

Preliminary Findings of Lunar Dust Testing on Radiator Performance

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The Risk of Radiator-Dust Demonstration (R2D2) tests were developed to assess the effects of lunar dust on heat rejecting radiators at Glenn Research Center. R2D2 allows for quick-turnaround testing with the ability to make agile adjustments to testing conditions. The test involves operating radiator prototypes in a thermal vacuum while simulant is deposited on the radiator face sheet. The steady state thermal response to dust deposition was studied, and the initial results did not imply a correlation between dust adhesion and radiator performance given these test conditions. This paper discusses the test design, the conclusions of the test, and the next steps for continuing to study the effects of lunar dust on radiators.

I. BACKGROUND

The Fission Surface Power (FSP) project aims to install a 40 kWe nuclear reactor on the lunar surface to power ground exploration and research (Ref. 1). The system's Power Conversion Systems (PCS)- which will convert reactor heat into usable electricity- must reject heat in order to generate power. Radiators are the ideal medium for this due to their passive nature and their ability to reject heat in a vacuum.

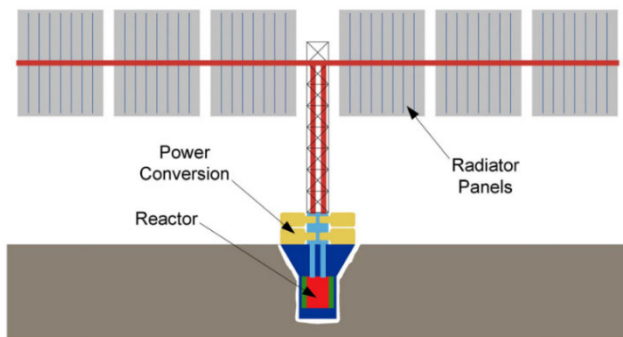


Fig. 1. 2008-era Fission Surface Power Concept (Ref. 2)

Radiators have been used on lunar missions since the Apollo program. The adhesion of dust was an unexpected challenge in early missions (Ref. 3). In knowing this, FSP is initiating the assessment of radiator dust as a potential risk. This effort has led to the Risk of Radiator-Dust Demonstration (R2D2), to develop an in-

house testing procedure to begin to evaluate the effects of dust adhesion on radiator samples.

These preliminary R2D2 tests have taken place in Glenn Research Center's VF-13 using 12"x12" Graphite Fiber Reinforced Composite (GFRC) radiators and JSC-1A lunar regolith simulant.

II. METHODOLOGY

This test is based off of DMFlex (Ref. 4), a platform for evaluating dust mitigation strategies on solar arrays in lunar conditions. Much of the structure design and operations were conceived for DMFlex and were adapted to fit the needs of radiator testing.

The full radiator assemblies consist of a heater block, a heat pipe, and a radiator. The heater block serves to simulate the heat rejected from the PCS. These each consist of two aluminum blocks with embedded electric cartridge heaters, which are clamped around the evaporator end of the heat pipe. This titanium-water heat pipe passively pumps heat to the radiator, which is comprised of two uncoated carbon fiber face sheets which sandwich an aluminum honeycomb core. The thermal energy transferred to the radiator is rejected primarily by the carbon face sheets via the emission of black-body radiation.

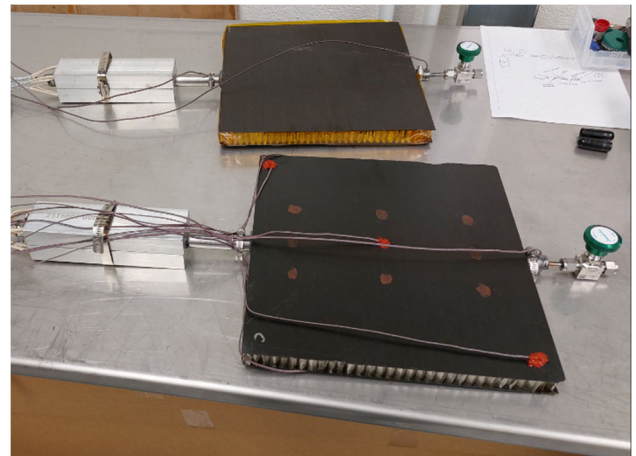


Fig. 2. The Radiator Assembly Pair

The radiator assemblies were mounted inside an aluminum frame, tilted 15 degrees toward the ground. This orientation is a carryover from the DMFlex solar panel setup, which enables the dust to roll off the panel without allowing it to pile up. Each assembly was mounted on Kapton® tape to ensure electrical isolation between the radiator assemblies and the aluminum frame.

Nine thermocouples (TCs) are attached to one half of each face sheet in a grid formation. For later analysis, thermal symmetry is assumed. Additionally four thermocouples were attached down the length of each heat pipe, ensuring that there is one over the evaporator and one over the condenser.

A two-stage motorized gantry was installed in the frame above the radiator assemblies. The top-level carrier on this gantry houses a vibrating platform on which a mesh sieve is mounted, which contains an amount of regolith simulant. During testing, the carrier is passed back and forth over the radiators while dust is shaken through the sieve.

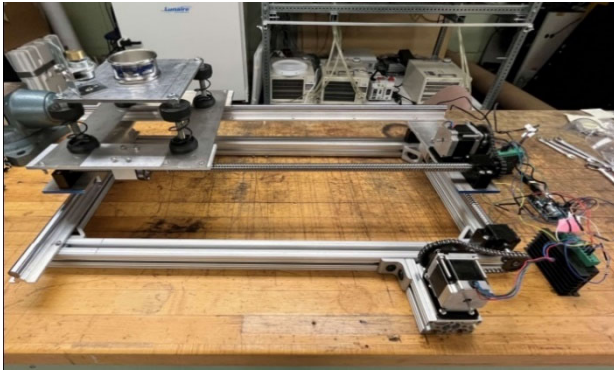


Fig. 3. Gantry, Carrier, and Sieve Assembly (Ref. 4)

R2D2 also includes a mechanism to study the effects of an electrically charged radiator panel. On each radiator assembly a positive electrical lead is fastened to the front-facing radiator panel. The negative leads are connected to the aluminum structure on which the radiators are mounted. The continuity tool on a multimeter verified that the radiators were electrically isolated from the aluminum structure.

Preparation begins for the test by loading the entire aluminum test structure into GRC's vacuum chamber VF-13. The chamber is allowed to pump down for at least 24 hours. On the day of a test the cartridge heaters are powered to known voltages and currents which result in a steady state heat pipe evaporator temperature of 200° C. The heat pipe is allowed to continue transferring heat into the radiators until the extremities of the radiator panels have reached a stable temperature.

The team conducted several “dry” runs to fully characterize the steady state thermal profile of the radiator panel sans-dust. One of the results of these tests was the

thermal response of the radiator as a function of time, which revealed that the radiator panels reach a steady state thermal profile after about three hours.

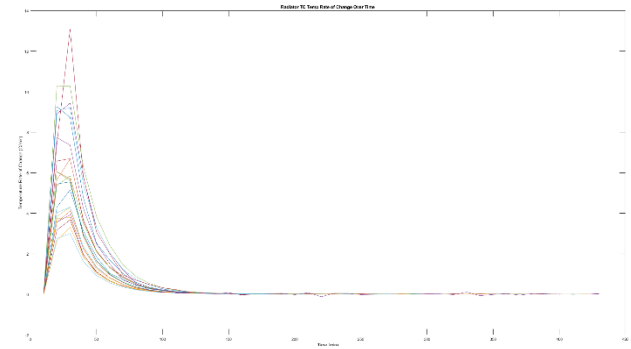


Fig. 4. The Thermal Rate of Change of a Radiator Panel

The full test is comprised of a series of sweeps during which simulant is shaken through the sieve onto the radiator panels below. To begin each sweep, the x-axis stepper motor is given a velocity value which was selected to result in 4-minute sweeps. When the carrier begins to move the power supply which controls the vibration motor is switched on. The carrier velocity and vibration motor voltage are both set to zero when the carrier reaches the other side of the aluminum structure.

After each deposition sweep of the carrier across the test platform, the voltage applied across the leads is increased and the deposition sweep is repeated. A sweep is performed every 25V from 0-100V. Following this, the entire set of sweeps is repeated but with the leads swapped to observe any affects from a reversed polarity. After the completion of all sweeps the radiators continue operating for several hours so that the steady state thermal response to dust deposition can be observed.

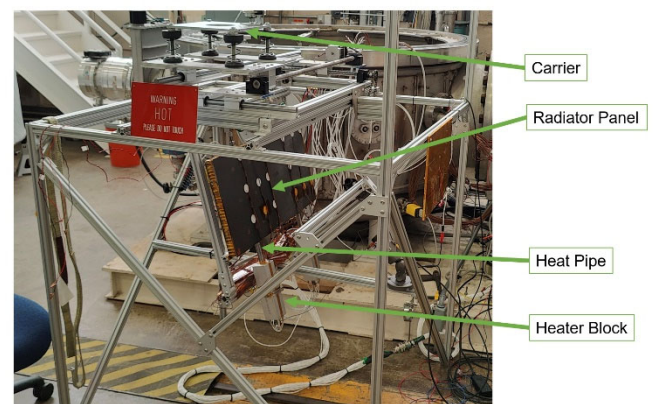


Fig. 5. Full Test Structure

A radiometric infrared camera is used for higher resolution temperature logging. The camera's radiometric output is a 2D heatmap formatted as a 16-bit grayscale image, where the temperature is stored as a linear multiple of a pixel's intensity. A known pixel/temperature pairing

can be used to determine the image's conversion parameter. The thermocouple positions make for ideal candidate locations since the temperature of each thermocouple position is logged. A MATLAB script was written to identify the X-Y pixel locations of the nine visible thermocouples on a single radiator panel and return the average pixel intensity value in a 5x5 pixel square around each location. One by one the script will adapt one of the nine calibration values and calculate the IR-derived temperatures of the other eight thermocouple locations. For each calibration value, the IR-derived and TC-derived temperature values are compared for accuracy. The calibration value which yields the most compatible IR/TC results is selected as the optimal calibration value used to determine the temperature of all other pixels in the grayscale image.

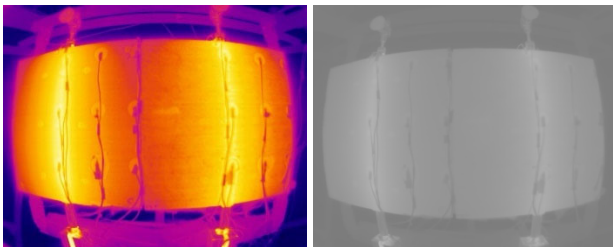


Fig. 6. Infrared Imaging of the Radiator Panels. Color Profile (left) and Radiometric Grayscale (right)

III. TESTING

Three total tests were conducted over the course of two weeks. In between tests the vacuum chamber was vented and opened, and the test structure was removed from the vacuum chamber for cleaning.

III.A. Test I

The first test began nominally as per the test plan. The first set of sweeps was performed from 0V through 100V. The charge leads were returned to 0V and the radiator was allowed to continue heating mid-day to allow for a possible long-term thermal response. The leads were then swapped, and the second set of sweeps was conducted. There was doubt amongst the team as to whether dust was being deposited on the radiators. Live footage from security cameras within the vacuum chamber did not yield visible footage of dust deposition. In addition, the deposition could not be picked up by the IR imaging nor had a thermal response been detected on the thermocouple readouts.

The team concluded that dust was *not* being deposited, and that another set of sweeps should be conducted with the vibration motor set to a higher voltage. As the voltage was ramped up the sieve was ejected from its seat on the carrier and overturned, spilling the remainder of the simulant onto the bottom of the vacuum chamber.



Fig 7. The Overturned Sieve after Test I.

III.B. Test II

The entire test operated nominally as per the test plan. The vibration motor was set to 13V for all sweeps, which had been determined to be the highest value for stable operation. The team had assumed once again that no visible dust deposition had occurred, but recorded footage revealed otherwise. Though showering dust was not visible, it was clear that on the first sweep the radiator panels were slowly accumulating a fine layer of simulant. No further accumulation was detected on additional sweeps.

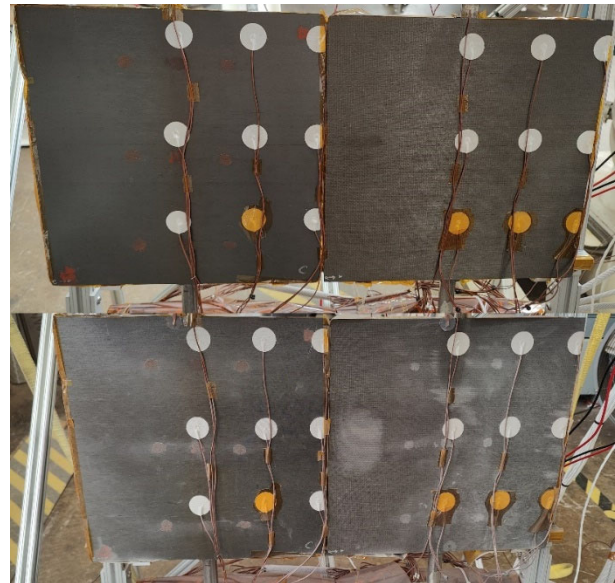


Fig 8. Radiator Panels Prior to Dust Deposition (top) and Post Deposition (bottom) after Test II.

III.C. Test III

For the third test the 75 micron sieve was replaced with a 250 micron sieve. The team was testing the theory that a 75 micron particle size was limiting in scope, as larger particles may also adhere to radiators in these conditions. A larger particle size would also limit sieve clogging, which was a suspected problem in the previous two tests. To isolate this altered variable, the voltage was kept at 0V for the duration of the test. Two sweeps were performed before the carrier became stuck. Despite this, the panels were allowed to continue to

operate so that the long-term thermal response could be studied. Upon removal of the structure from the vacuum chamber it is evident from the dust coverage pattern that most of the dust was deposited almost immediately in one location.

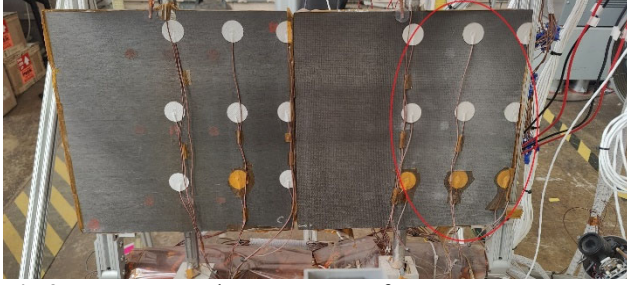


Fig 9. Concentrated Dust Pattern after Test III.

IV. RESULTS

Because the IR data is still being analyzed, in this document all conclusions will be drawn based on TC data. While lower resolution, the TC data is perhaps more precise than the IR data.

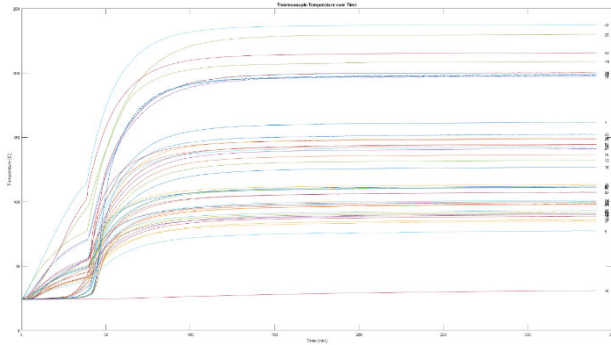


Fig 10. Thermocouple Data from Test II.

This study uses Test II data, as this is the only test that yielded definitive and even coating of dust on the front-facing radiator panels. Conventionally, one would observe how the power output from each panel changes throughout the test. The power of heat rejection via radiation is calculated as

$$\dot{Q} = \sigma e A (T_2^4 - T_1^4) \quad (1)$$

σ – Stefan Boltzmann constant

e – emissivity

A – panel area

T_2 – panel temperature

T_1 – ambient temperature

A problem is presented by the fact that the ambient temperature T_1 increases throughout the duration of the test, which isn't representative of a realistic lunar environment. This means that the differences from the heat rejection before and after dust deposition may not be due solely due to the emissive properties of the radiators.

However the panel temperature T_2 is a satisfactory indicator of the heat rejection performance.

Even without dust, there is a discrepancy between the amount of heat rejected from the front panel and the rear panel, likely due to the panel's tilt. The value $T_{\text{front}} - T_{\text{rear}}$ should remain constant while the radiator is operating at steady state. If the presence of dust affects heat rejection from the front side, a change in $T_{\text{front}} - T_{\text{rear}}$ will be identifiable.

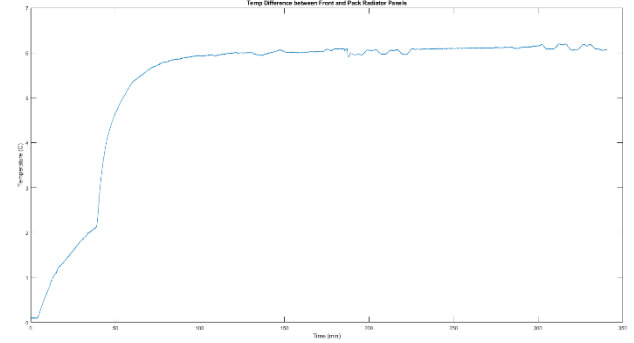


Fig 11. Temperature Difference $T_{\text{front}} - T_{\text{rear}}$ During Test II.

Prior to deposition, $T_{\text{front}} - T_{\text{rear}}$ is 6.07°C . The TC data shows that in its post-deposition state, $T_{\text{front}} - T_{\text{rear}}$ is 6.09°C . The difference in discrepancies is negligible, which indicates that in this study the deposition of dust did not have an effect on the thermal performance of the radiators.

V. Conclusion

V.A. Discussion

There are several factors that can be attributed to this result. The first factor is that perhaps in these test conditions, lunar dust does not have an effect on heat rejection. The emissivity of the radiator panels used in this study are 0.9 (Ref. 5) and the emissivity of JSC-1A is 0.89 (Ref. 6). This means that as the heat is transferred from the radiator panels to the simulant, the simulant is emitting blackbody radiation at a similar rate. While regolith's high emissivity would not pose an issue for heat rejection, its high absorptivity may adversely affect the total system performance. Even if these test conditions were similar to those on the lunar surface, the high solar absorbance of regolith might cause dust-coated radiators to absorb more heat than they can reject.

Another potential factor is dust quantity. Perhaps the total amount of dust that adhered to the panels was not enough to have an impact on heat rejection. Heat is rejected from both panels of each radiator assembly, but only one panel is exposed to the simulant. If the dust does affect the radiator performance, it is possible that it is negligible compared to the rejection capabilities of the radiator.

Lastly, it is likely that the conditions for maximum adhesion were not met in the scope of this

study. Video footage implied that the radiator panels were fully saturated at very low dust-density values. It is expected that in a true lunar environment the quantity of dust adhesion would be much greater. Future tests may include more precise emulation of a charged lunar environment in order to replicate the forces of attraction which result in dust adhesion.

These findings have been important for being able to identify what areas of testing are worthy of more focus.

V.A. Future Tests

There are additional tests that are slated to tackle some of the factors uncovered during the initial R2D2 tests. The next study may address the potential issue regarding dust adhesion saturation. The deposition quantity and charge characteristics may have limited the total amount of simulant that could adhere to the radiator panels. To emulate a worst-case dust coverage scenario, this new test will see the radiator panels manually coated in dust prior to vacuum chamber pump down. This will also help to characterize the maximum amount of adhesion achievable without a charge. This study may also include a flat up-and-down radiation orientation, so that dust can be piled onto the up-facing radiator for an exaggerated worst-case.

Future iterations of the R2D2 test setup would ideally include the instrumentation to measure small differences in mass. This would help to characterize the amount of simulant that adheres at different applied charges, as well as changes in thermal performance as a function of accumulated dust mass.

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