Recent NASA/GSFC cryogenic measurements of the total hemispheric emissivity of black surface preparations

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Abstract. High-emissivity (black) surfaces are commonly used on deep-space radiators and thermal radiation absorbers in test chambers. Since 2011 NASA Goddard Space Flight Center has measured the total hemispheric emissivity of such surfaces from 20 to 300 K using a test apparatus inside a small laboratory cryostat. We report the latest data from these measurements, including Aeroglaze Z307 paint, Black Kapton, and a configuration of painted aluminum honeycomb that was not previously tested. We also present the results of batch-to-batch reproducibility studies in Ball Infrared Black™ and painted aluminum honeycomb. Finally, we describe a recently-adopted temperature control method which significantly speeds the data acquisition, and we discuss efforts to reduce the noise in future data.

1. Introduction
High emissivity (black) surface treatments are of great interest in connection with NASA missions. When used on radiators facing toward deep space, they enable relatively large amounts of heat to be removed from cryogenic systems. The power radiated from a surface is described by the Stefan-Boltzmann Equation,

$\dot{Q} = \sigma A \varepsilon T^4$,  \hspace{1cm} (1)

where $\dot{Q}$ is the total radiated power in W, $T$ is the surface temperature in K, $A$ is the surface area in m², $\sigma = 5.67 \times 10^{-8}$ Wm⁻²K⁻⁴ is the Stefan-Boltzmann constant, and $\varepsilon$ is the surface’s total hemispheric emissivity. An $\varepsilon$ value of 1.0 would correspond to the maximum possible power per unit area, referred to as a blackbody. NASA also employs such surfaces on thermal absorbers in large cryogenic test chambers. In general, a surface with a high $\varepsilon$ also has a high absorptivity. The total hemispheric absorptivity, $\alpha$, is the fraction of incoming radiation from all directions which is absorbed by the surface. Shrouds, cooled to low temperature and coated with high-absorptivity surface preparations, are used in ground testing in large vacuum chambers to simulate the deep space environment. The performance of thermal systems destined for space flight, as well as their detailed finite-element thermal models, are verified inside such shrouds.

NASA’s Goddard Space Flight Center (GSFC) has a history of measuring surface emissivity. The most common method uses a reflectometer, bouncing monochromatic radiation off a surface and...
measuring the reflectance as a function of wavelength. These devices, however, are limited to wavelengths that are not long enough to cover the entire relevant blackbody spectrum at the lowest practical space flight radiator temperature of approximately 35 K. The total hemispheric emissivity, which determines the total heat radiated in all directions at all wavelengths, has been measured directly by hanging an object of known heat capacity in a very cold, black-painted shroud in a vacuum chamber and monitoring its cooling rate as a function of its temperature. This rate and heat capacity, along with the object’s size, allow one to determine the emissivity. This “transient” technique works well down to temperatures typical of many space flight radiators, but the uncertainty in the indicated emissivity becomes large at the lowest temperatures [1]. A similar, “steady-state” approach was to hang coated plates inside a cold shroud and apply various steady power values to heaters imbedded in the plates. The final steady sample temperatures and the power values were used to back out the emissivity. This method had advantages over the transient approach, but its implementation was expensive, and it also let to significant uncertainty at the lowest temperatures [2].

When the James Webb Space Telescope (JWST) program selected Ball Infrared Black™ (BIRB™) to coat its 35 K deep-space radiators, Ball Aerospace (BASC) re-started its production of this surface treatment. Due to the uncertainty in BIRB’s previously-measured emissivity at 35 K and the concern that the new application process would not exactly match that which had been used several years earlier, the project was interested in a new, more precise measurement of BIRB’s emissivity. We developed a new, precise and relatively inexpensive method of determining the total hemispheric emissivity down to 20 K. This technique used an innovative geometry in measuring the heat exchange between identically-coated surfaces held at slightly different temperatures, and in 2011 we published the results of measurements taken using samples of the new BIRB [3]. The high emissivity values measured down to 20 K led to a study of the emissivity of thinner BIRB coatings, in an effort to reduce the radiator mass [4]. At the same time we developed a “hybrid” approach to this measurement, using a previously-calibrated BIRB sample plate exchanging heat with previously un-measured samples. We used this approach to characterize three different candidate samples of painted aluminum honeycomb, which had been selected for additional JWST radiators [5]. Since that time we have characterized several additional coatings which will be used on JWST.

In this paper we give a brief description of the emissivity measurement method and a slight correction to earlier-published results. We also present the results of more recent measurements on additional surface preparations. Finally, we describe a recent significant improvement to the technique and discuss new information which may lead to further improvements in the future.

2. Measurement technique

The emissivity measurement approach has been described in detail in the references above, so here we simply provide an overview. The apparatus is shown schematically in figure 1. It used a simple geometry, consisting of a 20-cm-diameter 1100 aluminum “sample” disk suspended inside a “can” made of the same material. The sample’s top and bottom surfaces were coated with BIRB, and its outer edge was coated with aluminized Kapton tape. A heater and two thermometers were imbedded inside it, with their leads running out through three equally-spaced holes in its outer edge. The can consisted of top and bottom “cold plates” separated by a spacer ring bolted between the plates’ outer edges. In the original work the inner surfaces of the cold plates were coated with the same thickness of BIRB. Thermometers were centered on the outside cold plate surfaces, and a wire heater was wrapped around and epoxied to the outer edge of the spacer ring. The ring’s vertical inner surface was polished to a mirror finish. The can was supported on a suspension wires. A series of steady-state thermal balances was achieved at each average temperature with the sample
controlled at a temperature \( T_1 = T_{\text{avg}} + \Delta T/2 \) and the cold plates controlled at \( T_2 = T_{\text{avg}} - \Delta T/2 \), and 
\( \Delta T = (T_1 + T_2)/2 \). For each \( \Delta T \) value we measured \( \dot{Q} \), the sample’s control heater power. The spacing between the facing BIRB surfaces was small relative to the diameter, so we approximated a simple textbook case of heat exchange between two infinite parallel surfaces. For small values of \( \Delta T \) (less than 6% of \( T_{\text{avg}} \)), we showed that the emissivity could be approximated to better than 0.1% by

\[
\varepsilon = \frac{2}{4\alpha T_{\text{avg}}^3 \left( \frac{d\Delta T}{dQ} \right) + 1}.
\]

The uncertainty of this indicated emissivity was dominated by the uncertainty of the derivative in the denominator. Since the power was linear in \( \Delta T \), the derivative was determined by a linear regression, and we could drive down its uncertainty by balancing at more \( \Delta T \) values. A small correction to the results of equation (2) was required, because the BIRB area on the sample was slightly smaller than that of the cold plates. We used a Thermal Desktop™ model of the apparatus to determine this correction, which was on the order of 1%. The correction depended on the spacing between the sample and cold plate treated surfaces, so we had to re-calculate it when testing BIRB of a different thickness. In the original campaign we used this method to measure the emissivity of two different BIRB samples from 20 K up to room temperature, as will be discussed later.

One drawback to testing samples in this way is that it takes significant time to produce the sample disk. This process requires tedious wiring of the heater circuit and thermometers to be imbedded inside the sample, and careful epoxying together of two BIRB-coated plates. Another limitation is that the sample plate must have a relatively thin black coating in order to minimize edge effects. To avoid these issues, we adopted a “hybrid” testing approach in which we used a calibrated BIRB sample disk suspended between cold plates with the surface treatment to be tested. In the case of new BIRB samples the configuration was nearly identical to the original setup. For taller samples, such as the painted aluminum honeycomb, custom rings were placed between the cold plates and spacer ring to maintain the desired spacing between the warm and cold sample surfaces. This hybrid approach, configured for painted honeycomb, is shown schematically in figure 2.

Using the hybrid method, we determined the new emissivity \( \varepsilon_1 \) on the cold plates from

\[
\varepsilon_1 = \frac{1}{4\alpha T_{\text{avg}}^3 \left( \frac{d\Delta T}{dQ} \right) + 1 - \frac{1}{\varepsilon_2}}.
\]

**Figure 1.** The original test configuration, with four identical BIRB coatings.
Here $\varepsilon_2$ is the previously-measured emissivity of the sample disk surfaces, which we curve-fit as a function of temperature. The uncertainty in $\varepsilon_1$ was greater than that of $\varepsilon_2$, since the former includes the uncertainty of the original BIRB measurement and of the hybrid measurement.

In our previous publications on emissivity measurements, the area $A$ in equations (2) and (3) was determined at room temperature. This was an error, however, since the aluminum samples plates are slightly smaller at lower temperatures. We now scale the area values in these equations based on published values of aluminum’s thermal contraction [6]. Since we have the same heat exchange for a smaller surface area, the indicated emissivity values are slightly higher when this correction is applied.

3. Results

3.1. BIRB data

In figure 3 we graph the results to-date for BIRB samples. The data from earlier publications are included with their proper corrections for thermal contraction. The 2 mm and 1.5 mm thick BIRB were measured using 4 identical coated surfaces as shown in figure 1. The 2 mm thick BIRB’s sample disk was later used in all of the hybrid configuration measurements, and figure 3 includes the curve fit that was used in the hybrid data analysis using equation (3). Clearly there is significant uncertainty in the fit below about 40 K, and this shows up in the hybrid data. For example, the original 0.8 mm thick BIRB data actually rises at lower temperatures below 40 K. We believe this is not accurate, but rather a result of this curve fit. If time allows, we hope to eventually re-calibrate the 2 mm thick BIRB at the lowest temperatures and re-analyze the hybrid data with smaller error bars. The 0.8 mm thick BIRB, which matches the density to be used on the flight radiators, was re-tested after a heat treatment up to 410 K to simulate the affect of launch and ascent. This heating seems to have had a noticeable but barely significant effect on the emissivity. Two additional 0.8 mm thick BIRB samples were tested to determine the repeatability of the application process, and they are shown as upright and inverted triangles in figure 3. A final sample of this thickness, shown as $\times$ symbols, was generated when a test target was coated. Except for the 2 mm thick sample, which was the first coating made in the recent JWST campaign, all results match to within about 1 percent. It is possible that the coating process was improved somehow after the 2 mm samples were tested.

3.2. Aluminum honeycomb data

In figure 4 we graph the results to-date for samples of coated aluminum honeycomb. The data from our earlier publications are included with their proper corrections for thermal contraction, and they use the graph’s left-hand Y axis. These samples were painted with Chemglaze Z307 paint, and their cell
Diameters were all 3.175 mm. As described elsewhere [5], they were made with progressively shorter cell heights and thinner paint and cell walls in order to reduce the radiator mass. The cell heights ranged from 12.7 to 9.53 mm, the wall thicknesses were between 38.1 and 17.8 \( \mu m \), and the paint was between 16.3 and 8.4 \( \mu m \) thick. Sample 3, using the thinnest of all these characteristics, was selected as the flight configuration. When the actual flight honeycomb was painted, a new pair of cold plates was made to check for workmanship and repeatability of the process. This flight sample was tested at 35 and 40 K, and the results are included in Figure 4. There is no significant variation among any of these honeycomb samples.

More recently, a pair of cold plate samples was prepared to test a cheaper method of blackening aluminum honeycomb for use in cryogenic ground test facilities. The honeycomb was exposed to a liquid alkaline treatment known as Insta-Blak A-380 from Electrochemical Products, Inc. The results for these plates between 35 and 100 K are plotted as open circles in Figure 4, and they use the right-hand Y axis. Not only is the emissivity significantly lower than the Z307-painted samples, but it has a much stronger temperature dependence. This is most likely due to the cell walls having a combination of lower local emissivity and specularity for the wavelengths relevant to our temperature range. These results led to the Insta-Blak process being rejected for use in this application.

3.3. Kapton and Z307 paint data

Figure 5 shows data from three additional surface treatments characterized using the hybrid test configuration. Two of these samples were versions of black Kapton considered for use on the JWST observatory. The first was a 69 \( \mu m \) thick sample of Kapton 275XC, bonded to the cold plates with a thin layer of ScotchWeld 2216 epoxy. The second was Kapton 100XC, with a thickness of 25 \( \mu m \), and bonded to the plates with a high-temperature-cure film adhesive. Of these two samples, the former was known to have a somewhat higher electrical conductivity, and its transmissivity was measured by the GSFC Optics group. They found that between 30 and 300 K it transmitted less than...
1% of wavelengths shorter than 100 µm. Obviously, any radiation transmitted through the Kapton would be absorbed or reflected by the adhesive and aluminum beneath, and our emissivity measurement would not accurately characterize the Kapton. The Kapton 100XC sample had a higher indicated emissivity above 30 K, but its transmissivity was not measured. One significant result from this test was that it demonstrated our hybrid configurations’ ability to measure emissivity values below 0.7, which had not been done previously due to our focus on very black surface treatments.

The third data set in figure 5 is for Aeroglaze Z307 paint with measured thickness varying between 61 and 97 µm. These cold plates were painted as witness samples during painting of the walls of the large cryogenic shroud prepared for future JWST hardware testing at the Johnson Space Center. We compared our results with those of 2008 GSFC measurements using the transient cooldown method [7]. These earlier measurements characterized Z307 paint thicknesses ranging from 36 to 117 mm and found no systematic thickness dependence. Our data match these results to within about 1 percent above 50 K, but below this temperature the transient data drop more steeply than ours. At their lowest measurement temperature of 30 K, the transient data ranged from 0.64 to 0.7. We don’t understand the difference in results below 50 K, but the transient data had significantly larger reported uncertainty than ours in this temperature range.

4. Process improvements

Our emissivity measurements are significantly more challenging at low temperatures, as the sample heater power for a given \( \Delta T \) is roughly proportional to \( T^3 \). At 20 K the heater power ranges from about 10 to 120 µW. We have seen indications of a source of 10’s of µW into the hot sample plate in addition to the applied heater power, and we long suspected that it might be due to vibrations created by the cryocooler. Since we use the slope of power vs. \( \Delta T \) in our data analysis, we would not be affected by a steady “background” heat of this type. However, our measurements are vulnerable to

Figure 4. Data for aluminum honeycomb samples, as described in the text. The symbols are: solid circles – sample #1, squares – sample #2, solid diamonds – sample #3, open diamonds – flight sample, open circles – Insta-Blak-treated sample.
variations in this power during the time when we are doing multiple balances at a given average temperature. Often, particularly at 20 K, the power vs. $\Delta T$ would be linear for a few balances followed by a shift in the background power. Without understanding the cause of these shifts, we chose to re-run the entire set of balances until we got enough linear points to give a precise slope. Because of the long settling time at 20 K, this approach proved to be very time consuming.

Recently we have taken steps to address this issue. First, we successfully changed our temperature control technique to reduce the time per balance. We had always used temperature controllers to provide independent proportional-integral control of the cold plate can, the suspension ring, and the hot sample. At 20 K the power needed to hold the hot sample at a steady temperature is only 10’s of µW, but the sample’s heat capacity is relatively large. This results in a system time constant of more than 10,000 seconds, the maximum integral constant allowed by the controllers. To avoid overshooting when approaching a new set-point, we needed a low proportional gain and a very long integral constant, and the settling times were nearly half a day. We developed a faster technique involving switching the proportional gain values, turning off and on the integrator and seeding it during the approach to balance, but it still took several hours per balance.

We now use proportional-only control of the hot sample. With the appropriate gain, its temperature quickly reaches a steady value below the set-point. Then, instead of turning on the integrator, we shift the setpoint upward to bring the sample to within 1 mK of the original setpoint. The size of this set-point shift is proportional to the $\Delta T$ value, so we use it to predict the necessary setpoint for the following balance. This has reduced our settling time at 20 K to about one hour, so we can now achieve more balances before a shift in the background heating occurs.

Finally, we attempted to verify that the background heat source was the cryocooler vibrations. The cooler’s cold head gives the cryostat’s cold plate a horizontal mechanical impulse about twice per second. We installed an accelerometer on the cryostat’s vacuum shell and read the signal with a spectrum analyzer. We set the controllers to hold BIRB samples at a steady $\Delta T$ value centered at 20 K, and we monitored the vertical and horizontal vibration spectra and the hot sample heater power for 44 hours. The spectra were both “forests” of peaks separated by two Hz, and these peaks’ amplitudes

![Figure 5](image_url)
changed over time. We were able to identify a horizontal mode at 46 Hz with a strong inverse correlation to the heater power. Figure 6 shows the change in heater power from its maximum value and the 46 hertz horizontal mode amplitude scaled to match the power variations, both plotted against time. The correlation, though not perfect, is convincing evidence that cryocooler vibrations cause the background heating. We plan eventually to modify the cryostat to reduce the vibration amplitude reaching the emissivity apparatus. In the mean time, we may be able to monitor the 46 Hz peak during emissivity measurements and use its variations to select $\Delta T$ values for which the background heat was nearly constant.

Acknowledgements

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![Figure 6. Diagnostic data taken with BIRB samples held at a fixed $\Delta T$, centered at 20 K, for 44 hours. The thick dashed line is the difference between the hot sample heater power and its maximum value during this time. The solid line is the amplitude of a 46 Hz horizontal vibration mode scaled so that its maximum variation matches that of the power data.](image-url)