\frac{c_2}{M}} - 1 = e^{\frac{c_2}{\lambda T}}$ that is valid until high value of the temperature, leads to:

$$\frac{\emptyset_{det}(\lambda_1)}{\emptyset_{det}(\lambda_2)} = \frac{\varepsilon_1 \lambda_1^{-5} e^{\frac{-c}{\lambda_1 T_{obj}}}}{\varepsilon_2 \lambda_2^{-5} e^{\frac{-c}{\lambda_2 T_{obj}}}}$$

The object's temperature can be derived as:

$$T_{obj} = \frac{c_2(\frac{1}{\lambda_1} - \frac{1}{\lambda_2})}{In(\frac{\emptyset_{det}(\lambda_1)}{\emptyset_{det}(\lambda_2)} \frac{\lambda_1^5 \varepsilon_2}{\lambda_2^5 \varepsilon_1})}$$

For a pyrometer functioning at two wavelengths that are shut, the emissivity can be regarded as being identical for the two distinct wavelengths knowing that $\frac{\varepsilon_2}{\varepsilon_1} = 1$, the object's temperature can then be calculated without the information for the emissivity. This technique involves two corresponding wavelengths that require to be blocked from one another. The quantity of radiation that gets to the camera is significant sequentially to prevent obtaining a small ratio. This pertains to a condition where the temperature is greater than 500°C. A two-color pyrometer that is marketable generally has a temperature range from 500° to 2000°C. When measuring materials with a low emissivity, high temperature is a parameter that is essential for the IR device. Low emissivity objects that are enclosed by hot gases result in incorrect measurements if not taking into account the reflections from the ambient temperature. When measuring the temperature for pieces of metal, the ratio pyrometer is not an appropriate device.

Some of the uncertainties can be fixed by using more than one wavelength band referred to as multi-spectral pyrometry (Consigny, 2012) p.15.

3.4.2.3 Active Pyrometer

The active pyrometry is an alternative technique that can measure the temperature of the target without prior information for the emissivity.

The reflections from the IR source produced onto the object are used by this device to measure the object's reflectance ($\rho = 1 - \varepsilon$). When an object is brightened with an IR source for a given temperature, the calculated radiation is:

$$\_\emptyset_{det,ill} = \rho_{object\ \emptyset source}(T_{source}) + (1 - \rho_{object})\emptyset_{object}^{bb}(T_{object}) + \emptyset_{amb}(T_{amb})$$

When lacking the source, the radiation calculated is:

$$\emptyset_{det} = (1 - \rho_{object})\emptyset_{object}^{bb}(T_{object}) + \emptyset_{amb}(T_{amb})$$

(3.7)

Combining equations 3.6 and 3.7 gives the following expression.

$$\rho_{object} = \frac{\emptyset_{det,ill} - \emptyset_{det}}{\emptyset_{source}} \quad (3.8)$$

Now that the reflectance and emissivity is identified, the temperature of the object is obtained. The main challenge in this technique is the calculation of $\emptyset_{source}$. The shape of the object and the angle of incidence radiation generated by the source has a big effect on how the IR radiation is reflected by the target. Therefore, it is better to measure $\emptyset_{source}$ as the reflections are produced from the IR source. However, the IR source needs to be relative to the high reflectance of the object and the shape has to be identical to the object that has to be measured as well. This source needs to emit in the wavelength band identical to the detector, and it needs be strong enough to generate a high variance in the radiations that are measured.

This technique can also be applied with numerous bands of wavelength to enhance the precision; it is referred to as multi-band active pyrometry. Though this technique needs a source and detectors of numerous wavelengths but it is very difficult to initiate (Consigny, 2012).
The active millimeter-wave pyrometer has proved that it is capable of measuring emissivity as well as the temperature. The major issue for this procedure was that the set up of the measurement was just affected by the disturbance of the standing wave. A radiometer with physical translation was needed for each measurement to compensate for these effects (Woskov & Sundaram, 2002).

3.4.3 Thermometry Measurements

Thermometry of spectral radiation pertains to the strength of the measurement at a single wavelength, and a stable emissivity value that is not of influence by the wavelength.

3.4.3.1 DWRT

Dualwavelength radiation thermometry (DWRT) utilizes the strength of the measurements at two different wavelengths and compensates the emissivity using an algorithm to deduce the surface temperature.

3.4.3.2 MRT

Multispectral radiation thermometry (MRT) utilizes the strength of measurements at three or more wavelengths and a multiwavelength emissivity model to find out the surface temperature. The MRT is a technique considered for its capability to improve the precision in measurement and accounts for the complicated spectral difference in both radiation strength and emissivity (Wen & Mudawar, 2002).

3.4.4 Eppley Pyrgeometer

The values of the sky emissivity are acquired from an Eppley pyrgeometer that measures the radiation of the night sky radiation in units of watts/meter2 (Chen, Kasher, Maloney, Clark, & Mei).

3.4.5 Infrared Camera

An infrared camera is an instrument used to transfer an infrared radiation emitted from the material into an image or picture. It measures infrared radiation emitted from the material as well. The camera does not distinquish the objects by their color, -only by the amount of energy emitted from them. The color is a value associated with the image generated on the computer screen.

The infrared detector is the central part of the infrared camera. The purpose of this detector is to change radiation into electrical signals. Infrared detectors are divided into two kinds: thermal detectors and photon (quantum) detectors. Thermal detectors act like as a two-step converter. First, the material temperature is altered by the incident radiation that is absorbed. Second, the relative change in the material's physical property generates the electrical output of the thermal sensor. Photon (or quantum) is small quantity of light. The photon detector attracts photons from the infrared radiation. This results in altering the movement and concentration of free charge carriers in the element of the detector. Photon detectors have advantages over thermal detectors because they are more precise and faster in measuring. The element of the photon detector should be maintained at a very small temperature which would increase the cost and weight of the instrument (Consigny, 2012). (Faster means ms in respect to ns or µs of the latter detector) (Gruner, 2003).

3.5 Camera Software

3.5.1 ThermaCAM™ Researcher Professional

Before the camera was used, the software ThermaCAM™ Researcher Professional needs to be installed on the computer. This software only runs on these operating systems: Windows 2000, Windows XP (32-bit edition) and Windows Vista (32-bit edition). This software can also be ran on other operating systems such as Windows 98/ME and Windows NT 4.0. However, the user may not be able to use the software to its full capabilities (FLIR, 2009). The main function for the use of this software is to transfer live images through a camera's interface. It is also capable of collecting other IR (Infrared) images from other media such as SD Memory Cards from the ThermaCAM™ cameras.

3.5.2 Setup and Configuration

It is required to set up a software link between the ThermaCAM™ Researcher Professional and the IR camera. The camera needs to run for a moment so that its' detector is cooled to the point so it can generate a live picture (FLIR, 2009). Information can be pulled from the ThermaCAM™ Researcher Professional OLE. OLE stands for Object Linking and Embedding. It's an automatic way to transport documents and information between programs in Windows operating systems. The IR images are capable of being transported as well. To display a quality picture from the IR camera, a link needs to be established (FLIR, 2009).

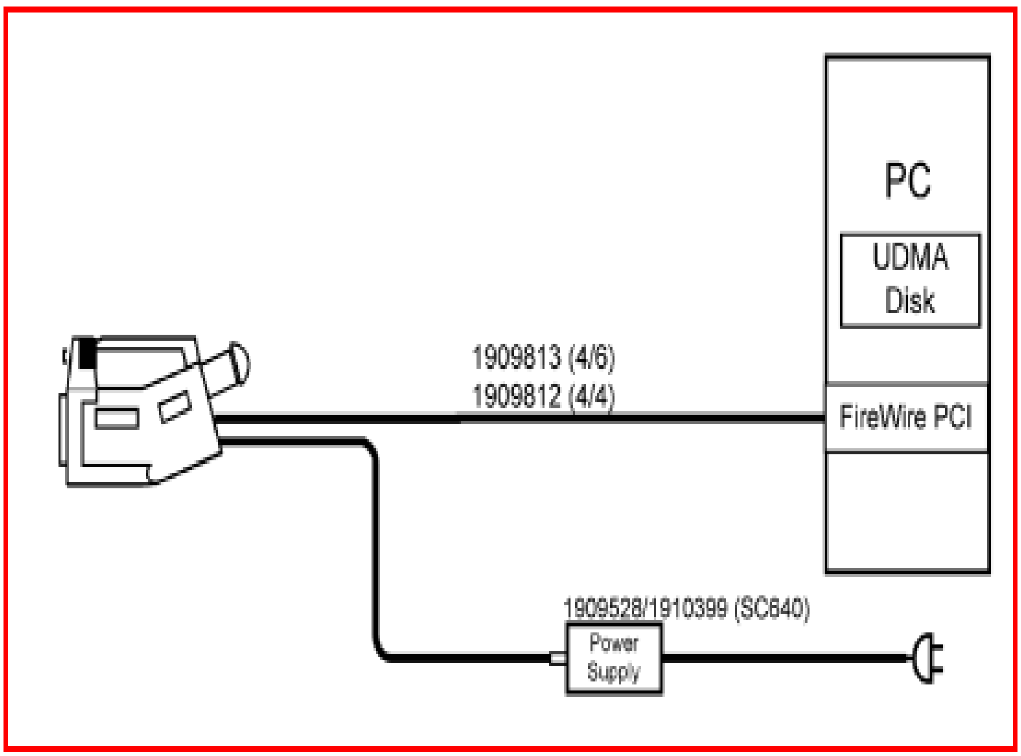

Figure 21: Configuration for setting up the infrared camera to a desktop computer (FLIR, 2009).

3.5.3 Measurement Functions

The measurements for surface temperature and emissivity can be accomplished using these analysis tools: isotherm, spotmeter, area, and line (FLIR, 2009).

3.5.3.1 Isotherm Tool

The isotherm tool is an indicator for a thermal picture that pinpoints sections of the thermal radiation from the object. The emissivity needs to be uniform all over the object in order for accuracy. There are five kinds of isotherms in the ThermaCAM™ Researcher Professional. The interval isotherm is generally used in measurements. This tool pinpoints a temperature at a specific width. There is an indicator in the color range to designate the position of the isotherm. (FLIR, 2009).

3.5.3.2 Spot meter Tool

The spot meter tool determines the temperature at a specific spot on the material. I can acquire the temperature, the temperature in relation to the reference temperature, emissivity, object distance, and the co-ordinates of the spot meter. The Spot meters are referred to as SP01, SP02, etc. A spot meter is generated using the spot meter in the toolbar and then selecting a requested position of the sample in the picture (FLIR, 2009).

3.5.3.3 Area Tool

The area tool determines the average temperature of a particular section of a material. The area is referred to as AR01, AR02, etc. It determines the maximum, minimum, average, and standard deviation temperature of the selected section of the picture and provides these values as results where it can be viewed and examined. It determines these values in respect to these object constraints: reference temperature, emissivity, distance of the object, and co-ordinates for the area (FLIR, 2009).

3.5.3.4 Line Tool

The line tool determines the maximum, minimum, average, and standard deviation temperature down the path of line that is bendable or straight. The line is referred to as LI01, LI02, etc. The difference is that it focuses on the straight or bended line within the picture (FLIR, 2009).

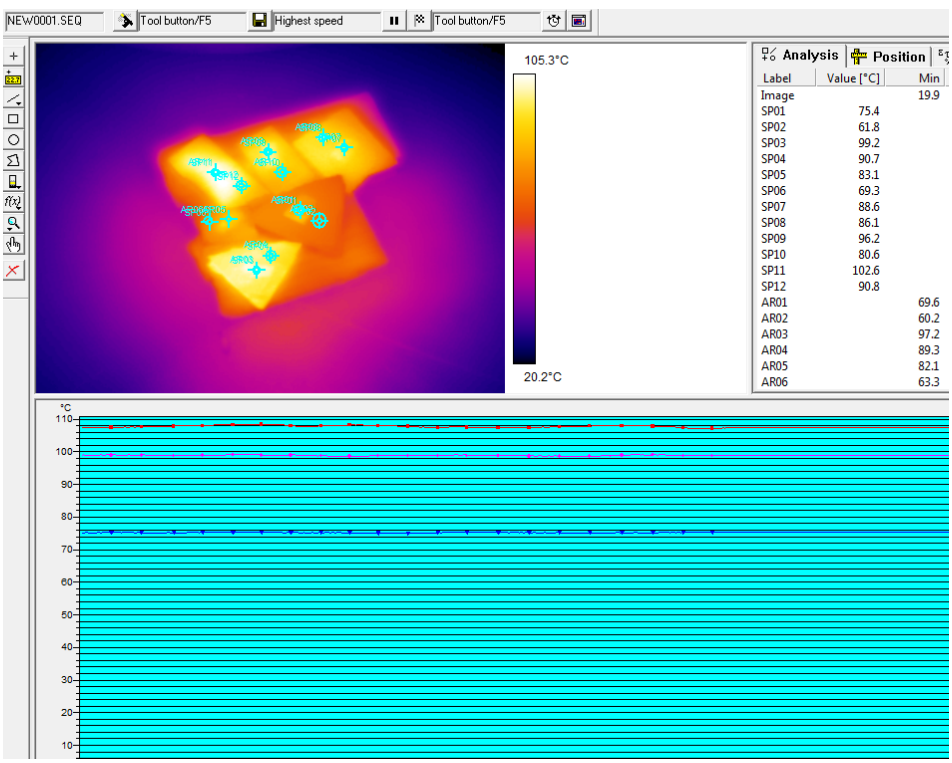

Figure 22: Prescreen layout

The IR camera was used to generate a prescreen layout that displays the infrared images of the samples, temperature scale, or distribution. This helps to understand the behavior of temperature between the different samples.

3.6 Settings

3.6.1 Producing a Quality Picture

Once the setup for the software is up and running, a suitable measurement range can be chosen, auto-adjust it and focus it. The values for object parameters should be ccurate or else this can make the measurements that were obtained inaccurate. That would result in mistakes in reading and analyzing the live pictures. These parameters define physical properties for object, its surroundings, and the atmosphere between the camera and the object. The colors of the picture can be altered for measuring the correct surface temperature of the roofing samples (FLIR, 2009).

3.6.2 Color Scale

The radiation calculated by the Infrared camera depends on both the temperature and emissivity of the material. A range of colors is added to the picture to illustrate the strength of the radiation or the distribution of temperature. The selected colors can be used to enhance distinction for each specific sample when determining the emissivity and surface temperature. To obtain a accurate measurement for the surface temperature, it is important to counteract the effects produced by the variation of radiation sources (FLIR, 2009).

3.6.3 Object Parameters

There are object parameters that must be provided by the camera. Those object parameters are the object's emissivity, the reflected temperature, the distance of the camera from the object, and the relative humidity as it can be seen in Figure 23.

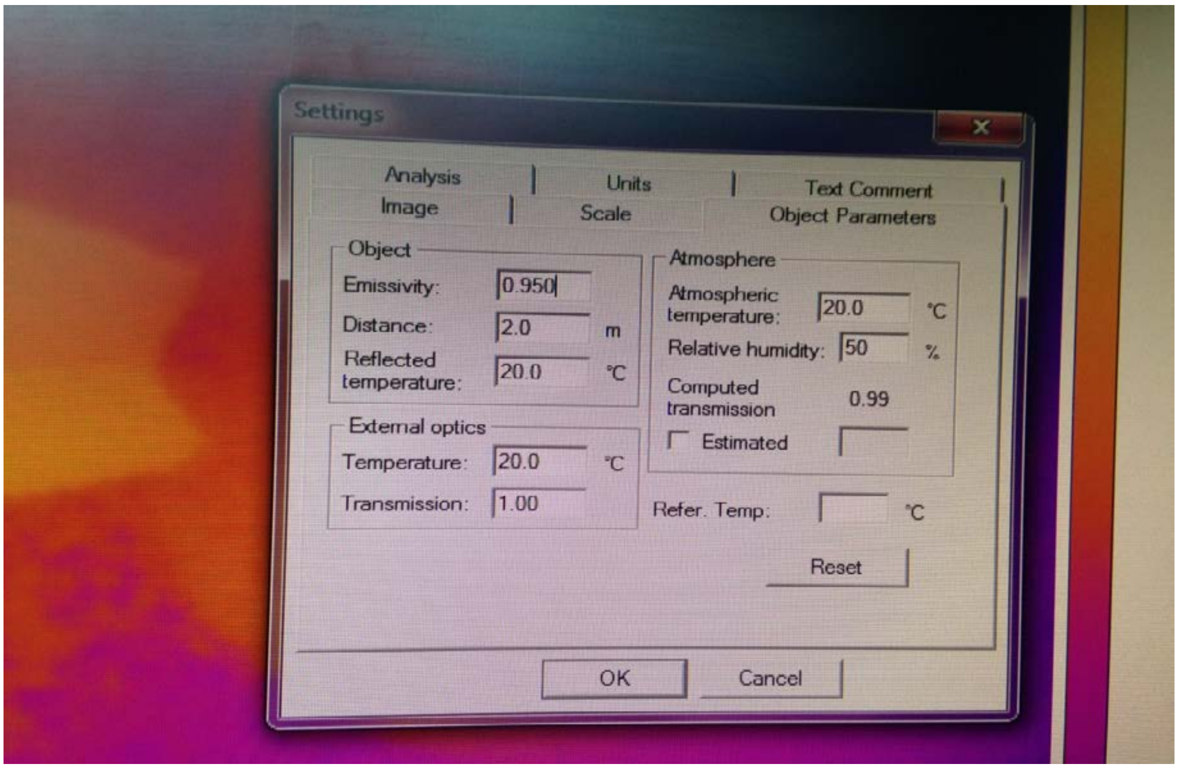

Figure 23: Object parameters

The atmospheric temperature, humidity, and distance are parameters used to obtain accurate values for the surface temperature and emissivity. These parameters for the IR camera have default values that need to be set.

3.6.3.1 Humidity

Errors when obtaining measurements can occur if the humidity in the air is greater than 50 percent, the distance between the camera and the material samples is greater than 2 meters, and if the temperature of the object is moderately near to that or identical to the atmospheric temperature. That's why it is essential to compensate for the conditions of the atmosphere precisely. The transmittance is heavily affected by the air's relative humidity. Therefore, the value of the relative humidity needs to be set accurately to compensate for the transmittance

.

3.6.3.2 Distance

If the distance between the camera and material samples is less than 2 meters with normal humidity in the air, the value of relative humidity doesn't need to be changed and can be left at a default value. If the approximation of the atmospheric conditions is better than what the default value is, the approximated value can be input for the transmission. If the value of the transmission is set to 1, this will eliminate the need for compensation (FLIR, 2009).

3.6.3.3 RAT

The reflected apparent temperature (RAT) is the parameter pertaining to the reflected radiation of the object. This temperature demonstrates every parasitic sources of heat impacting the view aiming at and reflecting in the path of the camera. For some cameras it is also referred to as the background temperature or ambient temperature. If the emissivity is low and the temperature of the object is moderately close to that of the ambient it is essential to compensate for the reflected temperature accurately. If not, the camera will see itself mirrored in the external optics. For example, a house window can reflect a plants reflected temperature.

The IR camera is reading that the thermal radiation of the object is greater than the object itself. Object reflections increase the amount of radiation of the reflected material (Infrared Training , 2002).

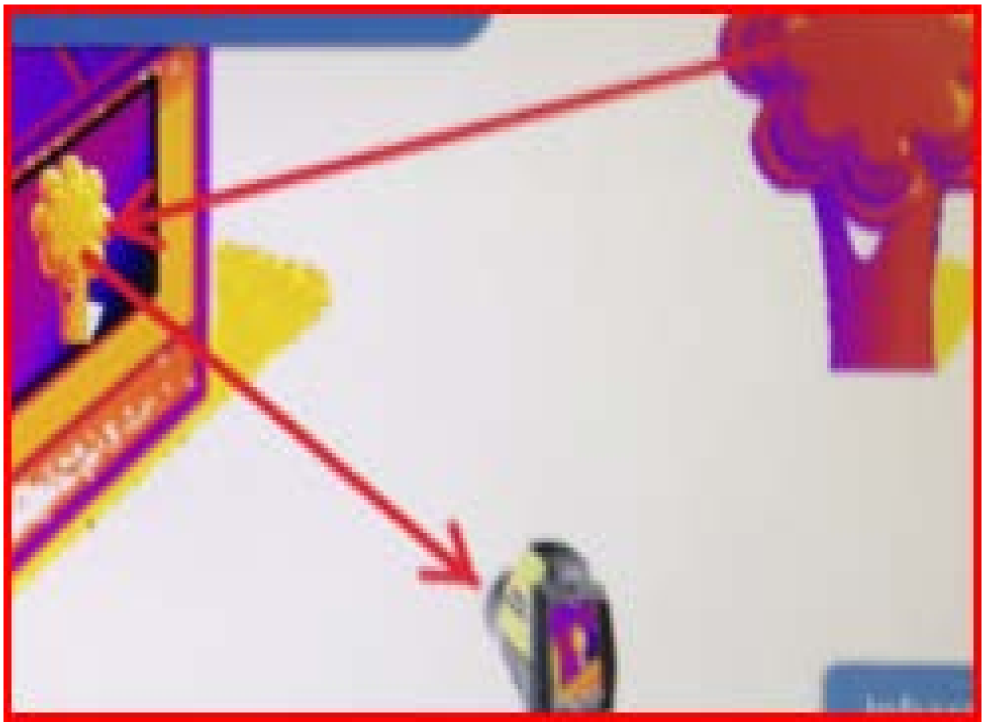

Figure 24: Tree adding infrared energy to emitted window due to reflection (Infrared Training , 2002)

The changes in reflected apparent temperature can affect what the camera is displaying when measuring infrared energy. The reflected apparent temperature is a parameter that is the key to use in combination with the emissivity. This parameter is required to devise temperature measurements. The camera reads the energy that the object reflects as well as the energy that the object emits. The problem is that the camera cannot distinguish which one is which. But there is way to deduce the difference between the target's reflectance and emittance by applying appropriate compensation techniques: high emissivity black tape, matte black paint, or formation of a blackbody from a sample. This is what needs to be done when trying to compensate for errors due to infrared reflections (Infrared Training , 2002).

Figure 25 below involves a transformer fixed on top of a telephone pole. The goal is to find the emissivity of the target that is the transformer. The challenge is that the pole is too high to reach and there is too much reflectance of apparent temperature from the sky produced by the transformer. Aluminum foil is desirable to offset the error due to infrared reflections.

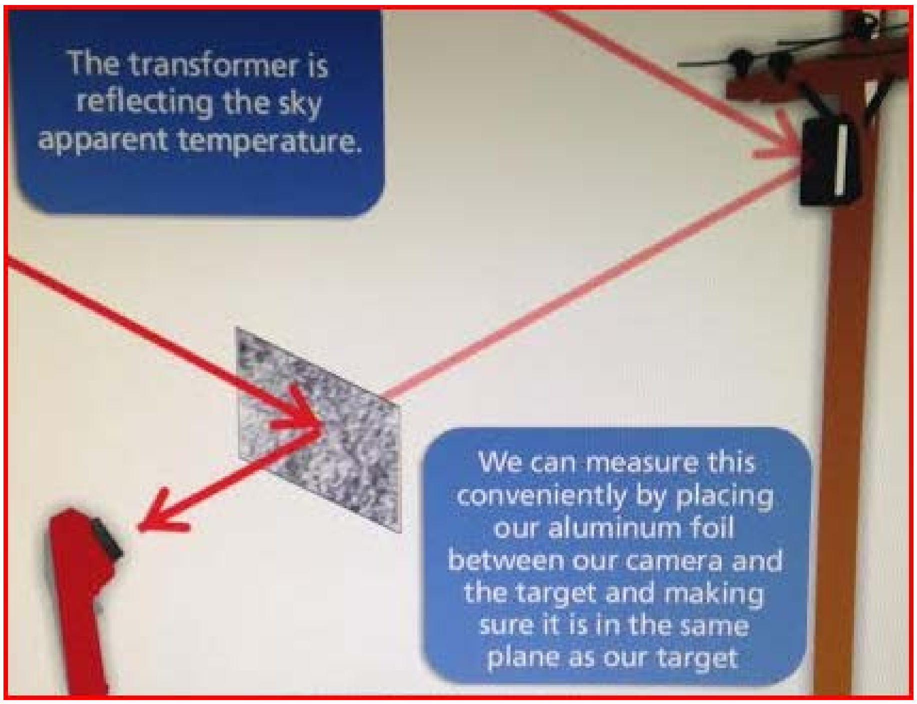

Figure 25 Aluminum foil apply to offset error of reflecting material (Infrared Training , 2002)

If a mechanic performs a maintenance checking on a truck's engine outside, one would have the truck moved into the garage of the auto shop, so that the reflected temperature can be monitored to a more steady value. It makes it easier to perform and finish the maintenance check. In a visible world, one can view objects by light of reflectance.

In the world of infrared we view anything that is brightened by the infrared light in relation to a temperature value. Hot objects will have a bright glow like the color yellow and objects that are cold are going to be darker or the color purple or dark blue. High emissivity objects are able to be viewed since it pertains to energy emitted. Low emissivity objects can be viewed as well since it relates to the energy which is reflected (Infrared Training , 2002).

3.7 Two Types of Reflectors

There are two types of reflectors of reflection: specular and diffuse. A specular reflector is a sharp reflection like a thermogram in a television screen as seen in Figure 26.

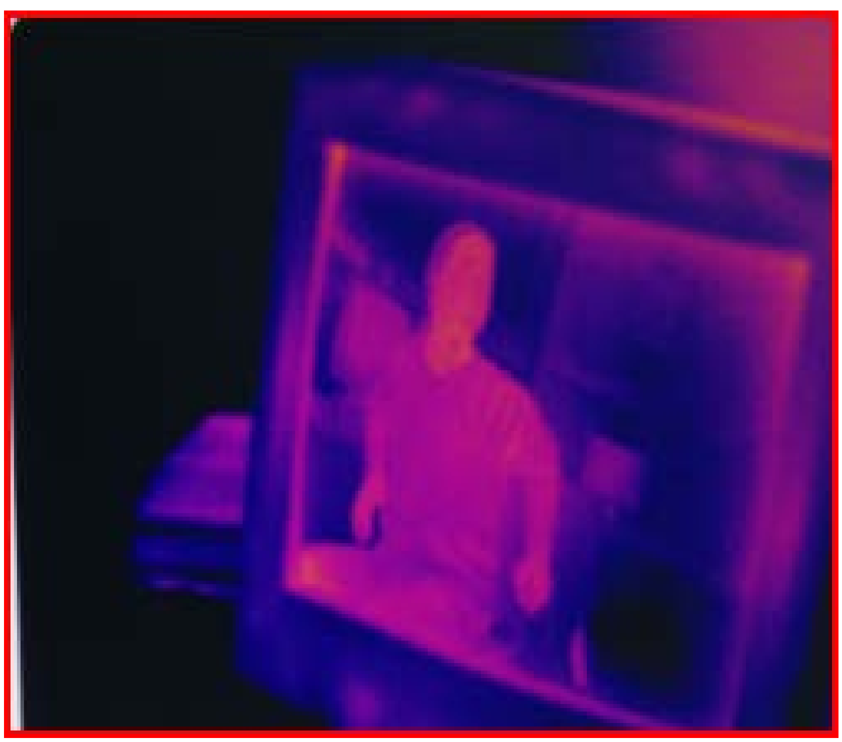

Figure 26: An example of Specular Reflection (Infrared Training , 2002)

3.7.1 Specular Reflector

The reflection pertains to objects that have smooth, flat, or even surfaces. Any objects that have a glossy exterior or any objects that are metal will exhibit specular reflections (Nayar, Ramamoorthi, & Hanrahan). Therefore, the incident light is emitted from the power source onto the material sample. It forms from a bright spot known as a highlight and it produces a light of radiance that is reflected along a straight path into the eye or camera. θ represent the angle in the zy plane. Φ represents the angle in the xy plane as shown in figure 27 below.

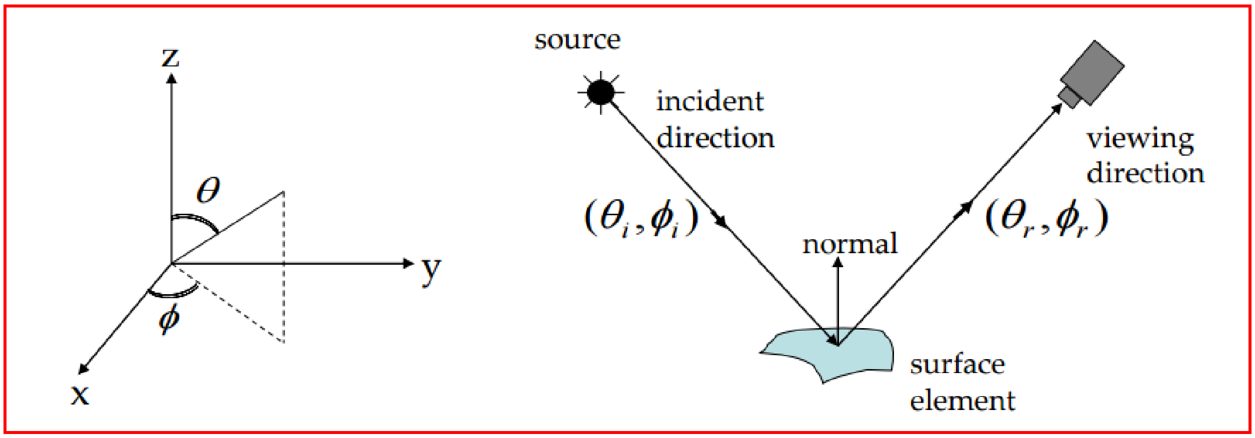

Figure 27: Specular reflection (Nayar, Ramamoorthi, & Hanrahan)

3.7.2 Diffuse Reflector

Diffuse reflection is a reflection of any object that is emitting thermal radiation that is greater than itself. It is seen from Figure 28 that it is very hazy. The surface appears to be hot but it’s not. That’s why it is imperative to have understanding of what reflected temperature is so IR picture can be deduced.

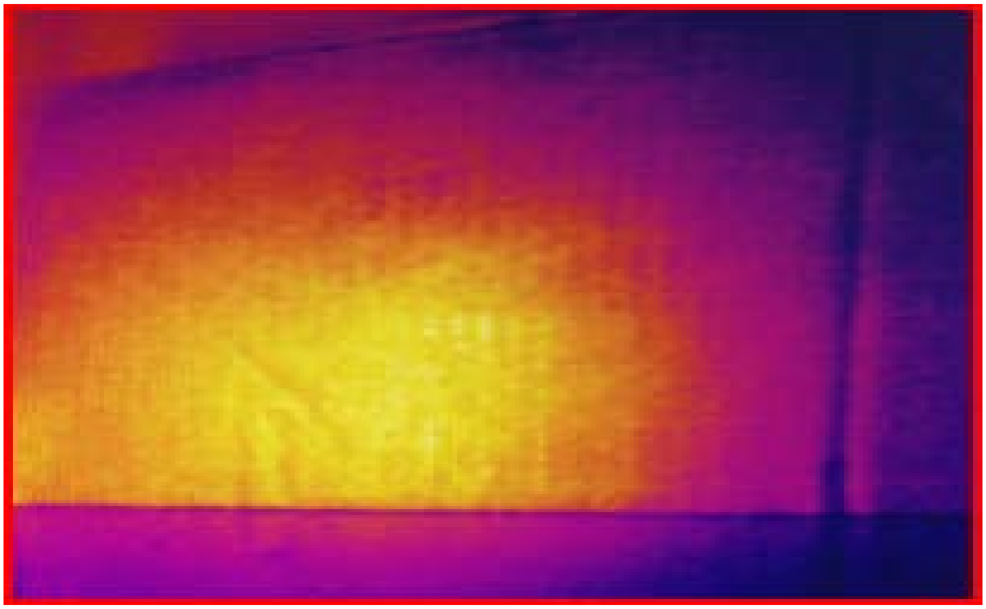

Figure 28: Diffuse Reflection (Infrared Training , 2002)

This reflection pertains to objects that have a rough, bumpy, or uneven surface. Objects that have a matte finish and nonmetal objects such as clay and asphalt will exhibit diffuse reflections (Nayar, Ramamoorthi, & Hanrahan). These objects are conductors (materials that conduct heat) and non conductor materials are referred to as lambertian radiators. Lambertian radiators have emissivities that perform different than a blackbody (Consigny, 2012). The same process of the incident light is emitted from the heat source onto the material sample. Then the sample reflects the light of radiance in multiple paths as shown in figure 30. These reflections are not affected by the angle at which the camera is seen from. The emissivity of a blackbody is not influenced by the surface temperature, surface conditions, and the view of the angle. But the graybodies and lambertian radiators are susceptive to these sets of conditions (Consigny, 2012).

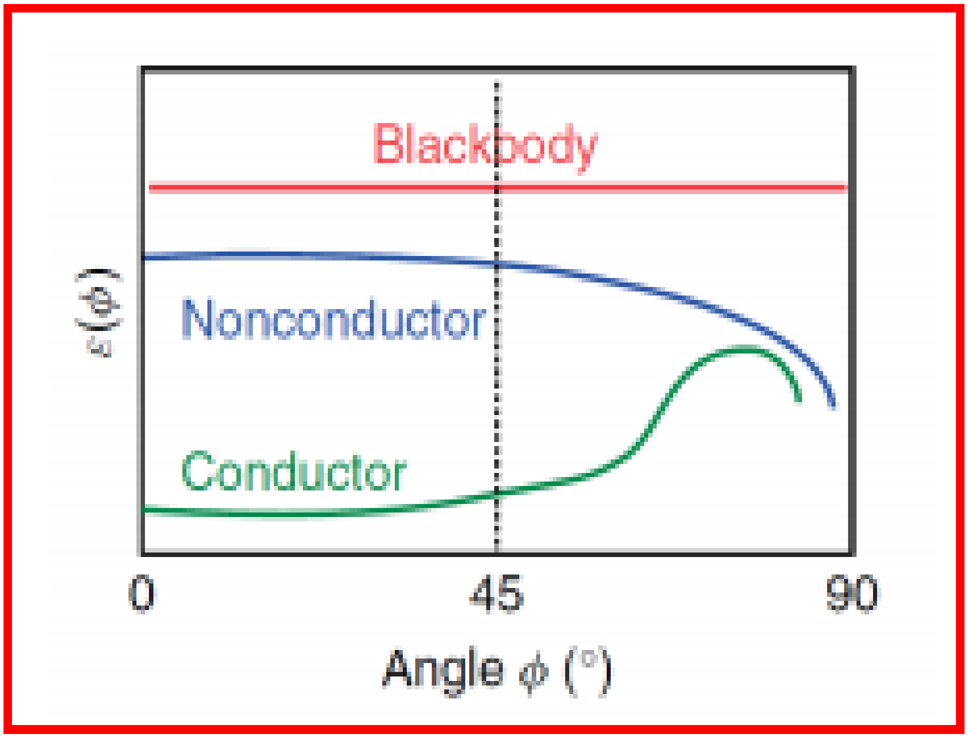

Figure 29: Representation of radiance for a blackbody and a lambertian radiator.

The emissivity for a blackbody is constant between normal incidence, φ = 90° and φ = 45° where a lambertian radiator is not (Consigny, 2012)

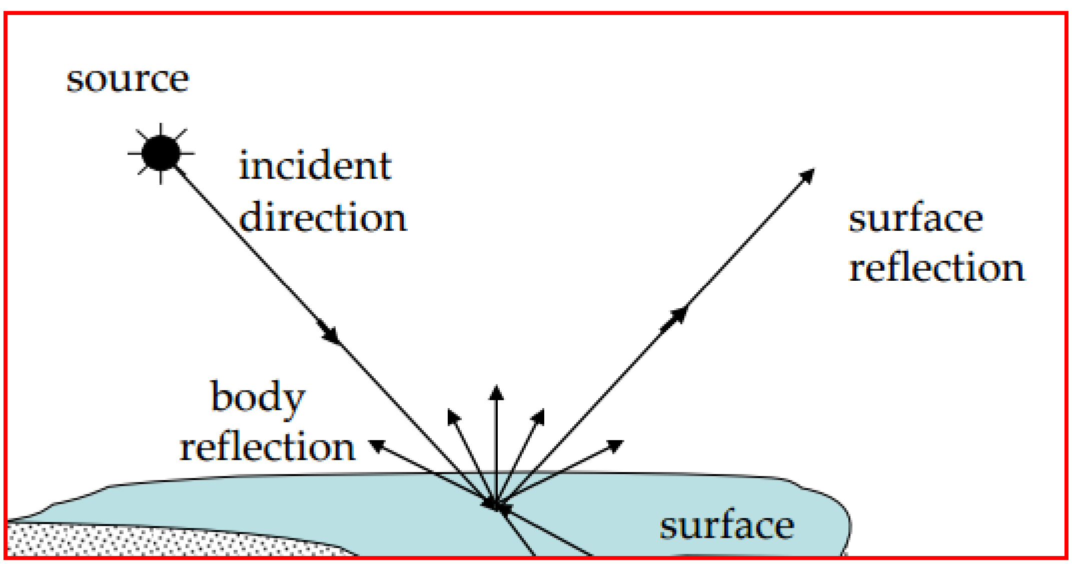

Figure 30: The process diffuse reflection (Body reflection) and specular reflection (Surface reflection) (Nayar, Ramamoorthi, & Hanrahan)

3.8 History of FLIR System

In 1978 FLIR systems were recognized to pave the way for the improvement for the high functionality of thermal imaging systems. It is the world leading infrared imaging system in design, manufacturing, and marketing. This device has been used for many different applications pertaining to commercial, government, and industrial use. As of now, the FLIR systems support four main companies with tremendous accomplishments in infrared technology since 1965. Those four main companies are the Swedish AGEMA Infrared, the U.S. companies Inframetrics, Indigo Systems, and FSI. FLIR Systems have sold over 40,000 infrared cameras globally.

FLIR Systems are a vanguard of modernization for the industry of infrared cameras. The company has continuously been designing, developing, and upgrading newer ones. FLIR Systems produce all essential electrical and mechanic components for the camera's structures. All procedures of fabrication for the camera are performed and monitored by their own engineers. The knowledge that the specialists possess for the infrared camera allows them makes certain that precision and consistency are essential components that are gathered into the thermal camera (FLIR, 2009).

CHAPTER 4

METHODOLOGY

The noncontact thermometer method was followed. For the experiment, The Infrared camera was used instead of the infrared radiometer as shown in Figure 32.

4.1 Emissivity Calculation

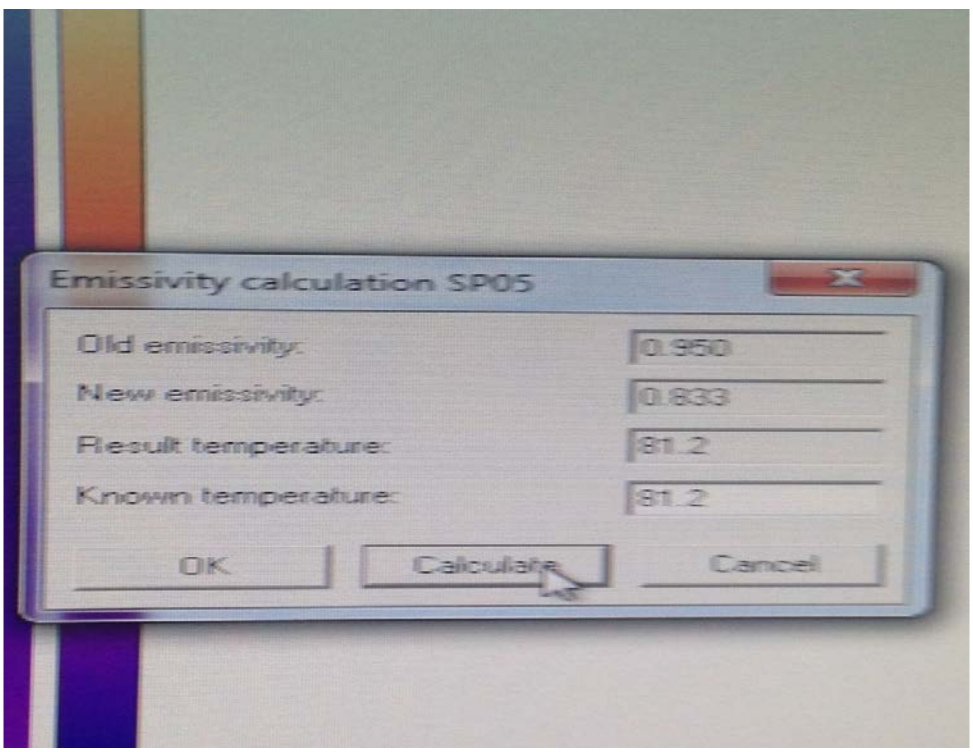

Figure 31: Emissivity calculation SP05

Figure 31 shows that only value for the known temperature can be entered or changed. Once that value is entered the result temperature will change to the same value as the known temperature. The new emissivity will be calculated. The emissivity is calculated for the material sample using the spot meter tool. This tool works by entering the known temperature measured by the camera that is greater than the ambient temperature. The value that was entered as the known temperature is the temperature of the SP06 which is the temperature of the material with a piece of black tape applied and the actual temperature of the material. Then the emissivity of the target will be calculated which is the new emissivity (FLIR, 2009)

4.2 Black Tape and Black Paint

Black electrical tape and black paint with a matte finish have emissivity values of approximately 0.95. The purpose of using the black tape or black paint is to prevent ambient reflections of the sample. Therefore, applying these two methods play the role of a blackbody, this will offset this error of spot reflections. When measuring a sample, it needs to look for a thermally stable surrounding that will not produce spot reflections. There are advantages and disadvantages between using black tape and black paint. The advantage of using black tape is that it allows to obtain the emissivity of the object. It is easy to use and it is non-destructive. The disadvantage is that it is not feasible to use at high temperature because the tape will melt. The advantage of black paint is that is can withstand exposures to high temperatures. The disadvantage is that over a wide range of temperature this can result in fluctuations of the emissivity of the object which will cause the measurements to be erroneous.

Figure 32: Electrical black tape with emissivity of 0.95

4.3 Device used in experiment

There were about one or two devices used in the experiment approach.t. While using one of these devices in conducting the experiment, it faceed some challenges, leading to some errors in measurements. Some changes were made using a different device.

4.3.1 Raytek Infrared Gun

Figure 33: Raytek Infrared Gun

This raytek infrared gun was used in my previous experiment in collaboration with a hot plate to determine the emissivity of the roofing samples. It has an output power of 1 mW and operates between wavelengths from 630-670 nanometers. The optic resolution must be ratio of 8:1. The gun has to be used at a minimum distance of 8 inches with a spot size of 1 inch and maximum distance of 24 inches with a spot size of 2 inches. This infrared gun is similar to a ratio pyrometer but without an emissivity setting capability. The gun has a default emissivity value of 0.95. The emissivity does affect the surface temperature of the material. Since this gun doesn't have an emissivity or temperature setting, the values cannot be adjusted. The temperature measurements recorded by this gun were incorrect. If a black tape was applied over the sample, a correct surface temperature can be obtained, while it doesn't tell the actual emissivity of the material. Also the method of proportion or slope formula in algebra cannot be used to find the emissivity because their emissivity and temperature are nonlinear.

4.3.2 Hotplate

Figure 34: Super-Nuova™ Digital Hot plate

This digital hot plate was used as a heat source to achieve heat measurements in the first experiment. A hot plate was used to heat the material samples to a temperature greater than the room temperature. The device was manufactured by the company ThermoFisher Scientific. This hot digital plate, the Super-Nuova™, allows to set or adjust exact constant temperatures. The knob is used to set the temperature. The knob is turned one way to increase the temperature and the opposite direction to decrease the temperature. Then when the knob is pressed it locks in the temperature so it can be saved and avoid unintentional changes. The presets feature allows the user to set four temperatures. The temperature adjusts in increments of 1° and the unit of the temperature is Celsius. This device can be used in an environment where the temperature is an the range from 0°C to 27°C, a relative humidity of 80 percent, and where condensation is not present. The calibration mode for the probe ensures that this is calibrated. The hot plate has a cast-aluminum stand and aluminum top to heat up the samples to an even temperature. There is also a hot top feature that alerts when the aluminum top is really hot so any unintentional burns can be avoided.

The disadvantage was that it took too long to heat the material samples to a desired temperature. Since the plate is made out of aluminum, it was highly reflective. This interfered with the measurements and the results obtained were not sufficient and incorrect. When using this device to heat up materials to a desired temperature, it should be in a vacuum space to prevent any heat loss. Heat loss could lead to errors in the measurements (Thermo Fisher Scientific Inc, 2015).

4.3.3 Heat Lamp

Figure 35: 250 Watt and 120 Volt Infrared Heat Lamp

The infrared heat lamp was used in the last experiment to heat up the material samples in place of the hot plate. The heat lamp was a better heat source and closely simulated the sun. This is a natural way of induced heating of all roofs. The infrared lamp was used to heat up the materials to a certain temperature at varying distances. The distance between the lamp and the roofing samples was changed to obtain different results. The measurements at 12, 11, 14, and 10 inches were taken. A measuring tape was used to indicate the actual distance between the heat lamp and roofing samples. The lamp has a life of 5,000 hours. This lamp generally is used for personal comfort. It can be used to heat smalls sections of the bathroom and eliminates freezing of water pipes, car radiators, and pumps. For body application is recommended that a person should be exposed no more than 30 min and at a distance no less than 18 in

4.3.4 ThermoVision™ A40M

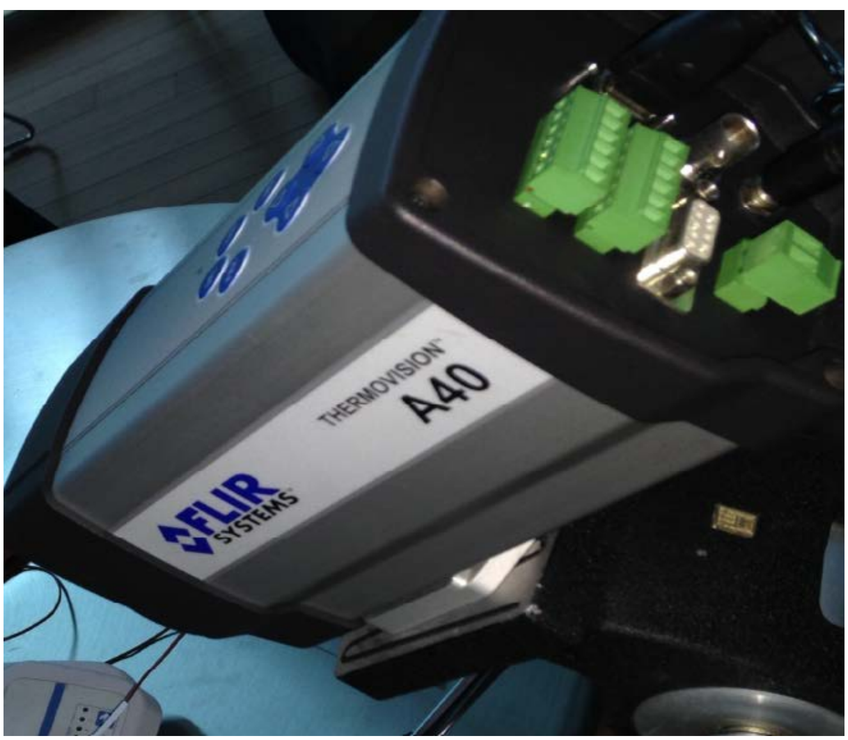

Figure 36: Infrared Camera: ThermoVision™ A40M

The infrared camera is the ThermoVision™ A40M manufactured by the company FLIR Systems. This device was used in my experiment to provide correct infrared pictures and recurring measurements of temperature. It is constructed from 76,800 single picture elements that are sampled 60 times per second by the electronic components of the camera. The software for this device allowed to determine the temperature and emissivity of the material samples shown in figure 14. The FPA detector machinery lets to view the changes in temperature with an infinitesimal value of 0.08°C.

The video images have a picture quality of 60Hz that produce clear pictures of mobile targets. As far as connectivity, this device can provide its own IP address permitting it to connect to a certain network. This device has a plug-and-play setup where I can plug the camera to the computer so it can generate high quality and real time images that display the thermal characteristics of the object. This camera can functions under extreme industrial conditions for extensive time periods. More than one option was selected such as target spots, color palettes, certain ranges of temperature, and more. Also, this device can be used to monitor a procedure with the SDK (software developers Kit). The SDK such as labview, Active X, and Visual Basic C++ allows to access the camera's measurements (FLIR Systems, Inc., 2005).

ThermoVision™ A40M Technical Specifications

Imaging Performance	
Field of view/min focus distance	24° x 18° / 0.3 m
Detector type	Focal plane array (FPA) uncooled microbolometer
Spectral range	7.5 to 13 μm
Spatial resolution (IFOV)	1.3 mrad
Thermal sensitivity @ 50/60Hz	0.08° C at 30° C
Focusing	Built-in focus motor
Image Presentation	
FireWire/Ethernet output	8/16-bit monochrome and 8-bit color
Video output	RS170 EIA/NTSC or CCIR/PAL composite video
Measurement	
Temperature ranges	Range 1: -40°C to +120°C (-40 to +248°F) Range 2: 0°C to +500°C (+32 to +932°F) Optional: Up to +1500°C (+2732°F) Optional: Up to +2000°C (+3632°F)
Accuracy (% of reading)	± 2°C or ± 2%
Measurement modes	Spot, Area, Difference
Automatic emissivity correction	Variable from 0.1 to 1.0
Individual emissivity settings	Individually settable
Measurement corrections	Reflected ambient, distance, relative humidity, external optics. Automatic, based on user input
Supplementary Lenses*	
Field of view/min. focus distance	7° Telescope (7° x 5.3°/4m) 12° Telescope (12° x 9°/1.2m) 45° Wide angle (45° x 34°/0.1m) 80° Wide angle (80° x 60°/ 0.1m) Close-up: 64/150 mm (FOV=64 x 48 mm at 150 mm); 34/80 mm (FOV=34 x 25 mm at 80 mm) Macro: 50 micron (14.3 to 18.7 mm focus; FOV=14.3 x 10.8 mm at 14.3 mm; FOV=15.1 x 11.2 mm at 18.7 mm; IFOV=45 μm at 14.3 mm; 47 μm at 18.7 mm)
Lens recognition	Automatic lens recognition and measurement corrections

Power Source	
AC operation	AC adapter 110/220 VAC, 50/60Hz (included)
DC operation	8-30V nominal, <6W
Environmental	
Operating temperature range	-15°C to +50°C (5°F to 122°F)
Storage temperature range	-40°C to +70°C (-40°F to 158°F)
Humidity	Operating and storage 10% to 95%, non-condensing
Encapsulation	IP 40 (Determined by connector type)
Shock	Operational: 25G, IEC 68-2-29
Vibration	Operational: 2G, IEC 68-2-6
Physical Characteristics	
Weight	1.4 kg (3.0 lbs)
Size	207mm x 92mm x 109mm (8.1" x 3.6" x 4.3")
Tripod mounting	1/4"- 20

User Configuration Table

TYPE	FUNCTION	REMARK
Digital Input	TTL level • Shutter disable • Store image • Batch enable	Isolation and relay function in external module
Digital Output	TTL level • Spot/Area threshold ALARM • Internal temperature sensor ALARM • V-sync	Isolation and relay function in external module
Analog Output	• Spot/Area out: 0-5V • Internal temperature sensor out: 0-5V	Scaled to T_{low} - T_{high} Isolation in external module
Analog Input	• External temperature sensor out: 0-5V	Scaled to T_{low} - T_{high} Isolation in external module

Figure 37: The technical specifications for the ThermoVision™ A40M Camera (FLIR Systems, Inc., 2005)

4.4 Experiments

4.4.1 Procedure

The Procedure for this experiment proceed in the following steps: 1) Place the infrared camera on the tripod or support mechanism at the preferred position. 2) Set the material samples at a certain distance within 2 meters of the camera. 3) Wait patiently for about 10 minutes for the camera to run after connection is established between it and computer. 5) Place the infrared heat lamp above the samples at a distance no less than 10 inches but no more than 15inches 6) Turn on the Infrared heat lamp wait about 15 minutes for samples to be heated above room temperature and so the black tape can be in thermal equilibrium with the samples. 7) Change the emissivity value in the settings from 0.920 to 0.950 for use of black electrical tape as you see below in figure 12. 8) Apply a piece of black tape to the portion of each material sample. The black tape will act as the surface modifying material. 9) Aim the infrared camera at the samples and focus on the section where the emissivity is to be calculated. 10) Use the spot tool which is the spot meter to record the surface temperature of the material without the black tape (SP01). 11) Then use the spot meter again to record the surface temperature of the material with the black tape (SP02). 12) Go to the menu box and select emissivity calculation for SP01 like the example shown in figure 31. 13) Input the temperature value found from using the black electrical tape. 14) Use that temperature value in the emissivity calculation to determine emissivity of the materials by using the emissivity calculation. 15) Repeat this procedure two more times. 16) Take the average of all measurements for each sample for the temperature and emissivity. (ASTM International , 2014)

Figure 18 Grey ceramic, brown ceramic, asphalt, and three pieces of cedar coated with aluminum, white, and black.

4.4.2 Experimental Setup

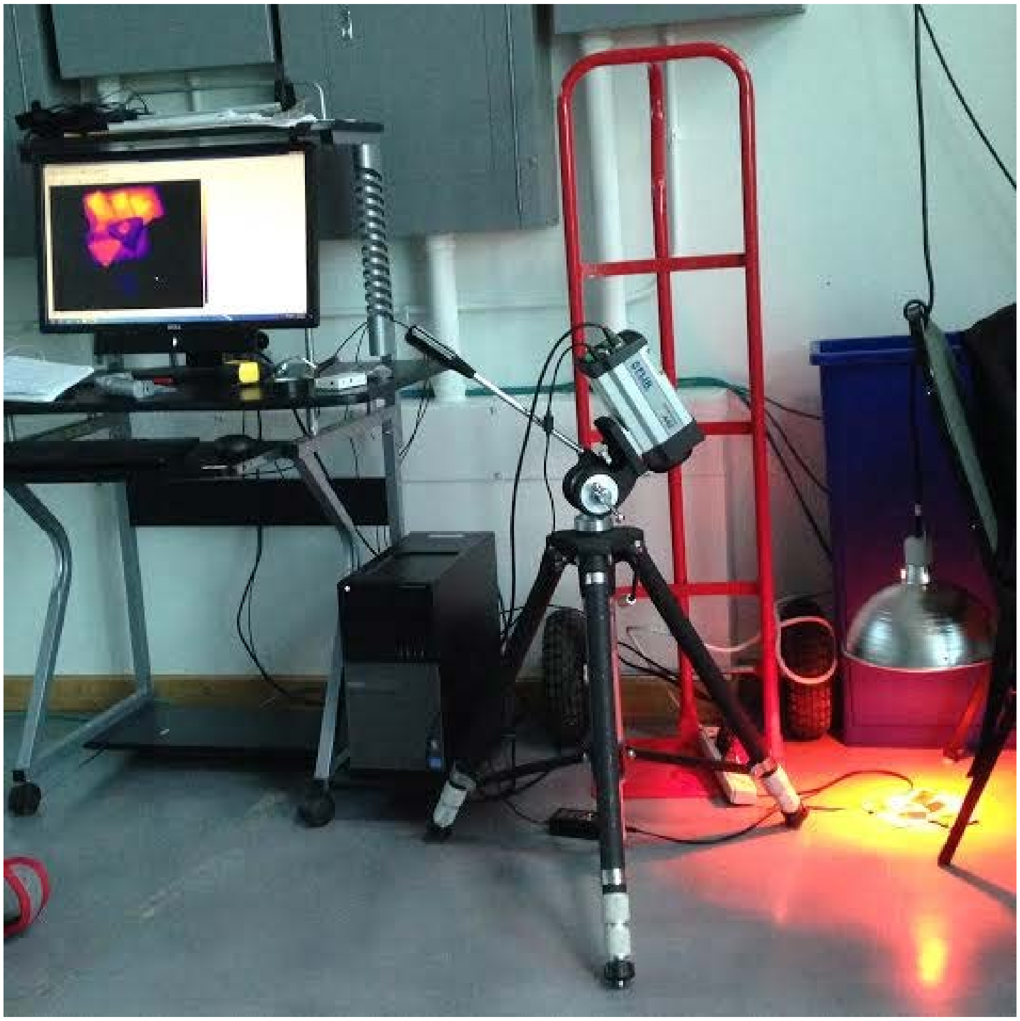

Figure 39: Experiment Setup

Figure 39 shows the IR camera placed on the tripod. The heat lamp plugged into the electric outlet on the ceiling. The camera was aimed at about a 33° angle to get a good live picture of the material samples. The samples were placed directly below the infrared heat lamp at a distance no lesser than 10 inched but not greater than 14 in. The chair was used to change the distance between the heat lamp and the material samples to obtain different results. The camera is connected to the computer with an interface cord.

The power cord of the camera is connected to the electric outlet of the surge protector on the floor. And the computer on the right is showing me the live picture of the samples emitted infrared energy.

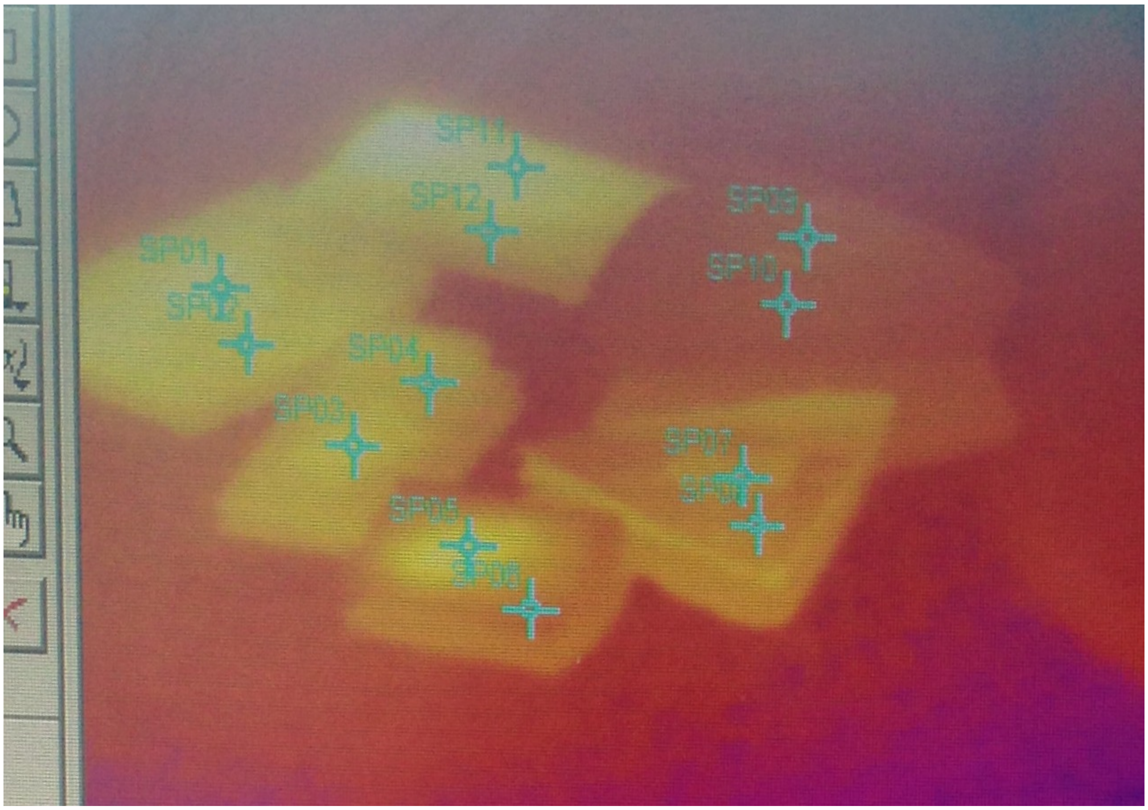

Figure 40: Roofing samples seen in the infrared image using spot meter tool.

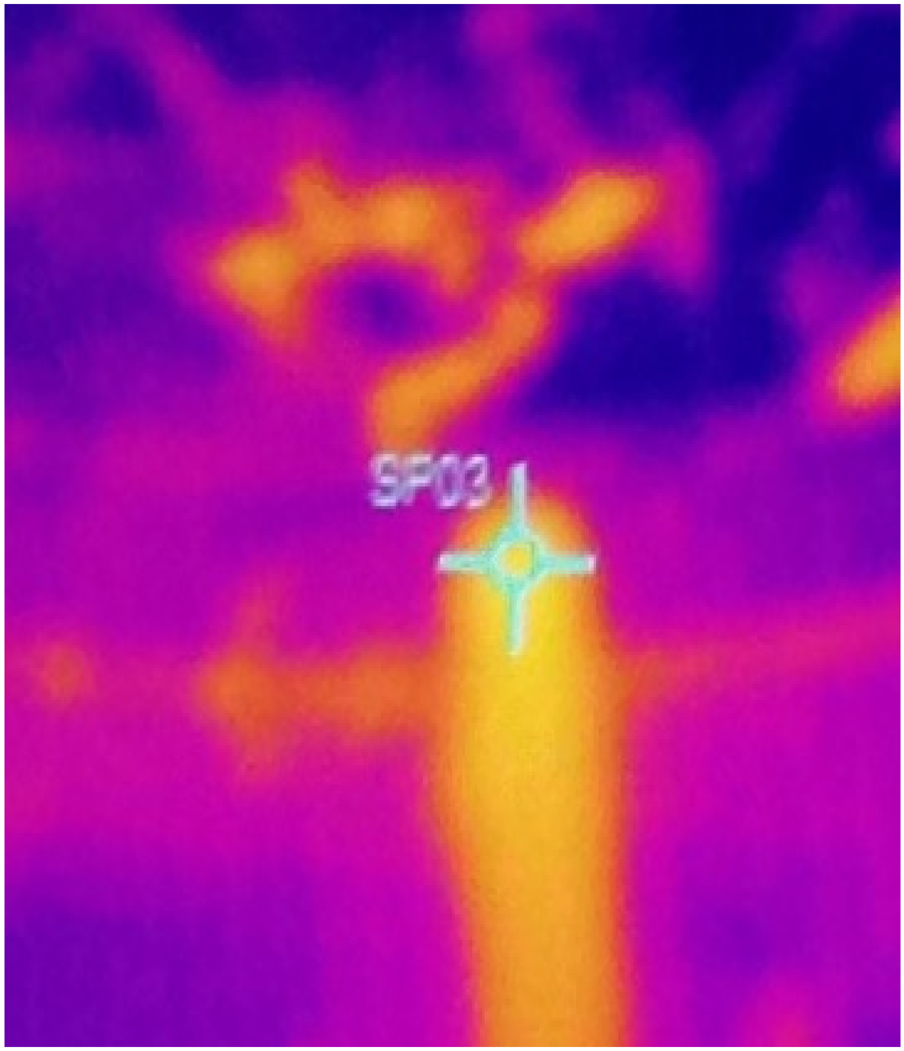

Figure 41: An example of spot temperature using the measurement tool spot temperature.

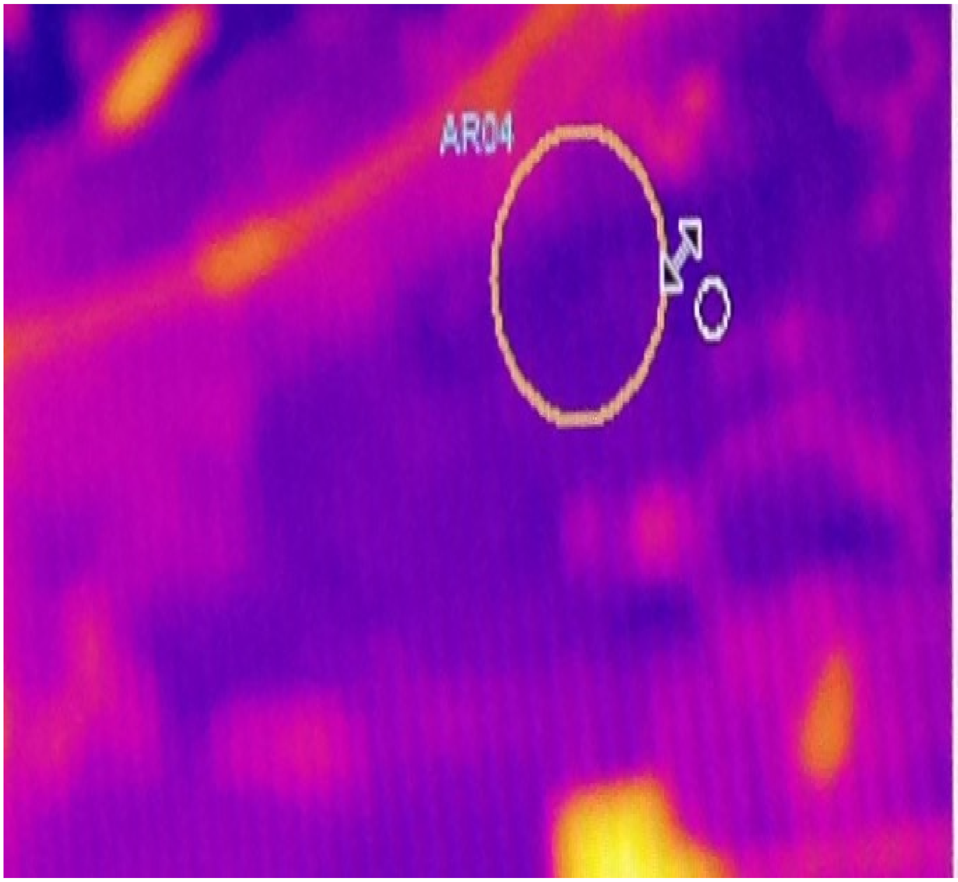

Figure 42: An example of using the measurement tool area which focuses on the section of the object.

CHAPTER 5

RESULTS AND DISCUSSION

The results from the experiment are recorded in tables 1-10. Each table shows data obtained at distances of 11.8, 12, and 14 inches between the heat lamp and the samples.

The heat lamp was positioned 12 inches above the samples. The results showed that for the average surface temperature; cedar coated with black paint had the highest value; the brown ceramic had the lowest value; and asphalt had the second highest value. Cedar coated with aluminum paint had the third highest surface temperature.

Based on the average emissivity value, the cedar coated with white paint had the lowest value which was close to the cedar coated with aluminum paint. The grey ceramic had the highest value, asphalt had the second highest and brown ceramic had the third highest. These results are reasonable because the cedar coated with aluminum paint has a high reflectivity thus having the lowest emissivity. A according the emissivity table, high reflective materials will have low emissivity values. The cedar coated with white paint had the lowest emissivity value out of all the samples. White paint was a little more reflective than aluminum paint based on the results.

The heat lamp was positioned 14 inches above the samples. The results showed that for the average surface temperature; asphalt the highest value; cedar coated black paint has the second highest value; and cedar coated white paint has the lowest surface temperature.

Based on the average emissivity value, asphalt had the highest and grey ceramic had the second highest. The cedar coated with white paint still had the lowest emissivity value. Then the material with the next lowest value was the cedar coated in aluminum. The difference in values between cedar coated with white paint and cedar coated with aluminum paint is greater now. A second set of heat measurements were taken on a different day with same distance of 14 in of the heat lamp's height position. The results showed for average surface temperature value, asphalt had the highest value and cedar coated with aluminum paint had the second highest. For the average emissivity values, grey ceramic had the highest and brown ceramic had the second highest. The cedar coated with white paint still had the lowest emissivity.

The heat lamp was positioned 11.8 inches above the samples. The results showed that for the average surface temperature grey ceramic had the highest value; cedar coated with aluminum paint had the second highest; and brown ceramic had the lowest surface temperature. Based on these results for the average emissivity, cedar coated with black paint has the highest value, grey ceramic had the second highest and brown ceramic had the lowest value. A second set of heat measurements were taken on a different day with same distance of 11.8 inches. For the average surface temperature, the results showed that the cedar coated with black paint had the highest, grey ceramic had the second highest value and cedar coated with aluminum paint had lowest value. The results for the average emissivity value showed that asphalt had the highest, cedar coated with black paint had the second highest and cedar coated with aluminum paint had the lowest.

The figures 44-61 and tables 1-10 in the appendix below show some uncertainties in the measurements taken for the emissivity and surface temperature at certain distances. The error bars in the graphs all show that the data are within a certain range close to the mean value. The mean value was based on the number of three measurements taken for each sample. There were few equations used in order to generate the error bars in these graphs. This equation: $S =$

$\sqrt{\frac{\sum(X-M)^2}{N-1}}$ is used to determine the standard deviation. The standard deviation determines how far the data is deviated from the mean value. X represents each data point, M represents the average of the data points and N represents the number of the data points so in this case it is three. The equation $\sigma_M = \frac{S}{\sqrt{N}}$ determines the standard error mean. The error bars displays a 95 percent confidence interval ranges from $M - (4.303)\sigma_M$ to $M + (4.303)\sigma_M$. This means 95 percent of the data points are inthis range. 4.303 is obtained from the t distribution table which is the 95 percent interval when N-1=2.

df	0.95	0.99
2	4.303	9.925
3	3.182	5.841
4	2.776	4.604
5	2.571	4.032
8	2.306	3.355
10	2.228	3.169
20	2.086	2.845
50	2.009	2.678
100	1.984	2.626

Figure 43: Abbreviated t table

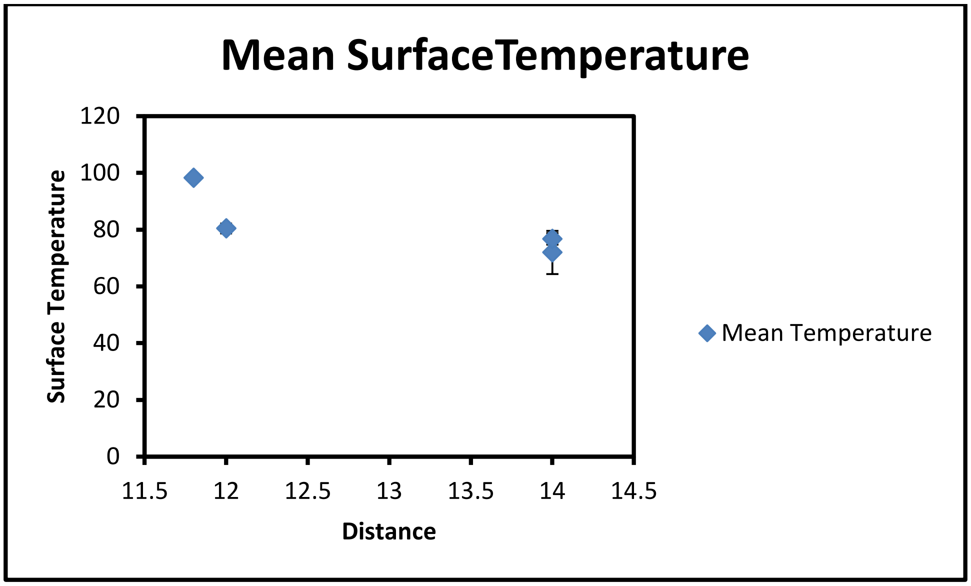

Figure 44: Surface temperature vs. Distance

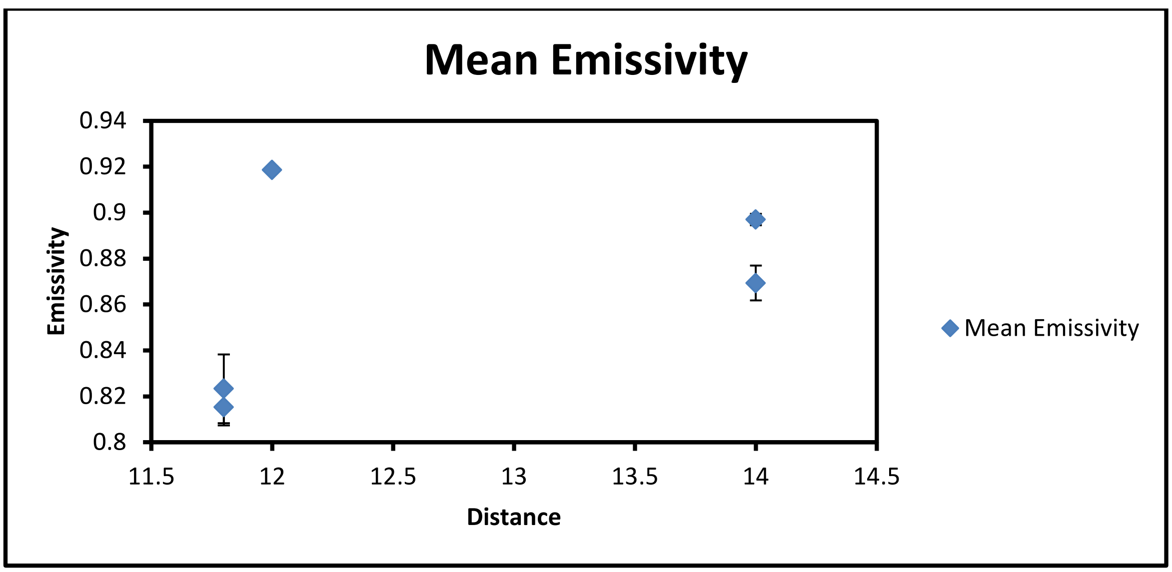

Figure 45: Surface temperature vs. Distance

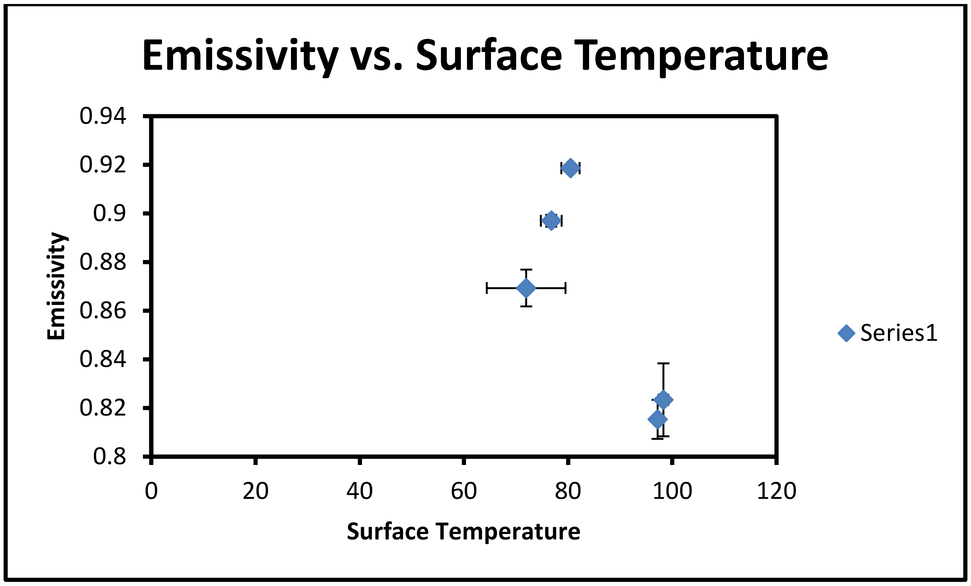

Figure 46: Emissivity vs. Surface temperature

Figure 44 shows that grey ceramic had the largest error for temperature measurements taken at 14 inches and the error in temperature measurements was smaller at 11.8 inches. In figure 45 it shows that ceramic had the largest error for emissivity measurements taken at 11.8 inches and minimal error in emissivity measurements at 12 inches. The pattern when looking at Figure 44 shows that the temperature decreased with increasing distance, the error bar pertaining to each data point recorded started diminishing. As seen in Figures 45 and 46, when this material had displayed high emissivity values the error bars were minimal but when they decreased, the error bars became more visible.

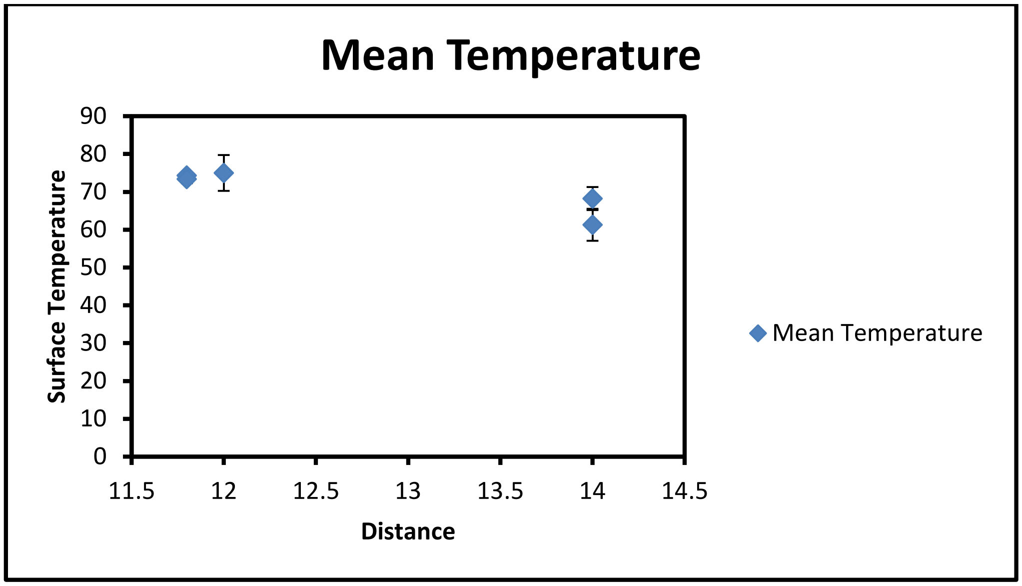

Figure 47: Surface temperature vs. Distance

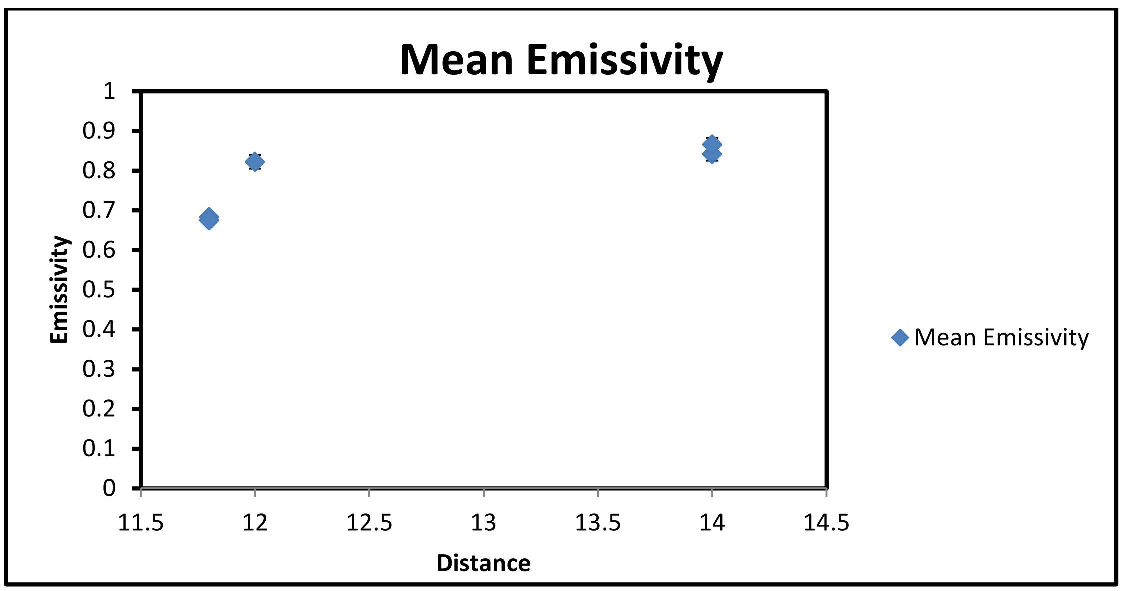

Figure 48: Emissivity vs. Distance

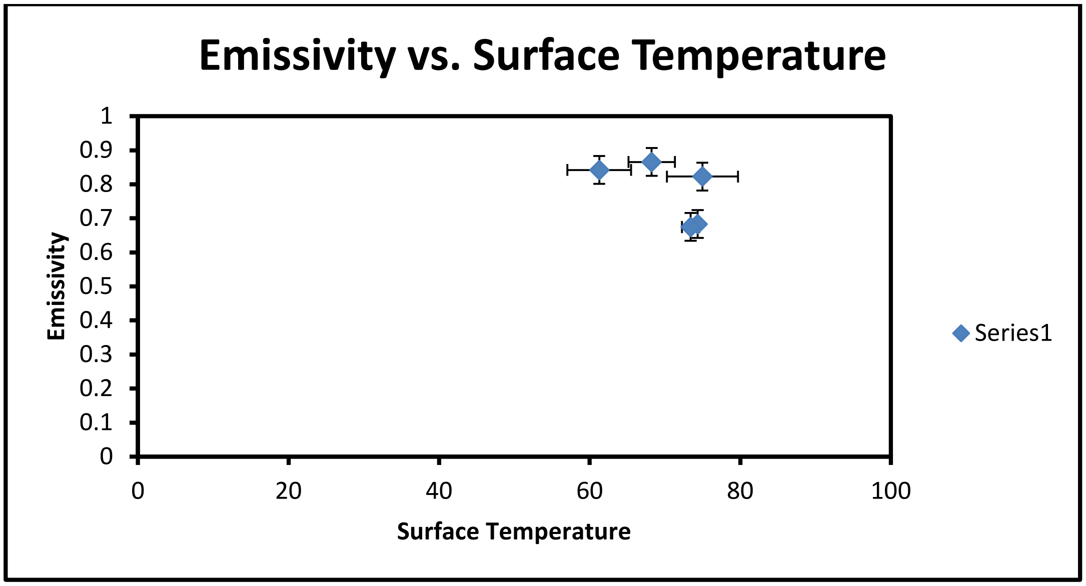

Figure 49: Emissivity vs. Surface temperature

Figure 47 shows that brown ceramic had the largest error in temperature measurements taken at 14 inches and 12 inches. At 11.8 inches, the error in temperature measurements was minimal. Figure 48 shows that the brown ceramic had the largest error for emissivity measurements taken at 14 inches and 12 inches. The error was extremely minute for emissivity measurements taken at 11.8 inches. Figure 49 shows there is more inaccuracy in the surface temperatures and minimal error in the emissivity measurements. As seen in Figure 48, the data points almost merge at the same distance for the two calculated emissivity values 0.683 and 0.675. As seen in Figure 49, the error bars is higher at temperatures where the emissivity values are high.

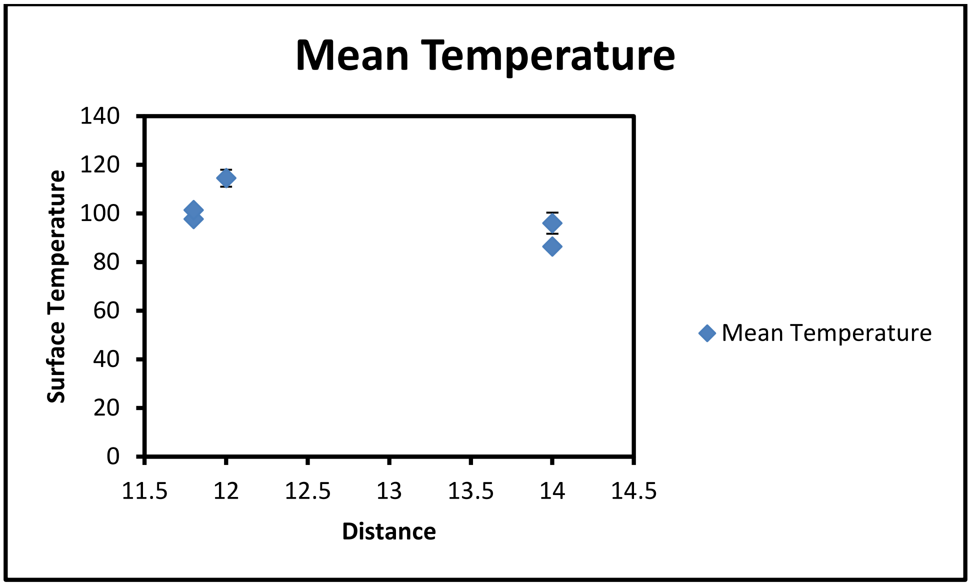

Figure 50: Surface temperature vs. Distance

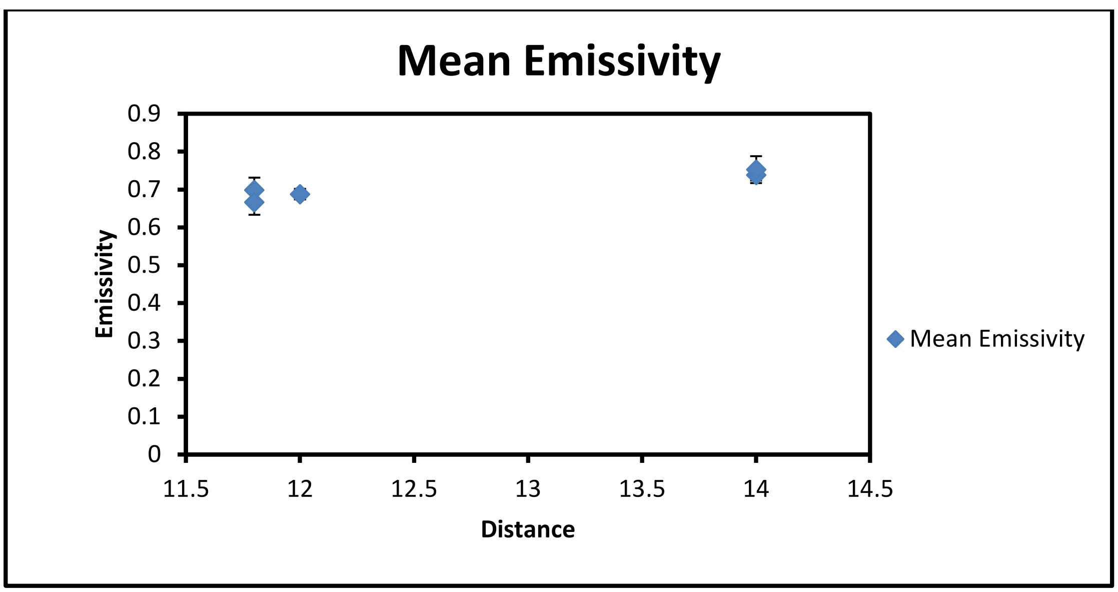

Figure 51: Emissivity vs. Distance

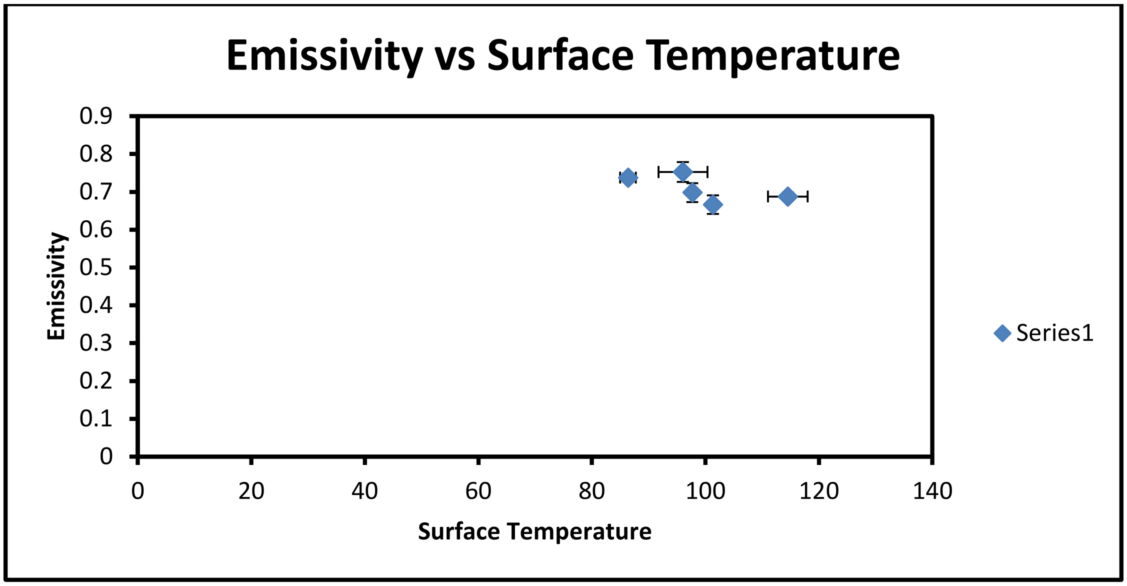

Figure 52: Emissivity vs. Surface temperature

Figure 50 shows that cedar coated with aluminum paint had the largest error for temperature measurements taken at 12 inches and 14 inches. The error was minimal for temperature measurements taken at 11.8 inches. Figure 51 shows that cedar coated with aluminum paint had the largest error for emissivity measurements taken at 11.8 inches and 14 inches. The error was minimal for emissivity measurements taken at 12 inches and 14 inches. Figure 52 shows the inaccuracy is visible at certain temperatures and emissivity values.

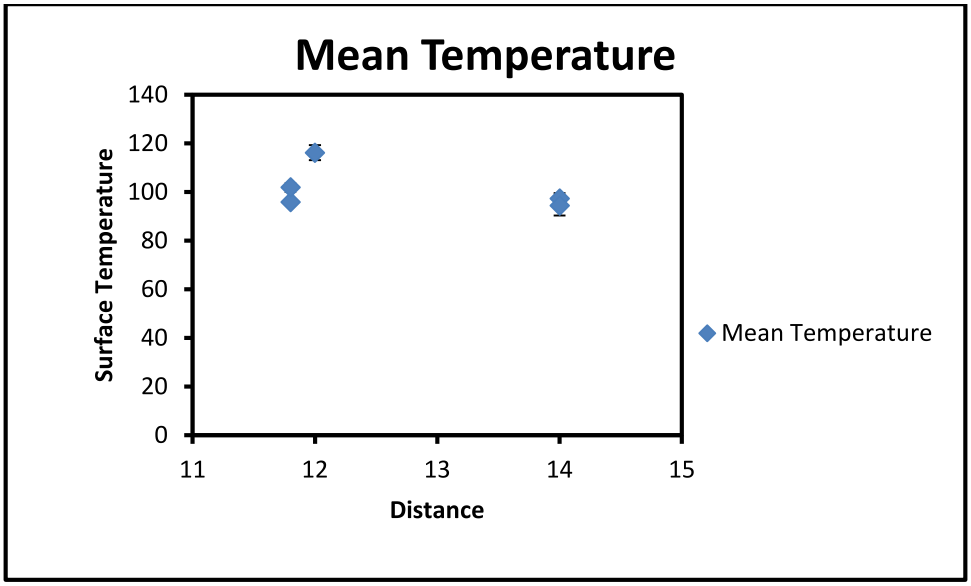

Figure 53: Surface temperature vs. Distance

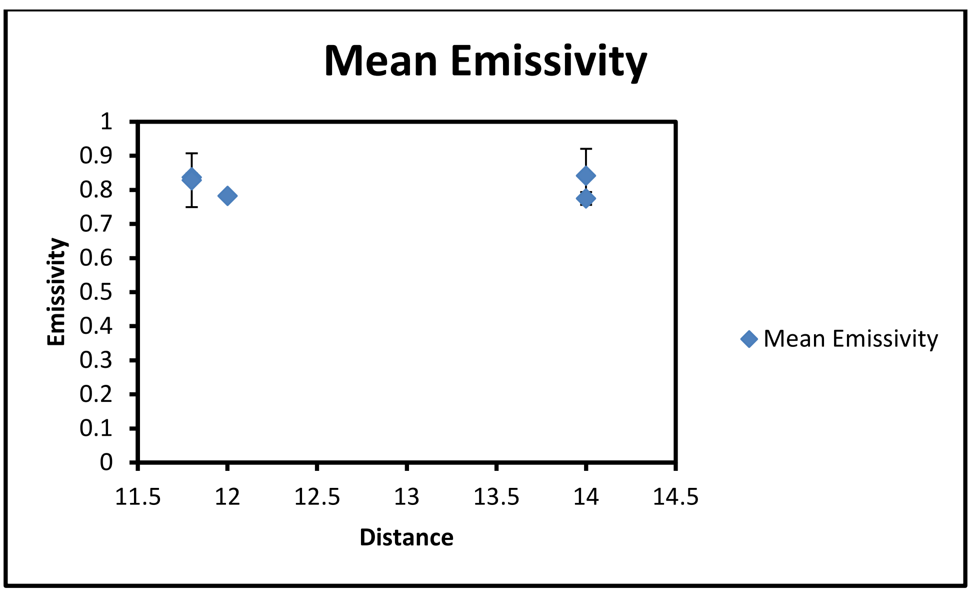

Figure 54: Emissivity vs. Distance

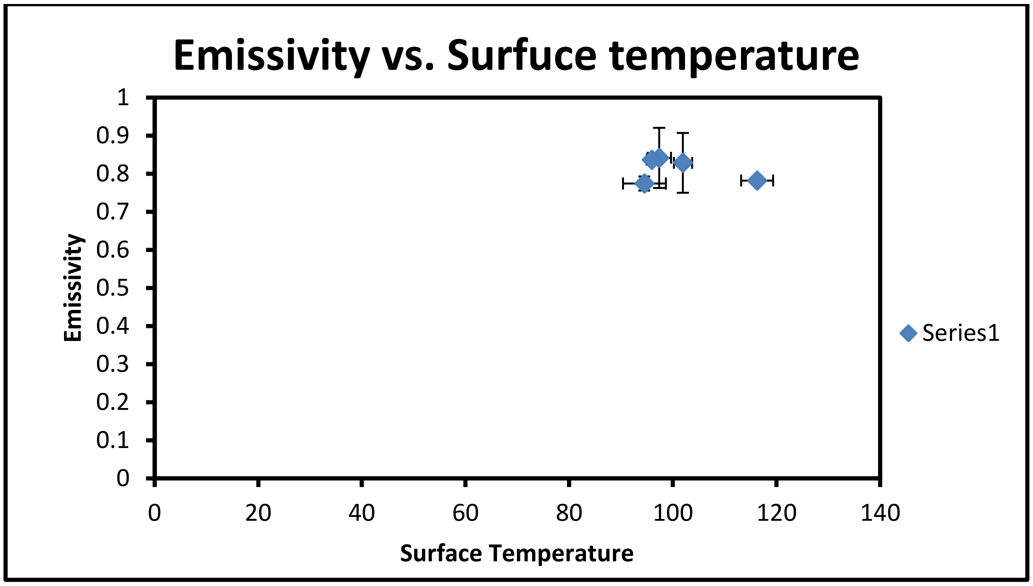

Figure 55: Emissivity vs. Surface temperature

Figure 53 shows that cedar coated with black paint had the largest error for temperature measurements taken at 14 inches and 12 inches. At 11.8 inches the error was small. Figure 54 shows that cedar coated with black paint had the largest error for emissivity measurements taken at 11.8 inches and 14 inches. Error was minimal for emissivity measurements taken at 12 inches. In figure 55, two data points with emissivity values of 0.842 and 0.837 have rather large error bars pertaining to the emissivity. The other two data points with temperatures of 116.2 and 94.5 Celsius have visible errors bars.

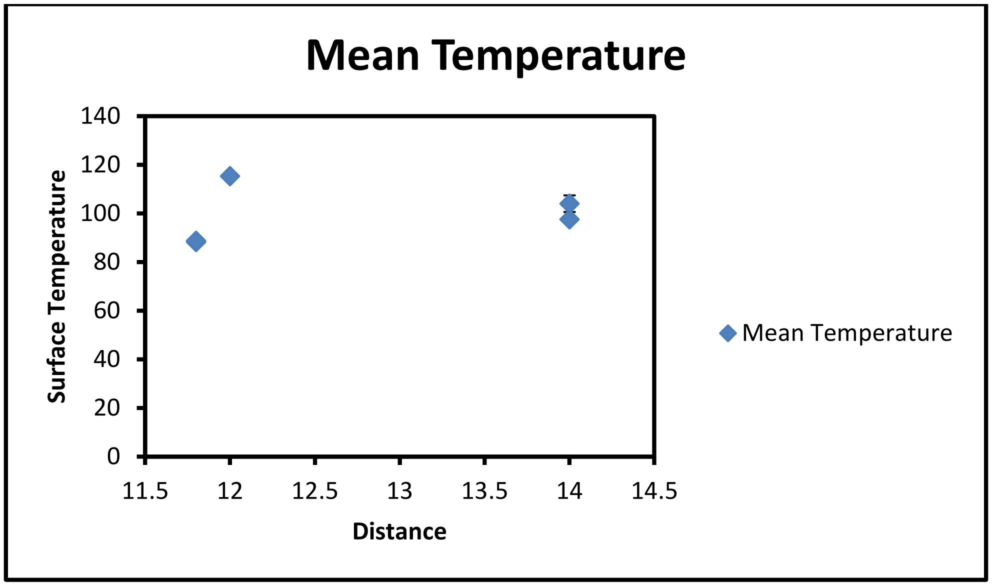

Figure 56: Surface temperature vs. Distance

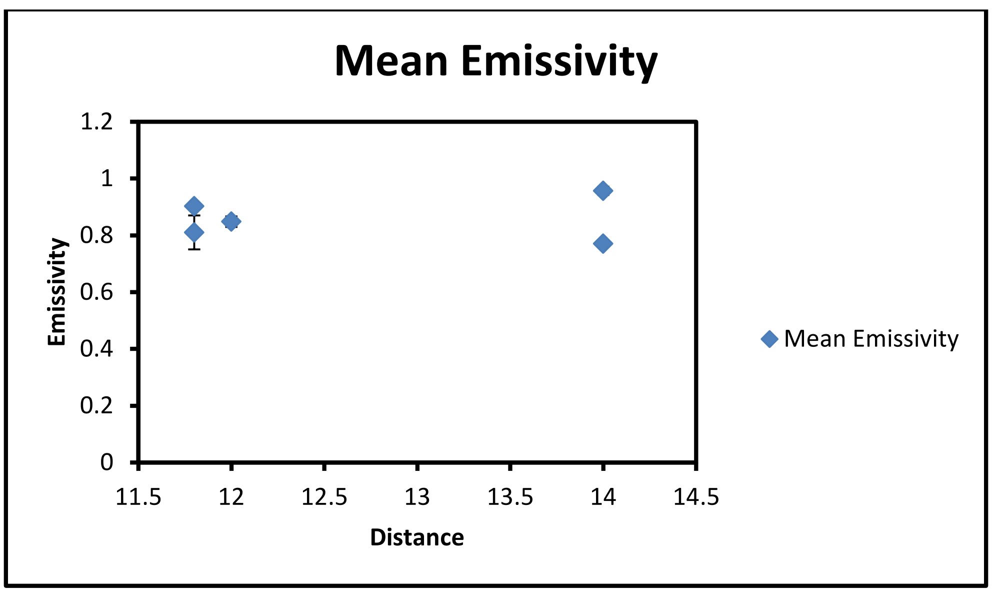

Figure 57: Emissivity vs. Distance

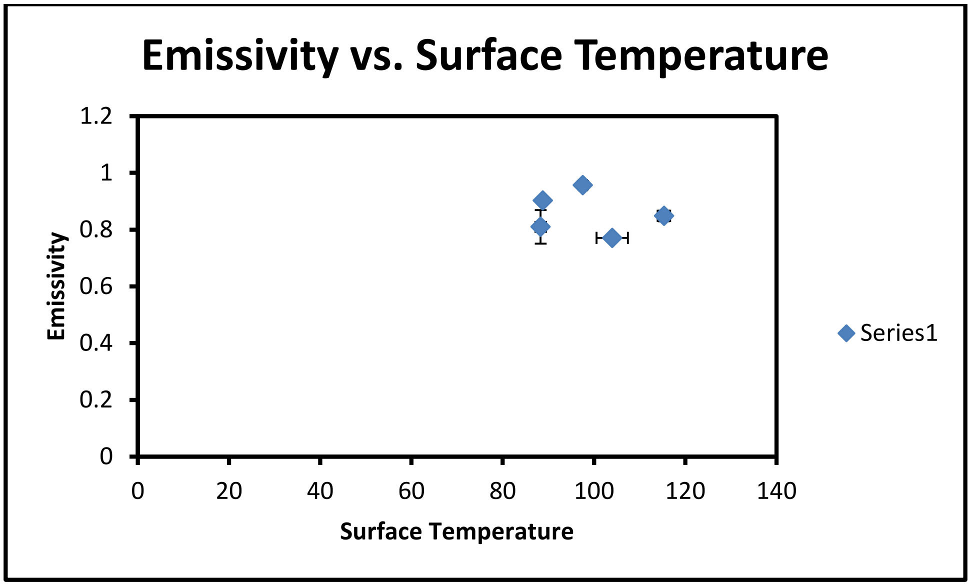

Figure 58: Emissivity vs. Surface temperature

Figure 56 shows that asphalt had the largest error for temperature measurements at 14 inches. The error was minimal for temperature measurements taken at 11.8 inches and 14 inches. Figure 57 shows that asphalt had the largest error for emissivity measurements taken at 11.8 inches and the error bars were minimal for emissivity at distance of 11.8 inches and 14 inches. As seen in Figure 58, there are error bars more visible at two data points. One data point at an emissivity of 0.810 and surface temperature at 88.3 Celsius shows error in the emissivity. The second point where the emissivity is at 0.771 and surface temperature is at 104 Celsius shows inaccuracy in the surface temperature.

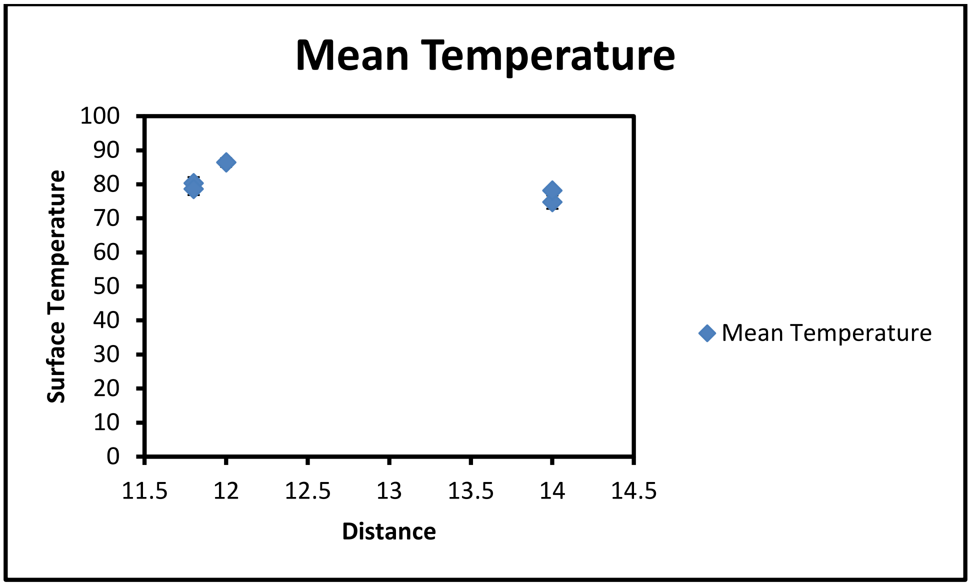

Figure 59: Surface temperature vs. Distance

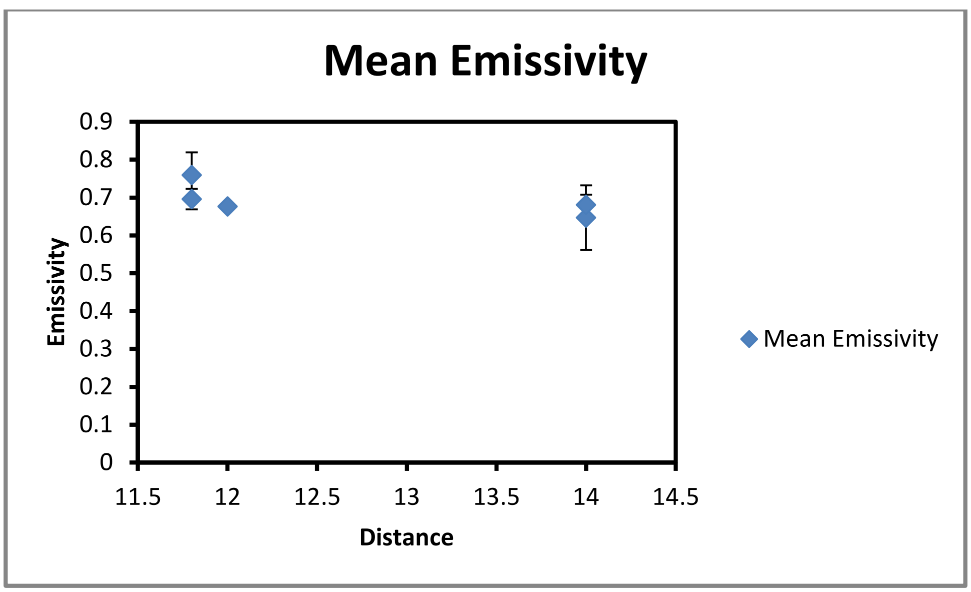

Figure 60: Emissivity vs. Distance

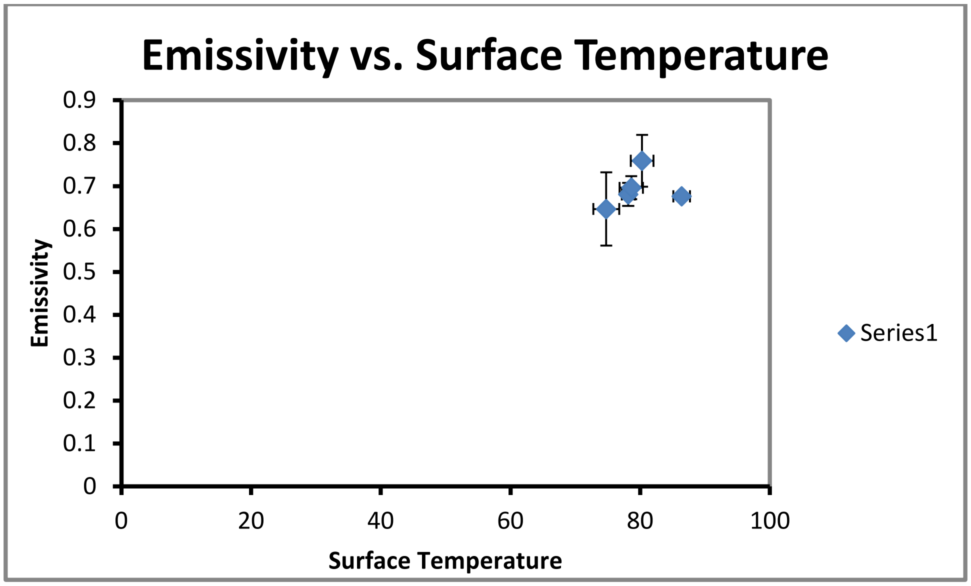

Figure 61: Emissivity vs. Surface Temperature

Figure 59 shows that cedar coated with white paint has hardly in error visible for temperature measurements taken at all three distances. The error bars are very similar the same for all the data points. Figure 60 shows that cedar coated with white paint had the largest error for emissivity measurements taken at 11.8 inches and 14 inches. There was little error in measurements at 12 inches. As shown in Figure 61, the error bars of two specific data points at emissivity values 0.647 and 0.759 displayed in Table 13 can be seen greatly in both the horizontal and vertical direction.

CHAPTER 7

CONCLUSIONS

The study is to determine the emissivity values of the roofing samples. The purpose of the experiment is to check if the emissivity values will match the given values in the emissivity table and if the values are constant when the surface temperature changes for the materials. This will determine how reasonable the emissivity values are. With this data, it also determine which material is better to be in the winter time and summer time.

During the experiment, six samples: asphalt, grey ceramic grey, brown ceramic and three cedar samples each painted a different color. All were heated by a heat lamp and had a piece of black tape applied. Then the IR camera took heat measurements which were used to find the emissivity of each sample. The experiment was done many times to observe the affect the distance the heat lamp from the roofing sample had on the surface temperature and emissivity. Since the temperature was rapidly changing, three measurements needed to be taken to get an average to determine reasonable data. The data was taken on three different days to check if the values changed and to see if any errors might have been made in measurement.

During this experiment, it was discovered that when the temperature of each sample fluctuated slightly as well as the emissivity. A material is able to emit more infrared energy than another material even if its' emissivity is lower. Based on the experiment, it is realized that a material with a higher surface temperature doesn't necessarily mean that it will have the highest emissivity value.

For example, when the heat lamp at a height of 11.8 and 14 inches, the grey ceramic had a higher emissivity value than asphalt, but the surface temperature of asphalt was higher than the grey ceramic. Asphalt, cedar coated with black paint and grey ceramic had the three highest emissivity values and overall. Then the two cedars, one coated with white paint and the other coated with aluminum had the lowest emissivity overall. One thing that was interesting was at 11.8 inches brown ceramic appears to be one of the most reflective materials compared to both cedars one coated with white paint and the coated with aluminum paint. Then at distances of 12 and 14 inches, this material was highly emissive compared to asphalt, grey ceramic and cedar coated with black paint.

Based on data related to the figures from 43 to 57, the standard deviation of the surface temperature is greater than the standard deviation of the emissivity. For the material samples: grey ceramic, brown ceramic, cedar coated with aluminum paint and cedar coated with black paint the standard deviation of the surface temperature was higher for distances 12 and 14 inches and low for a distance of 11.8 inches. For cedar coated with white paint, the standard deviation of the surface temperature was highest for the distances of 14 and 11.8 inches and the lowest for distance 12 and 14 inches. For asphalt the standard deviation was the highest at a distance of 12, 14 and 11.8 inches and the lowest for 14 and 11.8 inches as well. Overall asphalt and cedar coated with white paint had lowest standard deviation out of the six samples where the rest of the four had the highest. For all the materials except for asphalt, the standard deviation for the emissivity was the same for two or more distances.

Overall the results are reasonable. Asphalt, cedar and ceramic are materials that should have high emissivites according to values in the emissivity table. Since they are diffuse reflectors they should radiate more heat. Aluminum is a reflective material according the values in the emissivity table. When trying to make the surface of a material reflective, aluminum paint or foil applied on the top of the surface can make a material reflective as well.

The IR camera can determine which paint is highly emissive or reflective by performing heat measurements. Between the other two paints black and white, the results showed that black paint was highly emissive and white paint highly reflective. According to these results, it can be assumed that dark colors radiate more heat and light colors reflect more heat therefore colors affect the temperature. But during the experiment in the figure below, two cedar pieces: one coated with black paint and one coated with aluminum paint both appear to be the same color. The difference based on the figure below is that the cedar coated with black paint appears shiny making it more reflective and the cedar coated with aluminum paint doesn't look shiny at all. So based on this observation, color really doesn't affect the emissivity and temperature.

Figure 62: Three cedars piece coated with paint: White, Black and Aluminum

The knowledge gained from this experiment was that emissivity values changes constantly. The reason is because the position and angular view of the camera was adjusted to obtain good quality, clear and readable images on the computer.

Asphalt, cedar coated with black paint and coated with aluminum paint did have the overall highest surface temperatures. The emissivity of asphalt is not the highest out of the materials but it's not the lowest either. During the winter season, this would be the perfect material to use in a roofing design. Materials that are diffuse reflectors should perform better than materials that are specular reflectors. Diffuse reflectors are not affected by the angle at which they are viewed at and they disperse more light in all directions than just one light in one direction. With this material emitting a lot of the heat it will keep a house warm and minimize the use of a heater. Plus with asphalt being a very rough material, it would have a higher emittance than ceramics.

Ceramics have a more rigid surface. They are considered to be diffuse reflectors. Based on the overall results, grey ceramic had a higher emissivity value than brown ceramic. It would be a very good material in the winter season as well. Brown ceramic has a more rigid and curved surface than grey ceramic. The grey ceramic had the highest emissivity overall. The emissivity isn't affected by color but by shape and structure of the material. It can be concluded that since the grey ceramic is flatter than the brown ceramic it can emit more heat while having a higher surface temperature.

Cedar is considered to be a diffuse reflector. But how high the emittance is depends how rough or uneven the material's surface is. The three different colored paints used to coat the cedar will help determine how emissive or reflective each paint is. Cedar coated with black paint had a higher emissivity and surface temperature than the other cedars. It was in the top three in the results compared to asphalt and grey ceramic when having displayed the highest emissivity and surface temperature. Both cedars where one was coated with white paint and the other coated with aluminum paint had the lowest emissivity. Knowing that aluminum paint is highly reflective, it can be concluded that white paint is highly reflective as well. These two highly reflective paints gives the cedar materials a glossy look and make them highly reflective. They would be considered more of a specular reflector.

Determining which paint has the higher reflectivity depends on the heat exposure and the surface of the material it is coated on. Cedar coated with aluminum paint or white paint would be good roofing materials during the summer season. It will reduce the use of the air conditioning unit in a home. Cedar coated with black paint would be a good roofing material during the winter season. It will reduce the use of the heater in a home. Reduction of any electrical heating and ac unit will minimize the energy usage and cost. Since the emissivity is a fraction of the amount of energy a blackbody emits, it's also a fraction of the amount of temperature the material emits.

There were some uncertainties in the data that was obtained from the IR camera. The rapid change in the surface temperature couldn't be prevented or minimized. The model of the IR camera that was being used for the experiment became defective. This issue made it impossible to obtain any more heat measurements. If it was possible to record more measurements, the marginal error in the data would have been reduced. Having some way to measure the angular view of the camera would've resulted in better measurements since the angle of the camera affected the heat measurements. The cardboard box where the material samples laid on was not very well insulated. Cardboard alone could not prevent the heat transfer between the sample and the floor. It could be assumed that the fluctuations in the recorded data might have contributed to the errors in the data.

For future experiments, improvements could be made to make the results reliable. The IR camera should record data at different angles to determine how much of an affect the angle as on the readings. This will also establish which angle gets the best results. The underside of material samples could have been insulated to prevent heat transfer from the floor in the building. More heat measurements could have been taken to get more reasonable results to reduce any uncertainties. If another experiment could be conducted, it would be to determine the thermal conductivity of these roofing samples as well as building materials such as plywood and OSB (Oriented Strand Board) Sheathing. Using an appropriate instrument can determine what properties affect the thermal conductivity and if the values generated from a table are correct.

There is some research that has been done to come up with a roofing material where the color of the roof can be altered based on the surface temperature. With this method, the radiation heat transfer entering or exiting out of the attic could be monitored. By doing this, it can make a home more energy efficient by conserving money and energy.

Some researchers from MIT designed roofing tiles that is capable of altering its color with respect to the surface temperature. When the surface temperature is hot, the tile will turn white to avert the heat and when the ambient temperature is cold it will turn black to absorb the heat.

In other research, there is process of how color alteration works with these special roofing tiles. It involves a system of two mixed fluids where one fluid is black and the other one is white. The density of these fluids will be altered depending on the surface temperature. When temperature is hot, the white fluid will float to the top while the black fluid will be submerged.

When temperature is cold, the black fluid will float to the top and while the white fluid is submerged.

This method was substituted using a substance composed of an ordinary commercial polymer in a water solution since it was too difficult. The solution is enclosed between two films of flexible plastic, while the dark film is at the rear. When the ambient is at a specific temperature the polymer becomes denser and takes a shape of small droplets. These small droplets create a white surface and scatter light. So the emissivity would pertain to the property of the polymer.

Overall the IR camera was the appropriate device to use the experiment when determining emissivity. The emissivity values are always going to be different at every temperature value, but the emissivity value of a blackbody will be one. This is the only given value needed besides the temperature to determine the emissivity of other material based on the measurement formula that the IR camera uses. The procedure for the experiment needs to be done correctly in order to obtain correct data. This will help contribute to other researches that pertain to trying to determine what the emissivity of a material is and determines appropriate materials needed to design roofs. In conclusion, the brown ceramic would be the best material to use for roofing designs in both the summer and winter time; according to the results it seems to be the most reflective for one case and the most emissive for another.

Appendix A

Tables

Table 1

Grey Ceramic					
Distances	Data pt 1	Data pt 2	Data pt 3	Mean Temperature	Standard devia. Temp
12	78.1	79.0	79.4	80.5	1.76254
14	64.8	69.5	70.4	72.0	7.56126
14	75.1	73.7	73.6	76.8	2.02338
11.8	89.8	90.0	89.8	98.3	0.89574
11.8	88.0	88.2	88.6	97.2	0.37949

Table 2

Grey Ceramic					
Distances	Data pt 1	Data pt 2	Data pt 3	Mean Emissivity	Standard devia. Emissivity
12	0.919	0.919	0.918	0.919	0.00143
14	0.866	0.872	0.870	0.869	0.00759
14	0.898	0.896	0.897	0.897	0.00248
11.8	0.817	0.829	0.824	0.823	0.01497
11.8	0.813	0.814	0.819	0.815	0.00799

Table 3

Brown Ceramic					
Distances	Data pt 1	Data pt 2	Data pt 3	Mean Temperature	Standard devia. Temp
12	66.6	69.1	70.5	74.97	4.72895
14	55.5	57.1	58.2	61.27	4.23311
14	66.1	64.0	63.6	68.23	3.06625
11.8	61.3	61.2	61.0	74.33	0.28687
11.8	59.5	59.9	60.4	73.40	1.13847

Table 4

Brown Ceramic					
Distances	Data pt 1	Data pt 2	Data pt 3	Mean Emissivity	Standard devia. Emissivity
12	0.815	0.828	0.825	0.823	0.01691
14	0.841	0.836	0.849	0.842	0.01629
14	0.872	0.859	0.866	0.866	0.01616
11.8	0.685	0.679	0.684	0.683	0.00799
11.8	0.673	0.675	0.676	0.675	0.00379

Table 5

Cedar w/ Aluminum					
Distances	Data pt 1	Data pt 2	Data pt 3	Mean Temperature	Standard devia. Temp
12	114.4	112.7	116.5	114.5	4.72895
14	85.5	86.9	86.7	86.4	1.88111
14	98.6	95.5	94.0	96.0	5.82805
11.8	97.8	97.5	97.8	97.7	0.43030
11.8	101.3	101.5	101.2	101.3	0.37949

Table 6

Cedar w/ Aluminum					
Distances	Data pt 1	Data pt 2	Data pt 3	Mean Emissivity	Standard devia. Emissivity
12	0.686	0.683	0.694	0.688	0.01413
14	0.741	0.741	0.731	0.738	0.01434
14	0.736	0.759	0.762	0.752	0.03534
11.8	0.704	0.708	0.683	0.698	0.03336
11.8	0.672	0.651	0.676	0.666	0.03336

Table 7

Cedar w/ Aluminum					
Distances	Data pt 1	Data pt 2	Data pt 3	Mean Temperature	Standard devia. Temp
12	114.8	117.0	116.9	116.2	3.08632
14	96.7	98.4	97.0	97.4	2.25423
14	96.4	93.3	93.8	94.5	4.13476
11.8	95.5	96.1	96.3	96.0	1.03431
11.8	102.7	101.3	101.8	101.9	1.76254

Table 8

Cedar w/ Aluminum					
Distances	Data pt 1	Data pt 2	Data pt 3	Mean Emissivity	Standard devia. Emissivity
12	0.784	0.782	0.781	0.782	0.00379
14	0.808	0.847	0.871	0.842	0.07899
14	0.767	0.782	0.775	0.775	0.01865
11.8	0.839	0.84	0.832	0.837	0.01083
11.8	0.794	0.856	0.836	0.829	0.07861

Table 9

Asphalt					
Distances	Data pt 1	Data pt 2	Data pt 3	Mean Temperature	Standard devia. Temp
12	115.7	115.6	114.7	115.3	1.36827
14	97.2	97.9	97.6	97.6	0.87247
14	105.6	103.2	103.2	104.0	3.4424
11.8	87.9	88.8	88.2	88.3	1.13847
11.8	88.6	88.7	89.0	88.8	0.51716

Table 10

Asphalt					
Distances	Data pt 1	Data pt 2	Data pt 3	Mean Emissivity	Standard devia. Emissivity
12	0.849	0.841	0.856	0.849	0.01865
14	0.950	0.960	0.961	0.957	0.01511
14	0.773	0.771	0.769	0.771	0.00497
11.8	0.783	0.829	0.818	0.810	0.05968
11.8	0.904	0.906	0.899	0.903	0.00896

Table 11

Cedar w/ White					
Distances	Data pt 1	Data pt 2	Data pt 3	Mean Temperature	Standard devia. Temp
12	85.8	86.7	86.7	86.4	1.29090
14	73.9	74.9	75.5	74.8	2.00807
14	77.7	78.4	78.4	78.2	1.00403
11.8	81.1	79.7	80.2	80.3	1.76254
11.8	77.8	79	79.1	78.6	1.79721

Table 12

Cedar w/ White					
Distances	Data pt 1	Data pt 2	Data pt 3	Mean Emissivity	Standard devia. Emissivity
12	0.677	0.676	0.676	0.676	0.00143
14	0.607	0.664	0.669	0.647	0.08557
14	0.676	0.693	0.673	0.681	0.02680
11.8	0.787	0.75	0.741	0.759	0.06057
11.8	0.699	0.684	0.705	0.696	0.02687

Works Cited

Asphalt Roofing Manufacturers Association. (2015)., (p. http://www.asphaltroofing.org/residential/resources/faqs).

ASTM International . (2014, May). Standard Test Methods for Measuring and Compensating for emissivity Using Infrared Imaging Radiometers.

Bush, P. R., Miller, T., & Kriner, S. (2010, September 09). Cool Metal Roofing. *Whole Buliding Design Guide*, p. http://www.wbdg.org/resources/coolmetalroofing.php.

Campbell Scientific, Inc. (2001-2007). *Eppley PIR Precision Infrared Radiometer.* Logan, UT: Campbell Scientific, Inc.

Chemistry Explained Foundations and Applications. (2015). Ceramics. http://www.chemistryexplained.com/Bo-Ce/Ceramics.html.

Chen, B., Kasher, J., Maloney, J., Clark, D., & Mei, W. N. (n.d.). *Measurement of Night Sky Emissivity in Determining Radiant Cooling From Cool Storage Roofs and Roof Ponds.* Omaha.

Consigny, P. (2012). *Time and Space Resolved Measurements from Rocket Engines.* Stockholm, Sweden.

Evanczuk, S. (2011). Fundamentals of temperature-sensing devices. *Electronic Products*, http://www.electronicproducts.com/Passive_Components/Circuit_Protection/Fundamentals_of_temperature-sensing_devices.aspx.

FLIR. (2009). ThermaCAM™ Researcher Professional User's Manuel. FLIR.

FLIR Systems, Inc. (2005). ThermoVision™ A40M Industrial Automation. http://alacron.com/clientuploads/directory/Cameras/FLIR/A40M-Datasheet.pdf.

Fronapfel, E. L., & Stolz, B. J. (2006). Emissivity Measurements of Common Construction Materials. *InfraMation*, 1-7.

Gruner, K.-D. (2003). Principles of Non-Contact Temperature Measurement. 5-26.

Incropera, F. P., & Dewitt, D. P. (2007). Fundamentals of Heat and Mass Transfer. In J. Wiley. K Danvers, MA: Wiley.

Infrared Training . (2002). Learning Activity. http://IRtraining.inquisiqr4.com/.

Moghaddam, S., Lawler, J., & McCaffery, C. K. (2005). *Heat Flux-Based Emissivity Measurement.* College Park: Space Technology and Applications International Forum.

NASA. (n.d.). The Electromagnetic Spectrum. http://imagine.gsfc.nasa.gov/science/toolbox/emspectrum1.html.

Nayar, S., Ramamoorthi, R., & Hanrahan, P. (n.d.). *Basic Principles of Surface Reflectance.*

Parker, D., Sherwin, J., & Anello, M. (2001). *FPC Residential Monitoring Project: New Technology Development - Radiant Barrier Pilot Project.* Cocoa, Florida: Florida Solar Energy Center (FSEC).

Street Directory. (2015). Cedar Wood Benefits. *Street Directory*, http://www.streetdirectory.com/travel_guide/32566/home_improvement/cedar_wood_benefits.html.

Texas Instruments. (2014). *Thermocouple, Cold-Junction Compensation—Analog Approach.*

Thermo Fisher Scientific Inc. (2015). Super-Nuova™ Digital Hotplates. http://www.thermoscientific.com/content/tfs/en/product/super-nuova-digital-hotplates.html.

Wen, C.-D., & Mudawar, I. (2002). Experimental Investigation of Emissivity of Aluminum Alloys and Temperature Determination Using Multispectral Radiation Thermometry (MRT) Algorithms. *ASM International*, 2.

Woskov, P., & Sundaram, S. (2002). Thermal return reflection method for resolving emissivity and temperature in radiometric measurements.

zd.net. (n.d.). Color-changing roof tiles can absorb, reflect heat with the seasons. http://www.zdnet.com/article/color-changing-roof-tiles-can-absorb-reflect-heat-with-the-seasons/.