

# Effect of Illumination Angle on the Performance of Dusted Thermal Control Surfaces in a Simulated Lunar Environment

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## ABSTRACT

JSC-1A lunar simulant has been applied to AZ93 and AgFEP thermal control surfaces on aluminum substrates in a simulated lunar environment. The temperature of these surfaces was monitored as they were heated with a solar simulator using varying angles of incidence and cooled in a 30 K coldbox. Thermal modeling was used to determine the solar absorptivity ( $\alpha$ ) and infrared emissivity ( $\varepsilon$ ) of the thermal control surfaces in both their clean and dusted states. It was found that even a sub-monolayer of dust can significantly raise the  $\alpha$  of either type of surface. A full monolayer can increase the  $\alpha/\varepsilon$  ratio by a factor of 3-4 over a clean surface. Little angular dependence of the  $\alpha$  of pristine thermal control surfaces for both AZ93 and AgFEP was observed, at least until 30° from the surface. The dusted surfaces showed the most angular dependence of  $\alpha$  when the incidence angle was in the range of 25° to 35°. Samples with a full monolayer, like those with no dust, showed little angular dependence in  $\alpha$ . The  $\varepsilon$  of the dusted thermal control surfaces was within the spread of clean surfaces, with the exception of high dust coverage, where a small increase was observed at shallow angles.

## INTRODUCTION

National Space Policy calls for NASA to return humans to the Moon by 2020. Largely due to the lack of an appreciable atmosphere, the lunar surface environment is hostile. In addition to being at ultrahigh vacuum ( $10^{-12}$  Torr during the day at  $10^{-14}$  Torr during the night), there are thermal extremes (100 to 400 K), unshielded solar electromagnetic and particle radiation, cosmic radiation, and an unceasing bombardment of meteoroids. But of all of the environmental threats on the Moon, the one

singled out by Apollo astronauts as being the most worrisome is lunar dust. They were particularly surprised by how much the thermal control surfaces were affected. For example, even though they were equipped with dust covers and were brushed off at regular intervals, the batteries for the lunar roving vehicle ran hotter than anticipated, and in fact hotter than their rated operating temperature for part of the time (ref. 1). Since the new lunar architecture calls for the next generation of surface systems to operate on the lunar surface for years rather than the days required of Apollo systems, a joint task has been developed by the Dust Mitigation Project and the Advanced Thermal Control Project to quantify the effects of lunar dust on thermal control surfaces and to develop mitigation strategies.

The current lunar exploration architecture calls for exploring the lunar poles. Since the radiators will likely be facing up into space to radiate to the lowest temperature, solar radiation will be striking these surfaces at low angles. This study sought to determine the effect of solar incidence angle on the absorptivity ( $\alpha$ ) of pristine thermal control surfaces. The second objective was to continue the investigation into the effect of dust on the  $\alpha$  of the thermal control surfaces. The third objective was to determine the effect of dust on the angular dependence of  $\alpha$  of these surfaces.

## METHODS AND MATERIALS

This study utilized a white thermal control paint (AZ93) and a second surface mirror (Ag coated FEP Teflon®) as the thermal control surfaces. The thermal control surfaces were applied to 2.54 cm (1 in.) diameter aluminum substrates. The AZ-93 paint was applied by AZ Technology (Huntsville). The AgFEP appliques were

fabricated by Sheldahl (Northfield, MN) from 12.7  $\mu\text{m}$  (5 mil) thick FEP Teflon<sup>®</sup> which was coated with a few tens of nm of silver and a few tens of nm of Inconel as a sealing layer to prevent oxidation. They were hand-applied to the substrates using a film adhesive.

The tests were carried out using the NASA Lunar Dust Adhesion Bell jar (LDAB). The lunar simulation facility enables the simulated lunar dust to be heated, dried, plasma-cleaned, chemically reduced, and sieved onto samples *in situ*. It operates at a pressure of  $10^{-5}$  Pa ( $10^{-8}$  Torr). The sample, pristine or dusted, can be heated using a 20-Sun xenon arc lamp solar simulator, and radiatively cooled in a 30 K cold-box. Details of the LDAB are available elsewhere (ref. 2). One AZ-93 coated sample and one AgFEP sample were exposed during each test in a single sample holder. Figure 1 shows two samples mounted in the LDAB sample holder.

Approximately 15 g of JSC-1AF lunar simulant was placed in the activation bowl of the LDAB where it was stirred as a vacuum was pulled down to about 13 Pa (100 mTorr). At this pressure it was exposed to a radio frequency air plasma for 1 hr, with intermittent stirring, to remove organic contaminants. The chamber was then pumped down to about  $10^{-4}$  Pa ( $10^{-6}$  Torr) and the simulant was heated at least 16 hr to at least 200 °C, with stirring, to remove water. After cooling to room temperature, the chamber was backfilled with a 5 percent  $\text{H}_2$  in He gas to a pressure of 13 Pa and the dust was exposed to a radio frequency plasma for 1 hr, with intermittent stirring, to chemically reduce and to add hydrogen to the dust particle surfaces. This was to mimic the effects of solar wind. The  $\text{H}_2$ -He mixture was pumped out and the pressure again dropped to  $10^{-4}$  Pa. Then a recirculating He refrigerator was used to cool a cold box within the chamber to about 30 K. The resulting condensation of gases onto the surface of the cold box lowered the pressure in the chamber to about  $10^{-5}$  Pa. This was the level of vacuum under which most of the testing was carried out. The dust was transferred from the activation bowl to a 3 in. standard, 38  $\mu\text{m}$  stainless steel sieve for application to the samples.

One of the samples was positioned under a 20-Sun Xe arc lamp (Luxtel), and tilted to the desired incidence angle using a bubble-level type angle indicator. Incidence angles of 90°, 45°, 30°, and 10° were used. After the temperature recording software was started, the arc lamp was ignited. The sample was exposed for 800 sec, or until the temperature approached 200 °C, whichever came first. Then the second sample was positioned under the lamp and exposed for a similar duration. Then the lamp was extinguished, the angle returned to 90°, and the sample holder was translated into the cold box, which is lined with an absorbing material (Vel-Black) and maintained at about 30 K with a recycling helium refrigerator. The samples were allowed to cool for at least 20 min, or until the temperature of

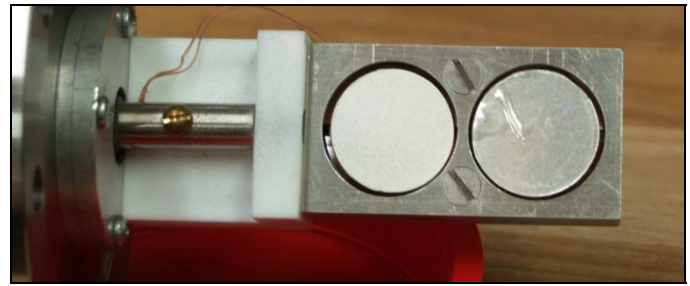


Figure 1.—Aluminum substrate coated with AZ-93 (left) and Ag/FEP (right) thermal control surfaces. The thin brown wires in the photo are two thermocouples, one connected to each sample.

both samples was below 15 °C, whichever took the longest. The sample was then pulled out of the cold box, though still in the vacuum chamber, and allowed to come to near equilibrium temperature before the next test was started.

After heating and cooling data had been collected at all four angles, the sample was positioned under a 25  $\mu\text{m}$  sieve filled with activated dust. Dust was sieved onto the sample at an angle of 90° in all cases. The sample was then translated under the Xe arc lamp, and heated at incidence angles of 90°, 45°, 30°, and 10°, and cooled using the procedure described above for the pristine samples.

In some cases a Kimball Physics (Wilton, NH) model FRA-2X1-2 electron flood gun sprayed electrons onto the dust as it dropped from the sieve onto the samples. The electron energy was set at 1000 V, and the emission current was about 200  $\mu\text{A}$ . It should be noted that this was a rather narrow beam, so only some fraction of the falling dust was directly exposed to the electrons.

Fractional dust coverage was determined from images obtained with an optical microscope at 100 $\times$  using image analysis software and a rigorous statistical procedure. The process has been described in detail elsewhere (ref. 3). The mean of 50 measurements was calculated for each sample, as was the 95 percent confidence interval.

The thermal modeling was done using Thermal Desktop (Cullimore & Ring Technologies), a PC based design environment for generating thermal models of electronics and vehicles. Thermal Desktop incorporates both parameter based finite difference surfaces with finite elements and CAD technology to model thermal problems. Thermal Desktop develops the capacitance and conductance network for input to SINDA/Fluint which is a comprehensive finite-difference, lumped parameter (circuit or network analogy) tool for heat transfer design analysis and fluid flow analysis in complex systems. Thermal Desktop 5.1 Patch 3 was used to generate the thermal model which consists of