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Reviews of Black Surfaces for Space and Ground-Based Optical Systems

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Abstract

An up-to-date list of available black surfaces for use in space and ground-based optical systems, with emphasis on baffle systems, is presented. Previously published reviews are outlined which describe the properties of many of the surfaces, and tables are presented which show the manufacturer and research sources.

1.0 Introduction

A black surface is a spectrally selective surface for which spectral absorptance is maximized over a range of wavelengths and angles of incidence. This paper provides a list of reviews, and identifies available black surfaces for use in optical systems and in particular for use in baffle systems. There are a large number of considerations to take into account in selecting a black surface for a specific application, particularly if it is for a space

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instrument Most importantly, the black surface selection process must be done from an overall systems point of view as described in another paper in this volume (Pompea and McCall, 1992). It is hoped that this pair of papers will serve as a useful "user's guide" for the selection of black surfaces for space baffles.

Black surfaces have many uses in optical systems such as stray light reduction for telescope baffles and lens edges, and for thermal control As optical system requirements become more stringent, so do the specifications and performance criteria of black surfaces There are thousands of different types of black surfaces created by processes that are commercially available. Of that, hundreds are suitable for ground-based optical systems but only about a hundred are presently known to be suitable for use in space-based optical systems Unfortunately, the data on these surfaces is diversley scattered in the literature Recently, two major reviews of the optical properties of black surfaces have taken place One review was the result of a study contract initiated by the Canadian Space Agency (CSA, Montreal, Quebec, Canada) for Canada's participation in the Far Ultraviolet Spectrum Explorer (FUSE), and the Spectrum-UV (SUV) satellite instruments. The purpose of that study was to investigate candidate black surfaces for use in space-based baffles, and their optical properties in the ultraviolet (UV) and visible spectral regions (McCall, 1992a) A second review is a user's guide to black surfaces to be published in the Handbook of Optics, second edition (Pompea and Breault, in press). Surfaces for use in the UV, visible, and infrared (IR) spectral regions were described for ground and space-based applications This paper attempts to summarize the salient points of both reviews, as the CSA study is not generally available and the latter study may not be published for some months

Optical black surfaces take many different physical forms. The main types are: (1) paints, (2) tapes, (3) fabrics, (4) anodized surfaces, (5) ion beam sputtered surfaces (sputter etched, sputter deposited, and sputter textured), (6) electrodeposited surfaces, (7) plasma sprayed surfaces, (8) chemical vapor deposited surfaces, and (9) surfaces with black optical thin film multilayer systems (produced via electron beam gun deposition, sputter deposition, ion vapor deposition, etc.). All these types are represented in the tables in this paper and have previously been used in either space or ground-based optical systems. Three other physical forms: powders, liquids, and stacked razor blades (the latter used for laser beam dumps, (Cady and Cheever, et al., 1987, and Evans, 1983)) can be eliminated from consideration for space use for practical reasons related to contamination and safety.

The above types of surfaces are made black through one or more of the following basic phenomena: (1) the addition of absorbing compounds in the surface, (2) the presence of large cavities or fissures (relative to the wavelength of the light) in the surface, (3) scattering from particles in the surface coating or from the substrate to diffusely reflect the incoming beam over a hemispherical solid angle (Bennett and Mattson, 1980, and Stover, 1990), and (4) interference effects in optical thin film multilayers which minimize the spectral reflectance of the multilayer system (Hass, Schroeder, and Turner 1956; Dobrowolski, 1981; Dobrowolski, Ho, and Waldorf, 1989; and, Dobrowolski, Sullivan, and Bajcar, 1992)

The baffle surface is often the largest optical surface in many optical instruments and should be chosen with as much care as the rest of the optics, particularly for space applications (Pompea and McCall, 1992) The present difficulties facing the optical designer who must select a black surface for such an application are fourfold First, is the difficulty in finding published reviews on black surfaces This paper attempts to rectify that by listing some of the previously published reviews and by presenting an up-to-date, comprehensive list of available black surfaces for use in space and ground-based, baffled optical systems The reader of the older reviews is cautioned that since their publication date many of the names, chemical formulae, and manufacturers and distributors of the surfaces have changed, and some of the important black paints are no longer made (see section 3.0) These changes are documented in this paper. Some inconsistencies and ambiguities in the published data arise because names have changed but the formulae remained the same, and vice versa.

The second and third areas of concern are the amount and accuracy of the published scattering data Scatter measurements of black surfaces have become increasingly important to optical designers in the last few years Unfortunately most of the data resides in government and industry files and is not published in the open literature Most of the data that is published is in the SPIE proceedings in the form of the Bidirectional Scattering Distribution Function (BSDF), although some measurements for the Total Integrated Scatter and the RMS roughness have been published In spite of the vast amount of scattering data available, there is concern in the optical community over the definition of BSDF, how it should be measured, how it should be specified (Schiff and Stover, et al, 1988), and the accuracy and repeatability (Bernt and Stover, 1990) of the measurements between labs, as demonstrated in several round robin studies (Leonard and Pantoliano, 1988, Leonard and Pantoliano, and Reilly, 1989) Large variations in the BSDF measurements can occur for the same surface measured by different facilities (Leonard and Pantoliano, 1988, Stover and

Gillespie, et. al , 1987). This results from differing procedures, instruments, and different types of scattering being measured, amongst other things Bartell, Dereniak, and Wolf (1980) estimated that it was unlikely that many BSDF measurements better than 20% were made before 1980. Leonard and Pantoliano, (1988) suggest that for preliminary baffle designs, one might consider the published BSDF data accurate to within an order of magnitude. For higher accuracy one should take new measurements with a type of "standard test method" outlined in Leonard and Pantoliano (1988), to avoid the above mentioned problems.

The fourth difficulty in the field is the process of selecting a black surface for an instrument as discussed by Pompea and McCall (1992). The selection process must be done from an overall systems point of view. Disastrous consequences can and have resulted for a space instrument, the science it produces, or both, if one or more of the following situations arise. a bad coating selection is made, the coating is applied with an improper application procedure, and the surface is not characterized properly prior to flight.

2.0 Reviews of properties of black surfaces

The scientific literature that reviews properties of black surfaces is application driven and primarily focused in the following diverse topics: (1) stray light reduction applications for telescope baffles, (2) heat resistant surfaces, (3) electrically conductive baffle surfaces, (4) laser applications such as beam terminators, (5) edge blackening compounds for lenses, (6) solar collector spectrally selective absorber surfaces, (7) naturally occurring black surfaces, (8) black surfaces for radiometric detectors, and (9) household, automotive, textile, photographic, and artistic applications, etc The emphasis of this paper and Tables 1-3 is in area (1), since the they were motivated by the CSA study mentioned earlier Areas (1) through (6) were surveyed to see which black surfaces were useful for the space environment. Areas (7) and (9) encompass thousands of surfaces. However, not much is known about their suitability for space use. Thus, they were excluded from the literature search There are, however, interesting exceptions For example, the paint called Floquil (Table 2) is a hobby paint for model train engines, sold as engine black ESA 110010 (Ferguson, 1992) Floquil has been used as an edge blackening compound for lenses in space instruments Stellar Optics Laboratories is presently conducting a comprehensive study which includes areas (6) through (9) to identify more black surfaces which are suitable for use in the space environment

Few reviews have been published on the topic of black surfaces for stray light reduction. The comprehensive review in the upcoming Handbook of Optics, second edition, presents previously unpublished scattering data for the UV and far UV spectral regions (Pompea and Breault, in press) McCall (1992a) reviewed the optical properties in the UV and visible spectral regions of available black surfaces suitable for use in space. Only a few hundred BSDF curves exist for that spectral region, and almost no data has been published for the spectral region at or below a few hundred Angstroms. Viehman and Predmore (1986) published UV and visible BRDF data for spacecraft thermal control and optical baffle materials. The lowest wavelength for which scattering data appears to have been published at, so far, is 304 Å (Jelinsky and Jelinsky, 1987). J Heaney, of NASA's Goddard Space Flight Center is also conducting research into the UV scattering properties of black surfaces.

Summaries of the optical properties of many materials in the far IR spectral region are reviewed by Wolf (1978), and Smith and Howitt (1986) Pompea, Shepherd, and Anderson (1988) presents optical data on a number of surfaces for the wavelengths 632 8 nm and 10.6 µm Smith reviews the optical properties of black surfaces for space applications that are intended for the far IR and submillimeter spectral region (Smith 1980, 1981, 1982, 1983, 1984, 1986, 1988, 1990; Smith and Howitt, 1986, Smith and Wolf, 1982) The most well reviewed category is that of solar collectors and spectrally selective absorber surfaces. Some comprehensive reviews are: Granqvist (1984, 1987), Hahn and Seraphin (1978), Seraphin and Meinel (1976), Hutchins (1988), and Seraphin (1979) Many of the black surfaces for use in space are commonly used in solar work (e g., black cobalt, black chrome, black nickel, and black copper.)

Other reviews and resources on the subject of black surfaces exist in the form of databases Breault Research Organization has one of the world's largest collections of scattering data on black surfaces TMA Technologies, Inc has made a number of recent measurements on surfaces. Stellar Optics Laboratories (SOL) maintains an up-to-date database of the available black surfaces, with emphasis on those used in space instrumentation. SOL's data base includes properties such as optical properties, mechanical properties, chemical composition, outgassing and particulate contamination test results, atomic oxygen effect results, radiation resistance test results, etc. (McCall, 1992b) Technical Information Services also maintains an up-to-date database of black surfaces and their properties as part of its emphasis on current optical technology and instrumentation

3.0 Available black surfaces

Tables 1, 2, and 3 are up-to-date lists of the available black surfaces and processes for space use (McCall, 1992b). Since the tables originated from the CSA study mentioned in the Introduction (McCall, 1992a), the tables place emphasis on black surfaces which might be used in space-based baffle systems. Thus, the entries in the tables are also applicable for ground-based baffles since the selection criteria for ground-based baffle systems are generally less stringent than for space-based baffles However, it should be noted that many more black surfaces not shown in Tables 1, 2, and 3, are suitable for use in ground-based instruments. Since the general phrase "space qualified" is a misnomer, the tables were compiled using selection criteria based on precedents. To be included in the tables a black surface or process had to satisfy one or both of the following criteria: (1) flown on a space instrument before (but not necessarily on the baffle), and (2) studied by a branch of NASA or a North American aerospace company as a serious candidate for use on space instrumentation (i.e. the black surface made the short list of potential candidates worthy of further study, but may or may not have been selected for the final instrument).

Tables 1, 2, and 3 list anodized surfaces, paints, and other forms of surfaces and processes (some of which are applicable to a wide range of metals), respectively There are many other black surfaces not included in the tables because they are either not studied for suitability for space use yet, or else known to be unsuitable primarily because of problems related to outgassing, environmental stability, and particulate contamination. The tables place no emphasis on the spectral region since some (but not all) surfaces are "black" over a broad range of wavelengths For instance, the patented Martin Black anodized process (Table 1) has become widely known for its use in the IR but was originally developed for its superior performance in the vacuum UV and visible spectral regions (Pompea, Shepherd, and Anderson, 1988). The tables are not exhaustive, but do list the most commonly used and available black surfaces used for optical systems, with particular emphasis on baffle surfaces

The most widely used black surfaces for space applications are the Aeroglaze paints (particularly Aeroglaze Z306), and the patented anodized processes from the Martin Marietta Astronautics Group (Martin Black, Infrablack, Enhanced Martin Black, and Post-treated Martin Black). Martin Black is known to be the blackest (i e, lowest BRDF) of the conventional diffuse black surfaces However black optical thin film multilayers (Table 3) can be produced which are blacker, and can exhibit reflectance as low as R=0.01% over a small range of wavelengths and angles of incidence.

Many of the names of the commercial black paints have changed in recent years. This is due to either formulae changes, or to formulae being sold to different companies, or to marketing decisions. The new and old names are listed in the first and last columns of Table 2. Two name changes worth highlighting here are that: (1) Lord Corporation changed the name of the Chemglaze paints to Aeroglaze paints although the formulae remained the same, and (2) AKZO Coatings, Inc. purchased the Cat-a-lac paints from Sikkens and the paints are now referenced by their numbers only· *463-3-8 (a diffuse black paint), and *443-3-8 (a glossy black paint) Note that Aeroglaze Z313 was also a popular paint for space use. Since it is no longer being manufactured it is not shown in the tables

Noticeably missing from the Table 2 is 3M's Nextel Velvet black paint, since it is no longer manufactured. It was the optical industry's standard black reference for many years (Cady and Cheever, et. al., 1987, Fernandez and Seasholtz, et al, 1988; Griner 1979; Smith, 1982; Smith, 1983, Smith and Wolfe, 1982, and Willey and George, et al., 1983). It is unfortunate that it is no longer distributed or manufactured anywhere in the world Besides the Nextel Velvet, 3M also produced Nextel Suede flat black paint. It is suitable for ground-based optical instruments only, since, unlike the Nextel Velvet paint the chemical composition renders it less suitable for use in space (Ames, 1990) Nextel Suede's same formula is now being manufactured and distributed by Redspot Paint and Varnish, Inc (Evansville, IN) under the name 3101-C10 Nextel Suede.

All but a few entries in Tables 1, 2, and 3 are diffuse, flat black surfaces since the majority of stray light reduction problems favor them. Glossy or specular black surfaces such as mirrors, black glass, or glossy paints are occasionally used for vane cavities in baffle structures (Freniere, 1986, Freniere and Skelton, 1986; Greynolds and Melugin, 1986) However, Breault (1983) cautions against the use of glossy black surfaces for most baffle applications. Gary Peterson, et al, of Breault Research Organization have shown that a class of highly specular reflective baffle designs proposed by Nick Stavroudis at Lockheed have excellent stray light suppression characteristics (Peterson, Johnson and Thomas, 1992) Such designs require fabrication techniques capable of producing a sequence of axiconic surfaces, and are currently limited to cylindrical geometries In Tables 1-3, the glossy black surfaces are the paints 443-3-17, and Aeroglaze Z302 (Fernandez and Seasholtz, et al., 1988) Hughes makes a glossy black anodized surface that is proprietary. In addition, many generic anodized surfaces are glossy Table 3 lists black optical thin film multilayer surfaces which will appear either glossy or flat black, depending on the smoothness of the substrate. For instance, a typically glossy black optical thin film multilayer system can appear like a flat black paint when it is deposited onto a roughened surface.

4.0 Conclusion

Of the thousands of black surfaces commercially available only about a hundred are known to be suitable for use on space instrumentation. The most common of these are shown in Tables 1, 2, and 3, which places emphasis on the application of space baffles. These are equally suitable for ground-based baffles, and many might be suitable to other applications as well (such as edge blackening compounds for lenses) New black surfaces are continually being developed with emphasis on either lower BRDF's, enhanced durability, or both Some of the institutions developing new black surfaces are: Ball Aerospace, Illinois Institute of Technology Research Institute, Martin Marietta Astronautics Group, Martin Marietta Energy Systems Incorporated (Optics MODIL, Oak Ridge National Laboratory), Martin Marietta (Orlando, Florida), Hughes Aircraft, the National Research Council of Canada (Thin Films Group, Institute for Microstructural Sciences, Ottawa, Ontario), Rockwell, and SPIRE Corporation. Work is being done on surfaces that have one or more of the following characteristics: laser resistant, radiation resistant, and capable of withstanding severe and unusual forms of environmental exposure for prolonged duration On the basis of the information to date, not much progress has been made towards a surface that combines all of those features

For the surfaces listed in this paper, many of their mechanical and chemical properties can be found from the information provided by the manufacturer. However, manufacturers do not often characterize the optical properties well enough to the satisfaction of baffle designers Thus, the published literature often must be relied on Unfortunately, relatively little optical scattering data has been published compared to what exists in internal industry and government files This paper provides a useful baseline description of the more common surfaces and the institutions that produce them It is only a brief summary of the information currently available

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Table 1: **Some available black anodized surfaces for optical instrumentation (McCall, 1992b).**

Current name (other names used)	Manufacturer or research source (contact)
Anodized surfaces, generic	
Infrablack	Martin Marietta Aerospace Denver, CO (D. Shepard)
Martin Black	Martin Marietta Aerospace Denver, CO (D. Shepard)
Martin Black, Enhanced	Martin Marietta Aerospace Denver, CO (D. Shepard)
Martin Black, Post-treated	Martin Marietta Aerospace Denver, CO (D. Shepard)

Table 2: Some available black paints for optical instrumentation (McCall, 1992b).

Current name (other names used)	Manufacturer or research source (contact)	Names used previously
Aeroglaze L300	Lord Corporation Erie, PA (V. Ferrel)	Chemglaze L300
Aeroglaze Z004	Lord Corporation Erie, PA (V. Ferrel)	Chemglaze Z004
Aeroglaze Z302	Lord Corporation Erie, PA (V. Ferrel)	Chemglaze Z302
Aeroglaze Z306	Lord Corporation Erie, PA (V. Ferrel)	Chemglaze Z306
Aeroglaze Z306 with microspheres	Goddard Space Flight Center Greenbelt, MD (T Heslin, J Heaney, M. Harper)	Chemglaze Z306 with microspheres
Aeroglaze Z307	Lord Corporation Erie, PA (V. Ferrel)	Chemglaze Z307
Ames 24E (Ames 24E2)	NASA Ames Research Center Moffett Field, CA (S. Smith)	
Cardinal 6450	Cardinal Industrial Finishes South Elmonte, CA (P. Pierce)	Cardinal 6550, also, Velvatane
Cornell Black	Cornell University Ithaca, NY (J. Houck)	
DeSoto Flat Black	DeSoto Inc., Chemical Coatings Div.	
Electrically conductive black optical paint	Jet Propulsion Laboratory Pasadena, CA (M Birnbaum, E Metzler, E. Cleland)	Has no trade name
Floquil (ESA 110010)	Floquil Polly S Color Corporation Amsterdam, NY (R. Melillo)	
IITRI Bone Black D-111 (IITRI D111)	Illinois Institute of Technology Chicago, IL (Y. Harada)	
LMSC Black	Lockheed Missiles and Space Co Sunnyvale, CA (J. Grammer)	
MH21-I	Illinois Institute of Technology Chicago, IL (Y. Harada)	
MH55	Illinois Institute of Technology Chicago, IL (Y. Harada)	
MH2200	Illinois Institute of Technology Chicago, IL (Y. Harada)	3M's ECP 2200 paint
Solarchem	Eastern Chem Lac Corporation Malden, MA (F. Alvarez)	
463-3-8	AKZO Coatings, Inc Orange, CA (K. McKowan)	Cat-a-lac 463-3-8, Bostik 463-3-8, also, Sikkens 463-3-8
443-3-8	AKZO Coatings, Inc Orange, CA (K McKowan)	Cat-a-lac 443-3-8, Bostik 443-3-8, also, Sikkens 443-3-8
443-3-17	AKZO Coatings, Inc. Orange, CA (K. McKowan)	Bostik 443-3-17, also, Sikkens 443-3-17

Table 3: **Some other types of available black materials and processes for optical instrumentation (McCall, 1992b).**

Current name (other names used)	Manufacturer or research source (contact)	Type of material or process
Black Chrome type surfaces	Martin Marietta Aerospace Denver, CO (D. Shepard)	Electrodeposition process
Black Cobalt type surfaces: Cobalt Black, Black Copper, Black Steel,etc.	Martin Marietta Aerospace Denver, CO (D Shepard)	Electrodeposition processes that can be followed by chemical or thermal oxidation
Black Kapton film	Du Pont Willmington, DE	Film
Black Nickel, Ball Black, NBS Black	(1) Ball Aerospace (2) NIST, Gaithersberg, MD	Deposition and etching
Black optical thin film interference coatings	(1) National Research Council of Canada, Thin Films Group, IMS Ottawa, Ontario, Canada (J A Dobrowolski, B T Sullivan) (2) Companies with optical thin film deposition equipment	Vacuum deposition techniques. -sputter deposition, -ion vapour deposition, -resistance heated source, -electron beam gun deposition, -etc.
Black Tedlar film	Du Pont Willmington, DE	Film
Boron Black	Martin Marietta Aerospace Denver, CO (D. Shepard)	Plasma spray deposition
Boron Carbide	Martin Marietta Aerospace Denver, CO (D. Shepard)	Proprietary process
Silicon Carbide	Martin Marietta Aerospace Denver, CO (D. Shepard)	Chemical vapour deposition
Textured Surfaces	(1) Optics MODIL, Oak Ridge National Laboratory (C M Egert) (2) SPIRE Corporation Bedford, MA (E.Johnson) (3) NASA Ames Research Center Moffat Field, CA (S. Smith)	Vacuum techniques: -sputter coated, -ion beam etched, -sputter coated then etched