Multispectral infrared BRDF forward-scatter measurements of common black surface preparations and materials
---or "How black is black in the IR?"

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ABSTRACT

Fundamental to the design of an infrared sensor is controlling the stray light and internal radiation emission. A series of Bi-directional Reflectance Distribution Function (BRDF) measurements at two infrared bandpasses in the MWIR and LWIR were acquired. Incident beams were oriented 10 and 60-degrees from normal. Forward-scatter (key to baffles and cold-shields) data is presented for infrared black surface preparations including: anodizing, copper oxide, nickel oxide, black paints, and trademarked black surfaces. Comparison is also made between selected surfaces before and after exposure to 78 Kelvin (LN_2) thermal cycles. This paper also includes scanning electron microscope (SEM) images and discrete Fourier transform (DFT)) measurements for selected black surfaces, including comparisons of damaged and undamaged nickel oxide.

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1.0 INTRODUCTION

In the infrared, stray light suppression and control of self-emission are intensely important to superior image cosmetics and the detection of signal near the noise level. Key to these attributes is the understanding of the surface reflection and emission properties. This is especially important to cold shield design, baffle design and internal component coatings. Generally, a Lambertian surface of low reflectance (black) is desired for these critical components. An ideal surface for this application, is highly absorptive and reflects (what small amount of light it does) in a Lambertian (non specular) fashion.

There is no better way to analytically characterize these properties that an inband measurement of the Bi-directional Reflectance Distribution Function (BRDF) over the geometries of interest. The BRDF was first described by Nicomedimus[1] to provide the needed information. The BRDF is measured as a function of angle and has the properties that a Lambertian reflector (perfect scatter) would have a flat response, while a reflective surface would have a strong peak at the Snell angle of the reflection.

With some training and experience, a human can become proficient at judging the "black" quality of surfaces in the visible bandpass. However, this is simply not possible in the infrared, as the wavelengths are far longer than perceptible by the human eye. For infrared systems, humans must rely on instrument measurements *only*.

The BRDF is a function of wavelength, incident radiation angle and receiving angle. This paper describes research limited to:

1.) Commonly used black surfaces
2.) Mid-wave infrared (MWIR) and Long-wave infrared (LWIR) regions
3.) Incident angles of the radiation at -10, -60, and in one case -45 degrees
4.) Direct forward-scatter measurements
5.) Some selected comparisons pertaining to thermal cycling and damage

The data were taken using an S-250 scatterometer manufactured by Surface Optics Corporation (SOC) as shown in Figure 1.0-1. The scatterometer is owned by NASA's Ames Research Center and the data were acquired at the Oregon Office of the Research Triangle Institute.

The data presented had good signal to noise as demonstrated by the S-250's measurement signal to its standard deviation signal. According to SOC, the field of view was approximately one degree square (although requested, more accurate data on FOV was not provided by SOC). Care was exercised to assure that the field of view was consistent on the test article from band to band and did not overfill the sample at high incident angles.

Selection of two bandpasses and two incident angles was deemed sufficient to characterize the materials for the stray-light rejection purposes of this research. A high incidence angle of -10 degrees from normal, and a low incidence of -60, was selected as the incident radiation angles as shown in figure 1.0-2. The majority of data presented here is forward-scatter data for source incidence angles of -10 and -60, with the positive being defined as the measured angle from the opposite side of normal than the incident beam, so that the Snell reflection occurs at 10 and 60 degrees.

Figure 1.0-1. The scatterometer used to acquire the data

For all the data presented in this paper MWIR refers to a bandpass of: 4.37- to 4.55 microns and LWIR indicates a bandpass of 10.083 – 11.113 microns.

An attempt was made to measure the noise floors in both the MWIR and LWIR bands. This was done by physically covering the entrance aperture of the instrument and acquiring data in the same manner. Figures 1.0-3 and 1.0-4 provide the noise level of the instrument, indicating that valid data is acquired in the MWIR for measurements above approximately 0.0001 /sr and above 0.001/sr for the LWIR. Additionally, the S-250 does report its standard deviation of multiple measurements, and these were consistently below the measurement by at least a factor of 3 or 4 (often lower than an order of magnitude) for measurements exceeding this noise floor of the following figures.

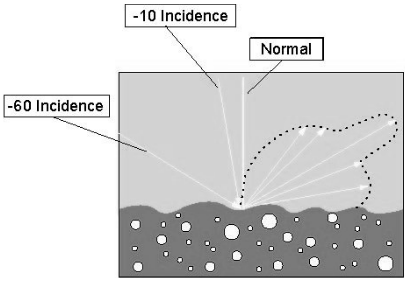
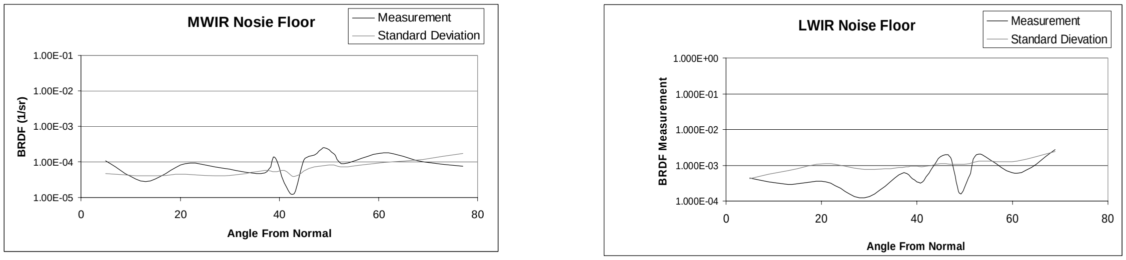


Figure 1.0-2. The geometry selected for these measurements

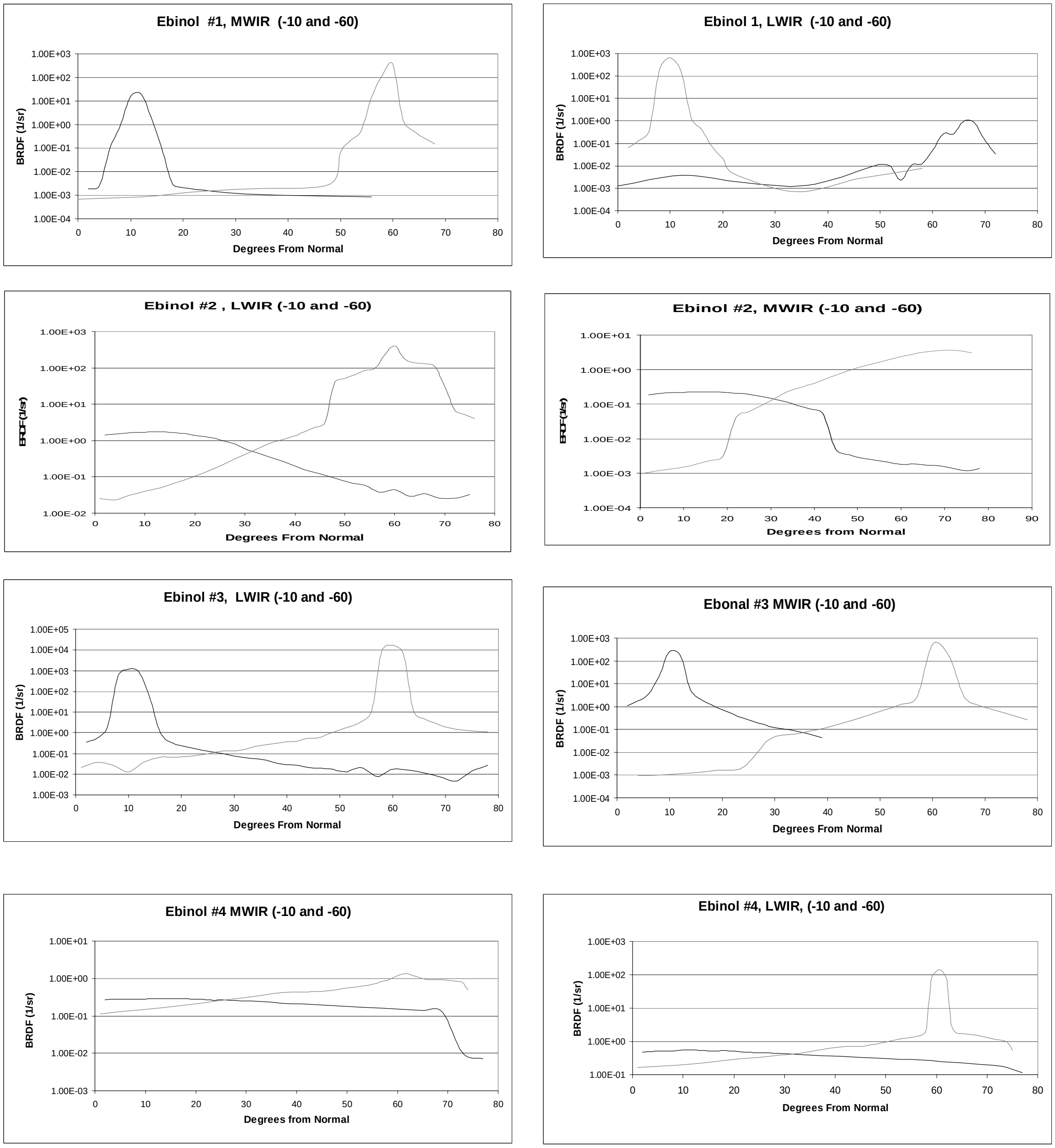


Figures 1.0-3 and 1.0-4. Equipment noise floor.

2.0 SURFACE CHEMISTRY

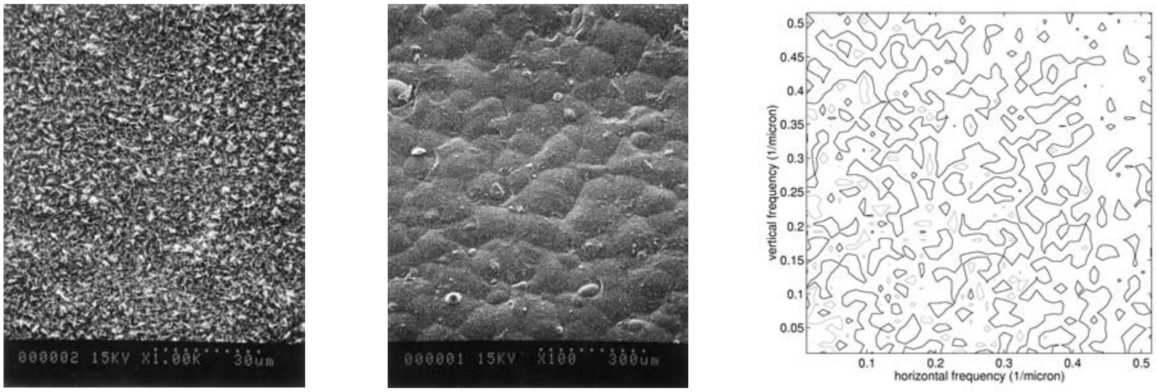
2.1 Ebinol

Ebinol is a copper oxide dendritic growth on a surface. Four different ebinol processes (from three different manufactures) were measured and have their BRDF's plotted for the wavelengths and incident angles of interest in figures 2.1-1 to 2.1-8. The incident angle of -10 from normal has a strong return at its Snell reflection angle of 10 and the incident angle of -60 has a strong return at 60. These figures, like the others in this paper, have both the incident at -10 and the incident at -60 plotted on the same chart; obviously the peak return for the -10 degree incidence is at 10 degrees, and likewise 60 for the -60 degree incidence. Although Ebinol appears very black in the visible and SWIR, all ebinols showed drastic specular characteristics in the LWIR.



Figures 2.1-1 to 2.1-8. BRDF of various ebinol processes

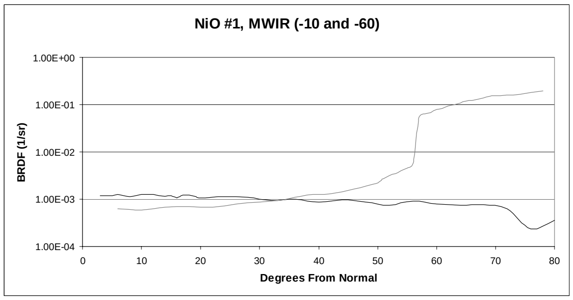
Ebinol process #4 showed the least specular characteristics, so it was selected to be used to acquire scanning electron microscope (SEM) images. The SEM images indicate random structure on the order of 1 to 2 microns as indicated in figure 2.1-9 and 2.1-10. Clearly, this results in a very flat black appearance for wavelengths shorter than a few microns, and the surface would be expected to be more specular at longer MWIR and LWIR wavelengths, as indicated in the BRDF plots above. A discrete Fourier transform (DFT) was performed on the image to assess the structure as a function of size and is shown in the figure 2.1-11 to the right. These figures indicate that the structure is random in size, but does not have much structure at the spatial frequencies required for strong Lambertian properties and absorptance in the LWIR.

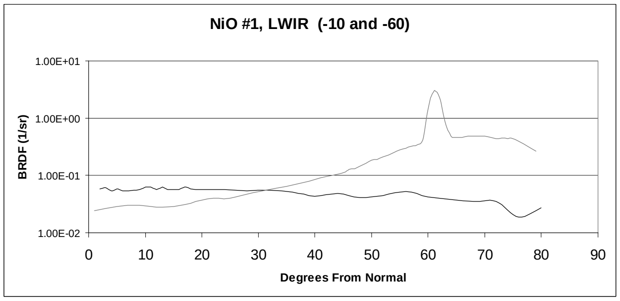


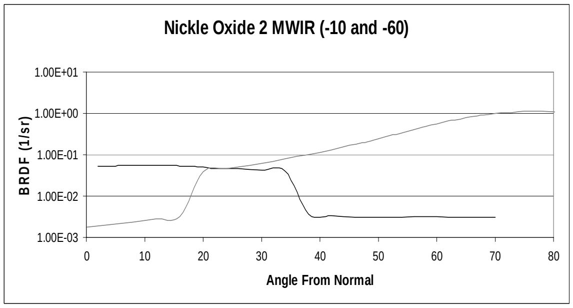
Figures 2.1-9 to 2.1-11. SEMs of ebinol (at two different scales) and a DFT of the SEM to indicate surface morphology structure, (SEM and DFT Courtesy of the Research Triangle Institute). These figures indicate excellent "black" performance below a few microns in wavelength, but reduced performance in the LIWR and MIWR.

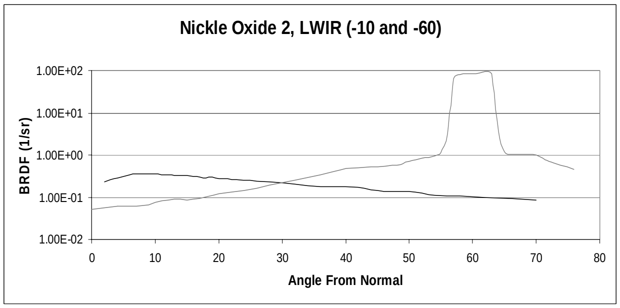
2.2 Nickel Oxide

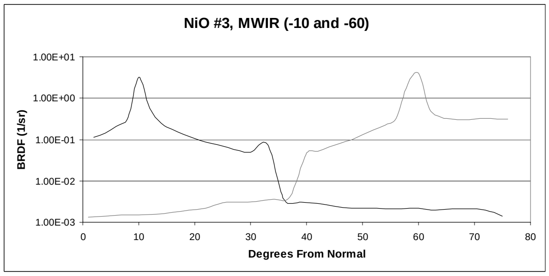
Another surface chemistry measured is a nickel oxide, analogous to the copper oxide of ebinol. Three samples from two vendors were measured and the results presented in the below figures. Typically, it measured "blacker" than ebinol; however, there still was significant specularity, especially for the 60 degree case in LWIR.

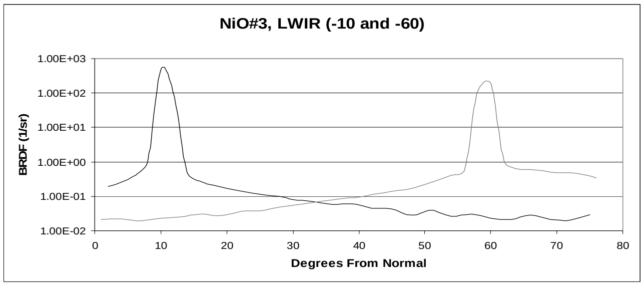




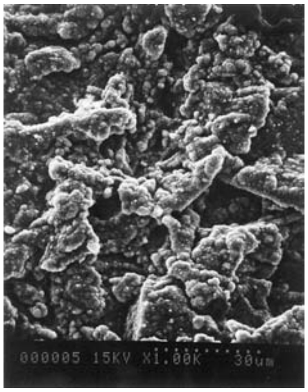




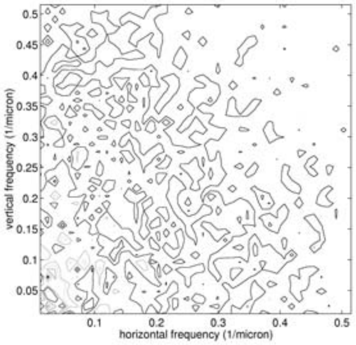




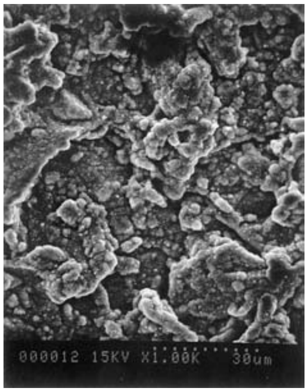
Interestingly, nickel oxide is considered to be a delicate surface. We selected a sample for deliberate pressure damage, by pressing a thumb into the surface. The sample showed qualitative changes and was more specular in the visible, indicating deleterious damage. However, the damage so clear with the human eye, resulted in minimal change in its infrared BRDF. The speculation is that the damage scrapes off some material from the scarping surface and merely re-arranges the rubble, still with structure larger than the wavelength of the light. This is qualitatively indicated by the SEM images before and after damage and quantatively indicated by the DFT plots before and after damage and the comparison BRDF plots below.



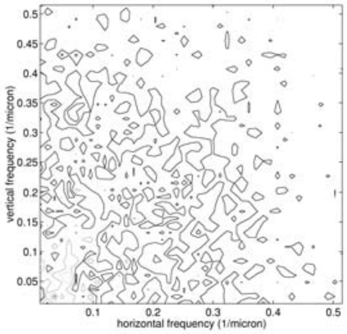
SEM of Undamaged Nickel Oxide #1



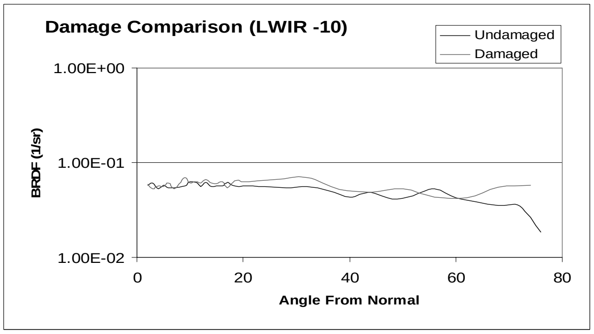
DFT of Undamaged Nickel Oxide

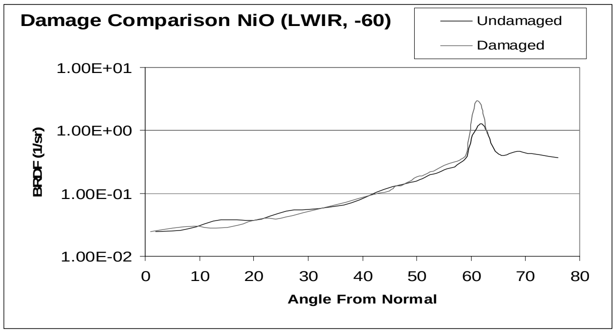


SEM of Damaged Nickel Oxide, Sample 1



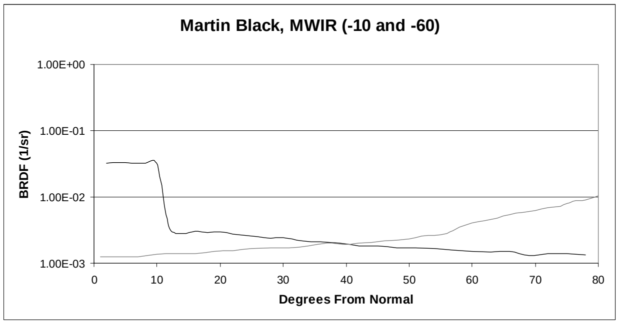
DFT of damaged Nickel Oxide, shows basically no difference.

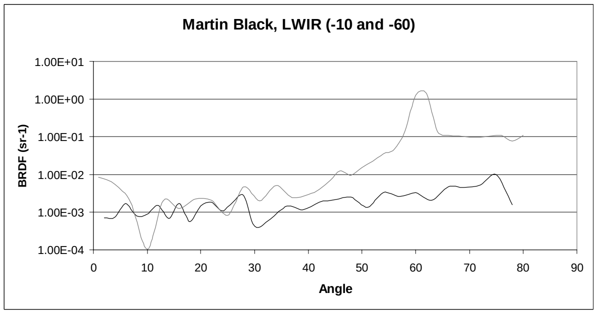




2.3 Martin Black^{TM}

A sample of Martin Black was measured and retained excellent properties even though the sample was over 10 years old. The figures below show the BRDF for this aged sample.

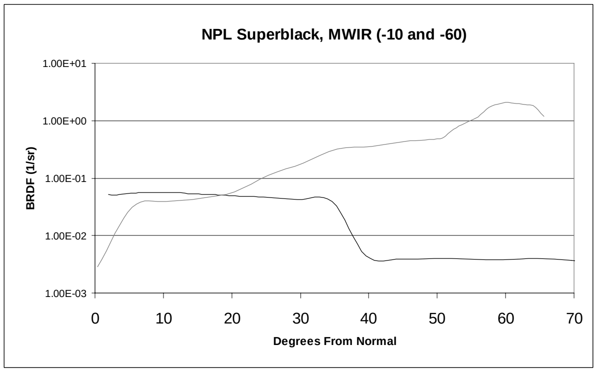


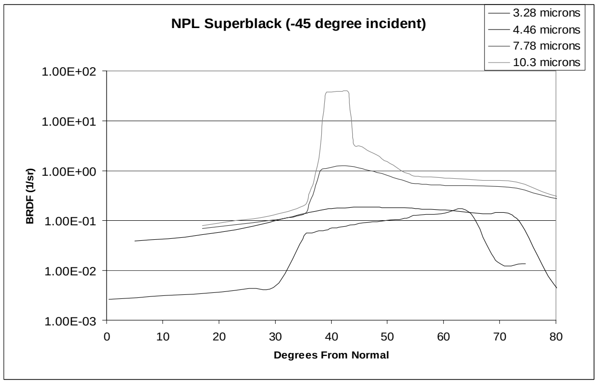


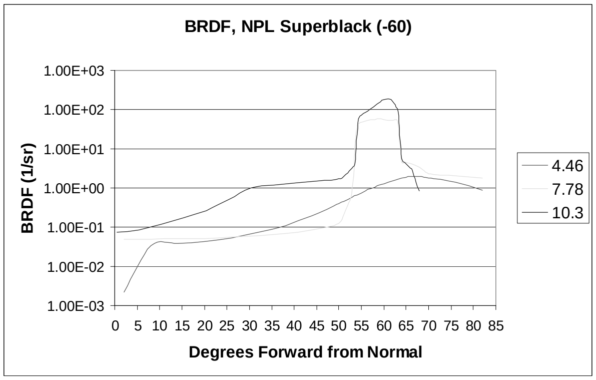
2.4 NPL Superblack^{TM}

A sample was supplied by NPL of their recently developed “superblack”[2]. Again, BRDF measurements at MWIR and LWIR were taken and the results presented below. It was not clear whether this sample was optimized for the wavelength of interest, or was a SWIR sample, but the results were somewhat discouraging for the LWIR as there was a significant specular peak present in the LWIR at low incidences.

The figures below show the acquired BRDF in the MWIR at -10 and -60 degrees angle of incident. Also shown is a plot of these and two additional bandpasses at an angle of -45 and -60 degree incidence. The sample is quite good at 3.28 microns, but exhibits continual increase in specular characteristics as wavelength increases, indicating the surface morphological structure is probably on the order of 1 to 3 microns in feature size.



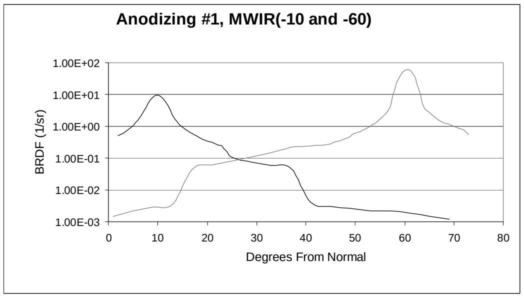


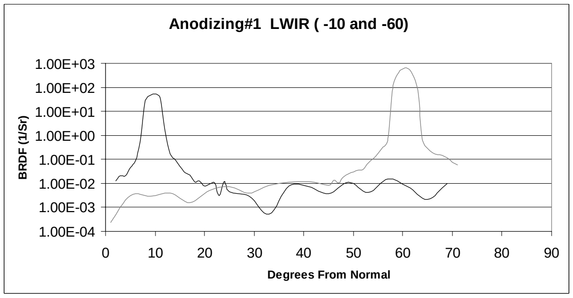


3.0 ANODIZING

Folklore has long held that rough-black anodizing of a surface results in a black Lambertian surface in the visible, SWIR, and somewhat into the MWIR and LWIR. MWIR and LWIR results are presented for three different anodization processes from three different vendors. In general the results indicate less reflection and more Lambertian surface than bare aluminum, but not by much, especially for the LWIR.

3.1 Process and Vendor #1





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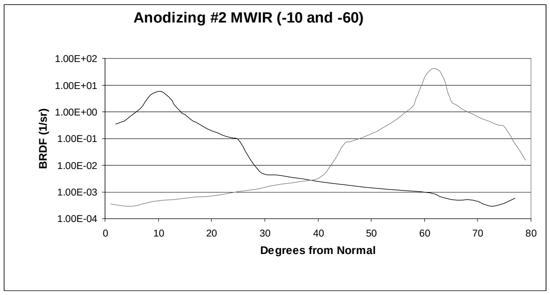
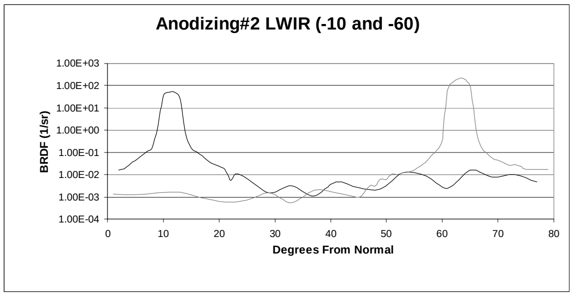
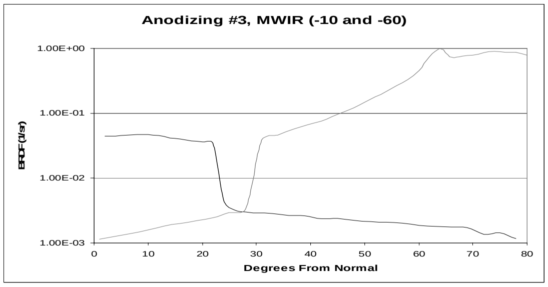
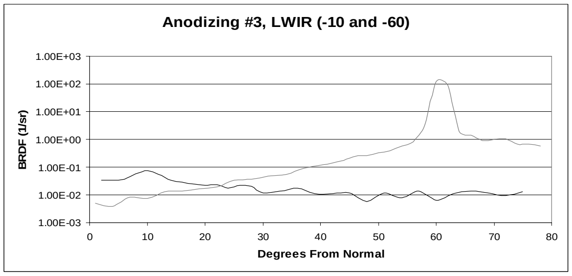




3.1 Process and Vendor #3:



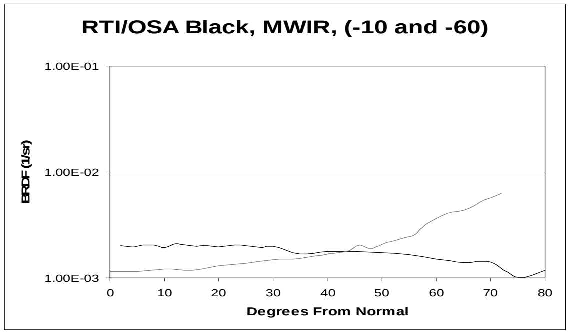


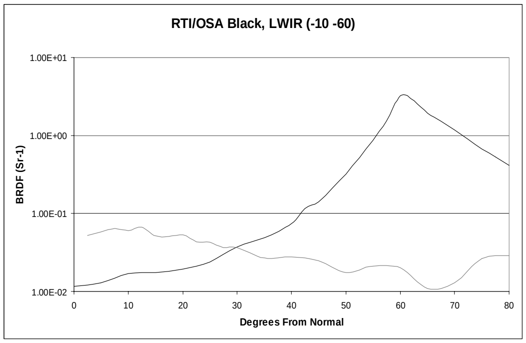
4. 0 PAINTS

The tested paints exhibited highly Lambertian characteristics and low reflectance, as it is easy for paints to get a surface roughness of a several microns. However, paints tend to weigh more than other black surface preparations, have outgassing concerns, and issues with flaking, especially when exposed to numerous cryogenic thermal cycles.

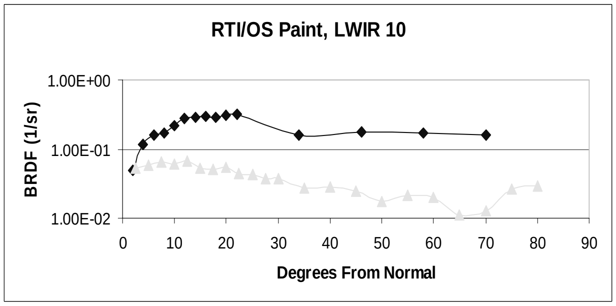
4.1 RTI/OSA Paint

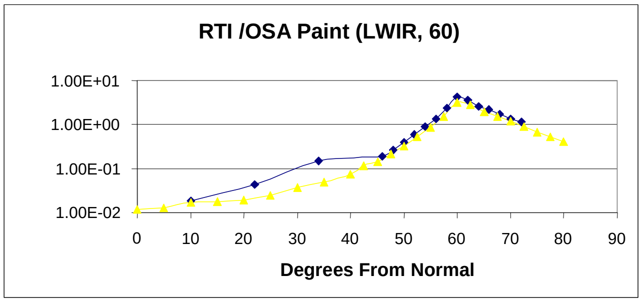
A joint effort between Optical Subassemblies and The Research Triangle Institute resulted in an excellent MWIR and LWIR paint. This paint is a specially formulated, very durable black, based on a mil-spec black paint. It survived multiple exposures to dunking in liquid nitrogen and experienced little outgassing beyond initial bake out. Its BRDF is presented in figures 4.1-1 and 4.1-2.



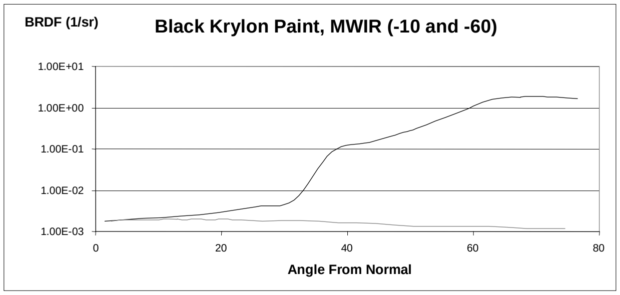


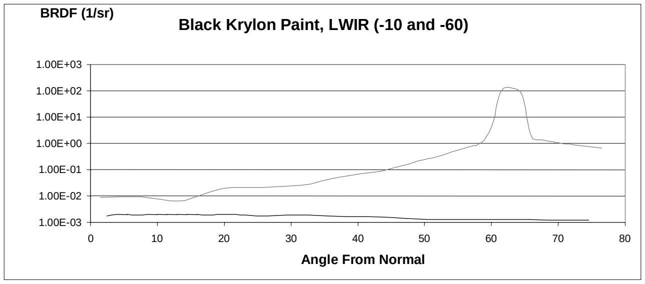
An interesting phenomenon was noted in all paints, and several surface chemistry applications. After multiple exposures to LN_2 dunks, the BRDF increased about an order of magnitude for high incidence beams as shown below, and only a slight increase for the low incidence beams, again as shown below with the RTI/OS Black paint. The upper curve (diamonds) represents the BRDF after dunking in $LN_{2,}$ the lower (triangles) before. Although presented for the RTI/OSA black, this phenomenon was repeatable with every paint, and most surface chemistries. The reason is unknown, but the author speculates that when contracted by the cryogenic temperatures, the surface morphology tilts, crushes and compresses. Then when warmed up, its top surface fails to fully decompress and return to its initial state--- presenting a partially smoother upper surface. These data indicate that most black surfaces will under perform when subjected to cryogenic temperatures, and the users should account for this when using measurements acquired at room temperature.



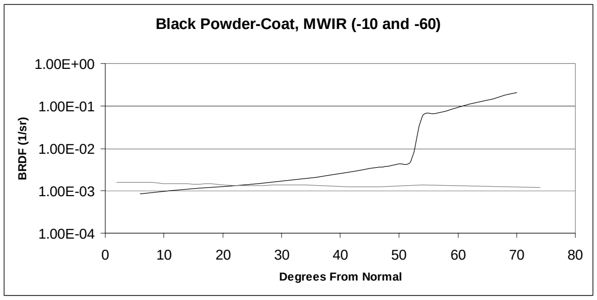


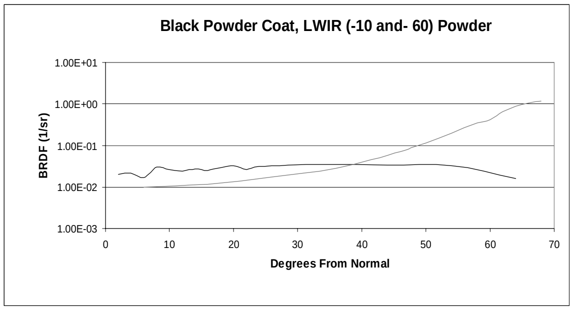
4.2 Krylon^{TM} Black



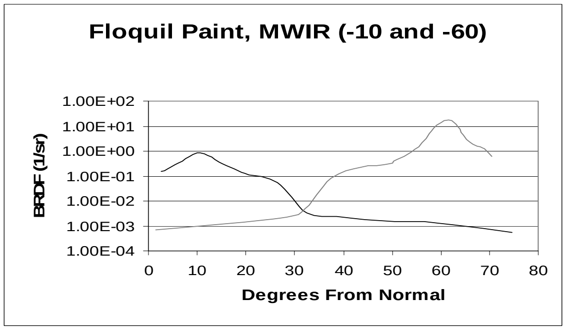


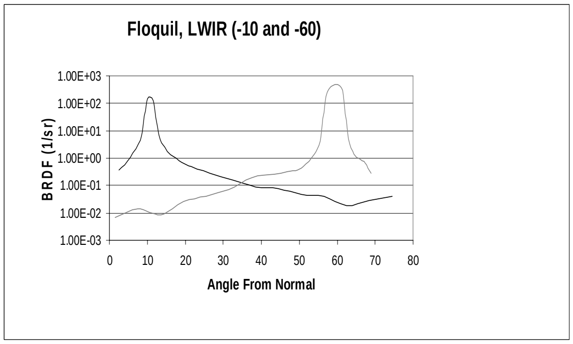
4.2 Powder –coat paint





4.3 Floquil™ Engine paint

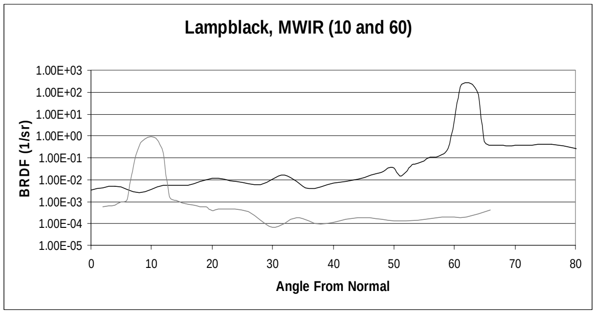


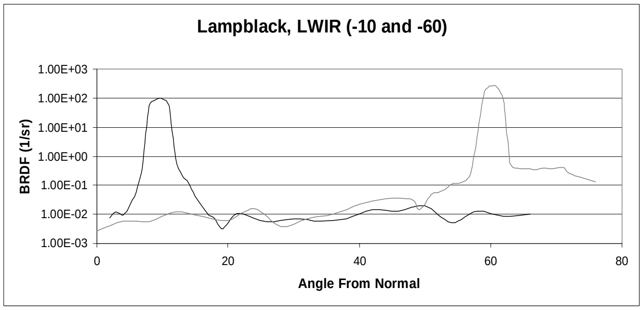


5.0 MISCELLANEOUS BLACK SURFACES

5.1 Lampblack

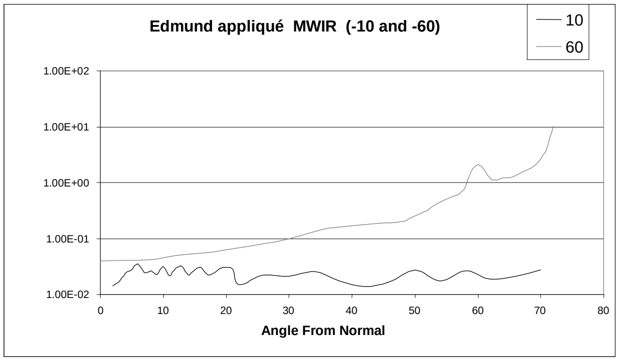
A slide of carbon lampblack, produced by a candle, was measured. This ancient technique is still often used by graduate students and others for a quick Lambertian black surface. The results are presented in the following figures, and are not too encouraging for the MWIR and LWIR.

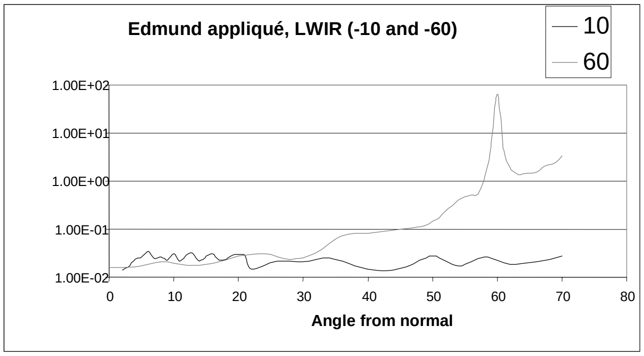




5.2 Edmund™ appliqué

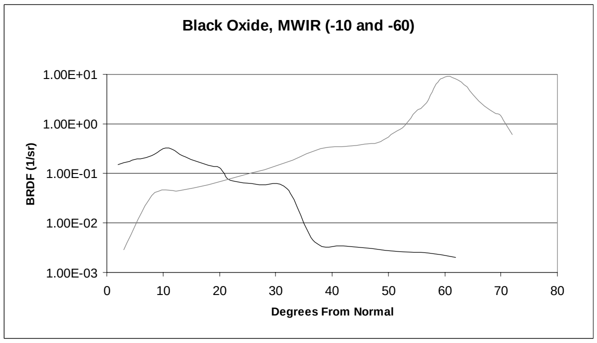
Edmund Industrial Optics markets a black appliqué which has excellent visible properties. Below is the BRDF for the MWIR and LWIR. Its properties are quite good in the MWIR and LWIR, except the sharp specular spike in the LWIR for the -60 degree incident case. Outgassing and thermal cycle testing was not conducted on this sample.

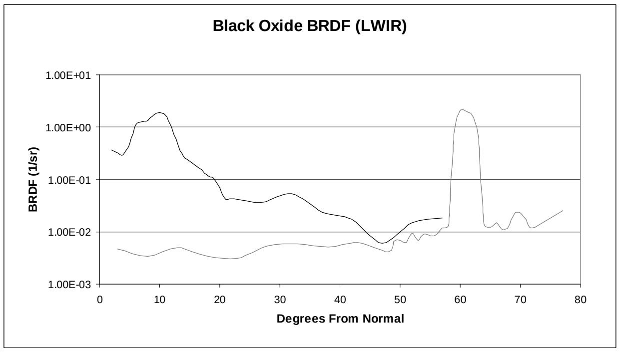




5.3 Black Oxide

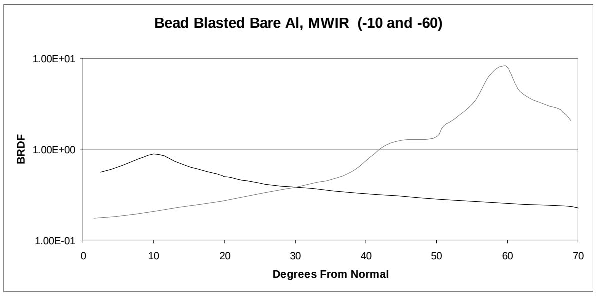
Black oxide is a common coating on fastener hardware (e.g., the necessary nuts, bolts and screws) that unfortunately, is often required to assemble baffles and light shields. Like anodizing, the black oxide coating does reduce the specularity and reflectivity over bare aluminum or stainless steel, but is far from ideal. If you can't paint the bolt heads with an appropriate paint, then use black oxide, but be aware that reflection will still occur form these fasteners.

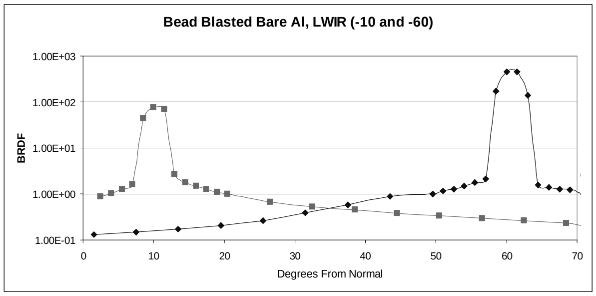




5.4 Bare Bead-Blasted Aluminum.

Bare bead-blasted aluminum would hardly be considered a black coating by anyone. However, the technique is used by many to improve Lambertian characteristics and reduce overall reflection. Obviously, the surface properties of a bead-blasted surface depends on the specifics of the individual bead blasting technique, so these generic results from one sample must be considered accordingly.
For an illustration to the user, below are the MWIR and LWIR measurements for one sample of this technique.





6.0 CONCLUSIONS

Some interesting conclusions include:

1). What is obvious to the eye bares no relation to the MWIR or LWIR characteristics, the researcher/engineer must take the measurements in the bandpass of interest.

2). SWIR black coatings are not necessarily black to the MWIR or LWIR.

3). Some commonly used 'blacks" such as ebinol aren't very "black" in the LWIR.

4). Paints tend to have superior "black" characteristics to most other processes, although they have other practical concerns such as flaking and thermal cycle durability issues.

5). Thermally cycling paints to cryogenic temperatures seem to result in a consistent increase in their BRDF by almost an order of magnitude for high incidence (near normal) sources and a slight, but measurable, increase in their BRDF for low incidence sources (far from normal).

6). Bead-blasting, anodizing and black-oxides only provide minimal decrease is reflectivity and minimal increase in Lambertian properties over bare metal. Exposed untreated metal parts (even bolt-heads) should be somehow treated; however using bead blasting, anodizing and black-oxide processes only provides marginal improvement in their characteristics for MWIR and LWIR bandpasses.

7). Coatings such as nickel oxide (and maybe others) may be more durable than they appear, although a visible damage can occur from small amounts of pressure, the IR characteristics may be basically unchanged.

8). DFF plots of SEM images provide a powerful tool in evaluating the performance of an infrared surface, as they indicate the structure size distribution as a function of spatial frequency. For a low-reflectivity Lambertian surface, it is desired that significant structural surface morphology exist in spatial frequencies corresponding to 2 to 5 times more than the wavelength of light of interest.

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