

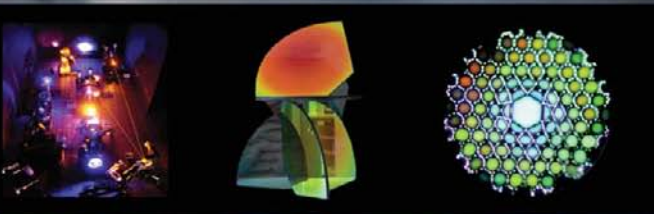
Third Edition

Sponsored by the Optical Society of America

HANDBOOK OF OPTICS

Volume IV

*Optical Properties of Materials, Nonlinear Optics,
Quantum Optics*



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HANDBOOK OF OPTICS

Volume IV
Optical Properties of Materials,
Nonlinear Optics, Quantum Optics

THIRD EDITION

Sponsored by the
OPTICAL SOCIETY OF AMERICA

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The concept of greatest importance regarding the use of aspheric surfaces is that *successful production of the total system is cast into considerable doubt if a surface is present which is not amenable to convenient testing*. While some aspheric optics may be nulled fairly easily, those which appear in polymer optical systems are frequently strong, exhibiting significant high-order derivatives. If the base curves are strong, especially strongly convex, there may exist no practical geometry in which to create a nulling optical system. And if a favorable geometry does exist, several optical elements may be necessary to effect adequate correction. One can easily approach a practical limit in this situation, since the manufacturing and assembly tolerances of the cascaded spherical elements may themselves (in superposition) exceed the theoretical correction requirement. The bottom line is that one should not proceed with cell design, or any other hardware design and construction, until the aspheric testing issues have been completely resolved.

3.8 COATINGS

Reflective Coatings

Given the fact that optical polymers exhibit specular properties similar to those of glass, it is not surprising that optical coatings are often necessary in polymeric optical systems. The coatings deposited upon polymer substrates fall mostly into four general categories. These include coatings to improve reflectivity, to suppress specular reflection, to improve abrasion resistance, and to retard accumulation of electrostatic charge.

Reflective coatings may be applied by solution plating, or by vacuum-deposition. These are most often metallic coatings, usually aluminum if vacuum-deposited, and normally chromium if applied by plating. The abrasion resistance and general durability of such coatings is rather poor, and susceptibility to oxidation quite high, if no protective coating is applied over the metal film. In some applications, especially involving vacuum deposition, the overcoat may be a thin dielectric layer, deposited during the same process which applies the metal film. If the reflective coating has been applied by plating, the overcoat may be an organic material, perhaps lacquer, and may be deposited separately by spraying or dipping. Not surprisingly, the quality of a surface so treated will be poor by optical standards, and probably suitable only for toy or similar applications.

Antireflection Coatings

Antireflection coatings are frequently utilized on polymer substrates, and may consist of a single layer or a rudimentary multilayer stack yielding better reflection-suppression performance. Due to the stringent requirements for control of the layer thicknesses, such coating formulations may be successfully deposited only in high-vacuum conditions, and only if temperatures in the chamber remain well below the service temperature of the substrate material. Elevated temperatures, necessary for baking the coatings to achieve good adhesion and abrasion resistance, may drive off plasticizing agents, limiting the "hardness" of the chamber vacuum. Such temperatures can ultimately soften the optical elements, so that their optical figure qualities are compromised. Relatively recent developments in the area of ion beam-assisted deposition have made possible improvements in the durability of coatings on polymer materials without having to resort to significantly elevated chamber temperatures.⁴⁰ See also Chap. 7, "Optical Properties of Films and Coatings," by Jerzy A. Dobrowolski in this volume of *Handbook*.

Antiabrasion Coatings

In general, many polymeric optical systems which could benefit from application of coatings are left uncoated. This happens because the expense incurred in cleaning, loading, coating, unloading, and inspecting the optical elements may often exceed that of molding the part itself. Some optics, particularly those intended for ophthalmic applications, are constantly exposed to abuse by abrasion,

and must be protected, cost notwithstanding. Antiabrasion coatings intended to provide immunity to scratching may be of inorganic materials (normally vacuum-deposited), or may be organic formulations.⁴¹

Inorganic antiabrasion coatings may be similar to those used for simple antireflection requirements, except that they may be deposited in thicknesses which amount to several quarter-wave-lengths. The practical thickness is usually limited by internal stress buildup, and by differential thermal expansion between coating and substrate. In general, the inorganic coatings derive their effectiveness by virtue of their hardness, and provide protection only superficially, since sufficient pressure will collapse the underlying substrate, allowing the coating to fracture.

Organic coatings for abrasion resistance normally derive their effectiveness from reduction of the surface frictional coefficient, thereby minimizing the opportunity for a hard contaminant to gain the purchase required to initiate a scratch. These coatings are often applied by dipping, spraying, or spinning. Coatings thus deposited usually destroy the smoothness which is required if the piece is to be qualified as a precision optical element.

Antistatic Coatings

Coatings applied for the purpose of immunization against abrasion, or suppression of specular reflection, often provide a secondary benefit. They may improve the electrical conductivity of the host surface, thus promoting the dissipation of surface static charge, and the accumulation of oppositely charged contaminants. In circumstances where antireflection or antiabrasion coating costs cannot be justified, chemical treatments may be applied which increase conductivity. These materials typically leave a residue sufficiently thin that they are undetectable, even in interferometric testing.

3.9 REFERENCES

1. R. M. Altman and J. D. Lytle, "Optical Design Techniques for Polymer Optics," *S.P.I.E. Proc.* **237**:380–385 (1980).
2. C. Teyssier and C. Tribastone, *Lasers & Optonics* **Dec**:50–53 (1990).
3. PPG Ind., Inc., Tech Bulletin-CR-39.
4. H. Dislich, *Angew. Chem. Int. Ed. Engl.* **18**:49–59 (1979).
5. H. D. Wolpert, *Photonics Spectra* **Feb**:68–71 (1983).
6. Plastics Desk Top Data Bank, pp. 803–837 (1986).
7. *Modern Plastics Encyclopedia—Eng. Data Bank*, McGraw-Hill, New York, 1977, pp. 453–708.
8. *Plastics Technology Manufacturing Hdbk. and Buyer's Guide*, 1986, pp. 358–740.
9. *C.R.C. Hdbk. of Laser Science & Technology*, vol. IV, pp. 85–91.
10. *Encyclopedia of Polymer Science and Technology*, vol. 1, John Wiley & Sons, 1976.
11. *Space Materials Hdbk*, Lockheed Missiles and Space Corp., 1975.
12. J. D. Lytle, G. W. Wilkerson, and J. G. Jaramillo, *Appl. Opt.* **18**:1842–1846 (1979).
13. D. C. Smith, Alpert et al., *N.R.L. Report* 3924, 1951.
14. R. E. Kagarise and L. A. Weinberger, *N.R.L. Report* 4369, 1954.
15. Rohm & Haas Product Bulletin-PL 612d, 1979.
16. *Catalogue of Optical Glasses*, Schott Glass Technologies, 1989.
17. J. D. Lytle, *S.P.I.E. Proc.* **1354**:388–394 (1990).
18. J. Hoogland, *S.P.I.E. Proc.* **237**:216–221 (1980).
19. A. Osawa et al., *S.P.I.E. Proc.* **1354**:337–343 (1990).
20. E. I. Betensky, *S.P.I.E. Proc.* **1354**:663–668 (1990).

21. L. R. Estelle, *S.P.I.E. Proc.* **237**:392–401 (1980).
22. K. Straw, *S.P.I.E. Proc.* **237**:386–391 (1980).
23. M. Muranaka, M. Takagi, and T. Maruyama, *S.P.I.E. Proc.* **896**:123–131 (1988).
24. J. D. Lytle, *S.P.I.E. Proc.* **181**:93–102 (1979).
25. A. L. Palmer, “Practical Design Considerations for Polymer Optical Systems,” *S.P.I.E. Proc.* **306** (1981).
26. D. F. Horne, *Optical Production Technology*, 2d. ed., Adam Hilger, Ltd., 1983 pp. 167–170.
27. J. R. Egger, *S.P.I.E. Proc.* **193**:63–69 (1979).
28. R. Benjamin, *Plastics Design and Processing* **19**(3):39–49 (1979).
29. R. F. Weeks, *Optical Workshop Notebook*, vol. I., O.S.A., 1974–1975, sect. XVII.
30. D. F. Horne, “Lens Mechanism Technology,” Crane, Russack & Co., New York, 1975.
31. J. Sneller, *Modern Plastics Intl.* **11**(6):30–33 (1981).
32. J. D. Lytle, “Workshop on Optical Fabrication and Testing,” *Tech. Digest*, O.S.A., pp. 54–57 (1980).
33. E. C. Bernhardt and G. Bertacchi, *Plastics Technology Jan*:81–85 (1986).
34. G. R. Smoluk, *Plastics Engineering Jul*:107 (1966).
35. *Plastics News*, Aug. 1989, pp. 8–9.
36. *Plastics World*, July 1979, p. 34.
37. M. H. Naitove, *Plastics Technology Apr.* (1984).
38. D. Malacara (ed.), *Optical Shop Testing*, John Wiley & Sons, New York, 1978, chaps. 9, 14.
39. G. W. Hopkins and R. N. Shagam, *Appl. Opt.* **16**(10):2602 (1977).
40. J. D. Rancourt, *Optical Thin Films-User's Hdbk.*, MacMillan, New York, 1987, pp. 197–199.
41. J. W. Prane, *Polymer News* **6**(4):178–181 (1980).

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CHARACTERIZATION AND USE OF BLACK SURFACES FOR OPTICAL SYSTEMS

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6.1 INTRODUCTION

Optical instruments and telescopes rely on black baffle and vane surfaces to minimize the effect of stray light on overall system performance. For well-designed and well-baffled systems, the black surfaces chosen for the baffles and vanes can play a significant role in reducing the stray light on the detector.¹⁻⁸ In space-borne systems, a large number of black surfaces play an important role. An excellent and comprehensive review of infrared surfaces is given by Persky.⁹ Additional infrared measurements of materials are given by Miller¹⁰ and Persky and Szczesniak.¹¹ Black surfaces are also used extensively in solar collector applications. Excellent reviews of spectrally selective surfaces for heating and cooling applications are found in Hahn and Seraphim¹² and in Granqvist.¹³ In many solar applications, high solar absorptance is desired along with low thermal emittance.¹⁴ In general, surfaces for solar applications will not be addressed in this chapter.

Black coatings are also used in radiometric detectors.¹⁵ Because the surface needed is often small, these surfaces may be even more specialized than the black coatings used for stray light reduction in optical instruments. This chapter will concentrate on the selection and characterization of black surfaces chosen for stray light suppression and suitable for application to relatively large areas of an optical system or optical test bed. Some examples of these uses are seen in Table 1.

The optical system designer has a wide repertoire of baffle surfaces from which to choose. Summaries of optical properties of materials were given by Wolfe,¹⁶ Pompea et al.,⁴ and McCall et al.¹⁷ Reviews of materials by McCall¹⁸ and Smith and Howitt¹⁹ emphasized the ultraviolet/visible and infrared properties, respectively. A number of company databases of scattering data are available, including one using the same instrument (for bidirectional scatter distribution function or BSDF measurements at 0.5145 μm) for approximately 15,000 data runs.²⁰ Large amounts of BSDF data are at Breault Research Organization and a BSDF database format has been proposed by Klicker et al.²¹ An organized effort to create specialized databases of optical properties of surfaces applicable to both ground- and space-based instruments has been undertaken and is proving to have great utility.²²

The choices of optical black surfaces are usually first narrowed by the nature of the application, the substrates available or possible, the wavelength or bandpasses of interest, the angles at which the surfaces must be nonreflective, and a host of system issues and environmental factors.⁵ As the system performance requirements have become more stringent, an array of surfaces has become available to meet these requirements. Many paints (e.g., Chemglaze Z306, SolarChem) (Table 2); anodized surfaces (e.g., Martin Black, Infrablack, Tiodize) (Table 3); etched, electrodeposited, and

TABLE 1 Possible Uses for Black Surfaces in Optical Systems and Test Beds

Apertures and field stops	Baffles	Barrels	Blackbodies	Choppers	Cold shields	Detector housings
Dewar interiors	Enclosures and testing structures	Lens edges	Laser light traps	Radiometers	Radiators	Simulators and targets

TABLE 2 Painted Surfaces

Surface Name or Designation	Manufacturer and/or Distributor (contact person)	Historical Notes	Surface Type	Main Literature References
Aeroglaze L300	Lord Corporation Chemical Products Division Industrial Coatings 2000 West Grandview Boulevard P.O. Box 10038 Erie, PA 16514-0038	Formerly called Chemglaze L300	Paint	24
Chemglaze Z004	Lord Corporation Erie, Pa.		Paint	24
Aeroglaze Z302	Lord Corporation Erie, Pa.	Formerly called Chemglaze Z302	Paint	25, 26, 24
Aeroglaze Z306	Lord Corporation Erie, Pa.	Formerly called Chemglaze Z306	Paint	27, 24, 28, 29, 30, 31, 20, 32, 33, 19, 34, 35, 36, 37, 38, 39, 40, 41, 42
Aeroglaze Z306 with microspheres	Lord Corporation Erie, Pa.	Formerly called Chemglaze Z306 with microspheres	Paint	43, 44, 45, 28, 24
Aeroglaze Z307	Lord Corporation Erie, Pa.	Formerly called Chemglaze Z307 (conductive)	Paint	24
Aeroglaze Z313	Lord Corporation Erie, Pa.	Formerly called Chemglaze Z313	Paint	35, 24
Ames 24E Ames 24E2	NASA Ames Research Center Moffet Field, Calif. S. Smith Sterling Software 1121 San Antonio Rd. Palo Alto, CA 94303		Paint	4, 46, 47, 34
Cardinal 6450	Cardinal Industrial Finishes 1329 Potrero Ave., So. El Monte, CA 91733-3088	Formerly called "Cardinal 6550"	Paint	48, 35
Cornell Black	Prof. J. Houck Department of Astronomy Cornell University Ithaca, NY 14853		Paint	39, 32, 33, 19, 49
DeSoto Flat Black	PRC-Desoto International, Inc. 5454 San Fernando Rd. Glendale, CA 91203		Paint	50, 35
Electrically Conductive Black Optical Paint	Jet Propulsion Laboratory, Caltech, 4800 Oak Grove Dr. Pasadena, CA 91109	Has no tradename	Paint	51, 52, 53

(Continued)

TABLE 2 Painted Surfaces (*Continued*)

Surface Name or Designation	Manufacturer and/or Distributor (contact person)	Historical Notes	Surface Type	Main Literature References
IITRI Bone Black D-111 (IITRI D111)	IIT Research Institute 10 West 35th Street Chicago, IL 60616		Paint	25, 54, 32, 34, 55, 38
LMSC Black	Lockheed Palo Alto Research Lab		Painted multi-player coating	32, 33, 19, 55
MH21-1	IIT Research Institute Chicago, Ill.		Paint	54
MH55	IIT Research Institute Chicago, Ill.		Paint	54
MH2200	IIT Research Institute Chicago, Ill.	Formerly 3M's ECP 2200 paint, but sold to IIT	Paint	26, 27, 56, 54, 57, 33, 19, 35, 58
Solarchem	Eastern Chem Lac Corporation 1080-T Eastern Ave. Malden, MA 02148		Paint	4
463-3-8	Akzo Nobel Coatings, Inc. 434 W. Meats Avenue Orange, CA 92665	Formerly called "Cat-a-lac 463-3-8" diffuse black paint	Paint	27, 56, 59, 60, 30, 58, 42, 55, 41
443-3-8	Akzo Nobel Coatings, Inc. Orange, Calif.	Formerly called "Cat-a-lac 443-3-8"	Paint	61, 25, 56, 59, 60, 58, 55, 41
443-3-17	Akzo Nobel Coatings, Inc. Orange, Calif.	Formerly called "Sikkens 443-3-17" glossy black	Paint	26, 60

Source: Adapted from McCall.²³

TABLE 3 Anodized Surfaces

Surface Name	Manufacturer	Notes	Surface Type	Main Literature References
Infrablack	Lockheed Martin, Denver CO 80201	For Al substrates only	Anodization process	43, 62, 63, 3, 64, 4, 46
Martin Black	Lockheed Martin Denver, CO	For Al substrates only	Anodization process	43, 25, 65, 62, 66, 63, 67, 3, 45, 68, 59, 69, 70, 32, 33, 46, 34, 35, 58, 55, 29, 38, 31, 64, 4, 20, 71, 39, 72, 37, 41, 38
Martin Black, enhanced	Lockheed Martin Denver, Colo.	For Al substrates only	Anodization process	63, 31, 4
Martin Black, posttreated	Lockheed Martin Denver, Colo.	For Al substrates only	Anodization process	63

Source: Adapted from McCall.²³

plasma-sprayed metal surfaces (Table 4) are now available to meet quite specific optical and system performance and environmental requirements.

New classes of surfaces are also being developed to give selected performance at specific angles and wavelengths. Other materials are being developed for applications where "hardened" laser-resistant or radiation-resistant materials are needed. A third area where much development is currently taking place is in the area of materials that are able to withstand severe and unusual forms of environmental exposure for long periods.

TABLE 4 Other Processes

Surface Name	Manufacturer	Notes	Surface Type	Main Literature References
Black chrome-type surfaces	Lockheed Martin Denver, Colo.	For many kinds of metal substrates	Electrodeposition process	63, 4, 41
Black cobalt-type surfaces (Cobalt black)	Lockheed Martin Denver, Colo. And many more companies	For many kinds of metal substrates; references to black copper, black steel, etc., are covered by black cobalt	Electrodeposition processes, and can be followed by chemical or thermal oxidation	63, 4, 73, 74
Black nickel (NBS black) (Ball black)	Ball Aerospace Electro-Optics Engineering Dept. P.O. Box 1062 Boulder CO 80306 and many others	For many kinds of metal substrate; Ball improved the patent developed by NBS	Deposition and etching process	65, 19, 29, 50, 37, 75, 76
Black Kapton film	DuPont Wilmington, DE 19898		Foil	35
Black Tedlar film	DuPont TEDLAR / Declair PPD, D-12082 1007 Market Street Wilmington, DE 19898		Foil	35
Boron black	Lockheed Martin Denver, Colo.	For many kinds of metals	Plasma spray deposition process	4, 63
Boron carbide	Lockheed Martin Denver, Colo.	For Ti substrates only	Proprietary process	4
Silicon carbide	Lockheed Martin Denver, Colo. And more companies	For many kinds of metals	Chemical vapor deposition	4
Textured surfaces	NASA Ames Research Center Moffet Field, Calif. (Sheldon Smith) Spire Corporation Patriots Park, Bedford, MA 01730 Optics MODIL, Oak Ridge National Lab Oak Ridge, TN 37831-8039	For many kinds of metal substrates	Either: —sputtered coated —ion beam etched —sputter coated then etched	77, 78, 79, 29, 80, 37, 81, 82, 79, 83
Black optical thin-film interference coatings	National Research Council of Canada Thin Films, Institute for Microstructural Sciences Montreal Road, Building M-36 Ottawa, Ontario, Canada, K1A 0R6	For metal, dielectric, or other substrates	Vacuum deposition techniques: —sputter deposition —ion vapor deposition —resistance-heated source —electron-beam gun deposition	84, 85, 86, 87

Source: Adapted from McCall.²³

The surface morphology of a “black” or diffusely scattering surface is only one determinant of its complex optical properties. However, for many surfaces, surface roughness plays a most significant role. This can be illustrated in Figs. 1 to 8, scanning electron micrographs of some important black or diffuse surfaces. The size and shapes of the surface features provide a valuable indication of how light will be absorbed and scattered or diffracted by such a surface. The creation and design of new

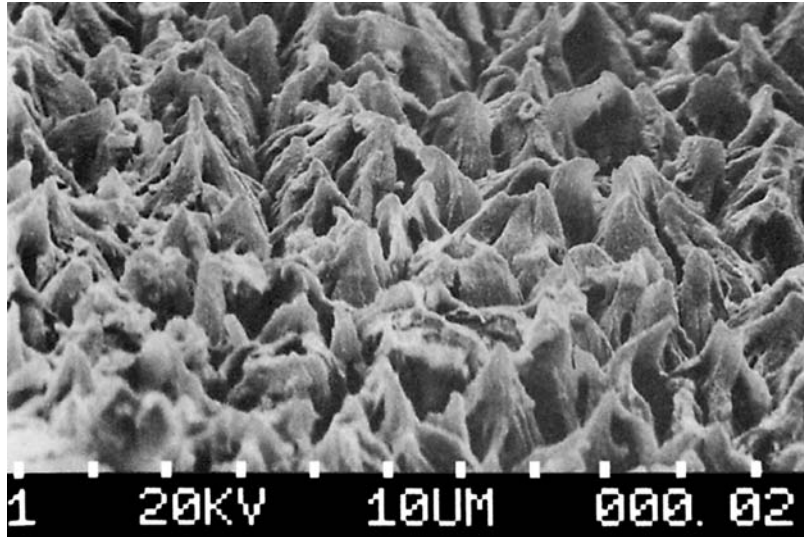


FIGURE 1 Scanning electron micrograph of Martin Optical Black, an anodized aluminum surface for ultraviolet, visible, and infrared use. (Photo courtesy of Don Shepard, Lockheed Martin, Denver.)

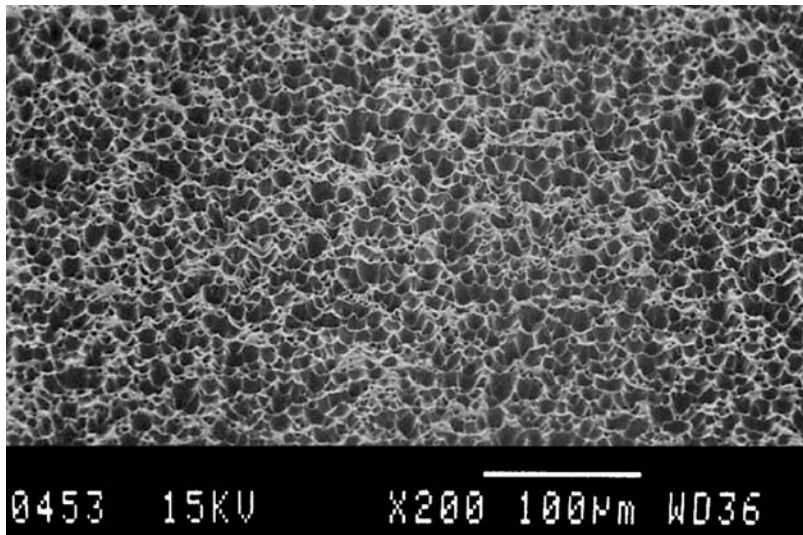


FIGURE 2 Scanning electron micrograph of Ball Black, an etched electroless nickel surface applicable to a variety of substrates. (Photo courtesy of Arthur Olson, Ball Aerospace Systems Group, Boulder, Colorado.)

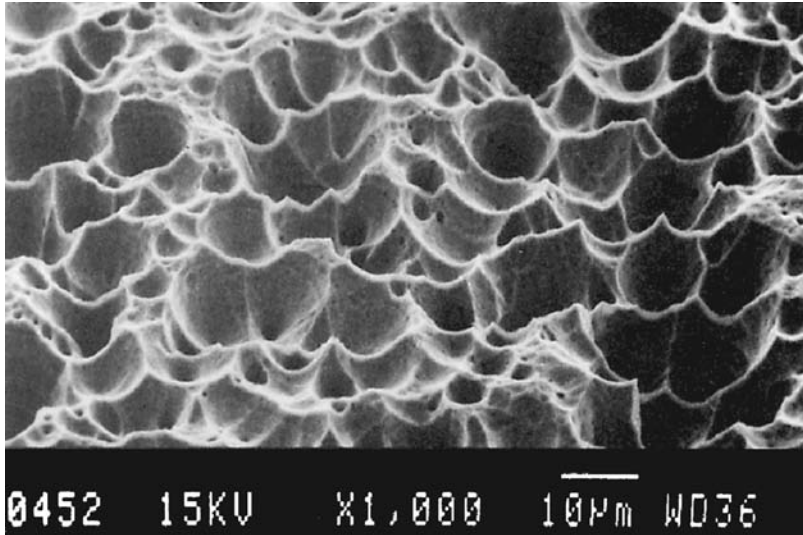


FIGURE 3 Scanning electron micrographs of Ball Black, an etched electroless nickel surface applicable to a variety of substrates. This surface is representative of a class of etched electroless nickel surfaces. (Photo courtesy of Arthur Olson, Ball Aerospace Systems Group, Boulder, Colorado.)

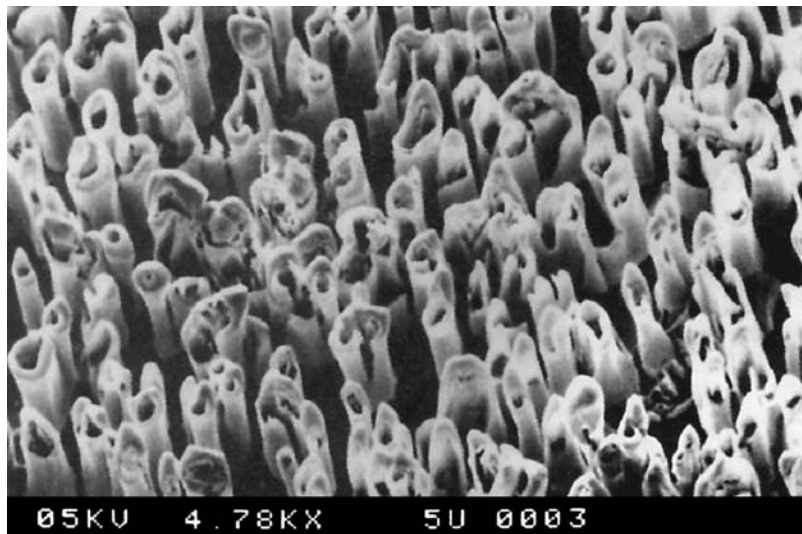


FIGURE 4 Scanning electron micrograph of a sputtered beryllium surface. (Photo courtesy of Roland Seals, Optics MODIL, Oak Ridge National Laboratory.)

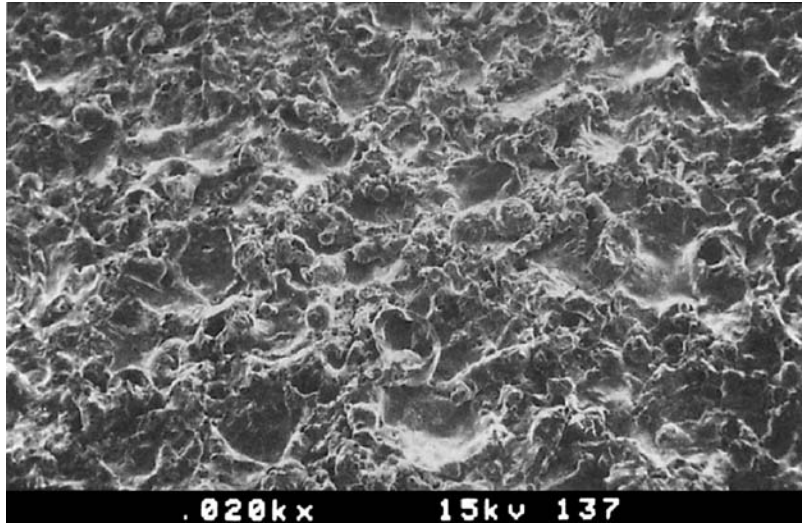


FIGURE 5 Scanning electron micrographs of Ames Perfect Diffuse Reflector (PDR) at 24 magnification. (Photo courtesy of Sheldon Smith, NASA Ames Research Center and Sterling Federal Systems, Palo Alto, Calif.)

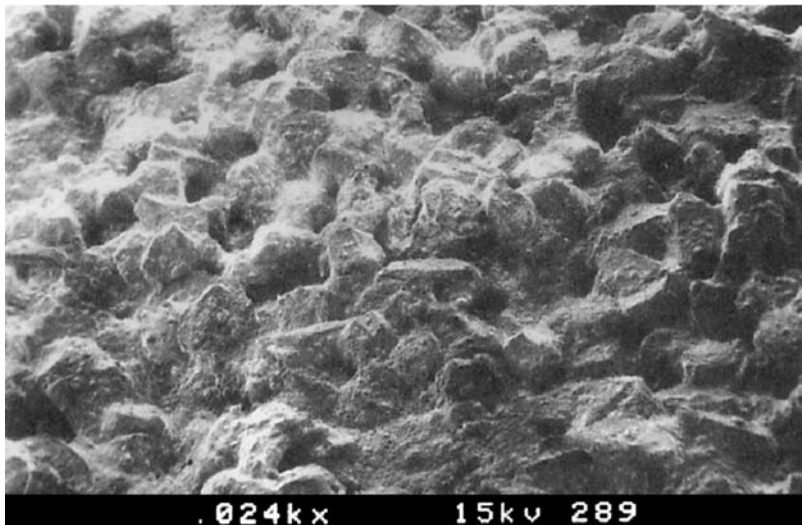


FIGURE 6 Scanning electron micrographs of Ames 24E at 24 $\times$ magnification. (Photo courtesy of Sheldon Smith, NASA Ames Research Center and Sterling Federal Systems, Palo Alto, Calif.)

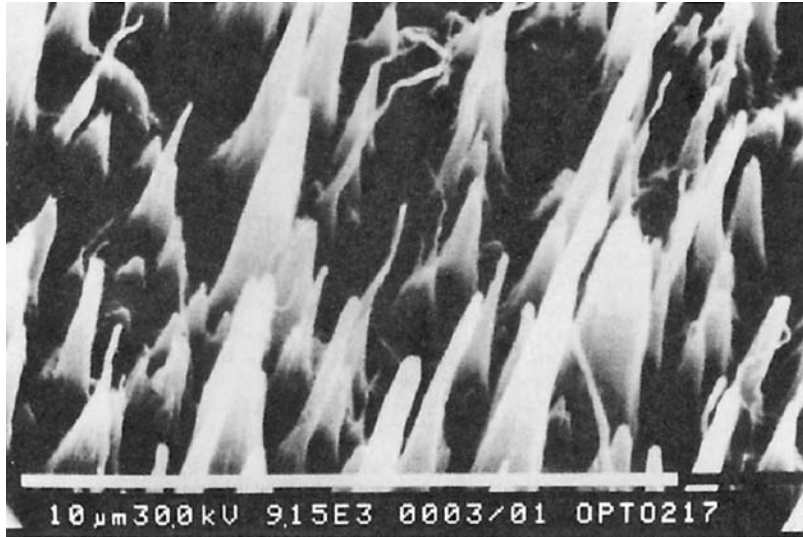


FIGURE 7 Scanning electron micrograph of a textured graphite surface created by bombarding a carbon surface with positive argon ions. (Photo courtesy of Chuck Bowers, Hughes Aircraft, El Segundo, Calif.)

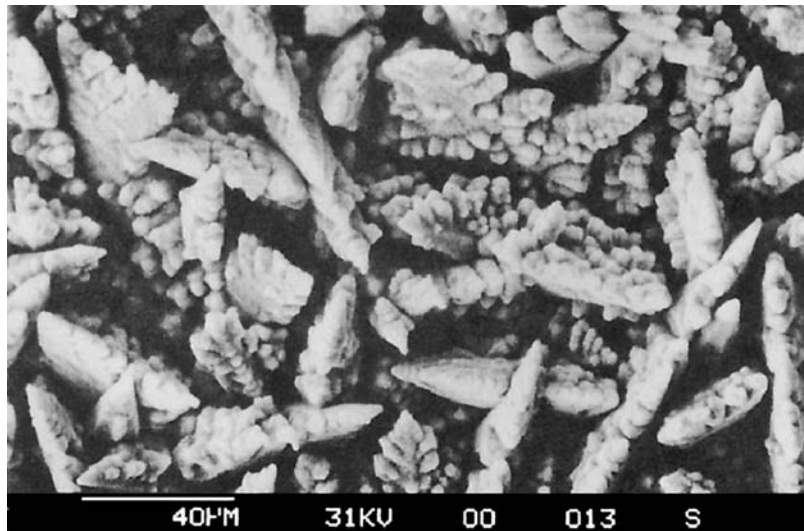


FIGURE 8 Scanning electron micrograph of Orlando Black surface, produced by electrodeposition of copper and subsequent oxidation in a proprietary process. (Photo courtesy of D. Janeczko, Martin Marietta Electronic Systems, Orlando, Fla.)

surfaces will be touched upon later, in the section on design techniques for creating new surfaces for specific applications.

This chapter gives a summary of the materials used in a variety of optical systems (with an emphasis on those that are currently available) and describes their optical and material properties so that the optical designer can begin the material selection process. As such, it is rather an extreme condensation of the data available. However, even the data presented here cannot be considered very definitive. There are a number of reasons for inconsistencies and ambiguities in the data presented. First, many of these surfaces and the processes that create them are evolving, and improving continuously. Even though the actual surface may change, the name may not. Thus, optical measurements of the same named surface that are separated by several years may not be consistent, even if the measurement techniques are consistent.

A second cause of inconsistency among data sets comes from the remeasurement of "archival" samples. When new measurement techniques or improved instruments become available, or the needs of a program demand new measurements, archival samples are retrieved and remeasured. Sometimes these archival samples may not have been stored properly and may not be in pristine or original condition. Other times, these samples may never have been archival in quality. They may have been marketing samples made without specific quality control and distributed widely. These measurements still enter the body of literature with the reader usually unaware of the important circumstances. For robust samples, poor storage may be of little importance. For more exotic materials (e.g., specialized baffles for space applications) that must be handled carefully, lack of proper handling can be of great importance. In this latter case, the measurements made on these degraded surfaces may not be representative.

Wolfe⁸⁸ compares the theory and experiments for bidirectional reflectance distribution function (BRDF) measurements of microrough surfaces. The BRDF of a surface is very useful in understanding the optical performance of a surface and is defined as the ratio of scattered radiance [$W/(cm^2sr)$] to surface irradiance (W/cm^2). Its units are inverse steradians. Radiance is used in the definition of BRDF in order to make the BRDF independent of the parameters of the measuring instrument, such as the detector aperture and distance to the detector. BRDF measurements can be made by a variety of instruments and can be made for any number of wavelengths. For example, BRDF measurements of surfaces have been made in vacuum ultraviolet to far-infrared wavelengths. However, the most common BRDF measurements that are made on black surfaces are probably made at convenient laser wavelengths of 0.6328 and 10.6 μm . It is important to keep in mind that these measurements may be of less predictive value if the system is operating at a substantially different wavelengths than where the measurements were made.

To make a BRDF measurement requires a light source, a sample mounted and illuminated by that source from a variety of angles, a detector to measure the scatter from the sample, and the computer/electronics package to accurately record the detection of the scattered light as a function of angle of incidence and detection angle.

While the optical properties of surfaces can be described or characterized through the use of specular and diffuse reflectance measurements, the use of BRDF measurements are very useful in characterizing both highly specular and highly diffuse surfaces and provide an excellent way to characterize the optical properties of any surface. The BRDF can be used to describe the angle-dependent optical scatter from any surfaces. The angular distribution of scatter can be used, in conjunction with computer modeling to calculate if the scatter from a black surface will be a limiting factor in the resolution or noise level of an optical system. BRDF measurements of surfaces are also used in computer graphics visualization programs to illustrate what a surface may look like under various illumination conditions. For some types of black surfaces, the angular distribution of scatter can be used to calculate a variety of surface parameters (e.g., surface roughness) if certain assumptions about the surface can be made. For opaque black surfaces, appropriate BRDF measurements in the wavelengths, angles, polarizations, and so on of interest have proven to be one of the best overall descriptors of the optical properties of the surface.

Measurements of optical quantities such as the BRDF, that are by definition measurement-device-independent, can also show large variations.^{89,90} No attempt has been made in this chapter to reconcile measurement discrepancies; indeed, no attempt to even identify the areas where conflicting data

occur is made. This would be a herculean task, but more importantly, it is probably unnecessary. The variations in the measurement process ensure that the optical description of black surfaces is still an order-of-magnitude science, or, at best, a half-an-order-of-magnitude science. Optical practitioners should use their own safety factor or better yet, have their own measurements made.^{5,17}

6.2 SELECTION PROCESS FOR BLACK BAFFLE SURFACES IN OPTICAL SYSTEMS

The selection of black surfaces is a systems issue; it must be addressed early and consider all aspects of system design and performance. It must also be examined from a total system performance perspective. Cost and schedule considerations have important effects on the decision and need to be taken seriously. A baffle structure that cannot be built with surfaces that cannot be coated is not a desirable state of affairs!

Similarly, proper financial and schedule support must be present. Black surfaces need to be taken as seriously as any other optical components, such as mirror surfaces or the thin films that act as filters. They deserve serious treatment in their design, fabrication, procurement, and testing. They are not last-minute design decisions or items to be created at the last minute. Since the baffle design and choice of surfaces often sets the final system performance (especially in infrared systems), it makes little sense to expend great energy and money to optimize other more traditional system components while ignoring stray light design and the surfaces so important in the design.

Figures 9 and 10 are a comparison of two processes that could lead to the selection of surfaces for an application. Figure 9 shows a process where design activities are done sequentially. In this process, stray light issues (including black surface issues) are left to the end of the program. In practice, with limited budgets, stray light and other fundamental system engineering issues are often not addressed at all in this process, or are addressed only at stages in the program where the system design is frozen, or cannot be changed without great expense. At this stage, when fundamental problems are found, they often have severe performance, budget, and schedule penalties. That many stray light and black surface problems are rectified (with severe penalties to schedule and budget) at late stages in programs attests to the overall importance of black surfaces to the ultimate success of a system.

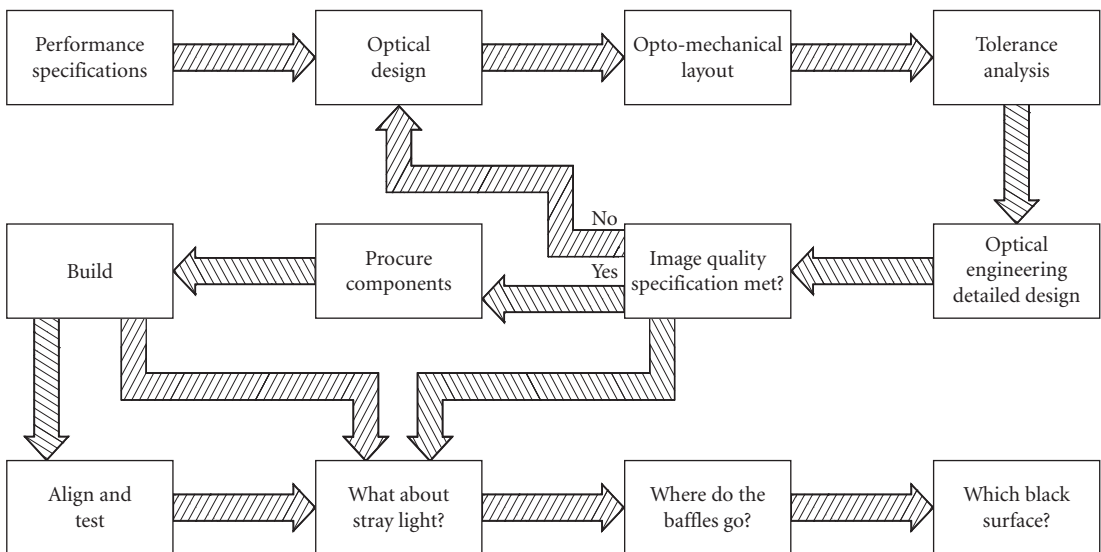


FIGURE 9 When selection of black surfaces is left to the end of a program, serious risks to the program are likely. (From Pompea and McCall.⁵)

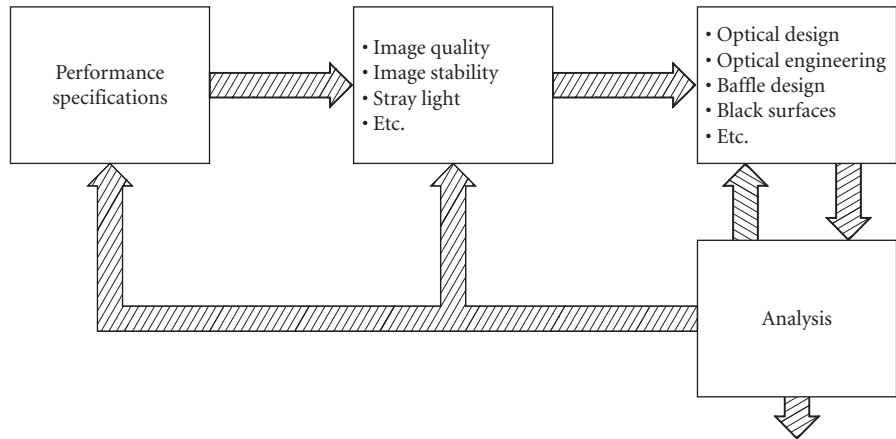


FIGURE 10 The most effective context for black surface selection is near the beginning of the program. This flowchart illustrates the early phase of a system-oriented design process. (From Pompea and McCall.⁵)

In an integrated systems engineering or concurrent engineering environment, illustrated in Fig. 10, the selection process begins early. There are many iterations of the design in the early stages, and close work among designers of different disciplines is essential. The level of detail increases with time, but no fundamental issues are decided without addressing their implication for the system and for each subsystem. This process is far superior to the one in the first flowchart, in which the surface selection process is treated as a trivial one and one waits until the end of the program to evaluate candidate surfaces. A review of general aspects of selection with emphasis on the system level issues inherent in the selection process is given by Pompea and McCall,⁵ McCall et al.,¹⁷ and Pompea.⁹¹

Once it has been decided to use black surfaces in an optical system, a whole host of system-level issues must be addressed to determine an appropriate coating or coatings. The high-level items include (1) purpose and position of the surface in the instrument, (2) wavelength(s) and waveband(s) of interest, (3) general robustness of the surface, (4) nature of the installation process, (5) environment of the optical system, (6) availability, (7) cost, (8) substrate, and (9) other mission or system requirements.

For systems that operate over a wide wavelength range, the selection process may be difficult because data may not be available over the entire wavelength range of interest. For example, the next generation of infrared and submillimeter telescopes are being designed for wavelengths between about 10 and 800 μm . Baffle coatings must be adequate over this entire wavelength range.

The position of the coating in the system and its function at that location is a critical item. For positions where the incident radiation is nearly normal to the surface, the optical considerations become less critical, since the reflectance at near-normal incidence does not vary as significantly at this angle for the most often used surfaces. Also, the BRDF is usually at its lowest value. There is a wealth of data at these near-normal incident angles.⁴

The corollary is that if surfaces must be used close to grazing incidence, the optical properties become extremely important to understand (and quantify for system predictions) just as the amount of data becomes vanishingly small.⁶ Although there is sufficient optical data on specular reflections from specular surfaces, there is relatively little information on specular reflections from diffuse surfaces, let alone BRDFs at large angles of incidence. For these reasons, optical designers try to use lambertian-like surfaces at near to normal incidence light paths as possible.

The robustness of the surface in its environment is a complex subject. Some specific areas that will be addressed here are the atomic oxygen environment of low earth orbit, outgassing in the vacuum of space, and particle generation by surfaces. The practical considerations of expense, schedule, ease of

cleaning, exportability, and availability of specialized surfaces all play important roles. For a unique space instrument, there are different manufacturing considerations than for a large-volume production process. The installation process is often overlooked. It often plays a key role in the successful use of many surfaces.

Exposed spacecraft surfaces often must not contribute to spacecraft charging problems. Some nonconductive surfaces support the buildup of charges that can create large electrical potentials between spacecraft components, or the spacecraft and the plasma and subsequent damage may result. This is particularly important in the region near a detector, which is often very charge-sensitive. Surfaces such as Martin Black do not support charges in excess of 200 V, since the coating can leak charge to the aluminum substrate. Textured metallic coatings, as a general rule, do not have surface charging problems. Some paints as well (e.g., Aeroglaze Z307) are designed to be conductive. Table 5 describes several surfaces used for thermal control in space craft. Some of these surfaces are designed to be conductive, to avoid charging effects. For space applications where charge buildup is not critical, nonconductive surfaces may be used.

Other considerations are the ability of a surface to withstand vibration, acceleration, elevated temperatures, thermal cycling, chemical attack (including atomic oxygen), solar and nuclear radiation, micrometeoroids, and moisture.

For the coating of baffle and (particularly) vane surfaces in ground-based telescopes, a further consideration may often be important. The baffle and vane surfaces in telescopes often have a large view angle or geometrical configuration factor (GCF) with the sky. This is particularly true for telescopes that operate without an enclosure or with a very large slit or opening to the night sky. In this case, the black baffle and vane surfaces must not radiatively couple strongly to the night sky. If there is a substantial view to the sky, and the emissivity of the surface is high, it will cool below the air temperature. This can create temperature-induced “seeing” effects which degrade image quality. The requirement that a surface be strongly absorbing of visible light, yet a poor emitter in the infrared is often a difficult one to meet. Table 6 gives the absorptivity and emissivity of some widely used surfaces.

In many laboratory or instrument applications, the use of one of a few standard black coatings or surfaces (such as the now unavailable 3M Black Velvet 101-C10) was entirely adequate to achieve the necessary performance of the optical system. In these applications, if the stray light performance was inadequate, it usually indicated that the stray light design, not the choice of black surface, was in error. The explanation was that the ignorance of some of the principles of stray light design could produce system performance five orders of magnitude worse than a poor choice of surfaces. The visibility of surfaces from the detector and the paths from those surfaces to the front of the instrument (not the optical properties or blackness of the surface) largely determine the total system performance. In stray light terminology, the GCF (geometrical configuration factor of surfaces) is more important than the BRDF (bidirectional scatter characteristics of surfaces).

TABLE 5 Black Nonconductive and Electrically Conductive Paints and Coatings for Space Use

Name	Type of Coating	Binder	Solar Absorptivity	Thermal Emittance
ML-210-IB	Thermal control	Inorganic	0.98±0.02	0.91±0.02
RM-550-IB	Thermal control	Inorganic	0.97±0.02	0.91±0.02
TMD-560-IB	Thermal control	Inorganic	0.95±0.02	0.91±0.02
AZ-1000-ECB	Thermal control conductive	Inorganic	0.97±0.02	0.89±0.02
MLS-85-SB	Thermal control	Organic	0.98±0.02	0.91±0.02
MLS-85-SB-c	Thermal control conductive	Organic	0.98±0.02	0.91±0.02

Source: Courtesy of J. Zweiner, AZ Technology, Huntsville, Alabama.

TABLE 6 Black Coatings

	$\overline{\alpha}_s$	$\overline{\epsilon}_n$
Anodize Black	0.88	0.88
Carbon Black Paint NS-7	0.96	0.88
Cat-a-lac Black Paint	0.96	0.88
Chemglaze Black Paint Z306	0.96	0.91
Delrin Black Plastic	0.96	0.87
Ebanol C Black	0.97	0.73
Ebanol C Black-384 ESH* UV	0.97	0.75
GSFC Black Silicate MS-94	0.96	0.89
GSFC Black Paint 313-1	0.96	0.86
Hughson Black Paint H322	0.96	0.86
Hughson Black Paint L-300	0.95	0.84
Martin Black Paint N-150-1	0.94	0.94
Martin Black Velvet Paint	0.91	0.94
3M Black Velvet Paint	0.97	0.91
Paladin Black Lacquer	0.95	0.75
Parsons Black Paint	0.98	0.91
Polyethylene Black Plastic	0.93	0.92
Pyramil Black on Beryllium Copper	0.92	0.72
Tedlar Black Plastic	0.94	0.90
Velestat Black Plastic	0.96	0.85

*Note: Solar absorptivity (0.3 to 2.4 μm) and normal emittance (5 to 35 μm) of black coatings.

Source: From Henniger.⁹²

6.3 THE CREATION OF BLACK SURFACES FOR SPECIFIC APPLICATIONS

The optical properties in the visible (e.g., BRDF at 0.6328 μm) at near-normal incidence between painted black surfaces and more specialized high-performance black surfaces usually do not differ by more than a factor of 10. For infrared and ultraviolet wavelengths, the performance of more specialized surfaces is far superior to many paints by a much larger factor. The optical designer must take care not to overspecify the optical performance properties required for a baffle surface. The lowest reflectance surface is not necessary for all applications. On the other hand, the choice of low-performance coatings has important consequences.

Some systems have been designed with an excessive number of vanes on their baffles. In these cases, the baffle system is probably too heavy, costs more than necessary to manufacture, and the excessive number of vane edges may be introducing extra diffraction effects that degrade the performance. The advantage of the high-performance coatings often lies not only in their optical properties, but in the considerable experience of their manufacturers in working on baffle systems, the reliability and consistency in the application process, and the superior documentation of the optical performance characteristics. The environmental resistance of the high-performance coatings is generally much better and much better documented than paints that are used for a wide variety of applications.

Black Surfaces as Optical Design Elements

The systems approach to the choice of black surfaces in optical systems that has been stressed here has led to the rule of thumb in stray light design that the choice of a black surface's optical properties should not be the first design issue considered. If the performance of the preliminary design is inadequate, the designer should look at the design carefully, rather than look for a better black surface to boost the performance. A flaw in the general system design is probably more responsible for the performance than the "blackness" of surfaces.

One reason for this approach is that the choice of a different black surface may not improve the performance, if the surface is used in the system in certain ways (e.g., grazing incidence). An important equalizing factor among many black surfaces is that they become highly specular when used at angles significantly different from normal incidence. This optical performance characteristic makes it critical for the baffle designer to conceptualize the paths and ranges of angles that are required, and to avoid using a surface where its performance is required at grazing incidence or close to it. The writing of scatter specifications is discussed by Stover,⁹³ and Breault² discusses sources of BRDF data and facilities where BRDF measurements are routinely made.

Black surfaces can be contaminated and their absorbing or diffuse structure can be destroyed by improper handling. This can lead to a significant degradation in their optical properties. A margin of safety should always be included in the performance estimates.

Many specific high-performance applications today require that black surfaces must become critical design elements that are used with only small "safety" factors. First, all of the principles of stray light design are used. If the required performance is barely achievable without optimizing the choice of black surfaces, then considerable attention must be paid to the choice of surfaces. Sometimes, designers must often use several black surfaces in an instrument or telescope; each particular black surface is used where its performance is optimal. In the past few years, a variety of black surfaces have become available to supplement the old standbys such as 3M Black Velvet (the mainstay of laboratories 10 years ago), and Chemglaze Z306 (now called Aeroglaze Z306) and Martin Black (the standard bearers for space instruments in the 1980s). Since the applications for these blacks are so specific, we refer to them as *designer blacks*. This term refers not only to new classes of surfaces that have been developed, but also to the creativity of optical and material scientists in modifying existing surfaces to create special properties for specific applications.

This new array of designer optical blacks can still be subdivided into the traditional categories of specular blacks and diffuse (lambertian) blacks. Glossy or specular black surfaces have been used for vane cavities and their use is reviewed by Freniere⁹⁴ and Freniere and Skelton.⁶¹ The approach is to reflect unwanted radiation out of the system or to attenuate it while tightly controlling its reflected direction. The use of specular baffles (reflective black or shiny) requires considerable care to avoid sending specular beams further into the instrument at some particular narrow angles.^{59,95} The increasing sophistication of stray light analysis programs makes this analysis much more complete. The most widely used specular black surfaces are Chemglaze Z302 and a paint formerly called Cat-a-lac Glossy Black, now available from Akzo as 463-3-8.

The lambertian black surface is often the most desirable type of surface to use in baffled telescopes and instruments. However, there is no *true* lambertian black, though several are extremely close for a near-normal angle of incidence. All diffuse blacks have larger BRDFs at large angles of incidence. Furthermore, these black surfaces can be further categorized by the wavelengths where they absorb best, the general categories being the ultraviolet, visible, near-infrared, middle-infrared, and far-infrared. They can also be distinguished by their degree of resistance to the atomic oxygen found in low earth orbit, their resilience under laser illumination, and their performance at narrow laser wavelengths or specific angles of incidence. The method of manufacture and the performance of these specialized surfaces may be proprietary or classified. Even if the general qualities of these surfaces that perform in these areas are known, the full range of test results on them often are not readily available.

Design Techniques for Creating Black Surfaces

Four general tools are available to the black surface designer to tailor the optical properties. Many highly absorbing surfaces use several of these effects to good advantage. The first tool is to use absorbing compounds in the surface. Examples of this are the organic black dye, which is a good visible absorber, in the Martin Black anodized surface and the carbon black particles found in many paints. Similarly, for the infrared paints, the addition of silicon carbide particles provides good absorption near 12 μm . The addition of compounds may create quite different properties at visible and infrared wavelengths; a visual observation of blackness is no guarantee of its infrared properties. The converse is also true. Titanium dioxide is a good infrared absorber, but is very reflective in the visible region. "Black," therefore, means absorptive in the wavelength region being discussed.

The addition of large (relative to the wavelength of interest) cavities, craters, or fissures in the surface can aid in the absorption process by requiring the radiation to make multiple reflections within the material before it leaves the surface. The same effect is achieved by growing large angular projections from a flat substrate. Each reflection allows more of the radiation to be absorbed. For example, a surface with a reflectivity of 15 percent (a rather poor black) becomes a very good black if the light can scatter or reflect three times within the surface before it exits. After three internal reflections, the 15 percent reflectivity black has become a $(0.15)^3$ or 0.34 percent reflective surface. The NBS Black and Ball Black surfaces are good examples of this; they are shiny electroless nickel surfaces until etched. After etching, the surface is filled with a plethora of microscopic, cavities that absorb enough light to create a surface that is black to the eye.

Black appliquéés can also be used to create rough absorbing surfaces.⁹⁶ These surfaces can be "tuned" for different wavelengths or for maximum absorptance at certain angles of incidence. This can be done by angling fibers or surface structure to provide cavities that are oriented normal to the angle of incidence. These materials have low reflectance at a variety of incident angles.⁹⁶⁻⁹⁸

Aerogels can also be used to create very black surfaces. Aerogels are highly porous materials nanometer-scale structures that can be synthesized through the removal of the pore-filling liquid. Of particular interest are carbon aerogels consist of 10-nm-sized particles, which are amorphous, connected in an interconnected network with approximately 10- to 50-nm pores and a pore volume of over 80 percent. Since carbon has inherent absorption in the infrared, this innately rough surface can have extremely low reflectivities over a broad wavelength range (e.g., 2 to 14 μm).⁹⁹

The third phenomenon is the use of scattering from the surface structure, from particles in the surface coating, or from the substrate to diffuse the incoming beam over a hemispherical solid angle. Even without any absorption, this dilution factor can be very important in destroying specular paths, particularly in the far-infrared, where broad wavelength absorption is difficult. For an introduction to surface roughness and scattering phenomena, see Refs. 33, 46, 93, and 100. An in-depth, very readable, treatment of scattering by small particles is given by Bohren and Huffman.¹⁰¹

The fourth phenomenon is based on optical interference of light in thin films. A black optical thin-film multilayer structure can significantly enhance, through optical interference, the amount of absorption of light in a multilayer structure over that of intrinsic absorption alone.⁸⁷ The black layer system technology has been used successfully in a range of applications.^{84-87,102,103} Optical thin films provide tremendous design flexibility. The reflectance, absorptance, and transmittance can be tailored as a function of angle and wavelength. Black multilayers may have a higher cost per unit of surface area, are generally limited to small surfaces, and have a strong angular sensitivity. This last characteristic can be used to great advantage for specialized applications. The films (especially those deposited by ion-beam process) are durable and are suitable for space use.

There is no ideal black surface. For good absorption across a wide wavelength band (e.g., 0.5 to 20 μm), the surface might be excessively thicker than is needed for a narrowband application. Even a "perfect" absorbing surface has disadvantages associated with higher emissivity (e.g., the surface radiates to the detector). In practice, even specular surfaces can be acceptable as black baffle surfaces under the right circumstances, although they are much more difficult to use. By design, they must direct the energy out of the system or in a direction that is not harmful to the system performance.^{95,104,105} Their alignment is critical and there are caveats for their use.⁵⁹ The "blackest" surface is not necessarily the best for a specific application.

In some other applications, a combination of low absorptance and high emittance are desirable. High emittance-low absorptance coatings are possible using a combination of techniques or surfaces. For example, a potassium silicate binder with zinc oxide or zinc orthotitanate particles can be applied to an anodized aluminum surface. In this case, the absorptance is less than 0.16 and the emittance is about 0.92.¹⁰⁶

6.4 ENVIRONMENTAL DEGRADATION OF BLACK SURFACES

Contamination control for terrestrial and spaceborne sensors is a very rapidly developing and important area. A good introduction to the field with extensive references is given in Refs. 2, 107 to 109. A good review of contamination assessment techniques given by Heaney¹¹⁰ and Nahm et al.¹¹¹ discusses scattering from contaminated surfaces. The prevention, detection, and removal of contamination should be important considerations early in the design of the sensor.

Three areas of great interest for spaceborne sensors are the effects of atomic oxygen, outgassing effects, and particle generation by surfaces. A large number of other effects can also influence the performance of surfaces or of the systems where those surfaces are installed over short or long periods. These include adhesion of coatings, radiation effects on coatings, thermal cycling effects, vacuum ultraviolet effects, and electrostatic charging effects, to name a few. It would be helpful if each new coating developed could be tested by a suite of tests relevant to the area of concern, similar to what was done in cryomechanical tests of Ames 24E2 infrared black coating.³⁴ All too often, the tests are done on different formulations at different labs and with different degrees of care. This makes it extremely difficult for the optical designer to have the data necessary to make good decisions.

The surface contamination of a black surface as well as aging effects can affect its optical properties. However, the effect of contaminants from black surfaces on mirror scatter in the optical system is much more pronounced. Williams and Lockie¹¹² use the BRDF as the sensitive parameter to judge the effects of dust, hydrocarbon oil, acrylic, and peelable coating residue on low-scatter mirror surfaces. Young¹¹³ describes the effect of particle scatter on mirrors. Shepard et al.⁷¹ have suggested that scattering properties of black baffle surfaces may be temperature-dependent. This may be a result of chemical changes in the surface or in changes to the surface as absorbed molecules are released at increased temperatures. Further work should be done at the temperatures of interest.

A large number of studies have been done to describe the behavior of black baffle surfaces to intense exposure to high-powered lasers and radiation, where damage to the surface is widespread. Accurate results can often be obtained using other vehicles to deliver energy into the surface. For example, rapid pulsed, low-energy electron beam irradiation of optical surfaces is described by Murray and Johnson¹¹⁴ as a cost effective way to test for radiation hardness. Black baffle surfaces are vulnerable even at low fluences because of their great absorptivity. The damage mechanisms are not well understood. Many of the damage mechanisms are related to the thermal shocks produced by rapid heating of a surface of thin layers on different materials. The destruction of surfaces not only reduces the ability of the surface to absorb stray radiation, but often also creates a contaminating cloud of particles that can greatly affect the optical system.

Atomic Oxygen Effects

Spacecraft surfaces on the early space-shuttle flights showed significant weight loss and aging effects. For example, on STS-1 the forward bulkhead camera blanket was milky yellow after the flight and the white paints on the shuttle exhibited exposure-related degradation effects. On later flights, surfaces such as Kapton showed significant mass losses. These effects were attributed to the interaction of the surfaces with the atomic oxygen present in low earth orbit.¹¹⁵ The atomic oxygen attacks the binder materials in paints, thus removing mass, and causes glossy surfaces to become more lambertian.¹¹⁶ Carbon particles are released when the binder is removed. The weight loss is due both to chemical processes and to erosional (kinetic energy) processes.

A second problem is that many surfaces have a glow associated with them when exposed to the atomic oxygen. Both of these phenomena undermine the effectiveness of baffle surfaces on space instruments. The effect of exposure to atomic oxygen on anodized black surfaces (Martin Black and Enhanced Martin Black) has been measured and simulations of atomic oxygen exposure on Chemglaze (now called Aeroglaze) Z306 paint has been done with a plasma etch chamber.⁶⁴

These tests showed that a carbon-black-based paint could be significantly degraded by atomic oxygen over time while anodized surfaces exhibited only small changes in their surface morphologies or in their visible and near-infrared reflectances. The graying of some smooth painted black surfaces is somewhat compensated for by an etching process that roughens these surfaces. If the exposure times are short, the etching action of the atomic oxygen may even improve the scattering properties of paints. However, removed material may show up on optical surfaces, degrading the optical performance, and it should be obvious that long exposure times would remove too much of the coating.

In general, however, the optical properties of surfaces degrade during longer exposure times and at higher atomic oxygen flux levels. Experiments in space on the long duration exposure facility (LDEF) have indicated how the properties of materials change after nearly six years of exposure to atomic oxygen. For Chemglaze (now called Aeroglaze) Z306 paint, for example, this exposure has led to a loss of the binder material¹¹⁷ and to loss of pigment. Some ion-textured surfaces were also flown as part of this experiment and showed high stability in the space environment.⁷⁹ The effects of space exposure on infrared baffle coatings were described by Blue and Perkowitz¹¹⁸ who showed that long-term exposure decreased the reflectance of these surfaces.

Outgassing

For space applications, the amount of outgassed material and its composition are of great importance. One of the primary dangers is that the outgassed products may form a film with undesirable properties on optical components. This hazard of space exposure is particularly relevant for cooled systems. For cryogenic systems, the continued outgassing of materials as they break down after long exposure to the space environment becomes an additional source of contamination on optical surfaces. Outgassing is also of concern for severe environments on the ground, though the correlation between vacuum testing and a behavior of black surfaces under severe heat in air is not well understood. For the context of this chapter, only vacuum outgassing measures will be considered. In either case, the condensation of volatile materials on optical components can lead to catastrophic system failure.

The two primary measures or tests of outgassing are the *total mass loss* (TML) and the percent *collected volatile condensable materials* (CVCN). An American Society for Testing and Materials (ASTM) Standard Test Method was developed for this purpose and is called E 595-77/84. Several NASA publications give values for TML and CVCN (Ref. 119 gives the most extensive listing; see also Ref. 120). For example, measurements at Goddard Space Flight Center of Chemglaze (now Aeroglaze) Z306 black urethane paint give a TML of 0.92 percent and a CVCN of 0.03 percent. Wood et al. shows the near-infrared absorption due to the outgassing products of Aeroglaze Z306 black paint. For the paint, the total mass loss was 2.07 percent. Ames²⁸ reports outgassing problems with Aeroglaze Z306 if exposed to temperatures greater than 40°C after a room temperature cure. However, many potential space material outgassing problems with this and other surfaces can be avoided completely with proper bakeout procedures. In 1993, a low volatile version of Z306 was being developed.

A third measure of outgassing relates to the water content of the material or surface. The *water vapor regained* (WVR) is a measure of the amount of water readsorbed/reabsorbed in 24 hours, while the sample is exposed to 25°C and 50 percent relative humidity (for extensive listings, see Ref. 119). This determination is done after the vacuum tests for TML and CVCN.

Particle Generation

Materials for space use must be able to withstand launch vibration without generating an excessive number of particles. This is not simply a coating or surface problem—it is a dynamics and substrate problem as well. The details of the baffle design and assembly play an important role in the generation

of particles. If a baffle surface is grossly distorted by the launch vibration, the adhesion of the black surface should not be blamed for the failure; the baffle design failed. A common source of particle generation is abrasion between coated baffle surfaces. For severe vibration environments and for fragile surfaces, special considerations are necessary.⁷⁰ Similarly, surfaces must be able to withstand thermal cycling without producing particles. As painted materials outgas and their composition is altered, particles in the paint can become dislodged.

Materials used in baffles can also get dusty or contaminated by exposure to outgassing products from the spacecraft. For an accessible ground-based black surface, normal cleaning procedures appropriate to the surface may be used, if they do not damage the texture or optical properties of the surface. For a baffle system already in space, the cleaning procedures developed to clean mirrors in situ may apply. These techniques include laser cleaning, plasma or ion cleaning, and jet snow cleaning (see, e.g., Ref. 121, and other papers in Ref. 109).

Baffle Material for Extreme Environments

One important form of degradation for earth-based materials involves the exposure of the surface to the elements of temperature cycling, sunlight, humidity, and other factors of its operating environment. This combination is a severe test of many surfaces. Unfortunately, there is very little data published on the environmental degradation of black surfaces that are exposed to the outdoor environment, or to high temperatures, such as might be found in a closed automobile in the summer. Often, a black surface that is very ordinary in its optical properties is chosen for use in an extreme environment. The reason is that it was the first surface that did not peel or fade significantly.

Space-based surfaces must withstand severe launch vibrations, temperature extremes, collisions with space debris and micrometeoroids, and exposure to ultraviolet radiation. Military missions have also added the requirement that these materials be hardened against nuclear or laser threats. For example, these baffle surfaces and their associated optics must still perform after exposure to high-power lasers.

In the simplest sense, these black surfaces must be able to either selectively reject laser radiation (a difficult requirement) or be able to absorb significant amounts of energy and not degrade. Most of the coatings have been developed for application to substrates, which can survive high temperatures, such as molybdenum, beryllium, tungsten, carbon/carbon, and titanium, because of their ability to withstand high flux densities of laser light. Generally, painted surfaces are completely inadequate. Even anodized surfaces on aluminum may not be adequate at these flux densities.

6.5 OPTICAL CHARACTERIZATION OF BLACK SURFACES

The baffle designer must be concerned about the optical properties of black surfaces over a large range of wavelengths and angles of incidence. Wolfe¹⁶ summarizes the relevant design data. Performance measurements, such as measurements of the specular reflectance and total hemispherical reflectance over a range of wavelengths are now supplemented by a more complete characterization of these optical surfaces: the bidirectional reflectance distribution function (BRDF).¹²² BRDF has units of inverse steradians and is usually measured at several discrete wavelengths, which are easily generated by the most common lasers. In particular, measurements at the HeNe laser wavelengths of 0.6328 μm and at the CO_2 wavelength of 10.6 μm are particularly valuable for visible and infrared applications. There is a notable shortage of BRDF data in the ultraviolet, from 1 to 4 μm , and for far-infrared wavelengths.

BRDF measurements at the same wavelength have the additional advantage that they are directly comparable. As Smith and Wolfe¹²³ point out, the directional reflectivity of a surface is convolved with the instrument function (a weighted mean of the detector solid angle), a unique characteristic of each reflectometer. An approximate deconvolution of the instrument function can be easily

performed by dividing the measured reflectance by the projected measurements, which are instrument independent as mentioned in ASTM Standard E12.09. However, simple specular reflectance measurements and spectra made on different instruments must first be divided by the projected detector solid angle before being compared. Several studies^{89,90} have detailed the variation between BRDF measurements made in different laboratories. With the advent of the ASTM standard, greater congruence among BRDF measurements in the future is probable.

Because of the value of BRDF measurements in comparing the scattering characteristics of surfaces, a large set of BRDF data of black baffle materials that have traditionally been used in optical devices of all types, as well as the scattering functions of some new materials are presented in this chapter. These measurements may be compared to previous measurements made on other instruments.⁶⁷

The specular and total hemispherical reflectance data thus become most valuable in describing some general characteristics of a surface over a wide wavelength range, while the BRDF data at a wavelength of particular interest allow the designer to characterize the angular scattering of the surface for angles of incidence of interest and for view angles from the detector. The total integrated scatter also is extremely useful for surface roughness determination.⁹³

This chapter provides the optical designer a useful summary of data. Sufficient data are presented to allow a determination of which surfaces might be appropriate for a given task. The data generally can be divided into two forms, the first being specular and hemispherical reflectance data over a wavelength range. These data allow the designer to choose a surface with the right basic properties over the wavelength range of interest. BRDF measurement provides a second form of data. The data are usually presented for a few characteristic angles of incidence (5° , 30° , 45° , and 60° are the most common) at each wavelength. These BRDF measurements are particularly useful as input to optical modeling or stray light modeling programs.

In stray light analysis programs such as APART,¹²⁴ ASAP,¹²⁵ and GUERAP,¹²⁶ as well as many other modeling programs, it is the mathematical value of the bidirectional reflectance distribution function that is used by the program models. In these programs, a library of BRDF functions for the most common surfaces is available for use by the analyst. For surfaces that do not explicitly have a BRDF associated with them in the code, the BRDF values can be input.

In most baffle designs, surfaces are used at angles not represented by the available BRDF measurements. Some surfaces are even used at angles close to grazing incidence where few measurements have been made. For these areas, the data available for the models are very limited, and often generous extrapolations are needed. A smooth transition between measurements at different angles or at very large angles of incidence, or from one wavelength to another is often assumed. The more unusual or nonrandom the surface, the more these assumptions or extrapolations should be questioned. Examples of how BRDF measurements are made and used in system designs and analysis are found in, for example, Refs. 3, 43, and 127 to 130.

Black surfaces are also used in radiators used for the thermal control of spacecraft. The hemispherical reflectivity can provide a general indication of the optical properties for a thermal analysis. The normal emittance at room temperature is also an important quantity for spacecraft design. Table 7 gives the hemispherical reflectance and normal emittance of some surfaces. Radiatively cooled surfaces are important for space infrared telescopes and, if designed properly, can provide a reliable means of reducing background radiation. Because of on-orbit degradation, the radiators must be sized for the appropriate performance at the end of the mission.

For these applications, the absorptivity and emissivity of surfaces as a function of wavelength and temperature must be well understood. Thus, room temperature measurements of normal emittance may not be very useful if the surface is to be used at cryogenic temperatures. Stierwalt^{41,132} has contributed greatly to the measurement of far-infrared emissivity of black materials. Clarke and Larkin¹³³ describe measurements on a number of black surfaces suitable for radiometry detectors where a low reflectance is needed, independent of wavelength. For opaque surfaces, the spectral emittance at a given wavelength is equal to the spectral absorptance, which is equal to one minus the spectral reflectance.

These parameters are very sensitive to coating thickness and may change with exposure to ultraviolet radiation from the sun, with damage from solar electron and proton radiation, damage from space debris and micrometeoroids, and with outgassing. In practice, the solar absorptance is measured

TABLE 7 Hemispherical Reflectance and Emittance of Some Common Spacecraft Surfaces

Surface	Thickness	Hemispherical reflectance at 546 nm (incidence angle, degrees)					Normal Emittance (300 K)
		20	40	60	70	80	
Cat-a-lac Black 463-3-8	0.002"	0.054	0.061	0.096	0.141	0.223	0.891
Black Velvet 401-C10	0.025"	0.035	0.036	0.047	0.058	0.085	0.911
Chenglaze Z306	0.005"	0.048	0.052	0.074	0.098	0.144	0.915
Chenglaze Z306 with silica powder		0.031	0.033	0.040	0.050	0.070	0.912
Chenglaze Z306 with 3M glass microballoons left on 20- μ m screen	0.006"	0.040	0.048	0.068	0.090	0.130	0.920
Chenglaze Z306 with 3M glass microballoons left on 44- μ m screen	0.010"	0.036	0.040	0.055	0.070	0.097	0.923
Chenglaze Z306 with 3M glass microballoons left on 63- μ m screen	0.011"	0.037	0.040	0.053	0.064	0.084	0.923
Scotchlite Brand Reflective Sheeting #3285 Black		0.059	0.062	0.095	0.156	0.318	0.909
Scotchlite Brand Reflective Sheeting "C" Black W/A #234		0.146	0.130	0.129	0.135	0.157	0.846
NiS-dyed Anodized Al from Light Metal Coloring Corp.		0.056	0.061	0.097	0.151	0.333	0.912
Sandoz-Bk Organic Black anodized Al from Almag Co.		0.041	0.048	0.064	0.082	0.129	0.884
Black Chrome anodized Al from Goddard SFC		0.028	0.031	0.053	0.083	0.156	0.625
NiS-dyed anodized Al from Langley Research Center		0.050	0.053	0.083	0.138	0.253	0.915
NiS-dyed anodized Al, substrate blasted with glass shot, from Light Metals Coloring Corp.		0.045	0.049	0.073	0.100	0.146	0.920

Source: Data courtesy of J. Heaney, Goddard Space Flight Center.¹³¹

by obtaining the reflectance from 0.3 to 2.4 μm , the region containing 95 percent of the sun's energy. The normal emittance is determined using an infrared spectrophotometer over the wavelength range 5 to 35 μm , where close to 90 percent of the energy of a 300 K blackbody is emitted (see Table 6). While these measurements are useful for design of radiators that operate near room temperature, further measurements are required in order to predict a surface's thermal emittance at lower operating temperature.

6.6 SURFACES FOR ULTRAVIOLET AND FAR-INFRARED APPLICATIONS

Many surfaces are multipurpose and are useful for a variety of wavelengths. Before discussing the properties of these surfaces, it may be instructive to look at several surfaces that are used for ultraviolet and far-infrared applications. In these wavelength regions, the performance of black surfaces is often critical to the performance of the optical instrument.

Black Surfaces for Ultraviolet Applications

For space telescopes or instruments operating in the ultraviolet, surfaces such as Martin Black have been used successfully. However, very few measurements of candidate baffle material have been made at wavelengths less than 0.3 μm (300 nm) and even fewer have been made at shorter ultraviolet wavelengths. Jelinsky and Jelinsky⁴⁰ studied the performance characteristics of a variety of surfaces and surface treatments for use on baffle materials in the Extreme Ultraviolet Explorer. They determined some scattering characteristics of several materials at 30.4, 58.4, and 121.6 nm.

Heaney¹³¹ has made some pioneering bidirectional measurements at 15°, 45°, 75°, and 85° at 58.4 nm (584 Å) of candidate baffle materials for space instrument applications. Interestingly, two of his samples are "bare" aluminum with no applied coating. The natural oxide present on uncoated aluminum samples is strongly absorbing at this wavelength and, by itself, reduces the reflectances to below 5 percent at near-normal incidence. The baffle surface candidates are described here and their optical properties are presented in the figures.

Roughened aluminum: Aluminum 6061 alloy, sheet finish, sandblasted to an unspecified degree of surface roughness. Uncoated (Fig. 11).

Gold iridite: Aluminum with a chromate surface coating produced in a room temperature chemical conversion process (Fig. 12).

Black nickel: Aluminum with a black nickel surface that was produced in an electroplating process with NiS and ZnS (Fig. 13).

Copper black: An aluminum substrate coated with approximately 80 to 100 nanometers of evaporated Cu to provide a conductive layer and then overcoated with an evaporated Cu black deposited at a chamber pressure in the 10^{-3} torr range (Fig. 14).

Black paint: An aluminum substrate painted with a carbon-loaded black silicone paint (NSB69-82) (Fig. 15).

Aluminum, grooved and blazed: An aluminum plate, 6061 alloy, with grooves cut at a blaze angle of about 20°, with a period of 1.1 mm, a depth of 0.4 mm, and otherwise uncoated (Figs. 16, 17, and 18).

Surfaces for Far-Infrared (>30 μm) Use

In the far-infrared wavebands, many surfaces such as paints, which have good visible absorptance, lose their absorbing and scattering characteristics. Although measurements have only been made at wavelengths longer than 15 μm on a few surfaces, the data suggest that most surfaces do not

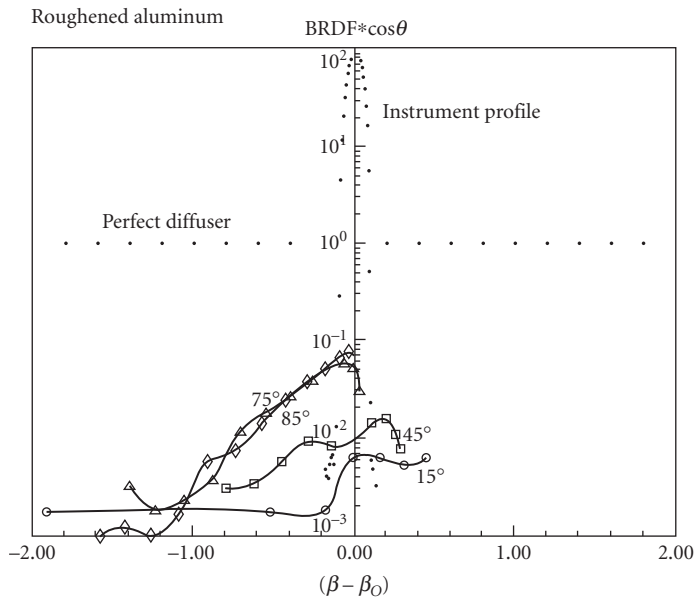


FIGURE 11 BRDF of roughened aluminum. Instrument profile and perfect diffuse reflector shown for reference. Wavelength is 58.4 nm. (From Heaney.¹³¹)

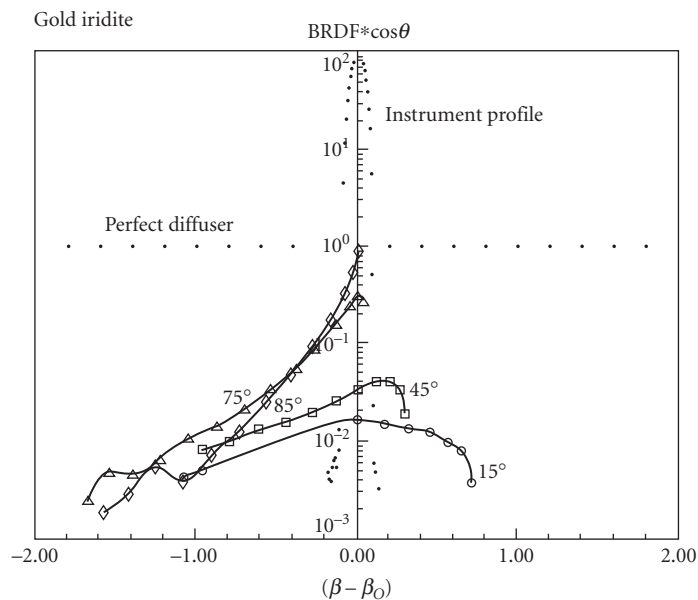


FIGURE 12 BRDF of gold iridite. Instrument profile and perfect diffuse reflector shown for reference. Wavelength is 58.4 nm. (From Heaney.¹³¹)

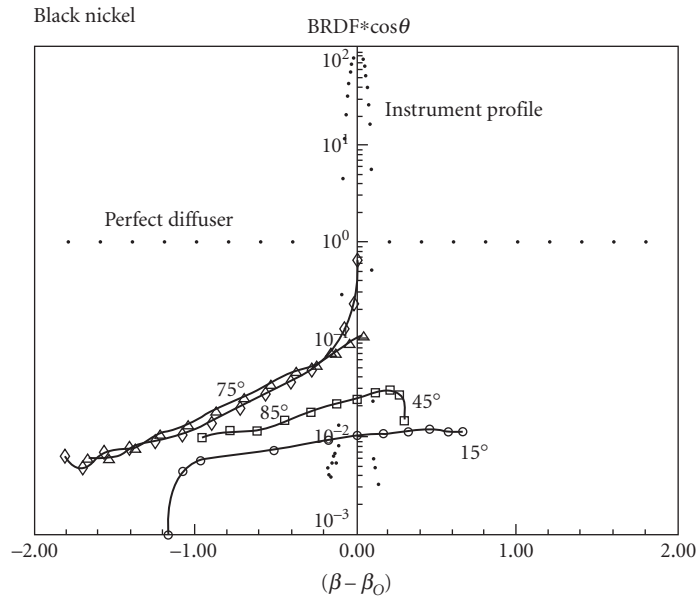


FIGURE 13 BRDF of black nickel. Instrument profile and perfect diffuse reflector shown for reference. Wavelength is 58.4 nm. (From Heaney.¹³¹)

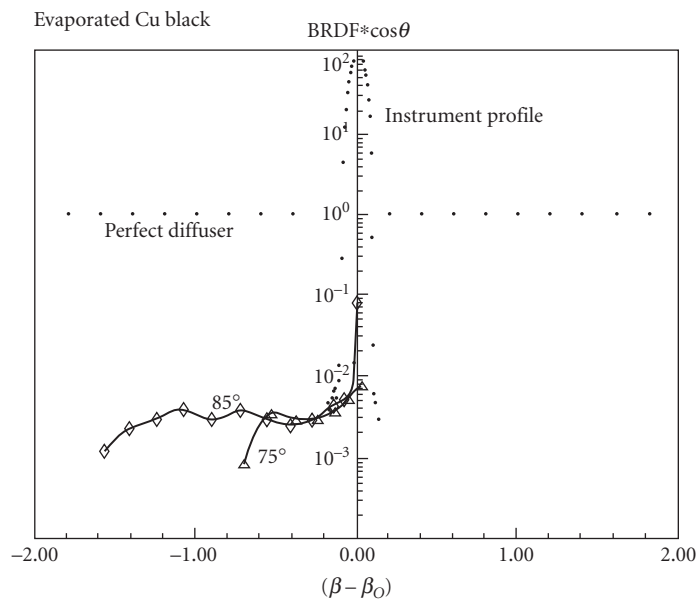


FIGURE 14 BRDF of evaporated Cu black. Instrument profile and perfect diffuse reflector shown for reference. Wavelength is 58.4 nm. (From Heaney.¹³¹)

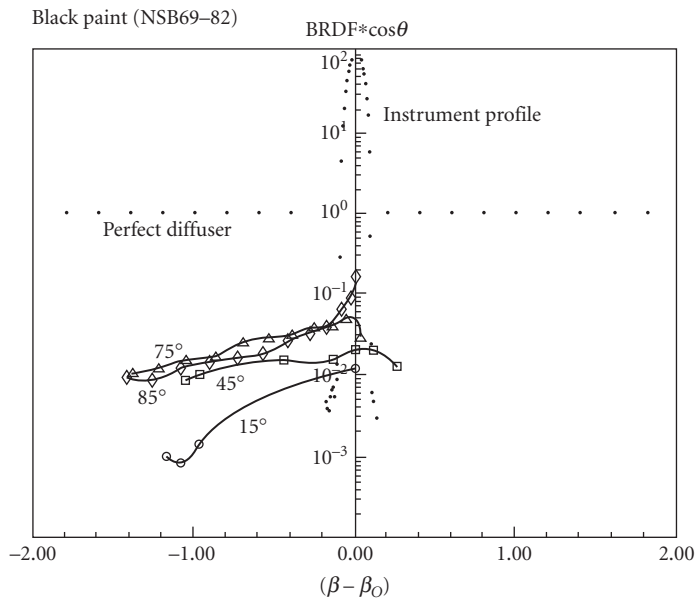


FIGURE 15 BRDF of NSB69-82 black paint. Instrument profile and perfect diffuse reflector shown for reference. Wavelength is 58.4 nm. (From Heaney.¹³¹)

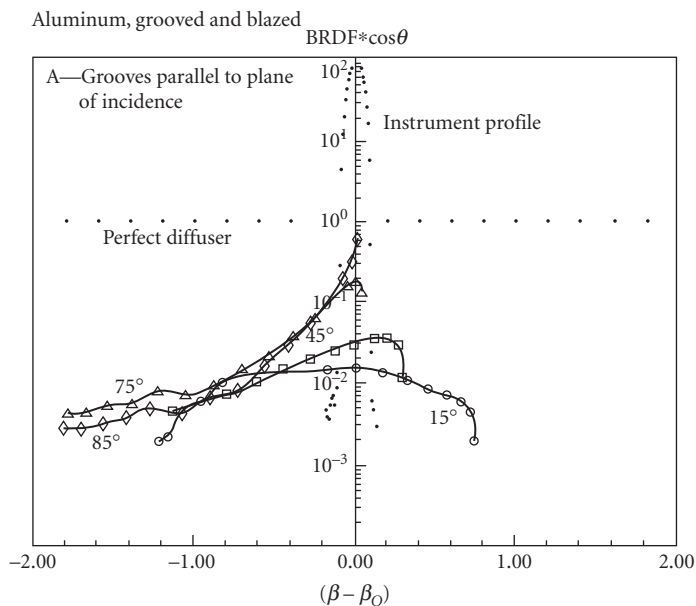


FIGURE 16 BRDF of aluminum, grooved and blazed, with grooves parallel to angle of incidence. Instrument profile and perfect diffuse reflector shown for reference. Wavelength is 58.4 nm. (From Heaney.¹³¹)

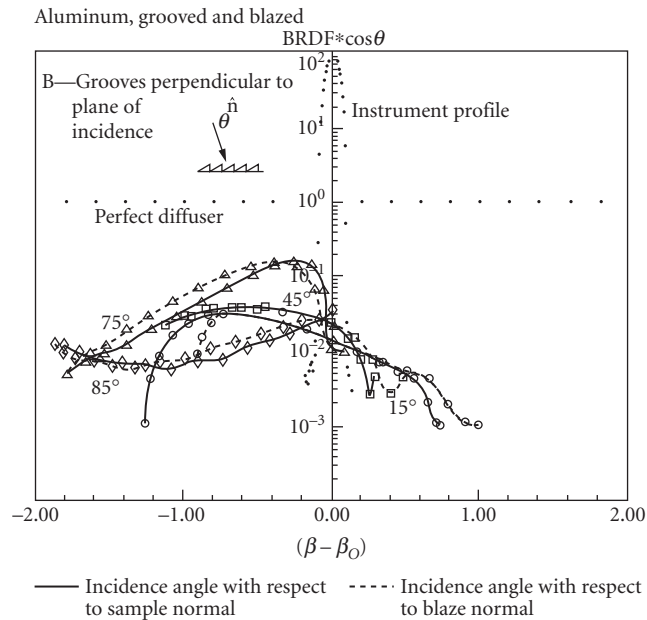


FIGURE 17 BRDF of aluminum, grooved and blazed, with grooves perpendicular to angle of incidence. Instrument profile and perfect diffuse reflector shown for reference. Wavelength is 58.4 nm. (From Heaney.¹³¹)

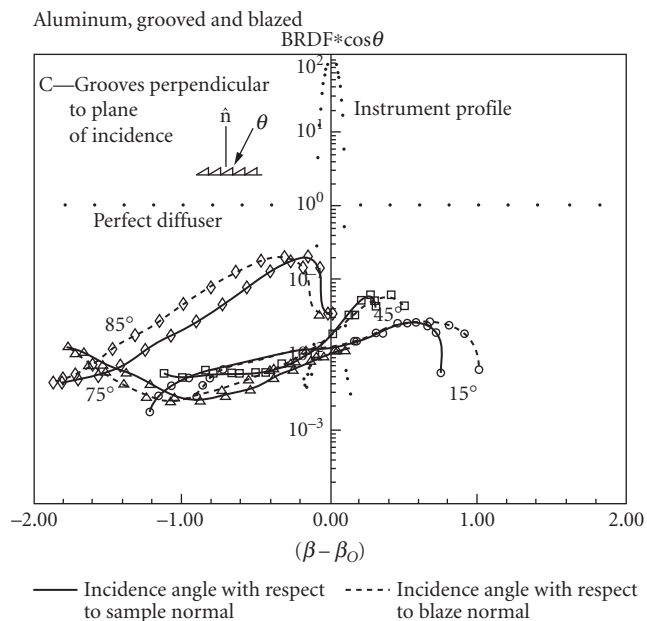


FIGURE 18 BRDF of aluminum, grooved and blazed, with grooves perpendicular to angle of incidence. Instrument profile and perfect diffuse reflector shown for reference. Wavelength is 58.4 nm. (From Heaney.¹³¹)

perform well as “blacks” for long wavelength operation.^{41,133} Smith³² points out that many coatings become transparent at longer wavelength and the substrate roughness enters strongly into the scattering characteristics. An example of this is Infrablack, a rough anodized surface that was previously described. The approach has been carried further in Ames 24E.¹³⁴ A number of approaches and surfaces have been developed to create effective surfaces at these wavelengths.

A model has been constructed³³ to describe the effect of coating roughness and thickness on the specular reflectance. Smith and Howitt¹⁹ survey materials for infrared opaque coatings (2 to 700 μm). They highlight the value of silicon carbide and carbon black for far-infrared absorption. Smith^{32,33,39,46,57,72,134–137} provides much of the reference work in this area.

The optical properties of the several infrared coatings and surfaces are given in Figs. 19 to 24. For applications in laboratories and in calibration facilities, surfaces like velvet, commando cloth, and even neoprene may be used. The long-wavelength measurements on these surfaces are given in Figs. 25 to 32. The long-wavelength coatings may be grouped into a few basic categories discussed here. As this area is one of rapid development for space infrared telescopes and space radiators, there will likely be many new approaches in the next few years.

Multiple-Layer Approach For reducing the far-infrared reflectance of baffles, a technique of using antireflection surfaces composed of multiple layers with a different refractive index in each layer was discussed by Grammar et al.⁵⁵ For such a coating to be effective, it must match the optical constants of free space with the large constants of the baffle substrate.

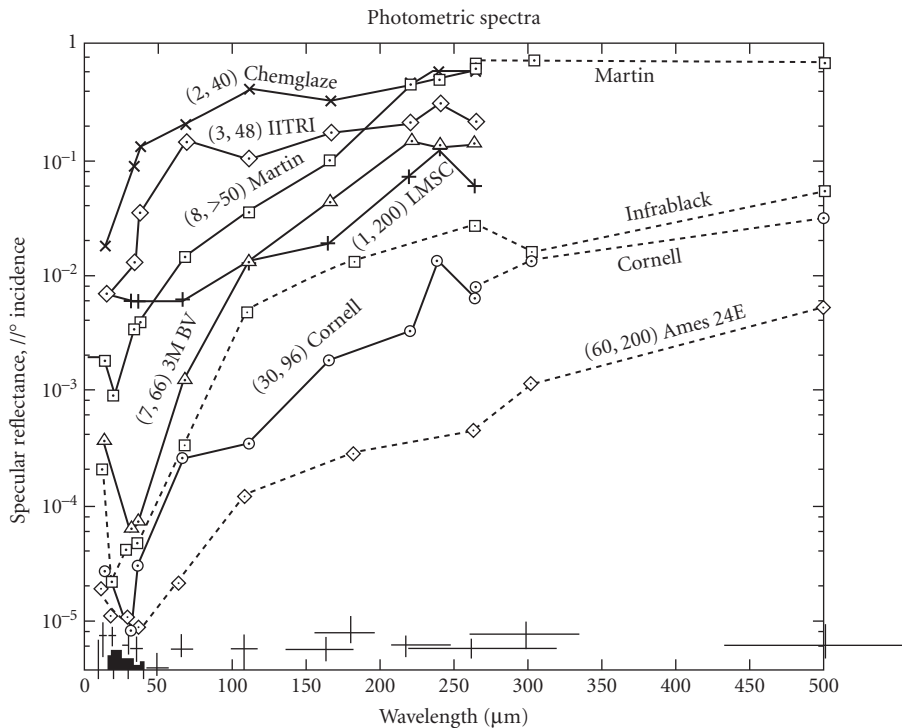


FIGURE 19 Specular reflectance spectra of eight black coatings. Measurements of coating roughness and thickness in micrometers are shown in parentheses before the name of each coating. Filter pass-bands are shown by horizontal error bars. The absorption bands of amorphous silicates are indicated by the solid histogram in lower left end of the graph. (From Smith.^{32,33,46})

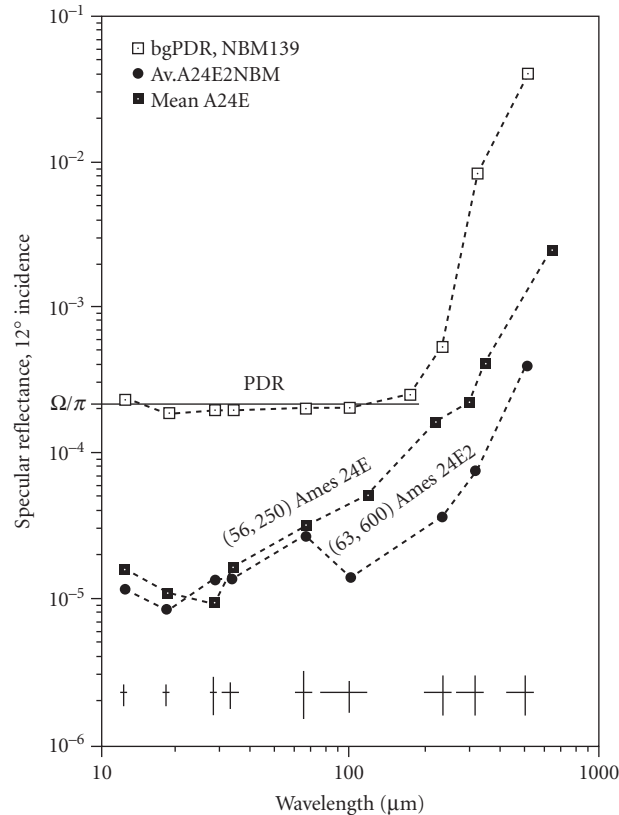


FIGURE 20 Specular reflectance spectra of PDR surface and two infrared black coatings. Dashed lines connect data points of a set, and the solid line indicates the theoretical value of reflectance for a perfect lambertian surface. The coating roughness and thickness are given in parentheses, and filter passbands are indicated by horizontal error bars. (From Smith.^{136,137})

Teflon Overcoat A polytetrafluoroethylene (Teflon) spray-on lubricant was used as an antireflection overcoat for opaque baffle surfaces in the far-infrared and submillimeter by Smith.⁵⁰ A thick Teflon overcoat created by spraying Teflon Wet Lubricant reduced the specular reflectance at millimeter and infrared wavelengths by a factor of two. The refractive index of the coating plays a more significant role than the thickness.

Cornell Black Houck⁴⁹ created a far-infrared black paint based on adding large particles of grit (silicon carbide #80 and #180 grit) to 3M Black Velvet Nextel 101-C10. This paint could be repeatedly cycled to cryogenic temperatures with no flaking or peeling. The far-infrared properties of Cornell Black are described by Smith.^{32,33} Since this 3M paint is no longer available, Cornell Black is not now generally used. The ECP-2200 (now called MH2200) replacement for 3M Black Velvet was studied by Smith and Howitt¹⁹ in an effort to create a paint similar to Cornell Black. Houck⁴⁹ gives complete instructions for making the Cornell Black paint.

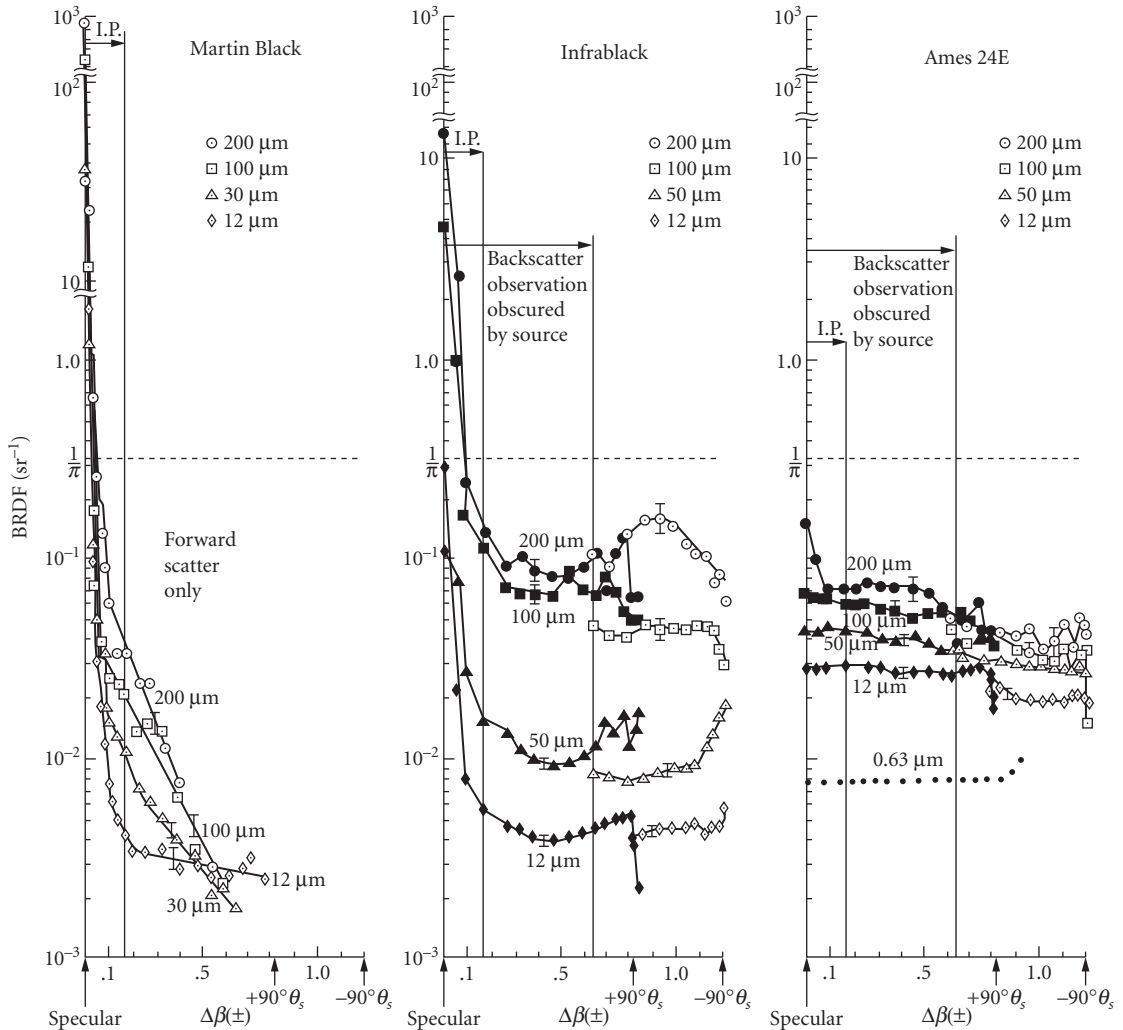


FIGURE 21 BRDFs of Martin Black, Infrablack, and Ames 24E. Note the different breaks in the ordinate scale of the Martin Black measurements used to compress its specular reflectance to fit the scale of the figure. Forward scatter data are solid symbols; backscatter data are open symbols. Forward and backscatter measurements at 0.6328 μm of Ames 24E are by D. Shepard of Martin Marietta (Denver) and are shown schematically by the dotted line in the right hand figure. (From Smith.⁴⁶) Smith¹³⁷ recalibrated this data; the relative comparison of these coatings remained essentially unchanged.

Infrablack Infrablack is a black anodized surface generally applied to 6061 Aluminum.^{31,64,138} It is highly suitable for space radiators, infrared baffles, and for applications where a high emissivity is desired. The specular reflectance of the Infrablack is conservatively one order of magnitude less than that of Martin Black across the spectral region from 12 to 500 μm . The reduced reflectance of Infrablack is attributed to a large increase in the roughness of its substrate prior to anodization. The diffuse reflectance characteristics of the Infrablack are different from Martin Black at the longer wavelengths. At 12 and 50 μm , the BRDF of Infrablack is considerably less than that of Ames 24E, while at 100 and 200 μm they are comparable.

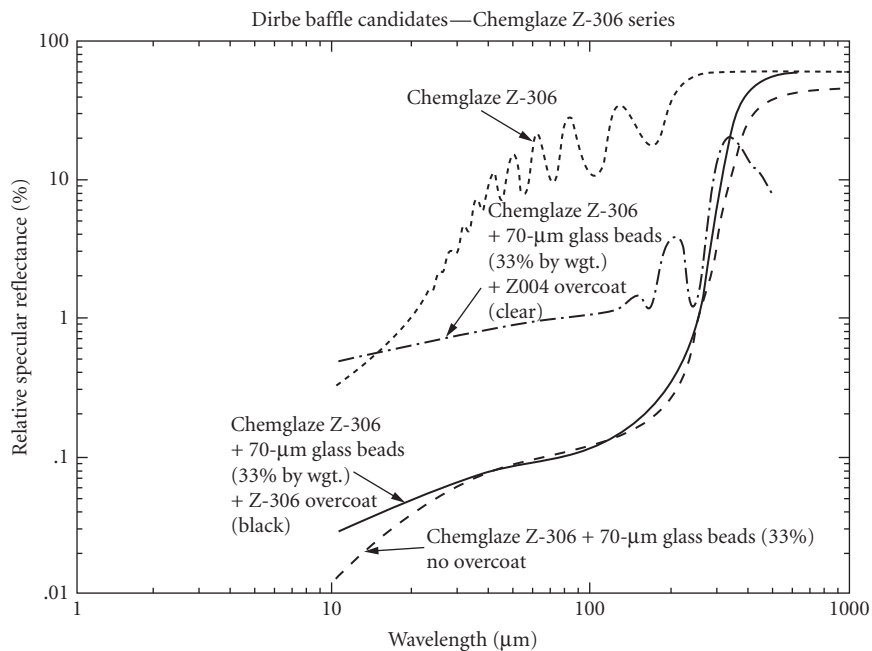


FIGURE 22 Specular reflectances of Diffuse Infrared Background Explorer candidate baffle surfaces based on Chemglaze (now Aeroglaze) Z-306, over the wavelength range 1 to 1000 μm . (From Heaney.¹³¹)

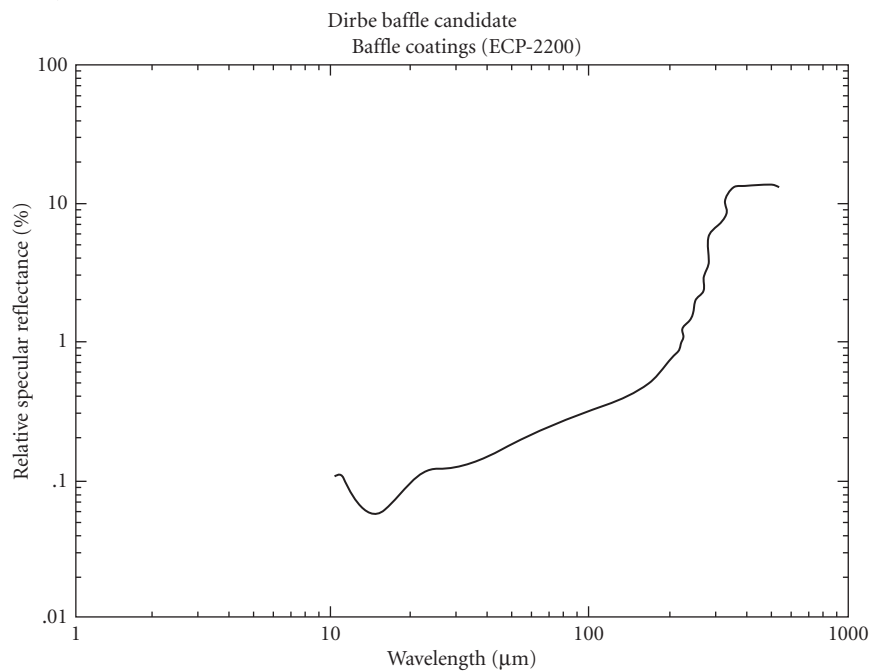


FIGURE 23 Specular reflectance of Diffuse Infrared Background Explorer candidate baffle surface based on ECP-2200 (now MH2200) black paint over the wavelength range 1 to 1000 μm . (From Heaney.¹³¹)

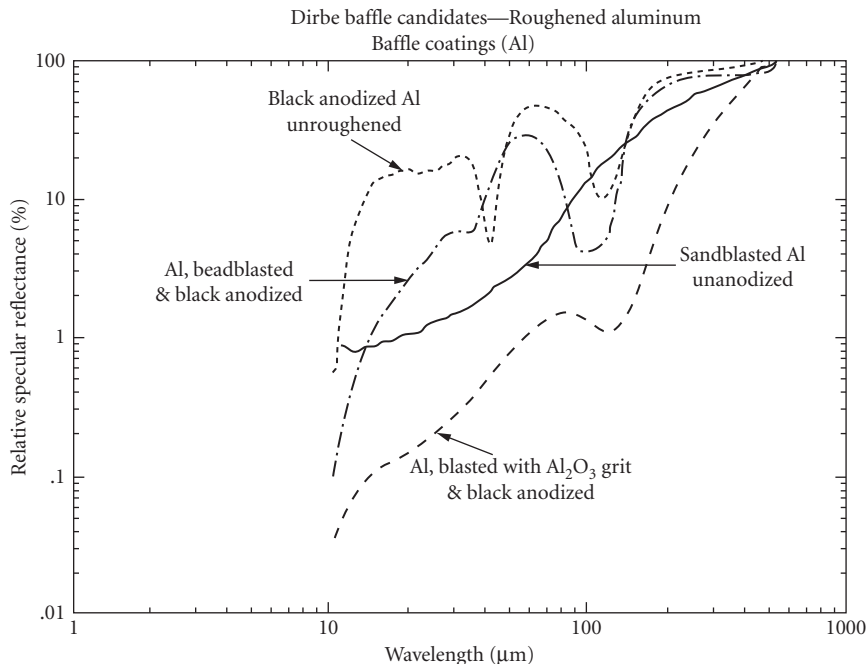


FIGURE 24 Specular reflectance of Diffuse Infrared Background Explorer candidate baffle surface based on roughened aluminum surfaces over the wavelength range 1 to 1000 μm . (From Heaney.¹³¹)

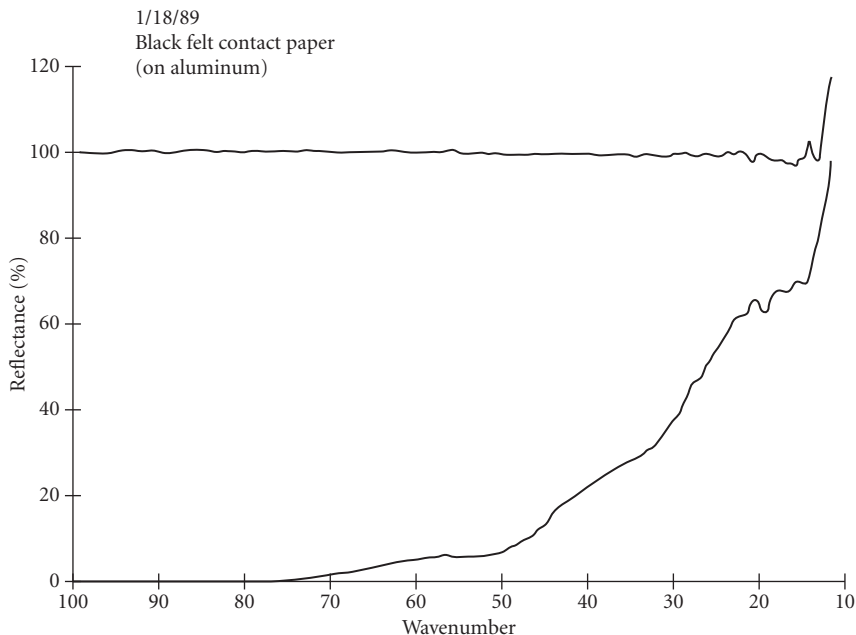


FIGURE 25 Reflectance of black felt contact paper from 100 to 10 wave numbers (100 to 1000 μm). (From Heaney.¹³¹)

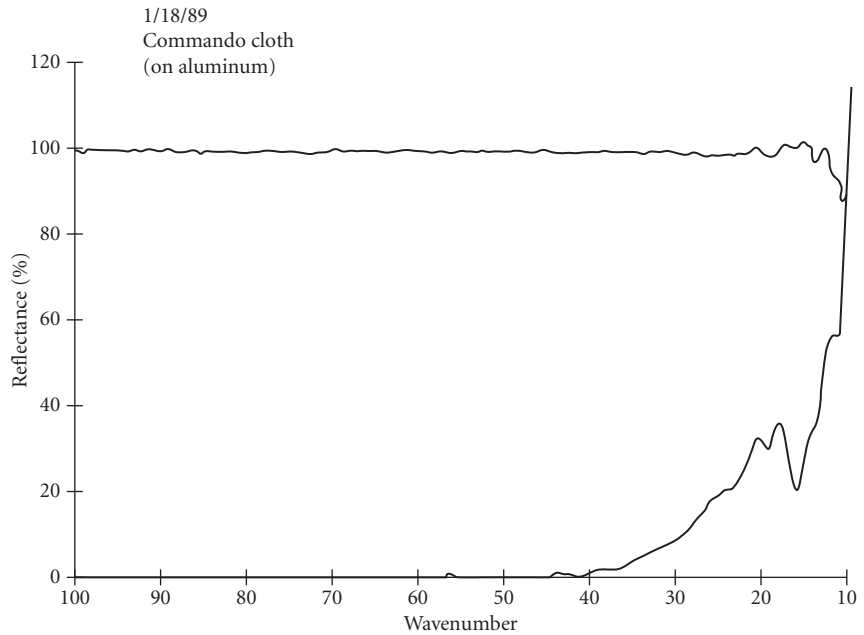


FIGURE 26 Reflectance of commando cloth on aluminum from 100 to 10 wave numbers (100 to 1000 μm). (From Heaney.¹³¹)

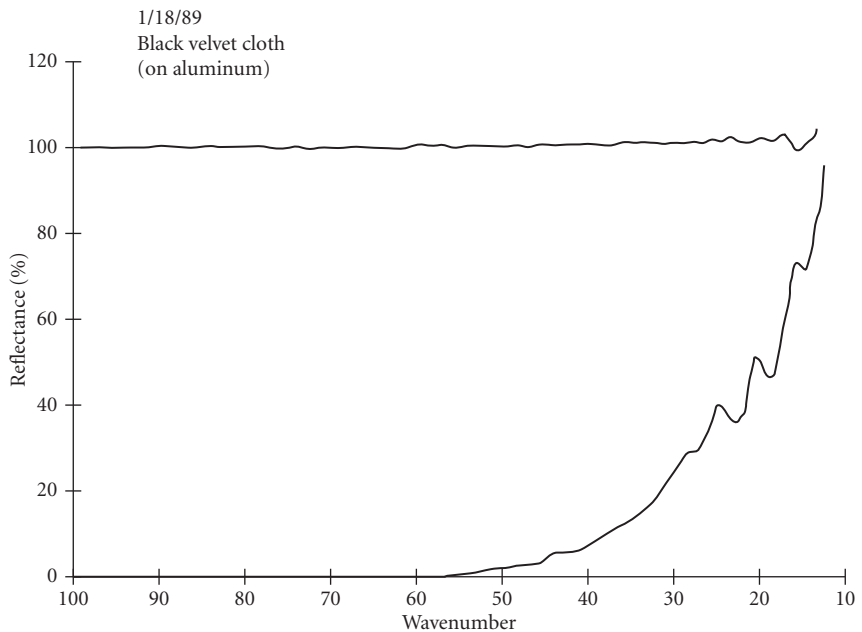


FIGURE 27 Reflectance of black velvet cloth on aluminum from 100 to 10 wave numbers (100 to 1000 μm). (From Heaney.¹³¹)

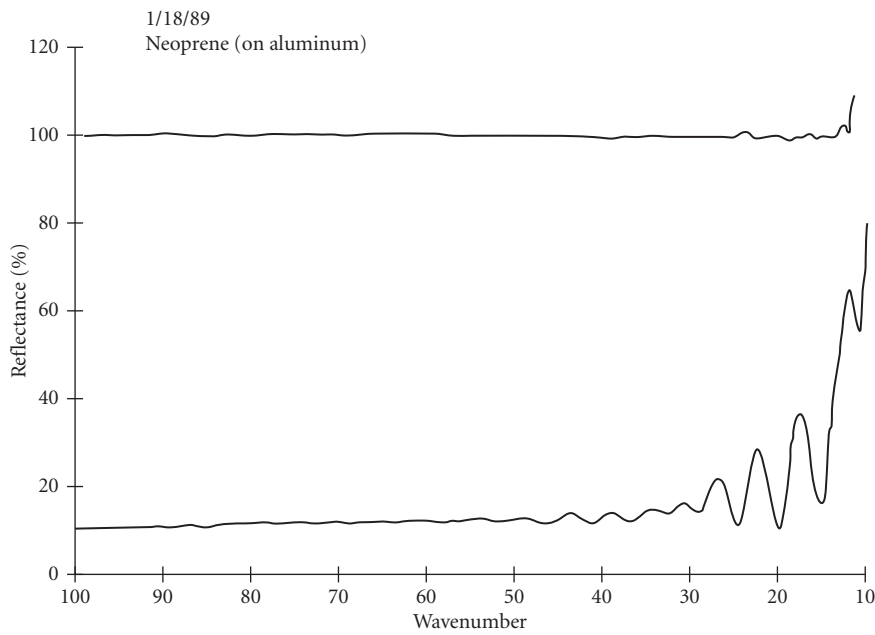


FIGURE 28 Reflectance of neoprene on aluminum from 100 to 10 wave numbers (100 to 1000 μm).
(From Heaney.¹³¹)

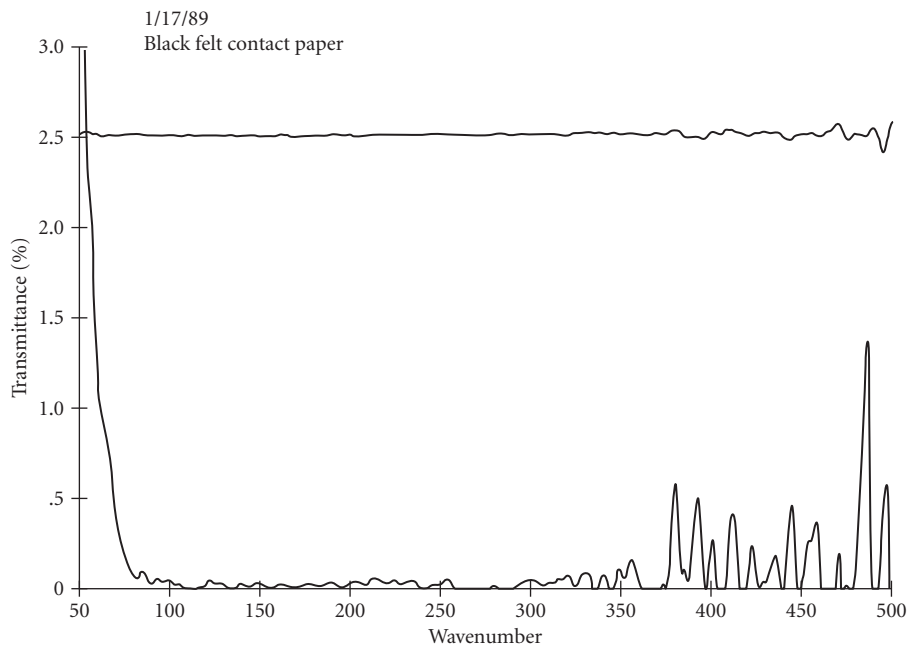


FIGURE 29 Transmittance of black felt contact paper from 50 to 500 wave numbers (200 to 20 μm).
(From Heaney.¹³¹)

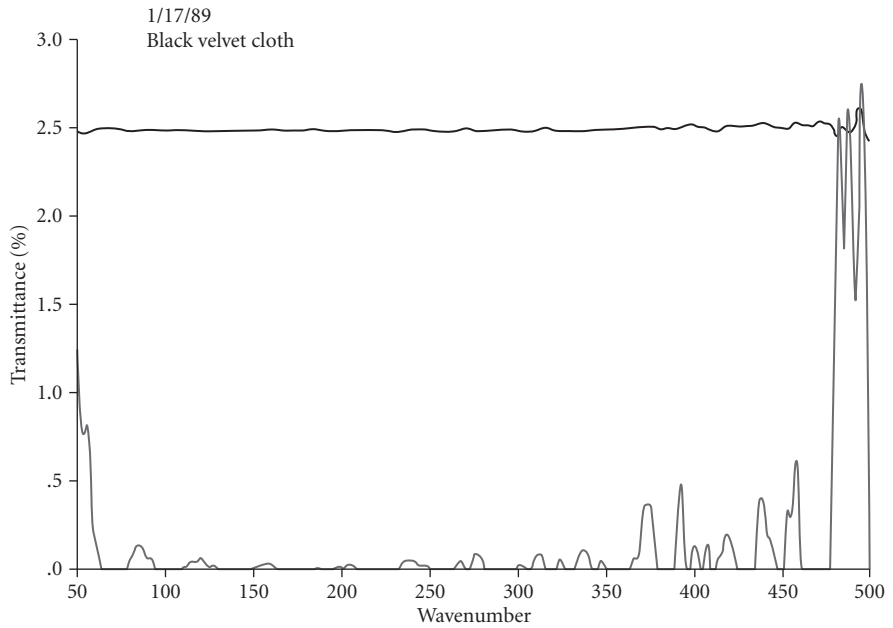


FIGURE 30 Transmittance of black velvet cloth from 50 to 500 wave numbers (200 to 20 μm).
(From Heaney.¹³¹)

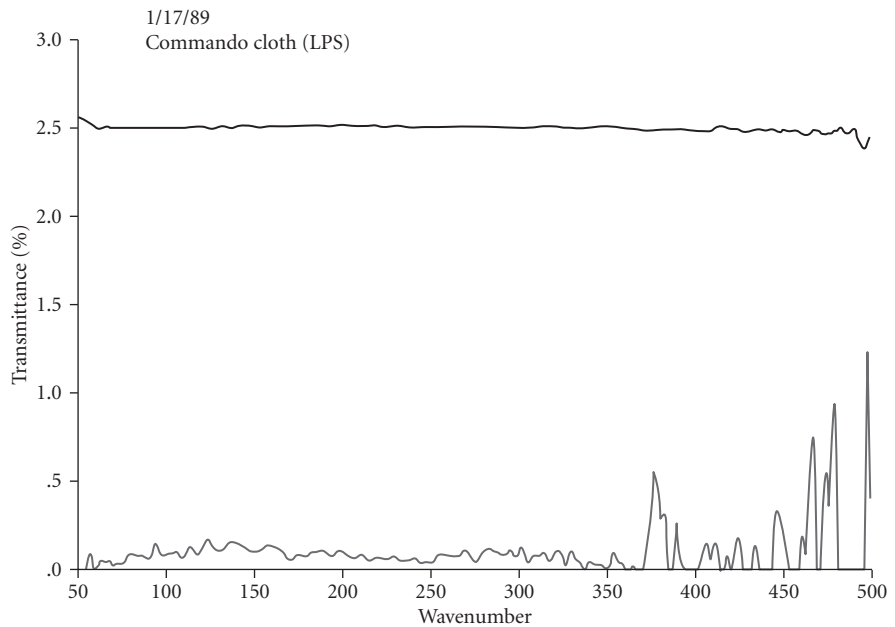


FIGURE 31 Transmittance of commando cloth (lps) from 50 to 500 wave numbers (200 to 20 μm).
(From Heaney.¹³¹)

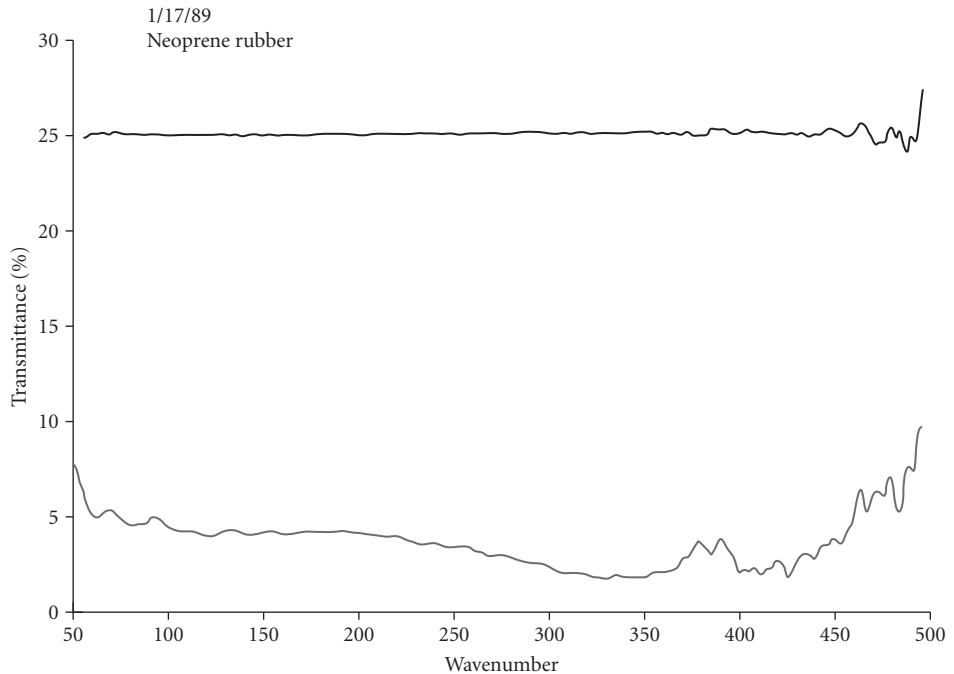


FIGURE 32 Transmittance of neoprene rubber from 50 to 500 wave numbers (200 to 20 μm). (From Heaney.¹³¹)

Ames 24E and Ames 24E2 Ames 24E is a new coating developed at NASA's Ames Research Center.⁴⁶ The coating is a very rough, very thick, highly absorbing coating composed largely of SiC grit and carbon black, and has very low far-infrared reflectance.⁴⁶ BRDF measurements show that this surface is a model lambertian surface at a wavelength of 10.6 μm at near-normal incidence. Ames 24E is nearly lambertian at longer wavelengths, even at 200 μm .

Ames 24E2 is a formulation using ECP-2200, carbon black, silicone resin, and #80 silicon carbide grit. The coating was developed for far-infrared space telescopes and can pass severe cryogenic cycling and vibration tests.³⁴ The coating is considerably less reflective at 100 μm than Ames 24E and has excellent absorption out to about 500 μm . Smith¹³⁷ has also developed a highly lambertian, diffuse reflectance standard, which he calls PDR, for perfect diffuse reflector. It shows lambertian behavior from 10 to about 100 μm .

6.7 SURVEY OF SURFACES WITH OPTICAL DATA

A Note on Substrates and Types of Coatings

Many different substrates are employed for baffle and vane surfaces. In particular, for space or cryogenic use, the 6000 series of alloys of aluminum (particularly 6061) are popular. They represent the baseline by which other materials are judged. Titanium and graphite epoxy are also widely used, and beryllium and carbon fiber substrates are becoming more common. For high-temperature applications or for resistance to lasers, materials with high melting points such as nickel, molybdenum, and carbon/carbon are used.

The distinction between substrate and surface or surface coating is blurry. When paints or other coatings are applied to a substrate, the distinction between the two is very clear. However, many surfaces today involve an extensive alteration of the substrate before the “coating” is applied. They may chemically alter the substrate to create the surface coating, which is an integral part of the substrate. In these cases, the use of the word substrate only serves as a description of the material that must be altered to create the black surface.

The classification of surfaces by substrate and/or type of coating or surface treatment is only one of the many ways available. However, it is a very useful form of classification, and will be used here.

6.8 PAINTS

Paints are easy to apply and their availability and usually low price make them ideal for laboratory experiments and instruments. However, their high outgassing rates and, in some cases, the large number of particles that can be liberated from them compromise their use in space-based applications. However, there are many space-qualified paints that have been flown in space. Notable among them is Aeroglaze Z306, and the derivatives of this basic paint system that have been developed at Goddard Space Flight Center.

The way that paint may be applied can greatly affect the optical properties. The most obvious are the number of coats and the thickness; the substrate preparation also plays a critical role. Brown²⁷ describes the effects of number of coats on optical performance for three diffuse paints. The importance of developing a procedure for painting that incorporates the paint manufacturers' application recommendations cannot be overstated. This procedure must also include process control requirements, cleanliness requirements, application process and surface preparation requirements, safety requirements, quality assurance requirements, and storage shipping requirements, as McCall¹⁸ describes in detail. A short description of a few of the more common paints is given here. Table 2 gives further reference data on these and other paints.

3M Paints and Their Current Derivatives

3M Nextel Black Velvet Several varieties of 3M Black Nextel paint from Minnesota Mining and Manufacturing Company have seen extensive use in ground-based instruments and were considered as standards for black coatings. These paints consisted of pigments with approximately 20 percent carbon black and 80 percent silicon dioxide. However, most of them are presently unavailable. Those that are available are manufactured under license by other companies. The optical properties of the original paint are given in Fig. 33.

The paint labeled 3M 101-C10 historically was one of the most widely used laboratory black paints; however, it is no longer made. Redspot Paint and Varnish (Evansville, Indiana) now makes a similar paint, but uses resin instead of glass microspheres, making it unsuitable for space applications according to Ames.²⁸ Two other paint varieties in the same line were 3M401-C10 and 3M3101 (see Figs. 34 and 35), apparently available from Red Spot Paint and Varnish.

The 3M Nextel Black Velvet was replaced by 3M SCS-2200 (3M Brand ECP-2200) (see Fig. 35). The optical differences between the original and its replacement are discussed by Willey et al.⁴² Illinois Institute of Technology now produces the ECP-2200 under the name MH2200 (see following).

Nextel 2010 A sprayable Nextel 2010 Velvet paint is available from the German company Mankiewicz Gebr. & Co., Hamburg, and has been used on several ground-based astronomical instruments, where cryogenic cycling durability is important. The 2010 surface has an outgassing rate of 1.3×10^{-4} g/cm² at 84°F (29°C) in a 20-hour test at 10^{-5} to 10^{-6} torr. The solar alpha of this surface (from the company literature) is about 0.97 and the normal emittance is about 0.95.

The total emissivity of different black surfaces was investigated with regard to their being used as a total radiation standard in the temperature range –60 to +180°C by Lohrengel.¹³⁹ The investigations showed that the matte varnish Nextel Velvet Coating 2010 black with an emissivity of 0.951 was

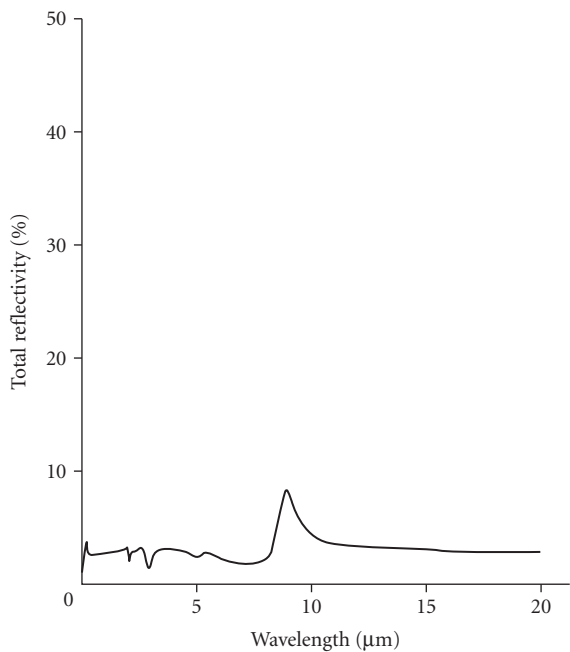


FIGURE 33 Total hemispherical reflectivity of 3M Nextel Black Velvet. (From Willey *et al.*⁴²)

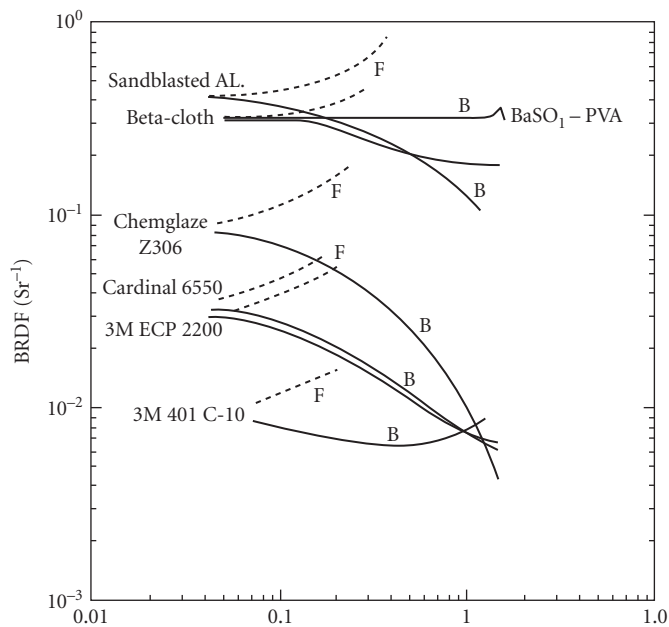


FIGURE 34 Comparison of BRDF profiles at an angle of 45° and 633-nm wavelength. (From Viehmann and Predmore.³⁵)

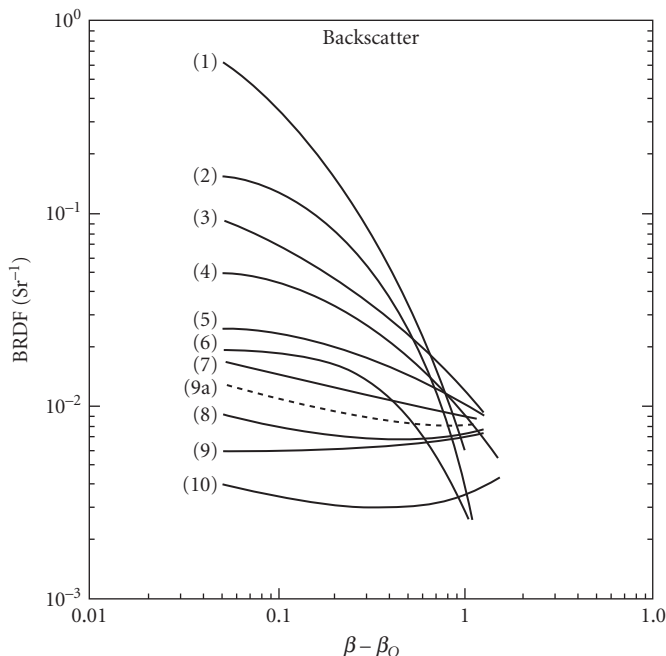


FIGURE 35 Comparison of BRDF profiles at an angle of 45° and 254-nm wavelength: (1) Reynolds Tru Color Diffuse; (2) Chemglaze Z306; (3) Sikkens 443; (4) Sanodal Fast Black GL; (5) Chemglaze Z306 plus microballoons; (6) Sanodal deep black MLW; (7) 3M 401-C10; (8) Chemglaze Z313; (9) DeSoto Flat; (10) DeSoto Flat after EUVSH; (11) Martin Black anodize. (From Viehmann and Predmore.³⁵)

best suited for these purposes. Additional changes to the surface (sprinkling of Cu globules, etching) could be made to increase the total emissivity by a further 0.007 or 0.016, respectively. The present availability of this paint from U.S. manufacturers is unknown.

Nextel Brand Suede Coating Series 3101-C10 C-10 is the black variety of this paint, available from Red Spot (see references). It is a low-gloss paint, with reasonable abrasion resistance (see Fig. 36). It has a soft-cushioned feel and suedelike appearance and was used on office equipment, furniture, and electronic equipment housings. The manufacturer recommends it for interior use only.

MH 2200 MH2200 (formerly ECP-2200, which was derived from the original 3M Nextel Black Velvet) is a one-part, flat black, nonselective solar absorber coating designed for high-temperature service (Fig. 37). When applied to aluminum substrates, the coating integrity and its "solar absorption" of 0.96 are unaffected by temperatures to about 500°C . The coating is 43 percent solids in xylene and is intended for nonwear applications. ECP-2200 is available from IIT Research Institute. It is touted as the substitute for 3M Nextel Black, but does not have the low BRDF at visible wavelengths of its former relative. It has a normal emittance of 0.95 at $10.6\ \mu\text{m}$ and an absorptance of 0.96 over the wavelength range of 0.35 to $2.15\ \mu\text{m}$. Its emittance is 0.86 on an aluminum substrate (normal emittance at 75°F from 2 to $25\ \mu\text{m}$).

Aeroglaze Z Series Aeroglaze (formerly Chemglaze) Z306 diffuse black paints are part of the Z line of single-package, moisture-curing, ASTM Type II, oil-free polyurethanes.²⁴ This paint has excellent chemical, solvent, and (if used with a primer) salt-spray resistance. This is a popular paint for aerospace

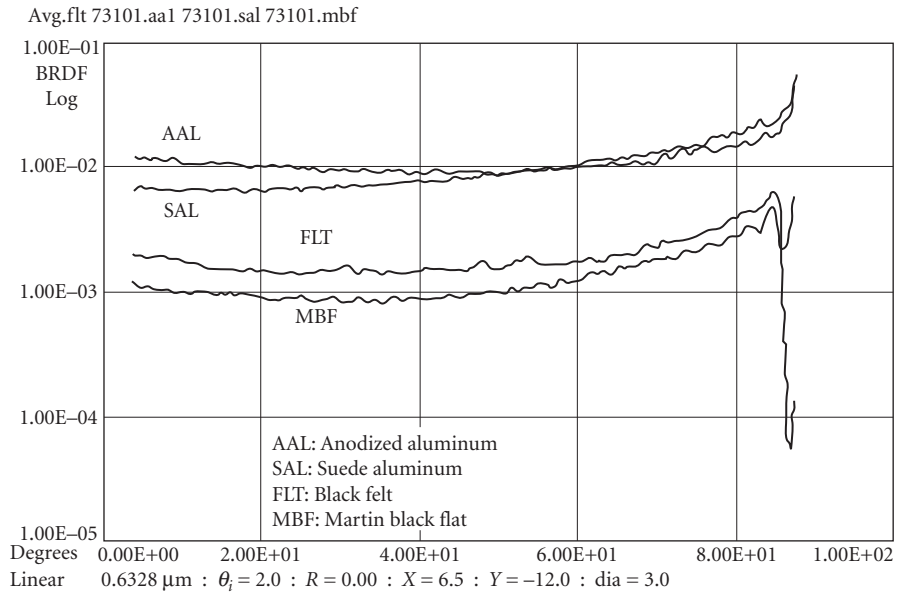


FIGURE 36 BRDF data for anodized aluminum, 3M Nextel Suede paint, black felt, and an aluminum flat with Martin Black wavelength is 633 nm, at near normal incidence. (From Cady *et al.*⁶⁶)

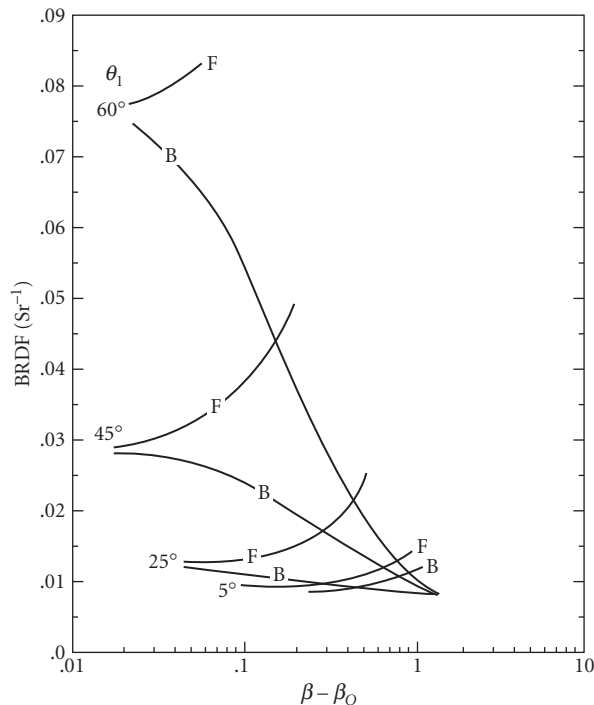


FIGURE 37 BRDF profiles of 3M ECP-2200 black paint 6550 at 633 nm. (From Viehmann and Predmore.³⁵)

use, especially after the discontinuation of 3M's 401-C10 Black Velvet Nextel.²⁸ For space use, the Aeroglaze 9924 and Aeroglaze 9929 primers are recommended. The optical properties are given in Figs. 34 and 38 to 43.

A low volatile version of the paint is being developed. In a version developed at Goddard Space Flight Center (based on the Z306)⁴⁴ glass microballoons are added to reduce the specular component, though the particles may be a source of particulate contamination. Other versions were developed at Goddard based on the Z004 paint. Goddard Black is a generic term for several paints of composition and optical properties different from Z306. This name is often incorrectly applied to the modified Z306 described here.

Akzo Nobel Paints Three paints sold formerly under the label Cat-a-lac are now known as Akzo 463-3-8 (formerly Cat-a-lac 463-3-8 diffuse black), 443-3-8 (formerly Cat-a-lac 443-3-8) (see Figs. 34 and 43 to 46) and 443-3-17 (formerly called Sikkens 443-3-17). The Bostic name is also formerly associated with these same paints. The 463-3-8 is the most diffuse of the three blacks, and the other two are considered "glossy." It is an epoxy-based system with low outgassing and low reflectance.

Cardinal Black From Cardinal Industrial Finishes. Optical data are given in Fig. 47.

Cat-a-lac Black (Former Name) This is an epoxy system with low outgassing and low reflectance. It is now manufactured by Sikkens Aerospace Finishes (see Akzo in the tables for address) and is described here.

DeSoto Black The PRC DeSoto Black is a flat black paint most suitable for the range 0.2 to 2.5 μm . It has a reflectance of between 2 and 3 percent over this range. Its emissivity is 0.960 compared to a 300 K blackbody, while its absorptivity over the solar spectrum is 0.924. DeSoto Black can meet outgassing requirements for space applications when vacuum baked. The weight loss is typically below 0.5 percent and the volatile condensable material is below 0.5 percent, similar to 3M Black Velvet.¹⁴⁰ A BRDF curve is given in Fig. 35.

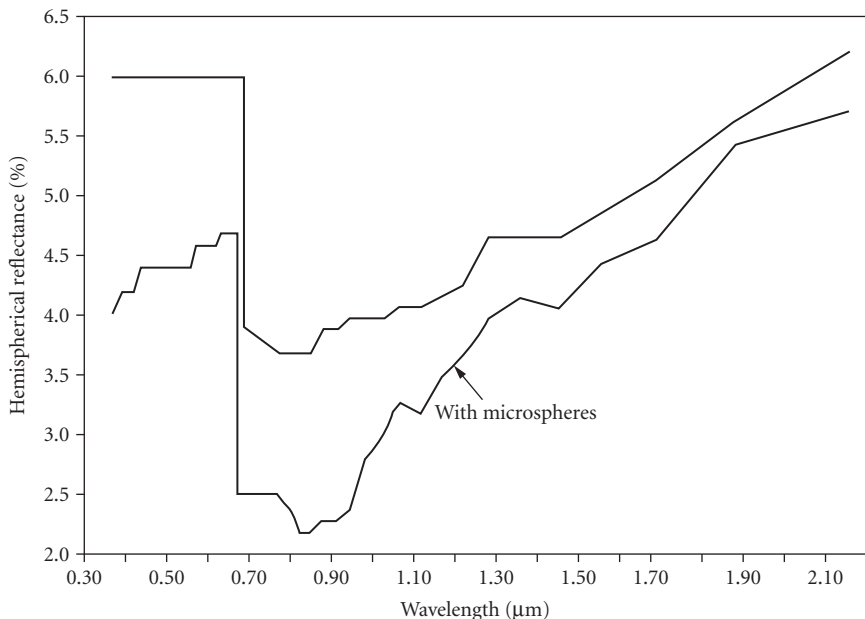


FIGURE 38 Diffuse visible and near-infrared hemispherical reflectance of Chemglaze (now called Aeroglaze) Z306, and Z306 with microspheres. (From Ames.²⁸)

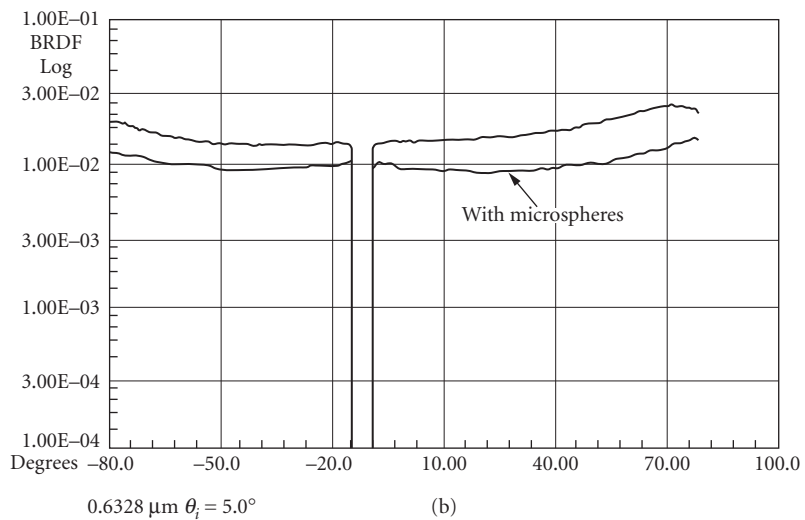
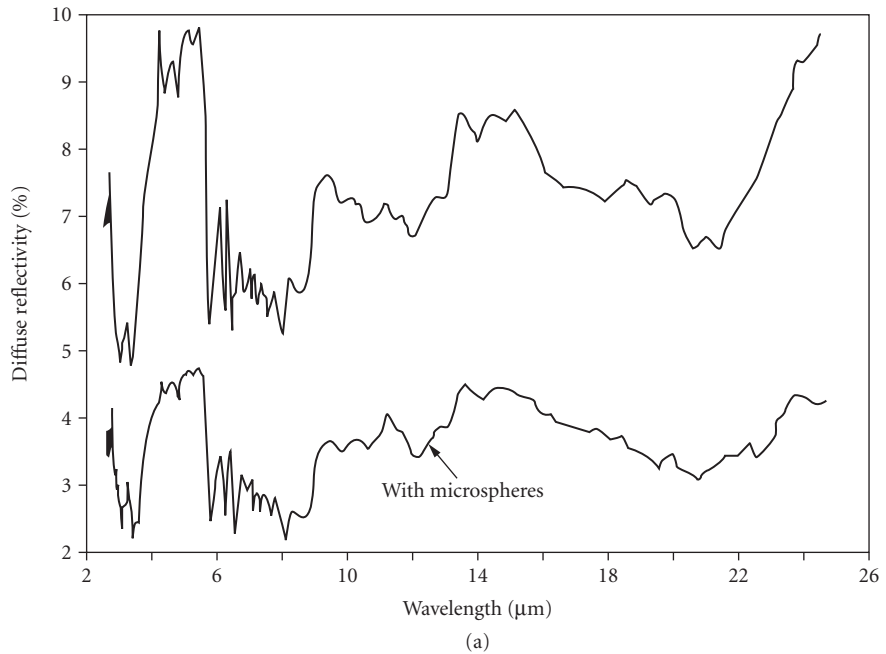


FIGURE 39 (a) Infrared diffuse reflectivity of Chemglaze Z306 (now called Aeroglaze) and Z306 with microspheres. (b) BRDF for Chemglaze (now Aeroglaze) Z306 at near-normal incidence (5°) at a wavelength of $0.6328 \mu\text{m}$. (From Ames.²⁸)

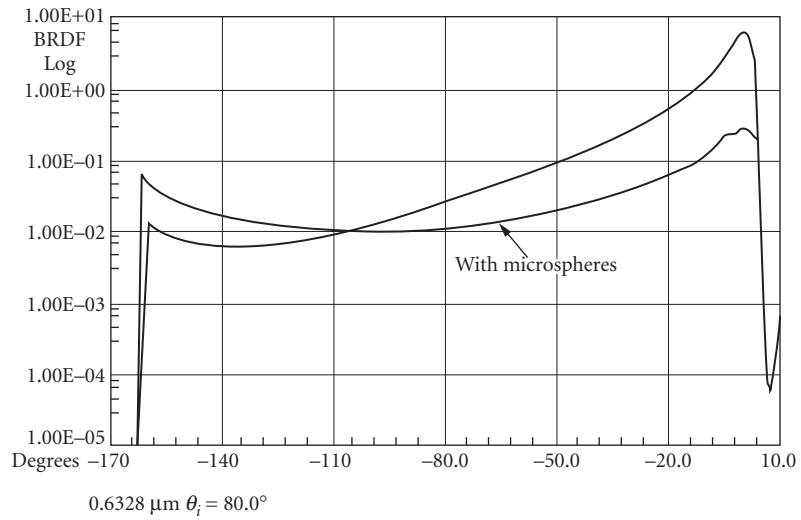


FIGURE 40 BRDF for Chemglaze (now Aeroglaze) Z306 at near grazing incidence (80°) at a wavelength of $0.6328 \mu\text{m}$. (From Ames.²⁸)

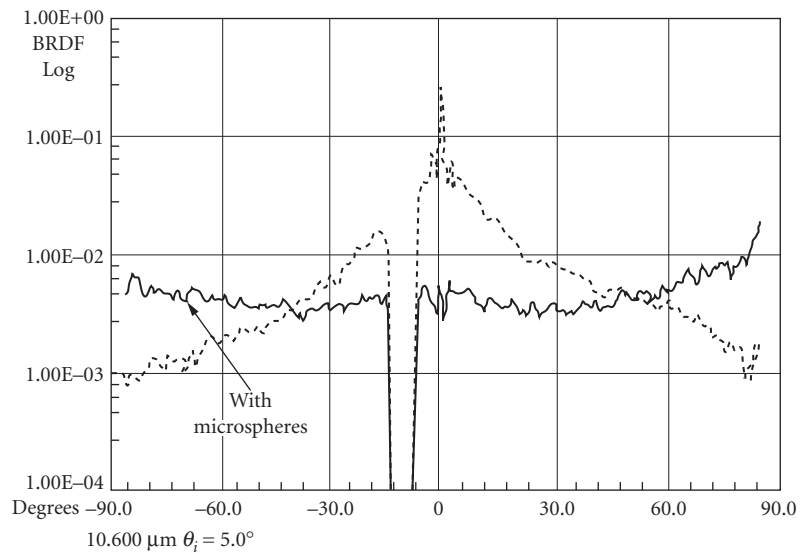


FIGURE 41 BRDF for Chemglaze (now Aeroglaze) Z306 at near-normal incidence (5°) at a wavelength of $10.60 \mu\text{m}$. (From Ames.²⁸)

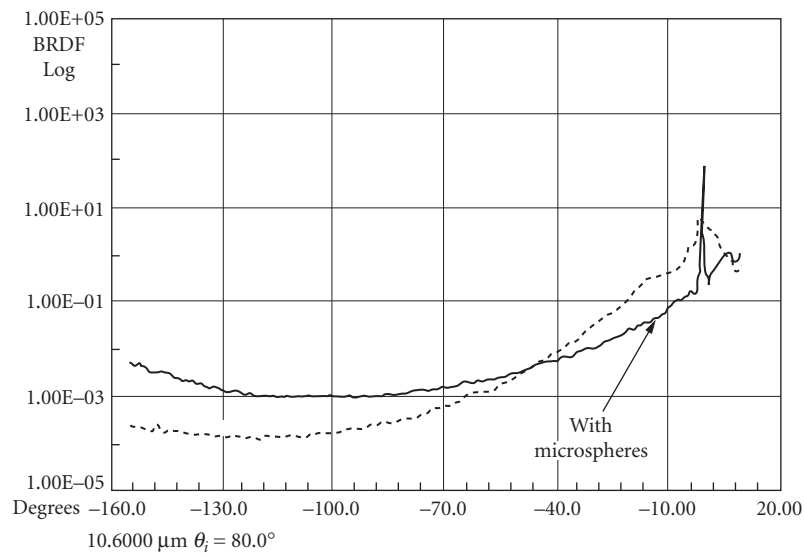


FIGURE 42 BRDF for Chemglaze (now Aeroglaze) Z306 at near grazing incidence (80°) at a wavelength of 10.60 μm. (From Ames.²⁸)

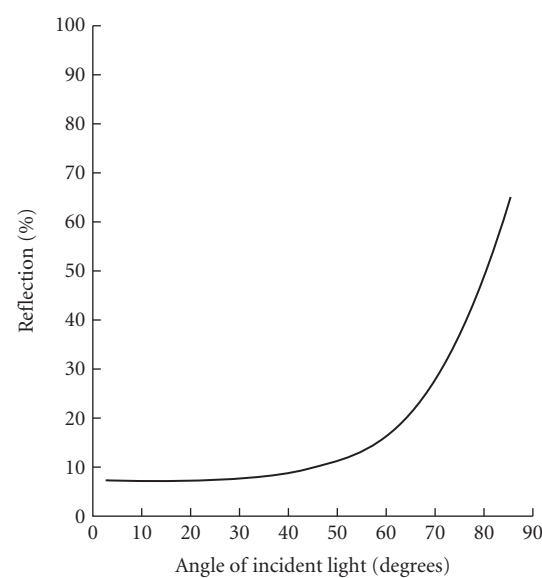


FIGURE 43 Specular reflection measured for Cat-a-lac glossy (now called Akzo 443-3-8) and for Chemglaze glossy (now called Aeroglaze Z302). The wavelength is 0.6328 μm. The two lines overlap. (From Griner.²⁵)

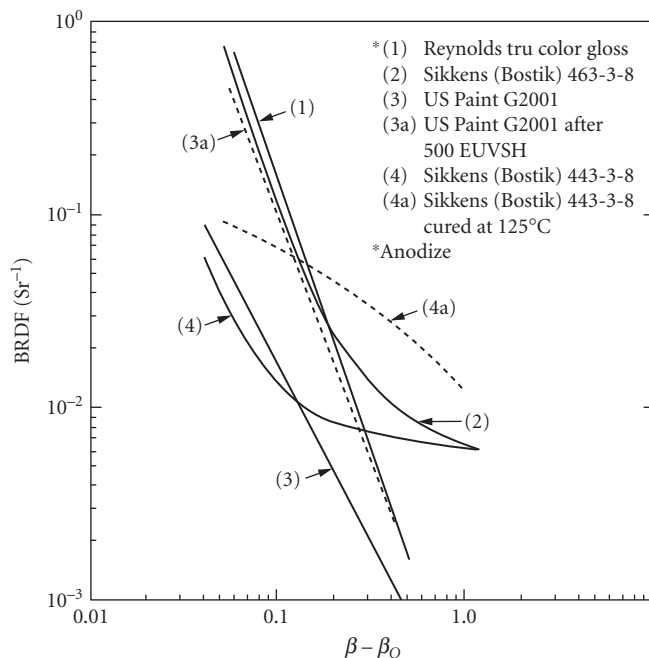


FIGURE 44 BRDFs of glossy surfaces at $0.254\ \mu\text{m}$ and 45° angle of incidence. (From Viehmann and Predmore.³⁵)

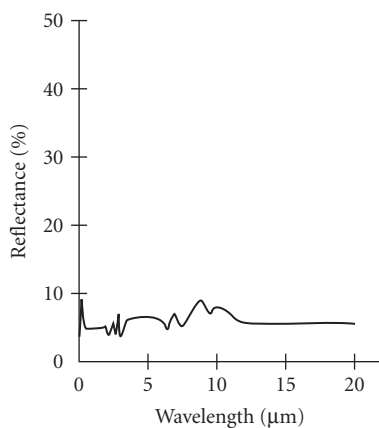


FIGURE 45 Total hemispherical reflectivity of Bostic 463-3-8 (now called Akzo 463-3-8) on bare aluminum. (From Willey et al.⁴²)

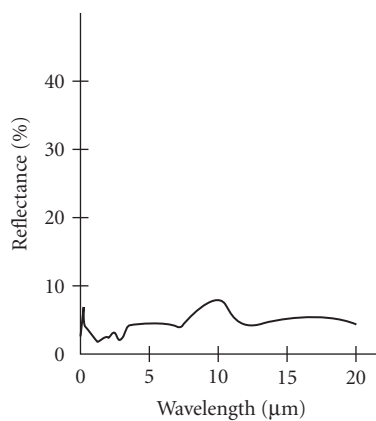


FIGURE 46 Total hemispherical reflectivity of Bostic 463-3-8 (now called Akzo 463-3-8) on ZnCr primer. (From Willey et al.⁴²)

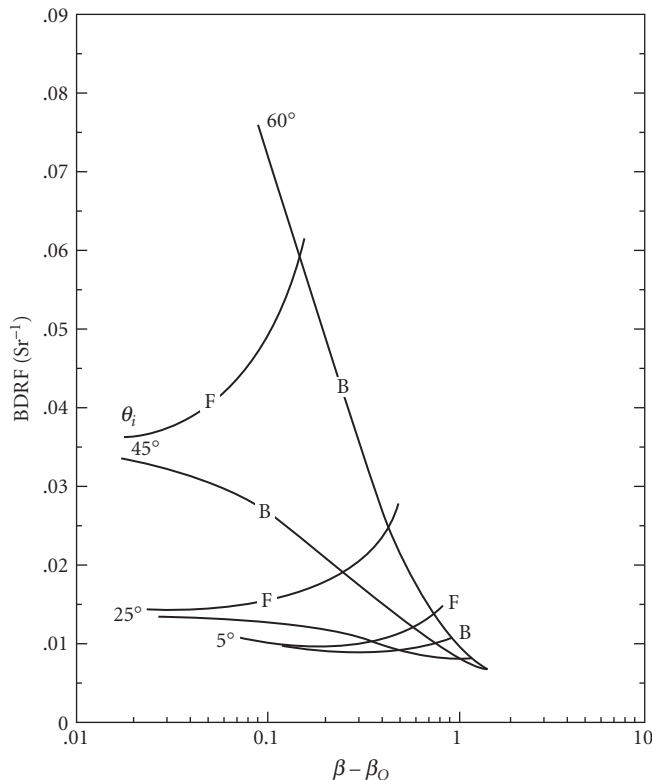


FIGURE 47 BRDF profiles of Cardinal black paint 6550 at 633 nm. (From Viehmann and Predmore.³⁵)

Floquil: Black for Lens Edges Lewis et al.¹⁴¹ discuss experiments to find low-scatter blackening components for refractive elements. With index of refraction matching, gains of several magnitudes in lower BRDF can be achieved over other edge-blackening techniques. The paint Floquil (Polly S Corporation) has been used as an edge-blackening compound and is discussed by Lewis. Smith and Howitt¹⁹ give a specular reflectance curve for Floquil in the infrared from 20 to 200 μm .

Parson's Black Prior to 1970, Parson's Black was a standard black reference.

SolarChem SolarChem is a black paint with excellent visible absorbing properties and has been suggested as a replacement for the unavailable 3M Nextel Black. The visible BRDF of SolarChem has a flat profile at near-normal angles of incidence (Fig. 48), while the 10.6- μm BRDF of SolarChem shows quite a different shape.⁸⁸ The surface is highly specular at 10.6 μm .

Anodized Processes

Anodized processes can produce fine black surfaces. The condition of the substrate plays an important role in the overall scattering properties of the surfaces. A common technique is to sandblast (vapor hone) the surface before anodization. Many varieties of grit may be used and each will produce a different kind of surface treatment. Sometimes, small pieces of grit can become embedded in the surface and this may affect the anodizing process. The BRDF of sandblasted aluminum surfaces are given in Figs. 49 and 50. Table 3 gives reference data on anodized surfaces.

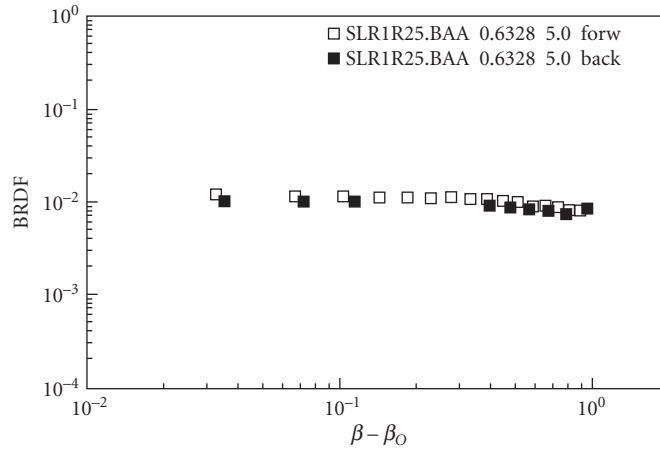


FIGURE 48 Visible (0.6328 μm) BRDF of SolarChem at 5° angle of incidence. (From Pompea *et al.*⁴)

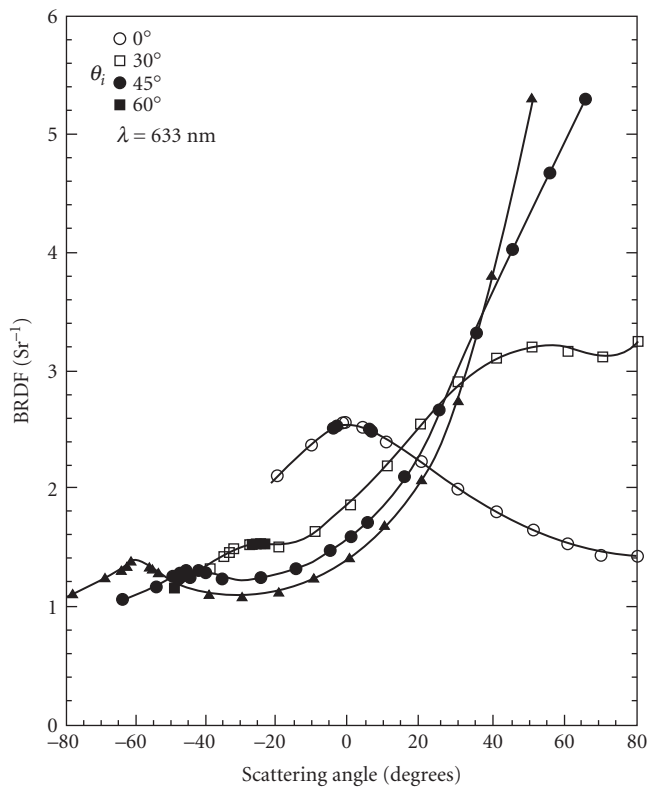


FIGURE 49 BRDF profiles of sandblasted aluminum. Open circle: 0° open square: 30° filled circle: 45° filled square: 60° ; wavelength of 633 nm. (From Viehmann and Predmore.³⁵)

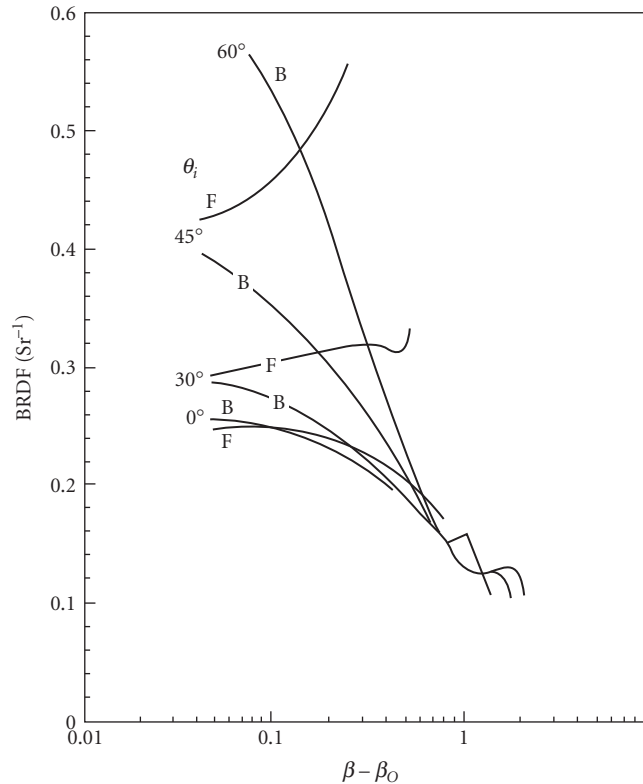


FIGURE 50 Forward (F) and back (B) scatter profiles of sandblasted aluminum. Wavelength of 633 nm. (From Viehmann and Predmore.³⁵)

Martin Black Martin Black is an anodized aluminum surface that is made microrough by a special anodization process developed by Lockheed Martin, Denver.^{142,143} It is made black from the inclusion of an aniline dye that is sealed into the surface. It was developed for the Skylab program and has been used on a wide variety of space instruments operating at vacuum ultraviolet to far-infrared wavelengths. The surface is rough, and scattering at several fundamentally different scale lengths occurs.

Special care in handling surfaces of this class is needed since the surface morphology consists of pyramids extending from the surface, and these features are easily crushed. The surface is still quite black, however, even if some surface damage occurs. The surface morphology works well for space applications as it does not support electrical potentials higher than 200 V, is not affected by temperatures as high as 450°C, by hard vacuum, or by ultraviolet radiation. It also has very low outgassing rates and will not delaminate even under severe environmental conditions.¹⁴⁴ It passes NASA SP-R-0022A specifications for outgassing.

The surface is also highly resistant to chemical attack by atomic oxygen prevalent in low earth orbit.⁶⁴ BRDF measurements of Martin Black show its lambertian character at 0.6328 and 10.6 μm . The reflectance spectrum shows significant reflectances at about 2.5 and 5 μm ; at other wavelengths, the reflectance is low. The optical data are given in Figs. 36, 51, and 52.

Enhanced Martin Black Enhanced Martin Black is similar in its properties to Martin Black, but was created to provide an even more durable surface for long exposure to atomic oxygen in low earth orbit. Experiments aboard the space shuttle confirm this superiority in the shuttle orbit environment.⁶⁴ The

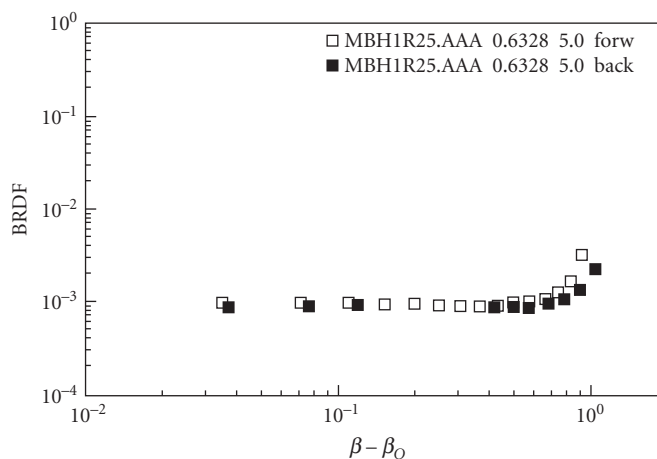


FIGURE 51 Visible ($0.6328\ \mu\text{m}$) BRDF of Martin Black at 5° angle of incidence. (From Pompea *et al.*⁴)

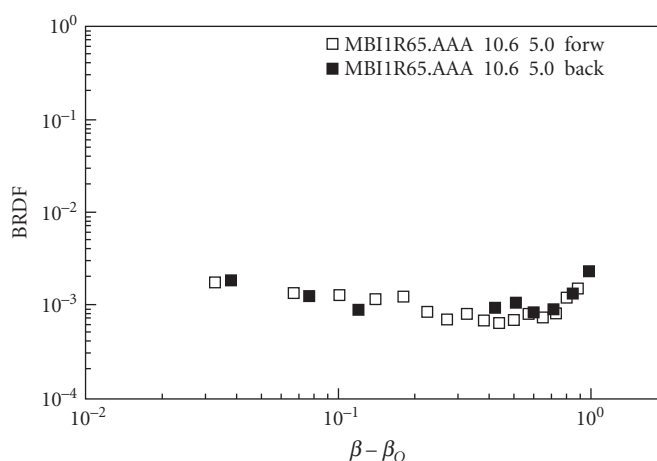


FIGURE 52 Infrared ($10.6\ \mu\text{m}$) BRDF of Martin Black at 5° angle of incidence. (From Pompea *et al.*⁴)

process refinements also reduced the near- and middle-infrared reflectances from about 40 percent at $2.3\ \mu\text{m}$ to about 25 percent and from about 15 percent at $5.5\ \mu\text{m}$ to about 3.5 percent, while maintaining an absorption of about 99.6 percent in the visible region.

Posttreated Martin Black Another variation of the Martin Black surface is designed for near-infrared applications. Posttreated Martin Black uses hydrogen fluoride to further reduce the near-infrared reflectance peak and eliminate the middle-infrared reflectance peak of Martin Black. The area under the $2.3\text{-}\mu\text{m}$ peak of Martin Black has been reduced by about two-thirds and the $5.8\text{-}\mu\text{m}$ peak of Martin Black has been eliminated.

Infrablack Infrablack is another anodized surface from Martin Marietta, which relies upon a very rough substrate to produce a diffusing and absorbing surface for wavelengths up to 750 μm .^{138,145} It was developed for the next generation of far-infrared NASA telescopes. It has also been used in experiments to measure the Stefan-Boltzmann constant where a “blackbody” surface with very high emissivity was needed. This type of surface can also be used in space radiators where high emissivity is beneficial. Like other anodized surfaces in this class, the Infrablack surface is fragile and care in handling is needed to avoid crushing the surface structure. As with Martin Black, even a mistreated or crushed surface will still be significantly more light absorbing than most other black surfaces. Infrablack can be tuned for maximum absorption between 100 and 500 μm . The BRDF in the visible and infrared for Infrablack is similar to Martin Black and Enhanced Martin Black; all exhibit relatively lambertian behavior in the visible at near-normal angles of incidence (Figs. 53 and 54).

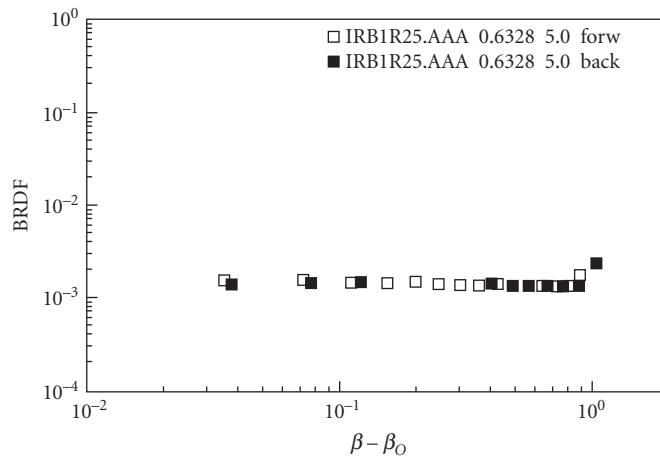


FIGURE 53 Visible (0.6328 μm) BRDF of Infrablack at 5° angle of incidence. (From Pompea et al.⁴)

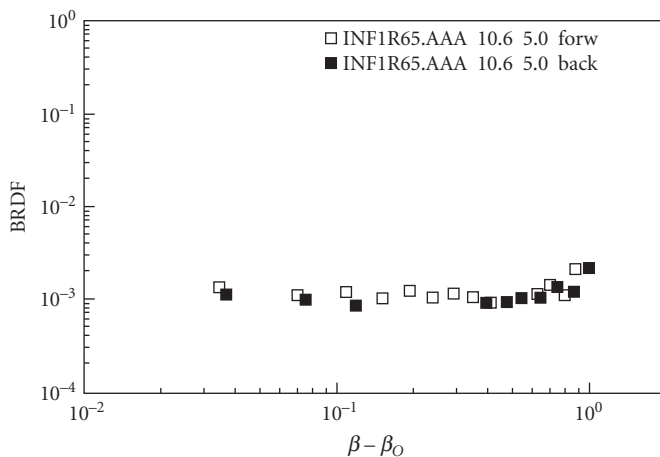


FIGURE 54 Infrared (10.6 μm) BRDF of Infrablack at 5° angle of incidence. (From Pompea et al.⁴)

DEEP SPACE BLACK DEEP SPACE BLACK (N-Science/Advanced Surface Technologies, Arvada, Colorado) shares many if not most characteristics of Martin Optical Black, a similar specialized anodization process. Like Martin Black it is extremely absorptive over a wide range of wavelengths from ultraviolet to the infrared and is best used on 6061 aluminum. The surface has good mechanical stability. The surface can be fine tuned for better performance in the near-infrared (1 to 5 μm) and for maximal durability in the low-earth orbit space environment. The total hemispherical reflectance in the 0.4- to 0.7- μm range is 0.37 and 0.78 percent in the 0.4- to 1.0- μm range. Like Martin Black, the surface does not support an electrical potential greater than 200 V and is robust under vibration and cryogenic cooling. When cryogenically cooled the surface has an emissivity in the far-infrared region (7 to 120 μm) of 0.985 or better.

This surface is used in controlling stray light or as black surface with high emissivity in a variety of optical systems such as detector cold shields and assemblies, detector calibration sources and blackbody cavities, thermal control and radiator surfaces, and spacecraft applications such as star trackers and cameras. DEEP SPACE BLACK is available in three variations:

DEEP SPACE BLACK-VIS: DSB-VIS is optimized for performance in the visible wavelength regime.

DEEP SPACE BLACK-Full Spectrum Basic: DSB-FSB is optimized to provide best performance over the largest wavelength regime possible. DEEP SPACE BLACK-Full Spectrum Enhanced: DSB-FSE is a special variant of DSB-FSB that has a more robust finish with the same outstanding optical characteristics of the FSB. DSB-FSE provides a somewhat improved optical performance in the near- and middle-IR. The performance in the visible region of the spectrum is maintained. This product is more suited to spacecraft applications, including those applications concerned with LEO environments.

Tiodize V-E17 Surface The Tiodize process is an electrolytic-conversion hard coating of titanium using an all-alkaline, room-temperature bath. It produces an antigall coating with good optical properties. The process can be used on all forms of titanium and its alloys and has been used in a wide variety of space vehicles and aircraft. The Ultra V-E17 coating is a black organic coating which changes the absorptivity and emissivity of titanium (0.62 and 0.89, respectively) to 0.89 and 0.91, respectively. The emittances were determined from a 25-point integration between 4.8 and 26.2 μm . The absorptance was determined by a 19-point integration between 0.32 and 2.1 μm . The surface has a total mass loss (TML) of 0.91 percent and no detectable volatile condensable material (VCM) in tests run at Ford Aerospace.¹⁴⁶ Its interaction with atomic oxygen is unknown.

TRU-Color Diffuse Black An electrolytic coloring process from Reynolds Aluminum.

Hughes Airborne Optical Adjunct Coating A cleanable specular black for use at 1 to 10 μm .

Etching of Electroless Nickel

The etching of electroless nickel provides a black coating useful for many applications. Some reference data on several electroless nickel processes are presented in Table 4. Kodama et al.¹⁴⁷ developed optical absorbing black films of etched nickel-phosphorus alloy deposited on substrates using an electroless plating process. Results of varying the plating and etching bath components and conditions were studied. They produced an optical absorber with a spectral reflectance of about 0.1 to 0.2 percent in the wavelength range of 488 to 1550 nm. The absorber showed substantial immunity to degradation in two accelerated-aging environments: 2000 hours in a dry-heat environment at 100°C, and 2000 hours in a damp-heat environment at 85°C and 85 percent relative humidity.

NBS Black This is a blackened electroless nickel surface developed for use as a solar collector at the National Bureau of Standards (now NIST) in Gaithersburg, MD.^{75,76,148} It consists of an electroless nickel-phosphorous coating that can be plated onto a wide variety of substrates such as metals, glass, ceramics, and plastics. This coating is subsequently etched using nitric acid, creating conically shaped holes into the surface, which act as light traps.

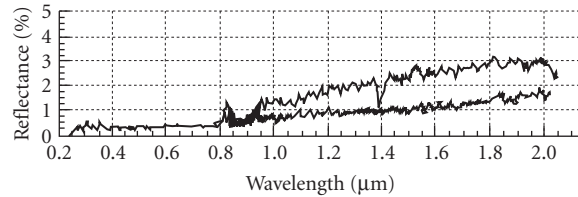


FIGURE 55 Total integrated scatter of NBS Black. The substrates are magnesium AZ31B-F (upper curve) and magnesium ZK60A-T5. Substrate is silica sandblasted. $\alpha = 0.978$. $\epsilon = 0.697$. (From Geikas.⁶⁵)

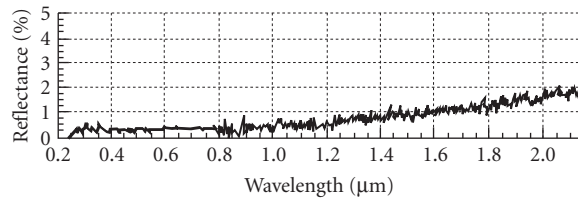


FIGURE 56 Diffuse scatter of NBS Black. The substrates are magnesium AZ31B-F and magnesium ZK60A-T5. The plots are overlaid and are virtually identical. Substrate is silica sandblasted. $\alpha = 0.978$. $\epsilon = 0.697$. (From Geikas.⁶⁵)

The specular reflectance is less than 1 percent over the range of 0.32 to 2.4 μm , making it an extremely black coating (Figs. 55 and 56). As this surface finish was developed for solar collectors, the surface has a high value for absorptivity (0.978), but a low value for room-temperature emissivity (about 0.5). The surface is moderately durable as the surface's relief consists of conical holes into the surface. The NBS Black process has been modified resulting in the next surface, which has greater infrared absorption.

Ball Black Ball Black is an optical black surface produced with modifications to the techniques just described—the selective etching on an electroless nickel surface to produce a multiplicity of conical light traps in the surface.^{29,65} The surface appears intensely black to the eye. The surface, however, is still an unaltered nickel-phosphorous deposit with the same chemical properties as the unetched surface, which was shiny. Ball Black can be plated on aluminum, beryllium, copper, stainless steel, invar, polycarbonate and ABS plastics, titanium, and some magnesium alloys. Since this process involves only deposition and etching of a metallic material, problems with outgassing or volatilization of the surface in a vacuum are minimal.

The surface is able to withstand rapid changes in temperature, with immersion into boiling water after being at liquid nitrogen temperature. The surface is sensitive to handling, though less so than surfaces like Martin Black. Small blemishes in the surface can be restored by re-etching without replating. The solar absorptivity can be made to vary between 0.71 and 0.995 and its room-temperature emissivity can be tailored to values between 0.35 and 0.94 by changes in the etching parameters. The directional reflectance increases by less than a factor of two from 1.5 to 12 μm . It has a BRDF of about 6×10^{-2} at normal incidence at 0.6328 μm . See Figs. 57 and 58 for optical data.

Plasma-Sprayed Surfaces

Boron Black Martin Marietta Boron Black is a surface that is black in the visible (solar absorptivity between 0.89 and 0.97, and emissivity of at least 0.86) and black in the infrared¹⁴⁹ (Fig. 59). Boron

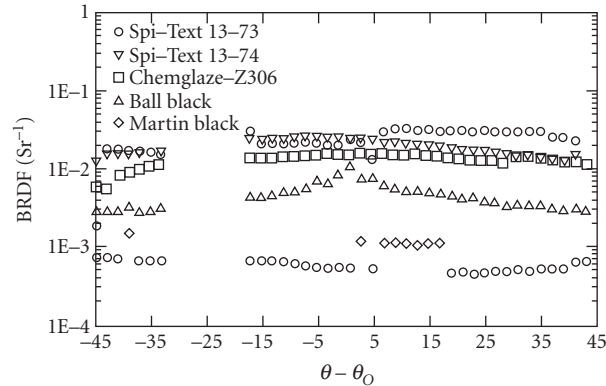


FIGURE 57 BRDF measurements at $0.6328 \mu\text{m}$ of textured metal surfaces from Spire Corporation and Chemglaze Z306 paint, Ball Black electroless nickel coating, and Martin Black anodized coating. (From Lompadó et al.²⁹)

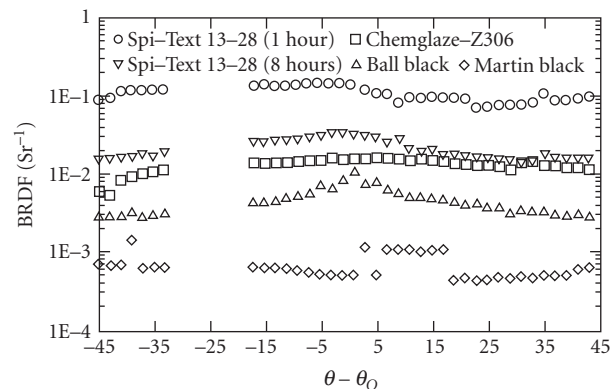


FIGURE 58 BRDF measurements at $0.6328 \mu\text{m}$ of two textured metal surfaces from Spire Corporation and Chemglaze Z306 paint, Ball Black electroless nickel coating, and Martin Black anodized coating. (From Lompadó et al.²⁹)

Black is a plasma-sprayed surface and can probably be applied to most metallic substrates. It has been applied to molybdenum, nickel, and titanium substrates. It offers a low-atomic-number surface with good optical properties and the ease of a plasma-spray deposition. The infrared BRDFs show a profile characteristic of a surface with lambertian profiles at near-normal angles of incidence.

Boron Carbide This is a Martin Marietta proprietary process. The boron carbide surface is applied to a titanium substrate. A 10- to 15- μm layer of B_4C is applied in a proprietary plasma-spraying process. BRDF measurements at 30° angle of incidence at two wavelengths illustrate that this surface is more lambertian in the visible.

Beryllium Surfaces Porous surfaces or those with steep-walled features which can trap radiation have been developed using plasma-sprayed beryllium and sputter-deposited beryllium by workers at Oak Ridge^{82,150,151} and at Spire Corp.¹⁵² who are developing baffles that can operate in severe environments.

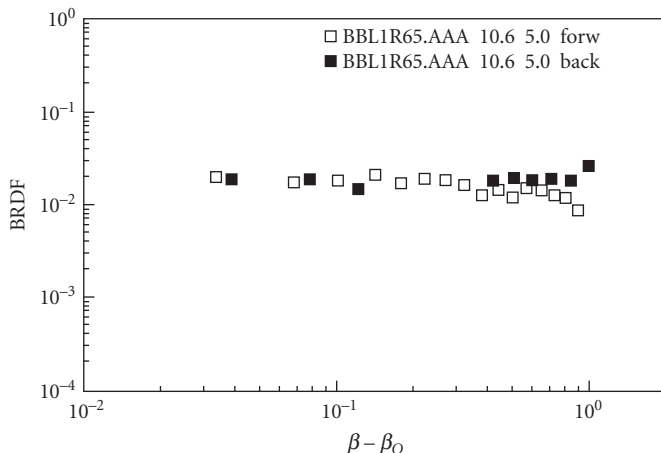


FIGURE 59 Infrared (10.6 μm) BRDF of Boron Black Black at 5° angle of incidence. (From Pompea *et al.*⁴)

Plasma-sprayed beryllium samples appear visually rough with a matte gray finish. The specular reflectance is approximately constant at about 1.6 percent from 2 to 50 μm , while the BRDF is lambertian in character at near-normal angles of incidence with a value of about $5 \times 10^{-2} \text{ sr}^{-1}$, equivalent to a total hemispherical reflectance of about 15 percent.

Beryllium surfaces with varying thicknesses and columnar grain sizes can also be created by low-temperature magnetron sputtering. The surfaces can then be chemically etched to enhance their absorptive properties. These surfaces exhibit less than 2 percent specular reflectance at near-infrared wavelengths. Very thick surfaces (350 μm) exhibit specular reflectances of less than 0.5 percent up to 50 μm wavelength.

A sputtered coating of Be on a Be surface can be made more absorptive through exposure to an oxygen plasma to form a layer of BeO on the surface of the coating.²⁹ Optical data are presented in Figs. 57, 58, 60, and 61.

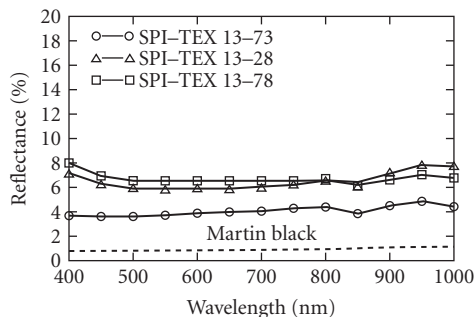


FIGURE 60 Total hemispherical reflectance in the visible bandpass for textured baffle materials from Spire Corp. The 13-73 surface is a textured aluminum surface. (From Spire.⁸¹)

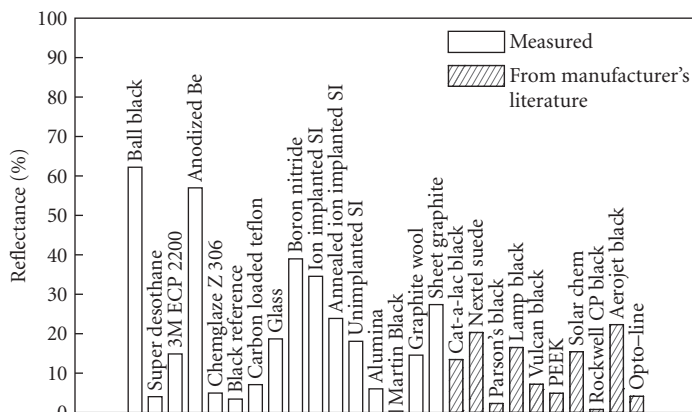


FIGURE 61 Total hemispherical reflectance data for baffle materials at 10.6 μm . The shaded measurements are from the manufacturer's literature and have not been independently verified. (From Johnson.¹⁵³)

Ion Beam-Sputtered Surfaces

Ion beam-sputtering processes can roughen surfaces of a large variety of compositions. An excellent review is by Banks in Cuomo et al.⁷⁷ (see also Ref. 78). A variety of sputtering processes can create rough features of various geometries that decrease specular reflections and create a black-appearing surface from a light-appearing substrate. Since the roughness is integral to the surface, these surfaces often have desirable environmental resistance to atomic oxygen. However, these surfaces also have tremendous surface area for trapping of contaminants and thus a potential for large outgassing rates if preventative steps are not taken. These surfaces are expensive to make in large areas, though they are becoming less expensive as coating facilities are built to harness this technology. They do have tremendous potential as diffuse baffle surfaces and as high-emittance surfaces for high-temperature space radiators.^{154,155} They are also cleanable and very durable.

Lompado et al.²⁹ and Blatchley et al.⁸³ describe several textured aluminum surfaces and give plots of their total hemispherical reflectance in the 0.4- to 1.0- μm range, as well as BRDF plots at 0.6328 and 10.6 μm (Fig. 60).

Electrodeposited Surfaces

Refer to Table 4 for further reference data on these surfaces.

Black Cobalt Black cobalt is a patented surface developed at Martin Marietta¹⁵⁶ which appears black in the visible, with a solar absorptivity of at least 0.96 and emissivity of at least 0.6. It is applied by an electrodeposition process to a substrate of nickel, molybdenum, or titanium; other substrates are also expected to work. It can be used at higher temperatures than anodized aluminum surfaces such as Martin Black. It is stable against loss of absorptivity at temperatures greater than 450°C for prolonged periods. The surface is not a lambertian surface at 10.6 μm (Fig. 62).

Black Chrome A black chrome surface developed for aerospace use¹⁵⁷ is black in the visible and is created by an electroplating process on a conducting substrate. Many metallic substrates can be used and samples on molybdenum, nickel, and titanium have been made. The preferred substrates are titanium and molybdenum. The coating process involves electrodeposition using chromium and chromium oxides. The visible BRDF is flat (Fig. 63), while the infrared profile shows the surface to

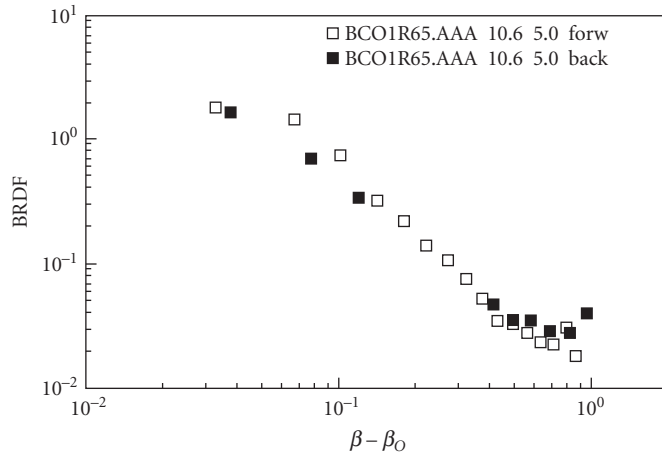


FIGURE 62 Infrared (10.6 μm) BRDF of Black Cobalt at 5° angle of incidence. (From Pompea *et al.*⁴)

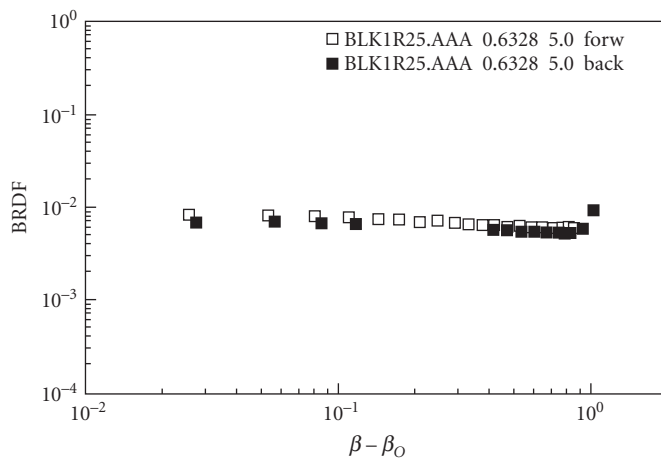


FIGURE 63 Visible (0.6328 μm) BRDF of Black Chrome at 5° angle of incidence. (From Pompea *et al.*⁴)

be largely specular in its scattering profile. The solar absorptivity is at least 0.95 and the emissivity can be tailored in the range of 0.4 to 0.8. The surface has excellent adhesion to the substrate.

Orlando Black Optical Coating A dendritic surface is produced by the electrodeposition of copper in a proprietary copper-plating formulation (Janeczko¹⁵⁸). The dendritic structure is then oxidized to form smaller structures superimposed on the larger ones. The surface has excellent broadband absorption properties from 0.4 to 14 μm and good absorptance at nonnormal angles of incidence (Fig. 64). It may be suitable for use at shorter wavelengths. The surface is usable in vacuum environments as well as a thermal reference in FLIR systems. A wide variety of materials can be coated including ABS plastic, nylon, Ultem, Noryl, fiberglass-reinforced epoxy, glass, stainless steel, copper, brass, nickel, aluminum, gold, and beryllium oxide. Dimensional allowances must be made for the thickness of the finish (approximately 0.001 in).

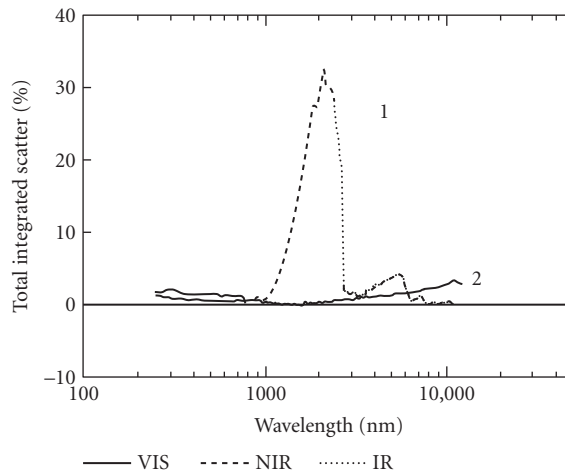


FIGURE 64 Total integrated scatter measurement of (1) and (2) Orlando Black commercially available anodized aluminum. (From Janeczko.¹⁵⁸)

Other Specialty Surfaces

Refer to Table 4 for further data on some of these surfaces.

Acktar Black Coatings (Acktar Ltd., Kiryat-Gat, Israel) Aktar makes a number of black coatings including Nano Black, Magic Black, Vacuum Black, Fractal Black, Ultra Black, and Metal Velvet. These inorganic coatings each have a wide range of working temperatures, very low outgassing (CVCN) in the 0.001 percent range and RML in the 0.167 percent range. Additionally the coatings have excellent adhesion to aluminum, copper, stainless steel, invar, kovar, glass, ceramics, polyimide, nickel, magnesium, titanium and other metals. There are options to make the coatings electrically conductive or nonconductive. The company also makes high emissivity foils.

Carbon Nanotubes and Nanostructured Materials Carbon nanotube arrays can also be used to create ultrablack surfaces. These surfaces are not yet practical for many applications but may have utility in specialized areas. For example, Yang et al.¹⁵⁹ have demonstrated that low-density vertically aligned carbon nanotube arrays can be engineered to have an extremely low index of refraction. The nanoscale surface roughness of the arrays contributes to an ultralow diffuse reflectance of 1×10^{-7} ; an order-of-magnitude lower compared to commercial low-reflectance standard carbon. The nanotube arrays can have an integrated total reflectance of 0.045 percent making it among the darkest materials ever fabricated.

Vorobyev and Guo¹⁶⁰ and Paivasaari et al.¹⁶¹ have also showed that laser ablation and altering of metallic surfaces can lead to greatly enhance optical absorptance.

Nanostructuring alone can enhance the absorptance by a factor of about three or more. The physical mechanism of the increased absorption is due to several effects including nanostructural, microstructural, and macrostructural surface modifications. The value of femtosecond laser ablation techniques using high fluences with a large number of applied pulses in reducing surface reflectivity may be applicable for a wide variety of metallic surfaces. Currently the process is time consuming for large area surfaces.

DURACON (American IMEX Corporation, Monroe, CT) DURACON is another high emissivity (>0.98 over the 0.55- to 1.8- μm range; >0.95 over the 2- to 20- μm wavelength range) durable black coating used in applications that cover a variety of wavelengths, especially the middle-infrared. It has

good thermal diffusivity and the interesting property that its conductivity can be tailored from low resistivity (less than $700 \Omega \text{ cm}$) to nearly an insulating surface. Thus, it can be used in environments where electrostatic discharge may be damaging to dielectric and insulating surfaces. It has good adherence and can be used on ceramic, glass, composite, plastic, and metal surfaces. It is durable to handling, unlike some anodized surfaces with surface structures that can be damaged by abrasion or direct compression. It also has very good ability to withstand wind shear at high Mach numbers and to withstand thermal cycling to 1000°F .

The surface can be applied by brush on, spray, or dip coating and any damaged areas can be repaired using a brushed on application of a fresh layer. The product is reported to be ready for normal regular use in 2 hours after this repair.

Electrically Conductive Black Paint Birnbaum et al.⁵¹ developed an electrically conductive, flat black paint for space use in places such as Jupiter's radiation belts where spacecraft charging effects can be important. Its small resistivity prevents the buildup of charge on the surface. It has a visual reflectance of less than 5 percent and other desirable optical properties.

Epnor laser black (Brooklyn, New York) This makes a well-known coating used in a variety of application. Laser Black is a multilayer metallic oxide that has a microdendritic structure susceptible to crushing. This inorganic coating does not outgas and when vibrated ultrasonically in acetone shows no flaking or chipping. It has good durability at cryogenic temperatures and can be applied to any metallic substrate and most plastics. It requires a deposition of copper approximately 10 to 12 μm thick. Laser Black is used in cold shields for micro-bolometers and in baffles.

Ebanol C This specialty cupric oxide coating can be applied per MIL-C-14550 undercoat and MIL-F-495 processes: immersion in a zincate bath followed by a high cyanide, low copper bath, and copper strike and dip in an Ebanol C solution.⁹

High-Resistivity Coatings Strimer et al.¹⁶² describe a number of black surfaces with high electrical resistivity for visible and infrared applications.

Sputtered and CVD Surfaces Carbon, quartz, and silicon surfaces have been modified by sputtering or by chemical vapor deposition^{163–165} to create surfaces that are black over the wavelength range of 1 to 15 μm . The textured surfaces are produced by sputtering with a low-energy (e.g., 500 eV) broadbeam ion source while adding impurities to the surface. The results from sputtering with this seeding process are structures in the form of cones, pyramids, and ridges. The exact nature of the surfaces created depends on the substrate temperature, ion and impurity fluxes, and the impurity species. The reflectivity of one modified silicon surface was below 1 percent throughout 1- to 25- μm wavelength range.

Silicon Carbide A silicon carbide surface for high-temperature applications was developed at Martin Marietta for application to a carbon-carbon substrate. It is applied to a hot substrate by a chemical vapor deposition process. The visible BRDF is flat, while the infrared profiles show the surface's specular nature at the longer wavelength.⁴

IBM Black (Tungsten Hexafluoride) This is a surface being produced at Martin Marietta, Orlando, using a process licensed from IBM. Any material that can tolerate 400°C can be used as a substrate for this process which involves vapor deposition of tungsten. The surface has dendritic structures that form light-absorbing traps. The surface looks like a collection of obelisks, does not outgas, and is rugged to the touch. Optical properties and an SEM photograph of the surface are given by Willey et al.⁴² The surface is very black in the 1- to 2- μm wavelength range.

ZO-MOD BLACK ZO-MOD BLACK (ZYP Coatings, Oak Ridge, Tenn.) is a high-emissivity coating applied like paint to ceramic porous and fibrous structures. On heating, a hard abrasion- and chemical-resistant, calcia-stabilized zirconium oxide coating is formed. The coating has high emissivity. The coating has been used inside of ceramic furnaces.

Gold Black Gold blacks are fragile surfaces made by evaporating gold in a low-pressure atmosphere of helium or nitrogen. The surface has good visible light absorption. The preparation and optical properties of gold blacks are given by Harris and McGinnies,¹⁶⁶ Blevin and Brown,¹⁶⁷ and Zaeschmar and Nedoluha.¹⁶⁸

Flame-Sprayed Aluminum Flame-sprayed aluminum is a very durable and very rough surface that has uses as an infrared diffuse reflectance standard. The parameters of the flame-spray process must be tightly controlled to create a similar surface each time.

Black Glass Black glass is available from Schott Glass Technologies, Duryea, Pa., in a glass called UG1, which is an ionically colored glass. Star Instruments, Flagstaff, Ariz., produces a glossy black glass called LOX8. It is a low-expansion copper glass with a coefficient of expansion of about 30 times lower than Pyrex.

Black Kapton The optical properties of Black Kapton are given in Fig. 65.

Other Surfaces Some other data is given for specular metallic anodized baffle surfaces (Fig. 66). This kind of basic treatment is adequate for some applications. The BRDF of Beta cloth is given in Fig. 67. Figure 68 shows the potential of various structured carbon surfaces to be highly absorbing over a wide range of angles. These kind of surfaces have great potential for the future.

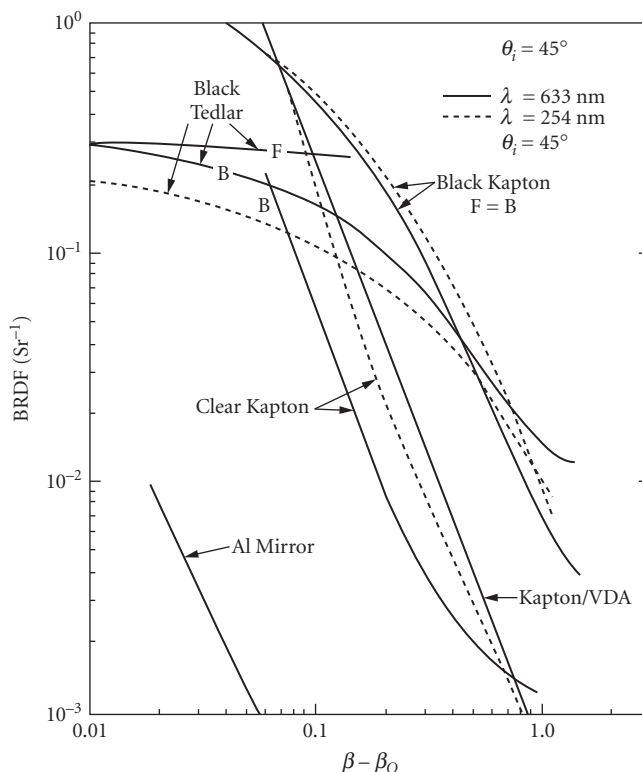


FIGURE 65 BRDFs of black Kapton and black Tedlar films. (From Viehmann and Predmore.³⁵)

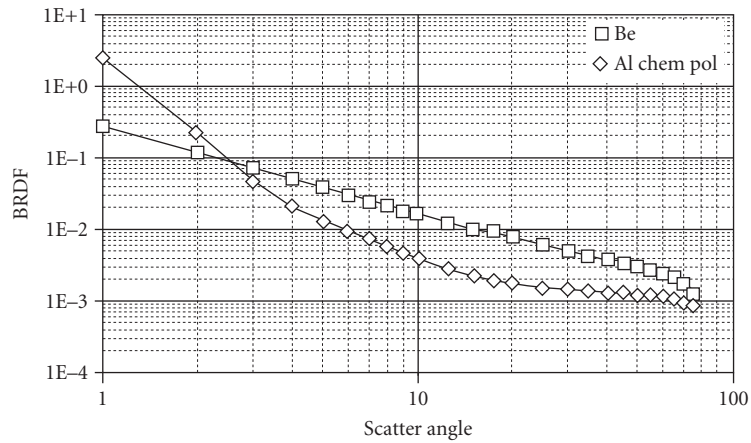


FIGURE 66 BRDF of specular baffle materials using Be and Al substrates that are polished and anodized. The measurements were made at $0.5145\ \mu\text{m}$. (From Schaub *et al.*²⁰)

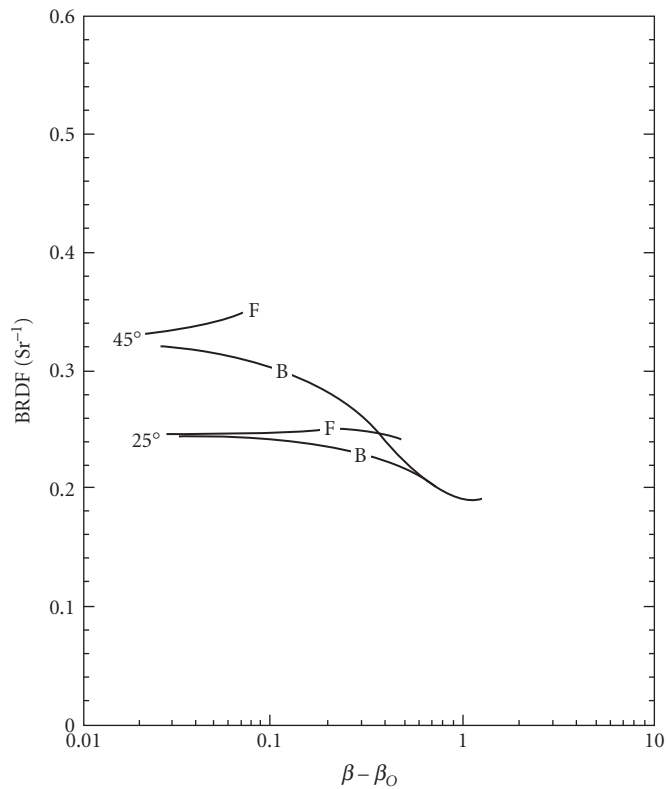


FIGURE 67 BRDF profiles of beta-cloth. Wavelength of $633\ \text{nm}$. (From Viehmann and Predmore.³⁵)

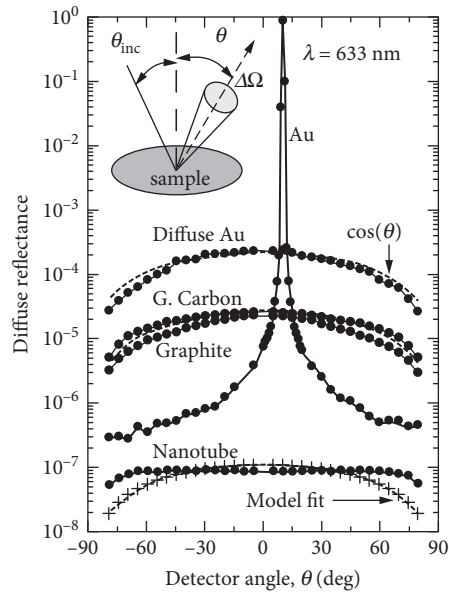


FIGURE 68 Diffuse reflectance of carbon nanotube samples compared to other carbon-based materials. (From Yang *et al.*¹⁵⁹)

6.9 CONCLUSIONS

Black surfaces are used as optical elements in a variety of ways. There is a great choice of surfaces available, but the selection of the appropriate surface is often problematical. The consequences of choosing the wrong surface are often quite severe.

For the selection process to be most effective, it must be done as early as possible. While the optical data on surfaces is relatively extensive, the data are often inconsistent or are not available for the particular wavelength of interest. The creation of large databases of optical and material properties is a great aid to the optical designer and materials consultant. Of great concern for space materials is the lack of very long term environmental test data. The synergistic effect of a number of degrading influences (e.g., solar ultraviolet, charging effects, atomic oxygen) is unknown for many interesting and potentially effective space materials. The use of specialized surfaces that can be tailored for very specific applications is an emerging trend and is likely to continue.

When black surfaces are used effectively in optical systems, the performance of the system can be greatly enhanced. However, when other approaches to stray light control are not implemented, even the “blackest” possible surfaces cannot establish the desired system performance. This cruel fact is a persuasive basis for an integration of black surface selection into the general stray light design studies, which today are nearly mandatory for the design of high-performance optical devices.

6.10 ACKNOWLEDGMENTS

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6.11 REFERENCES

1. W. L. Wolfe, "Scattered Thoughts on Baffling Problems," *Proc. SPIE: Radiation Scattering in Optical Systems*, SPIE, Bellingham, Wash., **257**:2 (1980).
2. R. P. Breault, "Stray Light Technology Overview of the 1980 Decade (And a Peek into the Future)," *Proc. SPIE: Stray Radiation in Optical Systems*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **1331**:2–11 (1990).
3. D. W. Bergener, S. M. Pompea, D. F. Shepard, and R. P. Breault, "Stray Light Performance of SIRTf: A Comparison," *Proc. SPIE: Stray Radiation IV*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **511**:65–72 (1984).
4. S. M. Pompea, D. F. Shepard, and S. Anderson, "BRDF Measurements at 6328 Angstroms and 10.6 Micrometers of Optical Black Surfaces for Space Telescopes," *Proc. SPIE: Stray Light and Contamination in Optical Systems*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **967**:236–248 (1988).
5. S. M. Pompea and S. H. C. P. McCall, "Outline of Selection Process for Black Baffle Surfaces in Optical Systems," *Proc. SPIE: Stray Radiation in Optical Systems II*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **1753** (1992a).
6. S. M. Pompea, J. E. Mentzell, and W. A. Siegmund, "A Stray Light Analysis of the 2.5 Meter Telescope for the Sloan Digital Sky Survey," *Proc. SPIE: Stray Radiation in Optical Systems II*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **1753** (1992b).
7. S. M. Pompea, R. Pfisterer, and J. Morgan, "A Stray Light Analysis of the Apache Point Observatory 3.5-Meter Telescope System," *Proc. SPIE*, SPIE, Bellingham, Wash., **4842**:128–138, (2003).
8. S. M. Pompea, "The Management of Stray Radiation Issues in Space Optical Systems," *Space Science Reviews* **74**:181–193 (1995).
9. M. J. Persky, "Review of Black Surfaces for Space-Borne Infrared Systems," *Rev. Sci. Instrum.* **70**:2193–2217 (1999).
10. John L. Miller, "Multispectral Infrared BRDF Forward-Scatter Measurements of Common Black Surface Preparations and Materials—or "how black is black in the IR?" *Proc. SPIE*, **5405**:25–35 (2004).
11. M. J. Persky and M. Szczesniak, "Infrared, Spectral, Directional-Hemispherical Reflectance of Fused Silica, Teflon Polytetrafluoroethylene Polymer, Chrome Oxide Ceramic Particle Surface, Pyromark 2500 Paint, Krylon 1602 Paint, and Duraflect Coating," *Appl. Opt.* **47**:1389–1396 (2008).
12. R. E. Hahn and B. O. Seraphin, "Spectrally Selective Surfaces for Photothermal Solar Energy Conversion," in *Physics of Thin Films*, vol. 10, Academic Press, Orlando, Fla., 1978.
13. C. G. Granqvist, *Spectrally Selective Surfaces for Heating and Cooling Applications*, vol. TT 1, SPIE Optical Engineering Text, Bellingham, Wash., 1989.
14. K. M. Yousif, B. E. Smith, and C. Jeynes, "Investigation of Microstructure of Molybdenum-Copper Black Electrodeposited Coatings with Reference to Solar Selectivity" *J. Mater. Sci.* **31**:185–191 (1996).
15. D. B. Betts, F. J. J. Clarke, L. J. Cox, and J. A. Larkin, "Infrared Reflection Properties of Five Types of Black Coating for Radiometric Detectors," *J. Phys. E: (London) Sci. Instrum.* **18**:689–696 (August, 1985).
16. W. L. Wolfe, "Optical Materials," Chap. 7, in *The Infrared Handbook*, W. L. Wolfe and G. J. Zississ (eds.), ERIM, Ann Arbor, Michigan, 1978.
17. S. H. C. P. McCall, S. M. Pompea, R. P. Breault, and N. L. Regens, "Reviews of Properties of Black Surfaces for Ground and Space-Based Optical Systems," *Proc. SPIE: Stray Radiation II*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **1753** (1992).
18. S. H. C. P. McCall, "Optical Properties (UV and Visible) of Black Baffle Materials and Processes for Use in Space," *Proprietary Report from Stellar Optics Laboratories* (78 Normark Drive, Thornhill, Ontario, Canada, L3T 3R1) to *Space Astrophysics Laboratory*, ISTS, Ontario, Canada, June 17, 1992.

19. S. M. Smith and R. V. Howitt, "Survey of Materials for an Infrared-Opaque Coating," *Proc. SPIE: Infrared, Adaptive, and Synthetic Aperture Optical Systems*, SPIE, Bellingham, Wash., **643**:53–62 (1986).
20. C. Schaub, M. Davis, G. Inouye, and P. Schaller, "Visible Scatter Measurements of Various Materials," *Proc. SPIE: Stray Radiation in Optical Systems*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **1331**:293–298 (1990).
21. K. A. Klicker, D. M. Fuhrman, D. R. Bjork, "A BSDF Database," *Proc. SPIE: Stray Radiation in Optical Systems*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **1331**:270–279 (1990).
22. S. H. C. P. McCall, R. L. Sinclair, S. M. Pompea, and R. P. Breault, "Spectrally Selective Surfaces for Ground and Space-Based Instrumentation: Support for a Resource Base," *Proc. SPIE: Space Astronomical Telescopes and Instruments II*, P. Bely and J. B. Breckinridge (ed.), SPIE, Bellingham, Wash., **1945** (1993).
23. S. H. C. P. McCall, *Black Materials Database of Stellar Optics Laboratories*, 78 Normark Drive, Thornhill, Ontario, Canada, L3T 3R1, unpublished, 1992c.
24. Lord Chemical Products Division, Industrial Coatings Office, 845 Olive Avenue, Novato, CA 94945, 1992.
25. D. B. Griner, "BRDF Measurements of Stray Light Suppression Coatings for the Space Telescope," *Proc. SPIE*, SPIE, Bellingham, Wash., **183**:98 (1979).
26. R. Fernandez, R. G. Seasholtz, L. G. Oberle, and J. R. Kadambi, "Comparison off the Bidirectional Reflectance Distribution Function of Various Surfaces," *Proc. SPIE*, SPIE, Bellingham, Wash., **967**:292 (1988).
27. C. W. Brown and D. R. Smith, "High-Resolution Spectral Reflection Measurements on Selected Optical-Black Baffle Coatings in the 5–20 Micrometer Region," *Proc. SPIE: Stray Radiation in Optical Systems*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **1331**:210–240 (1990).
28. A. J. Ames, "Z306 Black Paint Measurements," *Proc. SPIE: Stray Radiation in Optical Systems*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **1331**:299–304 (1990).
29. A. Lompado, B. W. Murray, J. S. Wollam, and J. F. Meroth, "Characterization of Optical Baffle Materials," *Proc. SPIE: Scatter from Optical Components*, J. Stover (ed.), SPIE, Bellingham, Wash., **1165**:212–226 (1989).
30. J. A. Muscari and T. O'Donnell, "Mass Loss Parameters for Typical Shuttle Materials," *Proc. SPIE*, SPIE, Bellingham, Wash., **287**:20 (1981).
31. S. M. Pompea, D. F. Bergener, D. W. Shepard, S. Russak, and W. L. Wolfe, "Reflectance Measurements on an Improved Optical Black for Stray Light Rejection from 0.3 to 500 Micrometers," *J. Opt. Eng.* **23**:149–152 (1984).
32. S. M. Smith, "Far Infrared Reflectance Spectra of Optical Black Coatings," *Proc. SPIE: Scattering in Optical Materials*, S. Musikant (ed.) Optical Society of America, Washington, DC, **362**:57–59 (1982).
33. S. M. Smith, "Specular Reflectance of Optical-Black Coatings in the Far Infrared," *Appl. Opt.* **23**(14):2311–2326 (1984).
34. S. M. Smith, "Cryo-Mechanical Tests of Ames 24E2 IR-Black Coating," *Proc. SPIE: Stray Radiation in Optical Systems*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **1331**:241–248 (1990).
35. W. Viehmann and R. E. Predmore, "Ultraviolet and visible BRDF Data on Spacecraft Thermal Control and Baffle Materials," *Proc. SPIE*, SPIE, Bellingham, Wash., **675**:67 (1986).
36. CAL, "Space Systems Process Procedure for the Preparation and Application of Chemglaze Z306 Black Paint for Space Applications," *Document PQ-CAL-SR-10333* from Canadian Astronautics Ltd., 1986.
37. M. M. Nordberg, C. Von Benken, and E. J. Johnson, "Reflectivity Changes in Optical Baffle Materials Following Pulsed Electron Bombardment," *Proc. SPIE*, SPIE, Bellingham, Wash., **1050**:185 (1989).
38. R. J. Noll, R. Harned, R. Breault, and R. Malugin, "Stray Radiation and Infrared Astronomical Satellite (IRAS) Telescope," *Proc. SPIE*, SPIE, Bellingham, Wash., **257**:119 (1980).
39. S. M. Smith, "Far Infrared (FIR) Optical Black Bidirectional Reflectance Distribution Function (BRDF)," *Proc. SPIE: Radiation Scattering in Optical Systems*, SPIE, Bellingham, Wash., **362**:161–168 (1980).
40. P. Jelinsky and S. Jelinsky, "Low Reflectance EUV Materials: A Comparative Study," *Appl. Opt.* **26**(4):613–615 (1987).
41. D. L. Stierwalt, "Infrared Absorption of Optical Blacks," *Opt. Eng.* **18**(2):147–151 (1979).
42. R. R. Willey, R. W. George, J. G. Ohmart, and J. W. Walvoord, "Total Reflectance Properties of Certain Black Coatings from 0.2 to 20 Micrometers," *Proc. SPIE: Generation, Measurement and Control of Stray Radiation III*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **384**:19–26 (1983).
43. D. C. Evans and R. P. Breault, "APART/PADE Analytical Evaluation of the Diffuse Infrared Background Experiment for NASA's Cosmic Background Explorer," *Proc. SPIE: Stray Radiation IV*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **511**:54–64 (1984).

44. T. Heslin, J. Heaney, and M. Harper, "The Effects of Particle Size on the Optical Properties and Surface Roughness of a Glass-Balloon-Filled Black Paint," *NASA Technical Note TND-7643*, Goddard Space Flight Center, Greenbelt, MD., May 1974.
45. D. C. Evans, "Principles of Stray Light Supp and Conceptual Application to the Design of the Diffuse Infrared Background Experiment for NASA's Cosmic Background Explorer," *Proc. SPIE*, SPIE, Bellingham, Wash., **384**:82 (1983).
46. S. M. Smith, "The Reflectance of Ames 24E, Infrablack, and Martin Black," *Proc. SPIE: Stray Radiation V*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **967**:248–254 (1988).
47. S. M. Nee and H. E. Bennett, "Characterization of Optical Blacks by Infrared Ellipsometry and Reflectometry," *Proc. SPIE* **1331**:249 (1990).
48. Cardinal, product information and MSDSs on Velvathane and 6450-01 paints, El Monte, Calif., 1992.
49. J. R. Houck, "New Black Paint for Cryogenic Infrared Applications," *Proc. SPIE*, S. Musikant (ed.), SPIE, Bellingham, Wash., **362**:54–56 (1982).
50. S. M. Smith, "A Simple Antireflection Overcoat for Opaque Coatings in the Submillimeter Region," *Proc. SPIE: Stray Radiation V*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **675**:55–60 (1986).
51. M. B. Birnbaum, E. C. Metzler, and E. L. Cleveland, "Electrically Conductive Black Optical Black Paint," *Proc. SPIE: Scattering in Optical Materials*, S. Musikant (ed.), SPIE, Bellingham, Wash., **362**:60–70 (1982).
52. E. C. Metzler, "Application of Temperature Control Paints," *JPL Doc. No. FS501424 D*, 21 March 1988.
53. R. P. Breault, "Stray Light Technology Overview in 1988," *Proc. SPIE*, SPIE, Bellingham, Wash., **967**:2 (1988).
54. IITRI, product information and MSDSs on paints MH-211, D111, and MH2200, from the Illinois Institute of Technology Research Institute, Chicago, Ill., 1992.
55. J. R. Grammar, L. J. Balin, M. D. Blue, and S. Perkowitz, "Absorbing Coatings for the Far Infrared," *Proc. SPIE: Radiation Scattering in Optical Systems*, G. Hunt (ed.) SPIE, Bellingham, Wash., **257**:192–195 (1980).
56. W. Driscoll, (ed.), and W. Vaughan (assoc. ed.), *Handbook of Optics*, McGraw-Hill, New York, 1978, pp. 7–112.
57. S. M. Smith, "Analysis of 12–700 Micrometer Reflectance Spectra of Three Optical Black Samples," *Proc. SPIE: Generation, Measurement, and Control of Stray Radiation III*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **384**:32–36 (1983).
58. C. L. Wyman, D. B. Griner, G. H. Hunt, and G. B. Shelton, *Opt. Eng.* **14**(6):528 (1975).
59. R. P. Breault, "Specular Vane Cavities," *Proc. SPIE: Generation, Measurement, and Control of Stray Radiation III*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **384**:90–97 (1983).
60. AKZO Coatings, Inc., product information and MSDSs on 443-3-17 and 443-3-8, Orange, Calif., 1992.
61. E. R. Freniere and D. L. Skelton, "Use of Specular Black Coatings in Well-Baffled Optical Systems," *Proc. SPIE: Stray Radiation V*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **675**:126–132 (1986).
62. T. R. Gull, H. Hertzog, F. Osantowski, and A. R. Toft, "Low Orbit Effects on Optical Coatings and Materials as Noted on Early Shuttle Flights," *RAL Workshop on Advanced Technology Reflectors for Space Instrumentation*, M. Grande (ed.), SPIE, Bellingham, Wash., June 16–18, 1986.
63. Martin Marietta, product information from Martin Marietta, 1992.
64. S. M. Pompea, D. W. Bergener, D. F. Shepard, and K. S. Williams, "The Effects of Atomic Oxygen on Martin Black and Infrablack," *Proc. SPIE*, R. P. Breault (ed.), **511**:24–30 (1984).
65. G. Geikas, "Scattering Characteristics of Etched Electroless Nickel Coatings," *Proc. SPIE: Generation, Measurement, and Control of Stray Radiation III*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **384**:10–18 (1983).
66. F. M. Cady, D. R. Cheever, K. A. Klicker, and J. C. Stover, "Comparison of Scatter Data from Various Beam Pumps," *Proc. SPIE*, SPIE, Bellingham, Wash., **818**:21 (1987).
67. F. O. Bartell, J. E. Hubbs, M. J. Nofziger, and W. L. Wolfe, *Appl. Opt.* **21**(17):3178 (1982).
68. L. D. Brooks, J. E. Hubbs, F. O. Bartell, and W. L. Wolfe, "Bidirectional Reflectance Distribution Function of the Infrared Astronomical Satellite Solar-Shield Material," *Appl. Opt.* **21**:2465 (1982).
69. R. P. Breault, "Specification of the Scattering Characteristics of Surfaces and Systems for Use in the Analysis of Stray Light," *Proc. SPIE*, SPIE, Bellingham, Wash., **181**:108 (1979).

70. P. J. Young, R. Noll, L. Andreozzi, and J. Hope, "Particle Contamination from Martin Optical Black," *Proc. SPIE*, SPIE, Bellingham, Wash., **257**:196 (1980).
71. D. F. Shepard, S. M. Pompea, and S. Anderson, "The Effect of Elevated Temperatures on the Scattering Properties of an Optical Black Surface at 0.6328 and 10.6 Micrometers," *Proc. SPIE: Stray Radiation V*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **967**:286–291 (1988).
72. S. M. Smith, "Bidirectional Reflectance Distribution Function (BRDF) Measurements of Sunshield and Baffle Materials for the Infrared Astronomy Satellite (IRAS) Telescope," *Proc. SPIE: Modern Utilization of Infrared Technology VII*, SPIE, Bellingham, Wash., **304**:205–213 (1981).
73. B. Vitt, "Properties of Black Cobalt Coatings," *Proc. SPIE*, SPIE, Bellingham, Wash., **823**:218 (1987).
74. M. G. Hutchins, P. J. Wright, and P. D. Grebenik, "SnO₂: Sb Dip Coated Films on Anodized Aluminium Selective Absorber Plates," *Proc. SPIE*, SPIE, Bellingham, Wash., **653**:188 (1986).
75. C. E. Johnson, "Unique Surface Morphology with Extremely High Light Absorption Capability," *Proc. Electro-less Nickel Conference*, No. 1, Cincinnati, Ohio, November 6–7, 1979.
76. C. E. Johnson, "Black Electroless Nickel Surface Morphologies with Extremely High Light Absorption Capacity," *Metal Finishing*, July, 1980.
77. J. J. Cuomo, S. M. Rossmagel, and H. R. Kaufman, *Handbook of Ion Beam Processing Technology: Principles, Deposition, Film Modification, and Synthesis*, Noyes Publications, Park Ridge, NJ, 1989. (See Chap. 17, Banks, B. A., "Topography Texturing Effects," 1989.)
78. B. A. Banks, "Ion Beam Applications Research—A 1981 Summary of Lewis Research Center Programs," *NASA Technical Memorandum 81721*, 1981.
79. M. J. Mirtich, S. K. Rutledge, N. Stevens, R. Olle, and J. Merrow, "Ion Beam Textured and Coated Surfaces Experiment (IBEX)," Presented at *LDEF First Postretrieval Symposium*, Orlando, Fla., June 3–8, 1991.
80. J. S. Wollam and B. W. Murray, *Proc. SPIE*, SPIE, Bellingham, Wash., **1118**:88 (1989).
81. Spire, product information from Spire Corporation (Appendix A–D of Spire Document FR 10106), Bedford, Mass., (1992).
82. C. M. Egert and D. D. Allred, "Diffuse Absorbing Beryllium Coatings Produced by Magnetron Sputtering," *Proc. SPIE: Stray Radiation in Optical Systems*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **1331**:170–178 (1990).
83. C. C. Blatchley, E. A. Johnson, Y. K. Pu, and C. Von Benken, "Rugged Dark Materials for Stray Light Suppression by Seeded Ion Beam Texturing," *Proc. SPIE: Stray Radiation II*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **1753** (1992).
84. G. Hass, H. H. Schroeder, and A. F. Turner, "Mirror Coatings for Low Visible and High Infrared Reflectance," *J. Opt. Soc. Am.* **46**:31–35 (1956).
85. J. A. Dobrowolski, "Versatile Computer Program for Absorbing Optical Thin Film Systems," *Appl. Opt.* **20** (1981).
86. J. A. Dobrowolski, F. C. Ho, and A. J. Waldorf, "Research on Thin Film Anticounterfeiting Coatings at the National Research Council of Canada," *Appl. Opt.* **28**:2702–2717 (1989).
87. J. A. Dobrowolski, B. T. Sullivan, and R. C. Bajcar, "An Optical Interference, Contrast Enhanced Electroluminescent Device," *Appl. Opt.* **31**:5988 (1992).
88. W. L. Wolfe and Y. Wang, "Comparison of Theory and Experiments for Bidirectional Reflectance Distribution Function (BRDF) of Microrough Surfaces," *Proc. SPIE: Scattering in Optical Materials*, S. Musikan (ed.), SPIE, Bellingham, Wash., **362**:40 (1982).
89. T. A. Leonard, T. A. and M. Pantoliano, "BRDF Round Robin," *Proc. SPIE: Stray Light and Contamination in Optical Systems*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **967**:226–235 (1988).
90. T. A. Leonard, M. Pantoliano, and J. Reilly, "Results of a CO₂ BRDF Round Robin," *Proc. SPIE: Scatter from Optical Components*, J. Stover (ed.), SPIE, Bellingham, Wash., **1165**:444–449 (1989).
91. S. M. Pompea, "Stray Radiation Issues on Adaptive Optics Systems," in *Adaptive Optics for Astronomy*, D. Alloin and J.-M. Mariotti (eds.), Kluwer Academic Publishers, Dordrecht, 1994.
92. J. H. Henninger, "Solar Absorptance and Thermal Emittance of Some Common Spacecraft Thermal Control Coatings," *NASA Reference Publication 1121*, 1984, p. 7.
93. J. Stover, *Optical Scattering: Measurement and Analysis*, 2nd ed., SPIE Press, Bellingham, Wash., 1995.

94. E. R. Freniere, "First-Order Design of Optical Baffles," *Proc. SPIE: Radiation Scattering in Optical Systems*, G. Hunt (ed.), SPIE, Bellingham, Wash., **257**:19–22 (1980).
95. G. Peterson and S. Johnston, "Specular Baffles," *Proc. SPIE: Stray Radiation in Optical Systems II*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **1753** (1992).
96. K. Snail, P. Brown, J. Costantino, W. C. Shemano, C. W. Schmidt, W. F. Lynn, C. L. Seaman, and T. R. Knowles, "Optical Characterization of Black Appliqués" *Proc. SPIE* **2864**:465 (1996).
97. S. R. Meier, "Characterization of Highly Absorbing Black Appliqués in the Infrared," *Appl. Opt.* **40**:2788–2795 (2001).
98. S. R. Meier, "Reflectance and Scattering Properties of Highly Absorbing Black Appliqués over a Broadband Spectral Region," *Appl. Opt.* **40**:6260–6264 (2001).
99. S. R. Meier, M. L. Korwin, and C. I. Merzbacher, "Carbon Aerogel: A New Nonreflective Material for the Infrared," *Appl. Opt.* **39**:3940–3944 (2000).
100. J. M. Bennett and L. Mattsson, *Introduction to Surface Roughness and Scattering*, Optical Society of America, 1989.
101. C. F. Bohren and D. F. Huffman, *Absorption and Scattering of Light by Small Particles*, John Wiley and Sons, New York, 1983.
102. R. Ludwig, "Antireflection Coating on a Surface With High Reflecting Power," U. S. Patent 4,425,022, Jan. 10, 1984.
103. J. A. Dobrowolski, E. H. Hara, B. T. Sullivan, and A. J. Waldorf, "A High Performance Optical Wavelength Multiplexer/Demultiplexer," *Appl. Opt.* **30** (1991).
104. W. I. Linlor, "Reflective Baffle System with Multiple Bounces," *Proc. SPIE: Stray Radiation IV*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **675**:217–239 (1986).
105. A. W. Greynolds and R. K. Melugin, "Analysis of an All-Specular Linlor Baffle Design," *Proc. SPIE: Stray Radiation IV*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **675**:240–248 (1986).
106. H. Babel and H. G. Lee, "High emittance low absorptance coatings," US Patent 5,296,285 (1994).
107. A. P. Glassford, (ed.), *Proc. SPIE: Optical System Contamination: Effects, Measurements, Control*, SPIE, Bellingham, Wash., **777** (1987). (Entire volume)
108. A. P. Glassford, (ed.), *Proc. SPIE: Optical System Contamination: Effects, Measurements, Control II*, SPIE, Bellingham, Wash., **1329** (1990). (Entire volume)
109. A. P. Glassford, (ed.), *Proc. SPIE: Optical System Contamination: Effects, Measurements, Control III*, SPIE, Bellingham, Wash., **1754** (1992). (Entire volume)
110. J. B. Heaney, "A Comparative Review of Optical Surface Contamination Assessment Techniques," *Proc. SPIE: Optical System Contamination: Effects, Measurements, Control*, P. A. Glassford (ed.), SPIE, Bellingham, Wash., **777**:179 (1987).
111. K. Nahm, P. Spyak, and W. Wolfe, "Scattering from Contaminated Surfaces," *Proc. SPIE: Scatter from Optical Components*, J. Stover (ed.), SPIE, Bellingham, Wash., **1165**:294–305 (1989).
112. V. L. Williams and R. T. Lockie, "Optical Contamination Assessment by Bidirectional Reflectance-Distribution Function (BRDF) Measurement," *Opt. Eng.* **18**(2):152–156 (1979).
113. R. P. Young, "Low Scatter Mirror Degradation by Particle Contamination," *Opt. Eng.* **15**(6):516–520 (1976).
114. B. W. Murray and Johnson, E. A., "Pulsed Electron Beam Testing of Optical Surfaces," *Proc. SPIE: Conference on Optical Surfaces Resistant to Severe Environments*, paper no. 1330-01, San Diego, July 11, 1990.
115. M. McCargo, R. E. Dammann, J. C. Robinson, and R. J. Milligan, "Erosion of Diamond Films and Graphite in Oxygen Plasma," *Proceedings of the International Symposium on Environmental and Thermal Control Systems for Space Vehicles*, Joulouse, France, European Space Agency, Noordwijk, The Netherlands, October, 1983, pp. 1–5.
116. A. F. Whittaker, "Atomic Oxygen Effects on Materials," *STS-8 Paint Data Summary*, Marshall Space Flight Center, January 1984.
117. J. L. Golden, "Results of an Examination of the A-276 White and Z-306 Black Thermal Control Paint Disks flown on LDEF," *NASA Conference Publication 10072*, First LDEF Post-Retrieval Symposium Abstracts, June 2–8, 1991.
118. M. D. Blue, and S. Perkowitz, "Space-Exposure Effects on Optical-Baffle Coatings at Far-Infrared Wavelengths," *Appl. Opt.* **31**:4305–4309 (1991).

119. W. A. Campbell and J. J. Scialdone, "Outgassing Data for Selecting Spacecraft Materials," *NASA Reference Publication 1134*, Revision 2, November 1990.
120. R. E. Predmore and E. W. Mielke, *Materials Selection Guide, Revision A*, Goddard Space Flight Center, August 1990.
121. R. V. Peterson, W. Krone-Schmidt, and W. V. Brandt, "Jet-Spray Cleaning of Optics," *Proc. SPIE: Optical System Contamination: Effects, Measurement, Control III*, A. P. Glassford (ed.), SPIE, Bellingham, Wash., **1754** (1992).
122. J. A. Gunderson, "Goniometric Reflection Scattering Measurements and Techniques at 10.6 Micrometers," Thesis, Univ. of Arizona, 1977.
123. S. M. Smith and W. L. Wolfe, "Comparison of Measurements by Different Instruments of the Far-Infrared Reflectance of Rough, Optically Black Coatings," *Proc. SPIE: Scattering of Optical Materials*, S. Musikant (ed.), SPIE, Bellingham, Wash., **362**:46–53 (1983).
124. R. P. Breault, A. Greynold, and S. Lange, "APART/PADE Version 7: A Deterministic Computer Program Used to Calculate Scattered and Diffracted Energy," *Proc. SPIE: Radiation Scattering in Optical Systems*, G. Hunt (ed.), SPIE, Bellingham, Wash., **257** (1980).
125. A. W. Greynolds, *Advanced Systems Analysis Package (ASAP) Users Manual*, Breault Research Organization, Inc., Tucson, Ariz., 1988.
126. S. S. Steadman and B. K. Likeness, "GUERAP III Simulation of Stray Light Phenomena," *Proc. SPIE: Stray Light Problems in Optical Systems*, SPIE, Bellingham, Wash., **107** (1977).
127. R. P. Breault, "Current Technology of Stray Light," *Proc. SPIE: Stray Radiation V*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **675**:4–13 (1986).
128. F. D. Orazio, W. K. Stowell, and R. M. Silva, "Instrumentation of a Variable Angle Scatterometer (VAS)," *Proc. SPIE: Stray Radiation III*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **384**:123–131 (1983).
129. F. O. Bartell, "BRDF Measurement Equipment: Intrinsic Design Considerations," *Proc. SPIE: Stray Radiation IV*, R. P. Breault (ed.) **511**:31–34 (1984).
130. R. M. Silva, F. D. Orazio, and R. B. Sledge, "A New Instrument for Constant (Beta-Beta_s) Scatter Mapping of Contiguous Optical Surfaces of up to 25 Square Inches," *Proc. SPIE: Stray Radiation IV*, R. P. Breault (ed.), SPIE, Bellingham, Wash., **511**:38–43 (1984).
131. J. B. Heaney, Optics Branch, Code 717, Goddard Space Flight Center, Greenbelt, MD., private communication (unpublished data), 1992.
132. D. L. Stierwalt, J. B. Bernstein, and D. D. Kirk, "Measurements of the Infrared Spectral Absorptance of Optical Materials," *Appl. Opt.* **2**(11):1169–1173 (1963).
133. F. J. J. Clarke and J. A. Larkin, "Measurements of Total Reflectance, Transmittance and Emissivity over the Thermal IR Spectrum," *Infrared Physics* **25**:359–367 (1985).
134. S. M. Smith, "Formation of Ames 24E2 IR-Black Coatings," *NASA Tech. Memo 102864*, July (1991).
135. S. M. Smith, "BRDFs of Ames 24E, Ames 24E2, and Ames 47A at Photometric Wavelengths of 220 and 350 micrometers," *Sterling Technical Note TN-91-8441-000-74*, Sterling Software, Moffett Field, Calif., October 1991.
136. S. M. Smith, "An Almost "Perfectly" Diffuse, "Perfect" Reflector for Far-Infrared Reflectance Calibration," *Proc. SPIE: Stray Radiation in Optical Systems II*, Breault (ed.) **1753**:252–261 (1992).
137. S. M. Smith, Sterling Software, NASA Ames Research Center, private communication, April 1992.
138. S. M. Pompea, D. W. Bergener, D. F. Shepard, S. L. Russak, and W. L. Wolfe, "Preliminary Performance Data on an Improved Optical Black for Infrared Use," *Proc. SPIE: New Optical Materials*, SPIE, Bellingham, Wash., **400**:128 (1983).
139. J. Lohrengel, "Total Emissivity of Black Coatings," ("Gesamtemissionsgrad von Schwarzen"), *Wärme - Stoffübertrag* Springer-Verlag, Berlin, **21**(5):311–315 (27 July 1987).
140. V. Freibell, *Colorado, M & P Information Bulletin No. 82.21*, Ball Aerospace, Boulder, 7/27/82.
141. I. T. Lewis, A. R. Telkamp, and A. F. Ledebuhr, "Low Scatter Edge Blackening Compounds for Refractive Optical Elements," *Proc. SPIE: Scatter from Optical Components*, J. Stover (ed.), SPIE, Bellingham, Wash., **1165**:227–236 (1989).
142. J. F. Wade, J. E. Peyton, B. R. Klitzky, and R. E. Groff, "Optically Black Coating and Process for Forming It," U. S. Patent 4,111,762, September 5, 1978.

143. D. F. Shepard, Martin Black and Infrablack Contact at Lockheed Martin, P.O. Box 179, Denver, Colorado 80201.
144. J. F. Wade and W. R. Wilson, *Proc. SPIE*, SPIE, Bellingham, Wash., **67**:59 (1973).
145. S. M. Pompea, D. W. Bergener, and D. F. Shepard, "Reflectance Characteristics of an Infrared Absorbing Surface," *Proceedings 31st National Infrared Information Symposium*, National Bureau of Standards, Boulder, Colorado, 1983, p. 487.
146. W. Friedrichs, product literature from Tiodize Co., Inc., 5858 Engineer Drive, Huntington Beach, CA 92649.
147. S. Kodama, M. Horiuchi, T. Kunii, and K. Kuroda, "Ultra-Black Nickel-Phosphorus Alloy Optical Absorber," *Instrumentation and Measurement, IEEE Transactions* **39**:230–232 (1990).
148. C. Johnson, "Ultra-Black Coating due to Surface Morphology," U. S. Patent 4,361,630, 30, November 1982.
149. D. F. Shepard, R. J. Fenolia, D. C. Nagle, and M. E. Marousek, "High-Temperature, High-Emissivity, Optically Black Boron Surface," U. S. Patent 5,035,949, July 30, 1991, Martin Marietta Corporation.
150. R. D. Seals, C. M. Egert, and D. D. Allred, "Advanced Infrared Optically Black Baffle Materials," *Proc. SPIE: Optical Surfaces Resistant to Severe Environments*, SPIE, Bellingham, Wash., **1330**:164–177 (1990).
151. R. D. Seals, "Advanced Broadband Baffle Materials," *Proc. SPIE: Reflective and Refractive Materials for Earth and Space Applications*, SPIE, Bellingham, Wash., **1485**:78–87 (1991).
152. B. W. Murray and J. S. Wollam, "Space Durable Beryllium Baffle Materials," *SPIE Symposium on Aerospace Sensing*, Orlando, Fla., March 1989.
153. E. Johnson, Spire Corporation, Bedford, Mass., private communication, March 1992.
154. S. K. Rutledge, B. A. Banks, M. J. Mirtich, R. Lebed, J. Brady, D. Hotes, and M. Kusmaul, "High Temperature Radiator Materials for Applications in the Low Earth Orbital Environment," *NASA Technical Memorandum 100190*, 1987.
155. B. A. Banks, S. K. Rutledge, M. J. Mirtich, T. Behrend, D. Hotes, M. Kusmaul, J. Barry, C. Stidham, T. Stueber, and F. DiFillippo, "Arc-Textured Metal Surfaces for High Thermal Emittance Radiators," *NASA Technical Memorandum 100894*, 1988.
156. D. F. Shepard and R. J. Fenolia, "Optical Black Cobalt Surface," U. S. Patent 4,904,353, February 27, 1990, Martin Marietta Corporation.
157. R. J. Fenolia, D. F. Shepard, and S. L. Van Loon, "Optically Black Pliable Foils," U. S. Patent 4,894,125, January 16, 1990, Martin Marietta Corporation.
158. D. J. Janeczko, "Optics and Electro-Optics," Martin Marietta Corporation, Orlando, Fla., personal communication, 1992.
159. Z.-P. Yang, L. Ci, J. A. Bur, S.-Y. Lin, and P. M. Ajayan, "Experimental Observation of an Extremely Dark Material Made by a Low-Density Nanotube Array," *Nano Lett.* **8**:446–451 (2008).
160. A. Y. Vorobyev and G. Guo, "Effect of Nanostructure-Covered Femtosecond Laser-Induced Periodic Surface Structures on Optical Absorptance of Metals," *Appl. Phys. A* **86**:321–324 (2007).
161. K. Paivasaari, J. J. J. Kaakkunen, M. Kuittinen, and T. Jaaskelainen, "Enhanced Optical Absorptance of Metals Using Interferometric Femtosecond Ablation," *Optics Express*, **15**:13838–13843 (2007).
162. P. Strimer, X. Gerbaux, A. Hadni, T. Souel, "Black Coatings of Infrared and Visible, with High Electrical Resistivity," *Infrared Physics* **21**:7–39 (1981).
163. R. S. Robinson, and S. M. Rossnagel, "Ion-Beam Induced Topography and Surface Diffusion," *J. Vac. Sci. Technol.* **21**:790 (1982).
164. R. B. Culver, W. A. Solberg, R. S. Robinson, and I. L. Spain, "Optical Absorption of Microtextured Graphite Surfaces in the 1.1–2.4 Micrometer Wavelength Region," *Appl. Opt.* **24**:924 (1984).
165. C. W. Bowers, R. B. Culver, W. A. Solberg, and I. L. Spain, "Optical Absorption of Surfaces Modified by Carbon Filaments," *Appl. Opt.* **26**:4625 (1987).
166. L. Harris, R. T. McGinnies, and B. M. Siegel, "The Preparation and Optical Properties of Gold Black," *J. Opt. Soc. Am.* **38**(7) (1948).
167. W. R. Blevin, and W. J. Brown, "Black Coatings for Absolute Radiometers," *Int. J. Sci. Metrology* **2**(4):139–143 (October 1966).
168. G. Zaeschmar and A. Nedoluha, "Theory of the Optical Properties of Gold Blacks," *J. Opt. Soc. Am.* **62**(3):348–352 (1972).

6.12 FURTHER READINGS

- Anderson, S., S. M. Pompea, D. F. Shepard, and R. Castonguay, "Performance of a Fully Automated Scatterometer for BRDF and BTDF Measurements at Visible and Infrared Wavelengths," *Proc. SPIE: Stray Light and Contamination in Optical Systems* **967**:159 (1988).
- Banks, B. A., NASA Technical Memorandum 81721, Lewis Research Center, 1981.
- Bartell, F. O., E. L. Dereniak, and W. L. Wolfe, "The Theory and Measurement of BRDF and BTDF," *Proc. SPIE: Radiation Scattering in Optical Systems* **257**:154 (1980).
- Bennett, H. E. and E. L. Church, "Surface Roughness Measurement in the Submicrometer Range Using Laser Scattering," *Opt. Eng.* **18**:103 (1979).
- Bonnot, A. M., H. Belkhir, D. Pailharey, and P. Mathiez, *Proc. SPIE* **562**:209 (1985).
- Bonnot, A. M., H. Belkhir, and D. Pailharey, *Proc. SPIE: Optical Materials Technology for Energy Efficiency and Solar Energy Conversion V* **653**:215 (1986).
- Brooks, L. D. and W. L. Wolfe, "Microprocessor-Based Instrumentation for Bidirectional Reflectance Distribution Function (BRDF) Measurements from Visible to Far Infrared (FIR)," *Proc. SPIE: Radiation Scattering in Optical Systems* **257**:177 (1980).
- Davis, L. and J. G. Kepros, "Improved Facility for BRDF/BTDF Optical Scatter Measurements," *Proc. SPIE: Stray Radiation V* **675**:24 (1986).
- Duran, M. and C. Gricurt, "Hipparcos Telescope Stray Light Protection," *Proc. SPIE: Stray Radiation V* **675**:134 (1986).
- "Method of Forming Electrodeposited Anti-reflective Surface Coatings, U.S. Patent 5,326,454, Martin Marietta Corporation.
- Freniere, E. R., "Use of Specular Black Coatings in Well-Baffled Optical Systems," *Proc. SPIE: Stray Radiation V* **675**:126 (1986).
- Garrison, J. D., J. C. Haiad, and A. J. Averett, "Progress in the Commercialization of a Carbonaceous Solar Selective Absorber on a Glass Substrate," *Proc. SPIE: Optical Materials Technology for Energy Efficiency and Solar Energy Conversion VI* **823**:225 (1987).
- Hunt, P. J., R. Noll, L. Andreozzi, and J. Hope, "Particle Contamination from Martin Optical Black," *Proc. SPIE: Radiation Scattering in Optical Systems*, G. Hunt (ed.) **257**:196 (1980).
- LDEF, "The Long Duration Exposure Facility (LDEF) Mission I Experiments," NASA SP-473, NASA Langley Research Center, Washington, D.C., November 1986.
- Leger, L. J., J. T. Visentine, and J. F. Kuminecz, "Low Earth Orbit Oxygen Effects on Surfaces," presented at AIAA 22nd Aerospace Sciences Meeting, Reno, Nevada, January 9–12, 1984.
- Mende, S. B., P. M. Banks, and D. A. Klingensmith III, "Observation of Orbiting Vehicle Induced Luminosities on the STS-8 Mission," *Geophys. Res. Lett.* **11**:527 (1984).
- Ranbar Technology, Inc., Glenshaw, Pa., product information and MSDSs on Ranbar G113 Paint, 1990.
- Redspot Paint and Varnish Co., Inc., product information on Nextel Suede, P.O. Box 418, Evansville, In., 47703, 1992.
- Schiff, T. F., J. C. Stover, D. R. Cheever, and D. R. Bjork, "Maximum and Minimum Limitations Imposed on BSDF Measurements," *Proc. SPIE* **967**:50 (1988).
- Seraphin, B. O., (ed.), "Solar Energy Conversion—Solid State Physics Aspects," in *Topics in Applied Physics*, vol. 31, Springer Verlag, 1979.
- Sikkens Aerospace Finishes Division of Akzo Coatings America, Inc., 434 W. Meats Avenue, Orange, CA 92665.
- Stover, J. C., and C. H. Gillespie, *Proc. SPIE* **362**:172 (1982).
- Stover, J. C., C. H. Gillespie, F. M. Cady, D. R. Cheever, and K. A. Klicker, *Proc. SPIE* **818**:62 (1987).
- Stover, J. C., C. Gillespie, F. M. Cady, D. R. Cheever, and K. A. Klicker, *Proc. SPIE* **818**:68 (1987).
- Visentine, J. T., (ed.), *Atomic Oxygen Effects Measurement for Shuttle Missions STS-8 and 41-G, Volume I–III*, NASA TM-100459, 1988.
- Wood, B. E., W. T. Bertrand, E. L. Kiech, J. D. Holt, and P. M. Falco, *Surface Effects of Satellite Material Outgassing Products*, Final Report AEDC-TR-89-2, Arnold Engineering Development Center, 1989.

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OPTICAL PROPERTIES OF FILMS AND COATINGS

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7.1 INTRODUCTION

Scope of Chapter

In the broadest sense of the term, an optical filter is any device or material which is deliberately used to change the spectral-intensity distribution or the state of polarization of the electromagnetic radiation incident upon it. The change in the spectral intensity distribution may or may not depend on the wavelength. The filter may act in transmission, in reflection, or in both.

Filters can be based on many different physical phenomena, including absorption, refraction, interference, diffraction, scattering, and polarization. For a comprehensive review of this broader topic the interested reader is referred to the chapter entitled “Coatings and Filters” which appeared in the first edition of the *Handbook of Optics*.¹ This chapter deals only with filters that are based on absorption and interference of electromagnetic radiation in thin films. Optical thin-film coatings have numerous applications in many branches of science and technology and there are also many consumer products that use them. The spectral region covered in this chapter extends from about 0.003 to 300 μm (3 to 3×10^5 nm), although the main emphasis is on filters for the visible and adjacent spectral regions.

The discussion in this chapter is largely confined to generic thin-film filters, such as antireflection coatings, cutoff filters, narrowband transmission or rejection filters, reflectors, beam splitters, and so forth. Filters for very specific applications, such as filters for colorimeters and other scientific instruments, color correction filters, and architectural coatings, are, as a rule, not treated. Of the filters described, many are available commercially while others are only research laboratory prototypes. This review does not cover thin-film filters whose properties can be changed by external electric or magnetic fields, temperature, or illumination level.

In this introductory section some general considerations on the use of optical filters are presented. In the following sections, the theory of optical multilayers and the methods for their deposition and characterization are briefly discussed. These sections are useful for gaining a proper understanding of the operation, advantages, and limitations of optical coatings. The remaining sections then describe the properties of various generic thin-film filters.

For further information on this subject the interested reader is particularly encouraged to consult the books by Macleod,² Rancourt,³ and Baumeister.⁴

General Theory of Filters

There are many different ways of describing the performance of optical coatings and filters. For example, transmission and reflection filters intended for visual applications are adequately described by a color name alone, or by reference to one of the several existing color systems (see Chap. 10, Vol. III). There also exist other specialized filter specifications for specific applications. However, the most complete information on the performance of a filter is provided by spectral transmittance, reflectance, absorbance, and optical density curves. This is the method adopted in this chapter.

Referring to Fig. 1, at a wavelength λ the spectral transmittance $T(\lambda)$ of a filter placed between two semi-infinite media is equal to the ratio of the light intensity of that wavelength transmitted $I_T(\lambda)$ by the filter to that incident $I_0(\lambda)$ upon it,

$$T(\lambda) = \frac{I_T(\lambda)}{I_0(\lambda)} \quad (1)$$

The spectral reflectance $R(\lambda)$ of a filter is defined in a similar way,

$$R(\lambda) = \frac{I_R(\lambda)}{I_0(\lambda)} \quad (2)$$

At non-normal incidence the component of the intensity perpendicular to the interface must be used in the above equations.² The relationship between the transmittance $T(\lambda)$ and the density $D(\lambda)$ of a filter is given by

$$D(\lambda) = \log \frac{1}{T(\lambda)} \quad (3)$$

In this chapter, transmittances and reflectances will be plotted using either linear or logarithmic scales. The logarithmic scale is particularly well suited whenever accurate information about the low transmission or reflection region is to be conveyed. However, this is done at the expense of detail at the high end of the scale. A variant, the decibel scale, equal to $-10D(\lambda)$, is frequently used in the telecommunications field. Wavelengths are normally specified in micrometers (μm) because this is the most convenient unit for the whole spectral range covered in this chapter. In the following discussions the dependence of the transmittance, reflectance, and absorbance on wavelength will be implicitly assumed.

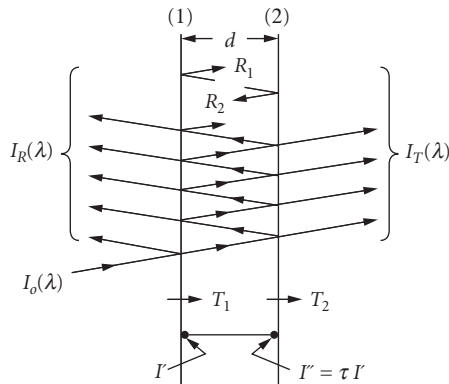


FIGURE 1 Specular transmission and reflection of light by a plane-parallel plate (see Sec. 7.1, subsection "General Theory of Filters").

Transmission and Reflection of Coatings on a Substrate

Many multilayer coatings are deposited onto a transparent or partially transparent substrate. Both the multilayer and the substrate contribute to the overall performance of the filter. For example, absorption in the substrate is frequently used to limit the transmission range of the filter. Reflectances at the filter interfaces need also to be considered. However, they can be reduced by anti-reflection coatings, or by cementing several components together.

In general, a filter can consist of multilayer coatings deposited onto one or both sides of a substrate. The overall transmittance T_{total} of a filter can be expressed in terms of the internal, or intrinsic transmittance τ of the substrate and the transmittances T_1 , T_2 and internal reflectances R_1 , R_2 of each surface of the substrate (Fig. 1).

The internal transmittance τ of a substrate is defined to be the ratio of the light intensity I'' just before reaching the second interface to the intensity I' just after entering the substrate (Fig. 1):

$$\tau = \frac{I''}{I'} \quad (4)$$

Expressions for the evaluation of the transmittance T and reflectance R of multilayer coatings are given in Sec. 7.2, subsection "Matrix Theory for the Analysis of Multilayer Systems."

Providing that the incident light is not coherent, there will be no interference between the beams reflected from the two surfaces of a substrate, even when the surfaces are plane parallel. A summation of all the partial reflections leads to the following expression for the overall spectral transmittance T_{total} of a filter:

$$T_{\text{total}} = \frac{T_1 T_2 \tau}{1 - R_1 R_2 \tau^2} \quad (5)$$

The reflection coefficients of uncoated interfaces can be calculated from Eq. (80), providing that the complex refractive indices of the substrate and of the medium are known. If all the materials in the filter are nonabsorbing, then

$$T_{\text{total}} = \frac{T_1 T_2}{1 - R_1 R_2} \quad (6)$$

If R_1 is small, an appropriate expression for T_{total} is

$$T_{\text{total}} \approx [1 - R_1(1 - R_2)]T_2 \quad (7)$$

However, this last approximation is not valid in general; some infrared substrate materials have high-reflection coefficients and in such cases Eq. (6) must be used.

Transmission Filters in Series and Parallel

To obtain a desired spectral transmittance it is frequently necessary to combine several filters. One common approach is to place several filters in series (Fig. 2a).

Because of the many different partial reflections that may take place between the various surfaces, precise formulas for the resulting transmittance are complicated.⁵ Accurate calculations are best carried out using matrix methods.⁶

To a first approximation, the resultant transmittance T' of a filter system consisting of k individual filters placed in series is given by

$$T' \approx T'_1 T'_2 T'_3 \dots T'_k \quad (8)$$

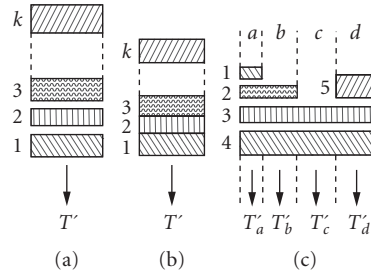


FIGURE 2 Transmission filters arranged in series and in parallel. The filters can be air-spaced (a), (c) or cemented (b).

Here T'_i is the total transmittance of filter i . This expression is valid only if the reflectances of the individual filters are small or if the interference filters are slightly inclined to one another and the optics are arranged in such a way that the detector sees only the direct beam.

Under other circumstances the use of this expression with interference filters can lead to serious errors. Consider two separate filters placed in series and let T'_1 , T'_2 , R'_1 and R'_2 correspond to the transmittances and reflectances of the two filters. If $T'_1 = T'_2 = R'_1 = R'_2 = 0.5$, then according to Eq. (8), the resulting transmittance will be $T' = 0.25$. For this simple case the precise expression can be derived from Eq. (5) and is given by

$$T' = \frac{T'_1 T'_2}{1 - R'_1 R'_2} \quad (9)$$

Evaluating this expression one obtains $T' = 0.33$. This is significantly different from the result obtained from the application of Eq. (8).

Some spectral transmittance curves cannot be easily designed by placing filters in series alone. For certain applications it is quite acceptable to place filters not only in series, but also in parallel.⁷ This introduces areas as additional design parameters. Thus, for example, the effective spectral transmittance T' of the filter shown in Fig. 2c would be given by

$$T' = \left(\frac{a}{A} T'_a + \frac{b}{A} T'_b + \frac{c}{A} T'_c + \frac{d}{A} T'_d \right) \quad (10)$$

where

A = overall area of filter,

a, b, c, d = areas of the four zones,

T'_a, T'_b, T'_c, T'_d = transmittances of four zones

The latter are given by

$$\begin{aligned} T'_a &= T'_1 \cdot T'_2 \cdot T'_3 \cdot T'_4 \\ T'_b &= T'_1 \cdot T'_2 \cdot T'_3 \\ T'_c &= T'_1 \cdot T'_2 \\ T'_d &= T'_1 \cdot T'_2 \cdot T'_3 \cdot T'_5 \end{aligned} \quad (11)$$

Great care must be exercised when using such filters. Because the spectral transmittance of each zone of the filter is different, errors will result unless the incident radiation illuminates the filter uniformly.

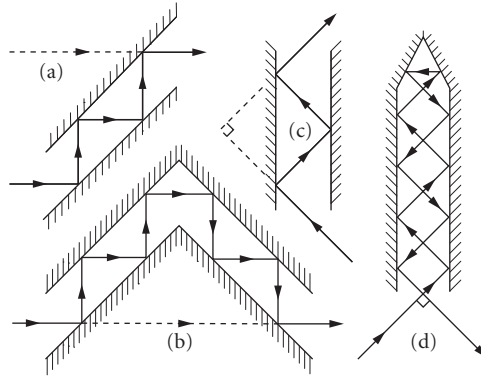


FIGURE 3 Various arrangements (a) to (d) for multiple-reflection filters.

Similar care must be used when employing the filtered radiation. One way proposed to alleviate these problems is to break the filter down into a large number of small, regular elements and to reassemble it in the form of a mosaic.⁸

Reflection Filters in Series

If radiation is reflected from k different filters, the resultant reflectance R' will be given by

$$R' = R'_1 \cdot R'_2 \cdot R'_3 \cdots R'_k \quad (12)$$

which is analogous to Eq. (8) for the resultant transmittance of filters placed in series. Many of the considerations of that section also apply here. For instance, R' will be significant only at those wavelengths at which every one of the reflectors has a significant reflectance. Metal layers (Sec. 7.15, subsection “Reducing Reflection with a Thin Metal Film”) and thin-film interference coatings can be used exclusively or in combination.

For the sake of convenience the number of different reflecting surfaces used is normally restricted. The outlines of some possible reflector arrangements given in Fig. 3 are self-explanatory. The arrangement shown in Fig. 3b does not deviate or displace an incident parallel beam. The number of reflections depends in each case on the lengths of the plates and on the angle of incidence of the beam. Other arrangements are possible.

Clearly, reflection filters placed in series require more space and are more complicated to use than transmission filters. But if in a given application these shortcomings can be accepted, multiple-reflection filters offer great advantages, which stem mainly from the nature of the reflectors available for their construction (see Sec. 7.16, subsection “Multiple Reflection Filters”).

7.2 THEORY AND DESIGN OF OPTICAL THIN-FILM COATINGS

Design Approaches

A thin-film designer may be asked to design a multilayer coating in which the transmittance, reflectance, and/or absorptance values are specified at a number of wavelengths, angles, and polarizations of the incident light. The designer may be required to provide a coating with many other more

complicated properties, including integral quantities such as CIE color coordinates, solar absorptance, or emissivity.⁹ The parameters that can be used to reach these goals are the number of layers in the multilayer, its overall thickness, the layer thicknesses and the refractive indices and extinction coefficients of the individual layers and of the surrounding media. Clearly, the more demanding the performance specifications, the more complex the resulting system. Many different methods have been developed for the design of multilayer coatings. For a good overview of this topic the interested reader is referred to the books by Macleod,² Knittl,¹⁰ and by Furman and Tikhonravov.¹¹ Here only the most important methods will be mentioned.

Graphical vector methods provide the most understanding of the problem, but the necessary approximations limit them to the solution of problems in which the final reflectance is not too high. Admittance diagrams and similar chart methods do not suffer from this limitation, but they are best applied to problems in which the specifications are relatively simple.¹² Many problems can be solved using the known properties of periodic multilayer systems.¹³ Analytical synthesis methods yield solutions to problems in which quite complex spectral transmittance or reflectance curves are specified.^{14,15} However, solutions frequently obtained in this way call for the use of inhomogeneous layers that are often more difficult to deposit, or for homogeneous layers with optical constants that are outside the range of known materials. Numerical design methods are the most flexible of all because they can be applied to problems with very complex specifications requiring a large number of layers for their solution.^{16,17} They are usually based on the matrix theory of optical multilayer systems and are particularly powerful for the solution of complicated spectral problems when combined with analytical methods.

Matrix Theory for the Analysis of Multilayer Systems

If electromagnetic radiation falls onto a structure consisting of thin films of several different materials, multiple reflections will take place within the structure. Depending on the light source and the layer thicknesses, the reflected beams may be coherent and interfere with one another. This optical interference can be used to design optical multilayer filters with widely varying spectral characteristics. In this section the basic equations for thin-film calculations are presented and some general properties of interference filters are listed. For a thorough discussion of this topic the reader is referred to the work of Macleod^{2,18} and Thelen.¹⁹

Consider the thin-film system consisting of L layers shown in Fig. 4. The construction parameters comprise not only the refractive indices n_j and the thicknesses d_j of the layers $j = 1, 2, \dots, L$, but also

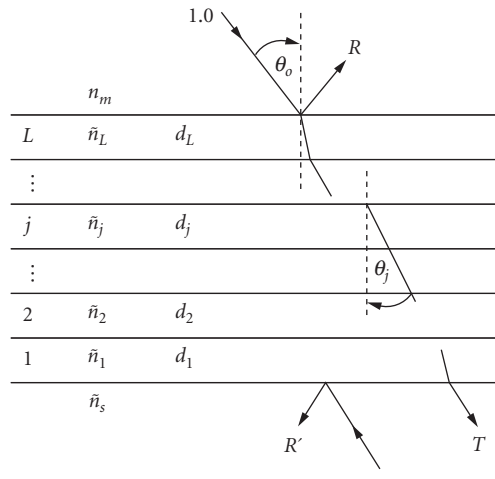


FIGURE 4 Construction parameters of a multilayer.

the refractive indices n_s and n_m of the substrate and the incident medium. The angle of incidence θ , the wavelength λ , and the plane of polarization of the incident radiation are the external variables of the system. It should perhaps be mentioned here that in some application areas it is more customary to use the grazing angle of incidence θ_g , where $\theta_g = 90 - \theta$.

The most general method of calculating the transmittance T and the reflectance R of a multilayer from the above quantities is based on a matrix formulation^{20,21} of the boundary conditions at the film surfaces derived from Maxwell's equations.²¹

It can be shown that the amplitude reflection r and transmission t coefficients of a multilayer coating consisting of L layers bounded by semi-infinite media, for the general case of obliquely incident light, are given by

$$r = \frac{\eta_m E_m - H_m}{\eta_m E_m + H_m} \quad (13)$$

and

$$t = \frac{2\eta_m}{\eta_m E_m + H_m} \quad (14)$$

where

$$\begin{pmatrix} E_m \\ H_m \end{pmatrix} = \mathbf{M} \begin{pmatrix} 1 \\ \eta_s \end{pmatrix} \quad (15)$$

E_m and H_m are the electric and magnetic vectors, respectively, in the incident medium, and $\mathbf{M}$ is a product matrix given by

$$\mathbf{M} = \mathbf{M}_L \mathbf{M}_{L-1} \cdots \mathbf{M}_j \cdots \mathbf{M}_2 \mathbf{M}_1 \quad (16)$$

In the above equation $\mathbf{M}_j$ is a 2×2 matrix that represents the j th film of the system:

$$\mathbf{M}_j = \begin{pmatrix} m_{11} & im_{12} \\ im_{21} & m_{22} \end{pmatrix} = \begin{pmatrix} \cos\delta_j & \frac{i}{\eta_j} \sin\delta_j \\ i\eta_j \sin\delta_j & \cos\delta_j \end{pmatrix} \quad (17)$$

where

$$\delta_j = \frac{2\pi}{\lambda} (n_j d_j \cos\theta_j) \quad (18)$$

the quantity $n_j d_j \cos\theta_j$ is the *effective optical thickness* of the layer j for an angle of refraction θ_j . In Eqs. (13) to (17) η represents the admittance of the medium, substrate, or layer and is given by

$$\eta = \begin{cases} \frac{n}{\cos\theta} & p\text{-polarization} \\ n\cos\theta & s\text{-polarization} \end{cases} \quad (19)$$

depending on whether the incident radiation is polarized parallel (p) or perpendicular (s) to the plane of incidence. Clearly, for normal incidence of light, the value of the admittance is equal to the refractive index. The angle θ_j is related to the angle of incidence θ_0 by Snell's law

$$n_m \sin\theta_0 = n_j \sin\theta_j \quad (20)$$

The intensity transmittance and reflectance are

$$T = \frac{\eta_s}{\eta_m} |t|^2 \quad (21)$$

$$R = |r|^2 \quad (22)$$

and the phase changes on transmission and reflection, ϕ_T and ϕ_R , are given by

$$\phi_T = \arg t \quad (23)$$

$$\phi_R = \arg r \quad (24)$$

More often than not, multilayer coatings are specified in terms of T and R and the phase changes on reflection and transmission are usually not of direct interest to the users. Exceptions are reflectors for interferometers.²² It has also been found that specifying certain values of ϕ_T , ϕ_r was useful in controlling the solution type obtained by some thin-film design methods.²³

If the materials in a multilayer are all nonabsorbing, then $T + R = 1$. Should one or more materials absorb, then in the above equations the refractive indices of these materials must be replaced by their complex refractive indices $\tilde{n}$, defined by

$$\tilde{n} = n - ik \quad (25)$$

where k is the extinction coefficient of the material. Even though all the elements of the layer matrix for such a material are now complex, its determinant will still be unity. The absorptance of the multilayer is then calculated from

$$A = 1 - T - R \quad (26)$$

Certain important general conclusions about the properties of multilayer filters can be drawn from the above equations.

1. The properties of thin-film systems vary with angle of incidence [Eqs. (18), and (19)]. For some applications this is the major disadvantage of interference filters compared to absorption filters.
2. This variation depends on the polarization of the incident radiation [Eq. (19)]. The following equations define T and R for obliquely incident nonpolarized radiation:

$$T = \frac{1}{2}(T_p + T_s) \quad (27)$$

$$R = \frac{1}{2}(R_p + R_s) \quad (28)$$

The dependence of T and R on polarization has been used for the design of polarizers (see Chap. 13, Vol. I). However, like the angular variation, it is a disadvantage for most other applications. Many researchers have investigated ways of reducing these effects.^{13,24-27}

3. Transmittance curves of nonabsorbing multilayers composed of layers whose optical thicknesses are all multiples of $\lambda/4$ show symmetry about λ_0 when plotted on a relative wavenumber scale λ_0/λ [Eqs. (17) and (18)].
4. A proportional change of all the thicknesses of a nonabsorbing multilayer results merely in a displacement of the transmittance curve on a wave-number scale [Eq. (18)]. Thus a thin-film design can be utilized in any part of the spectrum subject only to the limitations imposed by the dispersion of the optical constants of the materials used.
5. The reflectance and absorptance of a filter containing absorbing layers will depend, in general, on which side of the filter the radiation is incident (Fig. 5). However, the transmittance does not depend on the direction of the incident light.

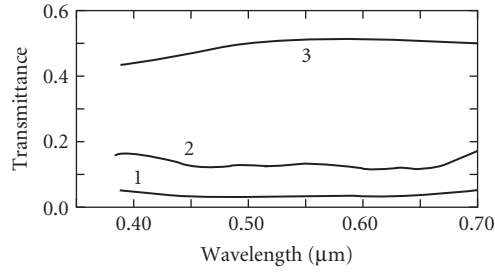


FIGURE 5 Spectral characteristics of a thin chromium alloy film on glass. Curve 1: transmittance; curves 2 and 3: reflectance from the glass and air sides, respectively. (After *Liberty Mirror*.²⁸)

Layers	n_m	Sublayers
L	n_L	L_{sub}
		L_{sub}^{-1}
		$\vdots$
$\vdots$		
j	n_j	$\vdots$
		j_{sub}
		$\vdots$
$\vdots$		
2	n_2	
1	n_1	$\vdots$
		3
		2
		1
n_s		

FIGURE 6 Subdivision of layers for the evaluation of the electric field within a multilayer (see Sec. 7.2, subsection “Matrix Theory for the Analysis of Multilayer Systems”).

An important parameter is the electric field amplitude squared, $|E|^2$. The susceptibility of a multilayer to high-power laser damage is proportional to the highest value of this quantity within the multilayer. One way to evaluate E is to subdivide each layer of the system into L_{sub} sublayers (Fig. 6) and to evaluate the partial matrix products P_j ,

$$\mathbf{P}_j = \begin{pmatrix} p_{11} & ip_{12} \\ ip_{21} & p_{22} \end{pmatrix} = \prod_{k=1}^j (\mathbf{S}_k) \quad (29)$$

for all L sublayers, where S_k is the matrix of the k th sublayer. Then, the electric field amplitude at a point j in the multilayer is given in terms of the elements of the total and partial product matrices by the following expression:²⁹

$$E_j = \frac{4[p_{11}^2 + (n_s p_{12})^2]}{[m_{11} + (n_s m_{22}/n_m)]^2 + [(m_{21}/n_m) + n_s m_{12}]^2} \quad (30)$$

The analysis of optical thin-film systems [with computer programs based on Eqs. (13) to (30)] is relatively simple. The design of filters with any but the simplest spectral characteristics is a more complicated problem and one of the methods listed in Sec. 7.2, subsection "Design Approaches" must be used.

7.3 THIN-FILM MANUFACTURING CONSIDERATIONS

The optical, mechanical, and environmental properties of multilayer coatings depend on the materials used, on the deposition process and on the surface quality of the substrate.

There are many different methods for the deposition of thin films.³⁰⁻³² Some of the more common processes are reviewed below. The deposition methods and process parameters used affect the microstructure of the resulting layers. The films can be dense with an amorphous or a microcrystalline structure, or they may exhibit a columnar growth with considerable voids. The optical constants clearly depend on this microstructure and films of the same materials may sometimes have very different properties, depending on how they were deposited (see, for example, Ref. 33). The individual films in a multilayer may be under tensile or compressive stress and, unless materials and film thicknesses are selected to compensate for these stresses, the overall stress may be large enough to distort the substrate or cause the multilayer to break up. The mechanical properties of multilayer coatings also critically depend on the microstructure of the films. An excellent discussion of the effects of microstructure on the various properties of optical coatings has been given by Macleod.¹⁸

Optical Coating Materials

Many different materials have been used in the past for the construction of optical multilayer coatings. Some of the compounds used for the deposition of nonabsorbing layers for the ultraviolet, visible, and infrared parts of the spectrum are cryolite (1.35), LiF (1.37), MgF₂ (1.39), ThF₄ (1.52), CeF₃ (1.62), PbF₂ (1.73), ZnS (2.30), ZnSe (2.55), Si (3.5), Ge (4.20), Te (4.80), PbTe (5.50), and the oxides SiO₂ (1.48), Al₂O₃ (1.60), MgO (1.72), Y₂O₃ (1.82), Sc₂O₃ (1.86), SiO (1.95), HfO₂ (1.98), ZrO₂ (2.10), CeO₂ (2.20), Nb₂O₅ (2.20), Ta₂O₅ (2.10), and TiO₂ (2.45). The numbers in parenthesis represent the approximate refractive indices at the midpoints of the material transparency range. Some of the metals used in the same wavelength range for the deposition of reflecting or absorbing layers are Ag(0.12 - i3.45), Al(1.02 - i6.85), Au(0.31 - i2.88), Cu(0.83 - i2.60), Ni(1.80 - i3.33), Cr(3.18 - i4.41), Inconel(2.94 - i2.92), and Rh(2.00 - i5.11). The complex refractive indices of the metals given in the brackets correspond to a wavelength of 0.56 μm. The above values are approximate and are intended as a rough guide only. More extensive listings of coating materials are given, for example, by Macleod² and Costich.³⁴

As already mentioned, the properties of multilayers depend on the materials used for their construction. For example, layers made of oxides are, as a rule, harder than those made of fluorides, sulphides, or semiconductors. They are therefore preferred for use on exposed surfaces. Semiconductor materials should be avoided in filters that are to be used over a wide range of temperatures because their optical constants can change significantly. Some metals are soft and easily damaged while others tarnish when exposed to the atmosphere. Such coatings require further protective coatings, or should be cemented between two transparent plates. Other materials require the precoating with adhesion layers to ensure a good bond to the substrate. For example, frequently a Ni adhesive layer is deposited onto glass before coating with Au.

Evaporation

Conventional (nonreactive) or reactive evaporation from resistance, induction or electron beam gun sources is a low energy process (~ 0.1 eV) and the resulting films frequently have a porous structure. The porosity may vary with the material, the substrate temperature, the residual pressure in the deposition chamber, the deposition rate and angle of incidence of the vapour on the substrate. Values of porosities ranging from 0 to 40 percent have been observed. On exposure to the atmosphere some of the voids in the film may adsorb water vapor. This increases the effective refractive index of the films and results in a shift of the spectral features of the multilayer towards longer wavelengths ("ageing"). This shift is partially reversible—by placing the filter in an inert atmosphere or in a vacuum, or on heating, some of the adsorbed water vapor can be removed. Unless it has been allowed for at the design stage, such ageing can render some filters useless.

The microstructure of the films can be significantly affected by bombarding the substrate during deposition with energetic ions from an auxiliary ion beam source.^{35–37} The additional energy (~ 50 to 100 eV) results in denser films. Hence, coatings produced by *ion-assisted deposition* have higher refractive indices and exhibit less or no ageing on exposure to the atmosphere.

The *ion-plating* process can result in even denser coatings.^{38–40} In this high deposition rate process the starting material must be a good conductor and is usually a metal. Argon and a reactive gas species are introduced into the chamber and, together with the evaporant, are ionized. The ions are then accelerated to the substrate with energies of the order of 10 to 50 eV. Transparent films with near-bulklike densities and low temperature variation of refractive index can be obtained by this process. For most materials the layers are glasslike and the interfaces remain smooth. This results in a lower scatter. *Plasma-ion-assisted deposition* is a process that also produces such good quality coatings, but it has the advantage over the ion-plating process that it does not require a conducting evaporant, so that fluorides and other nonconducting materials can be deposited with it.^{41–43}

Conventionally evaporated thin films can be under compressive or tensile stresses. If not controlled, these stresses can distort the substrate or cause the multilayer to break up. The magnitudes of the stresses depend on the material and on the deposition conditions. It is often possible to select the materials and process parameters so that the stresses of the various layers counteract each other. In contrast, almost all ion-plated layers are under compressive stress. It is therefore more difficult to produce stress-compensated multilayers by this process.

Sputtering

Reactive or nonreactive DC, RF, AC, or pulsed magnetron sputtering are also used to deposit optical multilayer coatings. Very many variants of this process exist.⁴⁴ Most are significantly slower than evaporation and the targets can be quite expensive. Filters produced by magnetron sputtering may therefore also be more expensive. However, the process is stable, provides excellent control over the thicknesses of the layers and can be readily scaled to provide uniform coatings over large areas. Both metal and metal oxide layers can be produced. Sputtering is an energetic process and results in dense, bulklike layers that exhibit virtually no ageing.

In *ion-beam sputtering* an energetic beam of inert ions is aimed at a target made of the material that is to be deposited. Atoms or clusters of atoms of the material are dislodged from the target and land on the substrate with a high energy (about 10 to 200 eV). This is the slowest physical vapor thin-film deposition method described here and it cannot yet be readily scaled for the coating of large components. However, it yields the highest quality coatings. Many of the high reflectance coatings for laser gyros, in which no significant losses can be tolerated, are produced in this way.

Deposition from Solutions

In this procedure the substrate is either dipped in an organo-metallic solution and withdrawn at a very steady rate from it, or the solution is applied from a pipette onto a spinning substrate. The substrate is then placed in an oven to drive off the solvent. The thickness of the film depends on the

concentration of the solvent and on the rate of withdrawal or spinning. Other factors that influence the process are temperature and humidity, as well as the freshness of the solution. Although it yields quite porous films, this method is of interest because many of the layers produced in this way have a high laser damage threshold. The process has also been adapted for the coating of quite large area substrates with multilayer antireflection coatings for picture frame glass and for display windows.

Other Deposition Methods

Great strides have been made in the development of various *chemical vapor deposition methods* for the production of optical coatings.⁴⁵ These processes often take place in the presence of plasmas operating at microwave and/or radio frequencies. The advantage of this approach is that it is relatively easy to produce robust layers with intermediate optical constants through the use of appropriate mixtures of two or more reactant gases. However, most of the reactants used are toxic and their handling requires special care.

Atomic layer deposition is inherently a slow deposition process that is capable of depositing very precise, conformal layers onto irregular-shaped substrates. Recently it has been demonstrated that it can be a commercially viable process if large chambers that contain stacks of closely packed substrate holders are used for the simultaneous coating of hundreds of objects.⁴⁶

Thickness Control during Deposition

The performance of many optical multilayers depends critically on the thicknesses of the individual layers. The control of the layer thicknesses during their formation is therefore very important. Many different methods exist for the monitoring of layer thicknesses. For very steady deposition processes, such as sputtering, simple timing can give good results. However, the most common techniques used are quartz crystal and optical monitoring. The former is very sensitive and can be used for thin and thick films, as well as transparent and opaque films. However, it is an indirect method and requires careful calibration. This is usually not a problem whenever layers of established coating materials are formed using a standard geometry and deposition conditions. Optical monitoring can be performed directly on the substrate, or indirectly on a witness glass. The quantities measured are usually T , R , or the ellipsometric parameters. One advantage of direct optical monitoring is that the parameters measured are usually closely related to the required performance. Furthermore, with optical monitoring, a real-time error determination and compensation is possible after the deposition of each layer, through the reoptimization of the remaining layers of the system.⁴⁷ With this method even quite complicated multilayer structures can be manufactured. This process is now used in many laboratories. Even better results should be possible in the future when the above process is combined with ion-beam etching to adjust the thicknesses of layers that exceed the intended value.⁴⁸

7.4 MEASUREMENTS ON OPTICAL COATINGS

Optical Properties

Transmission, Reflection, and Absorption The most commonly used instrument for the measurement of the optical performance of thin-film coatings is the spectrophotometer. The wavelength dispersion of commercial instruments for the 0.185 to 80.0 μm spectral range is usually provided by prisms or by ruled or holographic gratings. Grazing incidence gratings, crystals, or multilayer coatings are used in the soft x-ray and extreme ultraviolet (XUV) spectral regions. Fourier transform spectrometers are capable of measurements from about 2 to 500 μm . A variety of attachments are available for the measurement of specular and diffuse reflectance. Absolute measurements of T and R that are accurate to within ± 0.1 percent are difficult to make even in the visible part of the electromagnetic spectrum. Measurements at oblique angles of incidence are even more difficult.

Very small absorptions of single layers are normally measured with calorimeters.⁴⁹ The losses of high performance laser reflectors are obtained from measurements of the decay times of Fabry-Perot interferometer cavities formed from these mirrors.⁵⁰

Roughness of the substrate and irregularities occurring within individual films and the layer interfaces give rise to light scattering in all directions.^{51–53} For many applications it is important to minimize this scatter. Special instruments, called scatterometers, are used to measure the angular variation of the light scatter. Such data provides information about the substrate and multilayer.⁵⁴

The transmittance, reflectance, and absorptance of some optical coatings are affected by exposure to atomic oxygen and by electron, proton, and ultraviolet irradiation. They also depend critically on the cleanliness of the components measured. In space contamination of optical components can also take place.^{55,56}

Optical Constants A reliable knowledge of the optical constants of all the materials used in the construction of optical multilayer coatings is essential. There exist many different methods for their determination.⁵⁷ These include methods that are based on refractometry, photometric, and spectrophotometric measurements of R and/or T , polarimetry, singlewavelength or spectroscopic ellipsometry, various interferometric methods, attenuated total reflection, or on a combination of two or more of the above methods. Excellent monographs on the various methods will be found in Palik's *Handbook of Optical Constants of Solids*.^{58,59} Some are suitable for measurements on bulk materials and the results are valid only for films produced by the more energetic deposition processes described above. The optical constants of porous films must be measured directly. They will depend on the deposition parameters and on the layer thickness, and may differ significantly from those of bulk materials.⁶⁰ Special methods have to be used for the determination of the optical constants in the x-ray, XUV, and sub-millimeter regions. The accurate measurement of very small, residual extinction coefficients of transparent coating materials is difficult. Generally it involves the use of laser calorimetry or the use of the film as a spacer layer in a bandpass filter. It is also very important to be able to measure the thickness of the film independently.

Laser Damage A measure of the ability of an optical component to withstand high laser irradiations is the laser damage threshold (LDT). There are several ways of defining this quantity. One frequently used definition is based on a plot of the percentage of components that are damaged when they are exposed to different laser fluences. The value of the fluence corresponding to the intersection of a mean curve through the experimental points with the ordinate is defined to be the LDT. It is thus the maximum fluence at which no damage is expected to the component.

Absorption is the main cause for laser damage. The incident radiation that is absorbed in the optical component will be converted into heat. If the thermal conductance of the optical component is too low, the temperature of the local hot spot on the mirror will rise to a value at which damage occurs. The damage will therefore depend on the thermal conduction of the materials of which the mirror blank is made. For example, some high reflectivity mirrors consist of coatings on Si or Cu substrates that are water-cooled during use.

Thermal conductivities of thin films are several orders of magnitude smaller than those of the corresponding bulk materials. (Exceptions to this are some fluoride layers.) This compounds the problem. To increase the LDT, the deposition methods are optimized to obtain thin films with more bulklike thermal conductivities.

Absorption damage usually initiates at defects and other imperfections. In the case of the substrate, it may occur at or below the surface, even when the substrate material is nonabsorbing. It is very important to avoid materials with color centers and subsurface damage and inclusions. The substrate surface must be very smooth and devoid of scratches, digs, and pores, otherwise polishing compounds and other contaminants can be trapped. It is imperative that the substrate be perfectly clean prior to coating. Electric fields associated with the above imperfections increase the absorption by an amount that is proportional to the refractive index of the material.

The coating materials used for the construction of high LDT multilayers must be very pure, with absorption edges far away from the wavelength of interest. As a rule, materials in thin-film form have

extinction coefficients that are orders of magnitude larger than those of the corresponding bulk materials. Currently the processes used to produce high LDT coatings include ion-beam sputtering, sol-gel deposition, and electron beam gun evaporation. To reduce the effects of the residual surface roughness, the thicknesses of the layers are often adjusted to shift the peaks of the electric field away from the layer boundaries.

The form that the damage takes depends to a large extent on the materials. Pitting of the coatings is probably due to the evaporation of the thin-film materials. Delamination may be due to poor adhesion of the layers to the substrate, to undue stresses in the films and/or to a poor match between the expansion coefficients of the layers and the substrate.

The LDT also depends on the laser pulse duration. For very short pulses (<10 ns) thermal conductance does not play a role in the process. For higher values, the LDT is proportional to the square root of the pulse duration. For high repetition rates the LDT depends on the repetition rate. To achieve a long life (10,000 or 100,000 pulses) in an industrial environment, the laser should be operated at a fraction (say, $1/4$ or $1/10$) of the nominal LDT. In CW lasers it is not the LDT, but the power handling capability that is of essence. Long before damage takes place, the heating can cause a distortion of the surface that, in turn, can result in loss of power and in mode and focussing problems.

The development of high LDT of laser coatings is so important, that conferences have been held in Boulder, Colorado, on this topic every year since 1970. For more detail the reader is referred to the proceedings of these conferences,⁶¹ as well as to an article written by Ristau.⁶² There exists also a draft international standard on this topic. An increasing number of thin-film vendors include in their catalogues LDT information on all or some of their products. Independent LDT test services are provided by several commercial companies and publically funded institutions.

Mechanical Properties

Optical multilayer coatings are frequently required to operate under severe mechanical and environmental conditions. Quite frequently meeting these requirements is more difficult than to achieve the necessary optical performance. A number of standards deal with the substrate and coating quality (MIL-0-13830B), the adhesion of coatings (MIL-M-13508C, MIL C 48497), their abrasion resistance (MIL-C-675A, MIL C 675C, MIL-C-14806-A, MIL C 48497), hardness (MIL-M-13508C), and resistance to humidity (MIL-C-675A, MIL-C-14806-A, MIL-810-C, MIL C 48497), salt solution (MIL-C-675-A) and salt spray (MIL-M-13508-C, MIL-C-14806-A). Most of these standards are reprinted in Rancourt's book.³ Depending on the application, multilayer coatings may be required to meet one or more of the above standards. An overview of the subject of stresses and hardness of thin films on a substrate has been recently published by Baker and Nix.⁶³ Sapiuha and her coworkers compared various mechanical properties of three commonly used oxide layers produced by different deposition processes.⁶⁴

Analytical Analysis Methods

In addition to optical and mechanical measurements, multilayer coatings can be subjected to a number of analytical measurements. These include Auger electron spectroscopy, energy dispersive x-ray analysis, Rutherford backscattering, secondary ion mass spectrometry, transmission electron microscopy and x-ray photoelectron spectroscopy.^{63,65} Some of these tests are destructive. However, when a multilayer coating is subjected to these tests, they yield fairly accurate information about the number of layers in a system, and on the composition, thickness, and structure of the individual layers.⁶⁶

7.5 ANTIREFLECTION COATINGS

Effect of Surface Reflections on Performance of Optical Systems

The reflectance of an interface between two nonabsorbing media of refractive indices n_1 and n_2 is given by

$$R = \left[\frac{n_1 - n_2}{n_1 + n_2} \right]^2 \quad (31)$$

An expression for the total transmittance T_0 of a nonabsorbing plane-parallel plate that takes into account the effect of multiple internal reflections within the plate can be obtained from Eq. (9):

$$T_0 = \frac{1-R}{1+R} \quad (32)$$

Of this light only a fraction $(1-R)^2$ passes through the plate without undergoing any reflections.

An expression for the transmission of a number of such plates placed in series is of interest. It helps to explain the effect of multiple reflections between the various plates on the performance of devices such as tripple glazings and photographic objectives. It can be shown⁶ that the total transmittance T_{total} of m plates placed in series is given by

$$T_{\text{total}} = \frac{T_0}{m - T_0(m-1)} \quad (33)$$

The amount of light transmitted directly T_{direct} is

$$T_{\text{direct}} = (1-R)^{2m} \quad (34)$$

The light T_{stray} that undergoes multiple reflections before transmission is responsible for spurious images and stray light in the image plane. It is given by

$$T_{\text{stray}} = T_{\text{total}} - T_{\text{direct}} \quad (35)$$

The variation of T_{direct} and T_{stray} with R , for several values of m , is shown in Fig. 7. The refractive indices of the plate material plotted against the upper x axis assume that the plates are in air.

It will be seen that even for a relatively small number of low-refractive-index plates the ratio $T_{\text{stray}}/T_{\text{direct}}$ becomes significant. This means that in an image-forming system under unfavorable conditions the stray light can completely obscure the image.⁶⁷ Second, even in nonimaging optical systems the loss of light $(1 - T_{\text{direct}} - T_{\text{stray}})$ can become quite prohibitive.

Both these problems can be overcome by reducing the surface reflection through the application of suitable antireflection coatings to the plate boundaries. Since antireflection coatings with zero reflectance across the whole spectrum cannot be constructed, the spectral reflectance $R(\lambda)$ of antireflection coatings is usually chosen to minimise the integral

$$\int_{\lambda} R(\lambda) I(\lambda) S(\lambda) d\lambda \quad (36)$$

where $I(\lambda)$ and $S(\lambda)$ are the spectral-intensity distribution of the incident radiation and the spectral sensitivity of the detector, respectively. A low reflectance is thus needed only in the spectral region in

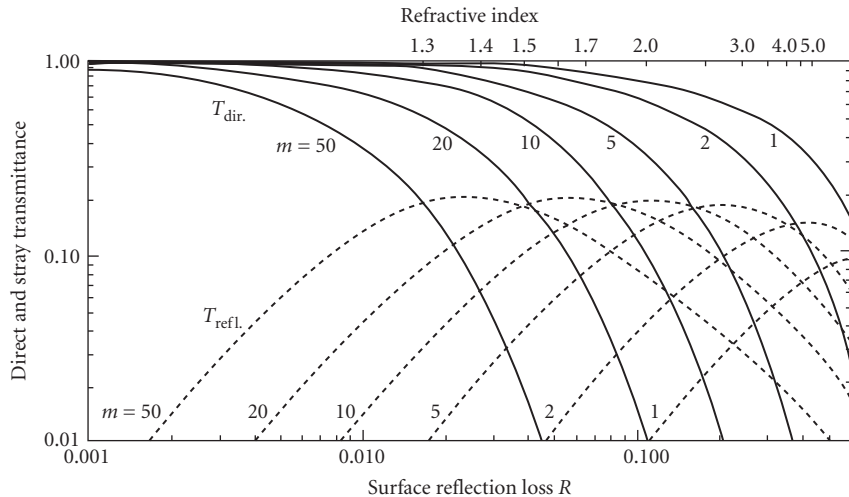


FIGURE 7 Transmittance of a system of m parallel plates of surface reflectances R for directly transmitted radiation T_{direct} and for radiation that suffers multiple reflections before transmission T_{stray} . The upper x axis is calibrated in terms of the refractive index of the plates for the special case when the plates are in air.

which $I(\lambda)S(\lambda)$ is significant. It should be emphasized here that in addition to this requirement, for most applications antireflection coatings must be mechanically very tough, withstand drastic climatic and thermal variations, and stand up to the usual lens-cleaning procedures. Some examples of improvements in the performance of image-forming and non-image-forming optical systems obtained through the use of antireflection coatings are given by Mussett and Thelen⁶⁷ and by Faber et al.⁶⁸

Antireflection coatings can be based on homogeneous layers or on inhomogeneous coatings. One can further classify them into single layer, digital, or structured, and homogeneous multilayer or complex inhomogeneous layer coatings (Fig. 8a to f). Because of their industrial importance, antireflection coatings for the visible and infrared spectral regions have been the subject of much research and development. Two books have been written on this topic^{69,70} and there exists a very extensive literature in scientific and technical journals. For a review of this literature and for a systematic discussion of antireflection coatings, the reader is referred to the excellent review articles by Cox and Hass⁷¹ and by Mussett and Thelen.⁶⁷ A recent report on the present state of the art has been published in the Japanese language. In this section, only a brief summary will be given of the results obtained thus far, intended to aid in the selection of antireflection coatings for particular applications. The calculated data is presented on a logarithmic scale. The relative wavenumber scale facilitates the calculations of the width of the effective region of a coating in different parts of the spectrum.

Antireflection Coatings Made of Homogeneous Layers

The single homogeneous-layer antireflection coating (Fig. 8a) was the first antireflection coating and perhaps is still the most widely used. Theoretically it should be possible to obtain a zero reflectance at one wavelength with single dense films. However, because of a lack of suitable low-index coating materials, this cannot be realised in practice for substrates with indexes less than about 1.9. Nevertheless, even with the available materials a very useful reduction in reflection in a broad spectral region is obtained for all common glass types, the reflectance never rising above that of the uncoated surface (Fig. 9, curve 8). With the sol-gel method it is possible to produce homogeneous porous oxide and fluoride films with very low refractive indices.⁷²⁻⁷⁵ Such films have excellent optical characteristics

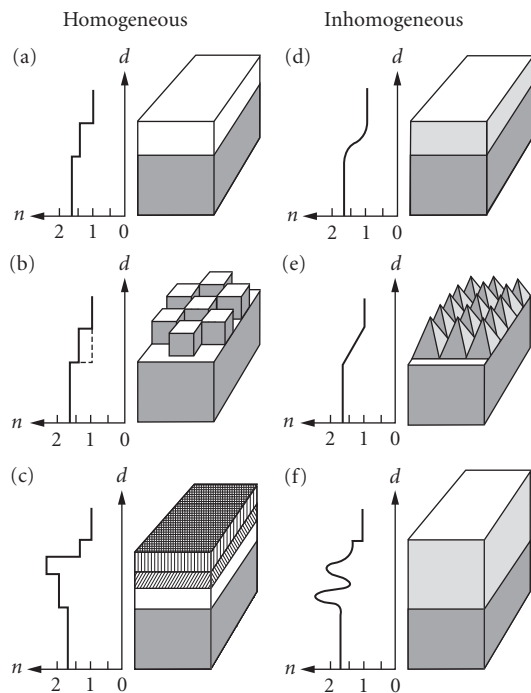


FIGURE 8 Structure and effective refractive index profiles of various types of antireflection coatings. (a), (b), (c) homogeneous single layer, digital and multilayer AR coatings and (d), (e), (f) simple inhomogeneous layer, structured and more complex inhomogeneous layer AR coatings.

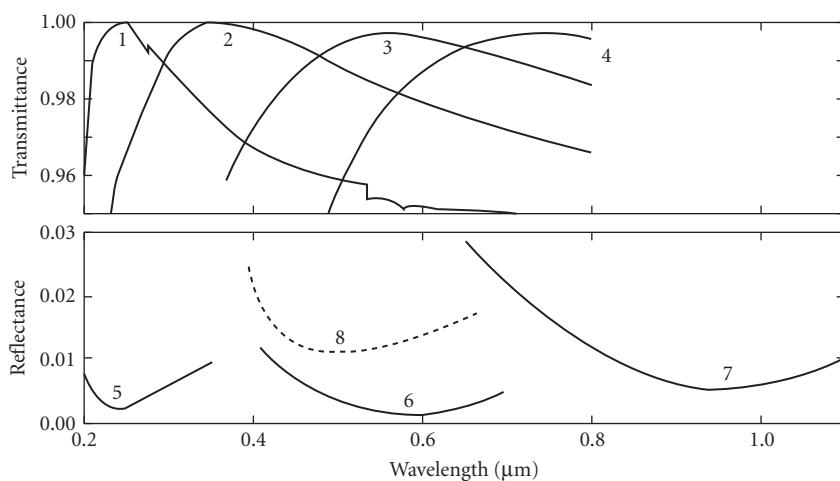


FIGURE 9 Performance of single layer porous homogeneous antireflection coatings on various substrate surfaces. Porous silica on fused silica (1, 3, 5); on glass (6); on KDP (7); SF_8 (4). Porous MgF_2 on fused silica (2). A conventional single layer antireflection coating on glass is shown for comparison (8). (Curve 1 after Wilder;⁷² curve 2 after Thomas;⁷⁴ curves 3 and 4 after Thomas;⁷⁵ curves 5–7 after O'Neill;⁷³ and curve 9 after Balzers.⁷⁶)

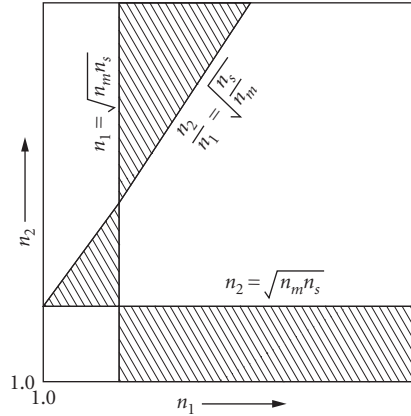


FIGURE 10 Refractive index combinations (*shaded areas*) of two-layer antireflection coatings with which a zero reflectance at one wavelength can be achieved.

(Fig. 9) and have laser damage thresholds that are considerably higher than those produced by conventional means. However, these gains are at the expense of mechanical strength and long-term stability. Low-refractive index coating materials can also be simulated by the deposition or etching of subwavelength structures (Fig. 8*b, e*). The effective refractive index depends on the volume fraction occupied by the structures.⁷⁷

If more than one layer is used, all the degrees of freedom could be used to either (1) obtain a more complete antireflection in one particular spectral region; (2) increase the width of the spectral region over which the reflectance is generally low; or (3) obtain a coating in which the low reflectance is very uniform across the spectrum.^{78,79} Vlasov has shown with the aid of a diagram of the type shown in Fig. 10 that even for a two-layer antireflection coating there exists a large number of refractive index combinations which will yield zero reflectance at one wavelength.⁶⁹ As the number of layers and the overall thickness of the antireflection coating increases, it becomes possible to find solutions for a particular problem that not only fully meet the most important above desiderata and almost satisfy the others but are also based on the use of the mechanically most satisfactory coating materials.

The conditions that are satisfied by the refractive indexes and thicknesses of various types of antireflection coatings are given in Table 1. In a few cases where they are very complicated, reference is made to a paper in which they are set out in full. The calculated transmittance curves of antireflection-coated surfaces of glass (Fig. 11*a* to *c*), quartz (Fig. 11*d*), germanium (Fig. 11*e* and *f*), silicon (Fig. 11*g*), and other infrared materials (Fig. 11*h*) utilize refractive indexes that for the most part correspond to real coating materials, and hence the curves represent realistic solutions rather than the theoretically best possible ones. The actual refractive indices used in the calculations (and optical thicknesses where they do not correspond to a multiple of $\lambda/4$) are given in Table 1.

Figure 11*a* shows the performance of several antireflection coatings on glass for applications which require the highest possible efficiency for a limited wavelength region. Of these the coating 2.1 has probably found the greatest acceptance. A typical measured performance curve for such a coating is shown in Fig. 12. Antireflection coatings with a low reflectance in a broad spectral region are shown in Fig. 11*b* and Fig. 13. Coatings of the type 3.4 probably find the widest application in practice. The performance of commercial coatings for quartz substrates are shown in Fig. 14.

Solutions listed in Table 1 presume that coating materials with the required refractive indices exist. This is frequently not the case and the thin-film designer must seek solutions based on available coating materials. For example, Furman⁸⁹ gives a series of practical two-, three-, and four-layer solutions for 10 different values of the substrate index ranging between 1.5 and 4.0, while Stolov provides⁹⁰ seven-layer solutions for 10 values of n_s , $1.46 \leq n_s \leq 1.82$.

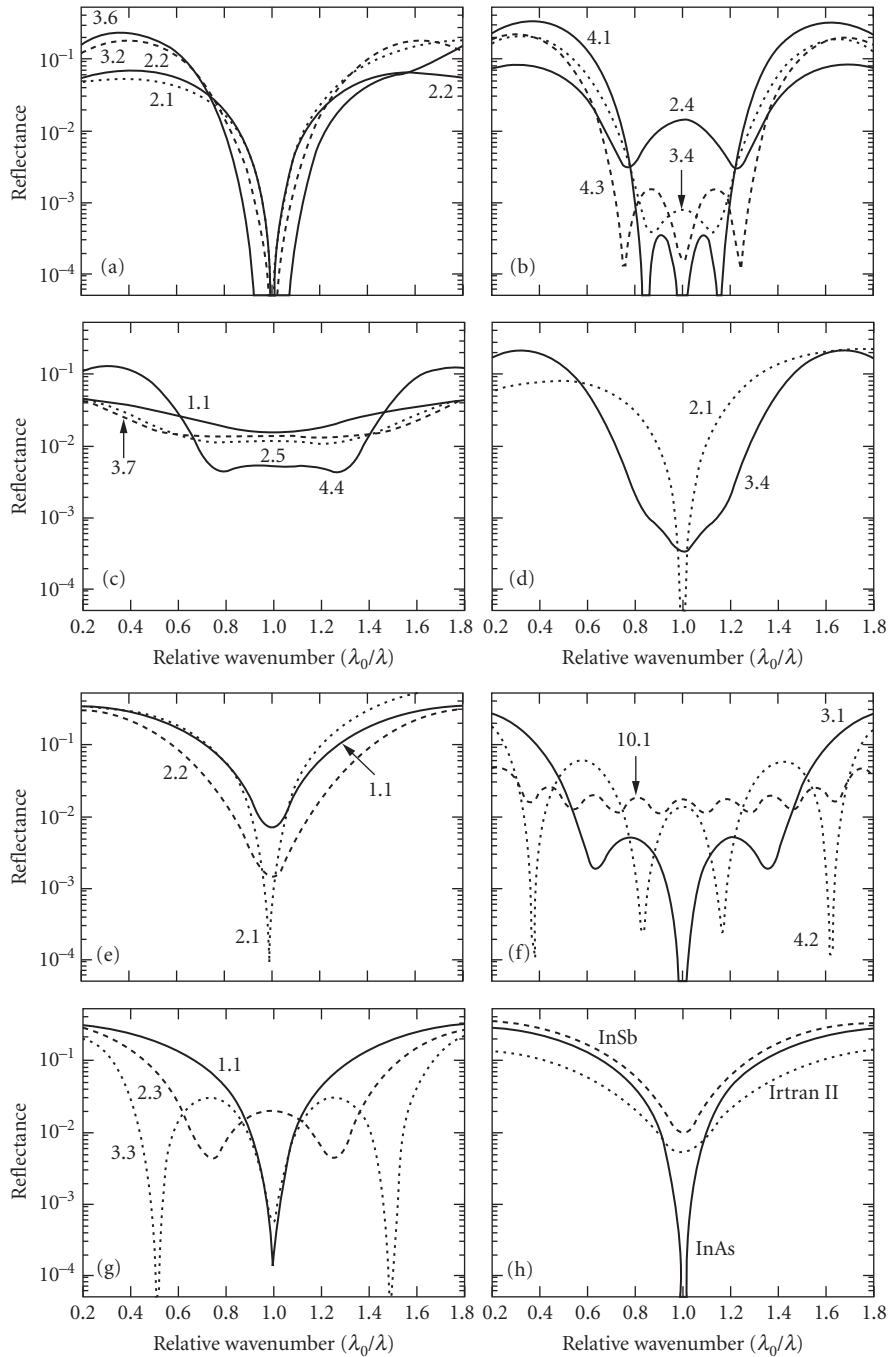


FIGURE 11 Calculated performance of various antireflection coatings. The numbers identifying the individual curves refer to Table 1. (a) High-efficiency antireflection coatings for glass; (b) broadband antireflection coatings for glass; (c) highly achromatic antireflection coatings for glass; and (d) antireflection coatings for quartz. (e) Antireflection coatings for germanium; and (f) broadband antireflection coatings for germanium. (g) Antireflection coatings for silicon and (h) single-layer antireflection coatings for Irtran II, InAs, and InSb.

TABLE 1 Some Antireflection Coatings^{80,81} (*The incident medium in all cases is air.*)

Type	Conditions or Reference	Substrate Material	n_s	n_1 ($n_1 d_1 / \lambda$)	n_2 ($n_2 d_2 / \lambda$)	n_3 ($n_3 d_3 / \lambda$)	n_4 ($n_4 d_4 / \lambda$)	n_m
1.1	$n_1 = \sqrt{n_s n_m}; n_1 d_1 = \frac{\lambda}{4}$	Glass	1.51	1.38				1.00
		Irtran II	2.20	1.59				1.00
		InSb	4.00	2.20				1.00
		InAs	3.40	1.85				1.00
		Ge	4.10	2.20				1.00
		Si	3.50	1.85				1.00
2.1	$\tan^2 \delta_1 = \frac{(n_1^2(n_m - n_s)(n_s n_m - n_2^2))}{(n_s n_2^2 - n_m n_1^2)(n_s n_m - n_1^2)}$	Glass	1.51	2.30 (0.0524)	1.38 (0.3250)			1.00
		Quartz	1.48	2.09 (0.0947)	1.48 (0.3255)			1.00
	$\tan^2 \delta_2 = \frac{n_2^2(n_m - n_s)(n_s n_m - n_1^2)}{(n_s n_2^2 - n_m n_1^2)(n_s n_m - n_2^2)}$	Ge	4.10	1.35 (0.0951)	4.10 (0.0586)			1.00
2.2	$n_2^2 n_s = n_1^2 n_m; n_1 d_1 = n_2 d_2 = \frac{\lambda}{4}$	Glass	1.51	1.70	1.38			1.00
		Ge	4.10	3.30	1.57			1.00
2.3	$n_1 n_2 = n_m n_s; n_1 d_1 = n_2 d_2 = \frac{\lambda}{4}$	Si	3.5	2.20	1.35			1.00
2.4	$n_1^2 - \frac{n_1 n_s}{2n_2 n_m} (n_m^2 + n_2^2)(n_1 + n_2) + n_2 n_s^2 = 0$ $\frac{1}{2} n_1 d_1 = n_2 d_2 = \frac{\lambda}{4}$	Glass	1.51	1.70	1.38			1.00
2.5	$n_1 d_1 = n_2 d_2 = \frac{\lambda}{4}$ (see Kard, Ref. 80)	Glass	1.55	1.484	1.32			1.00
3.1	$n_3 n_s = n_2^2 = n_m n_s;$ $n_1 d_1 = n_2 d_2 = n_3 d_3 = \frac{\lambda}{4}$	Ge	4.1	3.30	2.20	1.35		1.00
3.2	$n_1 n_3 = n_2 \sqrt{n_m n_s};$ $n_1 d_1 = n_2 d_2 = n_3 d_3 = \frac{\lambda}{4}$	Glass	1.53	1.80	2.14	1.47		1.00
3.3	$n_2^2 = n_m n_s, n_m n_1^2 = n_3^2 n_s$ $n_1 d_1 = n_2 d_2 = n_3 d_3 = \frac{\lambda}{4}$	Si	3.45	2.56	1.86	1.38		1.00
3.4	$n_3^2 n_s = n_m n_1^2;$ $n_1 d_1 = \frac{1}{2} n_2 d_2 = n_3 d_3 = \frac{\lambda}{4}$	Glass Quartz	1.51 1.48	1.65 1.65	2.10 2.10	1.38 1.38		1.00
3.5	$n_3^2 n_s = n_m n_1^2,$ $\frac{1}{3} n_1 d_1 = \frac{1}{2} n_2 d_2 = n_3 d_3 = \frac{\lambda}{4}$	Glass	1.51	1.659	2.20	1.38		1.00

(Continued)

TABLE 1 Some Antireflection Coatings^{80,81} (*The incident medium in all cases is air.*) (Continued)

Type	Conditions or Reference	Substrate Material	n_s	n_1 ($n_1 d_1 / \lambda$)	n_2 ($n_2 d_2 / \lambda$)	n_3 ($n_3 d_3 / \lambda$)	n_4 ($n_4 d_4 / \lambda$)	n_m
3.6	(see Thetford Ref. 81)	Glass	1.52	1.80 (0.1799)	2.20 (0.4005)	1.38 (0.2402)		1.00
3.7	$n_1 d_1 = n_2 d_2 = n_3 d_3 = \frac{\lambda}{4}$ (see Kard, Ref. 80)	Glass	1.55	1.53	1.454	1.32		1.00
4.1	$n_1 n_4 = n_2 \sqrt{n_m n_3}$; $n_1 d_1 = n_2 d_2 = \frac{1}{2} n_3 d_3 = n_4 d_4 = \frac{\lambda}{4}$	Glass	1.51	1.38	1.548	2.35	1.38	1.00
4.2	$n_1 n_4 = n_2 n_3 = n_m n_5$; $n_1 d_1 = n_2 d_2 = n_3 d_3 = n_4 d_4 = \frac{\lambda}{4}$	Ge	4.0	2.96	2.20	1.82	1.38	1.00
4.3	(see Kard, Ref. 80)	Glass	1.55	1.846	2.289	2.014	1.32	1.00
4.4	(Design derived from Kard, Ref. 82.)	Glass	1.55	1.656 (0.2417)	1.888 (0.2463)	1.832 (0.2390)	1.38 (0.2424)	1.00
10.1	$n_l d_s = n_s - (11-l) \frac{n_s - n_9}{10}$, $l = 1, 2, \dots, 10$ $n_1 d_1 = n_2 d_2 = \dots = n_{10} d_{10} = \frac{\lambda}{4}$ [see Kard, Ref. 80]	Ge	4.00	$n_1 = 3.735$...		$n_9 = 3.735$	$n_{10} = 1.35$	1.00

Wiley has given a useful empirical expression which relates the average reflectance R_{avg} in the visible and near-infrared spectral region $\lambda_{\text{min}} \leq \lambda \leq \lambda_{\text{max}}$ to the overall optical thickness $\Sigma(nd)$ of an antireflection coating composed of layers of refractive indices n_M, n_H and a single, outermost layer of index n_L .⁹¹

$$R_{\text{avg}} = 0.01 \left[\frac{\lambda_{\text{max}}}{\lambda_{\text{min}}} (n_L - 1) \right]^{3.4} \left(\frac{\lambda_{\text{max}}}{\Sigma(nd)} \right)^{0.63} [(1.2 - \Delta n)^2 + 0.42] \quad (37)$$

The above expression is valid for the following parameter values:

$$\begin{aligned} 1.5 \leq \frac{\lambda_{\text{max}}}{\lambda_{\text{min}}} \leq 3.0 \quad 1.17 \leq n_L \leq 1.46 \quad 1.38 \leq n_M, n_H \leq 2.58 \\ 1.0 \leq \frac{\Sigma(nd)}{\lambda_{\text{max}}} \leq 3.0 \quad 0.4 \leq \Delta n = n_H - n_M \leq 1.2 \end{aligned} \quad (38)$$

A method for the design of optimum or near-optimum two-material antireflection coatings for a given substrate, coating materials, and overall thickness has recently been described.⁹²

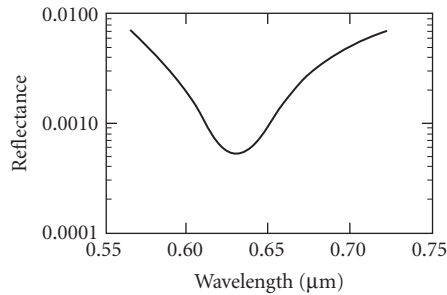


FIGURE 12 Reflectance of a high-efficiency antireflection coating on glass. (After Costich.¹⁷²)

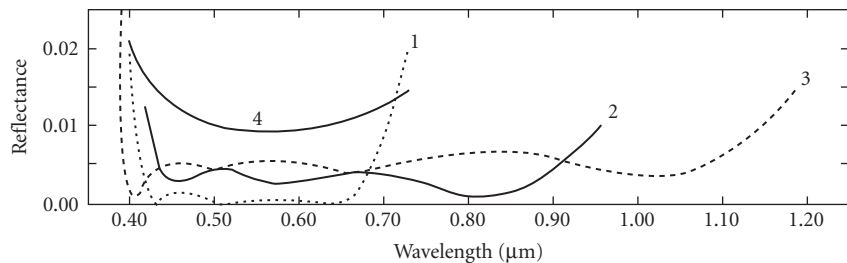


FIGURE 13 Reflectances of three broadband antireflection coatings. (Curve 1 after Turner;¹⁷³ curve 2 after Optical Coating Laboratory;⁸⁴ curve 3 after Thin Film Lab;⁸⁵ and curve 4 after Balzers⁷⁶ corresponds to a single-layer AR coating on glass and is shown for comparison purposes.)

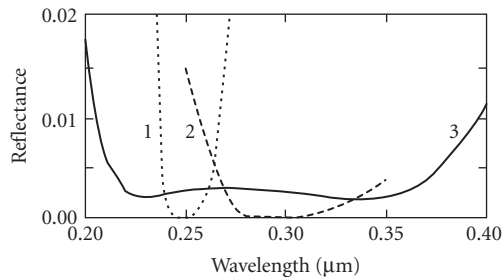


FIGURE 14 Ultraviolet antireflection coatings on fused silica. (Curve 1 after TecOptics;⁸³ curve 2 after Reynard Corp.;⁸⁷ and curve 3 after Spindler & Hoyer.⁸⁸)

Since for some applications the color introduced into an optical system by antireflection coatings is of paramount importance, it has been the subject of many studies.^{93–96} One way to avoid the problem is to utilise coatings that are particularly achromatic (Fig. 11c). Thus, for example, 50 surfaces coated with antireflection coating 4.4 would have a transmittance of 78 ± 3 percent across the whole visible spectrum. Nevertheless, of the coatings shown in Fig. 11c only the single-layer antireflection coating is being used extensively. Antireflection coatings can also be used to correct the residual color of lens systems.⁹⁷

Often transmittance rather than reflectance measurements are performed to evaluate antireflection coatings. In general, it is incorrect to assume that $T = 1 - R$. For instance, the transmission of antireflection-coated infrared materials depends not only on the efficiency of the antireflection coating but

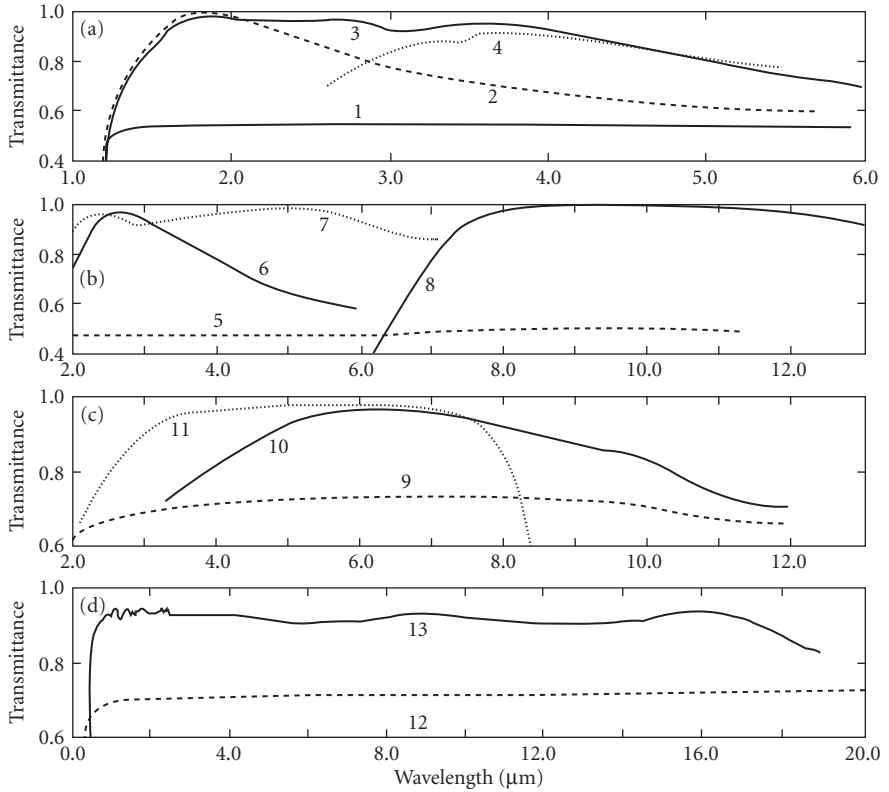


FIGURE 15 Transmittance of plates of infrared materials antireflection-coated on both sides. (a) Silicon. Curve 1: uncoated plate of 1.5 mm thickness; curve 2: single $\lambda_0/4$ layer of SiO_2 ($\lambda_0 = 1.8 \mu\text{m}$); curve 3: $\lambda_0/4$ coatings of MgF_2 and CeO_2 ($\lambda_0 = 2.2 \mu\text{m}$); and curve 4: hard carbon layer. (b) Germanium. Curve 5: uncoated plate; curve 6: single $\lambda_0/4$ layer of SiO ($\lambda_0 = 2.7 \mu\text{m}$); and curve 7: $\lambda_0/4$ coatings of MgF_2 , CeO_2 , and Si ($\lambda_0 = 3.5 \mu\text{m}$); and curve 8: environmentally stable, high laser damage threshold three-layer design based on ThF_4 and Ge . (c) Irtran II. Curve 9: uncoated plate of 2 mm thickness; curve 10: single $\lambda_0/4$ coating of CeF_3 ; and curve 11: $\lambda_0/4$ layers of MgF_2 and SiO ($\lambda_0 = 4.2 \mu\text{m}$). (d) Zinc selenide. Curve 12: uncoated plate and curve 13: extremely broadband AR coating composed of 398 layers produced by molecular beam deposition. (Curves 1–3, 5–7, 9–11 after Cox and Hass;⁷¹ curve 4 after Balzers;⁷⁶ curve 8 after Ohl⁹⁸; and curve 13 after Fisher.⁹⁹)

also on the thickness and temperature of the material. This is because of the finite scatter and absorption in such materials and because of the dependence, in some cases, of the latter on temperature. The measured spectral transmittances of three common antireflection-coated infrared materials at room temperature are shown in Fig. 15. Curves for other materials are given by Cox and Hass.⁷¹

Inhomogeneous and Structured Antireflection Coatings

The interface between two media with refractive indices n_1 and n_2 can be antireflection coated over a very broad spectral region by the application of a transition layer with an index that changes continuously from n_1 to n_2 (Fig. 8d). Many different refractive index profiles have been investigated in the past.^{100–103} Although some of these profiles are more effective than others, all reduce the reflectance to a fraction of a percent over the spectral region in which the coatings are transparent and do not

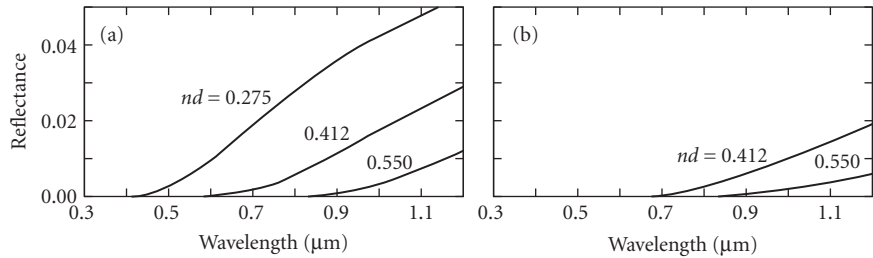


FIGURE 16 Calculated reflectances of the interfaces between two media antireflection-coated with inhomogeneous layers of indicated thicknesses and (complex) refractive indexes that vary smoothly, from the index of one medium to that of the other. (a) Two nonabsorbing media of indexes 1.52 and 2.36. (b) Glass-chromium interface with refractive indexes 1.52 and $2.26 - i0.43$, respectively. (After Anders and Eichinger.¹⁰⁷)

scatter excessively, and for which the optical thickness of the layer is at least one half wavelength (Fig. 16a). A further advantage of inhomogeneous antireflection coatings is that they are not sensitive to the angle of incidence.¹⁰⁴ Processes used for the production of inhomogeneous antireflection coatings include various additive, subtractive, additive/subtractive, and replication methods. Excellent reviews of this topic exist.^{105, 106}

In the additive method relatively dense inhomogeneous layers of varying compositions of two or more compounds are formed on the substrate by physical or chemical deposition processes. Such coatings are mechanically more durable than any other described in this section. However, because of a lack of coating materials with refractive indexes lower than about 1.35, solid inhomogeneous layers are not very suitable for the antireflection coating of air-glass interfaces. The several different inhomogeneous antireflection coatings of this type described in the past do not offer any special advantages over those composed of homogeneous layers.^{70, 108, 109} The situation is different in the case of high-index materials (Fig. 17). An even lower reflectance can be achieved by ending the inhomogeneous layer

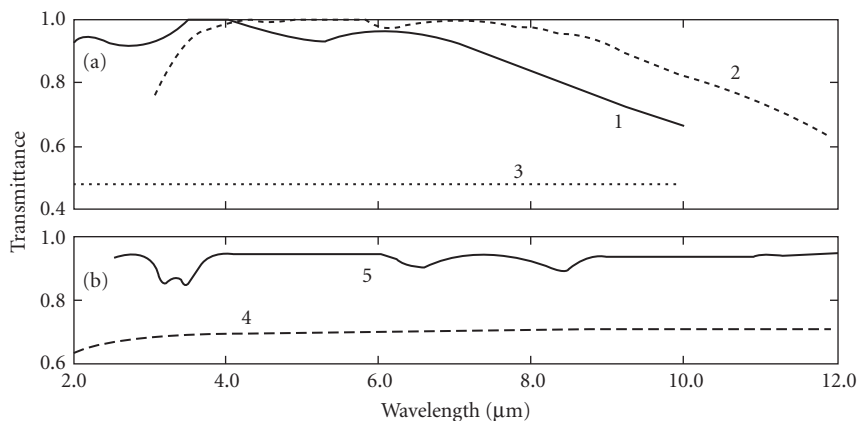


FIGURE 17 (a) Measured transmittance of a germanium plate coated on both sides with inhomogeneous antireflection coatings. Curve 1: 1.2- μm -thick film with an index that changes gradually from that of Ge to that of MgF_2 (after Jacobsson¹¹⁰); curve 2: 1.76- μm -thick film with an index that varies from 4.0 to 1.5, overcoated with a 0.74- μm -thick homogeneous MgF_2 layer (after Scheuerman¹¹¹); and curve 3: transmittance of an uncoated plate. (b) Measured transmittance of a TBI-5 plate. Curve 4: uncoated and curve 5: coated on both sides with ten 2.5- μm -thick homogeneous layers with refractive indexes that vary between 1.3 and 2.29 and that are obtained through the evaporation of suitable NaF-CdTe mixtures. (After Kuznetsov and Perveyev.¹¹²)

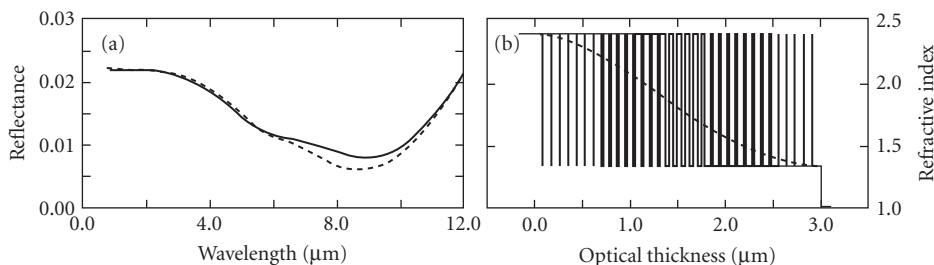


FIGURE 18 Calculated performances (a) and refractive index profiles (b) of an inhomogeneous layer coating and its two-material equivalent. (After Southwell.¹¹⁶)

when its index is equal to the square of that of the lowest-index coating material available. It is then possible to complete the coating by depositing an additional homogeneous quarter-wave-thick layer of that material (Fig. 17a).

A dense inhomogeneous layer can be approximated by a series of homogeneous layers of gradually decreasing refractive indexes (curve 10.1, Fig. 11f).^{113,114} Such layers can be prepared by evaporating a series of appropriate mixtures of two coating materials or, without mixing, by using the Herpin equivalent-index concept¹¹⁵ to simulate intermediate refractive indexes. An even more practical solution is to replace the inhomogeneous layer by a series of thin homogeneous layers of two materials only (Fig. 18).¹¹⁶

In another additive process a refractive index variation down to a value of 1.0 is achieved by depositing onto the substrate microspheres of transparent oxides or fluorides which form pyramid-like clumps (Fig. 8e).¹¹⁷ If losses due to scattering are to be low, the average lateral size of the features of this structure must be a small fraction of the shortest wavelength for which the coating is to be effective. A reflectance of 0.3 percent can be achieved, but the films are fragile.

The subtractive methods are attractive because they do not require expensive deposition equipment. The surface to be antireflection coated is leached and/or etched to form a porous transition layer in which the index varies with thickness. Not all optical materials can be treated in this way. However, special phase-separable glasses have been developed that lend themselves well to this process.^{118–121} Fairly durable antireflection coatings with a reflectance of less than 0.5 percent for the 0.35 to 2.5 μm spectral region have been produced in this way (Fig. 19a). Some other materials, such as Lexan, Mylar, and CR-39 plastic, require an ion implantation pretreatment before the etching can be applied.^{101,122}

In the technologically important additive/subtractive method, a single glasslike film is first deposited by a sol-gel process onto the surface that is to be antireflection coated. The composition of the film is such that, after phase separation, it can be readily leached and/or etched to form a porous microstructure with a controlled refractive index gradient.^{123,126} This eliminates the need for the use of expensive phase separation glass components. Such coatings have reflectances as low as 0.13 percent and a laser damage threshold that is 4 times higher than that of coatings produced by conventional physical vapor deposition techniques (Fig. 19b).¹²⁷ Variants of this process exist.

Microstructured surfaces can also be produced in polymeric and similar materials by a replication process from a suitable cast. Average reflectances in the visible of the order of 0.3 percent have been reported for surfaces treated in this way (Fig. 19c).¹²⁴

Recently there has been a renewed interest in antireflection coatings in which the variable porosities of leached or etched layers are simulated by dense regular shaped structures formed by photochemical or mechanical means. Clapham and coworkers appear to have been the first to demonstrate such devices.¹²⁸ They applied a photoresist to a surface, exposed it to two orthogonal sets of ultraviolet interference fringes, and then developed it to form a regular array of protuberances that could be optionally enlarged by additional ion-beam etching. Such surfaces can reduce the reflectance to less than 0.3 percent in the visible part of the spectrum (Fig. 19d).¹²⁵ The theory of such structures has been investigated by several workers^{129,130} and devices for wavelengths extending into the micrometer

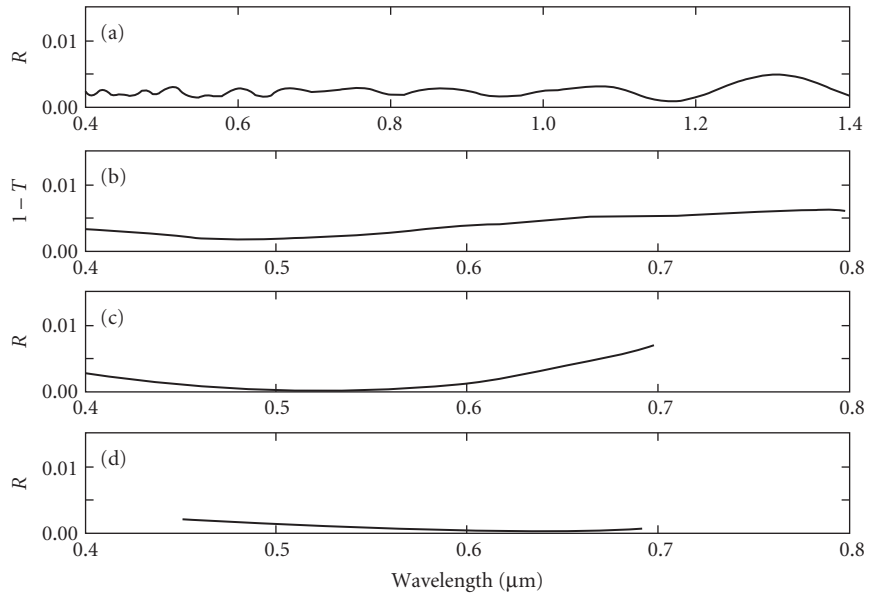


FIGURE 19 Measured performance of various broadband inhomogeneous antireflection coatings. (a) Subtractive process—leached and etched phase separation glass (after Asahara¹²⁰); (b) additive/subtractive process—leached and etched phase-separable film deposited onto fused silica (after Yoldas¹²³); (c) replication process on a cellulose acetate butyrate surface (after Maffitt¹²⁴); and (d) structured antireflection coating in photoresist (after Wilson¹²⁵).

and sub-millimeter region have been fabricated.^{77,121} Efficient laboratory prototype AR coatings produced by the glancing angle deposition process have been demonstrated by Kennedy and Brett.¹³¹

Universal AR Coatings

The idea of a universal AR coating which would reduce the reflectances of a range of substrates with different refractive indices has been first proposed by Vvedenski et al.¹³² Such an AR coating could simplify operations in a coating shop, because all substrates, regardless of the glass that they were made of, could be coated in one deposition run. The prize that one pays for this convenience is that the performance of an AR coating consisting of the same number of layers, but designed for one substrate only will be significantly better.

In Fig. 20 are shown the results obtained for two AR coatings of this type consisting of 11, 17 layers each (rows a, b, respectively). The coatings were designed to simultaneously reduce the reflectances of substrates of index 1.48, 1.55, 1.60, 1.65, 1.73, and 1.75. In column 1 the reflectances of the uncoated and of the coated substrates are shown. Also indicated are the average reflectances of all the coated substrates. The refractive index profiles of the six systems for the different substrate materials shown in a2, b2 differ only in the substrate refractive indices. Increasing the number of layers in the universal AR coatings shown in this figure will result in a diminishing return in the performance. Several papers on this topic have been published by Yeuch-Yeong Liou.¹³⁴

Antireflection Coating of Absorbing and Amplifying Media

Antireflection coatings for glasses and semiconductors in regions of weak absorption, and for present-day laser materials in which k_i , the imaginary part of the complex refractive index [Eq. (25)] is small and negative, differ little from those described above.¹³⁵

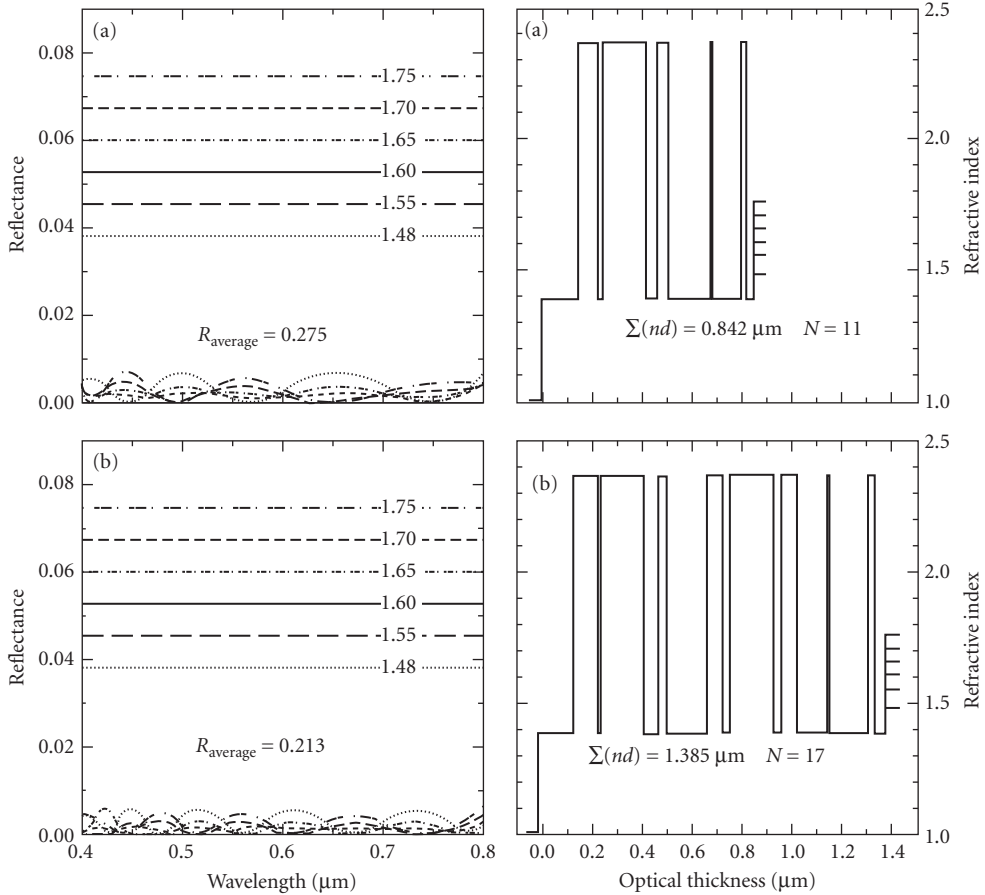


FIGURE 20 Universal AR coatings for substrates with refractive indices 1.48, 1.55, 1.60, 1.65, 1.70, and 1.75. Rows *a*, *b* depict solutions based on 11, 17 layers. Column 1 depicts the reflectances of the substrates before and after the application of the AR coating. In column 2 are shown the refractive index profiles of the solutions. (After Dobrowolski and Sullivan.¹³³)

The reduction of the reflectance of opaque materials for architectural, decorative and technical purposes leads to a corresponding increase in the absorption.^{136,137} This can be utilised to improve the efficiency of radiation detectors and to control the solar-absorptance and thermal-emittance characteristics of surfaces (see, for example, Ref. 138 and 139). A measured example of the reduction in the reflectance of a metal surface attainable with a homogeneous nonabsorbing layer is shown in Fig. 21.

Inhomogeneous transition layers whose refractive index and extinction coefficient change gradually from the values of one of the media to those of the other are also very effective.¹⁰⁷ The calculated reflectance of a glass-chromium interface coated in this way, useful for blackening of prism faces, lens edges, scales, and so on, is shown in Fig. 16*b*. Metal-air interfaces can be treated a little less effectively with single layers because of the lack of suitable low-index materials.

Antireflection Coating of Surfaces Carrying a Thin Film

For some applications it is necessary to deposit a certain film onto a glass surface. The objectionable reflectance that such a film would normally introduce can be avoided by incorporating it into an

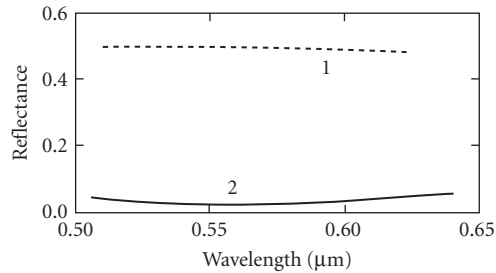


FIGURE 21 Antireflection coating of opaque metals. Curves 1 and 2: reflectance of chromium and of chromium with a ZnS layer. (After Lupashko and Sklyarevskii.¹³⁶).

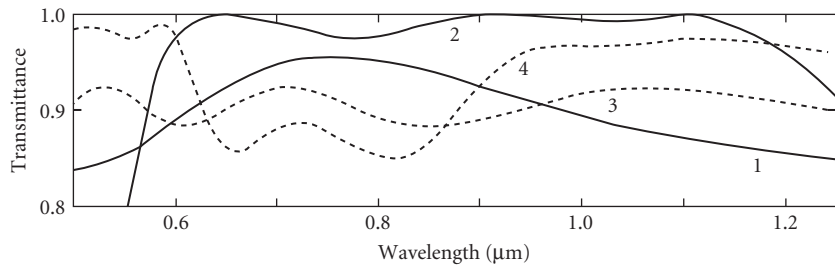


FIGURE 22 Calculated single-surface transmittance of antireflection coatings incorporating a conducting layer. Curves 1 and 2: glass of refractive index 1.755 coated with a 0.566- μm -thick SnO_2 layer before and after three dielectric layers were added to complete the antireflection coating and curves 3 and 4: as above except that the refractive index of the glass and the metric thickness of the SnO_2 film are 1.516 and 0.200 μm , respectively. (After Veremey and Gorbunova.¹⁴²)

antireflection coating. Thus, for example, Fig. 22 shows the calculated transmittances of two conducting layers before and after inclusion in antireflection coatings. The use of homogeneous and of inhomogeneous antireflection coatings with absorbing layers for ophthalmic purposes is described by Katsube et al.¹⁴⁰ and Anders.¹⁴¹

Antireflection Coatings at Nonnormal Angle of Incidence

The calculated performances at 0° , 45° , and 60° incidence of the three commercially most important antireflection coatings and of a 10-layer coating for germanium are shown in Fig. 23. The deterioration with angle of incidence is particularly severe for the narrowband high-efficiency antireflection coating. Figure 23d suggests that the closer the design of an antireflection coating approximates an inhomogeneous transition layer (Sec. 7.5, subsection “Inhomogeneous and Structured Antireflection Coatings”) the less angle-dependent is its performance.

To design an antireflection coating for one angle of incidence and one plane of polarization the effective thicknesses and refractive indexes [Eqs. (18) and (19)] of its layers should satisfy the relations set out in Table 1. In practice, small departures from those conditions are required to optimise the performance with good coating materials. Calculated curves for two sets of two- and three-layer coatings designed for use at 45° are shown in Fig. 24.

If the obliquely incident radiation is unpolarized, a compromise is necessary. The effective thicknesses are matched for the design angle, but the refractive-index conditions set out in Table 1

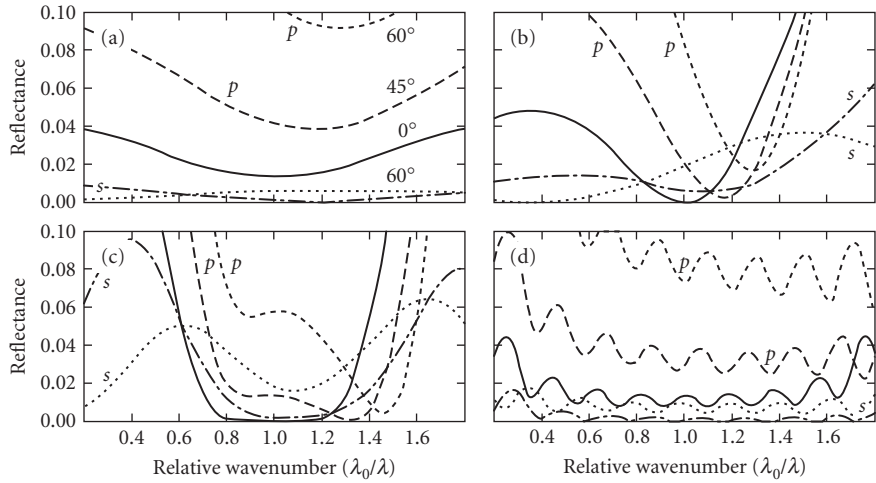


FIGURE 23 Calculated reflectance of (a) one-, (b) two-, (c) three-, and (d) 10-layer antireflection coatings (systems 1.1, 2.1, 3.4, and 10.1 in Table 1) at angles of incidence of 0° (solid curve), 45° (dashed curve), and 60° (dotted curve) for light polarized parallel and perpendicular to the plane of incidence.

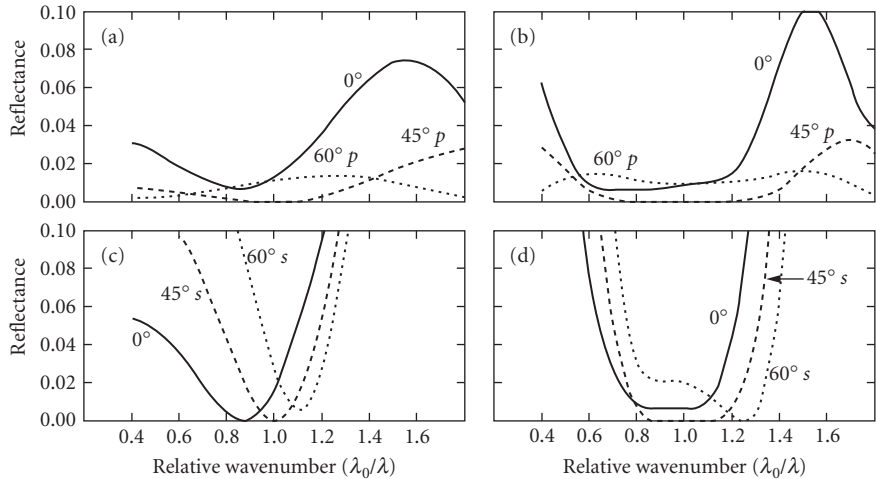


FIGURE 24 Calculated reflectance at 0° (solid curve), 45° (dashed curve), and 60° (dotted curve) of (a) and (c) two-layer and (b) and (d) three-layer antireflection coatings designed for light incident at 45° and polarized parallel or perpendicular to the plane of incidence. (After Turbadar.^{143,144})

are satisfied for normal incidence since they cannot be satisfied for both polarizations at the same time (Fig. 25).

Achromatic antireflection coatings can be designed that are optimised for both polarizations at the same time or that are suitable for use over a range of angles of incidence (Fig. 26b).^{24,145} But the problem becomes more difficult the greater the spectral and angular ranges required, especially if angles of incidence greater than 60° are involved.

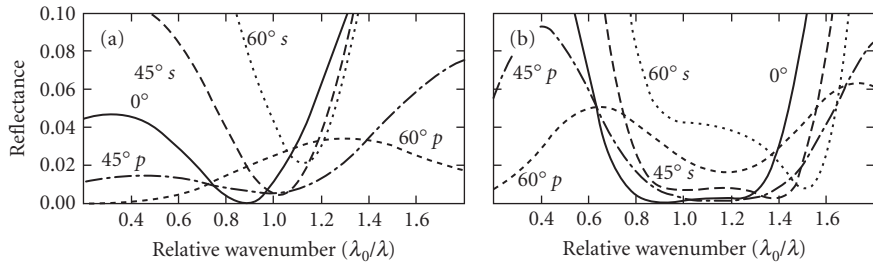


FIGURE 25 Calculated reflectance at 0° (solid curve), 45° (dashed curve), and 60° (dotted curve) of (a) two-layer and (b) three-layer antireflection coatings (systems 2.1 and 3.4 in Table 1) for use with unpolarized light, with the thicknesses of the layers optimized for an angle of incidence of 45°.

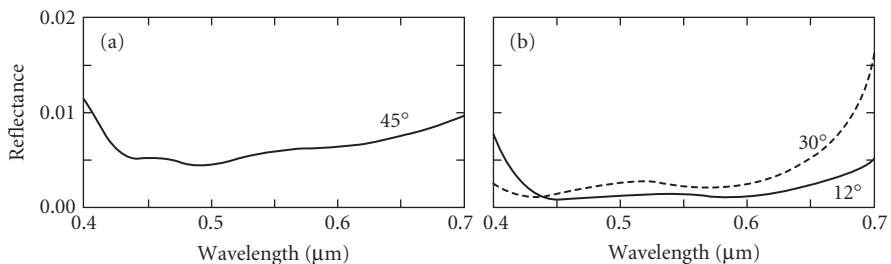


FIGURE 26 Average reflectances for unpolarized light of antireflection coatings designed (a) for 45° incidence and (b) for use with a convergent light cone of semi-angle of 30°. (*Optical Coating Laboratory*.⁸⁴)

In Fig. 27a is shown the variation with angle of incidence of the calculated average reflectance of a six-layer AR coating system for the He-Ne laser wavelength. The reflectance is less than 1 percent for all angles smaller than 60°, but only for a narrow wavelength region around the design wavelength. The performance was limited by the lowest available refractive index at the time.

It has been shown previously (Fig. 19) that, for normal incidence of light, the reflectance from an interface between two media with refractive indices n_s , n_m can be effectively removed over a broad spectral region by an inhomogeneous layer with a refractive index that changes gradually from n_s to n_m , providing that the optical thickness of this inhomogeneous layer is at least one half wavelength thick at the longest wavelength for which the reflectance is to be low. It has been shown numerically¹⁵¹ and theoretically,¹⁵² that this rule continues to hold for up to very high angles of incidence, providing that the *effective* optical thickness is at least one-half wavelength at the highest angle of interest. This means that broadband inhomogeneous layer AR coatings effective up to very high angles of incidence will be very thick. However, it is possible to transform such solutions to homogeneous layer systems with which, because of the additional thin-film interference effects, similar performances can be obtained with a small number of layers and much smaller overall optical thicknesses. Such solutions still call for the use of at least one layer with a refractive index that is very close to the medium index, n_m . Such solutions can be readily implemented for glass/glass interfaces (Fig. 27c). The angular measurements shown in this diagram were obtained with a laser light source, but the AR region was quite broad. When the medium is air and a maximum angle of incidence is 85° is stipulated, a refractive index of the outermost layer should be of the order of 1.02. In the infrared part of the spectrum there are a number of Reststrahlen materials with a refractive index that falls below unity. The measured average spectral reflectance for a number of angles of incidence of an AR coating based on such a material is shown in Fig. 27b. The antireflection region is narrow because the refractive index of the outermost layer has the required value only in a narrow wavelength band. In the visible part of the spectrum such indices can only be achieved with very porous or structured layers. Ways of producing such layers are

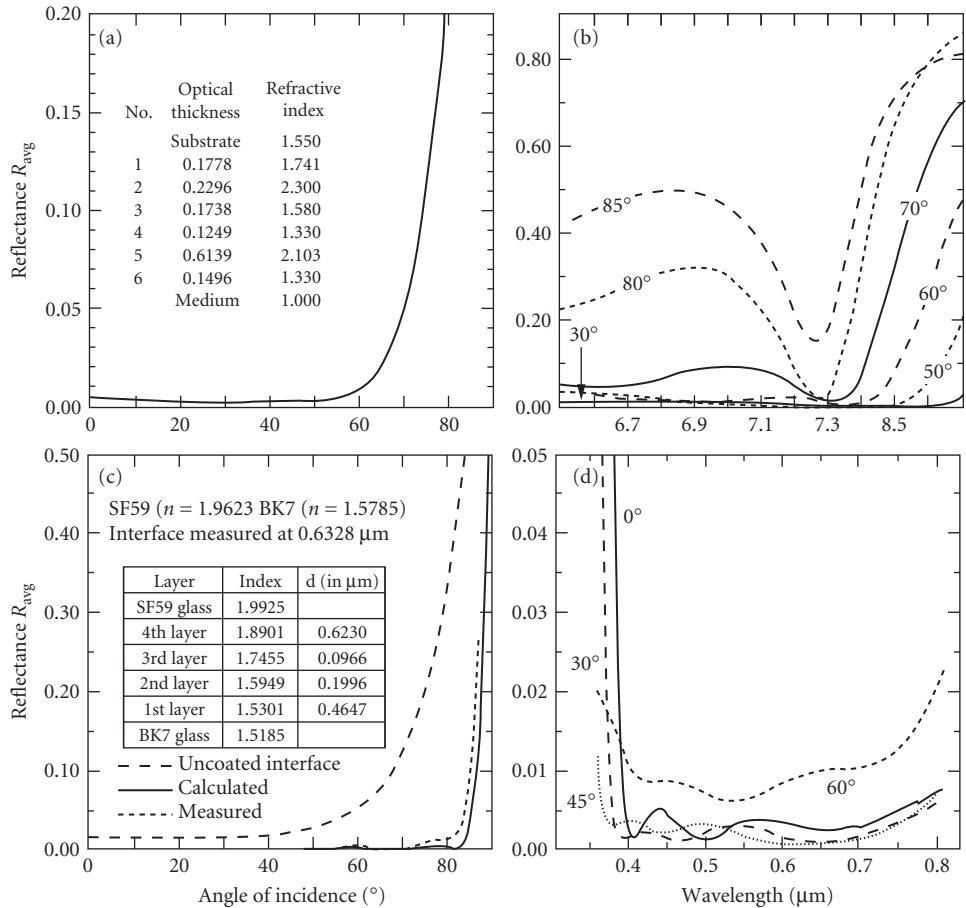


FIGURE 27 Wide angle AR coatings. (a) Calculated average reflectance of a conventional AR coating for the He-Ne laser wavelength for angles of incidence up to 60° (after Dobrowolski *et al.*^{146,147}); (b) measured average reflectance of a Si/air interface for angles of incidence up to 85° with an AR coating based on the use of a Reststrahlen material (after Dobrowolski *et al.*¹⁴⁸); (c) measured average reflectance of a glass/glass interface for angles of incidence up to 85° (after Ma *et al.*¹⁴⁹); and (d) predicted performance of a hybrid wide-band AR coating for angles of incidence up to 60° (after Schulz *et al.*¹⁵⁰).

being investigated at many laboratories. The predicted average reflectance of a hybrid AR coating consisting of seven solid thin films and an outermost structured layer is shown in Fig. 27d. It is expected to be less than 1 percent over a broad spectral region for all angles of incidence smaller than 60°. This will be a huge improvement over the performance of the coating depicted in Fig. 27a.

The design of antireflection coatings for very high angles of incidence has been considered by Monga.^{153,154}

Nonoptical Properties of Antireflection Coatings

Antireflection coatings, in addition to optical specifications, often have to satisfy additional, nonoptical requirements. One such requirement may be to provide scratch resistance to soft, plastic surfaces. In Fig. 28a is shown the measured reflectance of an AR coating produced by Schulz *et al.* for

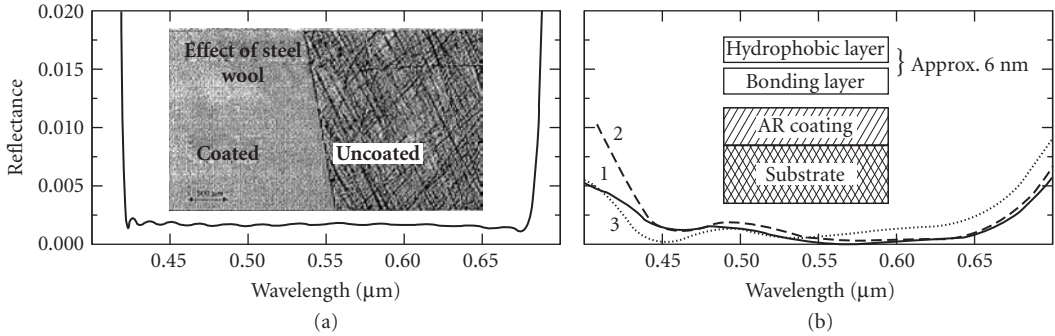


FIGURE 28 Nonoptical properties of antireflection coatings. (a) Measured reflectance of a 27-layer, 3- μm -thick $\text{SiO}_2/\text{Ta}_2\text{O}_5$ AR coating. The insert illustrates the effect of steel wool on the coated and uncoated portions of the substrate (after Schulz et al.⁴³). (b) Performance of a water- and dust-repellent AR coating. Curves 1 and 2 are the calculated and measured reflectances. Curve 3 is the performance after cleaning the coating with acetone (after Bruynnghe et al.¹⁵⁵).

a PMMA surface.⁴³ It consists of 27 layers of SiO_2 and Ta_2O_5 , with an overall metric thickness of over 3 μm , of which most corresponds to SiO_2 . The inset shows, that the AR coating provides good protection from abrasion. Bruynnooghe et al. describe an AR coating which repels water, oil, and dust (Fig. 28b).¹⁵⁵ This coating consists of a more or less conventional AR coating onto which is deposited a bilayer coating, the first part of which provides for good adhesion to the AR coating, and the second, the required hydrophobic properties. The total thickness of the bilayer is 0.006 μm .

7.6 TWO-MATERIAL PERIODIC MULTILAYERS THEORY

Nonabsorbing $[AB]^N$ and $[AB]^N A$ Multilayer Types

Let a periodic multilayer be composed of N periods AB , where A , B represent layers of refractive indexes n_A , n_B and optical thicknesses $n_A d_A$, $n_B d_B$. The most general representation of the complete multilayer is

$$\underset{1}{AB} \cdot \underset{2}{AB} \cdot \underset{3}{AB} \cdots \underset{N}{AB} = [AB]^N \quad (39)$$

In practice it is customary to write $[HL]^N$ or $[LH]^N$, depending on whether n_A is greater or less than n_B , respectively. The spectral-reflectance curve of the multilayer $[AB]^N$ will lie within a pair of envelopes which, at normal incidence, depend only on $n_A d_A$, $n_B d_B$, n_A , n_B , n_s , and n_m .^{156,157} For $n_s = n_m$ the lower of the envelopes becomes $R = 0$. The envelopes contain high-reflectance zones within which the reflectance at each wavelength increases monotonically with the number of periods, approaching 1.0 as N tends to infinity (Fig. 29). Outside these high-reflectance zones the curves exhibit subsidiary maxima and minima whose number depends on $n_A d_A / n_B d_B$ and which increases with N . The first-order high-reflectance zone occurs at a wavelength λ_1 given by

$$n_A d_A + n_B d_B = \frac{\lambda_1}{2} \quad (40)$$

and subsequent zones occur at wavelengths λ_q ($\lambda_1 > \lambda_2 > \lambda_3 \dots$) given by

$$N(n_A d_A + n_B d_B) = q \frac{\lambda_q}{2} \quad q = 2, 3, 4 \dots \quad (41)$$