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# In-Space Demonstration of Spray-on Solar White Paint

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# Abstract

Discs coated with spray-on solar white and two similar thermal control coatings were flown in low earth orbit for roughly five hours. While in orbit, the coated discs were exposed to direct sunlight and to deep space for short intervals. Measurements of disc temperatures showed that the spray-on solar white coating had the lowest absorption of sunlight. Numerical modeling was used to infer that spray-on solar white had a solar absorptance between 0.02 and 0.04 and a thermal emittance between 0.93 and 0.99, both of which are consistent with terrestrial laboratory measurements.

# 1. Introduction

The Applied Physics Laboratory at NASA Kennedy Space Center (KSC) has developed spray-on solar white, a cryogenic thermal control coating (CTCC) for spacecraft that is highly efficient at reflecting sunlight and emitting thermal energy. Spray-on solar white consists of yttrium oxide scattering particles bound in a potassium bromide crystal matrix. Details of the coating's development work, including formulation, application methods, and salient laboratory testing are provided in previous reports [1, 2], and the coating is patented [3].

In 2020, United Launch Alliance (ULA) was funded by NASA Space Technology Mission Directorate through a Tipping Point project to perform in-space demonstrations of technologies purposed for cryogenic fluid management, including the spray-on solar white CTCC. ULA and NASA jointly developed a payload designed to fly small, metallic discs coated with one of three different CTCC products, including spray-on solar white, and to expose them in low-earth orbit to direct sunlight and to deep space (i.e., the cosmic radiation background at about 3 K). The payload design was similar to a concept developed for a previous flight test on a CubeSat where coated aluminum discs were suspended by strings at the center of metal chambers [4]. In space, the discs were exposed to the external environment only through circular openings over the discs. This configuration provided each disc with almost equal exposure to the sun or to space through the circular openings. The chambers surrounding the discs were formed from a single piece of aluminum and were at essentially the same temperature, resulting in equal radiative transfer between the chambers and the discs. This design provided a nearly identical thermal environment for each disc so that differential temperature changes would be mostly due to differences in absorption from and emission to the external environment.

The goals of the present test were to 1) expose the three different CTCC products to an identical thermal environment in space and demonstrate that solar white provided lower temperatures than the other CTCC, and 2) to acquire temperature change data dominated by radiative transfer with the space environment that could be used with numerical modeling to infer values of total solar absorptance and thermal emissivity for the spray-on solar white paint. This report describes the test, including the payload package, the acquired data, and the numerical modeling analysis used to estimate solar absorptance and thermal emissivity from the test data.

## 2. Test Description

The payload contained six, identical aluminum discs with embedded temperature sensors. Two discs were coated with spray-on solar white. The other four discs were coated with one of two other thermal coatings (TC) products (two discs for each product), identified here as ‘TC1’ and ‘TC2’. Figure 1 depicts the payload without the front cover, showing six discs suspended by small wires inside individual chambers of a monolithic aluminum case.

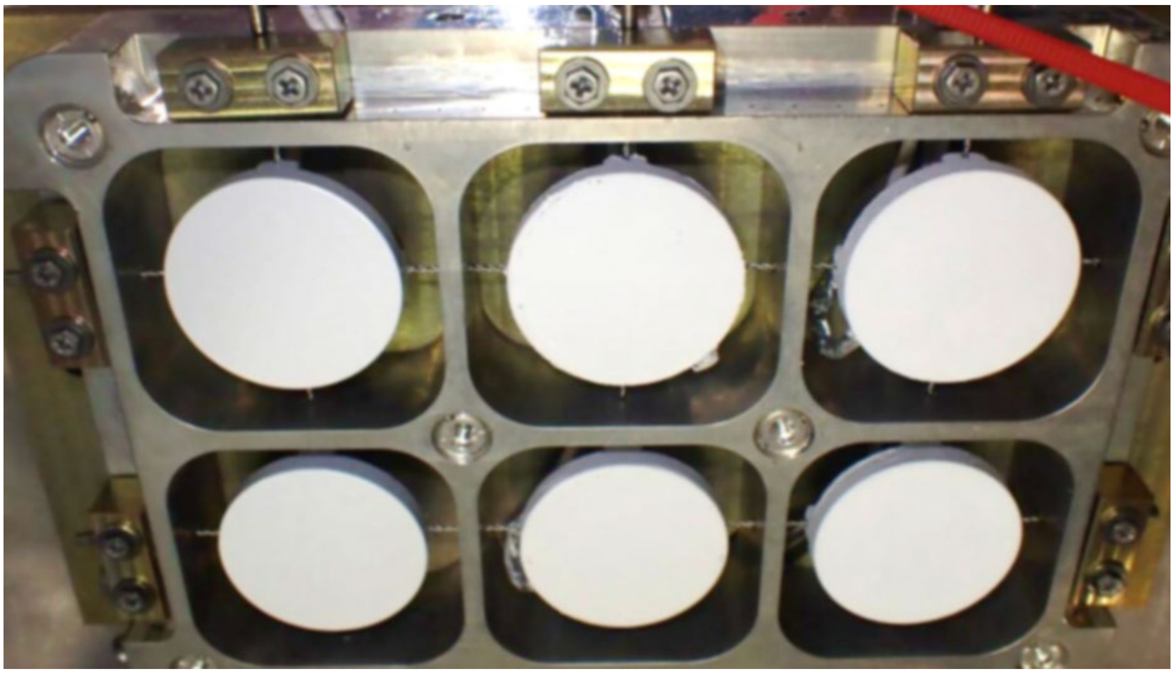

Figure 1. Discs with CTCC coatings mounted in payload case

The discs were suspended by 0.032-inch CRES safety wires that were routed through small feet on the back side of the discs. The wires were routed through small penetrations between chambers and through the outer case wall. Clamps outside the case held the wires with enough tension to avoid excessive disc movement during launch. Figure 2 depicts the case with a forward plate that had circular openings centered over the discs. The outer surfaces of the aluminum case were covered in silvered Teflon tape to minimize unwanted absorption of sunlight. The discs were 1.5 inches in diameter and roughly 0.5 inches thick, and the openings were 1.45 inches in diameter.

The discs were composed of a front and back plate, both machined from aluminum, that were epoxied together after attaching a RTD to the center of the back side of the front plate (i.e., the sun-facing plate). Figure 3 illustrates 1) the placement of the RTD sensors on the discs, and 2) the cable routing for the RTD sensors in the discs and the two additional RTD sensors that were embedded in the case. All RTD sensors were 3-wire, ceramic-coated, platinum elements that were tested by the supplier and calibrated to verify a maximum error of ±1 K from 44 K to 367 K.

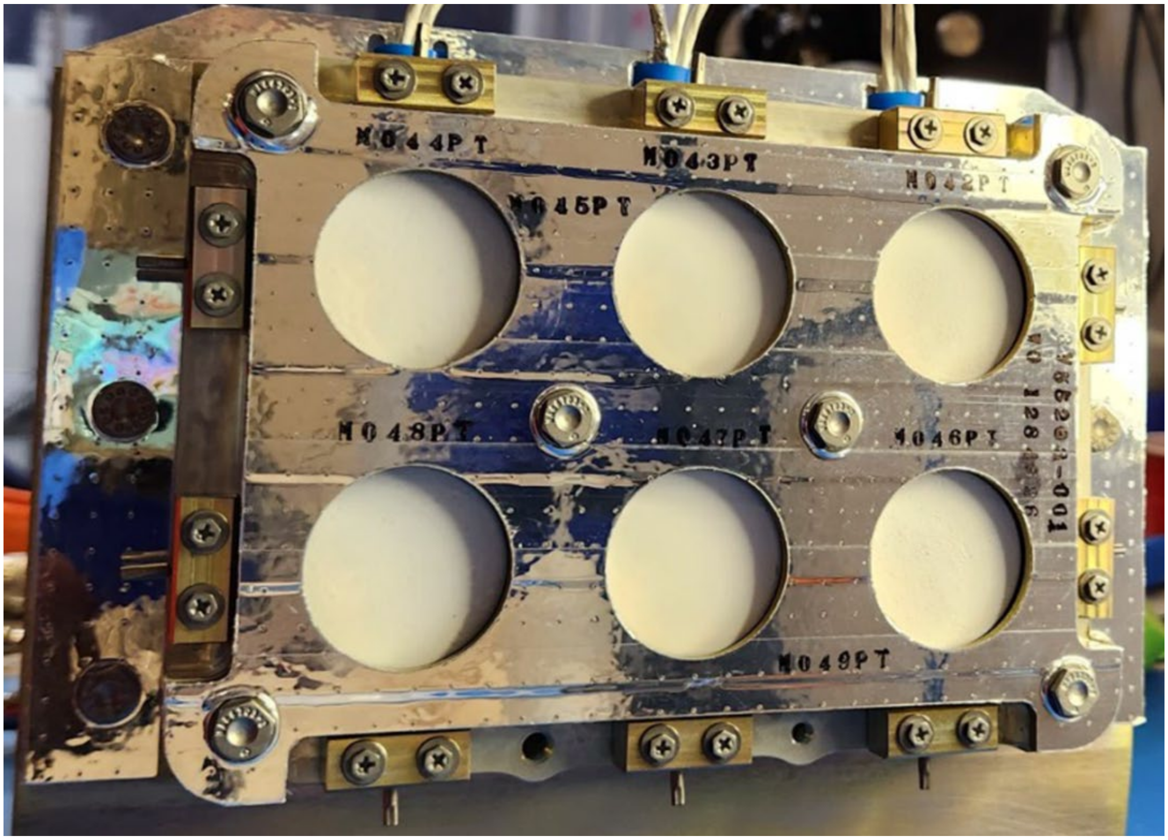


Figure 2. The payload with the front cover installed

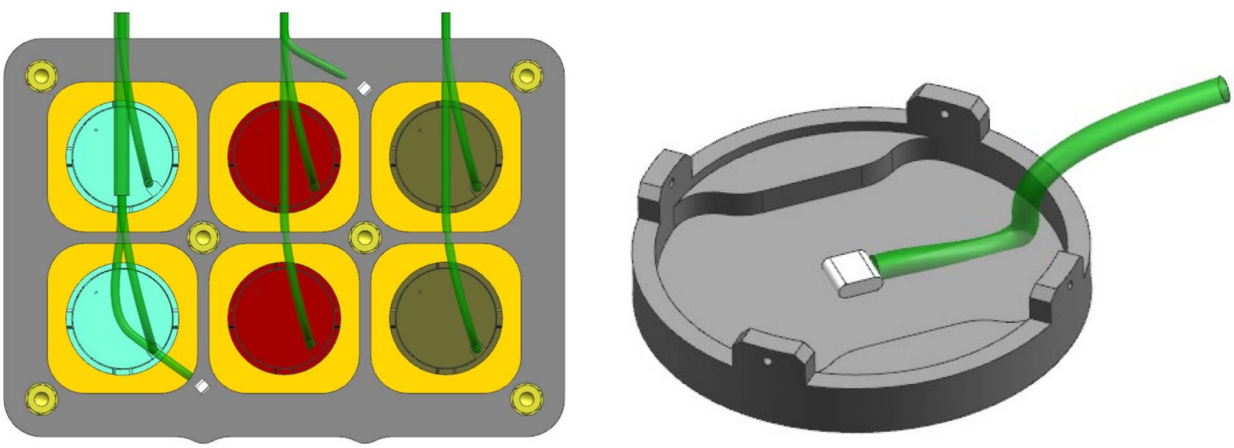

Figure 3. Cable routing and locations of temperature sensors on case (left), location of temperature sensor in discs on the back side of the front plate (right).

This design was intended to provide a well-controlled thermal system for the discs that facilitated 1) comparisons between the optical performance of the coatings, and 2) simplified numerical modeling of the disc temperatures. The dominant heat transfer path was radiative transfer between the discs and the sun or space. Additional heat transfer paths included thermal conduction from the case to the discs through the CRES wires, thermal conduction from the sensor cabling, radiative transfer between the case and the discs and the wires and the discs, and power dissipation by the RTD sensors.

Figure 4 depicts the payload installed on the payload attachment fitting on top of the Centaur second stage that was flown in the Vulcan Centaur CERT-2 mission, which launched on October 4, 2024. The payload was positioned such that the discs faced the outward radial direction and the top of the case pointed in the forward direction. Figure 5 presents the approximately 5 hours of temperature data that were recorded while the payload orbited Earth at time-varying attitudes. The temperature data were recorded with a vertical resolution of 0.9 K/bit at a sample rate of 6.25 samples per second. Note that some temperature and angle data are missing due to short periods of faulty data acquisition.

Table 1 summarizes salient flight intervals and temperature changes during these intervals. During the four ‘Sun Facing’ intervals, which are highlighted gray in Figure 5, the Sun was visible to the discs at a roughly constant oblique angle and the Earth was not visible. There were two ‘Space Facing’ intervals, which are highlighted red in Figure 5, during which the discs were pointed toward deep space and the vehicle shadowed the payload from the Sun and the Earth. During the single ‘Forward Pointing’ interval, the vehicle was maintained at an attitude that kept its forward vector point toward the sun, and the discs were pointed away from the sun and the earth. However, the payload attachment fitting, to which the payload was mounted, and the payload case (particularly the forward side) were pointed directly at the sun. During the ‘PTC Rolls’ (passive thermal control rolls), the vehicle was rotating about its longitudinal axis, resulting in a roughly sinusoidally varying exposure to the Sun and the Earth with a period that varied between about 5 and 13 seconds.

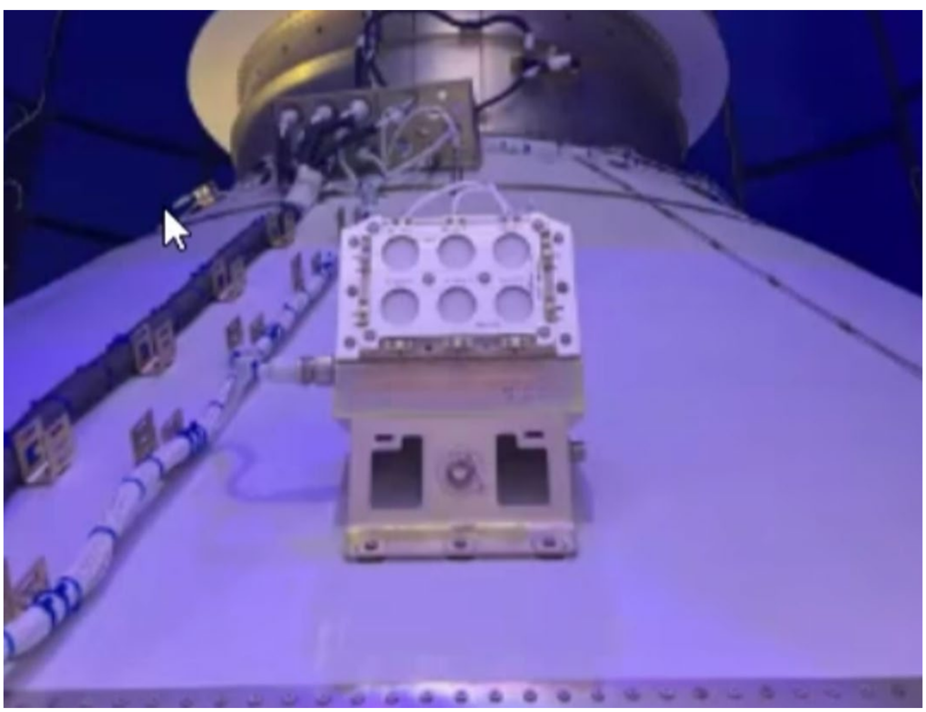

Figure 4. Payload installed on Centaur second stage.  TC1 discs are on the left, TC2 discs are in the center, and solar white discs are on the right.

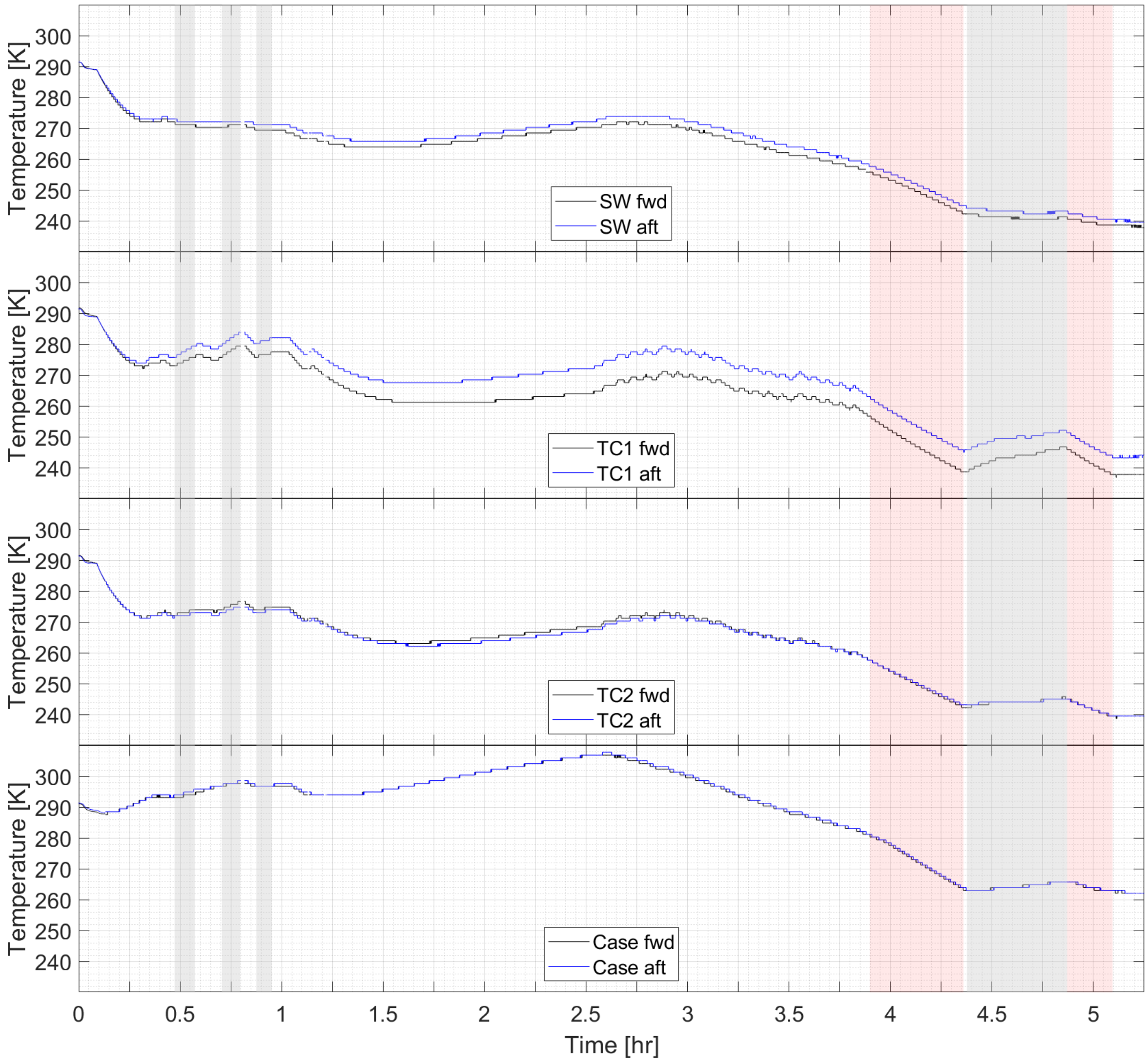

Figure 5. Measured temperatures during flight.

Table 1. Flight intervals and associated temperature changes.

| Interval | Start [hr] | End [hr] | Duration [hr] | Solar White fwd ΔT [K] | Solar White aft ΔT [K] | TC1 fwd ΔT [K] | TC1 aft ΔT [K] | TC2 fwd ΔT [K] | TC2 aft ΔT [K] | Case fwd ΔT [K] | Case aft ΔT [K] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1st Sun Facing | 0.47 | 0.57 | 0.10 | -0.9 | -0.9 | 2.7 | 3.6 | 1.8 | 0.9 | 0.9 | 1.8 |
| 2nd Sun Facing | 0.71 | 0.80 | 0.09 | 0.9 | 0.00 | 3.6 | 4.6 | 2.7 | 1.8 | 0.9 | 1.8 |
| 3rd Sun Facing | 0.88 | 0.95 | 0.08 | 0.0 | 0.00 | 1.8 | 1.8 | 0.9 | 0.9 | 0.00 | 0.00 |
| Forward Pointing | 1.18 | 2.52 | 1.34 | 4.5 | 3.6 | -8.2 | -5.5 | -2.7 | -2.7 | 12.9 | 12.9 |
| PTC Roll | 2.57 | 3.87 | 1.30 | -13.6 | -14.5 | -7.2 | -9.1 | -9.9 | -9.1 | -25.7 | -24.8 |
| 1st Space Facing | 3.90 | 4.36 | 0.46 | -13.5 | -12.6 | -18.0 | -17.2 | -15.3 | -14.4 | -18.2 | -17.3 |
| 4th Sun Facing | 4.38 | 4.87 | 0.49 | -0.9 | -0.9 | 7.2 | 5.4 | 2.7 | 1.8 | 2.7 | 2.7 |
| 2nd Space Facing | 4.87 | 5.09 | 0.22 | -2.7 | -2.7 | -8.1 | -7.2 | -5.4 | -5.4 | -2.7 | -2.7 |

# 3. Numerical Modeling

The goal of the modeling was to infer values of solar absorptance and thermal emissivity for the three different CTCC. Thermal Desktop was used to perform three-dimensional modeling of the disc temperatures. The case and the bracket attaching the case to the PAF were modeled as 2-D surfaces, the CRES wires were modeled as 1-D lines, and the discs were modeled as 3-D bodies. All values of material thermal conductivity and heat capacity were constant with temperature. Heat flow from the PAF to the bracket and case and from cabling was neglected, as was any heating due to collisions with ionospheric molecules. Note that in the modeling, the case temperature was not forced to the measured values.

Figure 6 shows the computed solar, earthshine, and earth albedo irradiances on the discs during the flight. Solar flux was calculated based on the October 4, 2024 Earth-Sun distance of 1.00037 AU. Earth shine values were latitude dependent with average values from September and October. Albedo was based on the average September/October values from 0° to -20° latitude based on the vehicle trajectory having a time averaged latitude of -10.3°. Directional irradiances were computed using the vehicle attitude and position and were used as heat sources in the model. The measured temperatures for the case and the samples at 0 hours were used as the initial values.

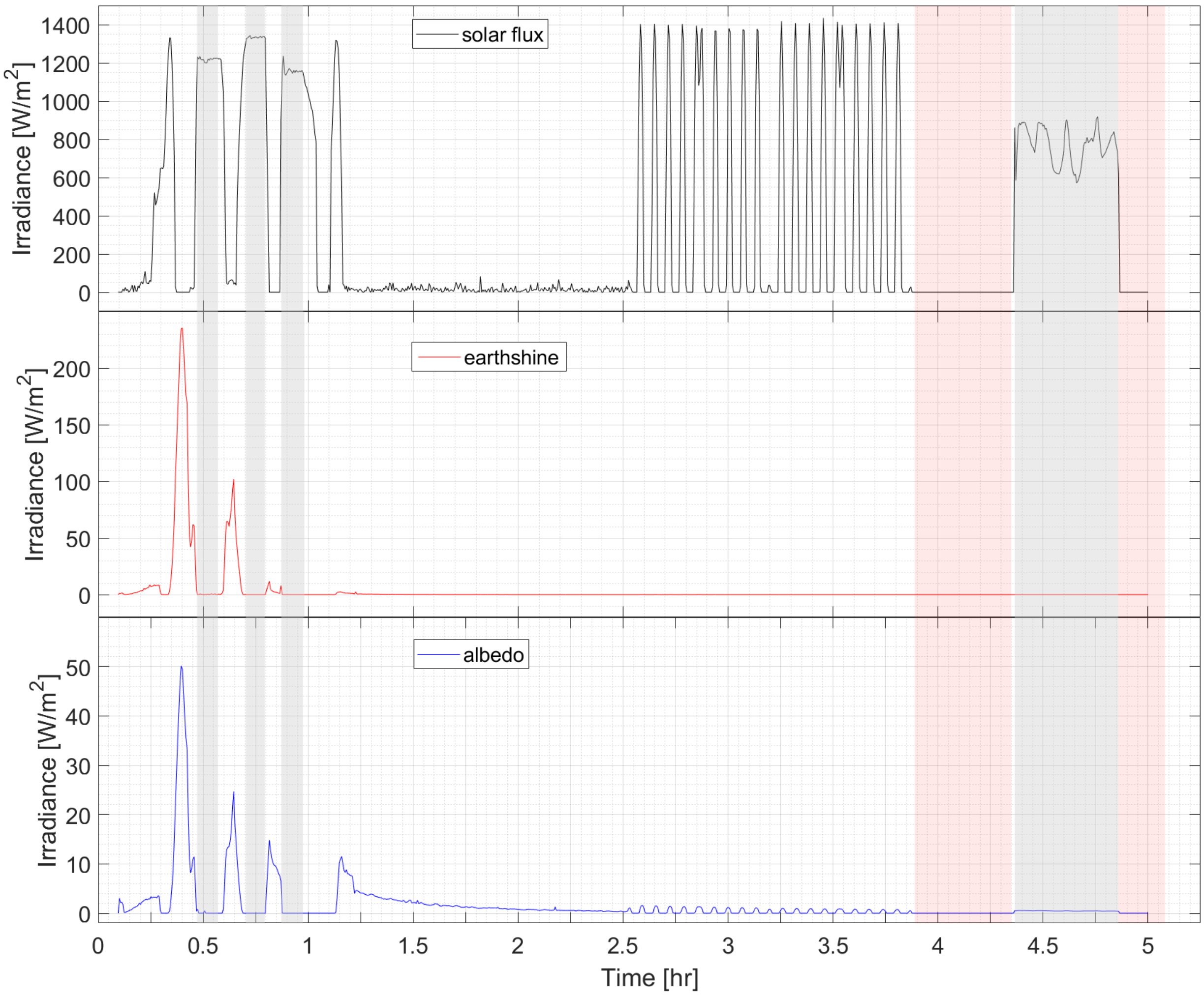


Figure 6. Computed values of solar, earthshine, and albedo irradiances on discs.

Several sets of model runs were performed with nominal, minimum, and maximum dispersions of various inputs, including irradiances, optical properties, and wire conduction (all assuming no heat dissipation from the sensors). The ranges used for these inputs are summarized in Table 2. Additional modeling was performed assuming the RTD dissipated 17.2 mW of power at the center of the front face of the samples with nominal values for irradiances and optical properties. Figures 7 through 9 show the modeling results for the different model input variations with the measurement data. In all plots, the curves labeled 'fwd' and 'aft' are the measurement data.

Table 2. Numerical model parameters

| Parameter | Minimum | Nominal | Maximum |
|---|---|---|---|
| Solar heating [W/m$^2$] | 1315.5 | 1370.7 | 1429.0 |
| Earth shine [W/m$^2$] | 189.3 | 110-268 | 261.8 |
| Albedo [W/m$^2$] | 0.6 | 0.7 | 1.3 |
| TC1 absorptivity | 0.2 | 0.27 | 0.34 |
| TC2 absorptivity | 0.12 | 0.145 | 0.17 |
| Solar white absorptivity | 0.02 | 0.03 | 0.04 |
| Case absorptivity | 0.04 | 0.055 | 0.07 |
| TC1 emissivity | 0.95 | 0.9 | 0.85 |
| TC2 emissivity | 0.99 | 0.95 | 0.91 |
| Solar white emissivity | 0.991 | 0.958 | 0.925 |
| Case emissivity | 0.91 | 0.9 | 0.89 |

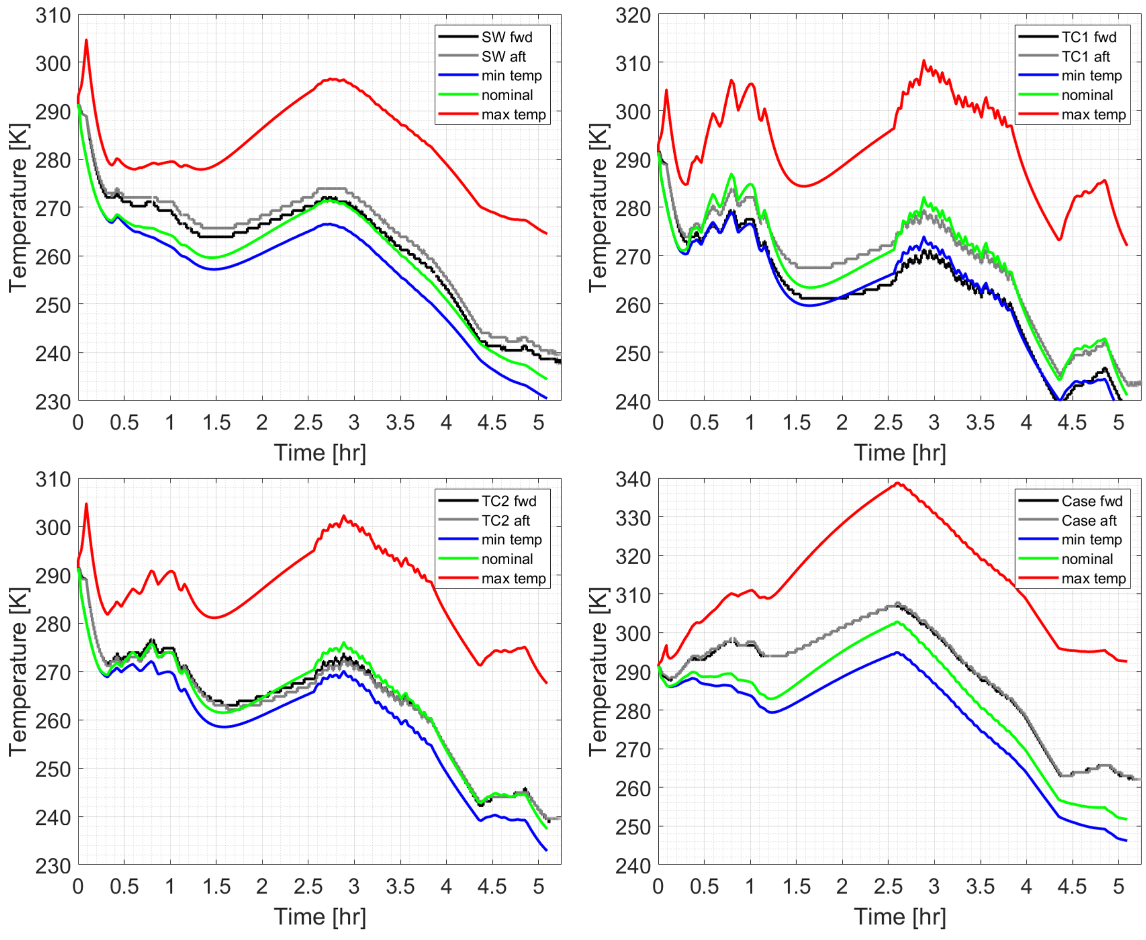


Figure 7. Measured data and model predictions for dispersed minimum, nominal, and maximum environmental irradiances.

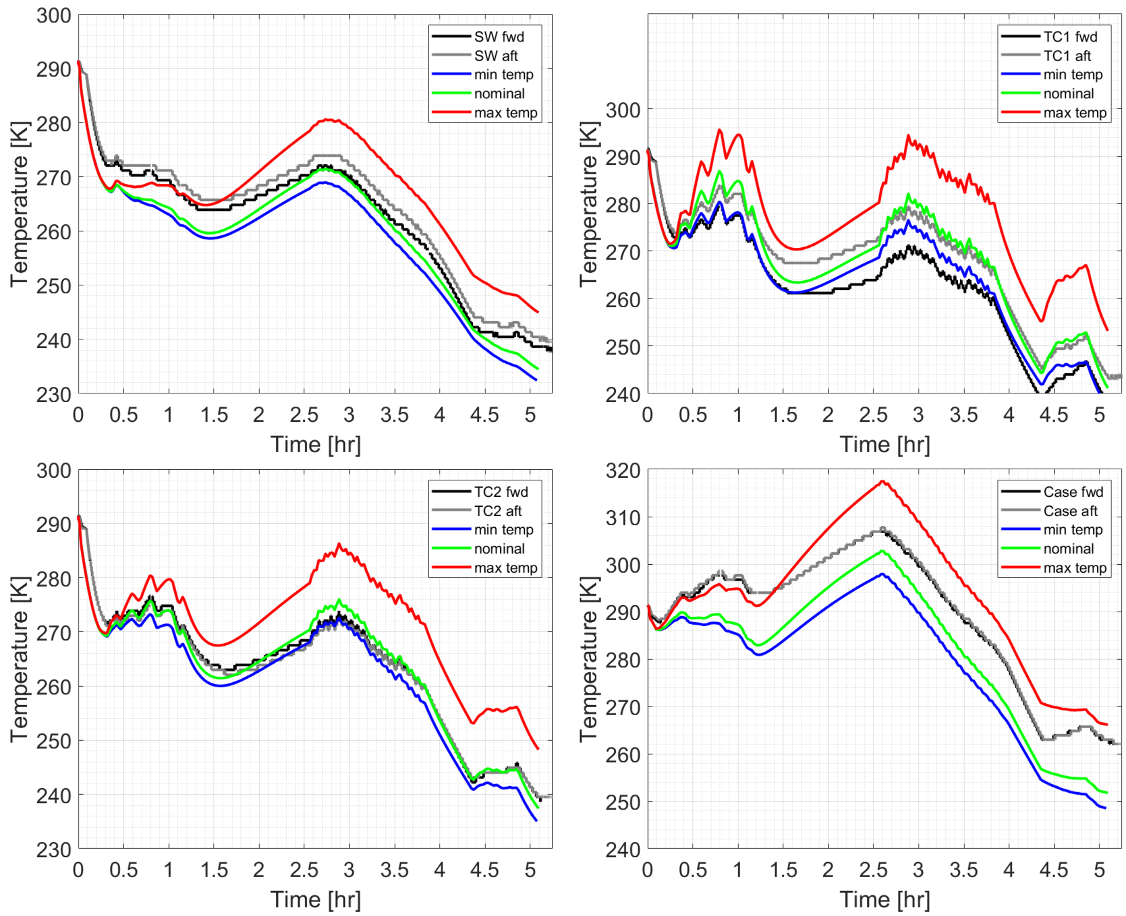


Figure 8. Measured data and model predictions for minimum, nominal, and maximum values of solar absorptivity and thermal emissivity.

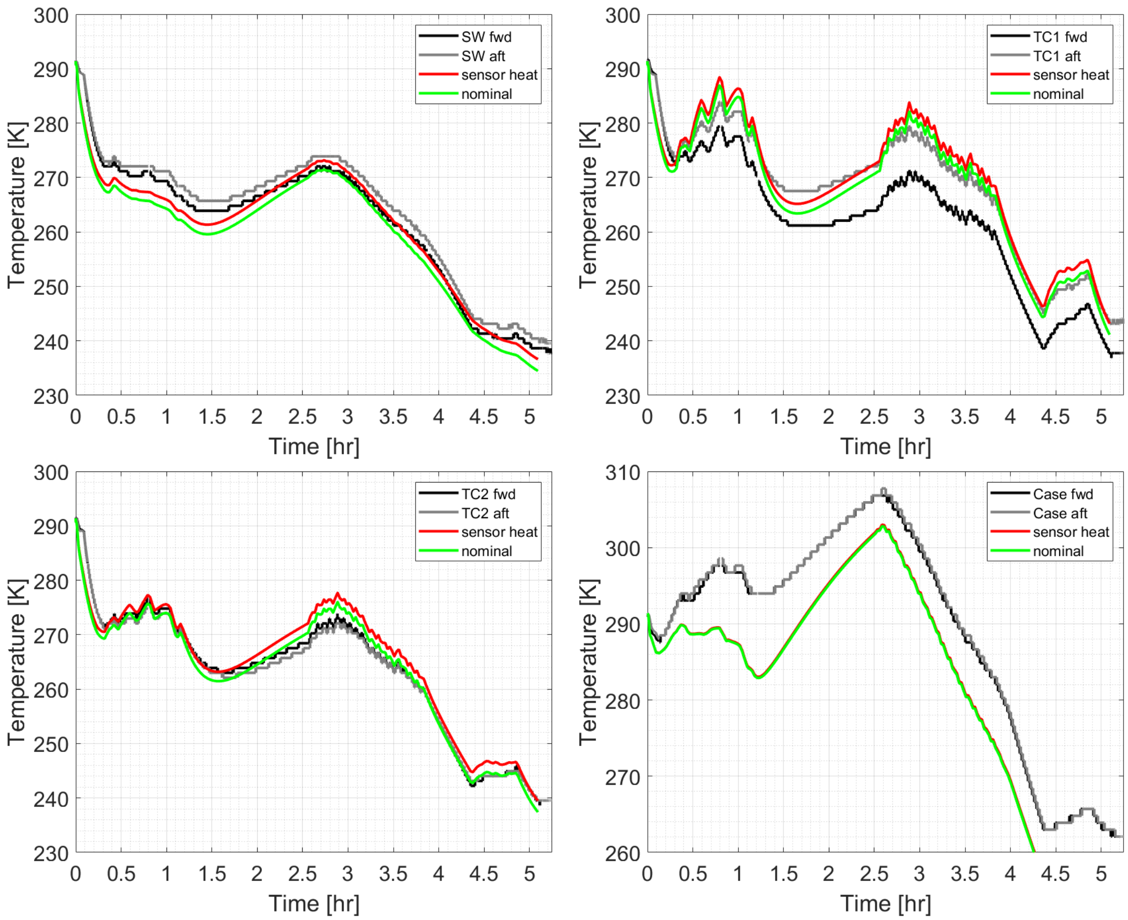


Figure 9. Measured data and model predictions for with (sensor heat) and without (nominal) RTD power dissipation.

# 4. Discussion

Two discs for each of the three coatings were flown for redundancy, and it was expected that similar temperatures would be observed for similarly coated discs. However, measured temperatures between two discs of the same coating evolved differently after the samples were exposed (i.e., after the payload fairing was jettisoned). Pre-launch temperatures were within 1 K, so it seems unlikely that instrumentation error could have been the source of the different temperatures. The temperature differences were smallest for the TC2 discs, which were mounted in the middle of the payload. This observation suggests that the differences may have been due to heat flow through the CRES wires used to mount the samples, which would be expected to be greater for the coupons on the sides since the heat paths through the wires are shorter. However, during the forward-pointing interval, when the front of the case was pointed directly at the sun for roughly 1.25 hours, even though the disc temperatures began increasing in response to heat flow from the case, the forward samples didn't show greater temperature changes. It seems more likely that temperature differences between similarly coated discs were due to slight misalignments, resulting in small differences in exposure to external sources.  It is possible that there were slight differences in coating qualities. Even though there were offsets between the temperatures for discs of a given coating, the changes in temperatures were similar and useful conclusions could be made.

In the four sun-facing intervals, the case, the TC1 discs, and the TC2 discs all exhibited an increasing temperature, with TC1 increasing the most, while the solar white discs showed either no change in temperature or a decrease in temperature. It can be concluded clearly from these results that Solar White provided the best thermal performance under direct solar irradiance. During the forward-pointing interval, the samples were not directly illuminated by the sun, but the forward side of the case was pointed directly at the sun. The temperatures for all discs decreased for the first half hour, but the decrease was smallest for the solar white discs. This can be attributed to three factors. First, the TC1 and TC2 discs started at higher temperatures, so their radiant emittance should have been greater, resulting in an initially greater decrease in temperature. Second, the discs were exposed to the Earth during the interval, and solar white is expected to absorb more radiant infrared energy from Earth than TC1 and TC2 since it has a greater thermal emissivity (and therefore greater infrared absorptivity). Finally, for the sample reason, solar white should absorb more radiant infrared energy from the case, and the case began heating rapidly shortly after the interval began.

It is more difficult to draw conclusions from the temperatures observed during the PTC roll. When the roll began, the case immediately began to cool, and during the first roughly 25 minutes, TC1 and TC2 continued to increase in temperature while solar white showed almost no temperature increase. Throughout the remainder of the PTC roll, the solar white discs exhibited the greatest decrease in temperature. The discs were exposed to the earth and sun for roughly equal amounts of time, but the radiant power from the sun was three orders of magnitude greater than from the Earth. Therefore, the observed temperature changes indicate the solar white discs absorbed less radiant energy from the sun.

In the first space facing interval, the TC1 discs and the case showed the largest decreases in temperatures. The first interval was roughly twice as long as the second interval, and the temperatures were greater at the start of the first interval than the second interval. As a result, all temperature changes in the second space-facing interval were smaller, with the largest changes occurring with the TC1 and TC2 discs. In both intervals, the solar white discs showed the smallest decrease in temperature, most likely due to them absorbing more infrared energy from the case.

The modeling results matched the measured data remarkably well considering the assumptions made in the modeling and the sensitivity of the modeling to the various model inputs given in Table 2. The modeling results in Figure 7 show that the nominal values for solar heating, earth shine and albedo were reasonable. The results attained when these values were used and the optical properties were varied, shown in Figure 8, were less clear, with measurements exceeding the predictions from the maximum optical property values for all discs and the case. The modeling and measurements match exceptionally well for TC2. For the TC1 discs, following the middle of the PTC roll, the measurements were significantly lower than the predictions made with minimum optical values. In all cases, the modeling predicted a larger initial temperature decrease than was observed in the measurements.

It is unclear why measurement and modeling temperatures diverged in the first 20 minutes. It appears there was a heat source during the first few minutes that was not included in the modeling, as evidenced by the several minutes of delay in the temperature decrease in the measurements. Following this delay, the measured and modeled temperatures decreased at roughly the same rates, indicating the unknown heat source terminated. Adding power dissipation from the RTDs to the model yielded the results shown in Figure 9, where there is generally a better match between measurement and modeling for solar white, but a worse the match for TC1 and TC2. Neglecting the RTD power and removing the initial temperature offsets introduced by the unknown, transient heat source yields the results shown in Figure 10, where the match between modeling and measurement for the solar white discs is substantially better and the match for the case is slightly better. For TC2, the match is still excellent, although it is slightly worse during the start of the PTC roll. For TC1, the temperature measured for the aft coupon still falls within the model results using the minimum and maximum optical properties. If removing the offset is a valid operation, then the optical properties in Table 2 are appropriate at least for solar white, TC2, and the case. Finally, these optical properties are similar to those determined through laboratory experiments.

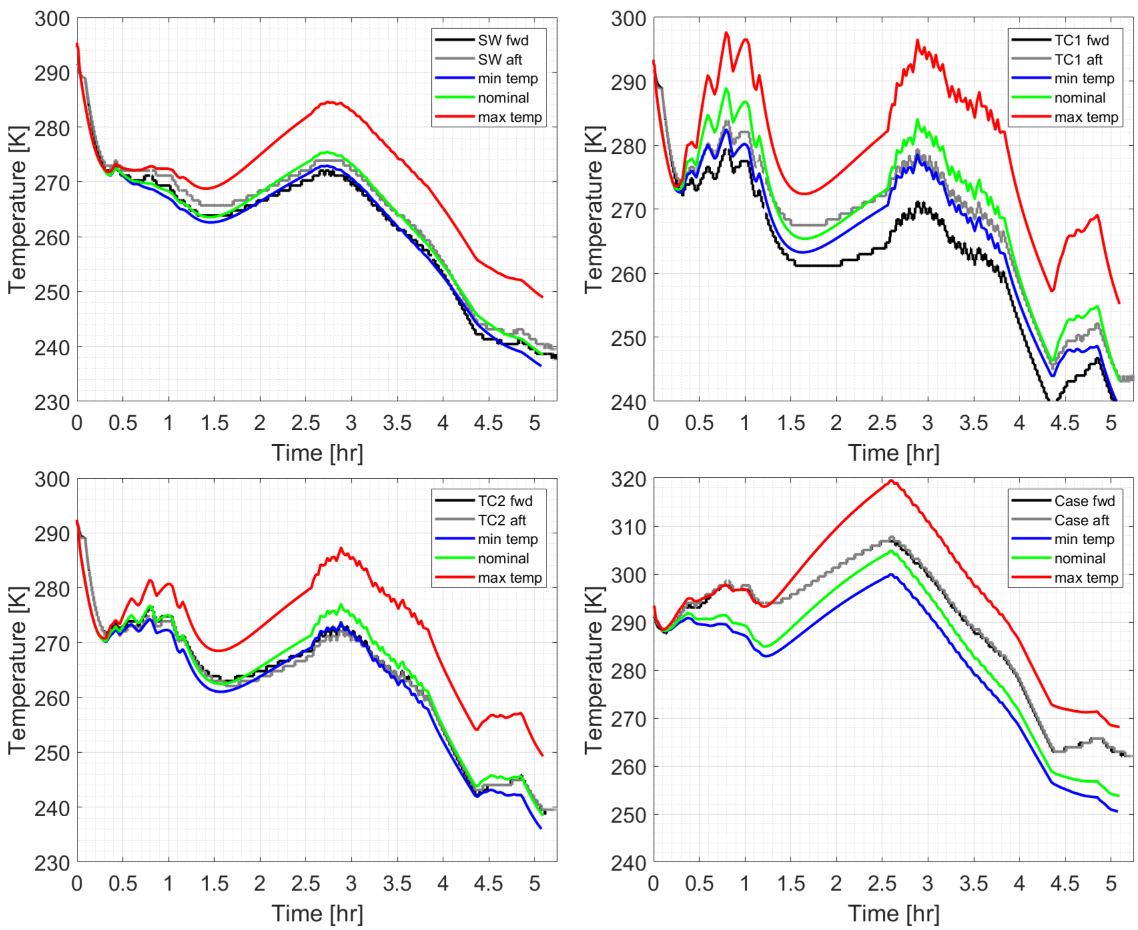


Figure 10. Measured data and model predictions for minimum, nominal, and maximum values of solar absorptivity and thermal emissivity with the model predictions shifted upward to eliminate the initial temperature offset.

## 5. Conclusion

Discs coated with one of three thermal control coatings, including spray-on solar white, were tested in low-earth orbit while being exposed to the Sun, the Earth and deep space. The discs coated with spray-on solar white exhibited the smallest temperature increase when exposed to direct sunlight. The numerical modeling that was employed to predict the expected temperature changes during flight indicates the spray-on solar white coating on aluminum exhibited a solar absorptivity between 0.02 and 0.04 and emissivity values between 0.93 and 0.99.

## 6. References


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