A Guide to Integrating Sphere Radiometry and Photometry

labsphere®
Leadership in Reflectance Technology

TECH GUIDE

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APPENDICES

1.0 Introduction to Sphere Measurements

This technical guide presents design considerations for integrating sphere radiometers and photometers. As a background, the basic terminology of Radiometry and Photometry are described. The science and theory of the integrating sphere are presented, followed by a discussion of the geometric considerations related to the design of an integrating sphere photometer or radiometer. The guide concludes with specific design applications, emphasizing lamp measurement photometry.

Radiometers and Photometers measure optical energy from many sources including the sun, lasers, electrical discharge sources, fluorescent materials, and any material which is heated to a high enough temperature. A radiometer measures the *power* of the source. A photometer measures the power of the source as perceived by the human eye.
All radiometers and photometers contain similar elements. These are an optical system, a detector, and a signal processing unit. The output of the source can be measured from the ultraviolet to the mid-infrared regions of the electromagnetic spectrum. Proprietary coatings developed by Labsphere allow the use of integrating sphere radiometers in outerspace, vacuum chambers, outdoors and in water (including sea water) for extended periods of time.

Two factors must be considered when using an integrating sphere to measure radiation: 1) getting the light into the sphere, and 2) measuring the light.

For precise measurement, each source requires a different integrating spheres geometry. Unidirectional sources, including lasers, can be measured with an integrating sphere configuration as shown in Figure 1.1. Omnidirectional sources, such as lamps, are measured with a configuration as shown in Figure 1.2. Sources that are somewhat unidirectional, such as diode lasers and fiber optic illuminators are measured with an integrating sphere configuration as shown in Figure 1.3. This configuration also works well for unidirectional sources and therefore is a preferred geometry.

The detector used in a measurement device can report measurements in numerous ways,these include:

— power
— approximate response of the human eye
— power over a wavelength band
— color

Photometers incorporate detector assemblies filtered to approximate the response of the human eye, as exhibited by the CIE luminous efficiency function. A radiometer is a device used to measure radiant power in the ultraviolet, visible, and infrared regions of the electromagnetic spectrum. Spectroradiometers measure spectral power distribution and colorimeters measure the color of the source.

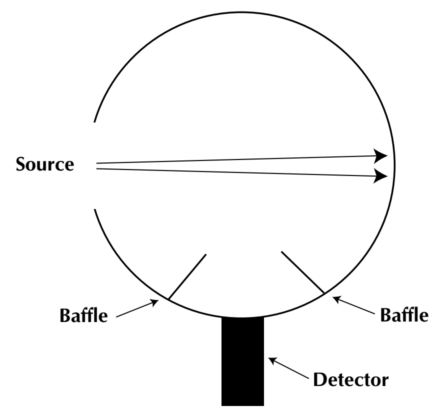


FIGURE 1.1

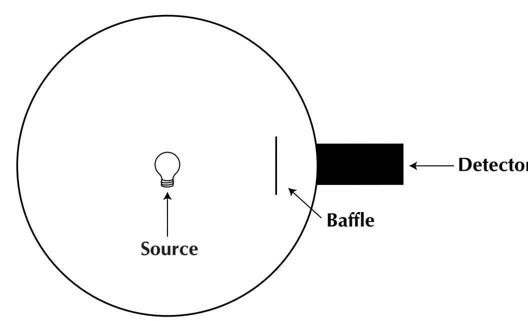


FIGURE 1.2

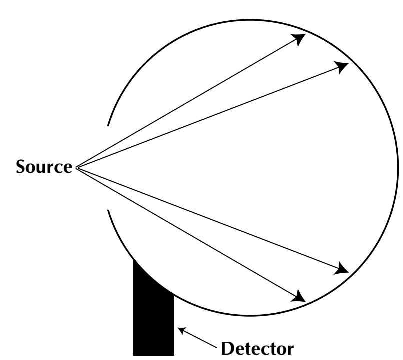


FIGURE 1.3

2.0 Terms and Units

Definitions

Photometry:	measurement of light to which the human eye is sensitive
Radiometry:	measurement UV, visible, and IR light
Colorimetry:	measurement of the color of light
Watt:	unit of power = 1 Joule/sec
Lumen:	unit of photometric power
Candela:	unit of luminous intensity

TABLE 1 — SPECTRAL AND GEOMETRIC CONSIDERATIONS

Choose the desired spectral response and the geometric attribute of the source to determine the units of measurement appropriate for the source.

Geometric \ Spectral	Radiometric	Spectroradiometric	Photopic
Flux	Power Watts	Power/wavelength interval Watts/nm	Luminous Flux Lumens
Flux/area	Irradiance Watts/m^2	Spectral Irradiance Watts/m^2 nm	Illuminance ft candle = lumens/ft^2 Lumens/m^2 = Lux
Flux/solid angle	(Radiant) Intensity Watts/sr	Spectral Intensity Watts/sr nm	(Luminous) Intensity Lumens/sr = candela
Flux/area solid angle	Radiance Watts/m^2 sr	Spectral Radiance Watts/m^2 sr nm	Luminance ft lambert =(1/pi)* cd/ft^2 Candela/m^2 = nit Lumens/m^2 sr = nit

3.0 The Science of the Integrating Sphere

3.1 Integrating Sphere Theory

The integrating sphere is a simple, yet often misunderstood device for measuring optical radiation. The function of an integrating sphere is to spatially integrate radiant flux. Before one can optimize a sphere design for a particular application, it is important to understand how an integrating sphere works. How light passes through the sphere begins with a discussion of diffuse reflecting surfaces. Then the radiance of the inner surface of an integrating sphere is derived and two related sphere parameters are discussed, the sphere multiplier and the average reflectance. Finally, the time constant of an integrating sphere as it relates to applications involving fast pulsed or short lived radiant energy is discussed.

3.2 Radiation Exchange Within a Spherical Enclosure

The theory of the integrating sphere originates in the principles of radiation exchange within an enclosure of diffuse surfaces. Although the general theory can be complex, the sphere is a simple solution to understand.

Consider the radiation exchange between two differential elements of diffuse surfaces.

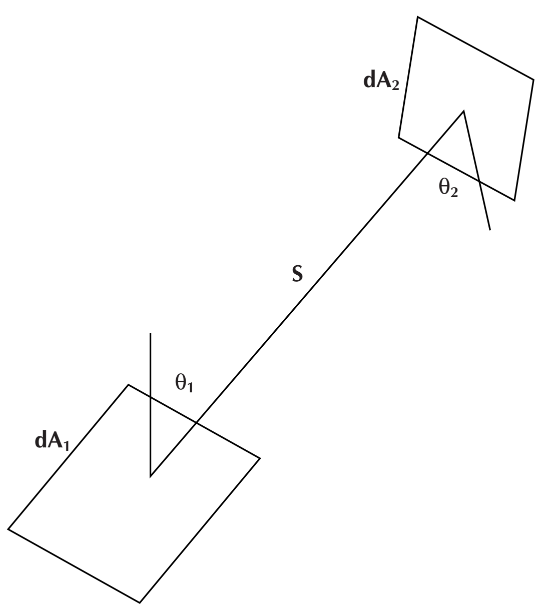


FIGURE 2

The fraction of energy leaving dA_1 that arrives at dA_2 is known as the exchange factor $dF_{d_1\text{-}d_2}$. Given by:

$$dF_{d1-d2} = \frac{\cos\theta_1 \cos\theta_2}{\pi S^2} dA_2 \qquad \textbf{EQ. 1}$$

Where θ_1 and θ_2 are measured from the surface normals.

Consider two differential elements, dA_1 and dA_2 inside a diffuse surface sphere.

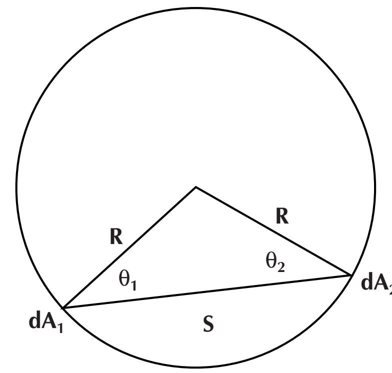


FIGURE 3

Since the distance $S = 2R\cos\theta_1 = 2R\cos\theta_2$:

$$dF_{d1-d2} = \frac{dA_2}{4\pi R^2} \qquad \textbf{EQ. 2}$$

The result is significant since it is independent of viewing angle and the distance between the areas. Therefore, the fraction of flux received by dA_2 is the same for any radiating point on the sphere surface.

If the infinitesimal area dA_1 instead exchanges radiation with a finite area A_2, then Eq. 2 becomes:

$$dF_{d1-d2} = \frac{1}{4\pi R^2}\int_{A_2} dA_2 = \frac{A_2}{4\pi R^2} \qquad \textbf{EQ. 3}$$

Since this result is also independent of dA_1 :

$$F_{1-2} = \frac{A_2}{4\pi R^2} = \frac{A_2}{A_s} \qquad \textbf{EQ. 4}$$

Where A_S is the surface area of the entire sphere. Therefore, the fraction of radiant flux received by A_2 is the fractional surface area it consumes within the sphere.

3.3 The Integrating Sphere Radiance Equation

Light incident on a diffuse surface creates a virtual light source by reflection. The light emanating from the surface is best described by its *radiance*, the flux density per unit solid angle. Radiance is an important engineering quantity since it is used to predict the amount of flux that can be collected by an optical system that views the illuminated surface.

Deriving the radiance of an internally illuminated integrating sphere begins with an expression of the radiance, L, of a diffuse surface for an input flux, Φ_i .

$$L = \frac{\Phi_i \rho}{\pi A} \quad (\mathrm{W/m^2/sr}) \qquad \text{EQ. 5}$$

Where ρ is the reflectance, A the illuminated area and π the total projected solid angle from the surface.

For an integrating sphere, the radiance equation must consider both multiple surface reflections and losses through the port openings needed to admit the input flux, Φ_i, as well as view the resulting radiance. Consider a sphere with input port area A_i and exit port A_e.

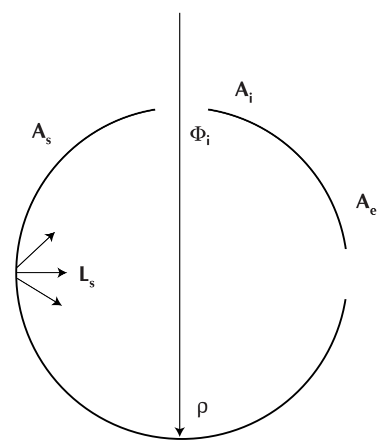


FIGURE 4

The input flux is perfectly diffused by the initial reflection. The amount of flux incident on the entire sphere surface is:

$$= \Phi_i \rho \left(\frac{A_s - A_i - A_e}{A_s} \right) \qquad \text{EQ. 6}$$

Where the quantity in parenthesis denotes the fraction of flux received by the sphere surface that is not consumed by the port openings. It is more convenient to write this term as *(1-f)* where f is the port fraction and $f = (A_i + A_e)/A_s$. When more than two ports exist, f is calculated from the sum of all port areas.

By similar reasoning, the amount of flux incident on the sphere surface after the second reflection is:

$$= \Phi_i \rho^2 (1 - f)^2 \qquad \text{EQ. 7}$$

The third reflection produces an amount of flux equal to

$$= \Phi_i \rho^3 (1 - f)^3 \qquad \text{EQ. 8}$$

It follows that after n reflections, the total flux incident over the entire integrating sphere surface is:

$$\Phi_i \rho (1 - f)\{1 + \rho(1 - f) + \ldots + \rho^{n-1}(1 - f)^{n-1}\} \qquad \text{EQ. 9}$$

Expanding to an infinite power series, and given that

$\rho(1-f) < 1$, this reduces to a simpler form:

$$= \frac{\Phi_i \rho (1 - f)}{1 - \rho(1 - f)} \qquad \text{EQ. 10}$$

Equation 10 indicates that the total flux incident on the sphere surface is higher than the input flux due to multiple reflections inside the cavity. It follows that the sphere surface radiance is given by:

$$L_s = \frac{\Phi_i}{\pi A_s (1 - f)} * \frac{\rho(1 - f)}{1 - \rho(1 - f)} \qquad \text{EQ. 11}$$

$$= \frac{\Phi_i}{\pi A_s} * \frac{\rho}{1 - \rho(1 - f)} \qquad \text{EQ. 12}$$

This equation is used to predict integrating sphere radiance for a given input flux as a function of sphere diameter, reflectance, and port fraction. Note that the radiance decreases as sphere diameter increases.

3.4 The Sphere Multiplier

Equation 12 is purposely divided into two parts. The first part is approximately equal to Eq. 5, the radiance of a diffuse surface. The second part of the equation is a unitless quantity which can be referred to as the sphere multiplier.

$$M = \frac{\rho}{1-\rho(1-f)} \qquad \text{EQ. 13}$$

It accounts for the increase in radiance due to multiple reflections. The following chart illustrates the magnitude of the sphere multiplier, M, and its strong dependence on both the port fraction, f, and the sphere surface reflectance ρ.

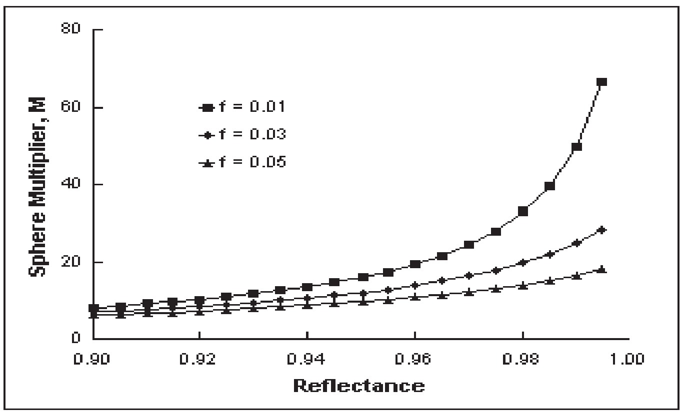


FIGURE 5

A simplified intuitive approach to predicting flux density inside the integrating sphere might be to simply divide the input flux by the total surface area of the sphere. However, the effect of the sphere multiplier is that the radiance of an integrating sphere is at least an order of magnitude greater than this simple intuitive approach. A handy rule of thumb is that for most real integrating spheres ($.94<\rho<.99$; $.02<f<.05$), the sphere multiplier is in the range of 10 to 30.

3.5 The Average Reflectance

The sphere multiplier in Eq.13 is specific to the case where the incident flux impinges on the sphere wall, the wall reflectance is uniform and the reflectance of all port areas is zero. The general expression is:

$$M = \frac{\rho_0}{1-\rho_w\left(1-\sum_{i=0}^{n} f_i\right)-\sum_{i=0}^{n}\rho_i f_i} \qquad \text{EQ. 14}$$

where; ρ_0 = the initial reflectance for incident flux

ρ_w = the reflectance of the sphere wall

ρ_i = the reflectance of port opening i

f_i = the fractional port area of port opening i

The quantity $\rho_w\left(1-\sum_{i=0}^{n} f_i\right)+\sum_{i=0}^{n}\rho_i f_i$ can also be described as the average reflectance $\overline{\rho}$ for the entire integrating sphere. Therefore, the sphere multiplier can be rewritten in terms of both the initial and average reflectance:

$$M = \frac{\rho_0}{1-\overline{\rho}} \qquad \text{EQ. 15}$$

3.6 Spatial Integration

An exact analysis of the distribution of radiance inside an actual integrating sphere depends on the distribution of incident flux, the geometrical details of the actual sphere design, and the reflectance distribution function for the sphere coating as well as all surfaces of every device mounted at a port opening or inside the integrating sphere. Design guidelines for optimum spatial performance are based on maximizing both the coating reflectance and the sphere diameter with respect to the required port openings and system devices.

The effect of the reflectance and port fraction on the spatial integration can be illustrated by considering the number of reflections required to achieve the total flux incident on the sphere surface given by Eq. 10. The total flux on the sphere wall after only n reflections can be written as:

$$= \Phi_i \sum_{n=1}^{n} \rho^n (1-f)^n \qquad \text{EQ. 16}$$

The radiance produced after n reflections can be compared to the steady state condition.

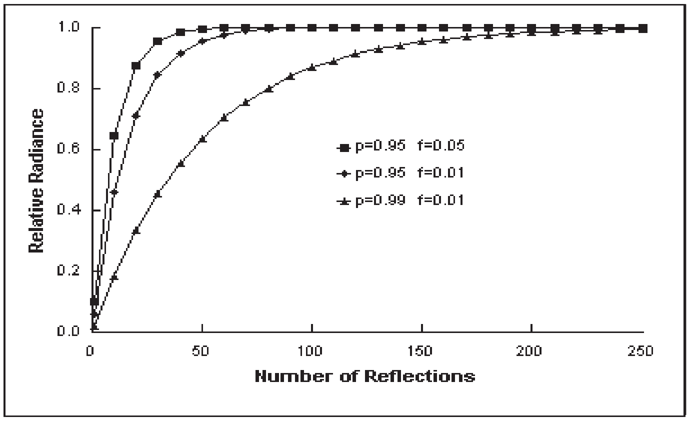


FIGURE 6

Since the integrating sphere is most often used in the steady state condition, a greater number of reflections produces steady state radiance as ρ increases and f decreases. Therefore, integrating sphere designs should attempt to optimize both parameters for the best spatial integration of radiant flux.

3.7 Temporal Response of an Integrating Sphere

Most integrating spheres are used as steady state devices. The previous analysis of their performance and application assumes that the light levels within the sphere have been constant for enough time so that all transient response has disappeared. If rapidly varying light signals, such as short pulses or those modulated at high (radio) frequencies, are introduced into an integrating sphere, the output signal may be noticeably distorted by the "pulse stretching" caused by the multiple diffuse reflections. The shape of the output signal is determined by convolving the input signal with the impulse response of the integrating sphere.

This impulse response is of the form:

$$e^{-t}/_{\tau} \qquad \textbf{EQ. 17}$$

where the time constant, τ, is calculated as:

$$\tau = -\frac{2}{3} \cdot \frac{D_s}{c} \cdot \frac{1}{\ln \overline{\rho}} \qquad \textbf{EQ. 18}$$

and $\overline{\rho}$ = the average wall reflectance
c = the velocity of light
D_s = the diameter of the integrating sphere

Time constants of typical integrating spheres range from a few nanoseconds to a few tens of nanoseconds.

4.0 Integrating Sphere Design

The design of an integrating sphere for any application involves a few basic parameters. These include selecting the optimum sphere diameter based upon the number and size of port openings and peripheral devices. Selecting the proper sphere coating considers spectral range, as well as performance requirements. The use of baffles with respect to incident radiation and detector field-of-view is discussed. Radiometric equations are presented for determining the coupling efficiency of an integrating sphere to a detection system.

4.1 Integrating Sphere Diameter

Figure 5 shows that decreasing the port fraction has a dramatic effect on increasing the sphere multiplier. For port fractions larger than 0.05, one begins to lose the advantage offered by the high reflectance coatings available for integrating spheres. The first rule of thumb for integrating spheres is that no more than 5% of the sphere surface area be consumed by port openings.

Integrating spheres are designed by initially considering the diameter required for the port openings. Port diameter is driven by both the size of devices, as well as the geometrical constraints required by a sphere system.

Consider the case of a two port integrating sphere with both ports of unit diameter. The relative radiance produced as a function of sphere diameter, D_S , for an equivalent input flux is proportional to:

$$L_s \propto \frac{M}{D_s^2} \qquad \textbf{EQ. 19}$$

The equation can be plotted as a function of reflectance for different sphere diameters. The resulting port fraction for each is shown in Figure 7.

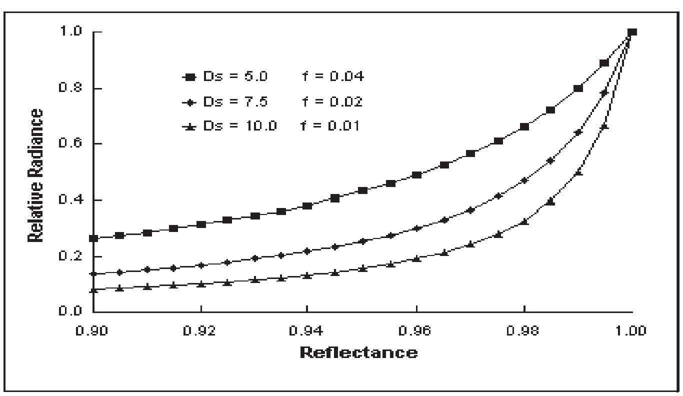


FIGURE 7

The smallest sphere produces the highest radiance in general. However, since the integrating sphere is usually employed for its ability to spatially integrate input flux, a larger sphere diameter and smaller port fraction will improve the spatial performance. Notice in Figure 7 that all three sphere designs converge on the same unit flux density as the reflectance approaches 1.0. Therefore, high reflectance integrating sphere materials such as Spectralon can optimize spatial performance at only a slight tradeoff in radiance efficiency.

4.2 Integrating Sphere Coatings

When choosing a coating for an integrating sphere two factors must be taken into account: reflectance and durability. For example, if there seems to be plenty of light, and the sphere will be used in an environment that may cause the sphere to collect dirt or dust, a more durable, less reflective coating can be chosen.

Items located inside the sphere, including baffles, lamps, and lamp sockets absorb some of the energy of the radiant source and decrease the throughput of the sphere. This decrease in throughput is best avoided by coating all possible surfaces with a highly reflective coating.

The sphere multiplier as illustrated by Figure 5 is extremely sensitive to the sphere surface reflectance. The selection of sphere coating or material can make a large difference in the radiance produced for a given sphere design. Consider the diffuse reflectors offered by Labsphere known as Spectraflect and Spectralon. Both are useful for UV-VIS-NIR applications in the 250 nm to 2500 nm spectral region. The typical spectral reflectance of each is shown in Figure 8.

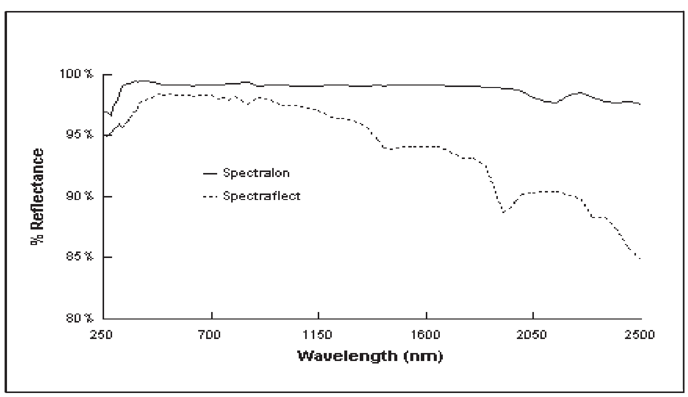


FIGURE 8

Both coatings are highly reflective, over 95% from 350 nm to 1350 nm, therefore, intuitively one might expect no significant increase in radiance for the same integrating sphere. However, the relative increase in radiance is greater than the relative increase in reflectance by a factor equal to the new sphere multiplier, M_{new}.

$$\frac{\Delta L_s}{L_s} \approx \frac{\Delta \rho}{\rho_0} * M_{new} \qquad \textbf{EQ. 20}$$

Although Spectralon offers a 2% to 15% increase in reflectance over Spectraflect within the wavelength range, an identical integrating sphere design would offer 40% to 240% increased radiance. The largest increase occurs in the NIR spectral region above 1400 nm.

4.3 Available Sphere Coatings

Modern coatings include barium sulfate based spray coatings, packed PTFE coatings, and Labsphere's proprietary reflectance materials and coatings: Spectralon®, Spectraflect®, Duraflect™, and Infragold™. Comparative properties of Labsphere coatings are presented in Appendix A. A description of each coating follows.

Spectralon Reflectance Material

Spectralon is a highly lambertian, thermoplastic material that is suitable for applications ranging from the UV-VIS to the NIR-MIR wavelength regions.

Spectralon spheres offer excellent reflectance values over the wavelength range from 250 nm to 2500 nm. This high reflectance in the ultraviolet and near-infrared regions make Spectralon the ideal material for a wide range of integrating sphere applications. Spectralon expands the temperature region for effective use of an integrating sphere and is stable to above 350°C. The material exhibits reflectance greater than 99% over the wavelength range from 400 to 1500 nm and greater than 95% from 250 to 2500 nm. The material is not well suited for applications above 2500 nm. Labsphere has developed three grades of spectralon material — optical, laser, and space quality.

Spectralon space-grade material has undergone extensive stringent materials testing. Upon exposure to UV flux for over 100 hours (tests were performed under vacuum conditions), Spectralon showed minimal damage. In addition to UV radiation, Spectralon was tested for susceptibility to proton damage. Samples were irradiated with 10^{10} protons/cm^2 at consecutive energy levels of 100 keV, 1 MeV and 10 MeV. No visual damage was observed on the samples.

Spectraflect Reflectance Coating

Spectraflect is a specially formulated barium sulfate coating which produces a nearly perfect diffuse reflectance surface. Spectraflect employs an alcohol-water mixture as a vehicle and is generally used in UV-VIS-NIR although most effectively in the 300 nm to 1400 nm wavelength range. The reflectance properties of Spectraflect depend on the thickness of the coating. Although the number of coats needed to attain maximum reflectance varies with the type of component, Labsphere typically applies more than twenty coats to each sphere. At a thickness above 0.4 mm, Spectraflect is opaque with reflectance of greater than 98% over the 400 nm to 1100 nm wavelength range. Spectraflect, sprayed onto degreased, sandblasted surfaces, exhibits thermal stability to 100°C. The coating is inexpensive, safe, and highly lambertian. Spectraflect is not usable in very humid environments and is not stable in changing environments. In these cases, Labsphere recommends Duraflect coating.

Duraflect Reflectance Coating

Duraflect, a durable white reflectance coating, is best used in applications from the VIS to NIR, 350 nm to 1200 nm. The coating is opaque with reflectance values of 94 to 96% over its effective wavelength range.

Labsphere recommends the use of Duraflect in place of Spectraflect for applications involving outdoor exposure, humid environments and underwater applications. Although Duraflect exhibits more environmentally stable properties than Spectraflect it does have some limitations and does not preclude the use of Spectraflect. Duraflect is unsuitable for use in the UV range and may be incompatible with certain plastic substrates.

Infragold Reflectance Coating

Infragold is an electrochemically plated, diffuse, gold metallic reflectance coating that exhibits excellent reflectance properties over the wavelength range from 0.7 µm to 20 µm. Reflectance data is traceable to the National Institute of Standards and Technology (NIST). The reflectivity of Infragold is 92 to 96% over the wavelength region from 1µm to greater than 20 µm.

4.4 Flux on the Detector

The sphere wall determines the total flux incident on a photodetector mounted at or near a port of the integrating sphere.

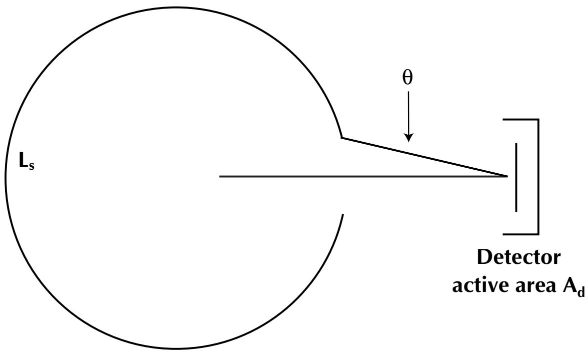


FIGURE 9

By definition, the total flux incident on the detector active area, A_d *(m^2)* is:

$$\Phi_d = L_s A_d \Omega \qquad \text{EQ. 21}$$

where: Ω = projected solid angle *(sr)* of the detectors field of view. A good approximation for Ω in almost all cases is:

$$\Omega = \pi \sin^2\theta \quad (sr) \qquad \text{EQ. 22}$$

In the case of imaging optics used with the detector, the angle θ is subtended from the exit pupil of the system. The detector is the field stop of the system.

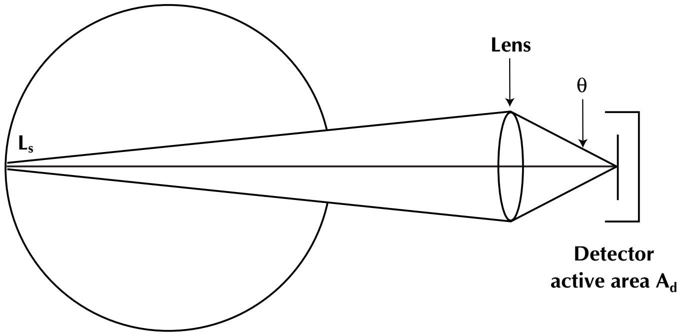


FIGURE 10

The f-number (*f/#*) of an optical system is also used to express its light gathering power. Therefore:

$$\Omega = \frac{\pi}{(2f/\#)^2} \quad (sr) \qquad \text{EQ. 23}$$

The efficiency of the optical system, which is generally a function of the transmittance and reflectance of individual components, must also be considered. Therefore the detector incident flux is:

$$\Phi_d = L_s A_d \frac{\pi}{(2f/\#)^2} \varepsilon_0 \qquad \text{EQ. 24}$$

where; ε_0 = optical system efficiency (unitless).

4.5 Fiberoptic Coupling

In many cases, light from the sphere is coupled to the detection system by way of a fiber optic device. A similar equation is used to calculate the incident flux gathered by a fiberoptic cable coupled to an integrating sphere.

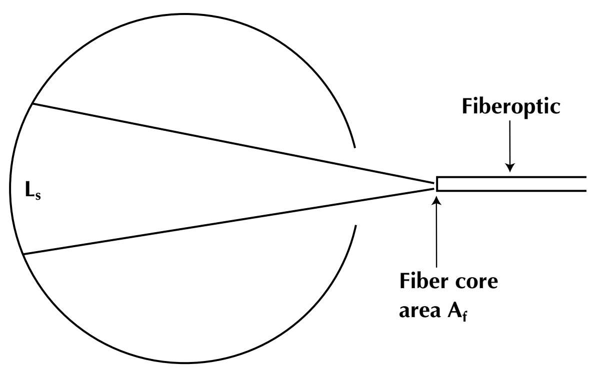


FIGURE 11

The numerical aperture (NA) of an optical fiber is used to describe its light coupling ability. The projected solid angle is:

$$\Omega = \pi (NA)^2 \quad (sr) \qquad \text{EQ. 25}$$

Reflectance losses at the air/fiber interface must be considered in determining the total flux accepted by the fiber. If *R* is the reflectance at the fiber face, then:

$$\Phi_f = L_s A_f \pi (NA)^2 (1 - R) \quad \text{(WATTS)} \qquad \text{EQ. 26}$$

For a single strand fiber, A_f is the area of the fiber end calculated for the core diameter. If a fiber bundle is used, this quantity becomes the individual core diameter times the number of fibers in the bundle. The light emanating from the other end of the fiber is a function of its length (cm), the material extinction coefficient (cm^{-1}), and the exit interface reflection.

4.6 Integrating Sphere Baffles

In general, the light entering an integrating sphere should not directly illuminate either the detector element or the area of the sphere wall that the detector views directly. In order to accomplish this baffles are often used in integrating sphere design.

Baffles, however, will cause certain inaccuracies simply because the integrating sphere is no longer a perfect sphere. Light incident on a baffle does not uniformly illuminate the remainder of the sphere. It is advisable to minimize the number of baffles used in a sphere design.

4.7 Geometric Considerations of Sphere Design

There are four primary considerations that must be taken into account in the design of an integrating sphere system: Source geometry, detector geometry, coating, and calibration. In many cases these topics become inter-related, but for this discussion they will be described separately.

4.7.1 Source Geometry

Sources can be separated into three types:

- Omnidirectional- sources that emit light in all directions
- Unidirectional - sources that emit in one direction;
- Partially directional - those that fit somewhere between unidirectional and omnidirectional.

The design challenge is to make spheres for each type of source that allow for accurate and repeatable measurements.

The first consideration related to source geometry is ensuring that the source does not directly illuminate the detector. This may mean that the designer will place a shield or "baffle" between the source and the detector. In other cases, it simply means that the detector needs to be located in a portion of the sphere that is not illuminated by the source.

The following are some typical designs that can be used for these types of sources. Most sphere designs can be based on one of these designs as long as the source geometry is correctly defined and identified.

Omnidirectional Sources

Many light sources, including commercial lamps, provide general illumination. The total luminous flux emitted by these lamps is more significant than the intensity in a single direction. The integrating sphere offers a simple solution to the measurement of total luminous flux (Figure 12).
In this design, the test source is placed inside an integrating sphere in order to capture all the light emitted from it. With a properly calibrated system, this geometry yields very accurate measurement results.

Unidirectional Sources

Some light sources, including lasers, are highly directional. These sources may be directed through an entrance port on the sphere (Figure 13). Although extremely highly directional sources could be measured directly by focusing the laser on the detector, the integrating sphere offers several advantages over the simple detector approach. First, the integrating sphere eliminates the need for precise alignment of the laser beam. Second, the sphere uniformly illuminates the detector eliminating effects of non-uniformity of the detector response. Third, the sphere naturally attenuates the energy from the laser. This attenuation protects the detector from the full strength of the laser and allows the use of faster, more sensitive detectors.

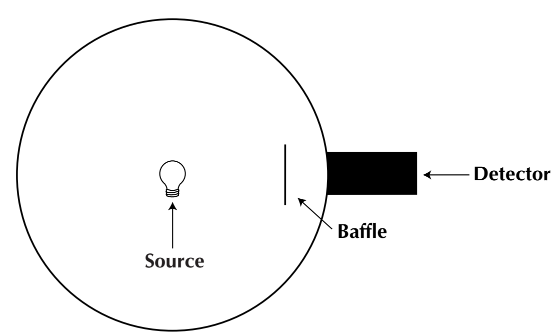


FIGURE 12

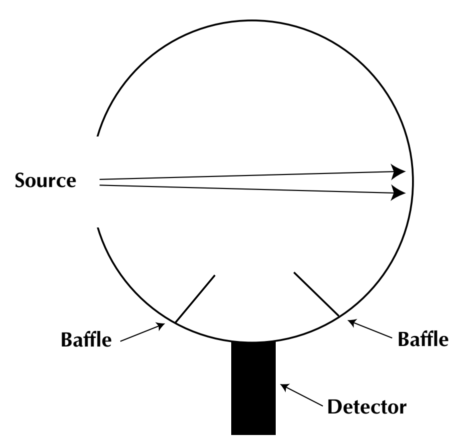


FIGURE 13

Sources that are neither Omnidirectional or Unidirectional

Other light sources, including laser diodes, fiber optic illuminators, fiber optics, and reflector lamps are neither highly directional nor omnidirectional. These light sources can be placed near the entrance port of the sphere so that all of the light is directed into the sphere. The sphere spatially integrates the light before it reaches the detector (Figure 14).

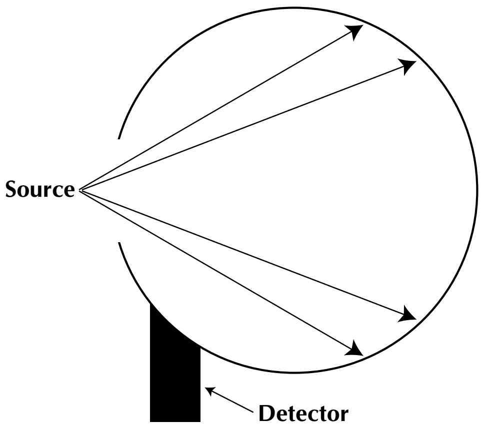


FIGURE 14

4.8 Detectors

It is important to understand the type of measurement to be made: Photometric, Radiometric, Spectroradiometric, or Colorimetric (i.e. power, visible power, spectrum, or color). Each uses a different detector or detector/filter combination as described below.

Photometers

Photometers measure the energy as perceived by the human eye. Matching the results of a physical photometer to the spectral response of the human eye is quite difficult. In 1924, the Commission Internationale de l'Eclairage (CIE) recorded the spectral response of 52 experienced observers. The data resulted in a standard luminosity curve, commonly called the photopic response of the standard observer.

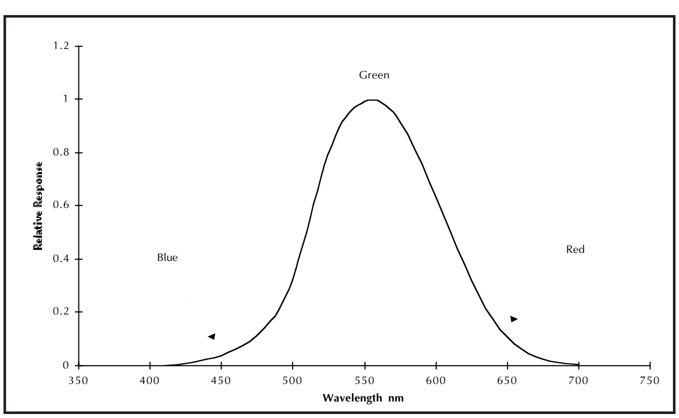


FIGURE 15

Generally, photometers will use a silicon detector that has a filter placed in front of it. The combined response of the detector/filter combination will be approximately that of the human eye, $V_{(\lambda)}$.

Radiometers

A radiometer is an instrument that measures the power of a radiant source. Power is described in units of watts, or joules per second. There are a variety of detectors that can be used depending on the wavelength range to be measured. A silicon detector allows measurements over the UV/VIS/NIR wavelength range (from 0.2 to 1.1 μm). A germanium detector allows measurements over the NIR wavelength range (from 0.8 to 1.8 μm). Other detectors are available for use over longer wavelengths.

One must be careful when specifying and using a radiometer. Due to the fact that detectors do not typically have a flat response (e.g. silicon has a response of about 0.6 A/W at 900nm, but about 0.4 A/W at 600nm) specifying a broad band measurement is very difficult. Typically they will be calibrated for use at a variety of wavelengths. Each wavelength will have an associated calibration factor, which will not give accurate results unless only light near that wavelength is entering the sphere. Alternatively, a narrow band filter can be placed in front of the detector so that only light of a specific wavelength band reaches it (the calibration must be performed with this filter in place). In this case, the result will be accurate regardless of the input, but the system may only be used for one wavelength band.

Spectroradiometer

A spectroradiometer is a device that measures power per wavelength interval as a function of wavelength. It is used to obtain detailed spectral information about the source. In addition, a spectroradiometer can be used to create a highly accurate photometer for sources such as arc and fluorescent lamps. Although a filter photometer is accurate over much of the photopic response curve, some divergence occurs in small sections of the spectrum. Therefore, the potential error associated with lamps with high emissions at those sections could be significant. A better approximation to this curve is obtained with spectroradiometers. Spectroradiometers typically come in two varieties: scanning monochromators and diode array spectrometers.

Colorimeter

A colorimeter measures and quantifies the color of the source. The detector consists of a combination of three or four filtered detectors. These detectors are used to simulate the $\bar{x}$, $\bar{y}$, and $\bar{z}$ CIE functions. The signal received from the detectors is used by a signal processor to calculate the chromaticity coordinates, x and y.

4.9 Detector Field-of-View

Once a detector is selected it must be placed on the sphere in the correct fashion. There are two important considerations for placing the detector. The first is that it is not directly illuminated by the source (as discussed earlier in this guide). The second is that the detector should not directly view a portion of the sphere wall that is directly illuminated by the source. The idea here is that the detector is supposed to be viewing the "integrated" light — the section of the sphere wall that the source illuminates is the one area that does not have radiance as calculated in EQ. 12, Section 3. In most cases this will mean that the field of view (FOV) of the detector will need to be limited by placing an aperture between the detector surface and the integrating sphere (Figure 16).

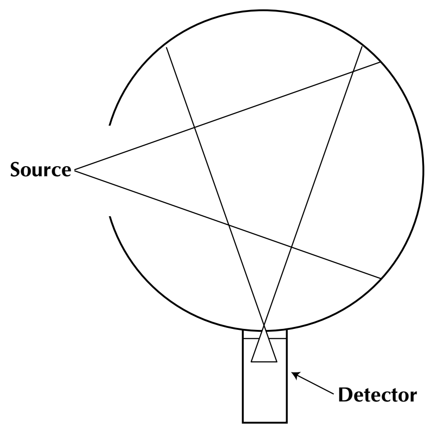


FIGURE 16

If, due to source geometry, this cannot be done the alternative is to have the detector "view" the entire sphere (or nearly the entire sphere). This is usually done with a satellite sphere or a diffuser over the detector.

Calibration

Calibration must be taken into consideration when designing an integrating sphere system. The designer needs to determine if the differing geometry and light levels between calibration and use will have effect on the sphere system. Calibration is further discussed in the following section.

5.0 Calibrations

5.1 Sphere Detector Combination

Each integrating sphere has a specific and unique throughput. The throughput of the sphere is affected by the detector that is placed at a port in the sphere. Because each sphere and detector combination is unique, the sphere and detector are calibrated as a unit.

5.2 Source Based Calibrations

All calibrated radiometer systems receive source based calibrations, as opposed to detector based calibrations. Because a radiometer measures the output of a source, it is calibrated by a similar known source. Lamp measurement spheres are calibrated with known lamp standards, traceable to the National Institute of Standards and Technology (NIST). Laser measurement spheres and fiber optic measurement spheres are calibrated by imparting a known amount of light of a similar spectrum.

5.3 Frequency of Calibration

Integrating spheres should be re-calibrated as part of the normal procedure for use. For example, lamp measurement spheres are opened and closed each time a lamp is measured. Opening and closing the sphere allows dust and dirt to enter the sphere and increases the likelihood that the throughput of the sphere will change. Depending on the cleanliness of the enviornment, these spheres should be calibrated on a daily or weekly basis.

When measuring lamps of different shapes, such as different size fluorescent tubes, the sphere should be calibrated each time a new shape is introdued to the sphere. As discussed above, the geometric shape of the lamp will affect the throughput of the sphere and the resulting readings. The method for correcting for this is discussed in section seven.

Small changes in the reflectance of the sphere coating result in proportionally larger effects on throughput. For this reason it is critical that the sphere's interior be kept extremely clean. Spectraflect, the most commonly used coating, is water soluble and cannot be easily cleaned. Duraflect and Spectralon may be cleaned with special processes. However, control measures must be used to protect Spectralon from oils or other substances it may absorb. Infragold can also be cleaned with special processes.

Because sphere coatings are easily damaged by incorrect use, Labsphere recommends yearly recoating and re-calibration.

5.4 Wavelength Considerations in Calibration

It should be stated that both the integrating sphere and the detector have responses that vary with wavelength. Figure 18 shows a typical throughput spectrum for a Spectraflect coated integrating sphere. Figure 17 shows the typical responsivity of a silicon detector.

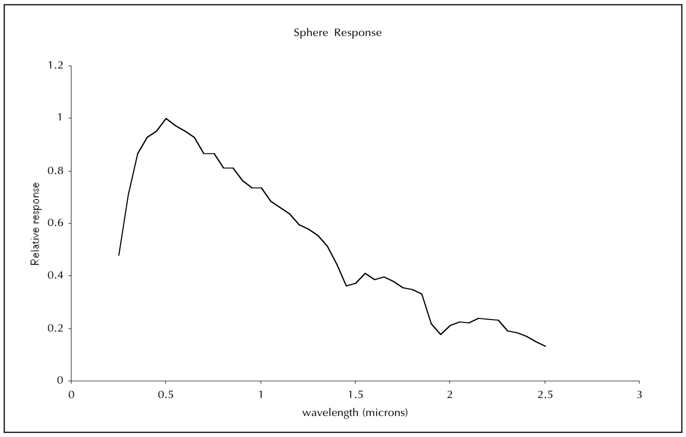


FIGURE 17

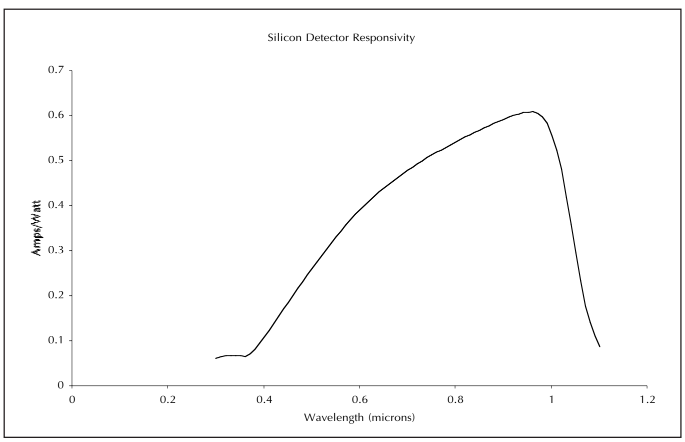


FIGURE 18

Due to these factors, it is imperative that single wavelength radiometric measurement systems be calibrated at a wavelength very near to that which will be measured. In the case of broadband measurements, the solution is not as clear. Luminous flux measurements, typically use a filtered silicon detector that nearly matches the photopic response of the human eye. If the responsivity match is very accurate the spectral differences between calibration source and measured source will not be a major error source. For the more economical detector/filter choices there can be significant errors (especially for relatively narrow band sources).

5.5 Calibration Considerations in the Design

In designing an integrating sphere system, a method of calibration should be considered. Depending on what sources are available for calibration, a perfectly good system may be impossible to calibrate. For example, a system designed to measure the output of a high power laser might dictate that a 20 inch diameter sphere be used in order to prevent saturation of the silicon detector that will be used. This is a reasonable design except that the only calibration source emits a very low level of light. In this case, the system will give very little signal on the detector when being calibrated. The solution to this problem may be to use a higher power calibration source.

In general, it is good practice to calibrate a system with approximately the same source geometry as the system will test. This may not always be possible since a system will be testing a wide variety of sources, however, when possible the effort should be made.

6.0 Sphere-based Radiometer and Photometer Applications

There are many different applications for sphere-based radiometers and photometers. This section describes a variety of these system designs and their applications.

Cosine Collection - Irradiance/Illuminance Measurement

For many scientific purposes it is important to understand how much radiant power, or luminous power, is incident on a surface, regardless of the originating direction. For example, if an epoxy is cured by irradiating it with a given amount of energy, it is important to be able to ensure that enough light is incident on the epoxy. The type of sensor needed is called a "Cosine Receptor" because for a point source the amount of power collected is proportional to the cosine of the angle between the source/detector line and normal to the detector surface. In some instances a glass diffuser is placed over the detector, but this does not always produce an accurate cosine collector. An integrating sphere, however, can make a very good cosine collector due to its insensitivity to angular alignment. Figures 19 and 20 are two examples of how an integrating sphere for cosine collection may be designed.

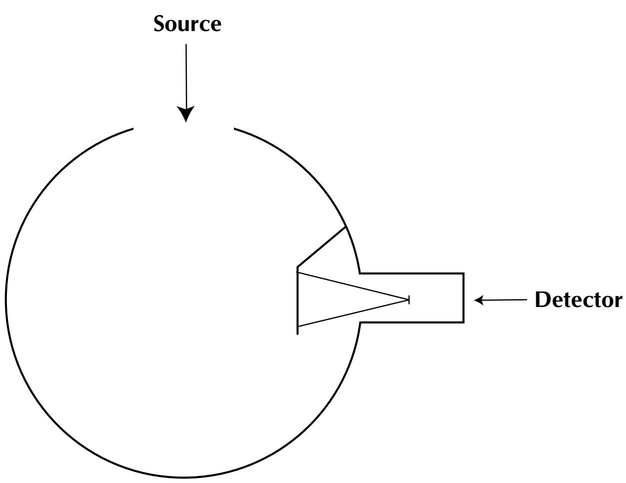


FIGURE 19

In both of these systems the baffle has some effect on the "cosine" response. Light striking the baffle will reflect more light out through the entrance port than light striking the sphere wall. The result of this is that light coming in at an angle such that it hits the baffle will result in an inaccurately low reading.

In the second example a conical baffle is placed between the entrance port and the detector. The effect of the cone shaped baffle is to lower the amount of radiation that reflects out of the sphere from the baffle, therefore reducing the error.

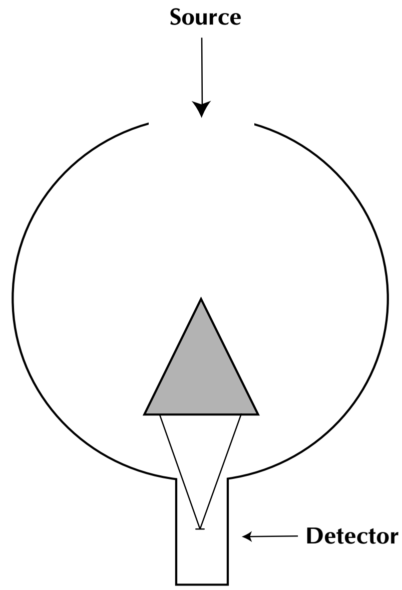


FIGURE 20

Laser and LED Power Measurement

Traditionally, laser power has been measured by focussing the laser directly onto a detector. This method requires the ability to collect all the laser light onto a sensor that can withstand its power density. This method has some inherent problems. The first problem is alignment — the process of aligning the beam to the detector can be difficult. Second problem is detector uniformity — the active area of the detector may not have a uniform response over its area, and slight motion of the laser light will result in variations in measured value. Finally, laser diodes typically have beam divergences of up to ±30 degrees or more. The process of collecting all of this radiation onto a detector can be nearly impossible.

An integrating sphere helps eliminate these problems. Since a sphere can be set up to allow for a wide range of input angles over a large area without substantially effecting the signal at the detector, it is an ideal device for quick and reliable laser power measurement. The same insensitivity to angular variations makes the sphere ideal for measuring laser diodes.

Figure 21 shows the design used for a Labsphere laser power measurement sphere. In this design both the detector and its field-of-view are kept in the forward portion of the sphere allowing for the test source to irradiate any portion of the rear hemisphere without effecting the sphere output.

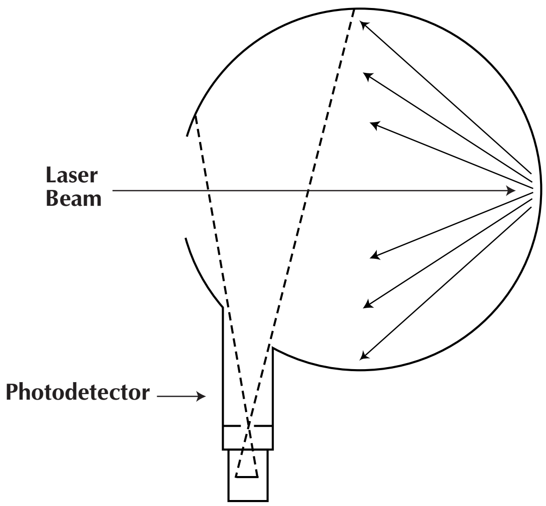


FIGURE 21

Fiber Output Measurements

There are two types of measurements for fiber optics: 1) output at the end of the fiber; and 2) loss across the length of the fiber. Integrating spheres may be used for either of these measurements.

There are numerous types of fiber optics currently in use. Each type of fiber has different output characteristics. Some have outputs with a high Numerical Aperture (NA), some have a low NA, some have diffusers built into the tip and some don't. There are fibers that have angle cleaves or polishes on the tip, and some that terminate in a short length of radially emitting fiber. To say that there is one sphere to measure the output of a fiber would be wrong. As with most other applications there is likely to be one sphere that will work for a large portion of these, but some will need a specially designed sphere.

Let us start with a fiber that emits in a relatively narrow cone of radiation. The sphere in Figure 22 shows a fairly accurate way of measuring the output.

For a situation with a more highly divergent fiber output a sphere used in the laser power measurement system, as shown in Figure 21, is more appropriate.

In both situations the calibration of the system is relatively straightforward. The system is calibrated by using a source of known output to shine into the sphere and measuring the detector response.

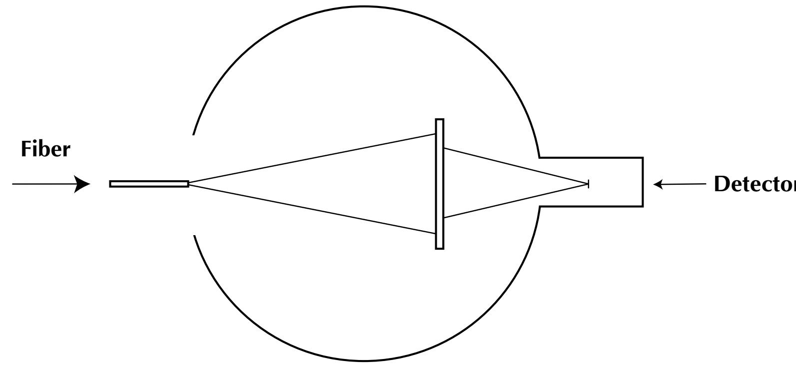


FIGURE 22

For cases where light is being emitted from the sides of a fiber being run through the sphere the problem is not simple. The sphere typically will have two ports for stringing the fiber through the sphere and another for the detector (see Figure 23). In a sphere like this the best way to calibrate is with a fiber of known emittance along its length. The reason for this is two-fold. First, there is no good way of getting light from an external source into the sphere. Second, the presence of the fiber in the sphere effects the throughput of the sphere, therefore it needs to be present in the calibration process.

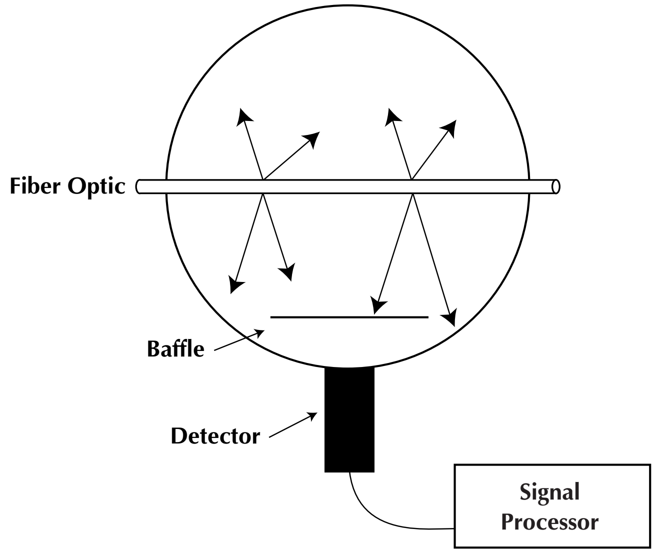


FIGURE 23

7.0 Lamp Measurement Radiometry and Photometry

There are a few major characteristics of a lamp that manufacturers and end-users find most important. These are the number of lumens, the color, and the efficiency (how many lumens of output per watt of energy). The choice of lamp measurement system will depend on three things: 1) measurement needed, 2) physical size of the lamp, 3) magnitude of the lamp output. This section describes the different methods and considerations for lamp measurement radiometry and photometry. In general, the measurement of a lamp's luminous flux and its spectral radiant flux are identical except in how the radiation is detected.

There are two generally accepted methods for measuring the total flux of a lamp. The first employs a goniometer that scans the whole sphere of radiation from the source. Integration over this scan yields a very accurate measurement of the lamp output, but the process is not always easy or quick. The second method employs an integrating sphere to capture all the radiation from the source at the same time. A detector is used to measure the output of the sphere. By comparing the output with a test lamp in the sphere to the output of a known standard in the sphere, the total flux emitted from the lamp can be calculated. This procedure can be done easily and quickly.

Sphere Design

Integrating spheres collect the total flux emitted from a lamp. Because an integrating sphere reflects and integrates all the light entering the sphere, the light received by a small area of the sphere is directly proportional to the total flux from a light source mounted within the sphere. The total flux from a test lamp is determined by comparing it to a calibrated working standard. The integrating sphere must include a lamp socket fixture, baffles, and a viewing port for the photodetector. In high accuracy measurements, an auxiliary lamp may be used to correct for lamp self absorption.

Sphere Diameter

Integrating spheres used for total flux measurements are generally large in diameter. Increased diameter minimizes geometric errors due to lamps, baffles, and support fixtures which are mounted internally. Larger spheres also dissipate heat more efficiently and minimize ultraviolet irradiance on the sphere wall. Excessive thermal and UV exposure can be detrimental to long term device performance.

Lamp physical dimensions must also be considered. The sphere diameter must accommodate the maximum length of the lamp under test. The CIE recommends that for tubular fluorescent lamps, the sphere diameter should be at least twice the longest dimension of the lamp, and that for compact lamps the sphere diameter should be at least ten (10) times the largest dimension of the lamp.

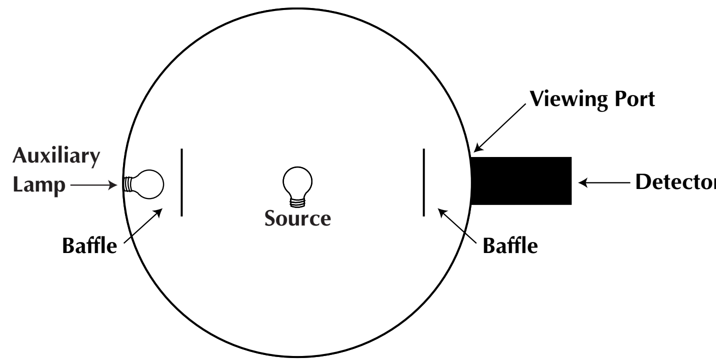


FIGURE 24
Lamp measurement sphere using a detector mounted directly at the viewing port.

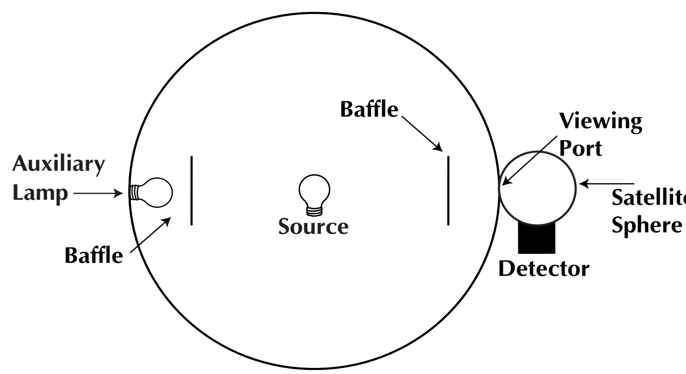


FIGURE 25
Lamp measurement sphere using a satellite sphere with detector mounted at the viewing port.

Baffles

The detector viewing port replaces a small portion of the sphere wall and receives the same amount of radiation as nearly all other parts of the sphere wall. Because the flux of the lamp is directly proportional to the illumination of the sphere wall, the detector must be baffled from direct illumination by the lamp. In total luminous flux measurements, a baffle is placed between the lamp and the detector port. The CIE recommendation for the placement of this baffle is that it be 1/4 to 1/6 the sphere diameter from the photometer head. The baffle is coated with the same material as the integrating sphere wall. The most common mounting arrangement places the lamp at the center of the integrating sphere and the baffle at approximately one-third of the radius from the viewing port. Lamp bulb diameter is obviously constrained since the bulb should not make physical contact with the baffle. Baffle size should be as small as possible, but large enough to prevent the lamp from directly illuminating the detector port. The most common baffle shape is circular, but rectangular or oblong baffles may be used for various lamp types.

Viewing Port

Comparing the flux of two lamps with different geometrical luminous flux distributions can contribute to measurement error. To minimize this error, the detector must exhibit a uniform spatial and angular response. There are two common methods of a achieving this response: 1) a diffuser is placed at the viewing port in front of the detector; or 2) a smaller auxiliary sphere with the detector attached is placed at the viewing port.

Auxiliary Lamp

An auxiliary lamp is used to correct for the self absorption of the reference and test lamps which are alternately substituted into the sphere. The auxiliary lamp remains inside the integrating sphere at all times. It is usually mounted diametrically opposite the detector port and baffled from direct view and direct illumination of lamps mounted at the sphere center.

7.1 Light Detection

Lumens are determined by weighting the spectral radiant flux by the photopic response of they eye. Two basic types of instruments are used to perform this measurement, photometers and spectroradiometers.

Photometers

A photometer is an instrument that directly measures light in accordance with the photometric system. Therefore, it requires the use of a detector that approximates the relative spectral response of the human eye. The associated standard spectral response is often referred to as the CIE luminous efficiency function, the V-lambda function, or more commonly, as the photopic response curve (Figure 26).

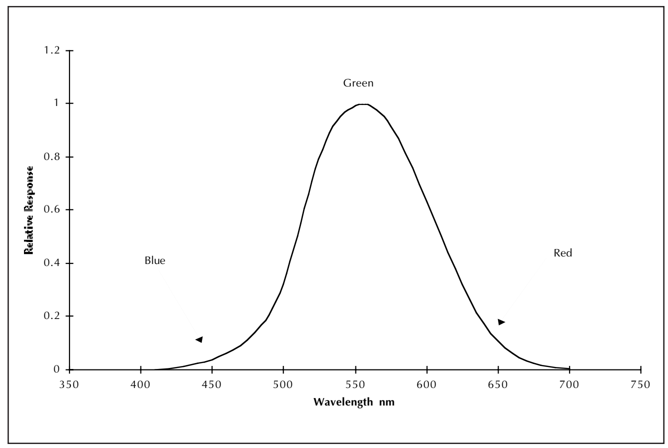


FIGURE 26

Ideally, the spectral response of the detector/filter/sphere system will exactly match the $V_{(\lambda)}$. Most commercially available "photopic response" detectors utilize a multi-layer glass filter to correct the inherent detector responsivity. The filter design is matched to the type of detector employed.

Detectors require signal conditioning and data display electronics. Data output needs to be linear with respect to input light levels over the required dynamic range. Digital data displays are preferred.

Spectroradiometers

Spectral radiant flux can be measured directly and the lumen calculation performed by a computer. The ability to obtain spectral information from the integrating sphere is advantageous for several reasons: 1) better lumen calculation, 2) calculation of chromaticity coordinates, 3) calculation of color rendering indices.

Perfect simulation of the CIE luminous efficiency function with a filtered detector is not possible and leads to measurement error. With spectral measurements, the spectral reflectance of the sphere wall and the relative spectral responsivity of the photodetector do not influence the results. By applying the photopic response in the software, a highly accurate lumen value is achieved.

Lumens data is not the only quantity that can be calculated from the output of a spectroradiometer. Spectral data is easily converted to yield important color properties such as chromaticity, correlated color temperature, and the color rendering indices.

Traditional spectroradiometers incorporate a differential grating monochromator to disperse the light spectrum. Scanning instruments sequentially step each individual wavelength onto a single photodetector. A more recent instrument is the photodiode array spectrograph. The spectrum is dispersed across a linear array of photodetectors. Each wavelength is captured simultaneously and the total spectrum can be displayed as a single “snapshot.” This is particularly useful for evaluating spectral changes with time.

7.2 Measurement Equations

Lamp Substitution

The luminous flux of a lamp under test is performed by comparison to a lamp standard of known flux. Both lamps are operated in turn in the integrating sphere and the detector signals recorded. One lamp is substituted for the other inside the integrating sphere.

The ratio of detector signals is equal to the ratio of actual lamp flux:

$$\frac{\Phi_t}{\Phi_s} = \frac{D_t}{D_s} \qquad \textbf{EQ. 27}$$

where;

Φt = flux of the test lamp
Φs = flux of the standard lamp
D_t = detector signal from the test lamp
D_s = detector signal from the standard lamp

Therefore, the test lamp’s flux is determined by multiplying the measured ratio of detector signals by the known flux of the standard lamp:

$$\Phi_t = \frac{D_t}{D_s} * \Phi_s \qquad \textbf{EQ. 28}$$

Auxiliary Lamp Correction

Equation 27 assumes a constant sphere throughput. However, a lamp placed inside the integrating sphere affects the throughput by self absorption. When substituting lamps of different absorption properties, a constant sphere throughput is not achieved.

Each lamp flux of equation 27 is modified by the lamp absorption:

$$\frac{\Phi_t * \alpha_t}{\Phi_s * \alpha_s} = \frac{D_t}{D_s} \qquad \textbf{EQ. 29}$$

where;

α_t = test lamp absorption
α_s = standard lamp absorption

In high accuracy measurements, the absorption can be corrected by using an auxiliary lamp. The detector signal is recorded for the auxiliary lamp with the test and standard lamps alternately mounted, but not operated, within the integrating sphere.

The test lamp’s flux is given by:

$$\Phi_t = \frac{D_t}{D_s} * \frac{A_s}{A_t} * \Phi_s \qquad \textbf{EQ. 30}$$

where;

At = detector signal for the auxiliary lamp, test lamp within sphere
As = detector signal for the auxiliary lamp, standard lamp within sphere

Spectral Measurements

A spectral lamp measurement is performed in a fashion almost identical to the luminous flux measurement. The lamp under test is measured by comparing the output of a spectroradiometer with the test lamp in the sphere to its output with a lamp of known spectral flux in the sphere. The calculations are totally analogous to the luminous flux equations, with the difference being that all the quantities in the equation are functions of wavelength.

The spectral flux is given of the test lamp by the equation:

$$\Phi_t(\lambda) = \frac{D_t(\lambda)}{D_s(\lambda)} * \Phi_s(\lambda) \qquad \textbf{EQ. 31}$$

And if auxiliary correction is applied this becomes:

$$\Phi_t(\lambda) = \frac{D_t(\lambda)}{D_s(\lambda)} * \frac{A_s(\lambda)}{A_t(\lambda)} * \Phi_s(\lambda) \qquad \textbf{EQ. 32}$$

Quantities such as luminous flux, correlated color temperature, chromaticity coordinates, and color-rendering indices can all be calculated from the spectral flux measured in this fashion.

7.3 Electrical Considerations

The integrating sphere is the principal component for total luminous flux measurements. Sphere induced errors must be minimized to achieve accurate results. However, since lamp output has a strong dependence on the lamp drive parameters accurate and stable electronics are vital to a good photometry system.

Power Supplies

Regulated power supplies are recommended for operating lamps during photometric testing. The amount of regulation employed determines the stability and resolution in total luminous flux measurements.

DC power supplies are recommended for incandescent filament lamps. Lamp standards of luminous flux are usually calibrated at a specific operating current. The routine measurements of other incandescent lamps are usually performed at rated voltage. Therefore, accurate measurements of operating current and voltage are required to realize good total luminous flux data.
The use of AC power supplies requires that the wave shape contain only a small amount of harmonic distortion. Fluorescent and discharge lamps also require the use of reference ballasts.

Sockets

Good electrical contacts are necessary to make total luminous flux and electrical operating parameter measurements meaningful. For measurements at rated or specified current only, any quality lamp socket can be used. The socket must be kept clean of flux or solder build-up which can occur after prolonged use.

Due to circuit resistance losses, actual operating voltage measurements should be performed at the base of the lamp. Kelvin type sockets are recommended for incandescent lamps. There are four contact sockets. Two contacts are provided for connecting the lamp to the power supply. Separate leads measure direct potential at the lamp base.

7.4 Standards

National standardizing laboratories are responsible for establishing a scale of total luminous flux. In the United States, this is maintained by the National Institute of Standards and Technology (NIST). Working lamp standards are available to industry through NIST calibration services. Several intermediate calibration laboratories supply NIST traceable working standards as well.

Incandescent lamps are generally used for lamp standards because of their inherently good stability and convenience in handling. The total uncertainty in the assigned values of total luminous flux for an incandescent lamp calibrated at NIST ranges from 1.4% to 1.8%.

Lamp Standards of Total Luminous Flux

Master lamp standards of total luminous flux should be obtained from either NIST or other accredited intermediate calibration laboratories. For general use, working standards should be prepared by calibrating them relative to the master standards.

Lamp standards are calibrated at a specific operating current which is best measured using a precision DC ammeter shunt. The shunt is a calibrated four terminal resistor. The potential developed across two measurement terminals is directly proportional to the applied current.

Standard lamps are often maintained in at least groups of three to detect any changes through intercomparison. NIST maintains working standards in groups of six. Lamp Standards are generally employed for fifty (50) hours of operation.

Prior to calibration, suitable lamp standards candidates must be seasoned and screened for output flux stability. Appendix A provides an overview of lamp screening and calibration procedures.

Precautions in maintaining lamp standards include keeping the bulb and base clean as well as avoiding mechanical shock. Large lamps are generally burned base-up to relieve mechanical stress of the hot filament. Miniature lamps are burned base down. Standards quality lamps should never be handled or moved with the filament still warm. The current applied to a standard lamp should never exceed the specified operating value.

7.5 Sources of Error

Measurement uncertainty is a function of the measurement process. Uncertainty analysis, as applied to any scientific experiment or physical measurement, provides an estimate of the size of the error that may be expected. Both random and systematic errors are considered.

Random errors provide a measure of the precision or repeatability of a measurement process. Random errors can be reduced by repeating a measurement.

Systematic errors cannot be reduced by repeating a measurement. Reduction of systematic errors often depends on the ability of the system operator or experimenter to recognize and quantify these errors. In total luminous flux measurements, the most obvious systematic error is the calibration uncertainty stated for the working standard lamp. Other systematic errors are discussed below.

Geometry

Geometric errors within the integrating sphere are associated with comparing test and standard lamps of different physical dimensions and flux distributions. The errors are minimized when comparing lamps of similar characteristics.

Geometric error arises from the spatial distribution of luminous flux inside the sphere. The total luminous flux from an internal lamp illuminates the sphere wall directly. This direct illuminance distribution may be non-uniform. From a port on the sphere wall, a photodetector can be sensitive to the illuminance distribution within its field-of-view. Therefore, the ratio of viewed illuminance may not be exactly proportional to the ratio of the total luminous flux for two lamps being compared. A detector which can receive light from over the entire sphere will minimize this effect. A diffuser window or small auxiliary sphere in front of the photodetector best achieves the required angular and spatial response.

Quantifying geometric errors to an acceptable degree of precision is a very difficult exercise. The presence of baffles, mounting fixtures, and the lamp itself affect the performance of the sphere photometer.

Although a detailed analysis has not been performed, an allowance of 1% for geometric errors is included in the uncertainty analysis of NIST transfer calibrations of total luminous flux. It is the largest of the associated systematic errors within assigned NIST uncertainties.

Spectral Response

A photometer incorporates a detector characterized by a spectral reponsivity which approximates the CIE luminous efficiency function. An exact match to the CIE luminous efficiency function is not entirely possible.

Spectral response errors with photopic response detectors occur for test lamps of different spectral distribution than those used as calibration standards. A goodness-of-fit value is often expressed to quantify the associated error. The goodness-of-fit is based on both the calibration source spectral distribution as well as the spectral response of the photopic detector. The CIE and DIN 5032 recommend a goodness-of-fit value called f1' as a universal method of specifying the quality of a photopic response detector.

In total luminous flux measurements, the spectral efficiency of the integrating sphere must be included in the spectral response analysis of the complete system. Integrating sphere efficiency decreases slightly towards the blue wavelengths of the visible spectrum due to the nature of the sphere coating. As the coating ages, the decrease in efficiency becomes more pronounced. Pale blue glass filters may be added to the photodetector assembly to correct for the induced spectral response shift of the sphere. Once corrected, the f1' value of the photopic detector can also apply with the integrating sphere.

The spectral efficiency of the integrating sphere is determined by ratioing the spectral distribution measured at the detector port for a lamp operating within the sphere to that measured directly of the lamp operating on the outside the sphere. A spectroradiometer is used for this measurement. The required spectral transmittance of the correcting blue filter is determined by:

$$T(\lambda) \propto \frac{S_o(\lambda)}{S_i(\lambda)} \qquad \textbf{EQ. 33}$$

where;

$T(\lambda)$ = filter transmittance
$S_o(\lambda)$ = lamp distribution outside the sphere
$S_i(\lambda)$ = lamp distribution inside the sphere

The spectral correction required may also be specified by measuring the induced shift in the lamp's correlated color temperature. The difference between the apparent color temperature within the sphere and the actual lamp color temperature is used to calculate the filter's color balancing power expressed as a transformation value in units of "reciprocal mega-Kelvins". Blue filter glasses have negative mired values. The filter's mired value is given by:

$$\left[\frac{1}{CCT_o} - \frac{1}{CCT_i}\right] * 10^6 \qquad \textbf{EQ. 34}$$

where;

CCT_o = lamp correlated color temperature outside the sphere
CCT_i = lamp correlated color temperature inside the sphere

Linearity

The output data displayed on a photometer must be linear with respect to input light levels. Linearity means that the output is exactly proportional to the input. The linearity of a photometer may be measured by either multiple source, multiple aperture, or inverse-square methods.

Lamp Absorption

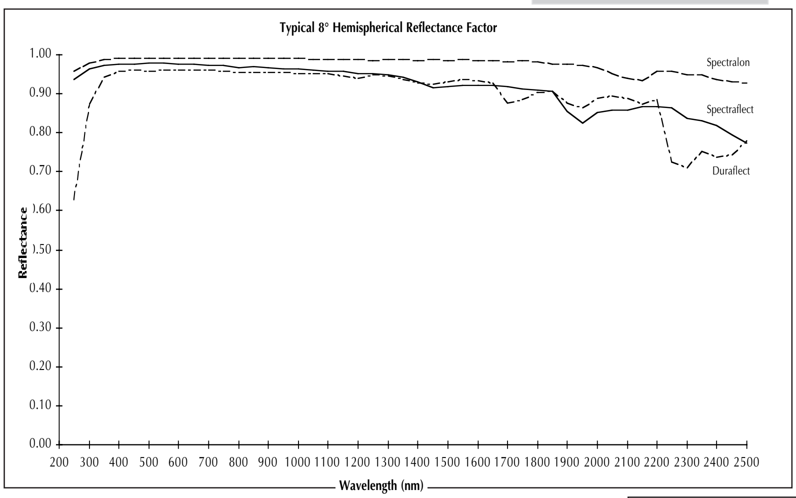
A lamp placed within the integrating sphere affects the sphere efficiency through self absorption. When measuring lamps of different absorption properties, a constant sphere efficiency is not achieved. The effect can be significant when measuring test lamps of a different type than those used for calibration. Correcting for lamp absorption requires the use of an auxiliary lamp.

Electrical Measurements

When calibrating with a standard lamp, operating current must be accurately set. The variation in total luminous flux for a tungsten filament lamp is approximately proportional to the variation in operating current to the sixth power.

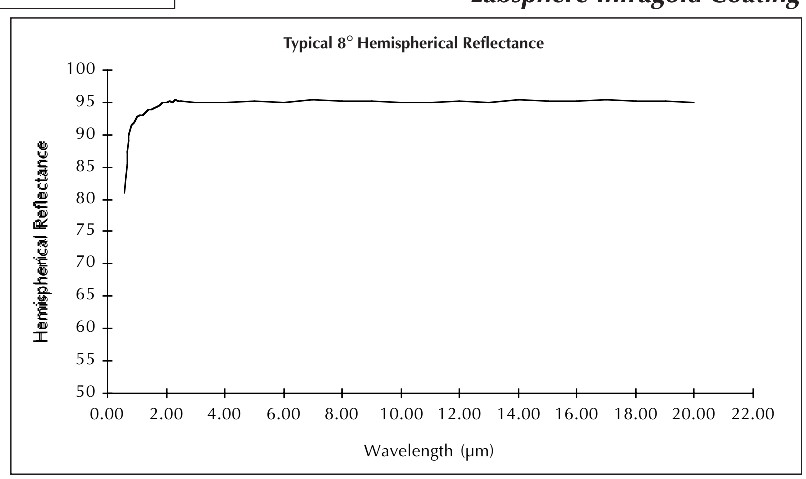
APPENDIX A - COMPARITIVE PROPERTIES OF LABSPHERE INTEGRATING SPHERE COATINGS

SPECIFICATION	SPECTRALON	SPECTRAFLECT	DURAFLECT	INFRAGOLD	INFRAGOLD-LF
Coating/Material:	Thermoplastic Material	Coating	Coating	Coating	Coating
Effective Spectral Range:	200-2500 nm	300-2400 nm	350-1200 nm	0.7-20µm	1->20µm
Reflectance:	99% from 400-1500nm	96-98% @600 nm	94-96% @600nm	92-96% from 1-16µm	90-94% from 1-16µm
Thermal Stability:	to 350° C	to 100° C	to 80° C		
Vacuum Stability:	no outgassing except for entrained air	slight outgassing at high vacuum	outgasses at 120° C	no outgassing	no outgassing
Water Permeability:	>0.001% Hydrophobic	—	Hydrophobic	—	—
Laser Damage Threshold:	>4.0 J/cm^2	1.7 J/cm^2	N/A	19.3 J/cm^2 @ 10.6µm	19.3 J/cm^2 @ 10.6µm
General Use	UV-VIS-NIR	UV-VIS-NIR	VIS to NIR	NIR-MIR	NIR-MIR
Advantages:	excellent reflectance lambertian thermally stable chemically inert no gloss problems machinable	excellent reflectance lambertian non-toxic	high reflectance lambertian durable suitable for: –underwater applications –outdoor exposure –low temperature conditions –humid environments	excellent reflectance lambertian thermally stable	high reflectance lambertian



▲ ***Comparative Reflectance Data***
Spectralon, Spectraflect, and Duraflect Coatings

▼ ***Typical 8° Hemispherical Reflectance Data***
Labsphere Infragold Coating



APPENDIX B — LAMP STANDARDS SCREENING PROCEDURE

Lamp Standards Screening Procedure

Below is the procedure used by Labsphere to screen calibrated lamps.

1. Obtain approximately one to two dozen lamps which are of similar type to the calibrated lamp. Season the lamps at rated voltage for 4% to 6% of their rated life. AC operation may be used for seasoning. At 105% of rated voltage*, the seasoning period is cut in half.
(*Not recommended for halogen lamps)

2. Record the relative light output of each lamp at a specified operating current. Regulated DC operation is recommneded. The lamps may be mounted within an integrating sphere. If a digital photometer is used, recordings should utilize the maximum number of available digits.

3. Compute a statistical mean of all lamp readings.

4. Normalize each lamp reading to the mean.

5. Repeat steps 2 thru 4 on three consecutive days.

6. For each lamp, determine a statisitcal mean and standard deviation of normalized results over the three measurement days.

7. For each lamp, compute a coefficient of variation. This is the standard deviation divided by the mean, multiplied by 100%. The coefficient of variation should be less than or equal to 0.5% for standards quality lamps. Do not calibrate lamps with larger variation.

APPENDIX C — REFERENCES AND RECOMMENDED READING

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