SPECULAR BLACK BAFFLE DESIGN
SPONSORED BY RAYTHEON MISSILE SYSTEMS
By
PATRICK AMBROSE THRASHER

A Thesis Submitted to The Honors College
In Partial Fulfillment of the Bachelors Degree
With Honors in
Optical Sciences & Engineering
THE UNIVERSITY OF ARIZONA
MAY 2014

Approved by:

[Signature]

Dr. Gerald Pine
Department of Aerospace and Mechanical Engineering
The University of Arizona Electronic Theses and Dissertations
Reproduction and Distribution Rights Form

The UA Campus Repository supports the dissemination and preservation of scholarship produced by University of Arizona faculty, researchers, and students. The University Library, in collaboration with the Honors College, has established a collection in the UA Campus Repository to share, archive, and preserve undergraduate Honors theses.

Theses that are submitted to the UA Campus Repository are available for public view. Submission of your thesis to the Repository provides an opportunity for you to showcase your work to graduate schools and future employers. It also allows for your work to be accessed by others in your discipline, enabling you to contribute to the knowledge base in your field.

Your signature on this consent form will determine whether your thesis is included in the repository.

Name (Last, First, Middle)
Thrasher, Patrick Ambrose

Degree title (eg BA, BS, BSE, BSB, BFA):
BS

Honors area (eg Molecular and Cellular Biology, English, Studio Art):
Optical Sciences and Engineering

Date thesis submitted to Honors College:
5-7-14

Title of Honors thesis:
Specular Black Baffle Design

The University of Arizona Library Release Agreement

I hereby grant to the University of Arizona Library the nonexclusive worldwide right to reproduce and distribute my dissertation or thesis and abstract (herein the "licensed materials"), in whole or in part, in any and all media of distribution and in any format in existence now or developed in the future. I represent and warrant to the University of Arizona that the licensed materials are my original work, that I am the sole owner of all rights in and to the licensed materials, and that none of the licensed materials infringe or violate the rights of others. I further represent that I have obtained all necessary rights to permit the University of Arizona Library to reproduce and distribute any nonpublic third party software necessary to access, display, run or print my dissertation or thesis. I acknowledge that University of Arizona Library may elect not to distribute my dissertation or thesis in digital format if, in its reasonable judgment, it believes all such rights have not been secured.

☐ Yes, make my thesis available in the UA Campus Repository!

Student signature: Patricia Date: 5-7-14

Thesis advisor signature: Harold D Irvine Date: 5/12/2017

☐ No. do not release my thesis to the UA Campus Repository.

Student signature: __________________________ Date: __________________________
Abstract

Raytheon Missile Systems has sponsored this project in order to determine the feasibility of using specular black paint, as opposed to diffuse black paint, as the coating for optical baffles. It is hypothesized that specular baffle designs may reduce stray light more efficiently than diffuse baffles; however, the computer models on which these claims are based have never been validated by experimental data. This project will attempt to prove that computer models of specular baffles are valid.
Team Member Roles

Patrick Thrasher, OSE: Team Lead
As team lead, Patrick Thrasher organized the roles of the team and oversaw each part of the project. In addition, he performed all of the design and analysis that was done in the FRED computer software.

Anthony Babicke, ME:
All mechanical manufacturing, paint and assembly was completed by Anthony Babicke. This included the design of the fabrication method, as well as selecting the proper tools, materials, and hardware.

Ashley Lancaster, OSE:
Ashley Lancaster primarily focused on information synthesis and presentation. This included the specific tasks of risk analysis and ensuring that system requirements are met.

Michael Portugal, OSE:
All work pertaining to the design and optimization of each baffle was performed by Michael Portugal. This work was performed by hand, in SolidWorks, and in MATLAB. He also was the team scribe, documenting the all of our team meetings and design process.

Alexandra Schluntz, OSE:
Alexandra Schluntz designed the test setup used to gather data from both baffles systems. In addition, as Purchase Lead, she gathered all materials and handled the finances and budget.
Contents
Introduction .............................................................................................................................................. 7
What is a Baffle? ..................................................................................................................................... 7
Specular vs. Diffuse Reflection .................................................................................................................. 7
Top-Level Requirements ............................................................................................................................ 8
Top-level Design ....................................................................................................................................... 8
Key Terminology ....................................................................................................................................... 8
Optical System ......................................................................................................................................... 8
Stray light ................................................................................................................................................ 9
Baffle ....................................................................................................................................................... 9
Vane ....................................................................................................................................................... 9
FRED ....................................................................................................................................................... 9
Computer/FRED model ........................................................................................................................... 9
Entrance Pupil (E) ................................................................................................................................... 9
Exit Pupil (E’) .......................................................................................................................................... 9
Tube Length (L) ...................................................................................................................................... 9
Inner Diameter (D) ................................................................................................................................. 9
Full Field of View (FFOV) ...................................................................................................................... 9
F/# ......................................................................................................................................................... 9
Irradiance (H) .......................................................................................................................................... 9
Point Source Transmittance (PST) ........................................................................................................... 10
Bidirectional Reflective Distribution Function (BRDF) .......................................................................... 10
Signal-to-noise Ratio (SNR) .................................................................................................................. 10
Baffle Requirements .............................................................................................................................. 10
Vane Design ........................................................................................................................................... 10
F/2, 30° FOV ......................................................................................................................................... 10
Paint Application ................................................................................................................................. 11
Isotropic ................................................................................................................................................ 11
5 layer coats ......................................................................................................................................... 11
Enamel paint ......................................................................................................................................... 11
Assembly ............................................................................................................................................... 11
Aluminum 6061 alloy ............................................................................................................................. 11
633nm optimization ............................................................................................................................... 12
Test Requirements ................................................................. 12

Camera ................................................................................. 12

Pixel array ........................................................................... 12

Responsivity $\geq 0.6\text{A/W}$ .................................................. 12

Variable integration time ...................................................... 12

Detector depth $< 1^{\circ}$ .......................................................... 12

Source .................................................................................. 13

Solar spectrum ..................................................................... 13

Extended Source .................................................................. 13

Hardware and Fasteners ....................................................... 13

Vary the angle of incidence ............................................... 13

Kinematically constrained baffle ........................................ 13

Room temperature .............................................................. 14

Summary of PDR Results ....................................................... 14

Subsystem/Sub-assembly and Interface Design ..................... 14

Reflection Mechanisms ....................................................... 14

Outline of Baffle Design ....................................................... 15

Diffuse Design .................................................................... 15

Specular Design .................................................................. 17

Equation Constraints .......................................................... 18

Vane Design ....................................................................... 19

Paint Application ............................................................... 19

Assembly ............................................................................. 20

System Test Setup .............................................................. 20

Camera .............................................................................. 22

Source .............................................................................. 22

Hardware and Fasteners .................................................... 23

Algorithm Description and Interface Document .................. 24

FRED Algorithm ............................................................... 24

MATLAB Algorithm .......................................................... 25

Analysis .............................................................................. 26

Implementation of Development Plan .................................. 29

Build Plan ........................................................................... 29
Test Plan........................................................................................................................................ 30
Analysis Plan.................................................................................................................................... 30
Requirements Review/Acceptance Test Plan ................................................................................. 31
Baffle Requirements ....................................................................................................................... 32
Vane Design....................................................................................................................................... 32
F/2, 30° FOV ................................................................................................................................... 32
Paint Application ............................................................................................................................. 32
Isotropic ......................................................................................................................................... 32
5 layer coats .................................................................................................................................. 32
Enamel paint .................................................................................................................................. 32
Assembly ......................................................................................................................................... 32
Aluminum 6061 alloy ..................................................................................................................... 32
633nm optimization......................................................................................................................... 33
Test Requirements .......................................................................................................................... 33
Camera............................................................................................................................................ 33
Pixel array....................................................................................................................................... 33
Responsivity ≥ 0.6A/W ................................................................................................................... 33
Variable integration time ............................................................................................................... 33
Detector depth < 1” ....................................................................................................................... 33
Source ............................................................................................................................................ 34
Solar spectrum................................................................................................................................. 34
Extended Source ............................................................................................................................ 34
Hardware and Fasteners.................................................................................................................. 34
Vary the angle of incidence ............................................................................................................ 34
Kinematically constrained baffle ................................................................................................... 35
Room temperature ......................................................................................................................... 35
References .................................................................................................................................... 36
Appendix A: Team Member Contributions.................................................................................... 37
Appendix B: Designs ....................................................................................................................... 38
Appendix C: FRED and MATLAB Scripts .................................................................................... 41
FRED Script .................................................................................................................................... 41
MATLAB Script............................................................................................................................. 42
Appendix C: Budget, Suppliers, and Bill of Materials .................................................................. 44
Introduction

What is a Baffle?

Imaging systems are designed for a specified field of view, but are sensitive to stray (unwanted) light entering the system from outside of the desired input angles. Optical baffles are used to manage stray light that is not within the field of view. Baffles range in complexity, but in essence, the simplest baffle can consist of a simple cylindrical tube placed in front of a system entrance pupil. The inside of the tube is textured with grooves or vanes to prevent stray light. Ideally, all of the light entering from an angle greater than the defined field of view will either be absorbed by the baffle or reflected back out of the system. That light should never reach the detector.

![Figure 1: Examples of Different Baffle Geometries](image)

Specular vs. Diffuse Reflection

When light reflects off a surface, the direction of the output light is determined by the interaction between the light and the material properties of the surface. For a purely specular surface, such as a mirror, light is reflected at an angle equal in magnitude to the incident angle, as measured from the normal to the surface. An ideal Lambertian (diffuse) surface reflects light equally over a hemisphere, regardless of the incoming angle.

For the purpose of this project, “specular paint” refers to paint that is quasi-specular, and “diffuse paint” refers to paint that is quasi-lambertian as labelled in the figure below.
Top-Level Requirements
The project encompasses the following objectives:
1) The team shall design two baffle systems: one utilizing diffuse black paint and the other utilizing specular black paint.
2) The team shall use computer software to model, predict, and analyze stray light performance of the two baffle designs.
3) The team shall build and test the two baffle designs.
4) The team shall compare the predicted performance of each system with the physical test results.
5) The team shall create a detailed report that documents the fabrication and testing process of each baffle design.

Top-level Design
The project has three subsystems: the computer models, the physical baffles, and the test setup. The baffle will be designed according to which paint is being used and initially put into a computer model that will characterize the Point Source Transmittance of the baffle over ±90°. The physical baffle will then be machined in real life and the PST will be calculated and compared with the computer model predictions.

Key Terminology
Please note that the definitions for FFOV and F/# in this paper deviate from typical geometrical optics conventions.

Optical System
An assembly of components and devices used to manipulate the propagation of light rays. An optical system can be as simple as a single CCD sensor, or as complex as a telescope.
Stray light
Any light that enters the system outside of the FFOV (see definition of FFOV below) and reaches the detector.

Baffle
A sometimes cylindrical tube placed in front of an optical system to block stray light.

Vane
A thin circular mask placed somewhere inside the baffle which blocks a portion of stray light.
Physical baffle: Refers to the systems that will be built and tested experimentally.

FRED
Computer software that performs stray-light analysis in optical systems.

Computer/FRED model
Refers to the computer models of the physical baffles.

Entrance Pupil (E)
The front opening in the baffle system. Light enters into the system at the entrance pupil.

Exit Pupil (E’)
The rear opening in the baffle system. Light collects onto the detector at the exit pupil.

Tube Length (L)
The length of the baffle between the entrance and exit pupils. The tube length axis is perpendicular to both pupil planes.

Inner Diameter (D)
The diameter of the baffle walls. It is by definition larger than either of the pupil diameters

Full Field of View (FFOV)
The range of input angles that an ideal optical system would collect, or what the system can “see” in the horizontal and vertical directions.

\[ FFOV = 2 \tan^{-1} \frac{E}{2L} \approx \frac{E}{L} \]

F/#
The f-number is defined as ratio of the length of the system divided by the diameter of the entrance pupil.

\[ F/\# = \frac{L}{D} \]
Irradiance (H)
A measurement of light power (Φ) divided by the surface area (A) over which said power is transferred.

Point Source Transmittance (PST)
A normalized measurement of the exit pupil irradiance over the entrance pupil irradiance.

\[ PST = \frac{H_{out}}{H_{in}} = \frac{\Phi_{E_t}/A_{E_t}}{\Phi_{E_t}/A_E} \]

The PST will be used to quantify our baffle systems, since outside the FFOV light should enter the baffle but never reach the detector and should give a PST value of 0.

Bidirectional Reflective Distribution Function (BRDF)
Characterizes the manner in which a surface will reflect light as a function of incident angle.

Signal-to-noise Ratio (SNR)
A ratio of the PST just inside the FFOV compared to just outside the FFOV.

\[ SNR = \frac{PST\text{(just inside FFOV)}}{PST\text{(just outside FFOV)}} \]

For example, if FFOV = 30°, then the PST just inside the FFOV would be measured around 14°, and the PST just outside the FFOV would be measured around 16°.

Baffle Requirements
The first half of the project requirements entails the proper modeling and construction of the diffuse and specular baffles.

Vane Design
The starting point for validating a FRED model of a specular black baffle involves the baffle geometry itself. The baffle design requirements identify the specific size and shape based on the specular and diffuse reflection mechanisms. The necessary equations for determining the baffle geometry are presented in a later section.

F/2, 30° FOV
A starting point for designing the baffle geometry is to define the optical system that will be placed behind the baffle. The F/# describes the amount (or bundle) of light that the system collects. The field of view (FOV) describes the maximum acceptance angles of the system (or what the system can “see”). Together these two parameters define the overall size and shape of the baffle.

For this project the F/# is 2, and the FOV is 30°. F/2 means the baffle length is twice the entrance diameter of the baffle. These two optical parameters simulate a typical aerospace telescope (e.g., VIIRS), which is part of the drive behind this entire project.
Paint Application

Isotropic

Perhaps the most critical step in building the physical baffles is the coating of the paint itself. The smoothness of the baffle coating will be the foremost uncertainty affecting the test data. This is because the reflection mechanisms are based off the angle of incidence between light rays and the surface. An isotropic (smooth) surface means the angle of incidence is constant everywhere. Bumps, scratches, and dirt will alter this incident angle and thus redirect the outbound path of light rays.

The requirement for the paint application is that the surfaces are qualitatively isotropic (smooth) based on the following procedure. To ensure that a smooth coating has been applied, the surface reflectivity is tested with a laser pointer. The laser pointer is aimed onto the surface at a sharp angle (almost parallel) and the reflected light is viewed on an adjacent wall. The specular paint is isotropic if the laser beam reflects into a single bright point on the wall. The diffuse paint is isotropic if the beam reflects into a very large area on the wall with uniform intensity everywhere.

5 layer coats

In a paper from Fermilab on the absorption of black paints, it was shown that the total reflectivity increases as the number of coats increases. For this reason, and to fill the machined grooves on the aluminum, the baffles are coated 5 times over. 5 layers is sufficient to pass the isotropic test outlined above.

Enamel paint

The diffuse paint choice is Testors enamel flat black. The specular paint choice is Testors enamel glossy black. Enamel paints do not need primer when being applied to machined aluminum, since the textured aluminum provides adhesion. Both paints successfully passed the test for isotropic surfaces when painted on some small aluminum samples.

One consideration when applying the two different paint types is the amount of thinner that must be added for either case. The flat black enamel mixture is 3 parts paint, 1 part thinner. The glossy black enamel mixture is 3 parts paint, 2 parts thinner. Upon drying the mixtures were inspected for opacity, and they both appear as expected.

Assembly

Aluminum 6061 alloy

The required material for making the baffle housing is aluminum 6061 alloy. 6061 alloy is a reliable structural material; it has low density, high strength, and is easy to apply coats onto. Both physical baffles will be machined by a CNC mill which directly imports the SolidWorks models.

The required surface roughness per ISO 1302 is N8, meaning that machining grooves will be visible on the aluminum. N8 is an intermediate surface roughness; coarse enough for paint to stick, but smooth enough to be covered up by a few layers of paint. N8 surface roughness is achieved with a standard CNC mill and aluminum 6061 alloy. Several aluminum samples have been prepared, and the surface roughness is ideal for applying paint.
633nm optimization
Both the FRED model and physical baffle design will be optimized for functioning at 633nm. This is because the BRDF measurement is conducted with a HeNe laser source.

Test Requirements
The second half of this project outlines the test procedure and data collection requirements.

Camera
The following requirements describe how using a camera core will affect the physical and computer baffle designs.

Pixel array
There are two options for an optical receiver: a simple photodetector, or a camera core. The photodetector gives a single voltage (or power) reading for any incoming signal; this output is essentially the same as the output from the MATLAB code described earlier. The camera gives an N x N array of voltages/power readings, based on the response at each pixel.

Two reasons are behind the need for a 2-dimensional image. First, an actual picture of what the stray light looks like will be useful to compare to the simulated FRED irradiance profiles. Second, the distribution of the stray light onto the receiver is very important for characterizing the SNR. Since a photodetector only gives one number, it is impossible to see the power distribution on the detector.

Responsivity ≥ 0.6A/W
The responsivity measures the efficiency of converting optical power into electrical current. A responsivity of 1 means that every photon is successfully converted into an output signal. If the responsivity is too low, there may be no data for stray light noise outside the FOV.

Variable integration time
Integration time describes the temporal interval over which the detector is collecting photons. Depending on the application, the integration time may need to be fractions of a second, or several minutes. The primary reason for a longer integration time is detecting dimmer light. A longer exposure time also compensates for a higher responsivity; the longer the exposure, the more photons get collected.

Detector depth < 1”
One of the most overlooked requirements of the baffle design is the location of the detector. Initially they were designed such that the detector rested flush against the back of the baffle, however this design is highly impractical. Most, if not all, consumer cameras have their detector recessed inside by about 1” or longer. For example, Nikon DSLR cameras (which we are not using) have a detector set at least 2” behind the front face of the camera to make room for shutters and other components.

The proposed limit to the length from the front of the camera to the detector must be no longer than 1”. The requirement originates from both the scale of the baffle’s physical dimensions and the size of the detector. The baffle length is roughly 5”, so adding 1” is a sizeable amount. However, the detector (~0.3” wide) is still relatively small compared with the baffle size, and this implies that the field of view
will be mostly unaffected. When the detector is set back 1” from the rear of the baffle in the FRED model, it was found that the field of view decreases by roughly 4°, which is not significant, and the FOV was not defined by a sharp edge but rather a linear falloff. As long as the FRED models parallel the physical baffle design and test setup, the data should agree.

Source

Solar spectrum

In the aforementioned subsystem descriptions, the aim of the test source is to simulate stray light from imaging the sun. Imaging the sun outside presents a number of uncertainties (weather, unwanted sources, etc.) which compromise the data’s reliability. Instead, the sun can be imitated by an optical source in the laboratory environment. The source is chosen based on having a power distribution vs. optical wavelength similar to that of the sun.

Observing the black body radiation figure below, it is true that the brightness of the source is proportional to the temperature. Intuitively, the hotter the source, the brighter the emission. From the figure below it is also true that the spectrum profile depends on temperature. The sun is a “white light” source because it emits across the visible radiation spectrum with relatively uniform brightness. Because the sun operates around 6000K, it is very hard to achieve this temperature (and hence its spectrum) in the laboratory environment.

Extended Source

The test setup requires an extended source; this means that the source must be a large enough area so that its edges can never be seen by the baffle. The drive behind this requirement is for calculating the stray light reduction ratio. The definition of the PST assumes that the baffle entrance aperture is completely filled with light. The quartz-halogen lamp emits over an area less than one square-inch, so the problem presented is that the lamp (by itself) is too small to fill the baffle.

Hardware and Fasteners

Several components are required in addition to the camera, baffle, and source. They must be secured onto a stable common surface with a number of fasteners. The baffle and camera also need to be mounted with a stable and precise rotation. What is most important here is that the threads match (¼-20).

Vary the angle of incidence

The fundamental quantity that both the test setup and the FRED model are trying to obtain is the point source transmittance (PST). The PST is a function of the angle of incidence between the source light and the entrance aperture plane. Therefore, the requirement is that this angle of incidence is varied in the test setup.

Kinematically constrained baffle

Mounting the baffle should not be underestimated because a faulty support could misalign the baffle or camera from the source. Furthermore, misalignments can go easily unnoticed while collecting data. The lenses, camera, and rotation stage are easy to mount because they have pre-drilled screw holes. The baffles are a custom design, and so a practical mount must be considered when machining.
The requirement is that both the baffle and the camera are securely mounted to the rotation state. The only intended degree of freedom for baffle movement is rotation about the front aperture, while the other two axes of rotation and all three dimensions of translation are kinematically constrained.

**Room temperature**

One of the less important risks to the test setup is the temperature of the baffle and detector. Primarily, if the irradiance of the light is too large, the temperature inside the baffle increases (also because aluminum has high thermal conductivity). Although this is unlikely with this project’s test setup, thermal management is a significant issue for real world telescopes, especially for systems faster than F/2. Furthermore, aerospace telescopes experience an extremely wide range of temperatures in the environment of space. The temperature can also affect the optical performance of the lenses and the source. The data is required to be taken at room temperature (~300K), and this must also account for any heat build-up inside the baffle.

**Summary of PDR Results**

All of the diagrams, engineering designs, and decision matrices are shown in Appendix B.

When designing our systems, our main concerns were the systems adaptability, machinability, simplicity, and cost effectiveness. Because our baffles are designed so that they would be able to be inserted to the front of any optical system, and restrict its FOV while also reducing stray light, regardless of the system it is used with. All of the designs that we made were equally adaptable. Since we needed to be able to physically make our baffles in order to test the accuracy of the computer models, we needed to take into account the difficulty of machining our designs. Fewer and simpler vanes would make the baffle easier to make. With the purpose of our project, it is important that our designs be relatively simple so that the data is easier to analyze and so that the published data would be easier to understand and grasp. The more attainable and repeatable our data, the more reliable our results will be. Finally, with our limited team budget, the cost effectiveness of our designs needed to be taken into account. In this cost effectiveness we looked at the actual cost of the materials for the designs as well as the cost of the time needed to make the parts.

With all of these considerations taken into account, we chose diffuse design 2 and specular design 1. We chose diffuse design 2 mainly because it had one less vane, and the distance between the last vane in design 1 and the end of the baffle is exceptionally small, making the machining more difficult. Specular design 1 was chosen mainly because it utilized straight vanes. The angled vanes had potential to perform better, but since our project is only to prove computer model accuracy, we did not need the added performance that the angled vanes provided, and they added a significant amount of difficulty to the machining.

**Subsystem/Sub-assembly and Interface Design**

**Reflection Mechanisms**

The focus for this project is on the Specular Baffle and verifying the ability of FRED to model the system. The diffuse model will be used for reference and control. Both baffles were carefully designed using the equations that are shown in the following section. These equations are tracing the limiting rays of the
system in order define the placement of each vane for optimal stray light reduction in both diffuse and specular scenarios.

For the diffuse design, the goal is to determine what light can hit the detector off of one reflection from a vane or baffle wall. Because this surface is diffuse, light will reach the detector as long as one ray can be traced that connects the incident spot and the detector.

For the specular design, the angle of incidence must equal the reflecting angle because of the law of reflection and again we are looking at the largest possible angle that could hit the detector. The part at the front of the baffle that hangs down from the edge is the baffle ‘lip’.

Outline of Baffle Design
Because the raytracing is an iterative process, the exact solutions to a given baffle geometry depend greatly on its size and the number of desired vanes. We confine our solutions to a baffle with N = 2 vanes, and only first-order reflections are considered (although the process is the same for higher orders).

Diffuse Design
In both designs, the driving characteristic is the way that the light will reflect off of the edge of the baffle. In the diffuse case, since light will reflect equally in all directions, the first ray was traced at the maximum possible angle that could enter the system. Another ray was then traced that directly connects the reflection point to the edge of the detector, since reflection angle is irrelevant.

Consider a two-dimensional coordinate system centered at the entrance aperture midpoint. The x-axis is the optical axis, and the y-axis is the radial plane. We henceforth define the entrance pupil as E, the exit pupil diameter as E’, the inner tube diameter as D, and the overall axial length as L.
First, trace a caustic ray to define the boundaries of the FOV that reach the collector. The caustic ray connects the inner edge of the entrance pupil with the edge of the detector.

\[ y_{ca}(x) = \frac{E}{2} + \frac{E' - E}{2L}x \]  

(1)

The first critical ray that hits the detector edge will be

\[ y_{c1}(x) = -\frac{D}{2} - \frac{D + E'}{2L}x \]  

(2)

The location of the first vane in the diffuse system is defined by the intersection of the caustic and first critical rays. The edge of the 1st vane is described by the point \((x_1, y_1)\). Solving this system, the 1st vane location becomes

\[ x_1 = \frac{L(D - E)}{2E' + D - E} \]  

(3)

\[ y_1 = y_{ca}(x_1) = \frac{E}{2} + \frac{E' - E}{2L}x_1 \]  

(4)

Now trace the second illumination ray from the bottom edge of the entrance aperture to the point of the first vane edge

\[ y_{i2}(x) = \frac{y_1 + E}{x_1}x - \frac{E}{2} \]  

(5)

The second critical ray is defined from the point where the second illumination ray hits the baffle edge, to the bottom edge of the detector. The intersection of the second illumination ray with the baffle edge will be located at

\[ x_{r2} = \frac{x_1(D + E)}{2y_1 + E} \]  

(6)

This intersection position is referenced from the first vane; note that \(x_{diff,2} > 0\) in most cases. The resulting equation of the critical ray will be

\[ y_{c2}(x) = \frac{D}{2} + \frac{D + E'}{2(L - x_{r2})}(x_{r2} - x) \]  

(7)
Repeat the process to find the 2nd vane coordinates with a system of equations where $y_{c2}(x) = y_{c0}(x)$

$$x_2 = \frac{D + E'}{L-x_{r2}} + \frac{D - E}{E' - E} + \frac{D + E'}{L-x_{r2}}$$

(8)

$$y_2 = y_{c0}(x_2) = \frac{E}{2} + \frac{E' - E}{2L}x_2$$

(9)

**Specular Design**

As with the diffuse design, the focus is on how the light would reflect off of the inner walls of the baffle. For the specular case, the reflected light will scatter at the same angle at which it entered the system. To design this baffle, the first construction ray intersects the edge of the baffle/vane, and reflects with the same angle to hit the detector. These rays represent the steepest angled rays that can actually reflect and hit the detector.

The following discussion outlines the basic principles of the specular baffle design. The guiding principle of the specular design is that the reflection of a ray off the baffle wall should obey the law of reflection. In other words, the angle of the illuminated and critical rays must be equivalent where they intersect each other. The caustic ray (eq. 1) is the same as for the diffuse design.

$$y_{c0}(x) = \frac{E}{2} + \frac{E' - E}{2L}x$$

(10)

The position of the first baffle vane correlates to the position of the first specular reflection. The critical ray is slightly different from the diffuse case here,

$$y_{c1}(x) = \frac{E'}{2} - \frac{D + E'}{2(L-x_{r1})}(x-L)$$

(11)
Using similar triangles between the illumination and critical rays, the point of specular reflection can be found from the illumination ray and the physical baffle parameters

\[ x_{r1} = \frac{L(D - E)}{2(D - E + E')} \]  

(12)

where \( x_{\text{spec},1} \) (usually > 0) is the distance from the entrance aperture to the point of the first specular reflection. So the first vane will be located where

\[
\begin{align*}
x_1 &= \frac{L(D + E') - E - E'}{E' - E + D + E'} \left( \frac{L}{L - x_{r1}} \right) \\
y_1 &= y_c(x_1) = \frac{E + E' - E}{2L} x_1
\end{align*}
\]  

(13)

(14)

Typically, the locations of the specular reflections are referenced from the previous vane or entrance aperture to the point of the reflection on the baffle inner diameter, so \( x_{\text{spec},1} > 0 \), \( x_{\text{spec},2} > 0 \). The vane coordinates are usually \( y_{\text{vane}} > 0 \), and \( x_{\text{vane}} < 0 \) (since everything is left of the detector).

The illumination and critical rays, respectively, are found to be

\[
\begin{align*}
y_{i2}(x) &= \frac{D}{x_{r2} - x_1}(x - x_1) + y_1 \\
y_{c2}(x) &= \frac{E' + D}{2(L - x_{r2})}(L - x) - \frac{E'}{2}
\end{align*}
\]  

(15)

(16)

The second point of specular reflection is

\[
x_{r2} = \frac{L(D - 2y_1) + x_1(D + E')}{2D + E' - 2y_1}
\]  

(17)

The second vane edge is located at the following coordinates

\[
\begin{align*}
x_2 &= \frac{D + E'}{L - x_{r2}} x_{r2} + D - E \\
&= \frac{E' - E}{L} + \frac{D + E'}{L - x_{r2}} \\
y_2 &= y_c(x_2) = \frac{E + E' - E}{2L} x_2
\end{align*}
\]  

(18)

(19)

**Equation Constraints**

The equations only consider first-order reflections. We found that the equations are only reliable with systems of F/2 or slower; the reason being that the tube width cannot accompany more than \( N = 1 \) vane
if the system is less than F/2. A rule of thumb is that the number of vanes that will fit into the baffle is roughly equal to the system’s F/#

\[ \text{# of vanes} \approx F/# \]

Vane Design
Once the exit pupil diameter, baffle length, ‘lip’ depth, and inner diameter are specified, the entire baffle system can be created with ease no matter how big the system is. The length is chosen based on the realistic size of similar baffles, while the exit pupil diameter is determined by the detector size. All other variables held constant, the ‘lip’ depth only affects the vane placement, all of which will be at their ideal placement if the equations above are used. The minimum thickness and depth of that ‘lip’ is determined solely by machinability. As the lip is shortened, the vane placement is changed so that a third vane is required in the diffuse design. This increases cost and decreases ease of machining.

Although the optimal baffle design uses vanes that are infinitely small, the physical baffle must have vanes with some finite thickness. The material being used is Aluminum 6061 and has a limit to how thin it can be before losing rigidity. For this reason, the vanes had to be thickened to 1/16 of an inch so that they can be still; be machined with a high level of accuracy. This thickness was expanded about the center of the vane so that the physical baffle more closely matches the ideal prediction.

For the Preliminary Design Report we came up with 4 total baffle designs, two specular and two diffuse, shown in the appendix. The two diffuse designs follow exactly the diffuse design equations, and as explained above, the difference in lip depth selected for each design changed the placement of the vanes and adding a third one in this case. The simplest design was selected based on the virtue of having fewer vanes, in accordance with the diffuse design evaluation matrix.

The two specular designs maintain the same lip depths and vane placements with one of the designs featuring angled vanes. This 45° angle will cause every ray that enters the baffle from outside of the field of view to undergo at least three reflections, resulting in a greater loss of power than the straight vanes. While this figure would increase the performance and reject more stray light, the specular design evaluation matrix revealed that the simplicity of the straight-vane design resulted in the better option, especially because higher performance is not the goal of this project. Both of the evaluation matrices are shown in the appendix.

Paint Application
The ability to apply a consistent coat of paint to the inside of the baffle walls is essential to this project. The paint application must be consistent within each baffle, such that the performance of the baffle is not adversely affected. In addition, the paint application must be the same on each BRDF sample and the physical baffles, as the BRDF samples must act as representative of the physical baffles.

Ideally, the paint would be applied in a clean room where there would be little to no dust particles that could affect the paint. However, careful attention to the cleanliness of the samples and the environment will function as a solution for the purposes of this project. In addition, instead of using a paintbrush or spray paint can that have potential to be uncertain in coats thickness and repeatability, a model airbrush attached to an air compressor will be used. The air compressor can be set to a specific pounds per square inch (psi). The psi is set at 22 for the paint application of the baffles as a higher psi caused the paint to spread unevenly, and a lower psi did not provide enough power for the paint to be sprayed.
From this point, enamel paints will be used. Enamel paint has a fast drying application and is more durable after application than latex based paints. In order to use enamel in the airbrush system, the paint shall be thinned out using a 3:2 paint to thinner ratio for flat black and a 3:1 paint to thinner ratio for glossy black. The thinning ratio is another step to repeatability. Before painting each baffle, the entire airbrush system will need to be cleaned for the new paint and the mixtures carefully measured in a measuring cup. After the paint set up is completed, there will be five coats of paint applied to the baffle from a distance of approx. 5 centimeters. Each coat is left to dry for a minimum of five minutes which will allow each coat to adhere. Enamel paint has the added benefit of being easily removable with paint thinner, thereby reducing the impact of any errors made during the painting process.

In order to verify that the paint has been properly applied, a laser test provides a visual inspection. In the case of the diffuse paint, a laser pointer shining on the painted surface produces a scattered reflection, with no significant visible correlation between the input angle and the resulting reflectance pattern. In the case of the specular paint, aiming a laser pointer at the sample results in a round circular reflection, with no evidence of streaking.

Assembly
In order to create the actual baffle, the machining process had to be perfected. The hard to reach areas in the baffle made for a difficult machining process. In addition, the baffle must be assembled such that it is possible to evenly and accurately paint the interior surfaces. In order to aid in this process, the baffle will be split into sections that will then come together and assemble an entire baffle, either diffuse or specular.

The baffle may not be cut out of one block of aluminum due to the limitations that the machine shop presents. If the baffle were to be cut out of one solid block, a 5 axis CNC mill would be needed. The machine shop that has given space to the project only has a 3 axis CNC mill so other methods need to be used. Because of this, the baffle shall be cut at each vane then added to the rest of the system, i.e.: as a washer. At the end of this process each section will be held together using four bolts that will span the length of the system to combine the entire baffle, both specular and diffuse.

In order to reduce machine time and simplify the testing process, the outer edges of the baffle will be left square. The aluminum may then be ordered as a square block which is both easier to order and easier drill screw holes in for mounting without messing up the rest of the baffle. The extra aluminum on the corners of the bar also allow the rods holding the baffle together to go through pieces that are irrelevant to our performance.

System Test Setup
The purpose of the test setup for our baffle system is to characterize the point source transmittance, or PST, of the system. The PST is a relationship between the incident power on a surface and that surfaces area giving it units of $W/m^2$ (per unit intensity). Because all of the light that is in the field of view should reach the detector, the ratio of PST values for the entrance and exit apertures should be one. Since the light outside the field of view should ideally never reach the detector, the ratio should sharply become zero outside the defined range.
Each of the two baffles was tested five times (one measurement taken at one degree increments from -90 to +90 degrees). Then, each baffle was rotated 90 degrees about the optical axis and tested five more times. These measurements are referred to as “Side 2”, as opposed to the previous “Side 1,” referencing the change in the side that the baffle was resting upon. This resulted in twenty total sweeps. A mounting plate was utilized on top of the rotation stage to ensure repeatability when the two baffles were exchanged. Each baffle was tested under the same conditions:

- Broad-spectrum white light source
- Collimated beam of diameter greater than the Entrance Pupil, such that the Entrance Pupil is always filled
- One sweep: baffle is rotated from -90° to +90°, with images recorded in increments of 1°
- Center of rotation is at the Entrance Pupil
- Sensor is mounted at Exit Pupil using a level for repeatability
- Dark measurement is used for calibration
- No other sources of stray light are present in the laboratory

Figure 6: Full laboratory test setup. From right to left: Light source, first collimating lens, second collimating lens, third collimating lens, baffle mounted on rotation stage.
Camera
The ideal solution for mounting the detector on the system would be to place it exactly at the Exit Pupil of the baffle. If this were possible, the PST could be calculated from the intensity distribution simply by dividing the detector output by its area. However, most off-the-shelf camera systems have mechanical assembly inside the camera that sets the detector back from the front edge; therefore, the detector will not be placed directly at the Exit Pupil of the baffle system. Rather, there will be an offset.

The chosen solution is a Thorlabs DCC 1240x sensor. It has a CMOS detector, so each pixel may be viewed individually. Its detector is 6.784 x 5.427mm. This camera is designed for use with a C-mount, which has an exact sensor depth of 17.526mm. This fits the requirement of <1". One of the most important things about this camera is its variable exposure times of up to 30sec, which allow very small amounts of light to be collected by the detector. This ended up being an unnecessary feature, since the integration time was less than 1ms in the end due to camera saturation.

Source
In most baffle systems, the biggest contributor to stray light is the sun. Because it is so bright and so close astronomically it poses a real problem to optical systems. Because of this, a source that would closely resemble the specular output of the sun was used. The sun is a very good example of blackbody radiation, which has a spectral output that has a direct relationship to the temperature of the source. This can be approximately achieved with a halogen source. These sources operate at very high temperatures which are close to those of the sun so they produce a similar spectral output. The ideal and halogen comparison is shown below.
Halogens can be made with many different types of materials. The type that was readily available to use in the test setup is a quartz-halogen fiber optic illuminator.

**Hardware and Fasteners**

The test setup must be performed on some sort of table that allows each individual component to be locked into place so the system is constant throughout the testing procedure. This is achieved with an optical table from Newport optics. In order to maintain the proper alignment of the system, the table is rated to have a deflection under loading that is $<5 \times 10^{-5}$ in. The table models that we have available to us in labs on the university campus use $\frac{3}{8}$-20 screws that are in a 1 x 1 in grid on the table surface to allow for attachments to the table. Because of this all of the screws that will be used in this set-up are going to be $\frac{3}{8}$-20 screws. This thread callout refers to the diameter of the screw without the threads and the number of threads per inch on the screw. These screws are standard for most imperial optical devices, including the rotational stage that we will be using.

The rotational stage has the option to move both rotationally and horizontally. It has a very high accuracy rotationally, which is the only way that we will be using the stage, of $0.01^\circ$ and a diameter of 110 mm. This stage was chosen with the diameter being the parameter of focus. Because the entrance aperture of the baffle must be located at the center of the rotational stage, the stage must support the off-center weight of the baffle and maintain its accuracy. Since the baffle itself needs to be mounted to the rotational stage, screw holes are drilled into the bottom face of the baffle shell so that an optical stand can be connected. A similar $\frac{3}{8}$-20 screw hole is already present on the camera for mounting to a tripod (an optical stand will be used instead). These stands are then inserted into an adjustable stand holder that can be fastened directly onto the rotation stage. There is a set of $\frac{3}{8}$-20 screw holes that are at pre-defined locations on the stage allowing for the proper alignment of the baffle and camera on the stage. Since all system components, excluding the lenses and light source, are going to fit on the stage, the camera will move with the baffle as the stage rotates.
The last part of the test set-up are the lenses. The only purpose of these lenses is to collimate the incoming light into a beam that can fully fill the entrance aperture of the baffle. The only requirement that this creates is the use of a large diameter lens as the collimating lens. Three lenses are borrowed from the College of Optical Science. The first two provide enough power such that the third lens, which is larger in diameter than the Entrance Pupil, can collimate the incoming light.

Algorithm Description and Interface Document

Since the purpose of this project is to verify a computer model, a computer model needed to be made. With the use of FRED optical modeling software, we were able to accurately replicate both of our designs as computer models. MATLAB was then used to process the data after an image was saved at each test angle.

FRED Algorithm

To speed up the process of the simulation, a script was written in FRED that would automate the process for us. This script is essentially a computer version of the test set-up previously described. A source is created with 10,000,000 individual rays which are then traced through the system. The propagation angle of these rays is then changed from 0-90 degrees. The reason that the simulation is only done from 0-90 degrees is because the computer simulation produces the exact same results since the paint application is perfectly uniform in the model. We were able to take the measured BRDF data from our paint samples and apply them to all of the internal surfaces of the baffle. This allowed FRED to accurately predict reflected ray angle regardless of the incident angle of the ray.

Below are the results of the BRDF matching that was used in FRED. It is almost impossible for FRED to perfectly match the measured BRDF data because it must represent it with a smooth, constant mathematical equation. The difficulty in this is that the data that it is interpolating has the 3 angles that our samples were tested at (5°, 55°, and 80°) and then must try to project the curve matching these 3 angles to a full range of angles from 0-90°. The figures below show the measured data and the functions that FRED used to match the data.

Figure 9: Measured BRDF data: Specular Paint
MATLAB Algorithm

In the MATLAB script, the functionality is essentially to read in the captured images and calculate the total pixel intensity. The main issue presented by this script was the various factors contributing to inaccurate data. First, since the detector was not located exactly at the exit pupil of the system, some light was clipped at the edge of the detector, causing the total intensity to linearly decrease as the angle was increased. To account for this, a linear fix was applied by calculating the area that was being clipped by the detector, scaling the total on axis intensity to that area, and adding it back into the calculation. This concept is illustrated below.
Figure 13: Images taken at Exit Pupil. Left: 0° incident angle. Right: +12° incident angle. A linear fix may be applied to the measured data to account for the loss in intensity when vignetting of the image occurs, as above.

The other factor that was taken into account when using this script was a cosine factor. When the entrance pupil is normal to the incoming collimated light, a circle of light is formed; however, when the baffle is rotated, a factor of the cosine of the angle of rotation is introduced (shown below).

Figure 14: Entrance Pupil at increasing angles of incidence from left to right. The Entrance Pupil shape no longer appears circular at higher angles of incidence; a cosine factor is attributable to the decrease in pupil area.

Analysis

The analysis of the data that is collected from the physical tests is performed by the MATLAB code that is described above and included in the appendix. Once the data was gathered and processed, it was compared to the theoretical computer model and script.

Data Processing

In total, each baffle had ten sets of 181 images. Using a script written in MATLAB (see appendices), the total intensity present in each image was calculated. From this data, the Point Source Transmission (PST) was calculated at each angle and averaged over the ten sets of data for each baffle. The PST was also calculated at the Entrance Pupil using a similar procedure. Next, the PST Ratio was calculated as a function of angle for each baffle. This is the ratio of the PST at the Exit Pupil to the PST at the Entrance Pupil. Shown below are these results for the diffuse baffle, before any further processing was applied.
As shown above, the PST Ratio appears to be triangular in shape, as opposed to the expected rectangle within the field of view (-14 to +14 degrees). This is due to the loss of light that occurs as we increase the angle within the field of view as described in the MATLAB script above. Within this range, the image of the entrance pupil is cut off at higher angles (Figure 13 above).

It is apparent in the plot shown above that there is a slight upward curve of the PST at the outer boundaries of the field of view. This upward trend is attributable to the elliptical appearance of the entrance pupil at larger incident angles. When this cosine factor is adjusted for, the upward trend at the boundaries of the field of view is eliminated, as shown below.
Specular Paint Inconsistencies

The specular data displayed an asymmetrical feature, whereas the expected data should be symmetric about the 0 degree axis. Looking more closely at the raw images from Side 1 of the specular baffle, streaks of light are discovered in the images taken at negative angles, but not on the positive side of 0 degrees (shown below). These streaks are due to inconsistencies in the applied paint. In images taken from Side 2 of the specular baffle, the streaks were present on the positive side of 0 degrees, consistent with our findings. Averaging the data from each side together removes the irregularities (Figure 19).

![Image of specular baffle with streaks](image)

Figure 18: Images taken at Exit Pupil; Specular Baffle, Side 1. Left: -10° incident angle. Right: +10° incident angle. The left image shows streaks of light contributing to the intensity measurement.

Comparison to FRED Analysis

The measured results were then compared against the results predicted by FRED. The data, compared to the FRED analysis in Figure MM, shows a higher PST Ratio for both the specular and the diffuse baffles. In the diffuse case, the measured PST ratio rises above a value of 1, which is considered impossible since we are not using a focusing system, as that would imply that more light is leaving the system than is entering it. In both cases, the error is an approximately constant factor of 1.16 as shown in the table below. This implies that the issue is caused by a constant amount of stray light entering the system. Because the error is constant offset that occurs in both the diffuse and specular cases, we may conclude that the specular prediction model in FRED operates as well as the diffuse prediction model in FRED.
Diffuse

Specular

Figure 19: The PST Ratio predicted by FRED is compared to the measured PST Ratio. The measured ratio is higher than the predicted ratio in both the diffuse and specular cases. The measured ratio for the diffuse baffle rises above a value 1, which implies that more light is leaving the Exit Pupil than is entering it. This is probably caused by stray light entering the system, as both the specular and diffuse baffles show a consistent increase in PST Ratio.

<table>
<thead>
<tr>
<th>Baffle Type</th>
<th>Offset from predicted at 0deg</th>
<th>Predicted Edge ratio</th>
<th>Measured Edge Ratio</th>
<th>Offset from predicted edge ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffuse</td>
<td>1.160244753</td>
<td>264.4709731</td>
<td>37.97169471</td>
<td>6.964950473</td>
</tr>
<tr>
<td>Specular</td>
<td>1.158395172</td>
<td>107.4676789</td>
<td>23.96267195</td>
<td>4.484795316</td>
</tr>
</tbody>
</table>

Table 1: Performance comparison of specular and diffuse baffles. The main consideration for our data is the ratio from just inside the field of view to just outside the field of view. With this data we were able to show that the specular baffle actually matched the computer model to higher degree of accuracy than the diffuse.

Implementation of Development Plan

Several key milestones that occurred throughout the build, test, and analysis phases of the project are now outlined.

Build Plan

The schedule that was put together anticipated that the machining process would begin by mid-December. This was not the case as there were some design clarifications that needed to be made, specifically with how to take into account the recessed detector. The difficulty arising with a detector that was not exactly at the exit of the baffle was that the designs would not match up with the physical baffle. Once this recessed detector was designed around the machining process could begin.

The machining process for the baffles consisted of three main steps: putting the designs into a 3D CAD software like Solidworks, an idea of how the actual manufacturing will be done, and finally generating sets of G-Code in order to run a CNC mill.

The first step of getting a 3D model of the baffle into Solidworks was halfway completed from the design phase. The reason that the design phase only got a portion of the 3D model done was because that model did not account for manufacturing of the baffles. This is how the second step of the machining process comes into play.
In order to actually get the physical baffles that were designed, it was determined that with the tools available to the team, it was necessary to split each baffle into three sections based on the vane locations. This was implemented due to the inability to make the precise cuts into the baffle without the splitting. Since the baffle was going to be three separate pieces coming together as one, the priority became to keep the inner dimensions exact. A fixture plate was created in order to do this and keep an origin on the CNC mill throughout the whole machining process.

The final step to the machining process was to generate the G-Code for each one of these baffle sections. In order to save time and not waste hours of manual G-Coding, a CAM software was used called MasterCam X7. This would take the 3D model from Solidworks and generate the G-Code based on predetermined cutting paths. Then this G-Code was loading into a HAAS CNC mill to complete the machining process.

Once the machining was completed for both the specular and diffuse baffles, the painting process began.

The painting process of the baffles was very rigorous in a sense that the paint coats needed to be applied evenly for both baffles and relative to each section. To make sure of sufficient testing quality, each section was painted with the same mixture of paint that was used on the sample pieces that got sent out for BRDF testing. They were applied one coat at a time and let dry for 15 minutes before repeating this for 5 times in total. This painting process was conducted in a paint booth to reduce the chances of allowing dust and other particles from ruining the inside of the painted baffles.

**Test Plan**

The test setup was designed and fully functional by early February. Testing was delayed due to the delay in machining and painting the baffles. The testing began in early March and was completed by late March. As planned, groups of two worked in scheduled shifts to records sweeps of the data.

After the first set of image files were taken, the FOV of the baffle was verified to be +/- 14 degrees and the stray light distribution was qualitatively verified to behave as expected. With these conditions met, post-processing in MATLAB began.

Once multiple sets of data were recorded, these were averaged to reduce errors and ensure correct functionality of the test setup. At this point, testing was complete. If inaccuracies in the reported data had been found, the contingency plan was to determine whether the data was undergoing a systematic error in the baffle design, or some stochastic process elsewhere. Since the data was shown to be accurate, this contingency plan was not implemented.

**Analysis Plan**

Data processing was an ongoing process while collecting measurements in order to streamline the project as a whole. Data processing was performed with MATLAB, so that test images could be quickly imported and analyzed. The MATLAB code was debugged and completed with the first round of data that was collected. This mitigated any errors in the setup and allowed for immediate adjustments to the code. It was a milestone to have all processed data before the conclusion of testing. This way, testing could have continued until the data was certain to be accurate.
Also during the course of data collection, work was underway on a research paper to detail the full process and analysis of the project results. During the summer the paper can be finalized and submitted for review at Raytheon prior to being submitted to an optical sciences journal.

Requirements Review/Acceptance Test Plan

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Reason</th>
<th>Solution</th>
<th>Compliance?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baffle Requirements</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vane Design</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F/2 30° FOV</td>
<td>Efficient design; typical optical values for aerospace telescopes</td>
<td>2.45” diameter entrance aperture 4.5” inner tube length</td>
<td>Y</td>
</tr>
<tr>
<td>Paint Application</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isotropic surfaces</td>
<td>Surface defects affect reflected light paths</td>
<td>Dual-piston compressor, siphon feed airbrush</td>
<td>Y</td>
</tr>
<tr>
<td>Multiple coatings</td>
<td>Increase reflectivity and smoothness</td>
<td>5 layer coatings</td>
<td>Y</td>
</tr>
<tr>
<td>Enamel paint</td>
<td>Does not need primer</td>
<td>Testors enamel flat and glossy black</td>
<td>Y</td>
</tr>
<tr>
<td><strong>Assembly</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al 6061 alloy</td>
<td>Good structural material</td>
<td>Mill parts with surface roughness N8</td>
<td>Y</td>
</tr>
<tr>
<td>633nm optimization</td>
<td>BRDF measurements conducted @ 633nm</td>
<td>Use 633nm for FRED stray light analysis</td>
<td>Y</td>
</tr>
<tr>
<td><strong>Test Requirements</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Camera</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pixel array</td>
<td>2D stray light distribution</td>
<td>Thorlabs DCC 1240x detector</td>
<td>Y</td>
</tr>
<tr>
<td>Variable Exposure time</td>
<td>Longer integration time collects dimmer signals</td>
<td>Thorlabs DCC 1240x has exposure time</td>
<td>Y</td>
</tr>
<tr>
<td>Detector depth &lt; 1”</td>
<td>Detector offset reduces FOV</td>
<td>Thorlabs DCC 1240x has detector depth of 17.542</td>
<td>Y</td>
</tr>
<tr>
<td><strong>Source</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar spectrum</td>
<td>Simulate sun and white light source</td>
<td>Quartz-halogen lamp</td>
<td>Y</td>
</tr>
<tr>
<td>Extended source</td>
<td>PST definition</td>
<td>Fiber optic illuminator</td>
<td>Y</td>
</tr>
<tr>
<td><strong>Hardware and Fasteners</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vary the angle of incidence</td>
<td>Test the PST as a function of angle</td>
<td>Mount the baffle on a rotation stage</td>
<td>Y</td>
</tr>
<tr>
<td>Kinematically constrained baffle</td>
<td>No movement except rotation on stage</td>
<td>Threaded holes on baffle; screw to stage</td>
<td>N</td>
</tr>
<tr>
<td>Room temperature</td>
<td>Nominal optical performance</td>
<td>Climate-controlled laboratory</td>
<td>Y</td>
</tr>
</tbody>
</table>

Table 2: Requirements Review and Performance
Baffle Requirements
The first half of the project requirements entails the proper modeling and construction of the diffuse and specular baffles.

Vane Design
The starting point for validating a FRED model of a specular black baffle involves the baffle geometry itself. The baffle design requirements identify the specific size and shape based on the specular and diffuse reflection mechanisms. The necessary equations for determining the baffle geometry are presented above.

F/2, 30° FOV
The solution is to build the baffles with a 2.45” diameter entrance aperture and a 4.9” inner tube length.

Paint Application
Isotropic
The solution to apply the paint is using a dual-piston air compressor and a siphon-feed airbrush. The dual-piston offers a more constant flow of air than a less expensive single-piston. The siphon-feed airbrush (as opposed to a gravity-feed) automatically pumps paint into the brush tip. This is important so that the airbrush can be held in any position when painting. A gravity-feed airbrush is less reliable in that the brush must always be aimed downwards for a constant flow.

5 layer coats
In a paper from Fermilab on the absorption of black paints, it was shown that the total reflectivity increases as the number of coats increases. For this reason, and to fill the machined grooves on the aluminum, the baffles are coated 5 times over. 5 layers is sufficient to pass the isotropic test outlined above.

Enamel paint
The diffuse paint choice is Testors enamel flat black. The specular paint choice is Testors enamel glossy black. Enamel paints do not need primer when being applied to machined aluminum, since the textured aluminum provides adhesion. Both paints successfully passed the test for isotropic surfaces when painted on some small aluminum samples.

One consideration when applying the two different paint types is the amount of thinner that must be added for either case. The flat black enamel mixture is 3 parts paint, 1 part thinner. The glossy black enamel mixture is 3 parts paint, 2 parts thinner. Upon drying the mixtures were inspected for opacity, and they both appear as expected.

Assembly
Aluminum 6061 alloy
The required material for making the baffle housing is aluminum 6061 alloy. 6061 alloy is a reliable structural material; it has low density, high strength, and is easy to apply coats onto. Both physical baffles will be machined by a CNC mill which directly imports the SolidWorks models.
The required surface roughness per ISO 1302 is N8, meaning that machining grooves will be visible on the aluminum. N8 is an intermediate surface roughness; coarse enough for paint to stick, but smooth enough to be covered up by a few layers of paint. N8 surface roughness is achieved with a standard CNC mill and aluminum 6061 alloy. Several aluminum samples have been prepared, and the surface roughness is ideal for applying paint.

633nm optimization

The solution in the FRED model will still use a simulated white light source because that is what will be used for the actual testing. The physical baffle geometry does not depend on the wavelength of light.

Test Requirements

The second half of this project outlines the test procedure and data collection requirements.

Camera

The following requirements describe how using a camera core will affect the physical and computer baffle designs.

Pixel array

The solution is to use the Thorlabs DCC 1240x. The sensor size is 6.784mm x 5.427mm with an effective resolution of 1.3 megapixels. The DCC 1240x has another advantage in that its detector has an anti-reflective coating. Secondary reflections can bounce off the detector and back into the baffle, affecting the stray light data.

Responsivity ≥ 0.6A/W

The responsivity is required to be at least 0.6 amps per watt for cost issues more than anything else. A more responsive detector than 0.6A/W marks a price increase of several hundred dollars. The solution is to use the Thorlabs DCC 1240x which has a variable gain up to 4x and an initial responsivity of about .2A/W. This gives it the potential for a responsivity of .8A/W.

Variable integration time

With the Thorlabs DCC 1240x detector, we can vary the integration time from .0009ms to 2000ms. With the variable gain that we can control, this will give us more than enough variables to ensure that we are not saturating the detector within the defined FOV, while we are also detecting enough light to be above the noise floor of the detector when we are outside the FOV.

Detector depth < 1”

The Thorlabs DCC 1240x has a detector depth 17.542mm. The FRED model will be made compatible by adjusting the distance from the detector plane to the back wall of the baffle. A recessed hole was machined into the back end of the baffle so that the camera can be as close to the actual system as possible. The detector depth is a quite troublesome requirement, because the ideal camera (detector depth = 0) that is needed for the baffle design is not commercially available.
Source

Solar spectrum
The solution is to use a quartz-halogen lamp. Halogen lamps operate at much higher temperatures (~4100K) than incandescent (tungsten) filaments. As a result its spectrum more closely resembles that of the sun. Visually, the quartz-halogen lamp emits a white light that looks much closer to the sun than incandescent lights. Since the camera is really only collecting visible light data, it is most important that visible radiation spectrum is on par with the solar spectrum.

Extended Source
The solution is a simple retrotelescope placed in front of the lamp, shown in the picture below. A magnifier lens enlarges the lamp beam into a collimator lens, and the collimating lens picks up the expanded beam and sends it into the baffle entrance aperture.

![Figure 20: Sample retrotelescope setup.](image)

Although the size of the magnifier does not matter, the collimator must have a diameter larger than the entrance aperture of the baffle. An extended source means that the lamp light must totally fill the front baffle opening, even as the baffle is rotated. To account for rotation, misalignment, and table vibrations, the collimator diameter will be larger than the aperture diameter.

Hardware and Fasteners
Several components are required in addition to the camera, baffle, and source. They must be secured onto a stable common surface with a number of fasteners. The baffle and camera also need to be mounted with a stable and precise rotation. What is most important here is that the threads match (¼-20).

Vary the angle of incidence
The solution is to mount the baffle and camera onto a rotation stage. The high precision rotation stage used moves in 1° increments, which is convenient because the FRED script also collects PST measurements in 1° increments. In both the FRED script and the physical test setup, the baffle must collect images of the source while the angle of incidence is varied from -45° to +45°.
Kinematically constrained baffle
The solution for mounting is to drill three ¼-20 threading holes into the baffle’s underside. The rotation stage contains a 1” x 1” grid of ¼-20 threaded holes. Three threaded posts can then be screwed into the baffle, and the posts can then be fastened into post holders which are locked onto the rotation stage. The camera already has a ¼-20 threaded hole on its underside, so it can also be attached to the rotation stage using a post and post holder.

The rotation stage will be mounted onto a Newport optical table. The table contains a 1” x 1” grid of threaded holes. The table is also equipped with shock absorbers which dampen vibrations from the floor of the building. The table vibrations have been measured to be 5*10^{-5} inches in maximum displacement, which is too small to affect the baffle alignment. Along with the rotation stage, the two lenses and the quartz-halogen lamp will be axially aligned on the optical table. Each lens will be retained by a V-groove lens holder and fastened onto the table by a threaded post and post holder.

Room temperature
The solution is a climate-controlled laboratory environment with a thermostat. Most of the heat will be dissipated by the lenses before it reaches the baffle entrance.
References

Breault, Robert P. “Specular Black Vane Cavities”.


Appendix A: Team Member Contributions

1. Alexandra Schluntz
   a. Introduction
   b. Project Directive
   c. What is a Baffle?
   d. Specular vs. Diffuse Reflection
   e. Top-Level Requirements
   f. Top-level Design

2. Anthony Babicke
   a. Subsystem/Sub-assembly and Interface Design
   b. Baffle
   c. Vane Design
   d. Paint Application
   e. Assembly

3. Patrick Thrasher
   a. System Test Setup
   b. Camera
   c. Source
   d. Hardware and Fasteners
   e. Algorithm Description and Interface Document
   f. Analysis

4. Michael Portugal
   a. Development Plan
   b. Budget and Suppliers
   c. Requirements Review/Acceptance Test Plan

5. Ashley Lancaster
   a. Risk Analysis and Mitigation
   b. Project Management Update
   c. Closure
   d. Appendix
Appendix B: Designs

Diffuse Design 1

Diffuse Design 2
Specular Design 1

Specular Design 2
### Specular Black Baffle Design

#### Final Report

5/7/14

---

#### Diffuse Baffle Comparison and Scoring

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Weight</th>
<th>Score</th>
<th>Reason</th>
<th>Score</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptability</td>
<td>0.35</td>
<td>10</td>
<td>Non-reimaging</td>
<td>10</td>
<td>Non-reimaging</td>
</tr>
<tr>
<td>Machinability</td>
<td>0.25</td>
<td>10</td>
<td>Possible</td>
<td>10</td>
<td>Possible</td>
</tr>
<tr>
<td>Simplicity</td>
<td>0.25</td>
<td>6</td>
<td>Extra Vane</td>
<td>9</td>
<td>EP Size</td>
</tr>
<tr>
<td>Cost Effective</td>
<td>0.15</td>
<td>7</td>
<td>Machining Time</td>
<td>8</td>
<td>Machining Time</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.0</strong></td>
<td><strong>8.55</strong></td>
<td></td>
<td><strong>9.45</strong></td>
<td></td>
</tr>
</tbody>
</table>

---

#### Specular Baffle Comparison and Scoring

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Weight</th>
<th>Score</th>
<th>Reason</th>
<th>Score</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptability</td>
<td>0.35</td>
<td>10</td>
<td>Non-reimaging</td>
<td>10</td>
<td>Non-reimaging</td>
</tr>
<tr>
<td>Machinability</td>
<td>0.25</td>
<td>10</td>
<td>Possible</td>
<td>10</td>
<td>Possible</td>
</tr>
<tr>
<td>Simplicity</td>
<td>0.25</td>
<td>9</td>
<td>Two vanes</td>
<td>5</td>
<td>Angled vanes</td>
</tr>
<tr>
<td>Cost Effective</td>
<td>0.15</td>
<td>8</td>
<td>Machining Time</td>
<td>7</td>
<td>Machining Time</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.0</strong></td>
<td><strong>9.45</strong></td>
<td></td>
<td><strong>8.3</strong></td>
<td></td>
</tr>
</tbody>
</table>
Appendix C: FRED and MATLAB Scripts

FRED Script

Sub Main
    ' This script computes the PST for the baffle

    Dim sourceID As Long, numAng As Long, i As Long, detectorID As Long
    Dim dAng As Double, angle As Double, PST As Double, Multiply As Double

    ' Initialize
    sourceID = FindFullName( "Optical Sources.Quartz-Halogen" ) ' determine the source
    Multiply = PI() ' constant
dAng = 1
numAng = (90-0) / dAng ' sweep from 0 to 90 degrees
For i = 0 To numAng-1
    angle = 0. + (i * dAng)
    SetSourceDirIthMultiAngle sourceID, 0, 0, -angle, True ' set source angle
    EnableTextPrinting False
    TraceCreate
    EnableTextPrinting True
    PST = cos(angle) * GetSurfAbsorbedPower(detectorID) / (Multiply * (.155^2))
        'determine incident detector power and calculate PST with cosine factor accounted for
    Print angle;", "; PST ' print result
Next i

FindFullName: This function searches through all of the definitions within the computer model and finds the string that has the quoted name, applying those properties to the listed variable. Each "." represents a subsystem in the model.

SetSourceDirIthMultiAngle: This function is used to set the angles of propagation for a source. sourceID was defined as the Quartz-Halogen source and the first zero defines the zero-based index of the particular angle. The next 2 numbers define the x and y angles of propagation respectively. The true is saying that the newly defined angle is now the new angle of the source.

The next set of lines are best defined as a set.
    EnableTextPrinting False
    TraceCreate
    EnableTextPrinting True

These three lines create the ray trace that is used for the PST calculation but prevent the defined rays from being shown in the text window since the rays themselves are never directly needed by the user.

GetSurfAbsorbedPower: This function looks at the node that is input to it and calculates the power that hits the surface

PST: This calculation is retrieving the power on the surface and dividing by its area. Because the PST at the entrance aperture is 1, this PST value is also the PST ratio between the entrance and exit apertures.
MATLAB Script

% ENGR 498 Project 1309: Specular Black Baffle Design
% Raytheon Missile Systems
% Anthony Babicke, Ashley Lancaster, Michael Portugal,
% Alexandra Schluntz, Patrick Thrasher

% This script sums the pixel intensities of each picture that we upload.
clear all
clc
dark = 18436080;
epcount = 334206417 - dark;
deg0_count = 257833670;

rxp = .107;
ring = .115;

detectorarea = (6.784/25.4)*(5.427/25.4);
xparea = pi()*(rxp^2);
imgarea = pi()*(ring^2);
eparea = pi()*(1.14^2);
scale = eparea/detectorarea;
epscale = scale*epcount;
flangedist = 17.526/25.4;

% pixel intensity per unit area
unit_intensity = deg0_count/imgarea;

deglist = zeros(1,181);
data = zeros(1,181);
start = -90;

for i = 1:181
    deglist(i) = start;
    start = start + 1;
end

format = 'C:\\Users\\Pat\\Google Drive\\ENGR 498\\H. Calculations\\Data\\Diffuse\\Side1\\Sweep5\\deg%d.bmp';
new_file = 'C:\\Users\\Pat\\Google Drive\\ENGR 498\\H. Calculations\\Data\\Diffuse\\DATADATADATA.xlsx';
for i = 1:181
    FILE = sprintf(format,deglist(i));
    linear_fix = 0;
    reset = 0;

    if (deglist(i)<14) && (deglist(i)>2)
        reset = -2;
    elseif (deglist(i)>-14) && (deglist(i)<-1)
reset = 1;
end

new_deg = deglist(i) + reset;

if reset ~= 0
    ang = deg2rad(new_deg);
    cutoff = flangedist*tan(ang);
    if cutoff>0
        offset = rxp - cutoff;
    else
        offset = rxp + cutoff;
    end

    theta_rad = 2*acos(offset/rxp);
    theta_deg = rad2deg(theta_rad);

    cutoff_area = ((rxp^2)/2)*(theta_rad - sin(theta_rad));
    linear_fix = cutoff_area*unit_intensity;
end

A = imread(FILE); %import images
Z = sum(A,2); %sum the intensity values of each row of pixels and print
answ
    data(i) = sum(Z) - dark; +% linear_fix - dark; %sum the list of row sums
for total pixel intensity
end

data;

%PST Calc%
for i = 1:181
    eppst = epscale/(cosd(deglist(i))*eparea);
    xppst = data(i)/xparea;

    ratio = xppst/eppst;
    ratio_mat(i) = ratio;
end

ratio_mat = transpose(ratio_mat);
xlswrite(new_file,ratio_mat,1,'A2:A182');

%To calculate dark and EP counts
reference = 'C:\Users\Pat\Google Drive\ENGR 498\H. Calculations\Data\Diffuse\Side1\Sweep1\dark.bmp';
A = imread(reference); %import images
Z = sum(A,2); %sum the intensity values of each row of pixels and print
answ
    data = sum(Z)
Appendix C: Budget, Suppliers, and Bill of Materials

Budget
The following table summarizes the final budget for the project.

<table>
<thead>
<tr>
<th>Expenditure</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>197.72</td>
</tr>
<tr>
<td>Tooling</td>
<td>323.86</td>
</tr>
<tr>
<td>BRDF</td>
<td>1189.10</td>
</tr>
<tr>
<td>Camera</td>
<td>432.39</td>
</tr>
<tr>
<td>Compressor/Airbrush/Paint</td>
<td>608.35</td>
</tr>
<tr>
<td>Poster</td>
<td>50.00</td>
</tr>
<tr>
<td>Marketing Consultant</td>
<td>490.00</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>$3291.42</strong></td>
</tr>
</tbody>
</table>

*Table 3: Final budget.*

Bill of Materials

<table>
<thead>
<tr>
<th>Item #</th>
<th>Part</th>
<th>Qty</th>
<th>Use</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>362582</td>
<td>Stormforce Dual Piston Compressor</td>
<td>1</td>
<td>Powering the airbrush</td>
<td>339.99</td>
</tr>
<tr>
<td>822791</td>
<td>HP-BCS Eclipse Airbrush Kit</td>
<td>1</td>
<td>Paint application</td>
<td>179.99</td>
</tr>
<tr>
<td>356063</td>
<td>.25oz Flat Black Enamel Paint</td>
<td>10</td>
<td>Diffuse surface coating</td>
<td>15.90</td>
</tr>
<tr>
<td>356030</td>
<td>.25oz Gloss Black Enamel Paint</td>
<td>10</td>
<td>Specular surface coating</td>
<td>15.90</td>
</tr>
<tr>
<td>30460</td>
<td>Universal Enamel Thinner</td>
<td>1</td>
<td>Paint application</td>
<td>10.99</td>
</tr>
<tr>
<td>27638</td>
<td>Nikon 1 J3 ILC</td>
<td>1</td>
<td>Test setup and data processing</td>
<td>432.39</td>
</tr>
<tr>
<td>61es5000</td>
<td>5”x5”x24” Aluminum 6061 Alloy Beam</td>
<td>1</td>
<td>Baffle housing</td>
<td>197.72</td>
</tr>
<tr>
<td>84510544</td>
<td>Hertel 2 Flute Endmill</td>
<td>2</td>
<td>Machining aluminum</td>
<td>92.26</td>
</tr>
</tbody>
</table>
Table 4: Bill of Materials.

<table>
<thead>
<tr>
<th>Item Description</th>
<th>Qty</th>
<th>Unit Cost</th>
<th>Subtotal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melin 90 degree Endmill</td>
<td>4</td>
<td></td>
<td>116.24</td>
</tr>
<tr>
<td>Thorlabs DCC 1240x</td>
<td>1</td>
<td>Detector</td>
<td>Borrowed</td>
</tr>
<tr>
<td>Negative lens</td>
<td>1</td>
<td>Source expander</td>
<td>Borrowed</td>
</tr>
<tr>
<td>Positive lens</td>
<td>1</td>
<td>Source expander</td>
<td>Borrowed</td>
</tr>
<tr>
<td>Large diameter rotational stage</td>
<td>1</td>
<td>Mounting baffle and camera</td>
<td>Borrowed</td>
</tr>
<tr>
<td>Quartz-halogen lamp</td>
<td>1</td>
<td>Light source</td>
<td>Borrowed</td>
</tr>
<tr>
<td>Newport optical table</td>
<td>1</td>
<td>Test setup surface</td>
<td>Borrowed</td>
</tr>
<tr>
<td>¼-20 threaded posts</td>
<td>5</td>
<td>Mounting baffle, camera, and lenses</td>
<td>Borrowed</td>
</tr>
<tr>
<td>Post holders</td>
<td>5</td>
<td>Mounting baffle, camera, and lenses</td>
<td>Borrowed</td>
</tr>
<tr>
<td>Small V-groove lens holder</td>
<td>1</td>
<td>Mounting negative lens</td>
<td>Borrowed</td>
</tr>
<tr>
<td>Large V-groove lens holder</td>
<td>1</td>
<td>Mounting positive lens</td>
<td>Borrowed</td>
</tr>
</tbody>
</table>

BRDF

The BRDF measurement is the most expensive purchase for this project and deserves its own discussion. A breakdown of a BRDF service is shown below. The BRDF measurement is charged on a per scan angle basis, and there are setup, mounting, alignment, and handling fees. For 6 total scan angles (3 for each sample), the total quote below is $1450. For the same measurement, a company in Tucson is able to perform the measurement for only $1100. The local company, The ScatterWorks, charged a flat fee of $250 per scan angle and giving a $350 total student discount.

Table 5: Final Invoice for the BRDF measurements from The ScatterWorks. An additional discount of $350 was granted by the company, resulting in $1100 total cost.

<table>
<thead>
<tr>
<th>Qty</th>
<th>Description</th>
<th>Part No.</th>
<th>Per Unit</th>
<th>Subtotal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Set-Up Visible (457nm to 780nm)</td>
<td>961-110-101</td>
<td>$250</td>
<td>$250.00</td>
</tr>
<tr>
<td>1</td>
<td>Set-Up UV/IR (325nm &amp; &gt;780nm)</td>
<td>961-110-201</td>
<td>$300</td>
<td>$300.00</td>
</tr>
<tr>
<td>1</td>
<td>Special Handling per hour</td>
<td>961-240-001</td>
<td>$150</td>
<td>$150.00</td>
</tr>
<tr>
<td>2</td>
<td>Sample Mount, Align and Focus</td>
<td>961-120-001</td>
<td>$150</td>
<td>$300.00</td>
</tr>
<tr>
<td>6</td>
<td>Visible Angle Scan - BRDF or BTDF</td>
<td>961-131-010</td>
<td>$150</td>
<td>$900.00</td>
</tr>
<tr>
<td>6</td>
<td>UV/IR Angle Scan - BRDF or BTDF</td>
<td>961-131-201</td>
<td>$150</td>
<td>$900.00</td>
</tr>
<tr>
<td>6</td>
<td>Visible Raster Scan - BRDF or BTDF</td>
<td>961-132-010</td>
<td>$250</td>
<td>$1500.00</td>
</tr>
<tr>
<td>6</td>
<td>UV/IR Raster Scan - BRDF or BTDF</td>
<td>961-132-201</td>
<td>$350</td>
<td>$2100.00</td>
</tr>
<tr>
<td>1</td>
<td>Lab Rental per day (flat fee)</td>
<td>961-250-000</td>
<td>$2500</td>
<td>$2500.00</td>
</tr>
</tbody>
</table>

Minimum Measurement Order $500.00

TOTAL $1,450.00
### 5.3.1 DCC1240x / DCC3240x

<table>
<thead>
<tr>
<th>Specification</th>
<th>DCC1240x</th>
<th>DCC3240x</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensor type</strong></td>
<td>CMOS</td>
<td></td>
</tr>
<tr>
<td><strong>Shutter system</strong></td>
<td>Electronic global and rolling shutter</td>
<td></td>
</tr>
<tr>
<td><strong>Characteristic</strong></td>
<td>Linear</td>
<td></td>
</tr>
<tr>
<td><strong>Readout mode</strong></td>
<td>Progressive scan</td>
<td></td>
</tr>
<tr>
<td><strong>Resolution class</strong></td>
<td>SXGA</td>
<td></td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>1280 x 1024 pixels (1.3 Megapixel)</td>
<td></td>
</tr>
<tr>
<td><strong>Aspect ratio</strong></td>
<td>5:4</td>
<td></td>
</tr>
<tr>
<td><strong>Bit depth</strong></td>
<td>10 bits</td>
<td></td>
</tr>
<tr>
<td><strong>Optical sensor class</strong></td>
<td>1/1.8 inch</td>
<td></td>
</tr>
<tr>
<td><strong>Exact sensitive area</strong></td>
<td>6.784 mm x 5.427 mm</td>
<td></td>
</tr>
<tr>
<td><strong>Exact optical sensor diagonal</strong></td>
<td>8.69 mm (1/1.64 inch)</td>
<td></td>
</tr>
<tr>
<td><strong>Pixel size</strong></td>
<td>5.30 μm, square</td>
<td></td>
</tr>
<tr>
<td><strong>Micro lens shift</strong></td>
<td>12°</td>
<td></td>
</tr>
<tr>
<td><strong>Sensor name, monochrome</strong></td>
<td>e2v Ev76C560ABT</td>
<td></td>
</tr>
<tr>
<td><strong>Sensor name, color</strong></td>
<td>e2v Ev76C560ACT</td>
<td></td>
</tr>
<tr>
<td><strong>Sensor name, NIR</strong></td>
<td>e2v Ev76C661ABT</td>
<td></td>
</tr>
<tr>
<td><strong>Special features</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Automatic hotpixel correction in the sensor, see <code>is_MedPixel()</code></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Multi AOI with 2 or 4 AOI, see <code>Camera basics: AOI()</code></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Sequence AOI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Sensor internal image scaler, downscaling by factor 1...4, see <code>is_SetSensorScaler()</code> and <code>ud880 Viewer: Size()</code></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Allows to switch between global and rolling shutter readout, see <code>is_DeviceFeature()</code></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Gain

- **Monochrome model (master gain)**: 4x
- **Color model (master / RGB)**: 4x / 3.96x
- **Gain boost**: 2x

#### Camera timing

<table>
<thead>
<tr>
<th>Specification</th>
<th>DCC1240x</th>
<th>DCC3240x</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pixel clock range (allowed/recommended)</strong></td>
<td>7 to 35 / 35'</td>
<td>5 to 85 / 85'</td>
</tr>
<tr>
<td><strong>Max. pixel clock with subsampling/binning</strong></td>
<td>85'</td>
<td>85'</td>
</tr>
<tr>
<td><strong>Frame rate (freerun mode)</strong></td>
<td>fps</td>
<td>25.8'</td>
</tr>
<tr>
<td><strong>Frame rate (trigger mode, 1 ms exposure)</strong></td>
<td>fps</td>
<td>24.7'</td>
</tr>
<tr>
<td><strong>Exposure time in freerun mode</strong></td>
<td>ms</td>
<td>0.009' to 2000'</td>
</tr>
<tr>
<td><strong>Exposure time in trigger mode</strong></td>
<td>ms</td>
<td>0.009' to 2000'</td>
</tr>
</tbody>
</table>

#### AOI

<table>
<thead>
<tr>
<th>Specification</th>
<th>Horizontal + Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AOI image width, step width</strong></td>
<td>Pixels</td>
</tr>
<tr>
<td><strong>AOI image height, step width</strong></td>
<td>Pixels</td>
</tr>
<tr>
<td><strong>AOI position grid horizontal, vertical</strong></td>
<td>Pixels</td>
</tr>
<tr>
<td><strong>AOI frame rate, 640 x 480 pixels (VGA)</strong></td>
<td>fps</td>
</tr>
<tr>
<td><strong>AOI frame rate, 320 x 240 pixels (CIF)</strong></td>
<td>fps</td>
</tr>
</tbody>
</table>
DCx Cameras

### Binning

| Mode                  | Horizontal + Vertical
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
<td>H + V combined, mono/color binning, H: additive, V: averaging</td>
</tr>
<tr>
<td>Factors</td>
<td>2x</td>
</tr>
<tr>
<td>Frame rate with 2x binning, 640 x 480 pixels (VGA)</td>
<td>fps 60.0</td>
</tr>
</tbody>
</table>

### Subsampling

| Mode | Scaler |

### Hardware trigger

<table>
<thead>
<tr>
<th>Mode</th>
<th>Asynchronous</th>
<th>Asynchronous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger delay with rising edge</td>
<td>μs</td>
<td>20 ±0.25</td>
</tr>
<tr>
<td>Trigger delay with falling edge</td>
<td>μs</td>
<td>33 ±0.25</td>
</tr>
<tr>
<td>Additive trigger delay (optional)</td>
<td>μs</td>
<td>15 μs..4 s</td>
</tr>
</tbody>
</table>

### Power consumption

| W | 0.3 to 0.7 | 1.3 |

---

**Not yet defined.**

---

**1** The maximum possible pixel clock frequency depends on the PC hardware used.

**2** Requires maximum pixel clock frequency.

**3** Requires minimum pixel clock frequency.

**4** Use of this function increases the frame rate.

**5** The power consumption depends on the sensor model and the pixel clock setting.

**6** Not yet confirmed

**7** DC3240N only

**8** Only for USB3.0 transmission (DC3240x), with USB2.0 - bit depth is 8 bit.

---

---

**Distance from threaded flange to active sensor area (flange back distance)**

- 17.525 mm
- 12.525 mm

Distance from threaded flange to PCB

Distance from active sensor area to PCB

Thickness of the glass cover of the sensor

Filter thickness (optional)

Refractive index

Maximum sensor height above the PCB
DCx Cameras

5.4.2 DCC1240x

[Diagram of DCC1240x]
Model 190
Convection Cooled 30 Watt Illuminator

Technical Information

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>115 V AC (230 V AC optional)</td>
</tr>
<tr>
<td>Lamp</td>
<td>30 Watt, 10.8 V, Type E17 quartz halogen</td>
</tr>
<tr>
<td>Color Temp.</td>
<td>3100° Kelvin</td>
</tr>
<tr>
<td>Lamp Life</td>
<td>200 hrs. full intensity</td>
</tr>
<tr>
<td>Lamp Output</td>
<td>1750 Lumens at fiber optic insertion plane</td>
</tr>
<tr>
<td>Fiber Optic Interface</td>
<td>Threaded / Top Cover</td>
</tr>
<tr>
<td>Intensity Control</td>
<td>4-Position Solid State Switch</td>
</tr>
<tr>
<td>Noise Level</td>
<td>0 dB</td>
</tr>
<tr>
<td>Adapters</td>
<td>ST-type adapter series</td>
</tr>
<tr>
<td>Safety Certifications</td>
<td>N/A</td>
</tr>
<tr>
<td>Dimensions</td>
<td>5.25&quot; x 5.50&quot; x 7.50&quot;, 9 lbs.</td>
</tr>
</tbody>
</table>

Options

<table>
<thead>
<tr>
<th>Input Type</th>
<th>Model &amp; PN</th>
</tr>
</thead>
<tbody>
<tr>
<td>115V Input</td>
<td>190-0000-100</td>
</tr>
<tr>
<td>115V w/ Single Gooseneck Light Guide</td>
<td>002819010001100</td>
</tr>
<tr>
<td>230V Input</td>
<td>190-0000-200</td>
</tr>
<tr>
<td>230V w/ Single Gooseneck Light Guide</td>
<td>00281901000200</td>
</tr>
</tbody>
</table>

Standard Features:
- No Noise, Vibration, or Air Particle Generation
- 10,000 Footcandles
- Intense, Cold Illumination
- 4-Position, Solid State Intensity Control
- Rugged, Convection-Cooled Enclosure
- 2 Year Warranty
- Vertical Design for Small Footprint

Accessories & Options:
- 115 or 230 V AC
- Optional Single Gooseneck Light Guide
- ST-1 Fiber Optic Light Guide Adapter
HP-CS

This multi-purpose, high-paint-flow, high-detail Eclipse Series airbrush covers a wide range of uses. Commonly used to spray premixed or heavier paints, it is well suited for uses demanding precise control of spray when applying moderate-to-large amounts of paint to a variety of surfaces and to various-sized areas. This Eclipse Series brush has established a new benchmark for excellence in an all-purpose airbrush.

- Gravity-feed airbrush features a unique 0.35-mm needle and nozzle combination for fine-detail spraying, but with high-paint-flow capacity

- Generous 1/3 oz. sized cup is designed with a new funnel shape, which makes for easy clean up and more efficient paint flow

- Automotive artists, fine artists and students will appreciate how well the Eclipse CS sprays heavier acrylics and Mecea Textile Colors, while maintaining high-detail spray characteristics

Parts Guides available in .pdf format. Adobe Acrobat Reader required. Click the Adobe Reader logo to download the most current version.
# HP-CS Specifications

<table>
<thead>
<tr>
<th>Paint Reservoir</th>
<th>Nozzle</th>
<th>Trigger Action</th>
<th>Spray Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3 oz. (9 ml) Gravity-Feed Cup</td>
<td>0.35-mm Drop-In Self-Centering Nozzle</td>
<td>Dual-Action</td>
<td>Hairline to 2 in. (50-mm) Round</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Features</th>
<th>Optional Features</th>
<th>Product Name</th>
<th>Item No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Cut-Away Handle Adjustable Main Lever Tension</td>
<td>0.5-mm Nozzle Pre-Set Handle Pre-Set Cut-Away Handle Solid Ergonomic Handle Crown Cap</td>
<td>Iwata Eclipse HP-CS Iwata Airbrush Deluxe Set</td>
<td>ECL 4500 IW 200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HP-CS</th>
<th>Tip Size</th>
<th>Nozzle</th>
<th>Nozzle Cap</th>
<th>Needle</th>
<th>O-Ring</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>.35mm</td>
<td>1604 2</td>
<td>1603 2</td>
<td>1617 2</td>
<td>N/A</td>
<td>-</td>
</tr>
<tr>
<td>Optional</td>
<td>.5mm</td>
<td>1604 1</td>
<td>1603 1</td>
<td>1617 1</td>
<td>N/A</td>
<td>-</td>
</tr>
</tbody>
</table>
## HP-CS Airbrush Usage

<table>
<thead>
<tr>
<th>Product Type</th>
<th>G3</th>
<th>G5</th>
<th>G6</th>
<th>HP-BCS</th>
<th>HP-SBS</th>
<th>HP-CS</th>
<th>HP-BS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illustrator</td>
<td>G</td>
<td>E</td>
<td>E</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td></td>
</tr>
<tr>
<td>Murals</td>
<td>G</td>
<td>E</td>
<td>F</td>
<td>E</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceramics</td>
<td>G</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>G</td>
<td>E</td>
<td>G</td>
</tr>
<tr>
<td>Fine Art</td>
<td>G</td>
<td>G</td>
<td>E</td>
<td>E</td>
<td>G</td>
<td>E</td>
<td>G</td>
</tr>
<tr>
<td>Student</td>
<td></td>
<td></td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td></td>
</tr>
<tr>
<td>T-Shirt / Textile</td>
<td></td>
<td>E</td>
<td>G</td>
<td></td>
<td></td>
<td>G</td>
<td></td>
</tr>
<tr>
<td>Photo Retoucher</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body-Art</td>
<td>G</td>
<td>G</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>Nail-Art</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>G</td>
<td></td>
</tr>
<tr>
<td>Cosmetics</td>
<td></td>
<td></td>
<td></td>
<td>G</td>
<td>G</td>
<td>E</td>
<td>G</td>
</tr>
<tr>
<td>Tanning</td>
<td>E</td>
<td>G</td>
<td>E</td>
<td>E</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RC Cars</td>
<td>G</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>G</td>
</tr>
<tr>
<td>Trains</td>
<td></td>
<td>G</td>
<td>G</td>
<td>F</td>
<td>E</td>
<td>E</td>
<td>G</td>
</tr>
<tr>
<td>Planes</td>
<td>G</td>
<td>G</td>
<td>E</td>
<td>E</td>
<td></td>
<td></td>
<td>F</td>
</tr>
</tbody>
</table>
### Table

<table>
<thead>
<tr>
<th>Model Builders</th>
<th>E</th>
<th>G</th>
<th>G</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dioramas</td>
<td>G</td>
<td>E</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>Figurines / Miniatures</td>
<td>G</td>
<td>G</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hobbyist</td>
<td>G</td>
<td>G</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>Craft</td>
<td>G</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>Taxidermist</td>
<td>G</td>
<td>G</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>Wood Carving</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>Sign Painter</td>
<td>G</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>Auto-Graphics</td>
<td>G</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>Clear Varnish</td>
<td>G</td>
<td>E</td>
<td>G</td>
<td></td>
</tr>
</tbody>
</table>

_E = Excellent Matchup  _F = Fair Matchup  _G = Good Matchup  _Blank = Not Recommended_

---

**The Sparmax Air Compressor is Ideal for Use with the Copic Airbrush System**

Use the air compressor instead of air cans. These Oil-less Air Compressors provide a constant, even air flow for ideal ink coverage. Each compressor includes an air hose.

---

**TC-2000 – Air Compressor**

- **Motor**: 1/6 HP AC
- **Airflow**: 28 LPM / 1 CFM
- **Max Pressure**: 40 PSI on / 60 PSI off
- **Weight**: 13.5 lbs
- **Size**: 9.4"(L) x 5.5" (W) x 6.6" (H)
- **Regulator/Moisture Trap/Gauge**
- **Airbrush Hangar**
- **One PU Cooling Airhose**
- **3 Adaptors to work with various brand airbrushes**
## 2 Flute Endmill


<table>
<thead>
<tr>
<th>Product Specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mill Diameter (Inch)</td>
<td>7/16</td>
</tr>
<tr>
<td>Number of Flutes</td>
<td>2</td>
</tr>
<tr>
<td>Material</td>
<td>Cobalt</td>
</tr>
<tr>
<td>Length of Cut (Inch)</td>
<td>2 3/4</td>
</tr>
<tr>
<td>Finish/Coating</td>
<td>Uncoated</td>
</tr>
<tr>
<td>Overall Length (Inch)</td>
<td>4 3/4</td>
</tr>
<tr>
<td>Single or Double End</td>
<td>Single</td>
</tr>
<tr>
<td>Shank Diameter (Inch)</td>
<td>3/8</td>
</tr>
<tr>
<td>Flute Type</td>
<td>Spiral</td>
</tr>
<tr>
<td>Helix Angle (°)</td>
<td>30.00</td>
</tr>
<tr>
<td>Flute Direction</td>
<td>Right Hand</td>
</tr>
<tr>
<td>Centercutting (Yes/No)</td>
<td>Yes</td>
</tr>
<tr>
<td>Cutting Direction</td>
<td>Right Hand</td>
</tr>
<tr>
<td>Extended Reach (Yes/No)</td>
<td>No</td>
</tr>
<tr>
<td>Chipbreaker (Yes/No)</td>
<td>No</td>
</tr>
<tr>
<td>Material Grade</td>
<td>M42</td>
</tr>
</tbody>
</table>
### 90 degree Endmill

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill Mills</td>
<td>3/8</td>
</tr>
<tr>
<td>Mill Diameter (Inch)</td>
<td>3/8</td>
</tr>
<tr>
<td>Point Angle (°)</td>
<td>90</td>
</tr>
<tr>
<td>Number of Flutes</td>
<td>2</td>
</tr>
<tr>
<td>Material</td>
<td>Cobalt</td>
</tr>
<tr>
<td>Length of Cut (Inch)</td>
<td>3/4</td>
</tr>
<tr>
<td>Finish/Coating</td>
<td>Uncoated</td>
</tr>
<tr>
<td>Overall Length (inch)</td>
<td>2-1/2</td>
</tr>
<tr>
<td>Shank Diameter (Inch)</td>
<td>3/8</td>
</tr>
<tr>
<td>Material Grade</td>
<td>M42</td>
</tr>
<tr>
<td>Cutting Direction</td>
<td>Right Hand</td>
</tr>
<tr>
<td>Flute Direction</td>
<td>Right Hand</td>
</tr>
<tr>
<td>Mill Diameter Tolerance</td>
<td>+0.0015/0.0000</td>
</tr>
</tbody>
</table>
Appendix E: Materials

MATERIAL SAFETY DATA SHEET
THE TESTOR CORPORATION
440 BLACKHAWK PARK AVENUE
ROCKFORD, ILLINOIS 61104

Telephone number: (815) 962-6654 (M-F 8:00 AM - 4:30 PM CDT)
24 hour Chemtrec telephone number:* (800) 424-9300
24 hour Chemtrec International number:* (703) 527-3887 (collect calls accepted.)
*TO BE USED ONLY IN THE EVENT OF CHEMICAL EMERGENCIES INVOLVING
A SPILL, LEAK, FIRE, EXPOSURE, OR ACCIDENT INVOLVING CHEMICALS.
Date prepared: 3/28/2012

This MSDS complies with OSHA 29 CFR 1910.1200 (The Hazard Communication Standard)

----------------------------------- SECTION I - PRODUCT IDENTIFICATION -----------------------------------

PRODUCT Identity (Trade Name): #1149 (T.TT, WM. CA) Flat Black Oil Base Brushing Enamel

----------------------------------- SECTION II - HAZARDOUS INGREDIENTS -----------------------------------

SPECIFIC CHEMICAL NAME | CAS # | % WT | OSHA PEL/TWA | ACGIH TLV/TWA
--- | --- | --- | --- | ---
VMEP Naphtha | 64742-89-8 | 15-20 | 300 ppm. | 300 ppm.
Mineral Spirits | 64742-88-7 | 25-30 | 500 ppm.* | 100 ppm.*
Magnesium Silicate Pigment | 14807-96-6 | 10-15 | 2 mg/cu.m.** | 2 mg/cu.m.**
Carbon Black Pigment | 1333-86-4 | 1-5 | 3.5 mg/cu.m. | 3.5 mg/cu.m.
Hydrous Aluminum Silicate Pigment | 1332-58-7 | 1-5 | 10 mg/cu.m.*** | 5 mg/cu.m.***
Amorphous Silica Gel | 112926-00-8 | 1-5 | 20 mpccf | 10 mg/cu.m.

* Stoddard Solvent as Guide
** Respirable Dust
*** Total Dust

----------------------------------- SECTION III - PHYSICAL/CHEMICAL CHARACTERISTICS -----------------------------------

BOILING RANGE: 246 to 370 deg. F
SPECIFIC GRAVITY (Water=1): 1.008
GALLON WEIGHT OF PRODUCT (Lbs/Gal): 8.40
VAPOR PRESSURE: 6.9 mm Hg @ 20 deg.C (calc.)
PERCENT VOLATILES (By Volume): 59.6
VAPOR DENSITY: Heavier than air.
EVAPORATION RATE: Slower than Ethyl Ether.

----------------------------------- SECTION IV - FIRE & EXPLOSION HAZARD DATA -----------------------------------

FLASH POINT (FPC): 68 deg. F
OSHA FLAMMABILITY CLASSIFICATION: Flammable Liquid - CLASS IB
FLAMMABLE LIMITS (calc.) IN AIR: LEL 1.0, UEL 7.0
EXTINGUISHING MEDIA: Alcohol resistant foam, carbon dioxide, or dry chemical.
SPECIAL FIRE FIGHTING PROCEDURES: Caution: Flammable. A stream of water could spread fire. Avoid breathing vapors. Keep personnel removed from and upwind of fire. Wear full protective equipment: Eye/Face Shield, Body (Full Bunker Gear), Respiratory (SCBA).
UNUSUAL FIRE AND EXPLOSION HAZARDS: Cool fire exposed containers with water spray (fog). Vapors may travel considerable distance to ignition source and flash back. Product may float and be reignited at water's surface. Overexposure to decomposition products may cause a health hazard.

57
Product Identity: #1149 Flat Black Brushing Enamel

SECTION V - SPILL OR LEAK PROCEDURES

STEPS TO BE TAKEN IF MATERIAL IS RELEASED OR SPILLED: Caution: Flammable. Contain spilled product by digging. Eliminate all possible ignition sources. Provide adequate ventilation. Equip emergency responders with appropriate personal protection equipment. Take up spill with an absorbent material and place in non-leaking container. Seal container for proper disposal.

WASTE DISPOSAL METHOD:
Do not incinerate closed containers. Dispose of in accordance with local, state, and federal regulations.

SECTION VI - HEALTH HAZARD DATA

PRIMARY ROUTES OF ENTRY: Inhalation and skin contact.

CARCINOGENICITY: NTP? NO IARC? YES* OSHA REGULATED? NO

EFFECTS OF OVEREXPOSURE:
EYE CONTACT: Short term liquid or vapor contact may result in slight eye irritation. Prolonged and repeated contact may be more irritating.
SKIN CONTACT: Prolonged and repeated liquid contact can cause defatting and drying of the skin which may result in skin irritation and dermatitis.
BREATHING: Vapors or mist may cause irritation to the throat, mucous membranes and upper respiratory tract. Inhalation overexposure can lead to central nervous system depression producing effects such as headaches, nausea, dizziness and loss of consciousness.
SWALLOWING: May result in vomiting. Aspiration (breathing) of vomitus into lungs must be avoided as even small quantities in the lungs may result in chemical pneumonitis and pulmonary edema/hemorrhage.
CHRONIC OVEREXPOSURE: Reports of animal test studies involving prolonged and repeated inhalation exposures to light hydrocarbon vapors have shown possible effects to the liver, kidney, and lungs. The relevance of these effects to man is unknown.
*Carbon Black component is an IARC Group 2B—Possible carcinogen.
WARNING: This product contains a chemical known to the State of California to cause cancer and birth defects or other reproductive harm.

SECTION VII EMERGENCY AND FIRST AID PROCEDURES

EYE CONTACT: Wash immediately with plenty of water for 15 minutes while holding eye lids open. Call a physician.
SKIN CONTACT: Remove any contaminated clothing and wash skin with soap and water thoroughly. If irritation persists, get medical attention.
BREATHING: Remove victim to fresh air and provide oxygen if breathing is difficult. Give artificial respiration if not breathing. Get medical attention.
SWALLOWING: Do not induce vomiting. Call a physician at once. If vomiting occurs, keep head below hips to prevent aspiration of liquid into lungs.
Specular Black Baffle Design

Product Identity: #1149 Flat Black Brushing Enamel

SECTION VIII- REACTIVITY DATA

STABILITY: Stable.

CONDITIONS TO AVOID: Avoid contact with heat, sparks, hot surfaces, open flames, and other ignition sources.

INCOMPATIBILITY (Materials to Avoid): Strong oxidizing agents.

HAZARDOUS DECOMPOSITION PRODUCTS: Carbon monoxide and unidentified organic compounds may be formed during combustion.

HAZARDOUS POLYMERIZATION: Will not occur.

SECTION IX SPECIAL PROTECTION INFORMATION

RESPIRATORY PROTECTION: Avoid prolonged or repeated breathing of vapors, mists and/or dusts. If exposure may or does exceed occupational exposure limits (Section II) use a NIOSH-approved respirator to prevent overexposure. In accord with 29 CFR 1910.134 use either an atmosphere-supplying respirator or an air purifying respirator with appropriate chemical/mechanical filters.

VENTILATION: If the product is used in a confined area, provide sufficient mechanical (general and/or local exhaust) ventilation to maintain exposure below TLV(s). Heavy solvent vapors should be removed from the lower levels of area, and all ignition sources (non-explosion proof equipment) should be eliminated if flammable mixtures will be encountered.

PROTECTIVE GLOVES: Solvent resistant are recommended for prolonged contact.

EYE PROTECTION: Chemical safety splash goggles.

OTHER PROTECTIVE EQUIPMENT: Eye-Wash Station, Safety Shower, Rubber Apron, Chemical Safety Shoes, Protective Clothing.

SECTION X SPECIAL PRECAUTIONS

PRECAUTIONS TO BE TAKEN IN HANDLING AND STORAGE: Read all label cautions. Store away from ignition sources in a cool well ventilated area. Handle as flammable liquid. Do not drop container.

This product is packaged and sold as a consumer good. This information is believed to be reliable and accurate, as of the date indicated. It is supplied on the condition that recipients will make their own determination as to its suitability and completeness for their purposes. The Testor Corporation assumes no responsibility for any damages resulting from reliance on this information.
MATERIAL SAFETY DATA SHEET
THE TESTOR CORPORATION
440 BLACKHAWK PARK AVENUE
ROCKFORD, ILLINOIS 61104

Telephone number: (815) 962-6654 (M-F 8:00 AM - 4:30 PM CDT)
24 hour Chemtrec telephone number: * (800) 424-9300
24 hour Chemtrec International number: * (703) 527-3887 (collect calls accepted.)
*TO BE USED ONLY IN THE EVENT OF CHEMICAL EMERGENCIES INVOLVING
A SPILL, LEAK, FIRE, EXPOSURE, OR ACCIDENT INVOLVING CHEMICALS.
Date prepared: 3/28/2012

This MSDS complies with OSHA 29 CFR 1910.1200 (The Hazard Communication Standard)

SECTION I - PRODUCT IDENTIFICATION

PRODUCT IDENTITY (TRADE NAME): #1147, #61147 (T, TT, WM, CA)
Gloss Black Oil Base Brushing Enamel

SECTION II - HAZARDOUS INGREDIENTS

SPECIFIC CHEMICAL NAME | CAS # | % WT | OSHA PEL/TWA | ACGIH TLV/TWA
---|---|---|---|---
Naphtha | 64742-09-8 | 20-25 | 300 ppm | 300 ppm
Mineral Spirits | 64742-06-7 | 30-35 | 500 ppm | 100 ppm
Carbon Black Pigment | 1333-86-4 | 1-5 | 3.5 mg/cu.m | 3.5 mg/cu.m

* Stoddard Solvent as Guide

SECTION III - PHYSICAL/CHEMICAL CHARACTERISTICS

BOILING RANGE: 246 to 370 deg.F
SPECIFIC GRAVITY (Water=1): .893
GALLON WEIGHT OF PRODUCT (Lbs/Gal): 7.44
VAPOR PRESSURE: 7.5 mm Hg @ 20 deg.C (calc.)
VAPOR DENSITY: Heavier than air.
PERCENT VOLATILE BY VOLUME: 59.9
EVAPORATION RATE: Slower than Ethyl Ether.

SECTION IV - FIRE & EXPLOSION HAZARD DATA

FLASH POINT (SFCC): 67 deg.F
OSHA FLAMMABILITY CLASSIFICATION: Flammable Liquid - CLASS IB
FLAMMABLE LIMITS (calc.) IN AIR: LEL 1.0, UEL 7.0
EXTINGUISHING MEDIA: Alcohol resistant foam, carbon dioxide, or dry chemical.
SPECIAL FIRE FIGHTING PROCEDURES: Caution: Flammable. A stream of water could
spread fire. Avoid breathing vapors. Keep personnel removed from and upwind of
fire. Wear full protective equipment: Eye/Face Shield, Body (Full Bunker Gear),
Respiratory (SCBA).
UNUSUAL FIRE AND EXPLOSION HAZARDS: Cool fire exposed containers with water
spray (fog). Vapors may travel considerable distance to ignition source
and flash back. Product may float and be reignited at water's surface.
Overexposure to decomposition products may cause a health hazard.
Product Identity: #1147, #51147 Gloss Black Brushing Enamel

SECTION V - SPILL OR LEAK PROCEDURES

STEPS TO BE TAKEN IF MATERIAL IS RELEASED OR SPILLED: Caution: Flammable. Contain spilled product by digging. Eliminate all possible ignition sources. Provide adequate ventilation. Equip emergency responders with appropriate personal protection equipment. Take up spill with an absorbent material and place in non-leaking container. Seal container for proper disposal.

WASTE DISPOSAL METHOD:
Do not incinerate closed containers. Dispose of in accordance with local, state, and federal regulations.

SECTION VI - HEALTH HAZARD DATA

PRIMARY ROUTES OF ENTRY: Inhalation and skin contact.

CARCINOGENICITY: NTP? NO IARC? YES* OSHA REGULATED? NO

EFFECTS OF OVEREXPOSURE:
EYE CONTACT: Short term liquid or vapor contact may result in slight eye irritation. Prolonged and repeated contact may be more irritating.
SKIN CONTACT: Prolonged and repeated liquid contact can cause defatting and drying of the skin which may result in skin irritation and dermatitis.
BREATHING: Vapors or mist may cause irritation to the throat, mucous membranes and upper respiratory tract. Inhalation overexposure can lead to central nervous system depression producing effects such as headaches, nausea, dizziness and loss of consciousness.
SWALLOWING: May result in vomiting. Aspiration (breathing) of vomitus into lungs must be avoided as even small quantities in the lungs may result in chemical pneumonitis and pulmonary edema/hemorrhage.
CHRONIC OVEREXPOSURE: Reports of animal test studies involving prolonged and repeated inhalation exposures to light hydrocarbon vapors have shown possible effects to the liver, kidney, and lungs. The relevance of these effects to man is unknown.
*Carbon Black component is an IARC Group 2B-Possible carcinogen.
WARNING: This product contains a chemical known to the State of California to cause cancer and birth defects or other reproductive harm.

SECTION VII EMERGENCY AND FIRST AID PROCEDURES

EYE CONTACT: Wash immediately with plenty of water for 15 minutes while holding eye lids open. Call a physician.
SKIN CONTACT: Remove any contaminated clothing and wash skin with soap and water thoroughly. If irritation persists, get medical attention.
BREATHING: Remove victim to fresh air and provide oxygen if breathing is difficult. Give artificial respiration if not breathing. Get medical attention.
SWALLOWING: Do not induce vomiting. Call a physician at once. If vomiting occurs, keep head below hips to prevent aspiration of liquid into lungs.
Product Identity: #1147, #61147 Gloss Black Brushing Enamel

SECTION VIII- REACTIVITY DATA

STABILITY: Stable.

CONDITIONS TO AVOID: Avoid contact with heat, sparks, hot surfaces, open flames, and other ignition sources.

INCOMPATIBILITY (Materials to Avoid): Strong oxidizing agents.

HAZARDOUS DECOMPOSITION PRODUCTS: Carbon monoxide and unidentified organic compounds may be formed during combustion.

HAZARDOUS POLYMERIZATION: Will not occur.

SECTION IX SPECIAL PROTECTION INFORMATION

RESPIRATORY PROTECTION: Avoid prolonged or repeated breathing of vapors, mists and/or dusts. If exposure may or does exceed occupational exposure limits (Section II) use a NIOSH-approved respirator to prevent overexposure. In accord with 29 CFR 1910.134 use either an atmosphere-supplying respirator or an air purifying respirator with appropriate chemical/mechanical filters.

VENTILATION: If the product is used in a confined area, provide sufficient mechanical (general and/or local exhaust) ventilation to maintain exposure below TLV(s). Heavy solvent vapors should be removed from the lower levels of area, and all ignition sources (non-explosion proof equipment) should be eliminated if flammable mixtures will be encountered.

PROTECTIVE GLOVES: Solvent resistant are recommended for prolonged contact.

EYE PROTECTION: Chemical safety splash goggles.


SECTION X SPECIAL PRECAUTIONS

PRECAUTIONS TO BE TAKEN IN HANDLING AND STORAGE: Read all label cautions. Store away from ignition sources in a cool well ventilated area. Handle as flammable liquid. Do not drop container.

This product is packaged and sold as a consumer good. This information is believed to be reliable and accurate, as of the date indicated. It is supplied on the condition that recipients will make their own determination as to its suitability and completeness for their purposes. The Testor Corporation assumes no responsibility for any damages resulting from reliance on this information.
Understanding Extruded Aluminum Alloys

Alloy 6061 is one of the most widely used alloys in the 6000 Series. This standard structural alloy, one of the most versatile of the heat-treatable alloys, is popular for medium to high strength requirements and has good toughness characteristics. Applications range from transportation components to machinery and equipment applications to recreation products and consumer durables.

Alcoa produces 6061 for use in standard and custom shapes, rod and bar products, and seamless and structural pipe and tube.

Alloy 6061 has excellent corrosion resistance to atmospheric conditions and good corrosion resistance to sea water. This alloy also offers good finishing characteristics and responds well to anodizing; however, when corrosive environments like seawater are critical, consider the use of alloy 5053. The most common anodizing methods include clear, clear and color eye, and hardcoat.

Alloy 6061 is easily welded and joined by various commercial methods. (Caution: direct contact by dissimilar metals can cause galvanic corrosion.) Since 6061 is a heat-treatable alloy, strength in its T6 condition can be reduced in the weld region. Selection of an appropriate filler alloy will depend on the desired weld characteristics. Consult the Material Safety Data Sheet (MSDS) for proper safety and handling precautions when using alloy 6061.

For screw machine applications, alloy 6061 has adequate machinability characteristics in the heat-treated T6-T651 condition. With T6-T651 mechanical properties, chips from machining (particularly turning and drilling) are difficult to break. Chip breakers are recommended, and special machining techniques (i.e., peck drilling) can improve chip formation. To enhance the machinability of its Econo-Rod®, Accu-Rod®, Econo-Plate® and Accu-Plate® products, Alcoa has developed a unique chemistry for alloy 6061, which conforms to industry specifications.

For minor bending applications, special forming tempers -T652, -T651, -T65 or -T6510 may be sufficient to facilitate bending (dependent upon bend radius and degree of bend). When more severe bends are required, a softer temper condition such as -T1, -T4 or even -O may be necessary to prevent cracking.

Alcoa offers alloy 6061 in a variety of standard tempers, as well as special tempers developed for unique applications. These are summarized below.

### 6061 Temper Designations and Definitions

<table>
<thead>
<tr>
<th>Standard Tempers</th>
<th>Standard Temper Definitions*</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>As fabricated. There is no special control over thermal conditions and there are no mechanical property limits.</td>
</tr>
<tr>
<td>O</td>
<td>Annealed. Applies to products that are annealed to obtain the lowest strength temper.</td>
</tr>
<tr>
<td>T1</td>
<td>Cool from an elevated temperature shaping process and naturally aged. (See Note B.)</td>
</tr>
<tr>
<td>T4, T4511</td>
<td>Solution heat-treated and naturally aged. (See Notes C &amp; D.)</td>
</tr>
<tr>
<td>T51</td>
<td>Cool from an elevated temperature shaping process and artificially aged. (See Note B.)</td>
</tr>
<tr>
<td>T6, T6511</td>
<td>Solution heat-treated and artificially aged. (See Notes C &amp; D.)</td>
</tr>
</tbody>
</table>

#### Alcoa Special Tempers**

| T45S             | For 6061 extrusions requiring maximum formability in the unaged condition and subsequently aged to -T6. May not meet -T6 minimum mechanical properties, but will meet -T6 minimum when properly aged. Test reports state -T6 properties to demonstrate heat treat capabilities, but extrusions are supplied unaged. (See Note A.) |
| T652, T6515      | For 6061 extrusions requiring good formability; meets standard 6061-T6 minimum properties. |
| T80S, T610       | For 6061 extrusions requiring improved forming characteristics not obtainable with -T652 and -T6515 tempers. Lower minimum properties of 35.0 ksi tensile & 30.0 ksi yield guaranteed to enhance formability. (See Note A.) |
| T6S4             | Applies to 6061 extrusions requiring maximum hardness for strength and good machinability. Same minimum tensile and yield strengths as standard -T6, but with lower minimum elongation of 6%. (See Note A.) |
| T6H, T6511H      | Alcoa’s “H” temper is offered for special applications requiring improved machinability and higher minimum mechanical properties than standard -T6 or -T6511. Minimum properties of 42 ksi tensile, 35 ksi yield, and 10.0% elongation are guaranteed. “H” temper is available for rod, bar and certain cold finished products with a principle thickness of .500” or greater. (See Notes C & D.) |
| T6G, T6511G      | Alcoa’s “G” temper is available for applications requiring a uniform grain structure to enhance anodized appearance for rod and bar sizes with a thickness of 2.00” or greater. A minimal peripheral grain band may still be present, but it is greatly reduced compared to standard -T6-T6511. Minimum mechanical properties are same as “H” tempers. (See Notes C & D.) |
| T6X, T6511X      | Alcoa’s “X” temper is available for special applications requiring a uniform recrystallized grain structure in extrusions less than 2” thickness to enhance anodizing appearance. Other benefits include improved machinability, same mechanical properties as 6061-T6/T6511. (See Notes C & D.) |
| T5S28            | For 6061 press-quenched and over-aged extrusions requiring improved stamping characteristics. Minimum mechanical properties are 26.0 ksi tensile, 16 ksi yield, 16% elongation. (See Note A.) |

*For further details of definitions, see Aluminum Association’s Aluminum Standards and Data Manual and Tempers for Aluminum and Aluminum Alloy Products. Note A: The specified special temper will not conform to Military, Federal, ASTM, ASME and AWS specifications. Note B: Applies to products that are not cold worked after cooling from an elevated temperature anodizing process, or when the effect of cold work in flattening or straightening may not be recognized in mechanical properties. Note C: Applies to products that are not cold worked after solution heat treatment, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical properties. Note D: Temper -T6511 and -T6511 apply to products that are stress-relieved by stretching.

**Alcoa Special Temper designations are unregistered tempers for reference only and provided for customer use to identify unique processing, material, or end-use application characteristics.
Alloy 6061 Chemical Analysis

<table>
<thead>
<tr>
<th>Percent Weight Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
</tr>
<tr>
<td>Fe</td>
</tr>
<tr>
<td>Cu</td>
</tr>
<tr>
<td>Mn</td>
</tr>
<tr>
<td>Mg</td>
</tr>
<tr>
<td>Zn</td>
</tr>
<tr>
<td>Ti</td>
</tr>
<tr>
<td>Others Each</td>
</tr>
<tr>
<td>Others Total</td>
</tr>
<tr>
<td>Aluminum</td>
</tr>
</tbody>
</table>

Average Coefficient of Thermal Expansion (68°F to 212°F) = 13.1 x 10^-6 (inch per inch per °F)

Alloy 6061 Mechanical Property Limits for Rod, Bar, Tube, Pipe and Standard Shapes

<table>
<thead>
<tr>
<th>Temper</th>
<th>Specified Section or Wall Thickness (inches)</th>
<th>Tensile Strength (ksi)</th>
<th>Elongation %</th>
<th>Typical Brinell Hardness</th>
<th>Typical Ultimate Shearing Strength (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min.</td>
<td>Max.</td>
<td>Min.</td>
<td>Max.</td>
<td>Percent Min. in 2 inch or 4D</td>
</tr>
<tr>
<td>Standard Tempers 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O</td>
<td></td>
<td></td>
<td>2.0</td>
<td>4.0</td>
<td>16.5</td>
</tr>
<tr>
<td>T1</td>
<td>Up thru 0.625</td>
<td>26.0</td>
<td>14.0</td>
<td>16</td>
<td>30</td>
</tr>
<tr>
<td>T4, T4514</td>
<td>All</td>
<td>26.0</td>
<td>16.0</td>
<td>16</td>
<td>65</td>
</tr>
<tr>
<td>T51</td>
<td>Up thru 0.625</td>
<td>35.0</td>
<td>30.0</td>
<td>8</td>
<td>65</td>
</tr>
<tr>
<td>T6, T6514</td>
<td>Up thru 0.249</td>
<td>38.0</td>
<td>35.0</td>
<td>8</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>0.250 and over</td>
<td>38.0</td>
<td>35.0</td>
<td>10</td>
<td>65</td>
</tr>
<tr>
<td>Alcoa Special Tempers 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T952, T6515</td>
<td>Up thru 0.249</td>
<td>38.0</td>
<td>35.0</td>
<td>8</td>
<td>95</td>
</tr>
<tr>
<td>T955, T6510</td>
<td>0.250 and over</td>
<td>35.0</td>
<td>30.0</td>
<td>10</td>
<td>95</td>
</tr>
<tr>
<td>T954</td>
<td>All</td>
<td>38.0</td>
<td>35.0</td>
<td>8</td>
<td>95</td>
</tr>
<tr>
<td>T6, T6511</td>
<td>1.000 and over</td>
<td>42.0</td>
<td>38.0</td>
<td>10</td>
<td>95</td>
</tr>
<tr>
<td>T6, T6511G</td>
<td>3.000 and over</td>
<td>42.0</td>
<td>38.0</td>
<td>10</td>
<td>95</td>
</tr>
<tr>
<td>T6X, T651X</td>
<td>2.500 thru 1.999</td>
<td>38.0</td>
<td>35.0</td>
<td>10</td>
<td>95</td>
</tr>
<tr>
<td>T5568</td>
<td>All</td>
<td>26.0</td>
<td>16.0</td>
<td>16</td>
<td>65</td>
</tr>
</tbody>
</table>

1. The mechanical property limits for standard tempers are listed in the “standards section” of the Aluminum Association’s “Aluminum Standards and Data” manual. 2. The thickness of the cross section from which the tension test specimen is taken determines the applicable mechanical properties. 3. For material of such dimensions that a standard test specimen cannot be taken, or for shapes thinner than 0.062”, the test for elongation is not required. 4. For stress-relieved tempers, the characteristics and properties other than those specified may differ somewhat from the corresponding characteristics and properties of material in the basic temper. 5. D = Specimen Diameter.

Comparative Characteristics of Related Alloys/Temper Changes

<table>
<thead>
<tr>
<th>Alloy/Temp</th>
<th>Formability</th>
<th>Machinability</th>
<th>General Corrosion Resistance</th>
<th>Weldability (Arc Inert Gas)</th>
<th>Brazability</th>
<th>Anodizing Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>High</td>
<td>DCBA</td>
<td>DCBA</td>
<td>DCBA</td>
<td>DCBA</td>
<td>DCBA</td>
</tr>
<tr>
<td>0661 -O</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6061 -T6, -T651, -T6511</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6061 -T4, -T4514, -T4511</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6061 -T51</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6061 -T6511</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6061 -T5526</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6061 -T651</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6061 -T6515</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6061 -T651X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6061 -T952</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6061 -T953</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6061 -T954</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6061 -T955</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6061 -T9568</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

© 12/02

Alcoa Distribution and Industrial Products

53 Pottsville Street
Cressona, PA 17929
Phone: 800-233-3165
FAX: 800-252-4546