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:

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

where R = percent reflectance
I = Solar Irradiance
$d\lambda$ = the wavelength interval of integration

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 upwards 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).

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_b 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-

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

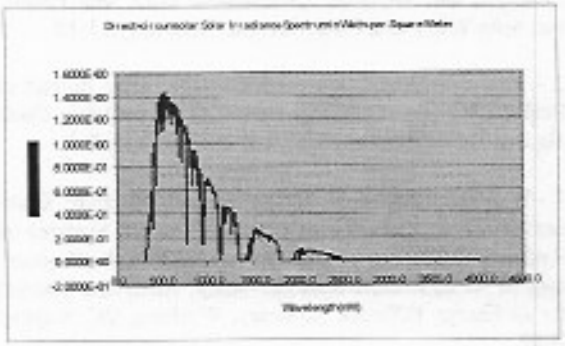


Figure 2: Laser light (632.8nm) scattering from a dilute 2% milk solution.



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

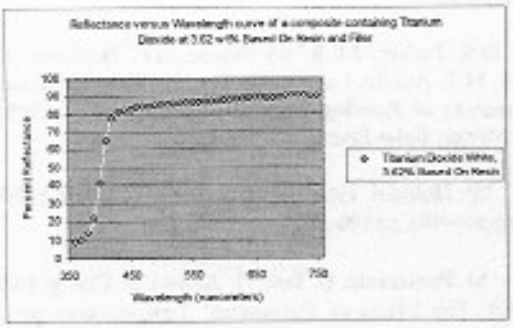


Figure 4: A reflectance curve of a phthalo blue and white pigmented thermoset composite.

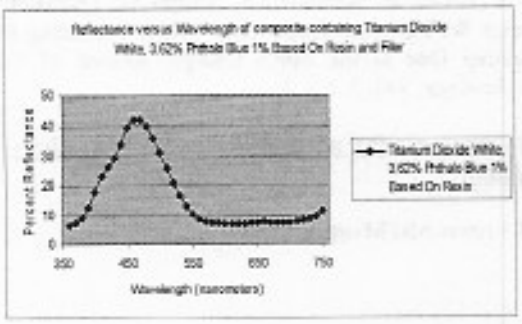


Figure 5: Plots of the spectral radiant excitance versus wavelength of a black body radiator at varying temperatures, calculated using Eqn. 3 (Wyszecki, Stiles, 1).

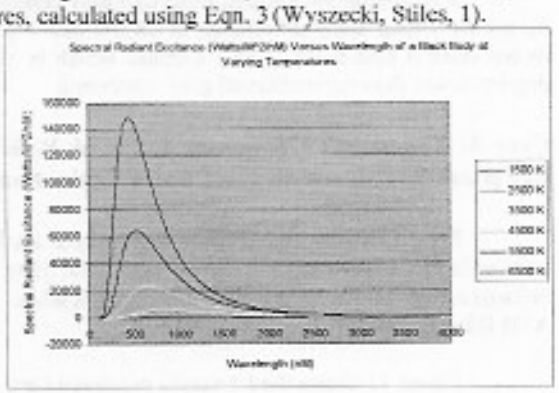


Figure 6: Black body radiated energy versus temperature, calculated using Eqn. 5 (Holman, 10).

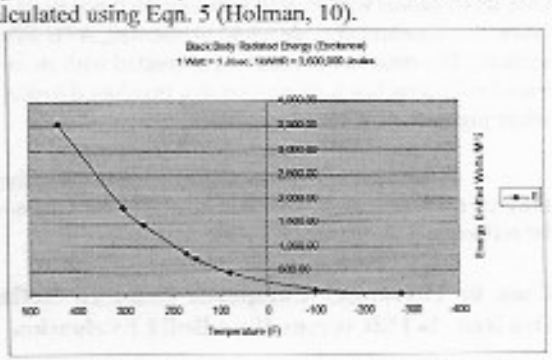


Figure 7: Radiated energy versus emissivity of a series of gray bodies with differing emissivity at 150F.

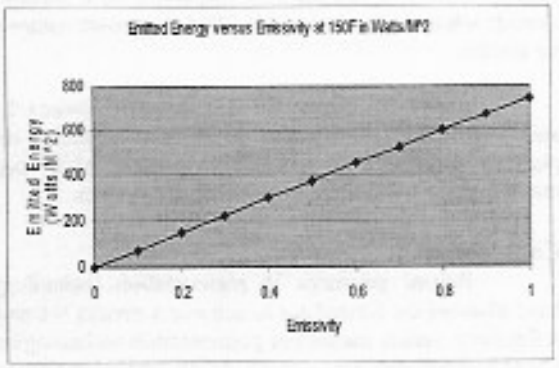


Table 1: Typical Emissivities of Common Objects (13);

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