A Guide to Reflectance Coatings and Materials

TECH GUIDE

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INTRODUCTION

Over the past 20 years, Labsphere has been involved with ongoing research to improve the state of the art in diffuse reflectance coatings and materials. Our dedicated Reflectance Research Laboratory is equipped with over 25 of the major spectrometers and spectrophotometers available today. This enables us to continue research for the improvement of current reflectance coatings and materials, as well as develop new materials. Our pioneering achievements in reflectance material research have produced a selection of coatings and materials that are accepted as industry standards. Our applications base is perhaps the largest in the industry, as we work closely with our customers to meet and exceed their optical and reflectance needs.

While many readers of this technical guide will have started their careers in optics dealing with traditional diffuse coatings and materials such as Opal Glass, Eastman 6080, or GE Integrating Sphere Paint™, this guide will serve as a refresher course in the new materials available to spectroscopists, optical engineers and designers. For the newcomer, we hope this guide serves to aid them in selecting the proper reflectance coating and material for their application, by both outlining the physical, spectral and environmental properties, as well as presenting the limitations that are inherent in any reflectance coating or material.

This guide should be considered a "work-in-progress", as we continually work toward improving and developing innovative, new reflectance products.

We hope you will find the information presented useful, and as always, we appreciate your comments and suggestions.

A GUIDE TO REFLECTANCE COATINGS AND MATERIALS

SECTION 1. DIFFUSE REFLECTANCE COATINGS

For integrating spheres and many other applications that require either diffuse illumination or collection, reflectance and scattering properties are of utmost importance. An ideal coating is non-specular (to decrease geometrical effects), durable, high in reflectance and spectrally flat over a wide wavelength range to give a flat spectral response in input or output.

For some prototyping applications, a white house paint may be sufficient. Most commercial white paints, however, are not particularly white, nor particularly stable. They typically have an integrated reflectance in the 85 - 88% range over the visible region of the spectrum and drop off sharply in the blue end due to the use of titanium dioxide as a pigment. Even a flat (matte) white paint has a significant specular component that may cause problems. If low throughput is acceptable, a sandblasted aluminum surface may suffice; but with a mean reflectance of around 55% the throughput will be extremely low and may not be indicative of the performance of a component or system with a high-reflectance diffuse coating. For applications in the infrared, a sandblasted metallic surface may suffice, however the formation of oxide coatings due to atmospheric exposure may change the character of the material over time.

To design or prototype a component or integrating sphere system, the best possible coatings should be used. To that end, Labsphere has developed five standard coatings that can be applied to many substrates that give a flat spectral response over a wide wavelength range, are highly diffuse and highly reflective, and are with a single exception, quite durable for optical coatings. These coatings, ***Spectraflect, Duraflect, Duraflect II, Infragold and Infragold-LF*** are described in the following section.

1.1 Spectraflect Reflectance Coating

Spectraflect is a specially formulated barium sulfate coating which produces a nearly perfect diffuse reflectance surface. Spectraflect is generally used as a reflectance coating in the UV-VIS-NIR region and is most effective over the wavelength range from 300 to 2400 nm. The range can be stretched to 185 nm before binder absorbtion peaks begin to appear. The reflectance of Spectraflect, as with all reflectance coatings, is dependent on the thickness of the coating. At thicknesses above 0.5 mm (0.020 inches), the coating is opaque with reflectance of >99% over the wavelength range from 400 to 1100 nm. Spectraflect is thermally stable to approximately 100° C. Above that temperature, it slowly decreases in reflectance, especially in the 250 to 450 nm range. The coating yellows rapidly at temperatures above 160° C, and outgasses slowly in high vacuum due to residual water entrapped in the binder. Spectraflect has been tested for laser damage threshold using a Q-switched YAG laser at 532 nm, the damage threshold is 1.7 J/cm^2.

Spectraflect is an inexpensive, safe, non-toxic, high reflectance coating that is useful over a fairly wide wavelength range. The material is highly lambertian in character. Spectraflect is limited by the fact that the binder is water soluble, thus the coating is not usable in very high humidity applications. For applications where this consideration must be taken into account, Labsphere Duraflect coatings are recommended.

Spectraflect is applied by spraying the coating onto a specially prepared surface. Surface preparation generally consists of degreasing followed by sandblasting to roughen the surface. Spectraflect coating can be applied to virtually any substrate, and is an ideal reflectance coating for items such as optical components, integrating spheres, lamp housings and spectral diffuser panels.

The reflectance data for Spectraflect reflectance coating is presented in Figure 1 on page 41.

1.2 Duraflect Reflectance Coating

Duraflect is a proprietary white reflectance coating for use where hostile environments, weathering and wear may affect a coating, yet high lambertian reflectance is required. Duraflect is generally used in applications in the visible to the very near IR, approximately 350 to 1200 nm. It is stable to approximately 80° C, with slight outgassing at high vacuum. Duraflect is water resistant and durable and can be used in high humidity conditions. The coating typically has a reflectance value of >95% over the wavelength range from 350 to 1200 nm. Duraflect is not recommended for use in the UV wavelength range. Duraflect is applied by spraying the coating onto a specially prepared surface. Surface preparation generally consists of degreasing followed by sandblasting to roughen the surface. For best results, Duraflect should be applied to metal or glass substrates. Pre-testing is recommended when applied to plastic substrates. Duraflect samples left outside in New Hampshire environment showed loss of <0.5% reflectance even after multiple washings to remove dirt. Duraflect has been used at low temperatures to coat integrating cylinders used to measure snow pack and is a common coating for reflectometers used in industrial on-line processes.

The reflectance data for Duraflect reflectance coating is presented in Figure 2 on Page 41.

1.3 Duraflect-II Diffuse White Coating

Duraflect-II is a specially formulated diffuse white reflectance coating for use in high-humidity environments. This coating is highly lambertian and exhibits excellent reflectance over the wavelength region from 300 to 1200 nm. Duraflect-II is a non-noxious, low volatile organic compound that exhibits superior optical properties and exceptional durability. The coating is ideal for both outdoor and laboratory applications that require high diffuse reflectance. The coating can be applied to most substrates including plastics and composites. It is applied by spraying or painting onto surfaces.

The reflectance data for Duraflect-II reflectance coating is presented in Figure 3 on Page 41.

1.4 Infragold NIR-MIR Reflectance Coating

Infragold NIR-MIR reflectance coating is an electrochemically plated, diffuse, gold-metallic coating which exhibits excellent reflectance properties over the wavelength range from 0.7 to 20 µm. Infragold has excellent vacuum stability, with no outgassing reported. Laser damage threshold is approximately 19.3 J/cm^2 @ 10.6 µm using CO_2 laser. This is considered above average for a plated surface. The threshold will increase if the material is cooled on exposure to laser, as in water-cooled integrating spheres or targets.

The typical reflectance of Infragold is >94% above 1000 nm and data is traceable to the National Institute of Standards and Technology (NIST). Infragold can be applied to metal parts, generally aluminum, nickel or steel, although it has been applied with success to copper and tungsten. It is generally used for reflectance integrating spheres and accessories for NIR to MIR applications and is suitable for many space applications.

The reflectance data for Infragold NIR-MIR reflectance coating is presented in Figure 4 on page 42.

1.5 Infragold-LF MIR-FIR Reflectance Coating

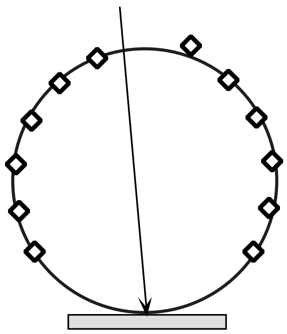
Infragold-LF MIR-FIR reflectance coating is an electrochemically plated, diffuse, gold-metallic coating which is ideal for use in the MIR-FIR wavelength range. Typical reflectance is >90% over the effective wavelength range. Infragold-LF is thermally stable, with no outgassing reported. This coating is the most highly lambertian and durable coating available for applications in the MIR-FIR wavelength region. Infragold-LF is suitable for integrating spheres and BRDF standards.

The reflectance data for Infragold-LF MIR-FIR reflectance coating is presented in Figure 5 on page 42.

Spectraflect Reflectance Coating

Reflectivity: @ 600 nm	96 - 98%
Effective Spectral Range:	350 to 2400 nm
Thermal Stability:	to 100°C
Laser Damage Threshold:	1.7 J/cm^2

LASER SOURCE

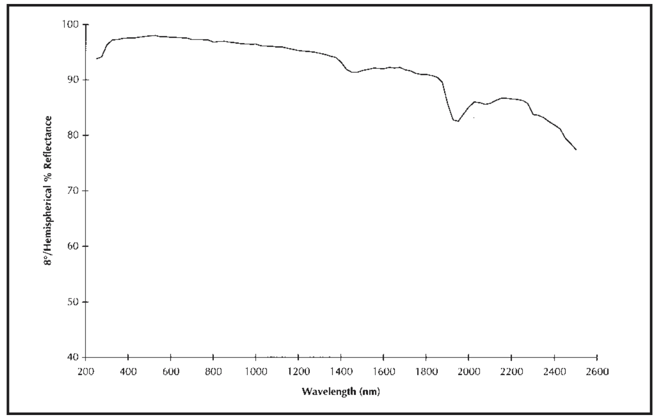


SPECTRAFLECT

BRDF - Spectraflect Reflectance Coating

Plot of intensity of scattered light vs angle for a sample of Spectraflect reflectance coating. The sample was illuminated with a 632.8 nm laser at 5° from normal. The data points are the measured values; the circle is a theoretical plot of a 100% reflecting, perfectly lambertian surface. (A discussion on Bidirectional Reflectance Distribution Function (BRDF) is found on pages 48 - 49).

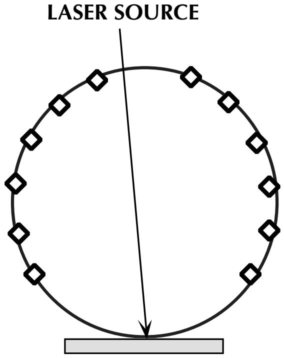
Figure 1 - Spectraflect Reflectance Coating



Duraflect Reflectance Coating

Reflectivity: @ 600 nm	94 - 96%
Effective Spectral Range:	350 to 1200 nm
Thermal Stability:	to 80°C
Laser Damage Threshold:	N/A

LASER SOURCE

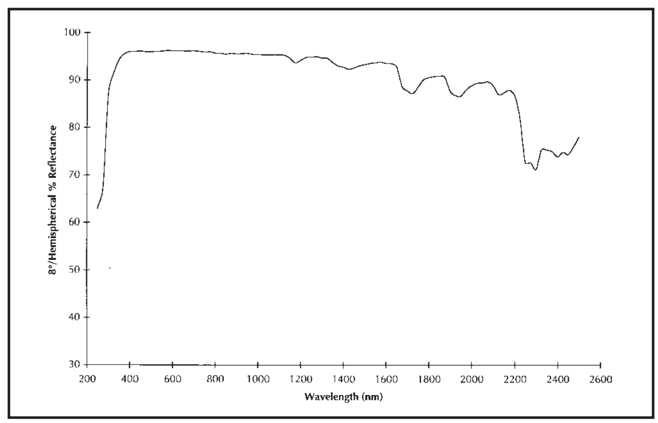


DURAFLECT

BRDF - Duraflect Reflectance Coating

Plot of intensity of scattered light vs angle for a sample of Duraflect reflectance coating. The sample was illuminated with a 632.8 nm laser at 5° from normal. The data points are the measured values; the circle is a theoretical plot of a 100% reflecting, perfectly lambertian surface. (A discussion on Bidirectional Reflectance Distribution Function (BRDF) is found on pages 48 - 49).

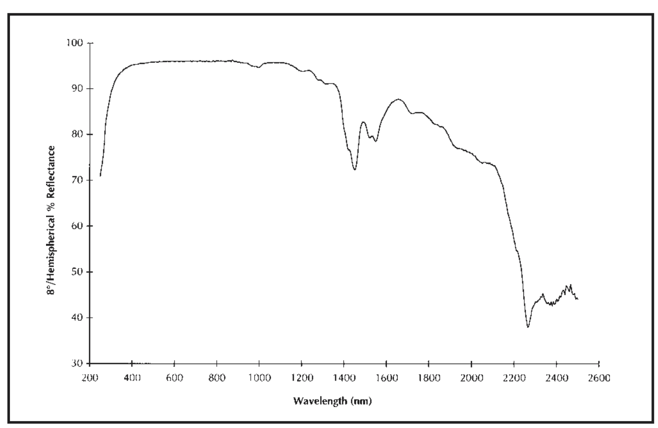
Figure 2 - Duraflect Reflectance Coating



Duraflect-II Reflectance Coating

Reflectivity: @ 600 nm	95 - 97%
Effective Spectral Range:	300 to 1200 nm
Thermal Stability:	to 100°C

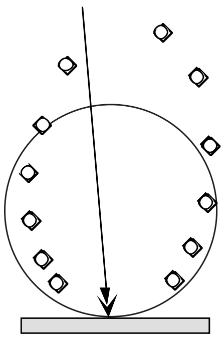
Figure 3 - Duraflect-II Reflectance Coating



Infragold NIR/MIR Reflectance Coating

Reflectivity: @ 1 - 16 µm	92 - 96%
Effective Spectral Range:	300 to 2400 nm
Thermal Stability:	N/A
Laser Damage Threshold:	19.3 J/cm² @ 10.6 µm

LASER SOURCE

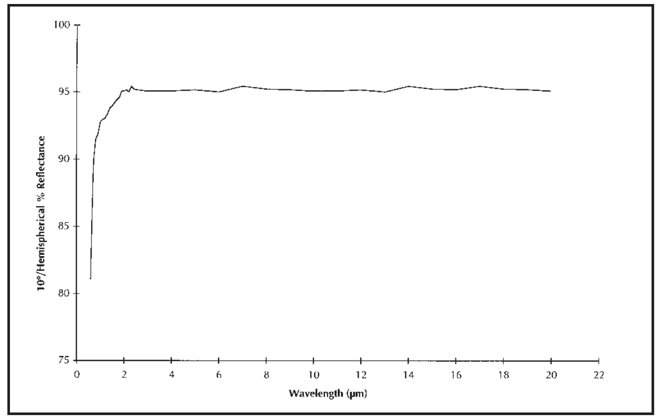


INFRAGOLD

BRDF - Infragold Reflectance Coating

Plot of intensity of scattered light vs angle for a sample of Infragold reflectance coating. The sample was illuminated with a 10.6 µm laser at 5° from normal. The data points are the measured values; the circle is a theoretical plot of a 100% reflecting, perfectly lambertian surface. (A discussion on Bidirectional Reflectance Distribution Function (BRDF) is found on pages 48 - 49).

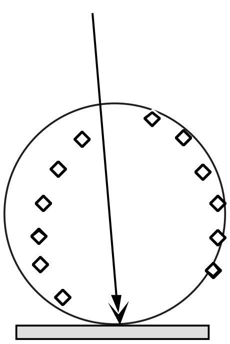
Figure 4 - Infragold NIR/MIR Reflectance Coating



Infragold-LF MIR-FIR Reflectance Coating

Reflectivity:	90 - 94%
Effective Spectral Range:	MIR-FIR
Thermal Stability:	N/A
Laser Damage Threshold:	19.3 J/cm² @10.6 µm

LASER SOURCE

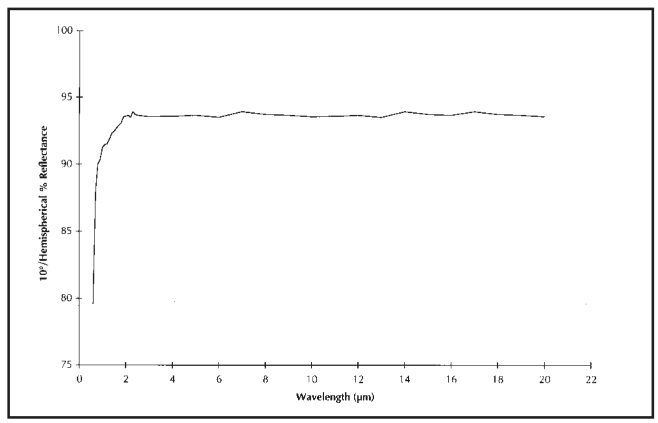


INFRAGOLD-LF

BRDF - Infragold-LF Reflectance Coating

Plot of intensity of scattered light vs angle for a sample of Infragold-LF reflectance coating. The sample was illuminated with a 10.6 µm laser at 5° from normal. The data points are the measured values; the circle is a theoretical plot of a 100% reflecting, perfectly lambertian surface. (A discussion on Bidirectional Reflectance Distribution Function (BRDF) is found on pages 48 - 49).

Figure 5 - Infragold-LF MIR/FIR Reflectance Coating



1.6 TYPICAL REFLECTANCE DATA OF LABSPHERE REFLECTANCE COATINGS

WAVELENGTH (nm)	SPECTRALON	SPECTRAFLECT	DURAFLECT	DURAFLECT II	INFRAGOLD	INFRAGOLD-LF
250	0.96	0.94	0.63	0.74	-	-
300	0.98	0.96	0.87	0.89	-	-
350	0.99	0.97	0.94	0.94	0.342	0.327
400	0.99	0.98	0.96	0.96	0.322	0.314
450	0.99	0.98	0.96	0.97	0.373	0.380
500	0.99	0.98	0.96	0.97	0.412	0.414
550	0.99	0.98	0.96	0.97	0.579	0.559
600	0.99	0.98	0.96	0.97	0.789	0.750
650	0.99	0.98	0.96	0.97	0.848	0.800
700	0.99	0.97	0.96	0.97	0.883	0.820
750	0.99	0.97	0.96	0.97	0.9000	0.837
800	0.99	0.97	0.96	0.97	0.911	0.858
850	0.99	0.97	0.95	0.97	0.921	0.869
900	0.99	0.97	0.95	0.97	0.925	0.871
950	0.99	0.97	0.96	0.96	0.931	0.877
1000	0.99	0.97	0.95	0.95	0.933	0.876
1050	0.99	0.96	0.95	0.97	0.933	0.877
1100	0.99	0.96	0.95	0.96	0.936	0.878
1150	0.99	0.96	0.95	0.96	0.937	0.878
1200	0.99	0.95	0.94	0.95	0.938	0.880
1250	0.99	0.95	0.95	0.94	0.940	0.883
1300	0.99	0.95	0.95	0.92	0.939	0.912
1350	0.99	0.94	0.94	0.91	0.939	0.884
1400	0.99	0.93	0.93	0.79	0.940	0.884
1450	0.99	0.91	0.93	0.70	0.941	0.893
1500	0.99	0.92	0.93	0.82	0.942	0.892
1550	0.99	0.92	0.94	0.77	0.944	0.904
1600	0.99	0.92	0.93	0.85	0.944	0.903
1650	0.99	0.92	0.93	0.88	0.944	0.908
1700	0.98	0.92	0.88	0.86	0.943	0.907
1750	0.98	0.91	0.88	0.86	0.944	0.909
1800	0.98	0.91	0.90	0.84	0.945	0.911
1850	0.98	0.91	0.91	0.82	0.944	0.910
1900	0.98	0.86	0.88	0.80	0.942	0.909
1950	0.97	0.83	0.87	0.77	0.939	0.907
2000	0.97	0.85	0.89	0.77	0.943	0.906
2050	0.95	0.86	0.89	0.75	0.943	0.907
2100	0.94	0.86	0.89	0.74	0.941	0.911
2150	0.94	0.87	0.87	0.69	0.944	0.912
2200	0.96	0.87	0.89	0.58	0.942	0.910
2250	0.96	0.86	0.73	0.44	0.943	0.908
2300	0.95	0.84	0.71	0.44	0.940	0.908
2350	0.95	0.83	0.75	0.44	0.942	0.909
2400	0.94	0.82	0.74	0.44	0.937	0.910
2450	0.93	0.80	0.74	0.47	0.939	0.911
2500	0.93	0.77	0.78	0.45	0.938	0.911
2.5-20µ	-	-	-	-	>0.940	>0.910

SECTION 2. SPECTRALON REFLECTANCE MATERIAL

Spectralon reflectance material is a thermoplastic resin that can be machined into a wide variety of shapes for the construction of optical components. The material has a hardness roughly equal to that of high-density polyethylene and is thermally stable to >350° C. It is chemically inert to all but the most powerful bases such as sodium amide and organo-sodium or lithium compounds. The material is extremely hydrophobic. Gross contamination of the material or marring of the optical surface can be remedied by sanding under a stream of running water. This surface refinishing both restores the original topography of the surface and returns the material to its original reflectance. Weathering tests on the material show no damage upon exposure to atmospheric UV flux. The material shows no sign of optical or physical degradation after long-term immersion testing in sea water.

Spectralon reflectance material gives the highest diffuse reflectance of any known material or coating over the UV-VIS-NIR region of the spectrum. The reflectance is generally >99% over a range from 400 to 1500 nm and >95% from 250 to 2500 nm. Surface or subsurface contamination may lower the reflectance at the extreme upper and lower ends of the spectral range. The material is also highly lambertian at wavelengths from 0.257 μm to 10.6 μm, although the material exhibits much lower reflectance at 10.6 μm due to absorbance by the resin.

The surface and immediate subsurface structure of Spectralon exhibits highly lambertian behavior. The porous network of thermoplastic produces multiple reflections in the first few tenths of a millimeter of Spectralon. Although it is extremely hydrophobic, this "open structure" readily absorbs non-polar solvents, greases and oils. Impurities are difficult to remove from Spectralon; thus, the material should be kept free from contaminants to maintain its reflectance properties.

The use of Spectralon should be limited to the UV-VIS-NIR. Spectralon exhibits absorbances at 2800 nm, then absorbs strongly (<20% reflectance) from 5.4 to 8 μm. Plated metal surfaces, such as the Labsphere Infragold-IR standards, are recommended as diffuse reflectance standards for the MIR.

Three grades of Spectralon reflectance material are available: optical-grade, laser-grade and space-grade. Optical-grade Spectralon is characterized by a high-reflectance and lambertian behavior over the UV-VIS-NIR wavelength region. Laser-grade Spectralon offers the same physical characteristics as optical-grade materials but is a different formulation of resin that gives enhanced performance when used in laser pump cavities. Space-grade Spectralon combines high-reflectance with an extremely lambertian reflectance profile and is the material of choice for terrestrial remote sensing applications. The reflectance data of optical-grade, laser-grade and space-grade Spectralon materials are shown on the following page.

2.1 Reflectance Data of Optical-, Laser- and Space-Grade Spectralon Reflectance Materials

Wavelength	SRM-99O	SRM-99L	SRM-99S
250	0.950	0.929	0.950
300	0.985	0.970	0.985
400	0.990	0.987	0.990
500	0.991	0.987	0.991
600	0.992	0.989	0.992
700	0.992	0.987	0.992
800	0.991	0.986	0.991
900	0.991	0.987	0.991
1000	0.993	0.988	0.993
1100	0.993	0.987	0.993
1200	0.992	0.985	0.992
1300	0.992	0.985	0.992
1400	0.991	0.982	0.991
1500	0.991	0.982	0.991
1600	0.991	0.982	0.991
1700	0.988	0.977	0.988
1800	0.989	0.976	0.989
1900	0.981	0.968	0.981
2000	0.976	0.957	0.976
2100	0.953	0.924	0.953
2200	0.973	0.944	0.973
2300	0.972	0.934	0.972
2400	0.955	0.926	0.955
2500	0.950	0.902	0.950

Figure 6 - Optical-Grade Spectralon Material

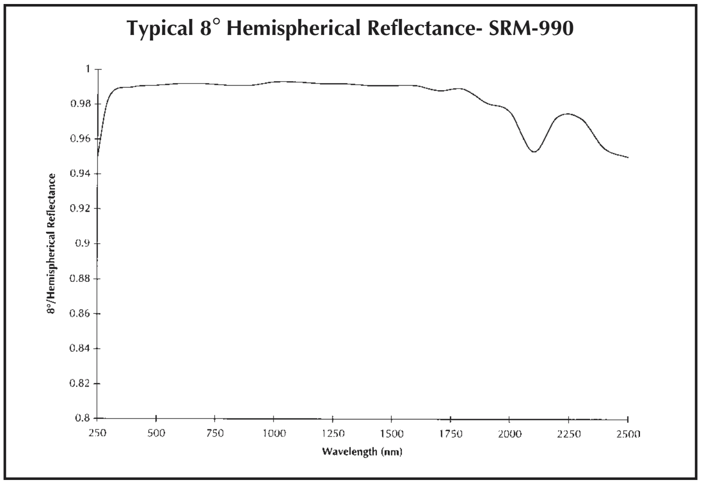


Figure 7 - Laser-Grade Spectralon Material

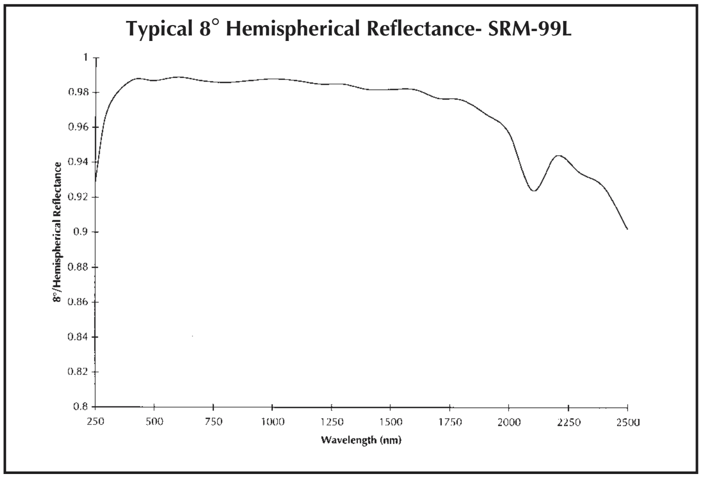
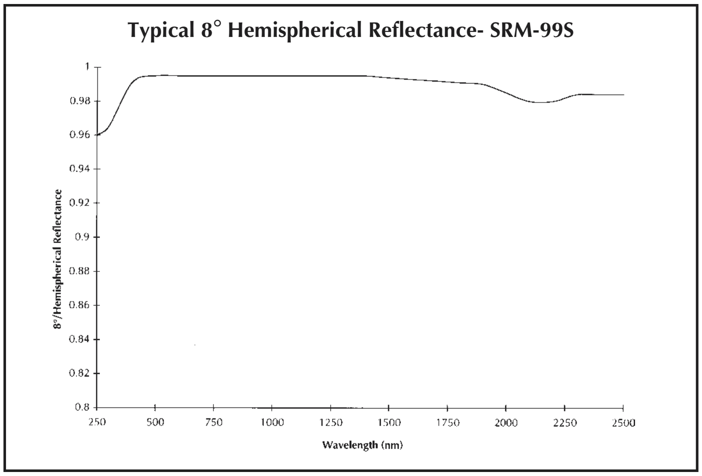


Figure 8 - Space-Grade Spectralon Material



SRM-99S space-grade Spectralon exhibits the same high reflectance and extremely lambertian profile as optical-grade Spectralon. Space-grade Spectralon, however, is fabricated under an advanced manufacturing process to ensure that the material is of the highest purity and cleanliness, essential for space applications.

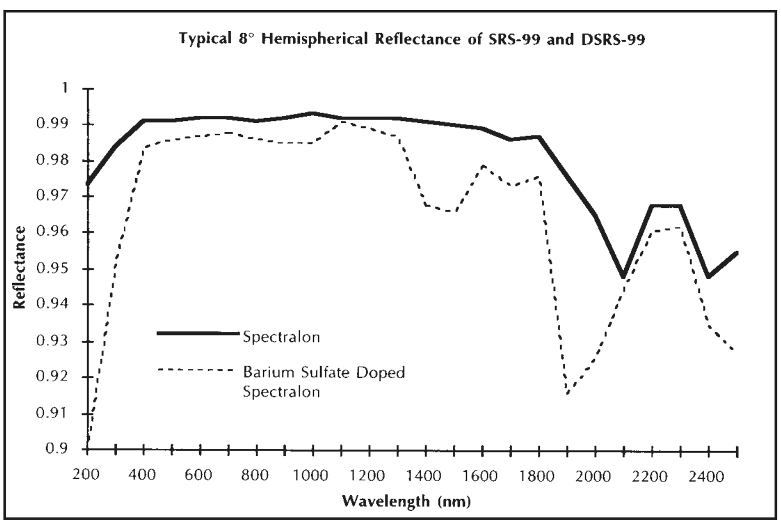
2.2 Physical, Thermo-Optical and Electronic Properties of Spectralon

Property	ASTM Test	Value
Density:	**	1.25 - 1.5 g/cm^3
Water Permeability:	D-570	<0.001% (hydrophobic)
Hardness:	D-785	20 - 30 Shore D
Thermal Stability:	**	Decomposes at >400°C
Coefficient of Linear Expansion:	D-696	5.5 - 6.5 x 10^{-5} in/in -°F; 10^{-4}°C^{-1}
Vacuum Stability:	**	No outgassing except for entrained air
Flammability:	**	Non-flammable (UL rating V-O)
		Incompatible with non-polar solvents and greases
Yield Stress:	D-638	208 psi
Ultimate Stress:	D-638	891 psi
Young's Modulus:	**	35774 psi
Elongation in 2 in.:	D-638	42.8%
Elongation at Failure:	D-638	91.3%
Poisson's Ratio:	E-132	0.296
Deformation under load:	D-621	13.3 % @ 250 lbs.
	D-621	22.6% @ 500 lbs.
Absorbance (a_s):	**	0.07
Emittance (e):	**	0.88
Volume Resistivity:	**	>10^{18} ohm/cm
Dielectric Strength:	D-149	18 V/μm
Refractive Index:	D-542	1.35
Flammability Rating:	UL-94	V-O

2.3 Reflectance Properties of Spectralon

Spectralon exhibits relatively flat spectral distribution over most of the UV-VIS-NIR. From 250 to 2500 nm, Spectralon exhibits a reflectance variance of <5% between 360 - 740 nm (VIS) the variance in reflectance is <0.5%. These spectral properties exceed those of most paints, which show strong absorbances in the UV due to absorbances by TiO_2 or similar pigments. The hydrophobic nature of Spectralon also leads to exclusion of water overtone bands in the NIR which may occur in barium-sulfate-based materials. The open structure of Spectralon causes both reflectance and transmittance, but not absorbance of light. For applications requiring totally opaque reflectance, barium sulfate may be added to Spectralon without greatly affecting the reflectance properties. Reflectance data of both Spectralon and barium-sulfate-doped Spectralon is shown in the following illustration (Figure 11).

Figure 9 - Reflectance Data of Spectralon SRS-99 and Barium-Sulfate-Doped Spectralon



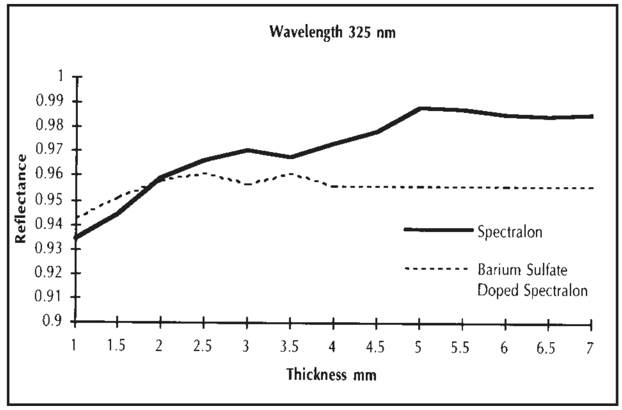
Wavelength (nm)	Spectralon SRS-99	Barium-Sulfate Doped-Spectralon
300	0.984	0.952
400	0.991	0.984
500	0.991	0.986
600	0.992	0.987
700	0.992	0.988
800	0.991	0.986
900	0.992	0.985
1000	0.993	0.985
1100	0.992	0.991
1200	0.992	0.989
1300	0.992	0.987
1400	0.991	0.968
1500	0.990	0.966
1600	0.989	0.979
1700	0.986	0.973
1800	0.987	0.976
1900	0.976	0.916
2000	0.965	0.926
2100	0.948	0.945
2200	0.968	0.961
2300	0.968	0.962
2400	0.948	0.935
2500	0.955	0.927

2.4 Reflectance Properties of Thin Sections of Spectralon

The reflectance of Spectralon decreases with decreasing thickness over most of the spectrum. Thin sections of Spectralon, less than 4 mm, may be doped with barium sulfate to maintain high reflectance and diffuse properties. The figures below illustrate the reflectance properties of thin sections of Spectralon and barium-sulfate-doped Spectralon.

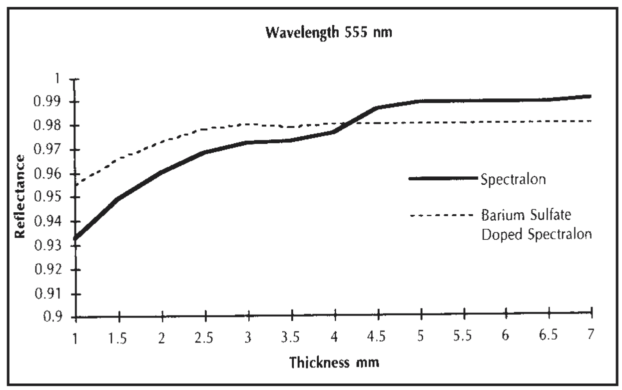
325 nm Thickness	Spectralon	Doped Spectralon	450 nm Thickness	Spectralon	Doped Spectralon
1.0	0.934	0.943	1.0	0.937	0.956
1.5	0.944	0.951	1.5	0.951	0.966
2.0	0.959	0.958	2.0	0.962	0.972
2.5	0.966	0.961	2.5	0.969	0.977
3.0	0.970	0.957	3.0	0.973	0.977
3.5	0.967	0.961	3.5	0.973	0.977
4.0	0.973	0.956	4.0	0.977	0.978
4.5	0.978	0.956	4.5	0.988	0.978
5.0	0.988	0.956	5.0	0.992	0.978
5.5	0.987	0.956	5.5	0.992	0.978
6.0	0.985	0.956	6.0	0.991	0.978
6.5	0.984	0.956	6.5	0.990	0.978
7.0	0.985	0.956	7.0	0.991	0.978

Figure 10



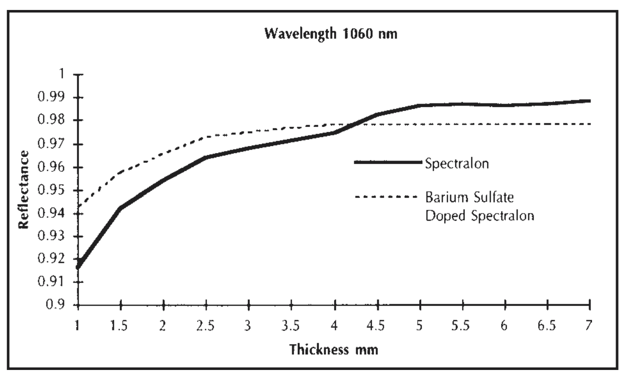
555 nm Thickness	Spectralon	Doped Spectralon	720 nm Thickness	Spectralon	Doped Spectralon
1.0	0.933	0.955	1.0	0.928	0.956
1.5	0.949	0.966	1.5	0.948	0.961
2.0	0.960	0.973	2.0	0.958	0.971
2.5	0.968	0.978	2.5	0.967	0.974
3.0	0.972	0.98	3.0	0.970	0.976
3.5	0.973	0.979	3.5	0.973	0.978
4.0	0.976	0.980	4.0	0.976	0.977
4.5	0.986	0.980	4.5	0.984	0.977
5.0	0.989	0.980	5.0	0.988	0.977
5.5	0.989	0.980	5.5	0.988	0.977
6.0	0.989	0.980	6.0	0.987	0.977
6.5	0.989	0.980	6.5	0.988	0.977
7.0	0.990	0.980	7.0	0.989	0.977

Figure 11



850 nm Thickness	Spectralon	Doped Spectralon	1060 nm Thickness	Spectralon	Doped Spectralon
1.0	0.922	0.955	1.0	0.916	0.943
1.5	0.946	0.959	1.5	0.942	0.958
2.0	0.956	0.969	2.0	0.954	0.966
2.5	0.966	0.973	2.5	0.964	0.973
3.0	0.969	0.975	3.0	0.968	0.975
3.5	0.972	0.979	3.5	0.971	0.977
4.0	0.976	0.983	4.0	0.974	0.978
4.5	0.983	0.983	4.5	0.982	0.978
5.0	0.985	0.983	5.0	0.986	0.978
5.5	0.985	0.983	5.5	0.987	0.978
6.0	0.986	0.983	6.0	0.986	0.978
6.5	0.986	0.983	6.5	0.987	0.978
7.0	0.987	0.983	7.0	0.988	0.978

Figure 12



2.5 Bidirectional Reflectance Distribution Function (BRDF)

The Bidirectional Reflectance Distribution Function (BRDF) is defined as the ratio of the radiance of a sample to the irradiance upon that sample, for a given direction of incidence and direction of scatter.

The incident direction is specified by two angles: the angle of incidence (θ_i), and the incident azimuth angle (ϕ_i). Similarly, the scatter direction is specified by the scatter angle (θ_s) and the scatter azimuth angle (ϕ_s). These angles are defined in the beam coordinate system represented in Figure 15.

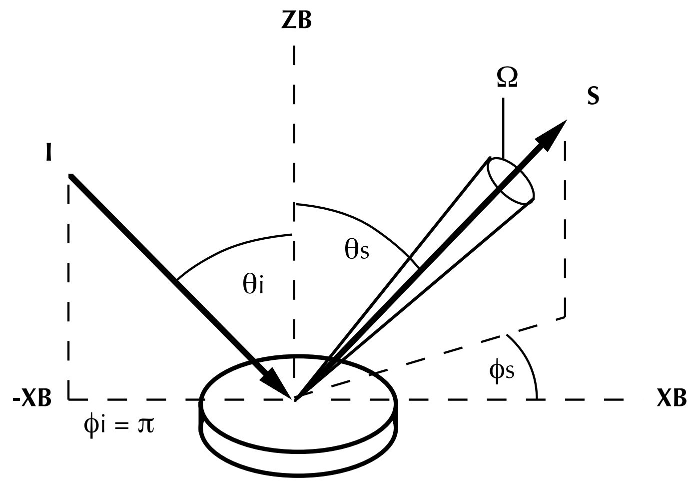


Figure 13 - Beam Coordinate System

The origin of the beam coordinate system is the point at which the central ray of the incident radiation (I) strikes the sample surface. The ZB axis is normal to the sample surface, and the XB axis lies in the plane defined by ZB and I. The incident direction is given by (θi,ϕi), where ϕi = π by definition. The scatter direction is given by (θs,ϕs). Ω is the solid-angle subtended by the receiver.

BRDF is typically measured using an apparatus which allows the sample to be illuminated with a collimated or slightly converging beam from a range of incident directions. A receiver, subtending solid angle Ω, views the entire illuminated area and can be positioned at a range of scatter directions. For any given configuration, an average sample irradiance is calculated from the power P_i incident on the sample and the illuminated area A. An average sample radiance L_e is calculated from the power P_s collected by the receiver, the receiver solid-angle, and the area of illumination. The sample BRDF is calculated as the ratio of these two quantities, as represented in equation (1).

(1) $$\text{BRDF} = \frac{L_e}{E_e} = \frac{(Ps/\Omega A\cos\theta_s)}{(P_i/A)} = \frac{P_s}{P_i\Omega\cos\theta_s} \quad [\text{sr-1}]$$

Alternatively, the relative radiance of the sample may be measured versus that of a standard whose BRDF is known for the bidirectional geometry in question. The sample BRDF may then be calculated by multiplying the resulting ratio by the known BRDF of the standard.

It is common practice to limit the collection of BRDF data to receiver positions in the plane of incidence, which is defined by the central ray of the incident flux and the sample normal. This is referred to as “in-plane” data. Similarly, data collected with receiver positions confined to the plane perpendicular to the plane-of-incidence, and containing the sample normal, is referred to as “cross-plane” data.

BRDF, with its units of inverse steradians, is a fairly abstract quantity. The BRDF of a given sample is closely related to a more concrete quantity, however, its bidirectional reflectance factor. This is defined as the ratio of the flux scattered in a given direction by the sample, to that which would be scattered in that direction by the perfect reflecting diffuser, under identical conditions of illumination. The relation between BRDF (B) and bidirectional reflectance factor (R) is expressed in equation (2).

$$\mathbf{R}(\theta_i,\phi_i,\theta_s,\phi_s) = \pi\mathbf{B}(\theta_i,\phi_i,\theta_s,\phi_s) \quad (2)$$

The BRDF of a perfectly diffuse (lambertian) sample would be constant for all bidirectional geometries. Note, however, that the power P_s collected by the receiver is strongly dependent on the scatter angle, θ_s, and becomes very small as θ_s approaches $\pi/2$. For this reason, the effects of system noise, and other sources of measurement error, become much more pronounced at large scatter angles.

Both the polarization state of the incident flux and the polarization bias of the receiver may be important variables in BRDF measurement. Many scattering materials significantly depolarize incident flux; other materials selectively absorb flux with a certain polarization. Complete characterization of sample scattering requires evaluation of these polarization effects. Note, however, that many BRDF instruments use sources of illumination, such as lasers, with a strong linear polarization, and the effects of this polarization are not always taken into account in reporting results. Figures 16 and 17 represent the BRDF of Spectralon under various polarization conditions.

Figure 14 - In-Plane BRDF at 633 nm - 30° Incidence Polarized Light

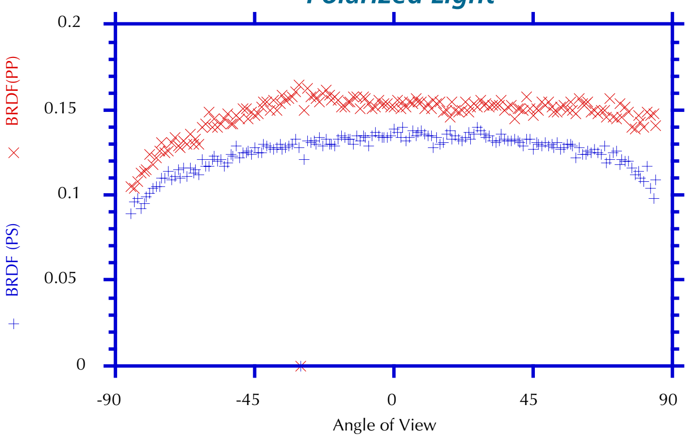
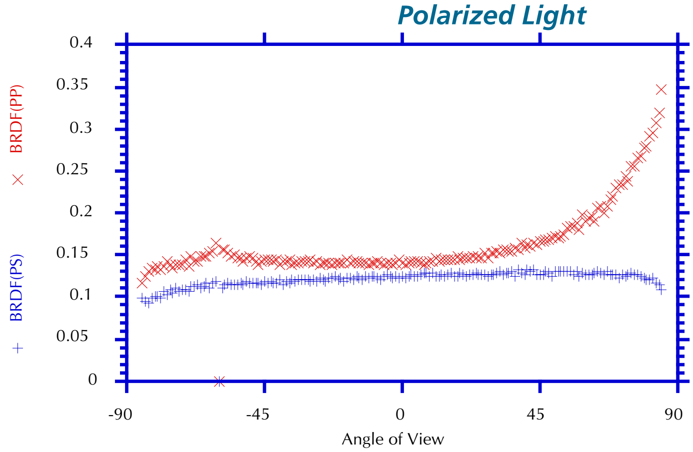


Figure 15 - In-Plane BRDF at 633 nm - 60° Incidence Polarized Light



Figures 14 and 15 - In-Plane BRDF of Spectralon at 633 nm

BRDF measurements are typically dependent on the polarization bias of the receiver and the source of illumination. These plots present data for Labsphere Spectralon Diffuse Reflectance Material, under linearly polarized illumination, where the direction of polarization is parallel (P) to the plane of incidence. The receiver is also polarized, with bias parallel (P) or perpendicular (S) to the plane of incidence. For a material which did not affect the polarization of the incident flux, observed BRDF for the cross-polarized configuration (PS) would be zero. For a perfect depolarizing sample, BRDF values would be identical for the two measurement configurations.

The foregoing account of BRDF measurements is based upon ASTM Standard E1392-90, “Standard Practice for Angle-Resolved Optical Scatter Measurements on Specular or Diffuse Surfaces.” This document includes an extremely detailed and lucid treatment of the subject of BRDF measurement, and is highly recommended as a starting point for further reading.

2.6 Variable Angle Reflectance Studies

Another measure of a material's ability to scatter light is its total hemispherical reflectance as a factor of the angle of the incident radiation. Spectralon samples ranging in nominal reflectance from 2% to 99% (measured at an incident radiation angle of 8°) were measured at incident angles of 45° and 61°.

The measurements were made using a Labsphere RSA-PE-9/19 Reflectance Spectroscopy Accessory for a Perkin-Elmer Lambda 9 Spectrophotometer. The samples were then measured for absolute reflectance using NIST tiles 2019a and 2021 as standards. The hemispherical reflectance factor was calculated as follows:

Reflectance Factor = $R_{(sample)} * R_{(ref)}$

Reflectance versus Incident Angle

Sample SRS-99 (99%)

Wavelength (nm)	ΔR(45°)	ΔR (61°)
300	+0.009	+0.010
600	-0.006	-0.005
900	-0.002	+0.001
1200	-0.002	-0.003
1500	-0.003	-0.002
1800	-0.004	+0.000
2100	+0.015	+0.013
2400	+0.022	+0.015

Sample SRS-60 (60%)

Wavelength (nm)	ΔR(45°)	ΔR(61°)
300	+0.026	+0.064
600	+0.021	+0.050
900	+0.033	+0.051
1200	+0.027	+0.042
1500	+0.024	+0.042
1800	+0.020	+0.040
2100	+0.029	+0.040
2400	+0.040	+0.042

Sample SRS-20 (20%)

Wavelength (nm)	ΔR(45°)	ΔR (61°)
300	+0.021	+0.051
600	+0.021	+0.051
900	+0.028	+0.059
1200	+0.024	+0.056
1500	+0.022	+0.055
1800	+0.020	+0.061
2100	+0.023	+0.050
2400	+0.023	+0.052

Sample SRS-02 (2%)

Wavelength (nm)	ΔR(45°)	ΔR(61°)
300	+0.021	+0.031
600	+0.017	+0.023
900	+0.008	+0.015
1200	+0.007	+0.014
1500	+0.004	+0.011
1800	+0.004	+0.010
2100	+0.008	+0.014
2400	+0.013	+0.022

VALUES SHOWN ARE ΔR/R

2.7 Environmental Testing of Spectralon Material

Spectralon was exposed to atomic oxygen from an ERC plasma stream, with a fluence of $\approx 5.3 \times 10^{20}$ oxygen ions per square centimeter, with a vacuum in the range of 10^{-5} torr. Post-exposure measurements of the Spectralon showed no change in either the reflectance or the BRDF of the material.(1)

Spectralon was bombarded with low energy protons at a current density of 10^{12} protons cm^{-2} at 40 KeV in a vacuum of $\leq 10^{-6}$ torr. As with the atomic oxygen exposure, no change was seen in either the reflectance or BRDF of the material from pre-exposure measurements.(1)

Spectralon test samples were exposed to deep and mid-UV (unfiltered Hg arc lamp) at a vacuum of $\leq 10^{-6}$ torr with the equivalent of 2 suns for 500 equivalent sun hours. At 110 sun hours, a lowering of reflectance of between 5 - 10 % in the UV was noted; at 500 sun hours, a slight yellowing in the VIS was noted, along with a 20% total drop in the UV (250 nm). However, upon returning to atmospheric conditions, the material returned to near original values, presumably due to oxidation and loss of the surface contaminants that caused the discoloration.(1) Data from another source indicates that the loss of reflectance in the UV and subsequent yellowing does not occur if Spectralon is subjected to a vacuum bakeout procedure. Spectralon has undergone extensive testing for UV-VUV exposure, proton bombardment, atomic oxygen exposure an α-Lyman radiation. Please contact Labsphere for a list of published articles for results of this testing.

Spectralon plates were subjected to electron beam bombardment with a beam energy of 10KeV at densities of 0.5, 1.0, and 5.0 nA cm-2. The Spectralon was uniformly charged to a potential of -6000V. Investigation of the discharge phenomenon over extended periods showed no discharge at any current density or charging.(1)

Spectralon has undergone two types of weathering and environmental tests. After measuring the initial reflectance of several samples, they were exposed to the outside environment of central New Hampshire for up to two years. At three month intervals, the samples were cleaned and gently sanded under a stream of tap water to restore the original surface finish. Measurements taken at 50 nm intervals throughout the visible wavelength region revealed essentially no change in reflectance. The results of those tests are shown below.

Environmental Exposure

Wavelength (nm)	Original Reflectance	Reflectance after Exposure 1 Month	4 Months	1.5 Years
400	0.988	0.987	0.988	0.986
450	0.990	0.988	0.988	0.990
500	0.989	0.985	0.987	0.985
550	0.987	0.983	0.987	0.986
600	0.987	0.984	0.988	0.988
650	0.987	0.985	0.988	0.988
700	0.986	0.983	0.988	0.987

In a second test, samples of the same material were immersed in sea water. After six months, no change in reflectance was noted. No surface preparation or cleaning was necessary as the samples were not wetted by sea water, neither initially or after six months immersion.

(1) MERIS Activities Report, Doc. No. PO.RP.LSP.ME.0008 10-28-93. This work was performed by Lockheed in conjunction with flight qualification of Spectralon Reflectance Material for use on the European Space Agency MERIS sensor, launched in 1997.

2.8 Spectralon Gray Scale Material

Spectralon can be doped with black pigment to produce spectrally flat gray scale standards and targets. Spectralon gray materials have physical and spectral properties similar to Spectralon and are useful as standards for calibration of various optical instruments, including those used in blood analysis, CCD arrays and night vision devices. The reflectance data of representative samples of Spectralon gray scale materials are shown below in Figure 18.

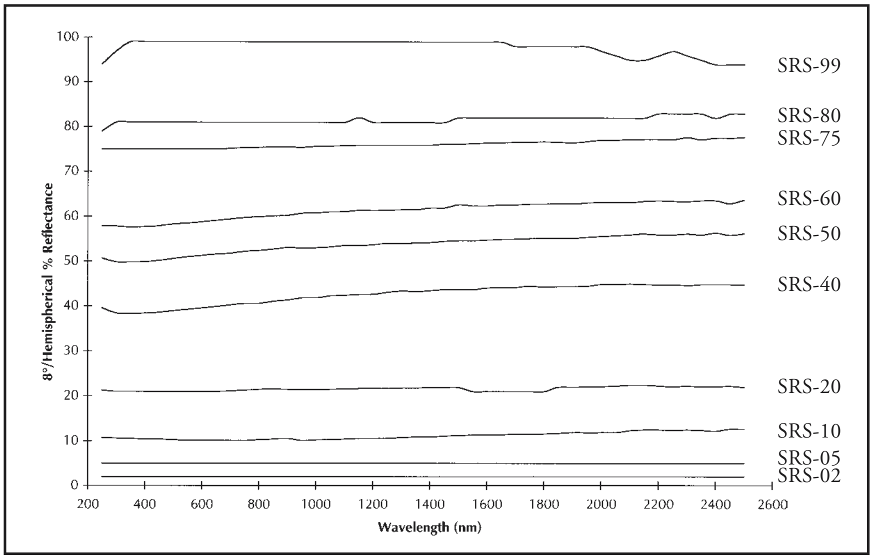


Figure 16 - Spectralon Gray Scale Reflectance Data

2.9 Spectralon High-Reflectance Gray Scale Material

Gray scale Spectralon is used to establish the linearity and accuracy of reflectance spectrophotometers and colorimeters, much in the way that calibrated neutral density filters are used in transmittance instruments. While standard Spectralon gray scale sets are suitable for users who need a wide dynamic range of reflectance, certain applications require sets of gray scale that are abbreviated in range but not in the number of steps of calibration. Industries such as clay and processed minerals, paper and paints may require such a scale, which fairly accurately reproduces the range of reflectances shown by such products.

High-reflectance gray scale Spectralon allows the user to calibrate and validate their instrument over a range of reflectance from 80 - 94%, in roughly 2% reflectance factor steps. The standards are available with NIST-traceable calibration in geometries of 8°/hemispherical (specular included or excluded) and 0°/45° geometry. The reflectance data of representative samples of high-reflectance gray scale Spectralon material is shown in Figure 19.

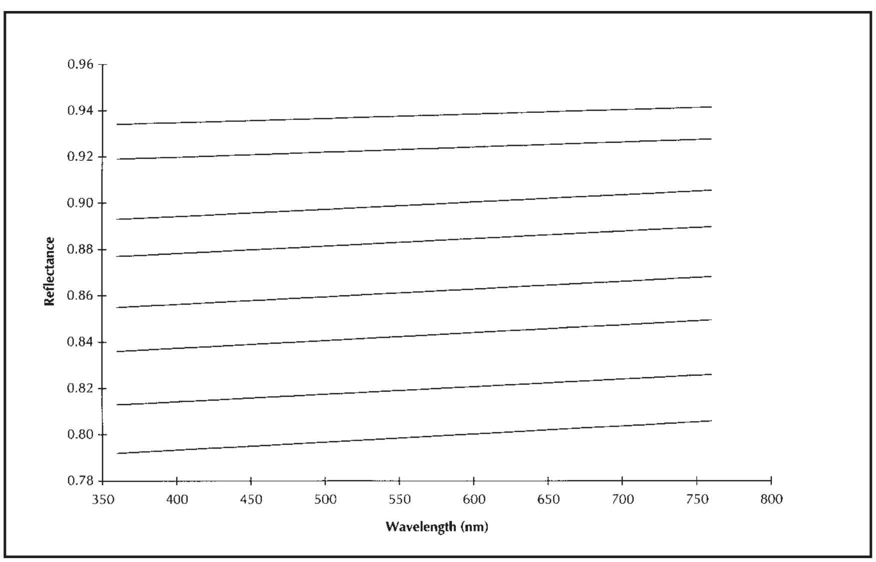


Figure 17 - Spectralon High-Reflectance Gray Scale Reflectance Data

2.10 Spectralon Color Materials

Several colorimetric standards are available today, including Spectralon color materials, ceramic tiles, painted chips and Carrera glass. Spectralon color materials have the same physical properties as Spectralon. Therefore, they solve many of the problems associated with other standards. Available in an endless range of colors, Spectralon color materials offer the durability typically lacking in painted chips and ceramic tiles. Unlike ceramic tiles, Spectralon color materials are not subject to the restriction of a specific measurement geometry.

Slight translucency in supposedly opaque material can cause errors due to undetected light losses. Spectralon color standards exhibit significantly less translucency error than Carrera glass standards. Spectralon color standards are also less temperature sensitive than previously available standards and thus less subject to chromatic drift when warmed under intense illumination.

***Figure 18** - Reflectance Data of Spectralon Color Standards Red, Yellow, Green and Blue*

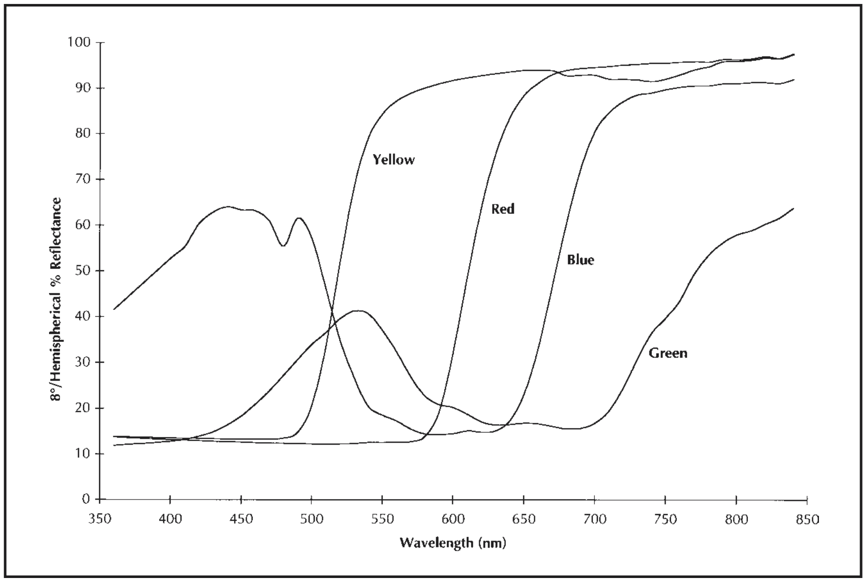
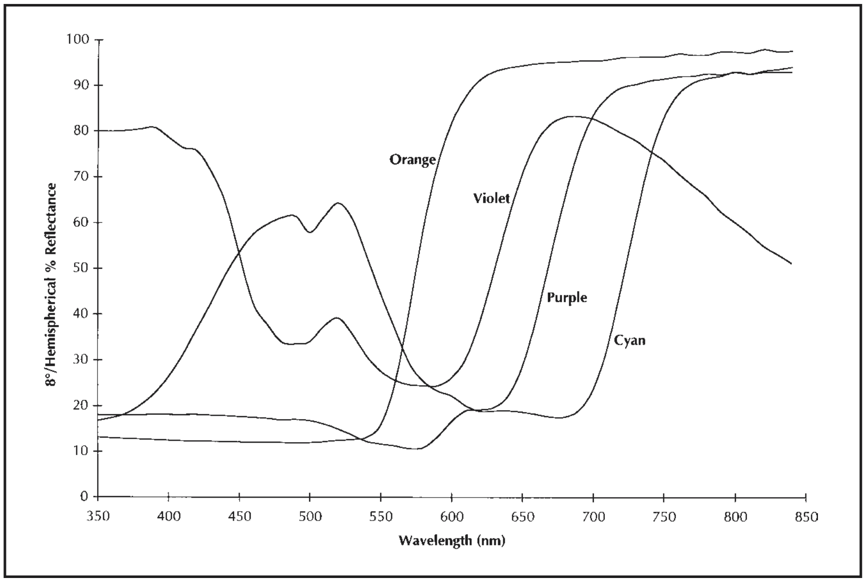


***Figure 19** - Reflectance Data of Spectralon Color Standards Cyan, Purple, Violet and Orange*



2.11 Spectralon Color Pastel Materials

Spectralon color pastel materials are particularly useful in the paper and textile industries, where colors are frequently less saturated than those used in plastics or metals. Color pastel materials exhibit the same high reflectance, lambertian behavior, stability and durability as Spectralon color materials, however, they contain a lower concentrate of color. Because of this formulation, the material is exceptionally non-thermochromic. This means that the material is unaffected by temperature shifts in the manufacturing or laboratory environment. The thermally stable properties of Spectralon color pastel material make it the ideal material for standards used in laboratory or manufacturing situations where the environment may be unpredictable. Spectralon color pastel standards aid in developing consistent color reproduction for manufacturers of products such as paper and textiles.

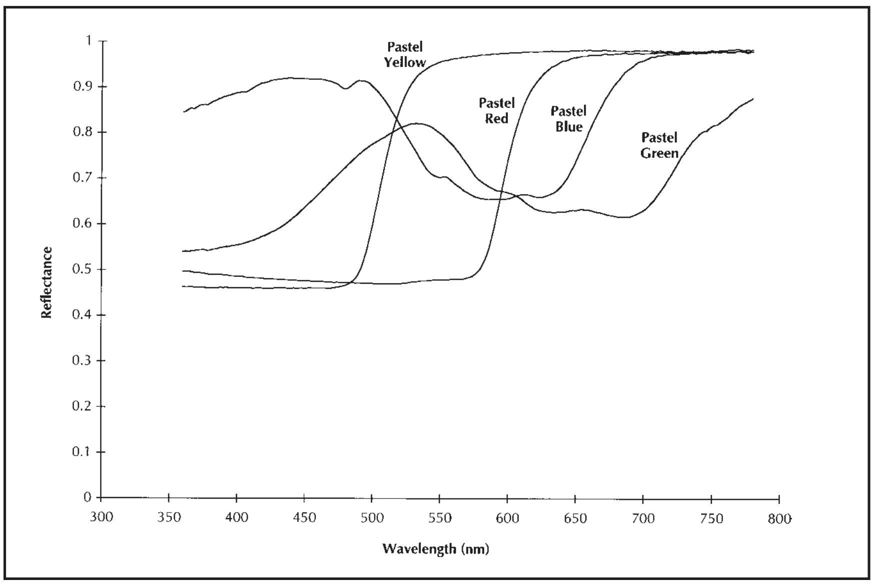


Figure 20 - Reflectance Data of Spectralon Color Pastel Standards Red, Yellow, Green and Blue

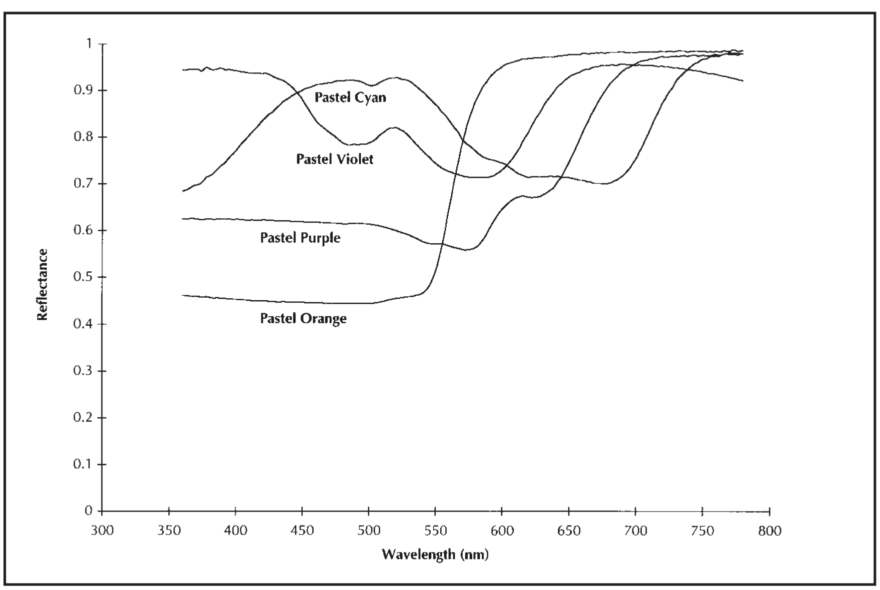


Figure 21 - Reflectance Data of Spectralon Color Pastel Standards Cyan, Purple, Violet and Orange

2.12 Spectralon Fluorescence Materials

Spectralon fluorescence materials provide highly stable, reproducible fluorescence reflectance over long periods in varying conditions. Spectralon provides the ideal matrix for inorganic fluors which are photochemically stable compared to their organic counterparts. The stability of the inorganic fluors, when combined with the durability of Spectralon, results in rugged, long-lasting fluorescence standards for both field and laboratory use.

The following charts show the Radiance Factor and Color Stimulus Function of Labsphere fluorescence materials.

Figure 22 - SFS-421 Blue-Violet Fluorescence Excitation Maxima at 421 nm

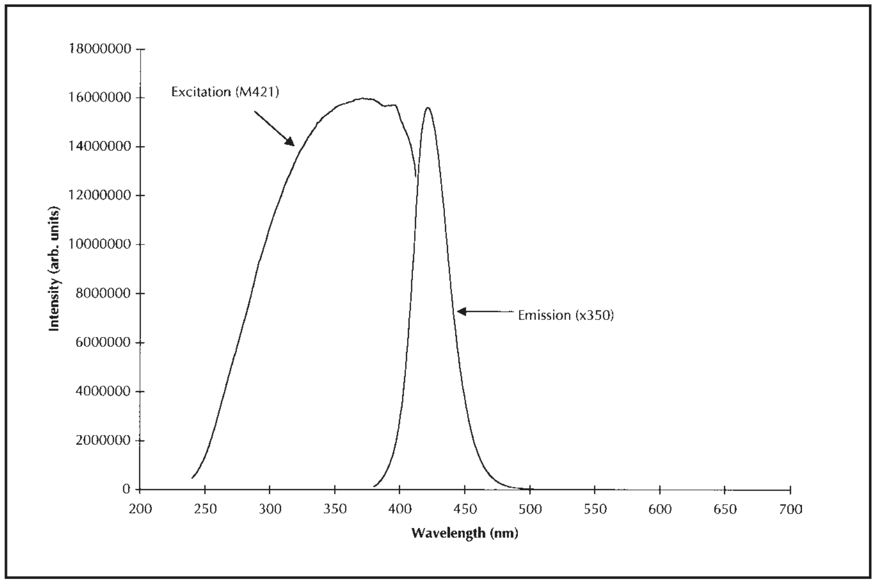
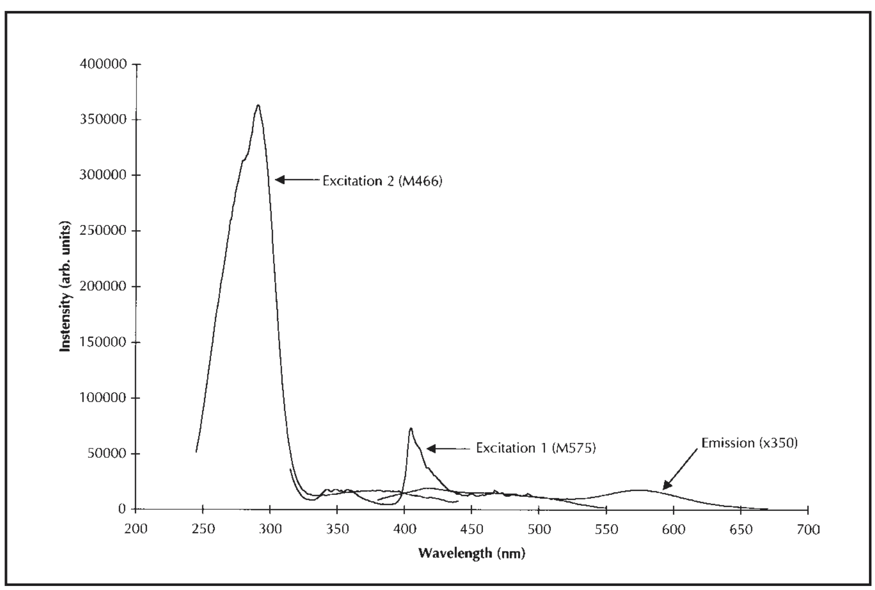


Figure 23 - SFS-466 Bright Blue Fluorescence Excitation Maxima at 466 nm, and 575 nm



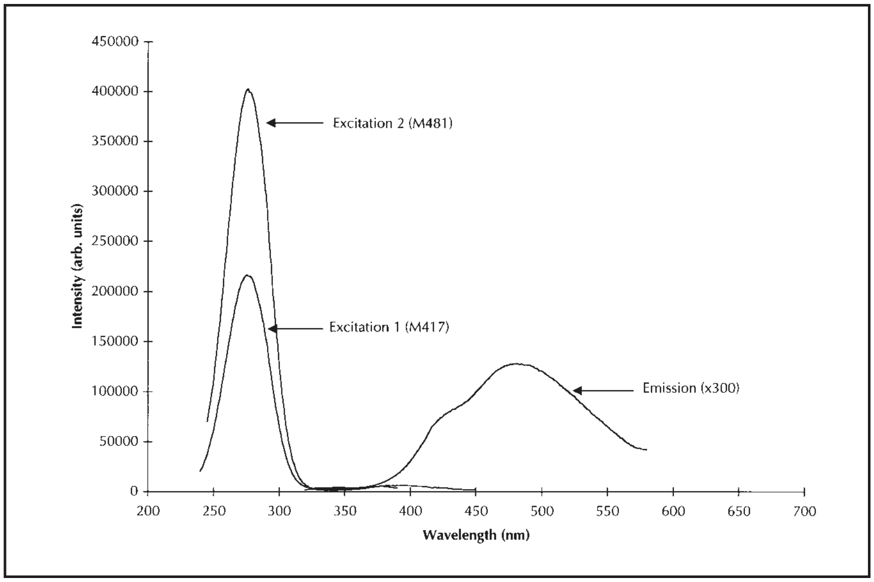


Figure 24 -
SFS-417
Broadband Blue/White Fluorescence Excitation Maxima at 417 nm, and 481nm

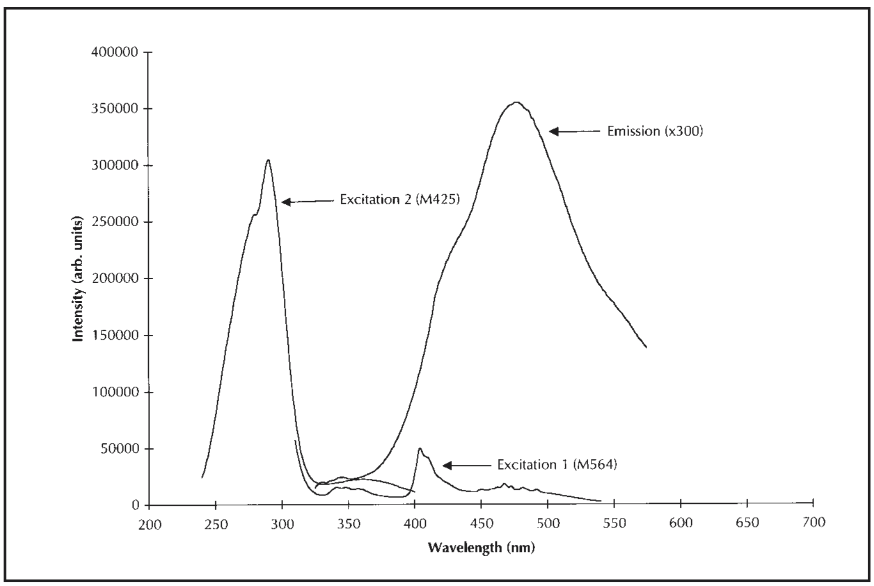


Figure 25 -
SFS-425
Broadband Bright Blue/White Fluorescence Excitation Maxima at 425 nm, and 564 nm

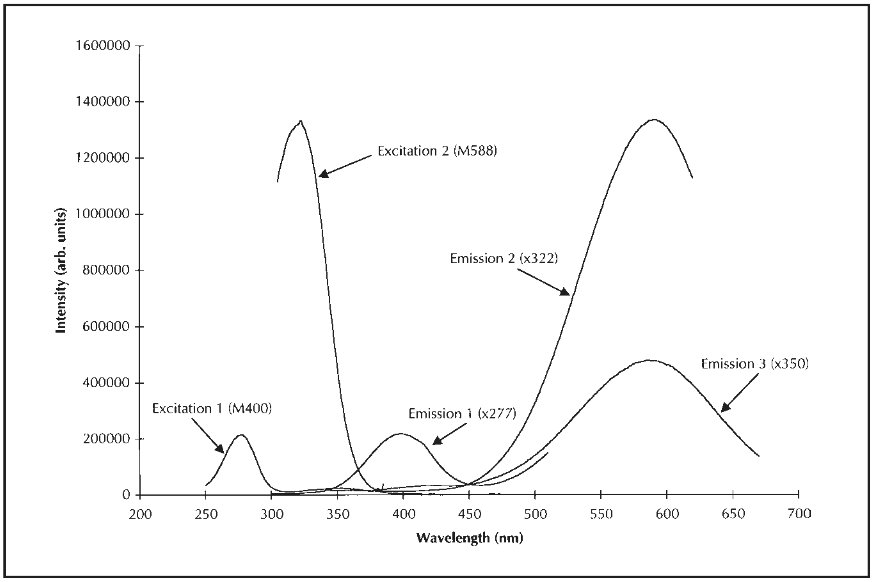


Figure 26 - SFS-400 Orange fluorescence Excitation Maxima at 400 nm, and 588 nm

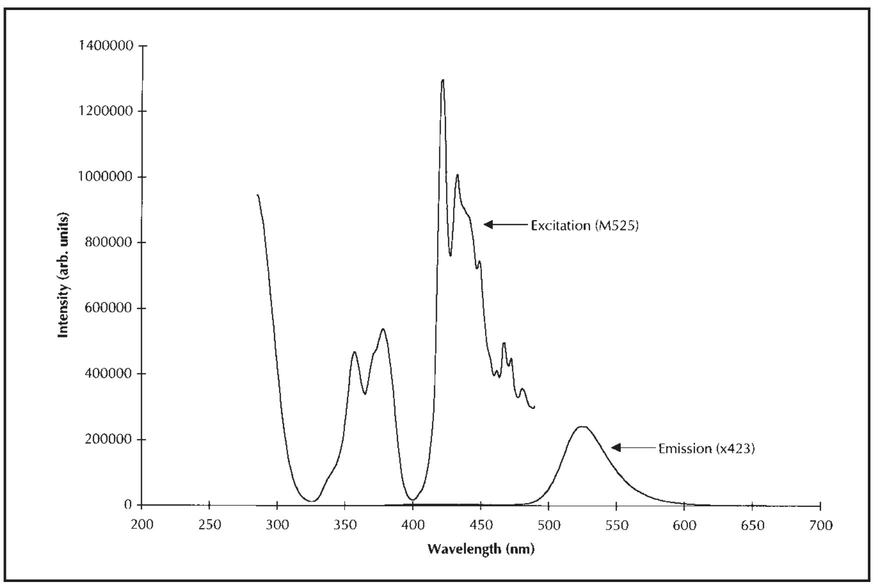


Figure 27 - SFS-525 Green Fluorescence Excitation Maxima at 525 nm

2.13 Spectralon UV-VIS-NIR Diffuser Material

Spectralon diffuser material consists of thin sections, generally between 0.1 and 1.0 mm, of specially formulated Spectralon. This material is designed to transmit and effectively scatter incident light. Diffusers fabricated from Spectralon are particularly useful for broad band diffusion of optical radiation, specifically over the UV, as well as the visible and near-infrared spectral regions. Spectralon diffuser material is invaluable in reducing the sensitivity of detectors to beam alignment and improving the uniformity of light sources.

Spectralon diffusers have a useful range from 250 to 2500 nm and are significantly more diffuse than double-ground quartz. By changing various parameters within the formulation, a range of transmittance can be obtained (see Figure 30). With an increase in transmittance, however, there is a corresponding lessening of the degree of diffuseness (see Figure 31). In addition, transmittance may vary by as much as 2-3% across a piece. These variations are a function of the thickness, density and other factors. At transmittances of 20% or less, Spectralon diffuser material is an almost perfect scatterer of incident radiation.

As with Spectralon reflectance material, diffuser material is totally hydrophobic and inert. When subjected to 24 hours of atomic oxygen exposure (plasma ashing) a minimal weight loss has been reported and no degradation of the optical properties was observed.

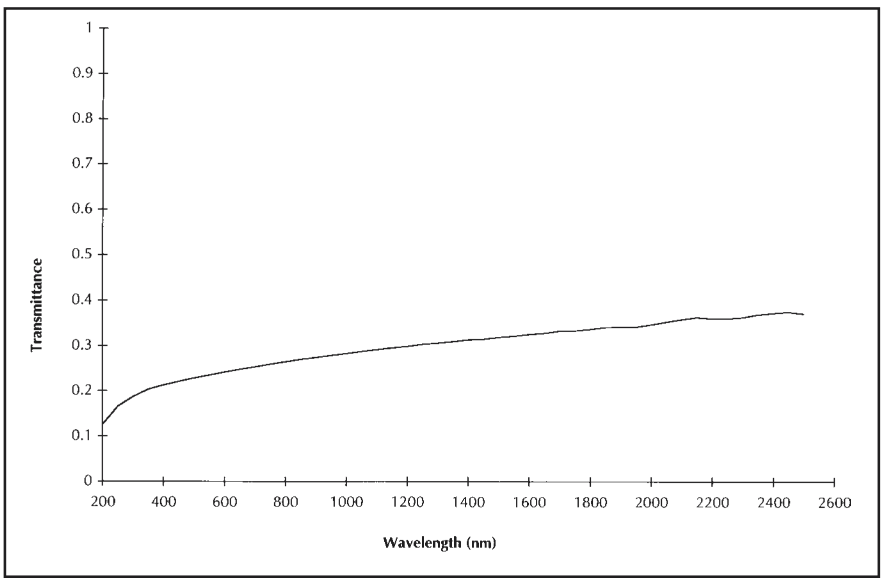


Figure 28 - Total Hemispherical Transmittance of Labsphere SDM Diffusers

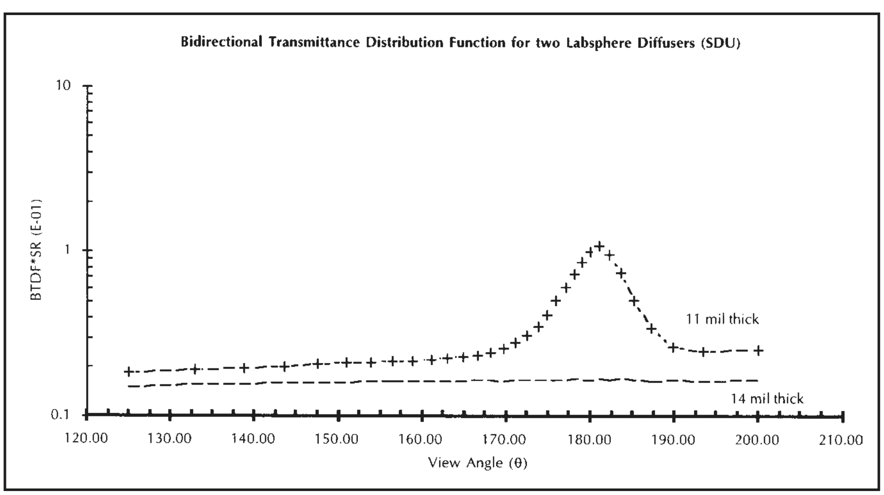


Figure 29 - Bidirectional Transmittance Distribution Function of Labsphere SDU Diffusers

(Data provided by D. Lowrance, Martin Marietta, Boulder, CO.)

LIST OF ILLUSTRATIONS

DESCRIPTION

GENERAL REFERENCES

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Erb, W., "Requirements for Reflectance Standards and the Measurement of Their Reflection Values," Applied Optics, 14 (2).

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Weidner, V.R. and J.J. Hsia, and K.L. Eckerle, "Exploratory Research in Reflectance and Fluorescence Standards at the National Bureau of Standards," Optics News, November, 18-20 (1986).

"Standard Practice for Angle Resolved Optical Scatter Measurements on Specular Diffuse Surfaces," ASTM Standard: E1392-90.