The Effect of Martian Dust on Radiator Performance

D. Keith Hollingsworth, Larry C. Witte, Ashley Higgins

Abstract—Thermal radiators are a critical element for lunar or Martian habitation missions. Experiments by the University of Houston and NASA have demonstrated a dramatic degradation in radiator emittance due to the accumulation of a Martian dust simulant. An ISSO mini-grant funded the development of an automated facility that will lower operational costs for future tests.

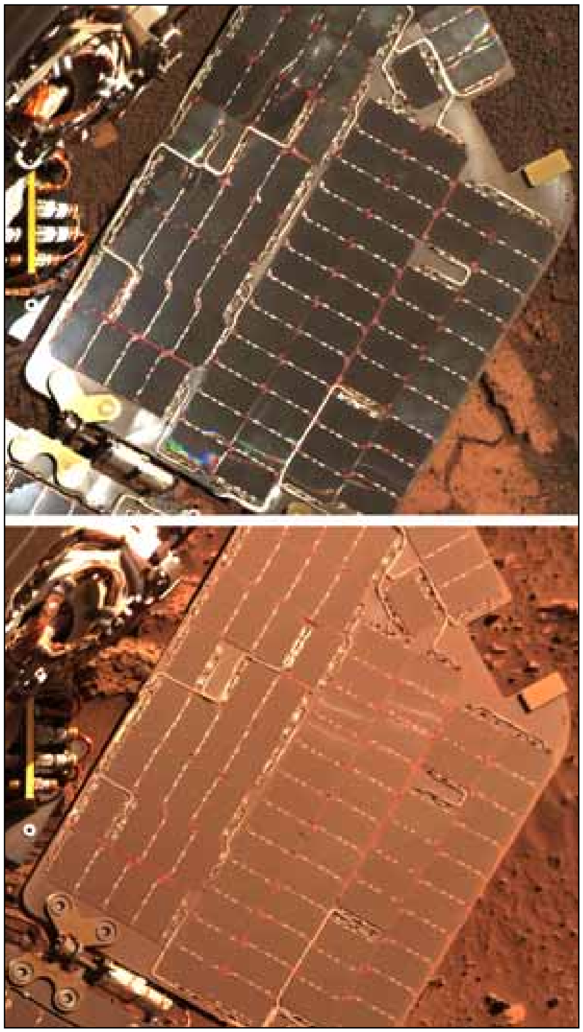
Dr. D. Keith Hollingsworth

The purpose of the ISSO mini-grant is to enhance an existing University of Houston/NASA Johnson Space Center effort to measure the radiative emittance of thermal radiator coatings laden with simulated Martian or Lunar dust. This larger project, the "Mars Radiator Characterization Experimental Program," has received NASA funding in 2002–2004 and has produced measurements of the reduction in effective radiative emittance as (simulated) Martian dust accumulates on surfaces coated with high-emittance materials.

This work is motivated by the expectation that radiators will be a critical element in the thermal control system for future robotic and human exploration missions to the moon and Mars. Radiator performance depends on the radiating surface area, the emittance and absorptance of the radiator surface, the operational temperature of the radiator, the effective sky temperature surrounding the radiator, solar radiation, and atmospheric irradiation levels. Radiative properties of the surface are affected by dust accumulation and surface oxidation.

Dust is expected to be a major contributor to the local environmental conditions at the Martian surface and may also be a substantial problem for long-term equipment on the lunar surface. The photos in Fig. 1, recently made of the rovers *Opportunity* and *Spirit* on Mars, demonstrate dust accumulation on exposed surfaces. *Opportunity* has little dust accumulation while *Spirit* carries a substantial dust layer. These rovers have been on the Martian surface for the same length of time but operate in different sectors.

A short description of the Mars Radiator Characterization Experimental Program[1,2] will help explain the objective of our ISSO project. An apparatus has been developed that allows the



Courtesy NASA/JPL-Caltech

Figure 1. The same section of the radiator array is shown from the two current Martian rovers: *Opportunity* (*top*) shows little dust accumulation; *Spirit* (*bottom*) shows significant accumulation.

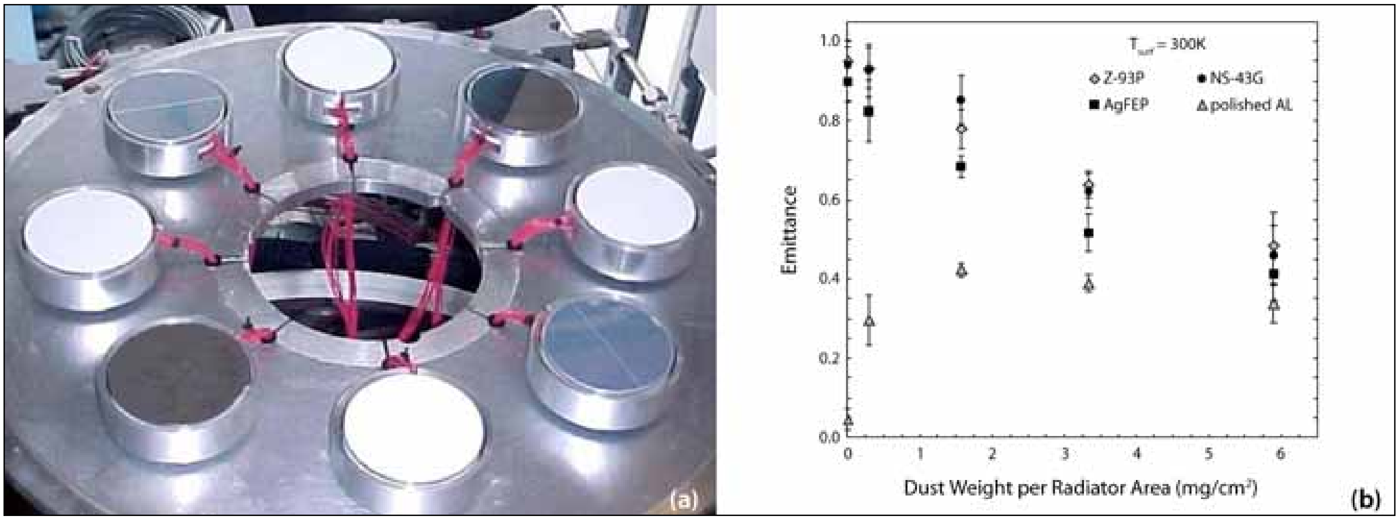
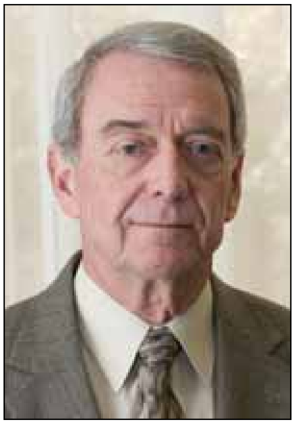


Figure 2. (a) Undusted coupons positioned in the chamber. In opposing pairs, starting at top and bottom center and moving clockwise: NS-43G white silicate paint, polished aluminum, Z-93P white silicate paint, 10 mil silver Teflon film; (b) Results for $T_{surface}$ = 300 K.



Dr. Larry C. Witte

measurement of radiative emittance of multiple test coupons in the JSC Energy Systems Vacuum Chamber. The chamber can produce a range of sky temperatures typical of Martian conditions. Eight radiator coupons were designed and fabricated with four different surface coatings. The Martian dust "simulant" used by NASA is Carbondale red clay. The coupon construction involves active guard heating that prevents heat loss from all surfaces other than the test surface of the coupon. The data acquisition system for the coupons includes a manual temperature control system (student operated).

An apparatus has been developed that deposits dust uniformly on multiple coupons *in situ* in the vacuum chamber. (An invention disclosure has been filed through NASA-JSC and UH.) Experiments were completed for seven temperature operating conditions under vacuum (10^{-6} torr). Figure 2(a) shows the eight coupons arranged in the vacuum chamber prior to testing. An example of the data obtained for a test surface temperature of 300 K for a range of dust loadings and effective sky temperatures is shown in Fig. 2(b). The effect is dramatic: high-emittance surfaces see an approximately 50 percent reduction in emissive power as the surface emittance drops toward that of the dust simulant (as shown by the polished aluminum coupon) for an accumulation of roughly 100 microns of dust at the highest loading.

The operation of the facility when conducted by a trained and experienced operator would often require more than three hours to obtain stable operation at a single set of conditions. One of the controlling factors in this expensive use of vacuum chamber resources is the capability of the operator to adjust the 16 heaters necessary to establish the eight coupons at steady-state conditions. By replacing manual operation with an automatic controller, the time required for a single run of the apparatus can be reduced significantly.

The goal of this mini-grant was to design and build an automatic controller that would integrate into the existing digital data acquisition system. Such an improvement in the experimental apparatus will allow more data to be collected during the same period of vacuum chamber operation and thereby improve future proposals to NASA that involve the use of this system.

Methodology

The system consists of eight test coupons that operate in a vacuum chamber. Each coupon is driven by two heaters: a main heater that provides the measured power to the radiator surface and a "guard" heater set to maintain the remainder of the coupon surface at the same temperature as the surface. The temperatures of the test surface and of the surrounding structure are measured by resistance temperature devices (RTDs). The temperature of the vacuum chamber walls is controlled by a separate system operated by NASA staff. During operation, a radiator surface temperature is selected and the main heater power is set by trial and error to obtain that temperature. The guard heater power is also set by trial and error so that the structure surrounding the test surface is also at the desired temperature so that no heat loss occurs through the structure. Of course, because a change in one heater setting affects the other heater, the adjustments are nontrivial and time-consuming. For all eight coupons there are a total of 16 RTDs to monitor and 16 heaters to adjust. An IoTech Daqbook data acquisition system monitors the temperature and power data while 16 precision DC power supplies provide manually-controlled current to the heaters.

All the data from the IoTech are recorded on a laptop computer. The data acquisition system includes two RTD acquisition/conversion cards which were operated in three-wire mode to remove the lead resistance from the computation of the temperature. The complete RTD acquisition system was calibrated in a controlled-

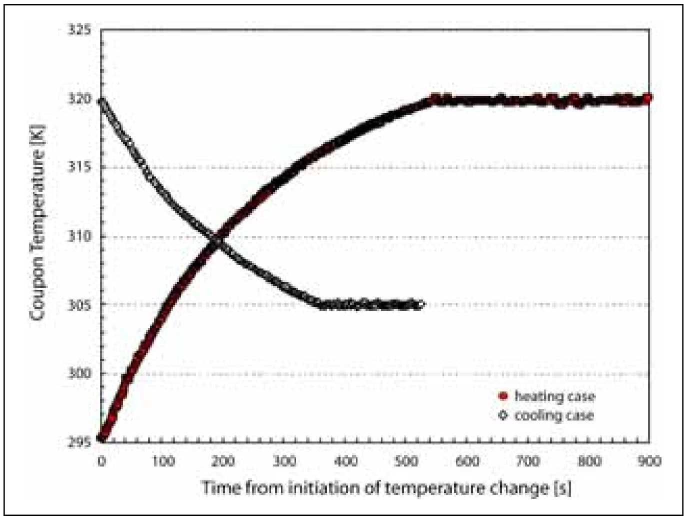


Figure 3. Heating of one coupon from room temperature to 320 K and cooling from 320 K to 305 K. For the heating case, the 95% confidence uncertainty during steady operation is ± 0.25 K, or 1.0% of the difference between the target and ambient temperatures. For the cooling case, the uncertainty during steady operation is ± 0.13 K, or 1.3% of the mean rise above ambient.

ROBOTICS—Jaime Hinke with a baccalaureate degree in mechanical engineering earned at the University of Houston studies robotics at NASA-JSC in the Robotics Group for Flight Control.

temperature environment prior to use in the vacuum chamber.

The ISSO mini-grant funded a conversion of this system to automatic control. The idea is that the measurements currently accessible would be used to compute an estimated set point for each heater. That set point would be communicated to the heater power supply electronically—so that manual adjustment via potentiometers of the heater power would be replaced by transistor-gated control of the heater power. Both the main and guard heaters were automatically controlled so that the coupon arrives at the set point temperature with essentially a zero temperature difference within the structure of the coupon.

To implement automatic control, four IoTech digital-to-analog boards and associated power conditioning were added to the data acquisition system. The custom power supply for the coupon heaters was modified so that either transistor control or potentiometer-control (manual operation) could be switch-selectable. For automatic operation, a custom-written software controller in the laptop generates appropriate heater settings which are then converted to analog voltages by the D-to-A boards. Those voltages drive power transistors which generate a sufficient current to drive the heaters at the desired power level. The resulting actual heater voltages, along with the updated coupon and guard temperatures, are read by the data acquisition system, and the process repeats itself.

A proportional integral (PI) control strategy was implemented in the same VisualBasic code that handles the data acquisition. An analytical model of the transient heat transfer between a coupon and the low-pressure vacuum chamber was created in MatLab to determine reasonable values for the constants that set the rate of approach and the integration time in the PI strategy. These values can be refined later during testing with the actual hardware.

Equipment

The equipment purchased included: four IoTech Inc. digital-to-analog voltage output cards ($1,600), which were placed into an existing data acquisition system, a power supply to drive the cards ($20), and various switches and cables to complete the facility ($90).

Results and Discussion

To demonstrate the automatic control system, one coupon is exercised in room air in the laboratory. For these tests, the NASA vacuum chamber was not available; however, operation of the system in room air is a more severe test of the control system than is operation in high vacuum. For the heating case shown in Fig. 3, the coupon is initially set at room temperature and the system given a target of 320 K. The coupon temperature traverses the 25 K difference in roughly nine minutes and is steady at an average of 319.8 K with a 95% (two-sigma) single-sample variation of ± 0.25 K. This uncertainty is 1.0% of the difference between the target and ambient temperatures and is on the order of the uncertainty produced by the measurement system.

For the cooling example, the coupon is initially at 320 K and is allowed to cool by natural convection under automatic control to a target temperature of 305 K. The cooling process occurs over six minutes, and the system achieves a steady state at 305.0 ± 0.13 K. This uncertainty is 1.3 percent of the mean rise above ambient. In vacuum, the heat transfer rate from the coupons would be much lower and the transients longer; however, we expect much faster response than the 2-3 hours-per-point typical of well-trained manual operation.

The controller operates well at room temperature and standard pressure. However, the question of how well it will operate in a vacuum must await the renewal of funding for the operation of

PAINT SAMPLES—Ashley Higgins (*l.*), master's candidate in mechanical engineering, stands with Dr. D. Keith Hollingsworth (*r.*) with paint sample on metal coupons (disks) designed to test the effect of simulated martian dust on silicate paint, aluminum, and silver Teflon film.

the vacuum chamber at the NASA Johnson Space Center. A volume at high vacuum is a far more stable thermal environment than one at standard pressure. While this stability means slower transients, it also means that the controller will be challenged to a lesser degree than under the test conditions shown in Fig. 3.

Conclusions

Automatic control has proven itself a successful and worthwhile addition to the system. A new proposal for $200,000 in funding for continued work featuring the strong potential of cost-savings produced by the improved system has been submitted to both the NASA Johnson Space Center Director's Discretionary Fund and to the NASA Constellation/Exploration Program.

References

[1] D. K. Hollingsworth, L. C. Witte, J. Hinke, and K. Hurlbert, "Reduction in the Emittance of Thermal Radiator Coatings Caused by the Accumulation of Simulated Martian Dust," *Applied Thermal Engineering* (2006). (*In press.*)

[2] D. K. Hollingsworth, L. C. Witte, J. Hinke, and K. Hurlbert, "The Effect of Martian Dust on Radiator Performance," *Proc*., ASME Summer Heat Transfer/Fluids Engineering Division Joint Conf. (2004): ASME HT-FED04-56577.

[3] G. A. Landis, "Dust Obscuration of Mars Solar Arrays," *Acta Astronaut.* 38 (1996): 885-91.

[4] P. P. Jenkins, G. A. Landis, and L. G. Oberle, "Materials Adherence Experiment—Technology," *Proc.,* 32nd Intersociety Energy Conversion Engineering Conf. 1 (1997): 728-31, (IECEC-97339).

[5] G. A. Landis, "Mars Dust Removal Technology," *Proc*., 32nd Intersociety Energy Conversion Engineering Conf. 1 (1997): 764-67, (IECEC-97345).

[6] K. R. Johnson and D. E. Brinza, "The Mars Thermal Environment and Radiator Characterization Experiment," *Proc*., 30th Intl. Conf. on Environmental Systems, (2000): 001CES-178.

Publications

Hollingsworth, D. K., L. C. Witte, J. Hinke, and K. Hurlbert. "The Effect of Martian Dust on Radiator Performance," *Proc*., ASME Summer Heat Transfer/Fluids Engineering Division Joint Conf. (2004): ASME HT-FED04-56577.

Hollingsworth, D. K., L. C. Witte, J. Hinke, and K. Hurlbert. "Reduction in the Emittance of Thermal Radiator Coatings Caused by the Accumulation of Simulated Martian Dust," *Applied Thermal Engineering* (2006). (*In press.*)

Presentations

Hollingsworth, D. K. "The Effect of Martian Dust on Radiator Performance," NASA Contamination and Coatings Workshop, Aug. 3–4, 2005. (*Invited paper*.)

Funding and Proposals

Hollingsworth, D. K., L. C. Witte, G. Tuan, and K. Hurlbert. "Dust Impact of Radiator Test Stand," NASA Johnson Space Center Director's Discretionary Fund, Nov. 2005, 2 years, $200,000. (*Not funded by JSC-CDDF. Currently submitted to NASA Constellation/Exploration Program, Level 2.*)