

# Investigation of Infrared Reflective Pigmentation Technologies for Coatings and Composite Applications

by

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## Abstract

Recent advances in pigmentation technology have allowed formulators to achieve a greater infrared reflectivity versus traditional pigmentation technologies in functional coatings, while maintaining the appropriate light absorption in the visible spectrum to impart color. The ability of functional infrared reflective coating systems to lower heat build-up results in reduced thermal warpage, reduced thermal cycling degradation, lower energy costs related to cooling, and improved comfort and functionality of dark color exterior objects such as park benches, hand railings, and even polymer concrete. This paper will impart knowledge of infrared pigmentation technology to the reader, and explore potential new applications of infrared reflective pigmentation technology in composites.

## Introduction

Rising energy costs continue to drive advances in new technologies designed to improve energy efficiency. One such technology is the use of specialty infrared reflective pigments used to impart color to an object, and reflect the invisible heat from the object to minimize heat build-up, when exposed to solar irradiance. Ultimately, the reflection of infrared energy lowers the heat build-up resulting in a reduction on the load of the cooling system, and therefore a cost savings.

In order to understand and maximize the functional mechanisms and effects of infrared reflecting pigmentation technologies, one must understand the sciences regarding solar radiation, black and gray body radiation, emissivity, reflectance, total solar reflectance, light scattering, light absorption, and relevant test methods. The following will explain.

## Electromagnetic Radiation

Electromagnetic radiation is a term used for wave energy consisting of magnetic and electric components propagating through space. There are many forms of electromagnetic radiation all around us. The electromagnetic spectrum includes wavelengths of energy (from lowest to highest energy) radio, micro, infrared, visible, ultraviolet, x-ray, and gamma ray radiation (Kotz, Purcell, 4).

Light is a form of electromagnetic radiation. The actual nature of light is quite complex. Light waves produced by a nuclear fusion reaction in our Sun, for example, propagate through space at a very high rate of speed, which is defined as a constant 300,000 kilometers per second in a vacuum. This is the phase velocity (or speed) of light. It takes light waves (also called photons) approximately eight minutes to reach the Earth after they have been generated by the Sun. All living things owe their existence to the Sun's energy bathing the Earth in a broad swath of electromagnetic radiation. Surrounding the Earth is a magnetic field shielding the Earth from much of the higher intensity radiation emitted by the Sun, such as x-rays. In addition, the molecules of gas, water vapor, and particles of dust in our atmosphere absorb a significant amount of electromagnetic radiation. The remaining electromagnetic radiation that reaches the Earth's surface is discussed in the following section.

The frequency of light as it is related to the wavelength of light is shown in Equation 1. This equation applies to light traveling in a vacuum.

$$F=c/\lambda \quad (\text{Eqn. 1})$$

F = the frequency of light in hertz (cycles per second)

$\lambda$  = wavelength of light in meters

c = speed of light in meters

When multi-chromatic light penetrates into a medium, a prism for example, the differing wavelength components of the light will travel at slightly different speeds in the medium due to the variation of refractive index with wavelength. This results in a separation of the light into its different color components. A commonly known example of this effect is a rainbow created by sunlight interacting with water droplets.

## Sunlight

Terrestrial solar radiation, or sunlight which reaches the ground, consists of three types of radiation; ultraviolet, visible, and near infrared. The ultraviolet portion of sunlight reaching the earth (also known as ionizing radiation) has a wavelength range of 280 nanometers to approximately 400 nanometers. One nanometer is one billionth of a meter. Visible light is typically discussed in wavelengths of nanometers or micrometers. One micrometer is one millionth of a meter. Visible light has a wavelength range of 400 to 700 nanometers (Kotz, Purcell, 4). This energy range is where the human capability of seeing and recognizing color exists (some people may be able to see color in an extended range of 380 – 740 nanometers). Near infrared radiation has a wavelength range of 700 nanometers to approximately 10,000 nanometers (nm), or 10 microns (um). Terrestrial

sunlight contains near infrared energy up to a wavelength of 4000 nanometers, however, most of the energy lies below 2500 nanometers.

## Solar Irradiance

Solar irradiance is the amount of energy impinging on a specific area of the Earth per unit time per unit wavelength. It is typically measured in watts per square meter per nanometer. Figure 1 shows the solar irradiance spectrum (ASTM, 14).

The integral (the area under the curve) of the solar irradiance spectrum is equivalent to the total amount of electromagnetic energy reaching the Earth per unit area per unit time and is expressed in watts per square meter. One watt equals one joule per second.

Ultraviolet energy is 5% of the total incident energy of sunlight. Visible light is 42% of the total incident energy, and near infrared light is 53% of the total incident energy. The actual energy breakdown will vary depending on the time of day, the location, and the atmospheric conditions where the solar spectral power distribution is measured (Holman, 5).

## Reflectance, Absorption, and Scattering of Light

When light energy strikes an object, one or more of the following may occur: reflection, scattering, absorption, or transmission.

When light waves interact with an object that exhibits a refractive index differing from the medium of light wave propagation, a portion of the light is reflected from the object. Percent reflectance expresses the amount of light energy reflected from an object at a specific wavelength. Reflectance can be specular (glossy) or diffuse (surface scattered). Specular reflectance consists of light reflecting at an angle opposite that of the incident angle. Mirrors (and glossy surfaces) exhibit a large degree of specular reflectance. Diffuse reflectance occurs when incident light is reflected at varying angles from a surface. Flat paints exhibit a high degree of diffuse reflectance.

The chemical composition of the pigment in a substrate may include chromophores, or components of a molecular structure that interact with, and absorb light resulting in color. Light absorption also results in the generation of heat, generation of free radical species, and free electrons. Absorption of near infrared light energy results in increased molecular vibration, or heat (Fessenden, Fessenden, 7).

Visible color is dictated by absorption in the 400 – 700 nanometer range. Traditional black pigmentation has a wide absorption over a large spectral range

whereas whites have a high reflectance over the entire visible range, or frequencies of light. Colorants exhibit selective absorption. Figure 3 shows the reflectance versus wavelength relationship of a titanium dioxide white pigmented composite. Figure 4 shows the reflectance versus wavelength relationship of a phthalo blue composite containing titanium dioxide. Note the differences in the reflectance curves.

Light is scattered when it penetrates into an object containing two or more phases of differing refractive indices. Figure 2 demonstrates the phenomena of light scattering. Scattering consists of an abrupt change in the spatial distribution of light. One such example is a pigmented coating or composite. Light penetrating into the coating or composite is scattered due to the difference of the refractive index of the pigment versus the polymer, or medium it is dispersed in. A portion of this scattered light exits the object and is included in the reflectance measurement. The spatial distribution and intensity of the scattered light is a function of the phase and wavelength of the incident light, the particle size, the particle morphology, the particle composition, and the medium composition.

Optimal hiding power (ability to mask the substrate) is achieved when the relative refractive index of the pigmentation to the medium it is occupying is as high as possible and the pigment particle size is approximately 1/2 to 1/3 the wavelength of the incident radiation. A pigment dispersion of titanium dioxide for example, with a primary particle size of 200 nanometers, will most efficiently scatter incident light with a wavelength of 520 nanometers assuming a refractive index of the pigment to be 2.74, and the refractive index of the medium to be 1.50 (Paul, 8). It is important to optimize the particle size distribution and spacing of the infrared reflecting pigments to increase the scattering efficiency relating to the longer wavelength components of the incident light (up to 2500 nanometers in the case of Sunlight).

## Total Solar Reflectance

Total solar reflectance (TSR) is a measure of the amount of incident solar energy reflected from a surface. In the terms of mathematics, the total solar reflectance is expressed as the integral of the percent reflectance times the solar irradiance divided by the integral of the solar irradiance when integrated over the 280 to 2500 nanometer range:

$$\%TSR = \frac{\int (\% R \cdot Id\lambda)}{\int Id\lambda} \cdot 100 \quad (\text{Eqn. 2})$$

where R = percent reflectance  
I = Solar Irradiance  
dλ = the wavelength interval of integration

Total solar reflectance is expressed as a percentage. Typical white coatings exhibit a total solar reflectance of 75% or greater. A white coating with a total solar reflectance of 75% by definition will absorb 25% of the incident energy. A black coating based on carbon black pigmentation may have a total solar reflectance as low as 3.5%, and therefore will absorb 96.5% of the incident solar energy.

## Black Body Radiation

Cooling effect optimization of infrared pigmentation technology requires a good understanding of emitted radiation, particularly in the infrared range. All objects emit radiation as a function of temperature. Understanding and maximizing the emissivity of an object allows a greater cooling benefit to be achieved by the formulator.

A black body is defined as an object that absorbs all incident radiation, and that emits specific wavelengths of energy as a function of temperature. Planck developed a mathematical formula yielding a black body's spectral radiant excitation per wavelength as it relates to the temperature of the body. This is known as Planck's law of black body radiation.

The spectral radiant excitation per wavelength per meter squared ( $M^2$ ) equals  $M_e$  (Wyszecki, Stiles, 1):

$$M_e = (c/4) u_e \lambda \quad (\text{Watts}/(M^2 * M)) \quad (\text{Eqn. 3})$$

$h =$  Planck's constant ( $6.626176 \times 10^{-34} \text{ J*s}$ )  
 $c =$  velocity of light ( $2.99792458 \times 10^8 \text{ M*s}^{-1}$ )  
 $k =$  Boltzmann constant ( $1.380662 \times 10^{-23} \text{ J*K}^{-1}$ )

where

$$u_e \lambda = 8\pi hc \lambda^{-5} (e^{hc/kT\lambda} - 1)^{-1} \quad (\text{J*m}^{-3}) \quad (\text{Eqn. 4})$$

$T =$  absolute temperature in Kelvins  
 $\lambda =$  wavelength in meters

Note: to convert  $M_e$  to Watts/( $M^2 * \text{nm}$ ), multiply by  $1 \times 10^{-9}$

Planck's law explains why an object such as an iron horseshoe has a red glow when placed in a furnace. As the temperature of the iron increases, the color will shift from red to the more energetic (bluer) wavelengths. Figure 5, calculated using Eqn. 3, (Wyszecki, Stiles, 1) shows a plot of the spectral radiant excitation of a blackbody at varying absolute temperatures. Note that as the temperature of a blackbody increases, the maxima of wavelength is shifted towards a higher energy or shorter wavelength.

The total energy radiated from a black body over all wavelengths at a constant absolute temperature measured in Kelvin is expressed in watts per square meter by the Stefan-Boltzmann Law as (Holman, 10);

$$\text{Energy Emitted} = \sigma(T^4) \quad (\text{Eqn. 5})$$

Where  $\sigma =$  Stefan-Boltzmann Constant  
 $= 5.670400 \times 10^{-8} \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$   
 $T =$  absolute temperature in Kelvins

Figure 6, calculated from Eqn. 5 (Holman, 10) shows a plot of the emitted energy per square meter of a black body radiator at typical temperatures encountered in every day life. Note that a black body radiator at a temperature of 200 degrees Fahrenheit emits a significant amount of thermal energy (just under 1000 watts per square meter).

## Gray Body Radiation

A gray body is an object deviating in emittance from a perfect black body radiator by a defined fraction expressed in terms of emissivity ( $\epsilon < 1$ ). By definition, a gray body's emittance is not wavelength dependent, and is therefore constant. In reality, the emittance of an object is dependent upon wavelength and angle of observation; intensity varies with the measured angle and measured wavelength (Holman, 6).

## Emissivity

The greater the emissivity of the surface of a given substrate (closer to that of an ideal black body radiator), the lower the heat build in the object, with all other variables remaining constant. For the formulator, this factor is quite important, as one will want to maximize emissivity when designing infrared reflecting coatings or composites; the greater the emissivity of an object, the greater the object's ability to radiate electromagnetic energy. Table 1 shows several emissivities of common objects (13).

Figure 7 illustrates the relationship between the radiated energy of a gray body at a constant temperature with changing emissivity.

## Test Methodologies – Heat Build Testing

Several test methods and procedures are available to aid the formulator using infrared reflective pigmentation technology. ASTM D 4803 is a test method predicting the heat build-up of exterior objects (objects exposed to the Sun) in the laboratory. This test method consists of placing the object to be tested above a thermocouple in an insulated box, and exposing the object to

a 250 watt heat lamp until thermal equilibrium is established. The resulting temperature delta above ambient is used to calculate a predicted heat build correlating to the temperature of an actual exposed exterior surface.

The vertical heat build maximum is defined as 41 degrees Celsius, and the horizontal heat build maximum is defined as 50 degrees Celsius. A carbon black based control is used to establish the maximum laboratory value, and this is used to calculate the theoretical heat build of the sample.

### **Test Methodologies – Solar Spectral Reflectometer**

The solar spectral reflectometer (SSR) is used to measure the percent total solar reflectance of an object. The SSR measures total solar reflectance based on four filtered detectors, and utilizes a tungsten filament light source. It is capable of four different air mass settings, and utilizes integrating sphere geometry with a twenty-degree observer. The resulting measurement is a percentage (%) total solar reflectance value. This instrument is crucial in the proper screening of materials and performing quality control tests on infrared reflective products. ASTM C 1549 utilizes the SSR in determining the solar reflectance of substrates.

### **Test Methodologies – Emissometer**

The emissometer is an instrument used to determine the emissivity of a specimen. It allows the formulator to characterize and maximize emissivity in order to achieve the greatest benefit from infrared reflective technology. ASTM E 408 is the standard test method for determination of total normal emittance of surfaces.

### **Test Methodologies –Thermal Imaging**

Thermal imaging is a process allowing the user to view radiation emitted from an object at wavelengths within 5000 to 13000 nanometers (5 – 13 um). The technology consists of a micro bolometer array coupled with specialty germanium based optics and image processing software. This technology allows the user to see the temperature of objects and has many uses, one of which is characterizing the performance of infrared reflective products, and the potential failure modes associated with such products.

### **Test Methodologies UV-VIS-NIR Spectrophotometer**

The UV-VIS-NIR is a spectrophotometer that measures the percent (%) reflectance or transmission over a wavelength range of 250 to 2500 nanometers (this varies by model; some instrumentation can measure up-

wards of 5000 nm). UV-VIS-NIR spectrophotometers come in single beam (absolute) and double beam (relative) modes of operation. Typical UV-VIS-NIR instruments have a high resolution, and allow detailed characterization of unique materials and polymers utilized in infrared reflecting applications. The UV-VIS-NIR provides a detailed look at object-light interactions outside of the visible spectrum and is also a critical instrument in identifying materials involved in specific failure modes, such as cross contamination. The UV-VIS-NIR is a necessary research tool when developing new synergistic IR reflective technologies (Parker, McIlvaine, Barkaszi, Beal, Anello, 9). ASTM E 903 outlines a standard test method for determining solar absorptance, reflectance, and transmittance of materials using integrating sphere spectrophotometers (Parker, McIlvaine, Barkaszi, Beal, Anello, 9).

### **Infrared Reflective Pigmentation Science – Keeping Objects Cool**

Infrared reflective pigmentation science utilizes the unique properties of specialty pigments to achieve a color of choice by reflecting, (or absorbing) the correct wavelengths of energy, and controlling the emissivity to the benefit of the user. Infrared reflective pigmentation technology allows the user to achieve a specific color space in the visible light range, while reflecting light in the near infrared range of the electromagnetic spectrum. This reflection of light in the near infrared reduces the equilibrium temperature of the object due to a lower overall energy absorption (less energy is absorbed and ultimately converted to heat).

Traditional colorants such as carbon black achieve a dark color space by efficiently absorbing visible light. However, this type of pigmentation also absorbs equally well throughout the near infrared. Because 53% of the Sun's incident energy is in the infrared, a significant amount of energy is absorbed and converted to heat causing an environmentally undesirable macro effect such as a Heat Island. Heat Islands occur in urban areas where ambient temperatures rise well above the temperatures of the surrounding area due to a large absorption of incident solar radiation resulting in a heat build-up effect (Pomerantz, Pon, Akbari, Chang, 11).

When an object pigmented with carbon black is exposed to sunlight, the temperature rise above ambient can easily exceed 80 degrees Fahrenheit. The resultant heat build-up of a roof, or building surface coated or pigmented with carbon black will cause increased heat transfer into the structure, and as a result, increase cooling loads on a structure. Increased cooling loads will contribute to an increase in utility costs (Akbari, Konopacki, 2).

Coatings formulated with infrared pigmentation are designed for application over substrates to improve among other things, their reflective, emissive, and visual attributes. Frequently these coatings are applied over substrates that are highly absorbing (low total solar reflectance) to yield a coated substrate with a higher total solar reflectance. Reducing the energy transferred into a system will reduce the overall equilibrium temperature of the system when all other variables remain constant. When designing an infrared reflective coating or cool coating, one must maximize total solar reflectance, maximize emissivity, and minimize all contamination by infrared absorbing materials.

### **IR Reflective Coatings - CASE 1: Infrared Reflecting Gray versus Traditional Gray**

The efficacy of infrared pigmentation technology is best demonstrated when comparing a traditional gray coating with an infrared reflective gray coating (Table 2). The gray coatings have a similar light to dark color value ( $L^*$ ) using the CIE LAB system, resulting in a  $\Delta L^*$  of 0.032. This indicates the coatings are achromatically equivalent. The total solar reflectance of the traditional gray coating is measured at 17.5%, and the total solar reflectance of the infrared reflective gray coating is measured at 47.1%. While the visible color difference is negligible, the total solar reflectance indicates a raw 29.6 % difference. The result is a reduced heat build-up as predicted by ASTM D 4803.

### **IR Reflective Coatings - CASE 2: Traditional Green versus Two Infrared Reflecting Greens**

Three green coatings were created to demonstrate the use of color matching with infrared reflective pigmentation. The first green (Green 1) was created using standard colorants. The second Green (Green 2) was created using infrared reflective pigmentation technology, and the third green (Green 3) was created using synergistic infrared reflective technology. All three green color matches are visually equivalent in color.

The total solar reflectance of the traditional green coating (Green 1) is measured at 7.6%, and the total solar reflectance of the infrared reflective green coating (Green 2) is measured at 20.2% (Table 3). The total solar reflectance of the third coating (Green 3) is measured at 36.8%. While the visible color differences were negligible, the total solar reflectance values indicate a significant difference, which has a pronounced impact on heat build-up as predicted by ASTM D 4803 (Table 3).

### **IR Reflective Technology - Example for Consideration:**

Traditional black asphalt shingles are well known for their ability to absorb heat in direct sunlight.

Roofers often toil in sweltering conditions when installing or replacing asphalt shingled roofs. Black asphalt shingles have a total solar reflectance of 3.5%, that is, they absorb over 96.5% of the incident solar radiation. This causes the roofs to heat to exceptionally high temperatures. Under the worst conditions, temperatures can well exceed 180 degrees Fahrenheit. This absorbed energy is conducted, convected, and radiated into the building structure via the large temperature gradient. This ultimately results in a hotter building requiring additional air conditioning to cool the rooms and at a greater energy burden. Assuming an average solar irradiance of 900 watts per square meter (an average value derived from the integral of the ASTM solar irradiance spectrum), this translates to energy absorption of 868.6 watts per square meter, or 868.6 joules per second.

Using infrared reflective pigmentation technology, the same black color space can be achieved using specialty infrared reflective pigmentation. By using specialty infrared reflective pigmentation the formulator can develop a coating with a total solar reflectance of approximately 29%. This greater solar reflectance means that although 71% of incident solar energy is absorbed, or around 639 watts per square meter of energy is absorbed, there remains a 26% reduction in energy absorption versus the asphalt shingle roof.

A second approach is to use a specialty synergistic infrared reflective technology. Utilizing this approach allows the formulator to have the visual effect of a dark color while achieving a higher solar reflectance. It is possible to produce a shade of black with a total solar reflectance of 47%, and net energy absorption of 53%, or 477 watts per square meter, and yield a 47% reduction in absorption of energy.

### **IR Reflective Technology – Contamination Concerns**

Contamination is a serious issue when using IR reflective technologies. For example, carbon black is a pigment that has much benefit to the composite and coatings formulators. Carbon black pigments generally produce strong shades, and are used for UV protection and low cost. However, carbon blacks are very strong ultraviolet, visible, and near infrared absorbers. Carbon black, even in low quantities (< 0.01%) can have a deleterious effect on IR reflective formulations. Infrared reflective colorants and IR reflective products developed from these colorants must be manufactured without cross contamination from IR absorbing materials such as carbon black.

### **IR Reflective Technology – Avoiding Warpage and Thermal Cycling**

The primary difficulty in pigmenting exterior thermoplastic substrates is in achieving a dark color space while avoiding warping of the thermoplastic. The structural integrity of a thermoplastic part will be reduced or fail completely if the temperature of the part exceeds the softening point of the base material. Traditional pigmentation must be used with caution in most exterior thermoplastic applications. Infrared reflective technologies are utilized to maintain a heat build below that of the softening point.

Thermal cycling occurs due to the expansion and contraction of materials due to the repeated exposure to temperature fluctuations from day to night. When materials are heated, they naturally expand, and then contract when they are cooled. Lowering the heat build by maintaining a high solar reflectance and high emissivity minimizes the effects of thermal cycling on structural components, and may improve the longevity of these components.

### **IR Reflective Composites – Possibilities**

The focus of infrared reflective technologies has been largely oriented towards the coatings industry. Many potential applications exist in the thermoset plastics industry as well. The underlying science behind the pigment – substrate interactions in a coating film are equally applicable in many ways to a pigmented thermoset composite matrix. To investigate the properties and performance of infrared reflective technology, specialty pigment dispersions were created in an unsaturated polyester resin. These dispersions were subsequently evaluated in an ATH (aluminum tri-hydrate) filled polyester thermoset compression molded composite at various loadings. Color readings, heat build, and total solar reflectance measurements were collected.

### **IR Reflective Composites – Relationship Of Total Solar Reflectance to Predicted Vertical Heat Build of Titanium Dioxide White, and Carbon Black Pigmented ATH Filled Thermoset Composites**

Although ASTM D 4803 was specifically created for predicting the heat build of vinyl substrates, it can be applied to other substrates such as wood and thermoset composites (Rabinovitch, Quisenberry, Summers, 12).

All composite heat build testing data was collected at equilibrium temperatures arrived at by analyzing data collected using a two channel data logging thermocouple. All composite data utilized the same carbon black standard control temperature,  $T_{1b}$  per ASTM D 4803, to assure consistent comparative results.

Figure 8 shows the relationship between total solar reflectance (%TSR) and vertical heat build, as predicted using ASTM D 4803, of four composite panels created at different loadings of titanium dioxide pigment dispersion (1.0%, 2.0%, 5.0%, and 10.0% respectively, based on resin and filler).

Figure 9 shows the relationship between total solar reflectance and vertical heat build, as predicted using ASTM D 4803, of four composite panels created at different loadings of carbon black dispersion (0.25%, 0.5%, 0.1%, and 2% respectively, based on resin and filler). The data clearly demonstrates the deleterious effects of carbon black in an infrared reflective composite where the goal is minimization of heat build-up.

The empirical properties outlined in figures 8 and 9 demonstrate the maximum and minimum benefits one may gain by using infrared reflective technologies in this ATH filled thermoset composite formulation. White exhibits the greatest degree of reflectance over the wavelength range of interest (excluding any improvements which may be gained in synergistic particle size distribution control, system resin effects, and filler influence) while carbon black exhibits the greatest absorption over the same wavelengths of interest at a given  $L^*$  value. Most colored infrared pigmentation will perform between these maximum and minimum boundaries at full opacity. This is due to the absorption effects of the colorants in the visible range. Even if the non-white pigmentation has the highest degree of infrared reflectance, the total solar reflectance will be lower than that of an opaque highly reflective white composite due to the energy absorption in the ultraviolet and visible portions of the spectrum.

### **Thermoset Composite Solar Reflectance Data Case 3: Black Composite Comparison**

When a traditional black composite is compared to an infrared reflective black composite, a raw 17.8% increase in total solar reflectance is achieved (Table 4). The heat build testing of the infrared reflective black composite per ASTM D 4803 yields an 8.5C lower predicted heat build-up. The net result is a visually similar, and cooler substrate when using the infrared reflective black versus a traditional black.

### **Case 4: Gray Thermoset Composite Comparison**

Table 5 compares three gray composites created at a similar light to dark value ( $L^*$ ) with different pigmentation chemistries. All three grays utilized 5% of a white dispersion based on the filled polyester system. Table 5 shows the solar reflectance,  $L^*$ , and vertical heat build of a traditional gray, IR reflective gray, and IR reflective synergistic gray. The infrared reflective gray achieves a 10.4 degree Celsius heat build advantage ver-

sus the traditional gray at a total solar reflectance of 42.2% as compared to a total solar reflectance of 20.9% for the traditional gray composite.

The synergistic infrared reflective gray composite shows a total solar reflectance of 56.3% and a predicted vertical heat build of 26.1 Celsius, which is 11.3 degrees lower than the traditional gray composite.

### **Case 5: Thermoset Composite Infrared Reflective Black %TSR versus Heat Build Evaluation**

Figure 10 shows the relationship between total solar reflectance and predicted vertical heat build of an infrared reflective black pigment dispersion in a white ATH filled thermoset composite system.

Figure 11 shows the L\* versus predicted vertical heat build of two sets of thermoset composite panels. One set of panels was created with carbon black pigmentation in a titanium dioxide white pigmented, ATH filled system. The other set of panels was created with an infrared reflecting black dispersion in a titanium dioxide white pigmented, ATH filled system.

Clearly, the composite panels created using the infrared reflecting black exhibit a much greater total solar reflectance at a given L\* value.

### **Case 6: Thermoset Composite Infrared Reflective Red %TSR versus Heat Build Evaluation**

Figure 12 shows the relationship between total solar reflectance and predicted vertical heat build of an infrared reflective red pigment dispersion in a titanium dioxide white pigmented, ATH filled thermoset composite system.

Figure 13 shows the relationship between L\* and total solar reflectance of an infrared reflective red pigment dispersion in a titanium dioxide white pigmented, ATH filled thermoset composite system.

### **Conclusions**

Recent advances in pigmentation technology have allowed the formulator to achieve a greater infrared reflectivity versus traditional pigmentation technologies. These technologies are currently being applied in various coatings applications, and the science behind the technology is applicable to thermoset composites.

A clear understanding of the function and composition of the composite material, along with proper pigmentation selection will yield composites with greater infrared reflectivity, higher total solar reflectance, and lower heat build-up while achieving the target color. This strategy allows the formulator to potentially add value and function to the composite matrix. This value

was not previously attainable using traditional pigmentation technology.

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- 13 - <http://snap.fnal.gov/crshield/crs-mech/emissivity-eoi.html>
- 14 – www.ASTM.org, ASTM G 173-03

Figure 1: The ASTM G-173 solar irradiance spectrum (ASTM, 14).

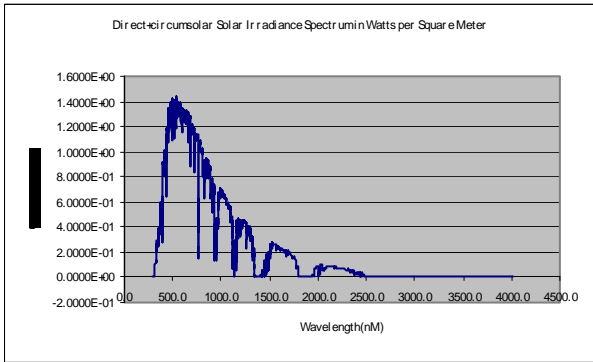


Figure 2: Laser light (632.8nm) scattering from a dilute 2% milk solution.



Figure 3: A typical reflectance curve of a white composite.

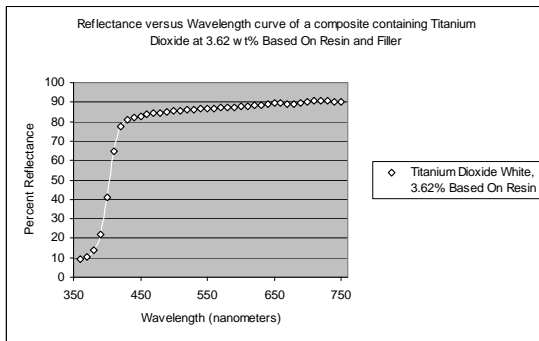


Figure 4: A reflectance curve of a phthalo blue and white pigmented thermoset composite.

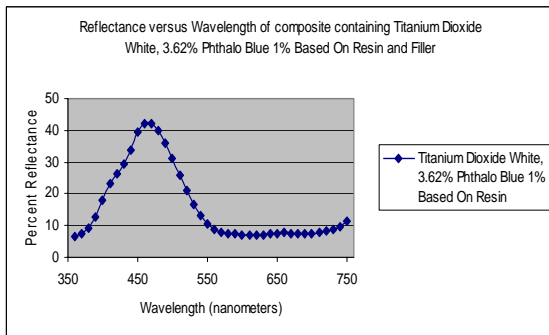


Figure 5: Plots of the spectral radiant excittance versus wavelength of a black body radiator at varying temperatures, calculated using Eqn. 3 (Wyszecki, Stiles, 1).

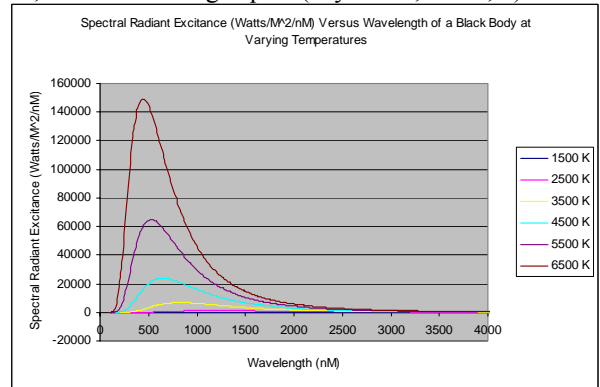


Figure 6: Black body radiated energy versus temperature, calculated using Eqn. 5 (Holman, 10).

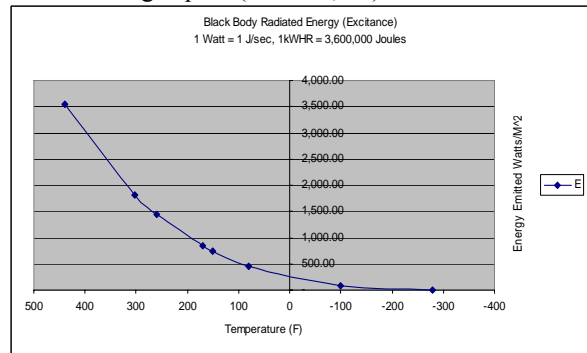


Figure 7: Radiated energy versus emissivity of a series of gray bodies with differing emissivity at 150F.

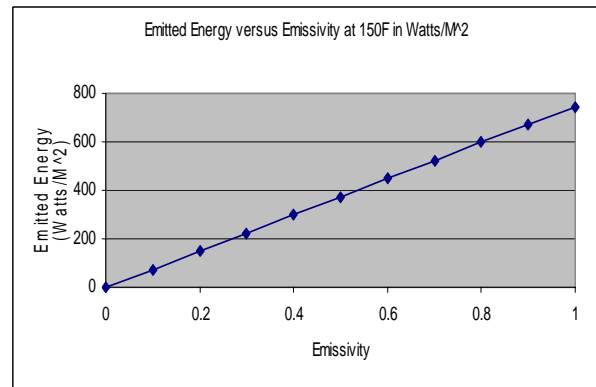


Figure 8: Titanium dioxide white pigmented composite predicted heat build versus %TSR relationship at 10.0%, 5.0%, 2.0%, and 1.0% dispersion loading based on resin and filler.

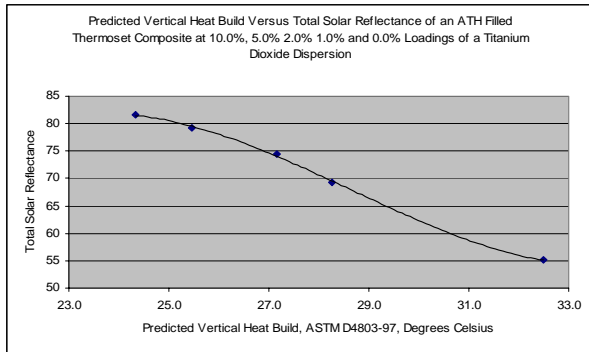


Figure 9: Carbon black and titanium dioxide pigmented composite heat build versus %TSR at 0.0%, 0.25%, 1.0%, 2.0% and 5.0% carbon black dispersion loading based on resin and filler (The white dispersion loading was held constant at 5.0% based on resin and filler).

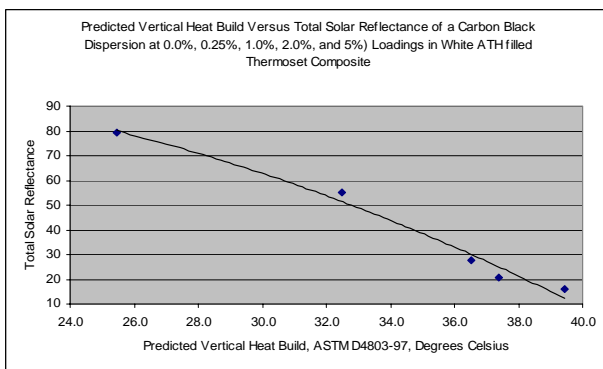


Figure 10: Infrared reflecting black and titanium dioxide pigmented composite heat build versus %TSR at 0.0%, 0.50%, 1.0%, 2.0%, and 5.0% infrared reflecting black dispersion loading based on resin and filler (The white dispersion loading was held constant at 5.0% based on resin and filler).

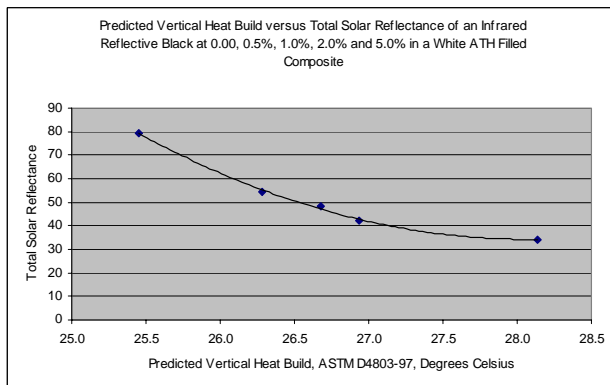


Figure 11: A plot of the relationship of L\* and predicted vertical heat build of a white ATH filled composite pigmented with carbon black, and a white ATH filled composite pigmented with an infrared reflecting black.

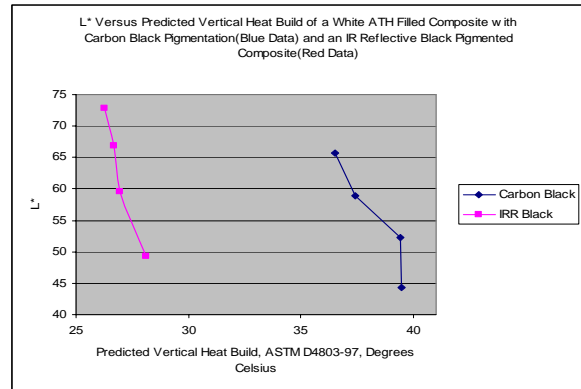


Figure 12: Total solar reflectance versus predicted heat build of an infrared reflective red composite at 0.0%, 0.50%, 1.0%, 2.0%, and 5.0% loadings with a white dispersion at 5%.

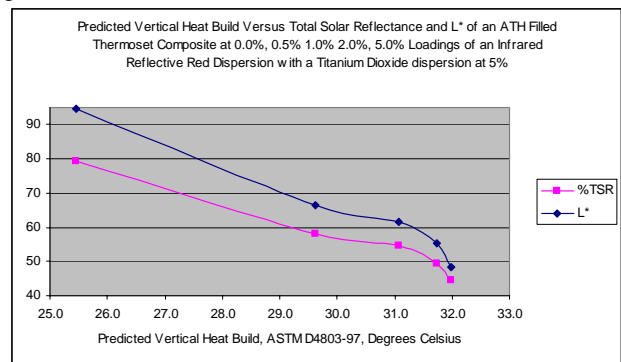
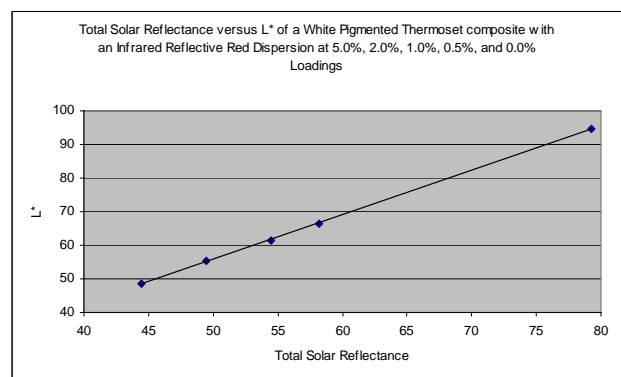


Figure 13: Total solar reflectance versus heat build of an infrared reflective red composite at 5.0%, 2.0%, 1.0%, 0.5%, and 0.0% loadings with a white dispersion at 5.0%.



**Table 1: Typical Emissivities of Common Objects (13);**

Polished Aluminum	0.039-0.057
Oxidized Aluminum	0.20-0.31
Polished Stainless Steel	0.11
Sand blasted Stainless	0.38
White Paint (Titanium Dioxide Based)	0.85 – 0.92
Leafing Aluminum Paint	0.23 – 0.29
Water	0.95
Aluminum Foil	0.03

**Table 2: L\*, %TSR, and Predicted Vertical Heat Build Data of a Traditional Gray, and Infrared Reflective Gray Coating\***

Sample	L*	%TSR	Vertical Heat Build (°C)
Trad. Gray	52.89	17.5	38.8
IRR Gray	52.86	47.1	26.8

\* Heat build test performed on coating over hardwood panel.

**Table 3: %TSR and Predicted Vertical Heat Build Data of Three Green Blends in a Coating System**

Sample	%TSR	Vertical Heat Build (°C)
Trad. Green(Green 1)	7.6	38.6
IRR Green (Green 2)	20.2	32.3
IRR Green (Green 3)	36.8	29.3

8% in clear waterbased acrylic coating over white thermoplastic substrate.

**Table 4: %TSR and Predicted Vertical Heat Build Data of a Traditional Black and an IR Reflective Black Composite**

Sample	%TSR	Vertical Heat Build (°C)
Traditional Black (2.5%)	5.7	39.6
IR Reflective Black (10.0%)	23.5	31.2

**Table 5: L\*, Solar Reflectance, and Predicted Vertical Heat build of various Gray Infrared Reflective Composites (Dispersion loadings based on resin and filler)**

	L*	%TSR	Vertical Heat Build (°C)
Traditional Gray (0.5%)	58.99	20.9	37.4
IR Reflective Gray (1.0%)	59.59	42.2	27.0
IR reflective Synergistic Gray (1.0%)	59.17	56.3	26.1