Advanced infrared optically black baffle materials*

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ABSTRACT

Infrared optically black baffle surfaces are an essential component of many advanced optical systems. All internal surfaces in advanced infrared optical sensors that require stray light management to achieve resolution are of primary concern in baffle design. Current industrial materials need improvements to meet advanced optical sensor systems requirements for optical, survivability, and endurability. Baffles are required to survive and operate in potentially severe environments. Robust diffuse-absorptive black surfaces, which are (1) thermally and mechanically stable to threats of x-ray, launch, and in-flight maneuver conditions, with specific densities to allow an acceptable weight load, (2) handleable during assembly, (3) cleanable, and (4) adaptive to affordable manufacturing, are required as optical baffle materials. In this paper an overview of recently developed advanced infrared optical baffle materials, requirements, manufacturing strategies, and the Optics MODIL (Manufacturing Operations Development and Integration Laboratory) Advanced Baffle Program will be discussed.

1. INTRODUCTION

Optical baffles offer an effective method for stray light management in advanced optical sensor systems[1,2,3]. In many optical systems baffles are key in determining the signal-to-noise level, and, thus, are important elements in increasing the pointing accuracy of the sensor. Baffles in infrared sensor systems are internal surfaces that suppress stray radiation, typically using geometrically designed vanes and surface morphology. Diffuse-absorptive surfaces and reflective surfaces are two types of light management baffles. Current industrial baffle materials do not meet the requirements for optical, survivability, and endurability criteria. Diffuse-absorptive baffles use surface features or porosity to absorb, scatter, or trap light. The surfaces are most effective as optical baffles when the features are steep-sloped with an aspect ratio comparable to or greater than the wavelength of light; the size of the features are comparable to or slightly smaller than the wavelength of light; and the pores are comparable to or slightly greater than the wavelength of light. Approaches have been taken to develop these features using plasma-sprayed beryllium, plasma-sprayed boron, sputter-deposited beryllium, and chemical vapor deposited boron carbide.

The objective of the Optics MODIL[4] Advanced Baffle Program is to develop and validate the integration of emerging advanced materials and enabling manufacturing technologies that can be used to produce hardened optical baffle systems for SDIO sensor systems, to demonstrate the technology with industrial participation, and to transfer the technology with "hands-on" experience. The approach is to leverage scaleable, advanced emerging materials and prior developed manufacturing technologies to achieve performance and to provide options and criteria for ground-based and space-based sensor systems design and manufacturing phases. Included in the mission is the demonstration of full-scale

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manufacturing of lightweight baffle vane components, monolithic structures, and systems with special features such as knife-edges and geometries meeting structural and shape requirements.

2. RESULTS AND DISCUSSION

2.1 Requirements

Development of baffle materials should target meeting optical requirements, survivable performance, mechanical robustness, and scaleability. Key requirements for advanced infrared baffles include optical performance, producibility, survivability, endurability to the space environment, weight, outgassing, mechanical, physical, and cryogenic properties. Survivability refers to withstanding a man-made threat to a required level whereas endurability refers to withstanding a natural environmental threat to a required level. From a mechanical point of view, an ideal baffle should have high thermal conductivity, high heat capacity for a low rise in temperature, low coefficient of thermal expansion for low deformation, low Gruneisen constant, low atomic number, high rigidity (Young's modulus and shear modulus), low density, high spall strength, high melting point to assist in preventing spall, and high yield strength.

Optical requirements; i.e., total hemispherical reflectance (THR) of which specular reflectance and scatter properties are a subset, for diffuse-absorptive baffles vary for each mission and sensor design. Depending on design, sensor systems may function within specifications with diffuse-absorptive baffles that have a total hemispherical reflectance of 15% from 1.0 to 30 microns; however, development goals should require diffuse-absorptive baffles that have a THR of less than 3% from 1.0 to 50 microns. THR of 15% and 3% translate into Lambertian BRDF (bidirectional reflectance distribution function) of $\sim 5 \times 10^{-2}$ sr^{-1} and $\sim 1 \times 10^{-2}$ sr^{-1}, respectively. Since the THR and scatter properties have a direct impact on the baffle system design complexity, number of baffle vanes, weight, costs, and manufacturing producibility, baffle surfaces with lower optical reflectance and Lambertian scatter values are recommended.

Outgassing and particulate blowoff during launch, in-flight maneuvers, and various threats are sources of contamination for mirrors. To meet the survivability criteria, hardened baffle cores to withstand x-ray threats and baffle surfaces that are thermally and mechanically stable to threats of x-ray, laser, and launch conditions are required. There should be less than 1% reduction in optical performance due to surface melt, blowoff, spallation, delamination, thermal shock, and shock over pressure after irradiation by a nuclear, laser, or launch threat. The debris or particulate blowoff levels during launch and in-flight maneuvers or after irradiation, imposed separately or simultaneously, should be less than $100/d^2$ particles per cm^2 where d is the diameter of particles in microns. The value[5] is based on Mie scattering theory. Survivability threat issues are different for each sensor program element.

The baffle surface should endure the space environmental conditions without degradation of the optical properties and without contributing contamination to the optical train and mirror surfaces. Outgassing of the diffuse-absorptive surfaces in the vacuum environment may result in condensates. Water is the primary outgassing component from baffle surfaces[6]. The water outgassing should be less than 1×10^{-11} moles/cm^2-s. Electromagnetic pulses (to 1.4 kW/m^2 peaking at 0.5 microns), protons (10^8 /cm^2/s in the range of 0.1-4.0 meV), electrons (10^8 /cm^2/s in the range of 0.1-4.0 meV), cosmic rays (1 /cm^2/s at $>10^9$ eV), ions (10^2-10^6 /cm^2/s), and atomic oxygen are space environmental conditions which may degrade the baffle surfaces. The space endurability requirements vary with mission. Internal cooling may be required under certain conditions for diffuse-absorptive baffles. All requirements should be met following exposure to the space conditions and after cryogenic cycling.

Reflective baffles may be more useful than diffuse-absorptive baffles in certain applications, especially where solar heat rejection is important, but are expected to be more expensive than absorptive baffles. However, the tolerances required for reflective baffles have not been fully documented. In some cases the first few vanes may be required to be reflective baffles.

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The producibility of baffle components and systems are important elements for each of the advanced emerging materials. The materials should be lightweight, rigid, robust (mechanically and physically stable), scaleable, and adaptive to affordable manufacturing. The development and validation of flexible manufacturing processes for a range of baffle configurations using the new improved materials are important to provide options to sensor systems designers and integrators. The configurations include single baffle component vanes and monolithic structures. The handleability of the baffles should be equal to or better than that for mirrors or lens and durable relative to normal installation procedures.

2.2 Optical properties and surface characteristics

Results for several advanced infrared optically black materials are discussed and compared to Martin Black in this section. The specular reflectance for each was measured from 2 to 50 μm. Scatter was measured at 10.6 um with an incidence angle of 30° using a 5-mm beam diameter and reported as BRDF. The BRDF for the advanced baffle materials are presented and compared to Martin Black in Figures 1 and 2. Figure 2 shows the instrument signature typical for all baffle samples. Note that the BRDF data for Martin Black are shown in Figures 1 and 2 using different scales. BRDF raster plots and scanning electron microscopy (SEM) photomicrographs at a range of magnifications were made.

Martin Black is considered as the optical standard to which the advanced diffuse absorbing materials are compared. Martin Black[7,8] is an anodized aluminum surface that is microrough exhibiting a matte black finish and contains a proprietary black dye. Specular reflectance typical for Martin Black is 0.7% at 10.6 μm and averages 0.6% from 2 to 50 μm as shown in Figure 3. The scatter typical for Martin Black is presented in Figures 1 and 2. The BRDF is Lambertian with an average value of 6.1×10^{-4} $ster^{-1}$. The particular sample shown has a slight specular component (peak at 0°), but the area of this peak is ~10^{-6} and has a negligible contribution to the total integrated scatter. The SEM photomicrograph (Figure 4) of Martin Black shows a range of features which produce the observed optical data.

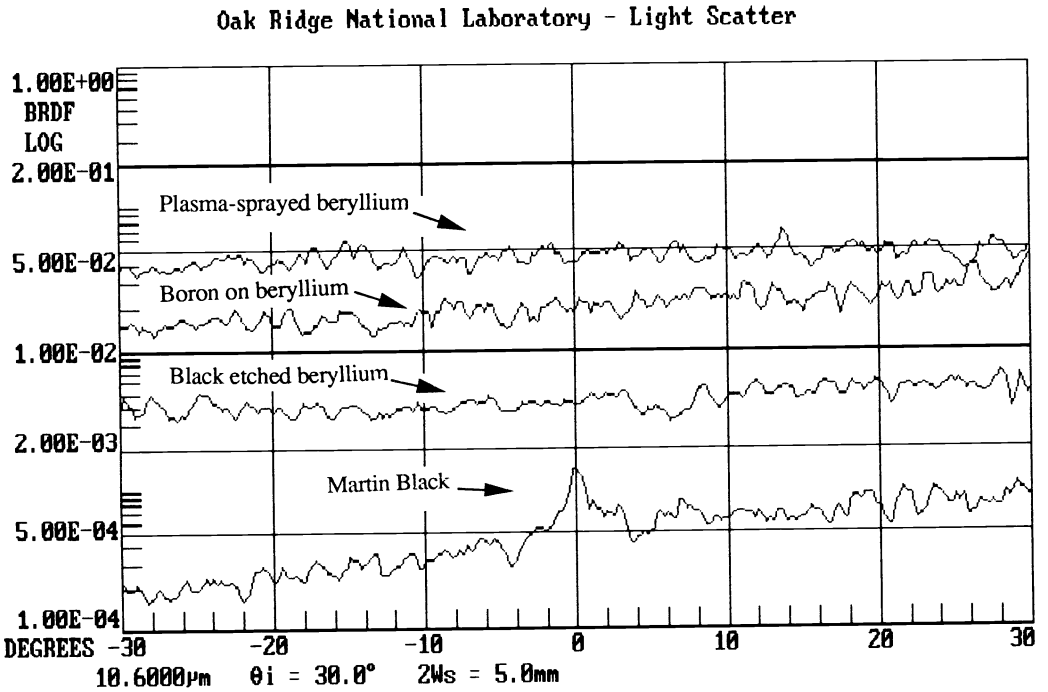


Figure 1. BRDF of Martin Black, black etched beryllium, boron-on-beryllium, and plasma-sprayed beryllium baffle materials.

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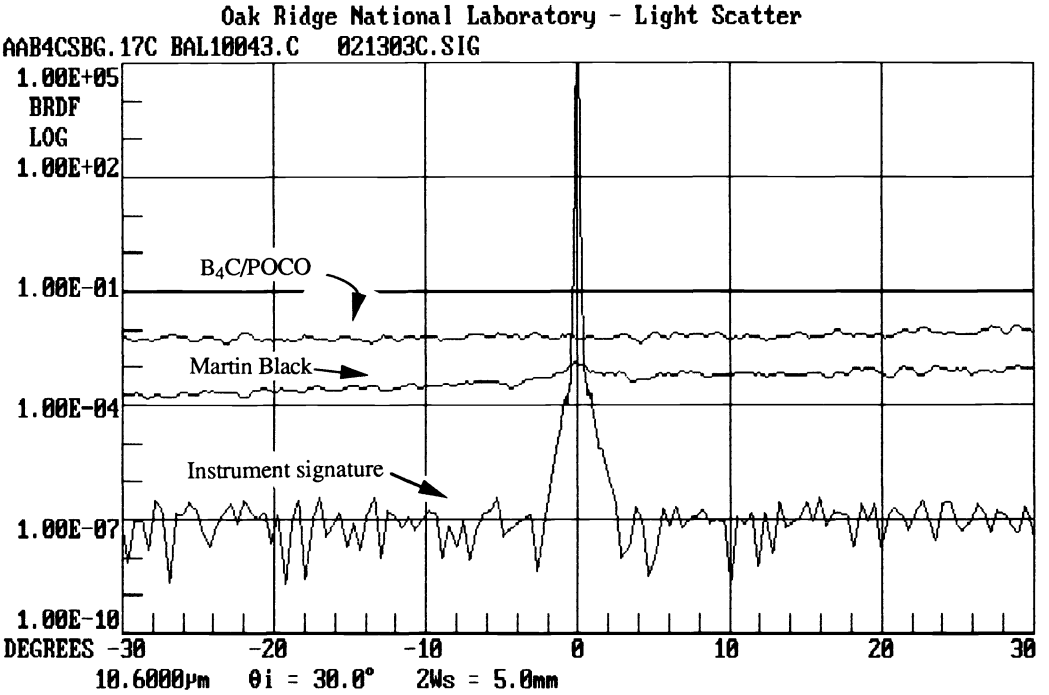


Figure 2. BRDF of Martin Black, boron carbide on POCO graphite (B_4C/POCO) and the instrument signature.

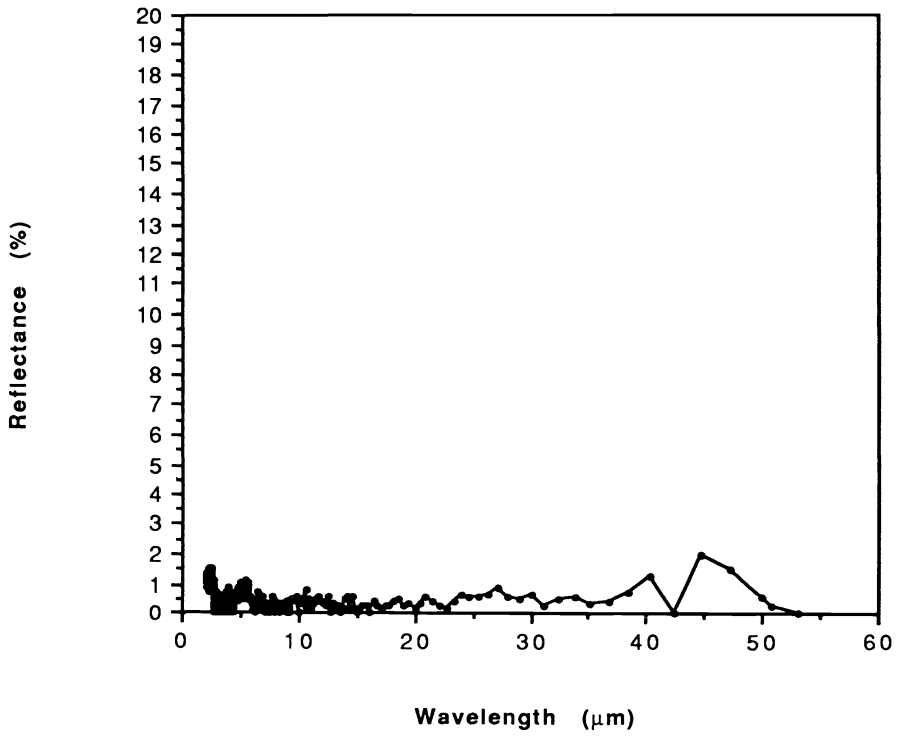


Figure 3. Specular reflectance of Martin Black.

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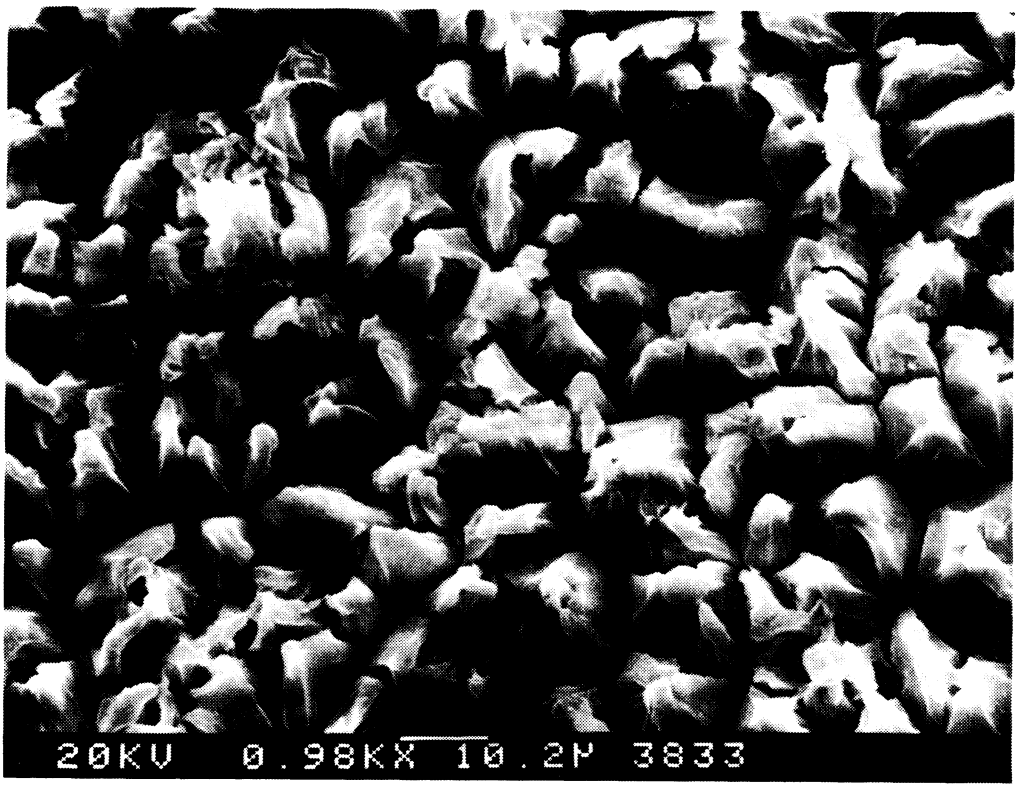


Figure 4. SEM photomicrograph of Martin Black with 10.2-μm bar.

Black etched beryllium was developed by Egert and Allred[9]. Before etching, the beryllium coating exhibits a uniform matte gray finish; whereas, after etching, the beryllium surface has a matte black finish, not unlike Martin Black. Scatter plots and reflectance for a typical sputtered and etched beryllium coating are presented in Figures 1 and 5, respectively. The IR reflectance is quite low for the black etched beryllium at 0.4% at 10.6 μm, averaging 0.4% from 2 to 50 μm, and ranging from less than 0.5% at 2 μm to 1.5% at 50 μm. The scatter measured at 10.6 μm shows a highly absorbing Lambertian behavior with an average value of 4.1×10^{-3} ster^{-1}. The Lambertian BRDF translates into a THR of ~1.3%. A SEM photomicrograph typical of black etched beryllium coating deposited on a smooth beryllium sheet is presented in Figure 6. Etching results primarily in attack perpendicular to the platelet faces along the c-axis of the grains. Etching also attacks smaller grains within the larger gains causing fine features. The result is a porous surface structure with small features (causing the visibly black nature) on a range of large features (infrared active). Figure 7 shows black etched beryllium deposited onto a rough surface as obtained for plasma-sprayed beryllium. This surface also consists of large columnar grains 40 to 50 μm in diameter with considerable inter-columnar porosity. The individual grains have been etched into a "rose-pedal" pattern of fine features due to etching along boundaries between smaller columnar grains within the larger grains. The fine features cause the visibly black appearance. Black etched beryllium represents a very versatile advanced baffle material which can be deposited onto a wide range of baffle core materials.

Plasma-sprayed beryllium samples visually appear rough with a matte gray finish. Optical scatter and infrared reflectance results typical of this material are shown in Figures 1 and 8, respectively. The specular reflectance of plasma-sprayed beryllium is approximately constant at about 1.6% from 2 to 50 μm. BRDF is Lambertian with an average value of 4.8×10^{-2} ster^{-1}. This scatter level translates into a total hemispherical reflectance of ~15%. SEM characterization of a plasma-sprayed beryllium sample, Figure 9, shows the surface to be very rough with considerable porosity. The surface consists of overlapping layers of smooth material with many spherical particles interspersed. The particles range in size from submicron up to approximately 45 μm with the largest portion being between 3 and 20 μm. Plasma-

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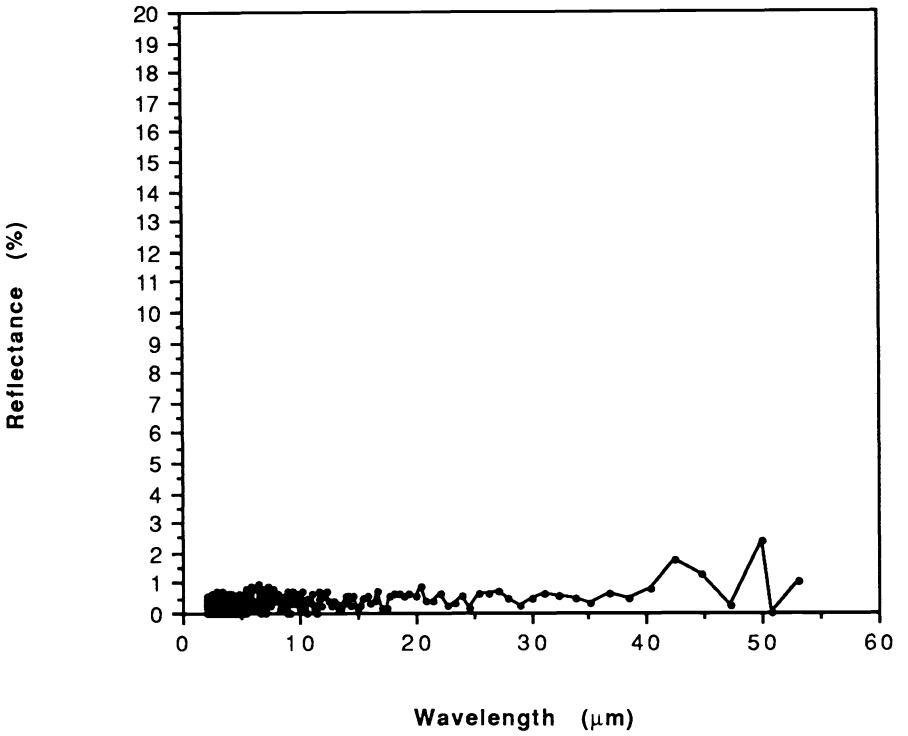


Figure 5. Specular reflectance of black etched beryllium.



Figure 6. SEM photomicrograph of black etched beryllium on a smooth substrate with 7.63-μm bar.

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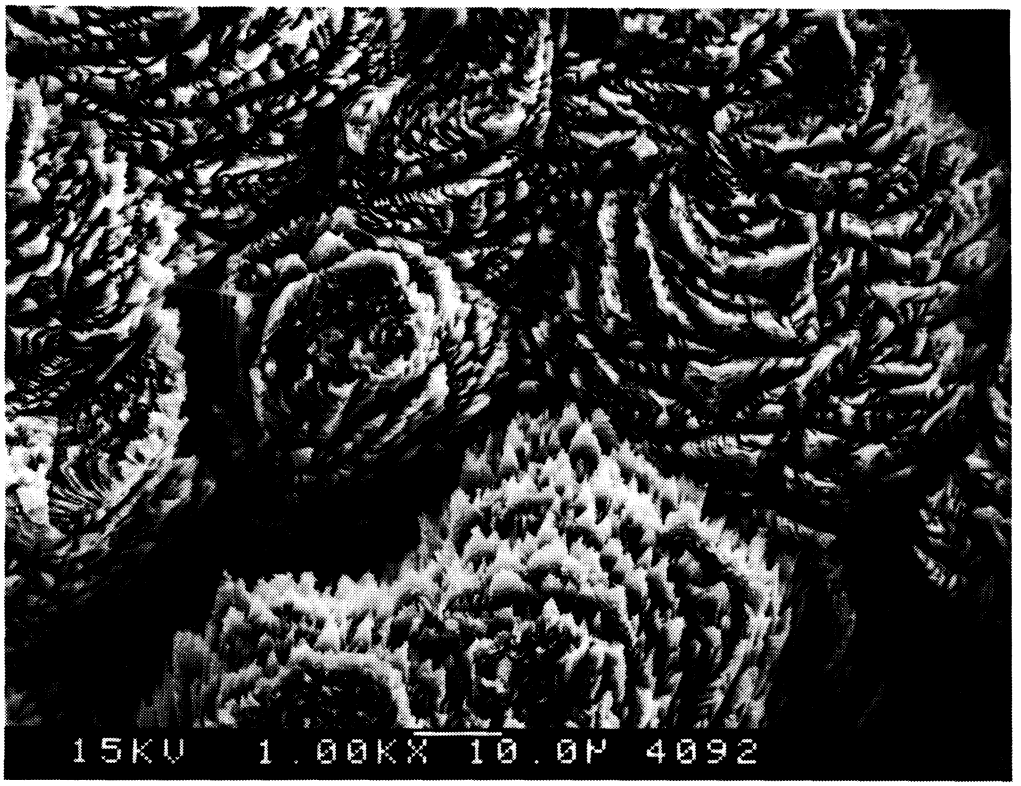


Figure 7. SEM photomicrograph of black etched beryllium on plasma-sprayed beryllium with 10.0-μm bar.

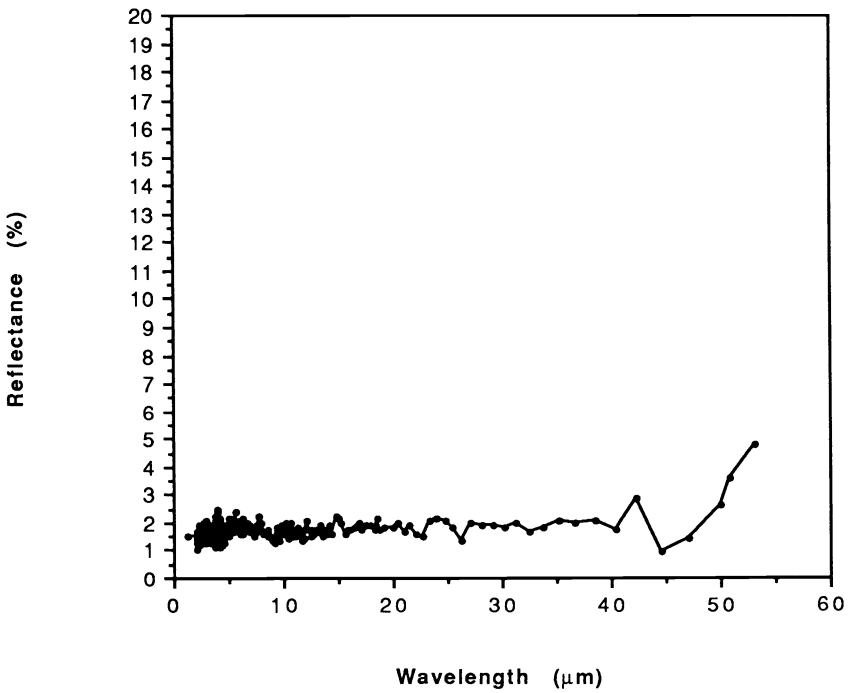


Figure 8. Specular reflectance of plasma-sprayed beryllium.

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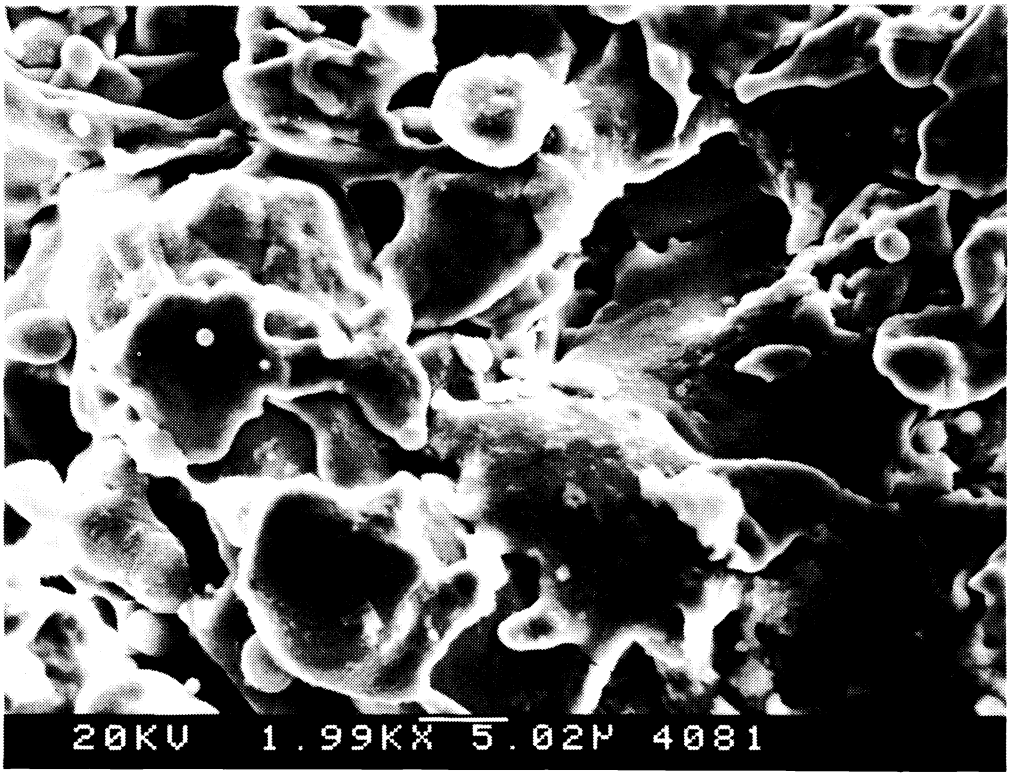


Figure 9. SEM photomicrograph of plasma-sprayed beryllium with 5.02-μm bar.

sprayed beryllium may be used as a light absorbing coating on various core materials, as a light absorbing free-standing structure, or as a baffle core onto which a diffuse absorbing coating such as the black etched beryllium may be deposited. The plasma-sprayed beryllium baffle surface is handleable and cleanable.

Plasma-sprayed boron has a matte dark gray finish. The specular reflectance is quite low, as shown in Figure 10, being 0.7% at 10.6 μm and averaging 0.7% from 2 to 50 μm. The average BRDF typical of the plasma-sprayed boron is Lambertian 1.5×10^{-2} ster^{-1} (Figure 1) which provides a THR of ~4.7%. SEM photomicrographs typical of plasma-sprayed boron reveal features similar to plasma-sprayed beryllium discussed above with the additional feature of porosity within the larger spherical features. Plasma-sprayed boron may be deposited as coatings on various baffle cores including free-standing, plasma-sprayed beryllium structures. The plasma-sprayed boron-on-beryllium baffle surface is handleable and cleanable.

Boron carbide (B_4C) deposited by chemical vapor deposition on POCO graphite has a matte light gray finish. The B_4C/POCO baffle material was developed by R. A. Lowden[10]. Scatter and specular reflectance measurements of typical B_4C on POCO are shown in Figures 2 and 11, respectively. The infrared reflectance is 0.7% at 10.6 μm and averages 0.6% from 2 to 50 μm. The low, Lambertian scatter properties result in an average BRDF of 6.8×10^{-3} ster^{-1}. The BRDF translates into ~2.1% THR. The highly porous surface, steeped-wall features characteristic of B_4C-on-POCO are evident in Figure 12.

The optical data for the advanced infrared black materials are summarized and compared to Martin Black in Table 1. The scatter levels for these materials are Lambertian as required for infrared optical black baffles and represent the lowest values obtained to date for infrared baffles of beryllium and boron-type materials. The developed advanced baffle materials are lightweight, stiff, scaleable materials that offer options to designers who require advanced baffle materials.

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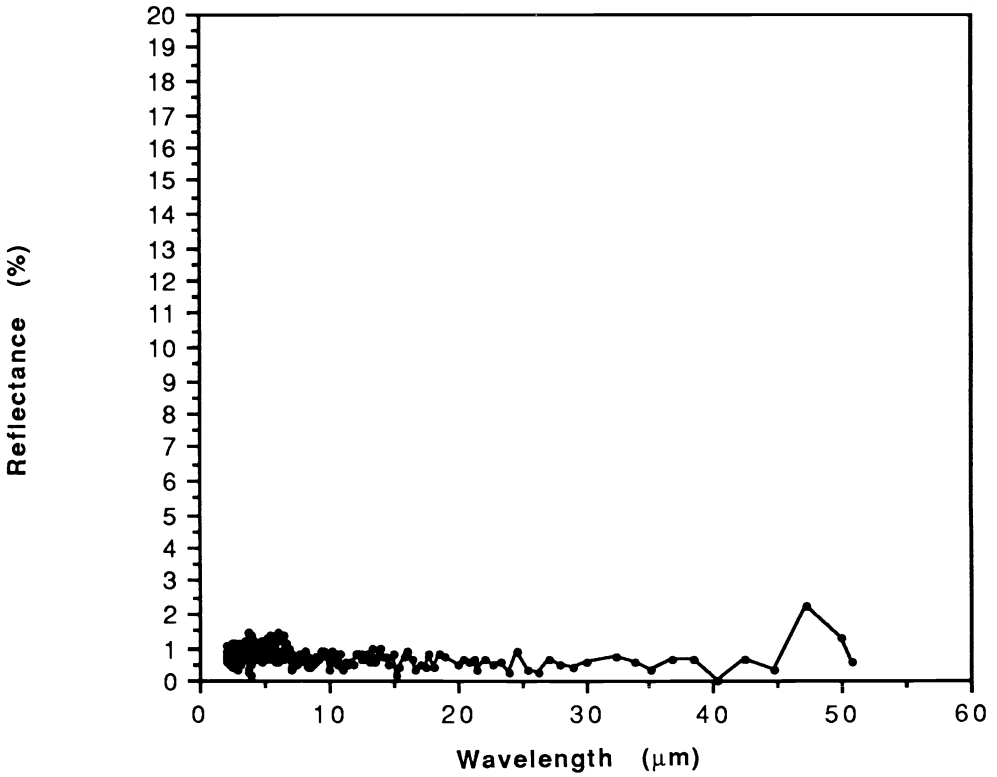


Figure 10. Specular reflectance of plasma-sprayed boron on beryllium.

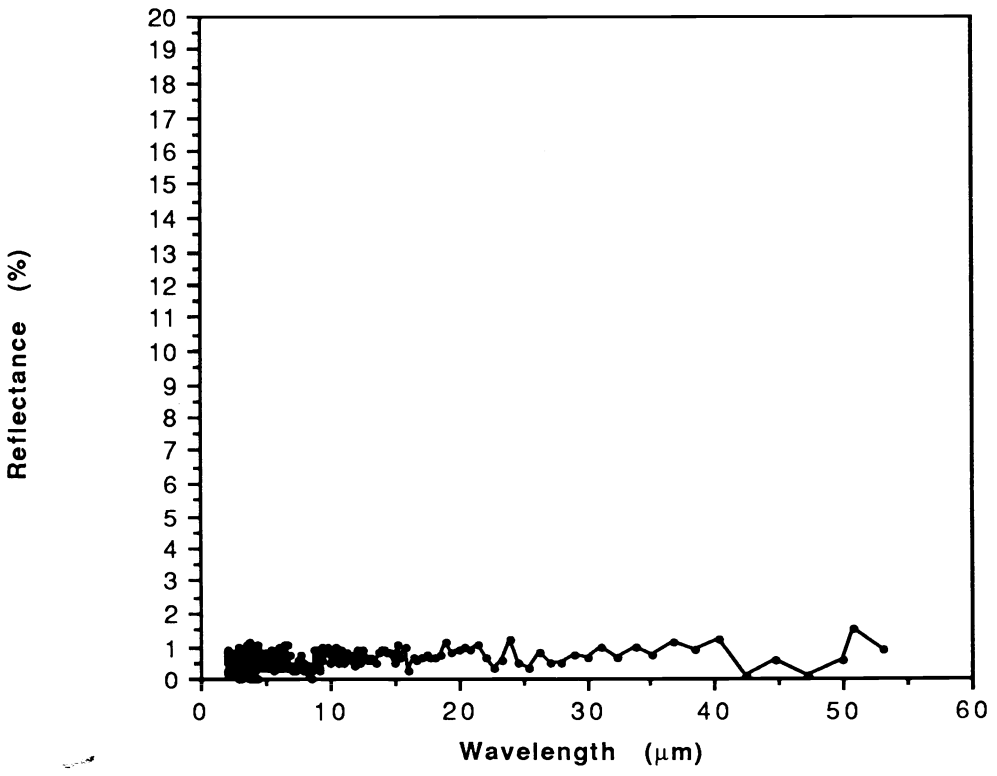


Figure 11. Specular reflectance of boron carbide on POCO graphite.

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Figure 12. SEM photomicrograph of boron carbide on POCO graphite with 10.0-μm bar.

Table 1. Optical Properties Summary

	Specular Reflectance		Optical Scatter @10.6 μm		
Material	@10.6 μm	Average 2-50 μm	BRDF	Lambertian	THR Estimated
Martin Black	0.7	0.6	6.1E-4	yes	.19
PS-Be	2.0	1.6	4.8E-2	yes	15.0
Etched Be/Be	0.4	0.4	4.1E-3	yes	1.3
PS-B/Be	0.7	0.7	1.5E-2	yes	4.7
B_4C/POCO	0.7	0.6	6.8E-3	yes	2.1

2.3 Vacuum outgassing

Quantitative measurements of outgassing for Martin Black, plasma-sprayed beryllium, and the black etched beryllium baffle materials using a calibrated system were performed at room temperature by Egert and Basford[6]. The measurements were made on "as-fabricated" samples which had not received any preconditioning (vacuum heating, etc.). Qualitative mass scans showed that the major outgassing component was water vapor. Mass scans for an aluminum control sample, plasma sprayed beryllium, and

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black etched beryllium were measured. Quantitative outgassing over the range 1 to 60 amu was recorded and stored digitally at two-minute intervals throughout the pumpdown of 5 to 8 hours. The quantitative outgassing results are presented in Table 2. Water vapor outgassing curves for each baffle type are presented in Egert's and Basford's paper[6]. The total amount of water vapor outgassed, determined by integrating the pressure-time curves and applying the appropriate calibration factor from the water vapor calibration runs, ranged from $1x10^{-5}$ to $4x10^{-5}$ moles/cm^2. To understand the outgassing kinetics for the baffle materials a pressure-time relationship was used as described by:

$$P = At^{-a}$$

where P is the water vapor pressure, A is a constant, t the pumpdown time, and a is the slope of the pumpdown curve in the power law dependence region. A value near 0.5 indicates outgassing dominated by diffusion while a value greater than one indicates physical desorption-based kinetics. The plasma-sprayed beryllium sample had a value near one indicating slower desorption kinetics than observed for the other materials. Black etched beryllium had initial outgassing kinetics characteristic of diffusion ($a = 0.63$); but after 100 minutes the kinetics ($a = 1.30$) became essentially similar to the other baffle materials.

Table 2. Baffle water vapor outgassing statistics

Sample	α	Total Water Evolved
Martin Black (Sample 1)	1.59	3.00×10^{-5}
Martin Black (Sample 2)	1.55	3.70×10^{-5}
Plasma-Sprayed Be	1.02	4.31×10^{-6}
Black Etched Be	0.63, 1.30*	1.06×10^{-5}
Al Control	N/A	1.42×10^{-7}

* $\alpha = 0.63$ for the first 100 minutes and 1.30 for the remainder of the test.

To compare these water outgassing values to a requirement of $1x10^{-11}$ moles/cm^2-sec, consider a specific, though idealized, case. An idealized cylindrically symmetric telescope housing with a 7.5-cm aperture radius and a 9-cm ID tube radius, 30-cm long, with 24 circular baffles 1.5-cm high has a total area for the baffle surfaces of approximately 5430 cm^2. Assuming a total baffle water vapor evolution of $4x10^{-5}$ moles/cm^2, 0.22 moles of water evolved during pumpdown or about 3.9 mL of liquid water. Using the requirement of $1x10^{-11}$ moles/cm^2-sec water outgassing for a pumpdown of 8 hours ($2.9x10^{-8}$ moles/cm^2), 0.03 mL of liquid water results. As a worst case assume half of the outgassed water freezes out onto the cold mirror surface. For a 15 cm-diameter mirror, $4x10^{-5}$ moles/cm^2 of ice produce more than 100-μm thickness of ice, whereas the $1x10^{-11}$ moles/cm^2-sec rate represents less than 1 μm of ice.

2.4 Producibility strategy

To provide options and criteria for sensor systems design and manufacturing phases, a number of baffle materials should be available representing a range of performances. Flexible manufacturing processes to fabricate a range of configurations are required for single baffle component vanes and for monolithic baffle structures. The configurations cover the gamut from single vanes that may be installed into a housing or support structure to monolithic baffle systems that form the support structure for the sensor system. There are a number of producibility issues[11] associated with each approach. The Optics MODIL baffle producibility strategy is to demonstrate fabrication of near-net-shape hardened baffle cores to a simplified design and precision finish special localized features such as knife-edges and installation mounts followed by preparation of the reflective or diffuse-absorptive surface. The integration of surface

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manufacturing technologies and core manufacturing technologies is a key step, and a preferable fabrication process would have the surface features produced during the core manufacturing step.

Plasma spray deposition represents a manufacturing process that may be used to produce free-standing baffle core structures to the desired thickness or a diffuse-absorptive coating on various baffle core structures such as beryllium sheet, carbon-carbon, or silicon carbide. An example of a plasma-sprayed baffle core would be a 0.025" free-standing beryllium baffle vane core which has been coated by black etched beryllium. The plasma spray deposition provides a high-rate, low-cost, repeatable manufacturing process which may be automated. The powder is injected into a high-temperature argon plasma (10,000° C) which produces rapid melting and accelerates the particles toward the target where the particles impinge and are instantaneously quenched.

Reflective or diffuse-absorptive baffle cores may be manufactured from high-purity, cross-rolled beryllium sheet. The process begins with cast high purity beryllium ingot which is fabricated into a bar, pack rolled into a plate, and pack cross-rolled into sheet of the desired thickness. For a reflective baffle, first the specular side of the beryllium vane is precision turned, and then the sheet is formed into the appropriate curved or elliptical shape. Noncontact polishing may be used to enhance reflectivity if needed. The back side of the beryllium sheet may be coated to provide the diffuse-absorptive surface. Preliminary work has demonstrated that the approach has potential, but further work is required to fully substantiate the process. Figure 13 shows 0.060" and 0.010" thick cross-rolled beryllium sheets which were formed to shape in a simple press and die. The 0.060" sheet required heating to ~700° C. The 0.010" sheet showed some wrinkles since the die was designed for the 0.060" thickness. To manufacture a diffuse-absorptive baffle component, the light-absorbing surface is prepared on a cross-rolled beryllium vane of the desired thickness. An example in Figure 14 shows a 0.060" beryllium sheet which was coated with

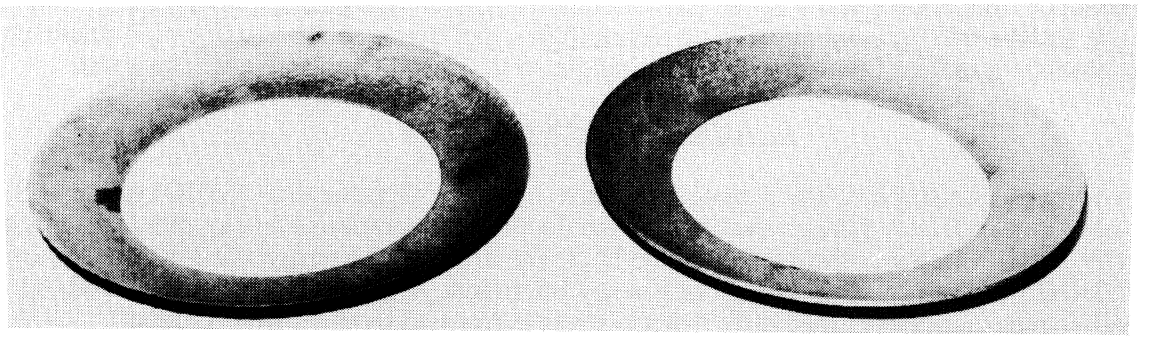


Figure 13. High-purity, cross-rolled beryllium sheet (0.010" and 0.060" thick, 6" OD) formed to shape.

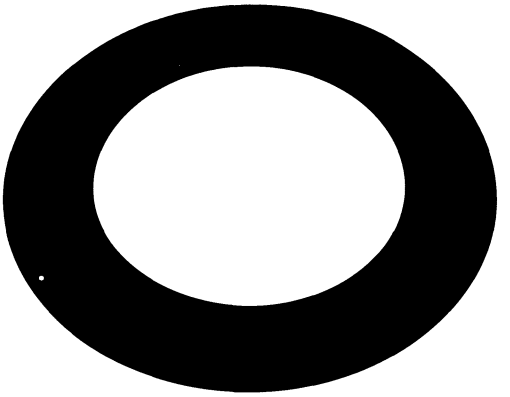


Figure 14. Cross-rolled beryllium vane 0.060" thick, 6" OD coated with the diffuse absorptive black etched beryllium.

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the diffuse-absorptive black etched beryllium. An example of using cross-rolled beryllium sheet to produce a honeycomb structure which may potentially represent a diffuse-absorptive baffle concept is shown in Figure 15.

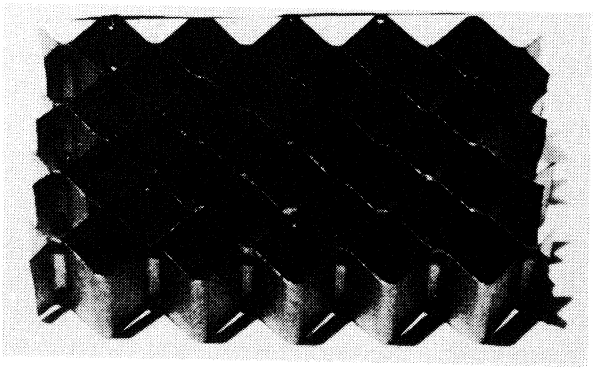


Figure 15. Honeycomb structure made from high-purity, cross-rolled beryllium sheet.

3. CONCLUSIONS

In summary, several advanced, lightweight, robust diffuse absorptive baffle materials have been demonstrated to provide options and criteria to sensor systems designers. The materials developed offer technologies which are scaleable and target survivable performance. Future work should investigate methods to enhance optical properties which have a direct impact on design complexity and producibility, integrate baffle surface and core manufacturing technologies, and demonstrate flexible manufacturing processes to produce a range of configurations for single vane components and baffle systems.

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