TFAWS 2015
Thermal Coatings Seminar Series Training
Part 1: Properties of Thermal Coatings

NASA GSFC Contamination and Coatings Branch – Code 546
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Agenda

• The Relationship of Coating Properties That We Can “Easily” Measure vs. the Properties We Need...$a_S$ & $\varepsilon_H$

• How Solar Absorptance is Determined
  • Description of Solar Reflectance measurement techniques
  • Typical data

• How Thermal Hemispherical Emittance is Determined
  • Conversion of normal emittance to hemispherical emittance
  • Emittance vs. temperature
  • Description of measurement techniques
  • Typical data

• Factors that Influence Thermal Radiative Properties

• BRDF – Specular and Diffuse

• GSFC Instruments Overview

• Types of Coatings Used at GSFC
Thermal Radiative Properties of Coatings

- Reflectance
- Transmittance
- Absorptance
- Emittance
Thermal Radiative Properties of Coatings

*(Information Obtained From Thermal Radiative Properties Coatings, Thermophysical Properties of Matter, Volume 9)*

- Radiant energy is reflected, transmitted and/or absorbed by a surface or material

\[ r + t + a = 1, \text{ for materials, where } t = 0, \ r + a = 1, \text{ or } a = 1 - r \]

Where: Reflectance = \( r \), Transmittance = \( t \), and Absorptance = \( a \)

- Emittance (\( e \)) is the rate at which a body radiates energy (heat) at a given temperature in relation to the rate a black body radiator radiates energy (heat) at the same temperature

- Kirchhoff’s Law
  - Ideal radiator, when in thermal equilibrium, the body emits radiant energy at the same rate at which it absorbs
    \[ \alpha = e \]

- In the Aerospace Industry, \( a \) and \( e \) are never directly measured – THEY ARE CALCULATED!
At GSFC, the instrumentation used to calculate the solar absorptance measures over the spectral range of 250 to 2800 nanometers (.25 to 2.8 microns). An integrating sphere is used to measure the coating’s reflectance for the solar absorptance calculation.

Solar Absorptance is the total solar energy absorbed by the surface divided by the total solar energy integrated as a function of the wavelength.

$$\alpha_s = 1 - \frac{\int_{250}^{2800} R(\lambda) \cdot S(\lambda) \, d\lambda}{\int_{250}^{2800} S(\lambda) \, d\lambda}$$

Where $R = \text{reflectance}$, $S = \text{solar energy}$, $\alpha_s = \text{solar absorptance}$, and $\lambda = \text{wavelength}$

The reflectance measurement is performed near-normal (angle of incidence $= 15^\circ$). This measurement is typically sufficient for most surfaces up to approximately $45^\circ$.

Whereas, when measuring cylindrical surfaces, spherical surfaces or angle of incidence greater than $45^\circ$, variations in the angle of incidence will influence the solar absorptance value and must be measured.

Typically the Johnson curve is used to represent the total solar energy over the solar spectrum.
Reflectance and the Johnson Curve

Johnson curve (blue) and the Polyrip clear/VDA (red)

Solar Absorptance value = .405
Directional Total Reflectivity

Incident Energy

\[ r_s \]

\[ r_d \]

\[ \phi \]

\[ \theta \]

\[ \beta \]
Two Types of Integrating Spheres

Edwards Type Integrating Sphere

Incidence Angle

Reference Beam

Sample Beam

Transmittance Sample Location

Detector

Sample

Transmittance

Reference

Four Port Comparison Integrating Sphere

Reference Beam

Sample Beam

Transmittance Sample Location

Detector

Reference
LPSR-300 Reflectometer Optical Schematic

115mm Integrating Sphere

Si and PbS Detectors

0.4μm to 2.8 μm High Pass Dichroic Filter

1/6.5 Prism Monochromator for 0.25 μm to 2.80 μm Range

Tungsten Filament Source

Collection Optics

Deuterium Source

Sample Under Test

2 Position Beam Deflector

160 Hz Tuning Fork Chopper

Variable Entrance Slit

Variable Exit Slit

3 Position Filter Wheel

LPSR-300

REFLECTOMETER OPTICAL SCHEMATIC

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Reflectance Curves of Various Thermal Coatings

Silver Composite Coating (CCAg)/Al  a = .07  e(n) = .67  09 Jul 2003
Z93P White Paint  a = .17  e(n) = .93  18 Sep 2002
2-mil Kapton/VDA  a = .42  e(n) = .83  09 Jul 2003
Germanium/Black Kapton  a = .49  e(n) = .85  11 Mar 2000
Aeroglaze Z306 Black Paint  a = .93  e(n) = .91  13 Mar 2001
Emittance Property Calculation

- **Normal Emittance**
  - At GSFC, the instrumentation used to calculate the normal reflectance measures over the spectral range of 5 to 100 microns at room temperature.
  - The normal emittance is calculated by measuring the reflectance of a material’s surface in the infrared region of the spectrum and subtracting the measured reflectance from one (for opaque coatings only).

\[
\varepsilon_N = 1 - \frac{\int_0^\infty R(\lambda)B(\lambda)d\lambda}{\int_0^\infty B(\lambda)d\lambda}
\]

- **Hemispherical Emittance**
  - For thermal modeling and analysis, the emittance must be in terms of a hemispherical (total body) emittance value. Converting normal emittance to hemispherical emittance can be accomplished by using a conversion table and chart by E. Schmidt, E. Eckert, and M. Jakob.
  - Hemispherical emittance can also be determined by calorimetric emittance measurement.
  - With the addition of an ellipsoidal attachment, GSFC also has the capability of calculating hemispherical emittance as a function of temperature by radiometric reflectance measurement.
Directional emissivity curve for a conductor with an index of refraction of $n = 5.7 + i9.7$
Hemispherical Emissivity Coordinate System

\[ \varepsilon_H = \frac{1}{\pi} \int_0^{2\pi} \varepsilon(\beta, \theta) \cos \beta \, d\omega \]
Ratio of Hemispherical to Normal Emissivity for Conductors

![Graph showing the ratio of hemispherical to normal emissivity for conductors. The x-axis represents normal emissivity ($\varepsilon_n$), and the y-axis represents the ratio $\varepsilon_h/\varepsilon_n$. The graph shows a decreasing trend as normal emissivity increases.]
Directional emissivity curve for a dielectric with an index of refraction of $n=1.5$
Ratio of Hemispherical to Normal Emissivity for Insulators

Ratio of Hemispherical to Normal Emittance for an Insulator

Ratio of Hemispherical to Normal Emittance ($\varepsilon_h/\varepsilon_n$) vs. Normal Emissivity ($\varepsilon_n$)
Illumination: Hemispherical
Detector: Directional ~7-10 deg
Detector type: CsI vacuum thermocouple
Detector Range: 5?–40μm?
Accuracy: ±0.02 sample must be gray
Measurement: Hemispherical-Directional Reflectance
Illumination: Hemispherical
Detector: 10° - 80°
Detector type: FTIR: Si, KBr, Pe
Detector Range: 2-100μm
Accuracy: ± ?
Measurement: Hemispherical-Directional Spectral
Temp200A Optical Diagram

Illumination: 15°
Detector: Hemispherical
Detector type: Pyroelectric
Detector Range: 3-35μm
Accuracy: ±0.01 for gray samples
           ±0.03 for non-gray samples
Measurement: Directional-Hemispherical Reflectance
Emittance by the Calorimetric Technique

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Dielectrics over Metals


** Oxide Thickness is represented as $\lambda/4$ at 550 nm.
Fig. 7. Typical spectral characteristics of selected coatings: A, evaporated aluminum, B, C, and D, evaporated aluminum over-
Fig. 1. The Planck distribution law, spectral radiance of blackbody radiation as a function of temperature and wavelength.
Emittance of a Hypothetical Coating and Two Black Body Temperature Curves

![Graph showing emittance of coating and two black body temperature curves.](image)

- **Red line**: Emittance of Coating
- **Blue dashed line**: Black Body 290° K
- **Blue dash-dotted line**: Black Body 90° K

**Y-axis**: Hemispherical Emittance

**X-axis**: Wavelength (microns)

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Calorimetric Results for A276

Aeroglaze A276 (3.0 mils)

Hemispherical Emittance vs. Temperature (°K)

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Infrared Reflectance of A276

Reflectance

Wavelength (microns)
Factors that Influence Thermal Radiative Properties

- Solar Absorptance and/or Emittance Values Influencing Factors:
  - Surface Finishes
    - Highly Polished (mirror-like/optical surface)
    - Polished
    - Buffed
    - Matt
    - Machined
  - Substrate Texture
    - Rough versus Smooth
    - Woven
    - Bead Blasted (sand, glass, etc...)
  - Immersion Rate for Chemical Coatings Processes (i.e., Anodized, Irridited)
  - Coating Thickness
  - Coating Adherence
  - Transmissivity
  - Electrical Conductivity
  - Contaminants
  - Sample/Hardware Size and Configuration
Solar Absorptance of a White Silicone Paint as a Function of Thickness
NASA-GSFC Thermal Control Coatings
Measurement Instrumentation

- AZTek Laboratory Portable Spectroreflectometer (LPSR-300 and LPSR-200)
- Cary 500 IR/Vis/UV Spectroreflectometer
- Geir-Dunkle DB-100 Reflectometer
- SOC-100 Infrared Spectroreflectometer (2μ - 100μ)
- Bi-Directional Reflectance Distribution Function (BRDF)
- Light Analyzer Microscopic Imager
- Calorimetric Emittance Chamber
Bi-directional Reflectance Distribution Function

- BRDF is a precise measurement of the intensity and direction of the reflection of light from a surface

\[
\text{Power reflected per unit area per solid angle} = \frac{\text{Power arriving per unit area} \times \cos(\theta_s)}{X}
\]

- BRDF is a point property of a surface. BRDF is a function of the direction of the incident light and the direction of the scattered light

- Our facility has the capability to measure light scattering at 632.8 nm, 442 nm, and 830 nm
Bi-directional Reflectance Distribution Function

• Perfectly diffuse or lambertian surface has constant BRDF;

\[
\text{Power reflected per unit area per solid angle} = \text{BRDF} \times \text{power arriving per unit area} \times \cos(\theta_s)
\]

• BRDF measurements/data are used to:
  • Calculate the amount of light or energy scattered by specific surfaces in critical applications
    • Example -- sunshield
  • Evaluate or monitor the condition of a surface with respect to contamination or roughness
    • Example -- optics (mirrors)
  • Determines specularity of surfaces for special cases
  • Calculate solar pressure
Types of Thermal Control Coatings

- **Paints** (Z93P, Z306, AZ93, Z93-C55, AZWLA2, Z276, Z307, etc...)
- **Metals** (Al, Ag, Au, Ni, Stainless Steel, Cu, Mg, Ti, etc...)
- **Sheet Films** (Kapton®, Ge/Black Kapton®, Black Kapton®, Teflon (FEP), etc...)
- **Tapes** (Ag/FEP, Al/FEP, Al/Kapton®, Al Foil, Kapton®, Black Kapton® etc...)
- **Vacuum Deposited Coatings** [Evaporated/Sputtered]
  - **Metals** (Al, Ag, Au, Ti, Ge, Cr, Ni, etc...)
  - **Dielectrics** (Al₂O₃, SiOₓ, CCAG, CCAl, Dark Mirror, etc...)
- **Conductive Coatings** (ITO, ATO, Ge, Z93-C55, Z307, etc...)
- **Anodized Aluminum** (Black, Hard, Clear, Plain, etc...)
- **Chemical Conversion** (Irridite, Alodine, etc...)
- **Optical Surface Reflectors** [OSR]
- **Solar Cells**
References
