

Methods for Modeling Lunar Dust in Thermal Desktop Based on Lunar Dust Level Sensor and Effects on Surfaces Test Data

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With the upcoming Artemis Missions and renewed interest in lunar exploration, there is an ongoing concern about how to analyze the impacts of lunar regolith on critical thermal components like optical coatings. Often, the Rule of Mixtures or similar relationships are considered sufficient for calculating how optical properties should change on a regolith-covered surface. However, recent studies by the Lunar Dust Level Sensor and Effects on Surfaces (LDES) team produced results that suggest lunar simulant coverage impacts the effective emissivity of surfaces in a nonlinear fashion, resulting from a complicated heat transfer path through the regolith layer. This paper documents the efforts to compare different methods of modeling dust in Thermal Desktop (TD) based on the LDES effective emittance values and the Lunar Highlands dust simulant's (LHS-1D) optical and thermophysical properties. Initial correlation to the undusted coupon data was done using a TD model of the test setup. Subsequent correlation for dusted coupons determines modeling effectiveness by comparing the model's sensor heater power used to test data, and the model's estimated radiation versus theoretical calculated radiation from the surface of the coating to the TVAC chamber shroud. The study found that the best heater power comparison resulted from modeling method 4, where error for the top heater correlation was within +/-10% and the error for the radiation check was within +/-5%. However, this study depicts a very specific use case and is not recommended to be adopted for general analysis until desired future work can be completed.

Acronyms and Nomenclature

LDES	=	Lunar Dust Level Sensor and Effects on Surfaces
LHS-1D	=	Lunar Highlands Dust Simulant
LN2	=	Liquid Nitrogen
PAC	=	Percent Area Coverage
ROM	=	Rule of Mixtures
RTD	=	Resistance Temperature Detector
TD	=	Thermal Desktop
TVAC	=	Thermal Vacuum Chamber
α	=	Absorptivity
ϵ	=	Emissivity
ϵ_{eff}	=	Effective Emissivity
μm	=	Micrometers
nm	=	Nanometers

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I. Introduction

Lunar regolith has been a thermal concern since before the Apollo missions even flew¹. To break down the reasons as to why, look into the specifics of one component of lunar regolith – lunar dust. The term lunar dust refers to any lunar regolith with a particle size of less than 20 μm , with the median size being approximately 0.30 to 0.60 μm ². These extremely small particles are highly susceptible to electrostatic and magnetic effects and, since the lunar surface has no natural grounding, they can easily be attracted to almost any non-grounded, charged surface even without being physically disturbed^{2,3}. Also, the additional influence of how dust acts in a low-gravity lunar environment introduces uncertainty into the effectiveness of mitigation techniques³. Transcripts from the Apollo missions described dust mitigation techniques, noting how dust was able to enter the habitable environment despite the meticulous steps taken to remove it from their EVA suits⁴.

These particles that can easily get onto surfaces but not easily be removed have a last main component to being a thermal concern, and this is its challenging optical and thermophysical properties. Measured simulant samples have generally high solar absorptivities (α) and infrared emissivities (ϵ)⁵. This leads to a comparatively higher α/ϵ ratio, requiring a surface to get hotter to reject the same amount of heat a lower α/ϵ ratio surface, such as a radiator. Particles that are the size of lunar dust also have relatively low thermal conductivities^{6,7}.

The issue then arises on what happens if a significant amount of lunar dust builds up on critical thermal surfaces, such as optical solar reflectors or radiator paint. Thermal control is key on the lunar surface and in lunar orbits due to the Moon's extreme surface environment and its influence on any orbiting bodies. The question then arises, how will thermal analysts consider the effects that dust will have on future hardware to avoid critical mission failures?

Historically, the method thermal analysts have used to analyze lunar dust on a surface is the Rule of Mixtures (ROM) equation, which varies the optical properties of a surface with a linear trend assumption⁸. These modified optics can then easily be input into Thermal Desktop for analysis. However, a recent study at Johnson Space Center has proven that lunar simulant does not accumulate on a surface in a linear fashion. In addition, another long running testing series has shown that lunar simulant has a much more influential effect on how a surface rejects heat than previously thought, and was able to calculate a metric, effective emissivity (ϵ_{eff}), to quantify it. This ϵ_{eff} value represents the heat transfer from the dusted surface to the surrounding environment, and this metric does not have a conventional method of application within the Thermal Desktop program. This study aims to use information from these recent studies to identify a modeling method that is easily implemented into TD in order to analyze the impacts of dust on surfaces with as little error as possible.

II. LDES and Testing Methodology

The Lunar Dust Level Sensor and Effects on Surfaces team (LDES) set out to quantify how lunar dust on radiator surfaces and coatings affected their emissive potential. This work is a legacy project from a previous Mars Dust study that used the same testing methodologies⁹. This work also compliments and adds to Gaier's 2010 study that had a similar test setup but instead used lunar regolith simulants¹⁰.

A. Test Setup

A full round of LDES testing is comprised of the following components: The dust simulant of choice, up to 8 test sensors, the 'Dust Distributor', and a Thermal Vacuum Chamber. First, the dust simulant chosen for the first round of LDES testing and used in this analysis is LHS-1D. This is an extra-fine grain Lunar Highlands regolith simulant with particles ranging from $<0.4 - 35 \mu\text{m}$ that has been designed for lunar dust testing¹¹. It is also speculated that LHS-1D has a thermal conductivity of less than what has been obtained from similarly sized particles of lunar regolith from the Apollo missions^{7,12}. The value used in this analysis was back calculated from the tested thermal diffusivity values of LHS-1D in the study "Specific Heats and Thermal Diffusivities of LHS-1 Lunar Regolith Simulant At Low Temperatures" and compared to an internal NASA LDES presentation⁶.

Second, the test sensors used in this round of testing are heritage from the Mars Dust study⁹. They consist of a central stackup comprised of a guard heater, a Teflon isolator, the main heater, and the coupon surface. Each heater has

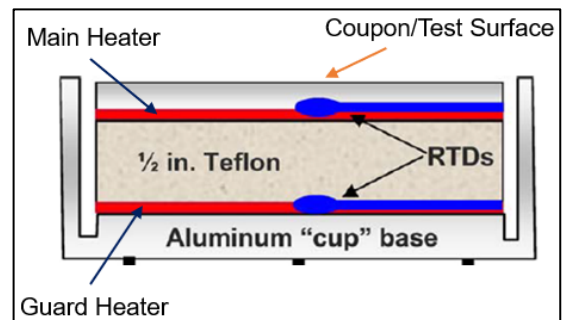


Figure 1. Cross Section of Test Sensor⁹. Location of materials within the sensor and overall shape of sensor "cup" are depicted.

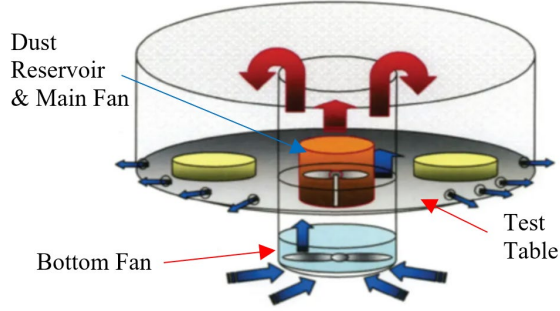


Figure 2. Diagram of Dust Distributor¹³. Figure shows how two fans assist in dusting test coupons.

distributed evenly onto any test sensor present on the test table. Dust is placed into the central reservoir, and the bottom fan assists in driving dust into the chamber. The test table can be removed from the assembly and transported. A full description of the distributor can be found in a paper recently brought by the LDES team to the 2023 Thermal and Fluids Analysis Workshop¹³.

The last part of the testing setup for this round of LDES testing is the TVAC chamber used. It is a small 3'x3'x3' chamber that uses Liquid Nitrogen (LN2) to cool the shroud. The inside of the chamber has a high emissivity coating, and it has an internal port that allows for data collection and power provision for the main and guard heaters.

B. Methodology

A single round of dust testing consists of two main stages: dusting and TVAC testing. For the dusting stage, a set amount of dust is weighed and deposited evenly around the bottom of the dust distributor's central reservoir. The test article is then sealed, turned on for a set amount of time, and then left undisturbed for another set amount of time so that any floating dust particles settle. The article is then carefully disassembled so that the table and any sensors sitting on it can be removed and transported into the thermal vacuum chamber.

The second main stage begins as the TVAC chamber is sealed. The heaters embedded in the central stackup are turned on before pump down and remain on until they reach setpoint. Once the test team observes that the heaters are running reliably at the setpoint, the chamber pump down procedure starts. Once the chamber reaches its setpoint, it will hold steady until the test team observes that the heaters are holding the setpoint temperature at a true steady-state condition or are consistently oscillating between heater power values that keep the temperature very near the setpoint, designated a "pseudo-steady-state" condition, for at least 10 minutes. The chamber is then repressurized, and the coupons are removed from the test chamber, reintegrated into the dust distributor, and are then ready to be dusted once again.

C. Findings and Associated Studies

As mentioned before, the overall goal of this testing was to determine how effective a radiator surface remains when coated with increasing amounts of dust. To represent this trend, equations (1) and (2) were developed in the Mars Dust paper in order to find ϵ_{eff} ⁹.

$$\epsilon_{eff} = \dot{Q}_{Rad} / \sigma A (T_{Rad}^4 - T_{Sky}^4) \quad (1)$$

Where $\dot{Q}_{Rad}$ is the total heat lost from the radiating surface, σ is the Stefan-Boltzmann constant ($5.6697 \times 10^{-8} \text{ W/m}^2\text{K}^4$), A is the area of the radiating surface, T_{rad} is the temperature in Kelvin of the radiating surface, and T_{sky} is the temperature in Kelvin of the shroud. $\dot{Q}_{Rad}$ is the unknown in the equation, but can be solved with (2), which attempts to find the heat input to the system by finding the power input from the heater and subtracting any that escaped through the Teflon isolator or into the shroud environment.

$$\dot{Q}_{Rad} = \left(\frac{(V_{meas} - V_{leads})^2}{R} \right)_{Heater} - \left(\frac{\Delta T}{L/kA} \right)_{Teflon} - C_{cal} * (Sk_{Air})_0 * (T_{Rad} - T_{Sky}) \quad (2)$$

Where $V_{meas} - V_{leads}$ is the total voltage input into the heaters, R is the resistance of the heaters, ΔT_{teflon} is the temperature difference between the top and bottom surface of the Teflon isolator, L_{teflon} is the thickness of the

Teflon, k_{teflon} is the thermal conductivity of the Teflon, and A_{teflon} is the surface area of the top or bottom of the Teflon. In the third term, C_{cal} is a calibration factor determined for each sensor using data from the baseline test run, S is the conduction shape factor, and k_{air} is the effective air conductivity, which is assumed to be very small but not negligible. The full, detailed equation flow can be found in the Mars Dust paper⁹.

Performing this calculation for each LDES tested coating results in trends that represent the Mars Dust Study trends shown in Figure 3, which displays the ϵ_{eff} of the sample's surface as the dust density increases⁹. Note that this is not the data graph for the LDES testing, it is based off of the Mars Dust Study results, and is included to show the trends of how low and high emissivity coatings behave¹⁴. Even at low levels of dust coverage, radiative coatings with high ϵ values are significantly impacted and drop in effectiveness quickly. For coatings with low initial ϵ , dust loading actually increases effectiveness up to a critical point, where it then drops in effectiveness at approximately the same rate as higher ϵ coatings.

The speculation on why this occurs is due to the aforementioned dust properties creating a very difficult conductive path for heat to flow from the coating to space. The small particle size and charged nature of the LHS-1D simulant creates an interesting phenomenon where particles do not uniformly coat the surface, but instead attach to other particles and make structures dubbed "fairy castles." Figure 4 below is a magnified photograph of the fairy castle structure, obtained from a testing series by E. Quick¹⁵.

There is a very clear arching structure made by multiple different sizes of dust particles. Because the dust layers settle in this way instead of falling in a uniform fashion, conductivity does not act similar to a solid layer. The energy flows through the gaps between the dust particles, through the low thermal conductivity dust particles themselves, and through the connections of the particles. Figure 5 below displays a graphic representation of the effect. Although more chaotic in nature, this thermal behavior is highly analogous to how heat flows through Multi-Layered Insulation (MLI). MLI intentionally creates a complicated heat flow path by utilizing multiple layers of low-emissivity materials to restrict radiation and forcing space in between them using specialized hardware or layers of scrim to reduce conduction.

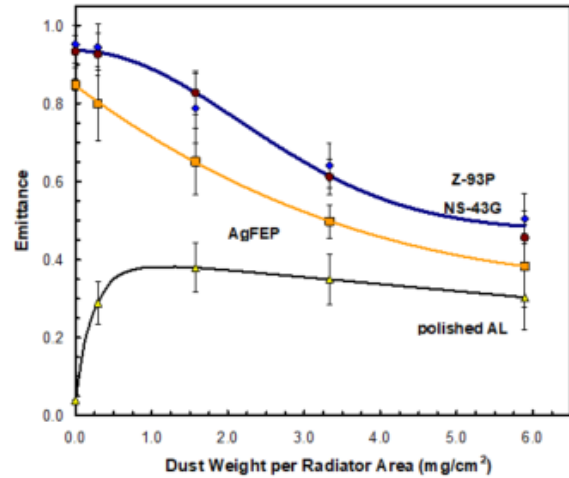


Figure 3. Mars Dust Study Effective Emissivity versus Dust Density Trends¹⁴. *High ϵ materials decrease, while low ϵ materials increase.*

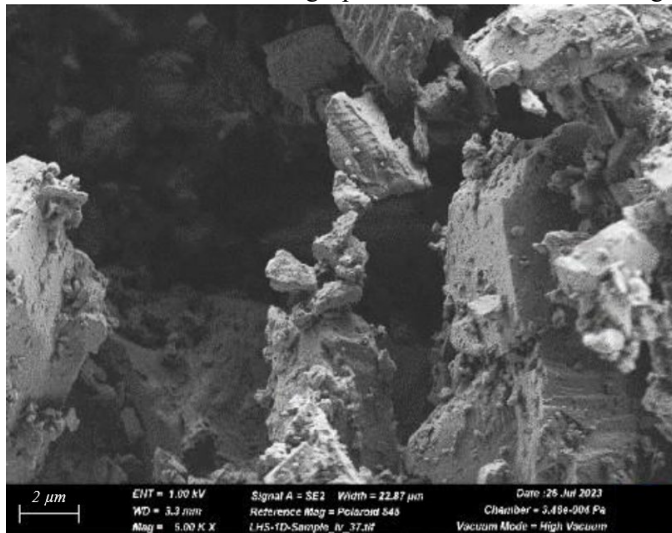


Figure 5. 5000x Magnification of a Fairy Castle in LHS-1D¹⁵. *Figure shows a fairy castle structure, where particles can be seen sticking together over a dustless void.*

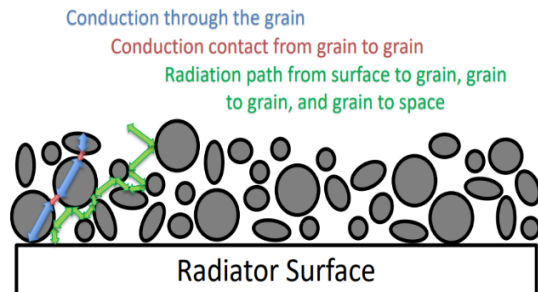


Figure 4. Example of the Heat Flow Through the Simulant Layer¹². *The complicated path is driven by conduction and radiation from and through dust particles.*

this surface will produce an insulative effect that traps heat within the radiator, sapping performance, degrading efficiency of the system the radiator serves, and potentially overheating critical components.

In the previously mentioned test series, using the imaging and data taken therefrom, Quick found that the percent area coverage (PAC) of the dust increased very quickly at low dust loading levels, and then saw a decrease in the slope after seeing dust loading levels of $\sim 0.5\text{--}1.0\text{ mg/cm}^2$ ¹⁵. This starkly contrasts to previous assumptions that are in line with the ROM theory, which assumes that PAC increases linearly with respect to dust loading. Figure 6 shows the results of Quick's study and curve fit for the LHS-1D data made by researchers at Texas A&M University (TAMU). The resulting equation integrates into this analysis through optics manipulation using the ROM. In the graph, PAC is assumed to never reach an absolute 100% coverage of the surface due to the fairy castle structures. The true nature of PAC and dust loading appears to be a sharp increase, and then a very slow increase after reaching a critical point. After this critical point, thickness will increase without a significant increase in PAC.

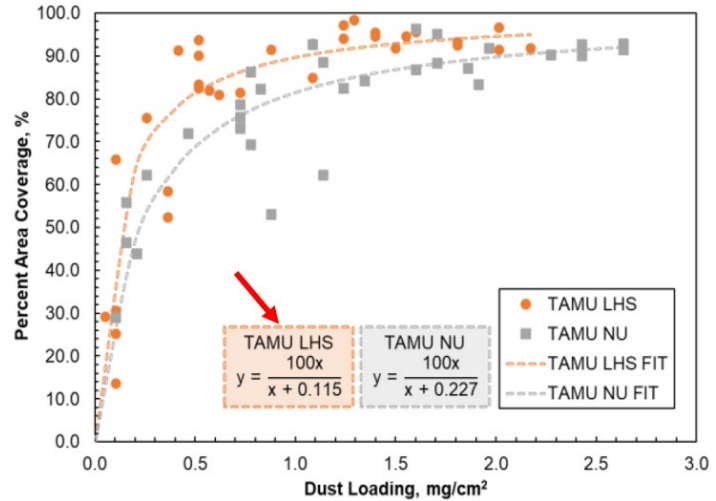


Figure 6. Best-Fit Equations for PAC as a Function of Dust Loading¹⁵. Image depicts how the PAC increases greatly at low dust loadings, then greatly decreases after a critical point.

III. Modeling and Baseline Correlation

To develop and test different methods for modeling dusted surfaces in TD, an accurate thermal model of the LDES test setup is first needed in order to correlate the initial round of LDES testing that did not include dust. After a satisfactory baseline correlation, the model can be assumed to be functional and will be used to analyze and compare the results for four different modeling methods.

A. Thermal Desktop Model

1. Model Overview

Thermal analysts at Johnson Space Center developed a Thermal Desktop model to represent the test setup as accurately as possible with minimal nodes and surfaces. Since the main metric of this study is heater power, the paths of heat leak to and from the sensor heaters should be modeled with greater accuracy. Therefore, the sensor and the wires immediately connected to the main and guard heaters are modeled in much more detail than other surfaces, such as the table surface and the shroud walls. It omits components insignificant to the main goal including the table's aluminum legs, the coupons' aluminum legs, and the detailed internals of the vacuum chamber.

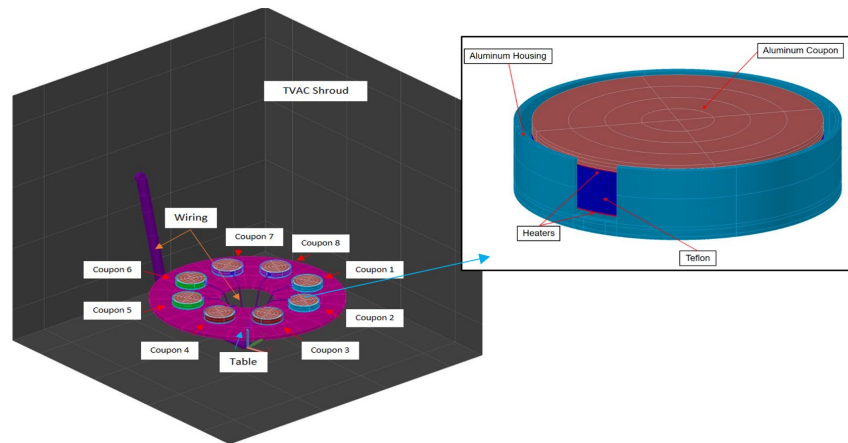


Figure 7. Thermal Model of Full Test Setup within the Shroud and Closeup of Sample Coupon.

2. Model Assumptions

Many parts of the thermal model were constructed using assumptions based on engineering judgement and existing literature. The only tested optical properties obtained were for the coatings used on the coupon surfaces and for the Teflon isolator. For all other materials identified by the test team, optical properties and thermophysical properties were obtained through research and specification sheets from known providers.

Conductances, such as through solder and adhesives, were calculated using a general thermal conductance equation, $G = kA/L$, and sensitivity analyses were completed on these values, varying them higher or lower by a reasonable amount that reflects the variability in the system to observe how they impact heater power results. A concise summary of the sensitivity studies are as follows:

1. The solder connecting the wires to the heaters initially calculated to ~ 4.5 W/K. The effects of increasing the conductance capped out at ~ 10.0 W/K, which resulted in a very small heater power usage increase. Since the change was almost negligible, the conductance was kept at the calculated value.
2. The conductance from the sensor to the test table initially calculated to ~ 0.03 W/K with a 50% error applied due to the coupons not being adhered to the table. Modifying the conductance only affected power usage of the guard heater, and decreasing the conductance to ~ 0.001 W/K provided the steady-state effect that the data reflected.
3. The emissivity of the aluminum cup of the sensor directly affected the guard heater's power profile. Decreasing the emissivity made the profile increase more linearly, while increasing it provided a more exponential increase, reflecting the data more accurately.
4. Increasing or decreasing the emissivity of the aluminum sides of the coupon surface made negligible impacts on the main heater's power usage.
5. An informal study by the LDES team reaffirmed the belief that the effect of free molecular conduction within the chamber is negligible.
6. Increasing or decreasing the conductivity of the Teflon isolator or the heaters themselves had negligible effects on both heaters.
7. The adhesive on the heaters initially calculated to ~ 7.0 W/K. Increasing the conductance that represented the adhesive increased heater power slightly until around 50.0 W/K. The higher value was kept to better represent a good adhesive bond.

Initial efforts for modeling the TVAC chamber were assisted by a previous colleague who specialized in making thermal vacuum chamber models for correlation. This reference informed that, since the TVAC chamber was generally small and simply designed, a detailed thermal map of internal temperature differentials was not needed, and the temperatures for the pump down procedure could be modeled as boundary nodes that follow the dataset.

Proportional heaters controlled by an analog-based controller were used in the LDES test series, allowing the control of the voltage input and giving noticeably smooth curves with a tight on/off band. To attempt to replicate this behavior's average trend, proportional heaters were also used within the TD model. The on/off temperatures were set to 0.50°F below and above the 80.0°F (26.7°C) setpoint, respectively and the sensors were set to hold steady at the midpoint temperature. The sense method was set to the minimum temperature and the nodes sensed were in the approximate locations of the RTD on the test heaters. This provided a smooth power increase that was then compared to the average of the heater power on/off values seen in the test data.

In addition to the coupon surface, other surfaces were also observed to see significant dusting: the test table, the wires of the heaters, and the sensor housing. To replicate the impact this extra dust coverage could have on the heaters, dust effects were added to these affected surfaces. The same dust coverage as the coupon surface was assumed to accumulate on the top of the sensor cup. A reduced dust coverage of *dust coverage* * 50% was assumed for other affected horizontal surfaces, while affected vertical surfaces were assumed to have *dust coverage* * 10%.

3. Error Analysis and Goals

Generally, thermal correlations for TVAC tests are done utilizing data from extensive thermocouple networks. For this testing, the only correlation data available is voltage and amperage readings for the two heaters within each sensor. Therefore, there are 16 data sets to use for this correlation effort. Note that there is one embedded RTD per heater; however, this is not a good correlation metric since, in the model and in reality, the heaters are conditioned before pump down and remain at a steady the 26.7°C setpoint throughout the duration of the test. This could be used as a "reality check" for the model but is not a worthwhile correlation metric.

The vast amounts of unknowns within this testing series introduces a large amount of potential error. The lack of thermocouples for correlation is the largest source of error, but there is also the human error involved in every step of the test methodology. The heaters used in the test were not brand new, and an issue with heater delamination also

appeared in later testing series. There were issues with the cleaning and maintenance of the coupon coatings, and humid conditions at JSC affected attempts to bake out the simulant. Lastly, there is inherent error with the instruments used to measure optics, with a ± 0.02 error bar for the absorptivity instrument and a ± 0.03 error bar on the emissivity instrument. It is also known that the emissivity instrument used has known difficulties when measuring lower ϵ materials, such as the aluminum coatings. However, one potential source of error, the heater line heat leak, was quantified during the testing series to be small enough to be considered negligible. Any baseline correlation case that required major modifications while still producing a generally high error was not considered as an effort to avoid outlying data that could have been the result of hardware issues.

For the baseline correlation error goal, as close to 0% deviation was desired. However, trying to quantify the maximum acceptable error, the analysis team referenced a similar correlation effort for the James Webb Telescope, which called out a heat flow maximum deviation allowance of $\pm 10\%$ ¹⁶. Due to the large amount of unknowns in the correlation, though, a tighter goal of $\pm 5\%$ was set for each main and guard heater power and coating radiation comparison. For final results, the modeling method with the lowest comparison error percentages will be more favored and errors will not stack.

B. Baseline Dustless Correlation

A good transient baseline correlation for the initial dustless cycle leads to a more accurate model for to evaluate the different methods of modeling dust in Section 4. It is important to note that a low percent error for the main heater comparison is more desired for correlation than any other metric. This is the recommendation from the LDES team because the test was specifically designed to focus on the energy balance at the coupon surface, as the least number of unknowns in the system occur here. The guard heater is a secondary correlation effort, as there are significantly more uncertainty factors that contribute to changes in power. It was not intended as a primary test correlation metric, but, since a lack of data points for correlation were available, guard heater power is used to help characterize each method's performance. Lastly, the radiation correlation is used as a "reality check" to ensure TD is performing as expected when introducing new modeling practices. Note that Coupon 7 was correlated but not recorded in any modeling methods, as it was the control coupon and was never dusted. Table 1 below tabulates a summary of the heater power error and radiation error between the data and model outputs.

Table 1. Percent Error of Data vs Model Comparisons.

Coupon		Heater Power		Radiation to Shroud
Coating	No.	Main	Guard	
White Paint	1	-4.62	-0.40	0.19
	2	-12.91	5.87	0.00
Rough Aluminum	3	-8.03	-1.59	1.73
	4	-1.42	1.98	2.23
Silver Teflon	5	-3.15	-0.66	0.12
	6	-4.06	2.76	-0.09
Polished Aluminum	7	-2.70	-0.23	8.68
	8	-4.68	19.70	6.07

The heater power error represents the differences between the averages of the last 600 seconds (10 minutes) of the data and model's heater power output. The thermal radiation values display the error between the theoretical radiation to the shroud and the calculated model output to the shroud for each coupon. The radiation calculation below takes into account only the top of the coupon surface where the coating is applied. This is due to a Bij study that was done to see if the sides of the coupon surface see the shroud, which would slightly increase the total radiation. The result of the study showed only 0.12% of the sides of the coupon see the shrouds, which is a negligible value and was thus not included in the equation. The value found from the equation is then compared to the model output obtained from the 'Qflow' TD tool, which was set up to obtain the total radiation from the nodes in the surface to the nodes in the shroud.

$$Q_{coupon_rad} = \epsilon_{coating} \sigma A_{coupon_top} (T_{rad}^4 - T_{sky}^4) \quad (3)$$

From Table 1's results, it was decided that Coupon 1, 4, and 5 would be the representative coupons for each different coating that would be correlated for the dusted cases. This is because they had the least number of

modifications and produced lowest error when compared to the measured ϵ and power output. For example, Coupon 5 was chosen over Coupon 6 because initial ϵ was only increased by 0.02 - which falls within the instrument error – instead of Coupon 6’s increase of 0.04, and Coupon 5 still had less error overall. Coupon 8 was not used, as modifications exceeding the reasonable amount of change were needed in order to correlate both heaters, and the guard heater and radiation value still exceed the target error goal. The secondary goal to compare the amount of radiation from the coupon surface to the shroud did not affect this decision, as all error comparisons for the usable coupons are less than 5%.

C. LHS-1D Interpolation Code

For future use, a potential modeling method should be usable for any desired coating, as it is highly probable that analysts will want to look at how LHS-1D impacts coatings or surfaces that are not in the LDES dataset. To do this, an interpolation code was developed to perform a curve-fit approximation based on the known data trends for the LHS-1D simulant. This code takes a user-defined initial coating ϵ and determines the best curve shape to use based on proximity to the closest LDES data curve. Then, the code will interpolate an ϵ_{eff} based off of a user-input areal dust density and automatically apply that value to the dusted surface.

This is a very simplified explanation of the functionality of the code, as it cannot be distributed publicly for use at this time. It is also only a first attempt at recreating how the different coatings outside of the coatings that the LDES team analyzed will actually behave. There is future work to try and do an official curve-fit study for this data with more complete dusted data sets.

IV. Modeling Methods Analysis

A. Modeling Method 1

The first modeling method analyzed aims to recreate the test setup as accurately as possible and solely uses LHS-1D simulant’s material properties of conductivity, specific heat, and density. No LDES ϵ_{eff} values are included in this method. These material properties are input into an insulation layer on the dusted surface, where TD will automatically calculate any conductance from the substrate to the insulation, as well as radiation and conduction within the layer itself. For the optics of the dusted layer, the non-linear ROM assumption, based on the findings shown in Figure 6¹⁷, was used to imitate how the coating will show through the dust layer. Emissivity is calculated as shown in Equation 4. Absorptivity is also calculated in this way, but is considered negligible due to the lack of any solar influence within the testing series or TD model. An example of the heat flow path and how the data behaves in thermal desktop is shown in the resistance network in Figure 8.

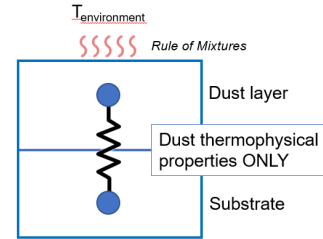


Figure 8. Method 1 Resistance Network

$$\epsilon_{ROM} = f_{dust} \times \epsilon_{dust} + (1 - f_{dust}) \times \epsilon_{clean} \quad (4)$$

Where f_{dust} is the PAC determined from Quick’s LHS-1D TAMU results, ϵ_{clean} is the emissivity of the pristine surface, and ϵ_{dust} is the emissivity of the dust¹⁵.

A similar modification was made for the thermal conductivity of the dust, as having an extremely low conductance represent the insulation layer would produce inaccurate results. Therefore, Equation 5 below was used to vary the conductance of the dust based on dust coverage⁷.

$$k_{adjusted} = \frac{k_{void} \times k_{dust}}{(v_{void} \times k_{dust}) + (v_{dust} \times k_{void})} \quad (5)$$

Where k_{dust} is the known conductivity of the dust simulant at ~300K, k_{void} is a high conductivity value that represents the “void”, v_{dust} is the percentage of dust present and is equivalent to f_{dust} , and v_{void} is the remaining percentage of the whole, or $1 - v_{dust}$. The resulting $k_{adjusted}$ has values in $W/m/K$.

Both the optics and the conductivity of the dust layer are recalculated for a “low” dust density of 0.25 mg/cm², a “medium” dust density of 1.18 mg/cm², and a “high” dust density of 2.07 mg/cm², where the high dust density is the

theoretical 100% percent area coverage case relayed by the LDES team and quantified by Quick as the apparent value where the PAC does not continue increasing significantly with increasing areal dust density¹⁵.

Results are shown in Table 2 below, and percent errors exceeding +/-10% are flagged in red for ease of comparison, and is an arbitrary cutoff.

Table 2. Percent Error of Data vs Model Comparisons for Low, Medium, and High Dust Densities.

Power and Radiation Comparisons - Percent Error					
Modeling Method			Dust Density (mg/cm ²)		
			0.25	1.18	2.07
Power	White Paint	Main Heater	-11.95	-16.97	-7.10
		Guard Heater	2.53	-11.04	-15.10
	Rough Aluminum	Main Heater	69.73	14.13	14.22
		Guard Heater	9.85	-4.94	-8.11
	Silver Teflon	Main Heater	-1.43	2.74	19.07
		Guard Heater	10.44	-5.07	-11.27
Radiation	White Paint		3.42	1.92	-0.30
	Rough Aluminum		5.50	2.85	1.92
	Silver Teflon		4.01	4.20	3.07

Method 1 has mixed results. All main and guard heaters are within +/-20% except for the low dust density for the rough aluminum coupon, which has a very high error of 70%. With the white paint coupon, there is high error across the board for the main heater, only falling below +/-10% at the high dust density. The silver Teflon coupon seems to perform the best at the low and medium dust densities. All radiation checks are within +/-10%, with only the low dust density results for the rough aluminum coupon exceeding +/-5%. These results are very interesting, as this method is the most accurate model recreation of the test setup out of all methods analyzed.

B. Modeling Method 2

This method builds upon the theory behind Method 1. Method 1 only introduced dust as a layer of insulation with material properties and no e^* to represent radiative effects through the layer. The LDES ϵ_{eff} will be introduced as the e^* value in the same property card as the dust thermophysical properties in an effort to account for both the conductive and radiative heat flow paths, seen in Figure 5. The optics of the coating are still calculated using ROM and k_{dust} is still varied as in Method 1. As in Method 1, both the optics and the conductivity of the dust layer are recalculated for the low, medium, and high areal dust densities. Additionally, the different ϵ_{eff} values for each density are obtained from the LDES data and input into the model. An example of the heat flow path represented in a resistance network is shown in Figure 9. Results are shown in Table 3 below, and percent errors exceeding +/-10% are flagged in red for ease of comparison, and is an arbitrary cutoff.

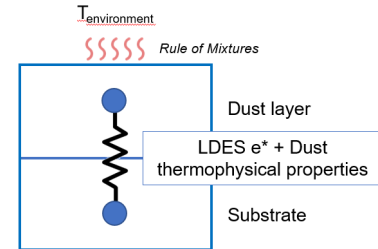


Figure 9. Method 2 Resistance Network

Table 2. Percent Error of Data vs Model Comparisons for Low, Medium, and High Dust Densities.

Power and Radiation Comparisons - Percent Error					
Modeling Method			Dust Density (mg/cm ²)		
			0.25	1.18	2.07
Power	White Paint	Main Heater	-13.65	-16.19	-3.42
		Guard Heater	7.11	-9.57	-13.84
	Rough Aluminum	Main Heater	64.86	13.11	16.76
		Guard Heater	14.70	-3.10	-6.51
	Silver Teflon	Main Heater	-3.55	1.39	19.47
		Guard Heater	15.46	-3.07	-9.43
Radiation	White Paint		0.01	-1.35	-1.94
	Rough Aluminum		0.05	-3.20	-3.50
	Silver Teflon		-0.14	-1.92	-3.25

For the white paint coupon, this method performs better than Method 1 at the medium and high dust densities. All coupons perform worse than Method 1 at the low dust density, but perform better than Method 1 for the guard heaters at medium and high dust densities. For the main heater power comparisons at medium and high dust densities, mixed increases and decreases are seen with the highest improvement being the white paint coupon at the high dust density.

Radiation comparisons for low dust densities improved, tending toward 0%, but the medium and high dust densities error slightly increased, but are still within +/-5%. There is a large outlier at the medium dust density for the white paint coupon. A claim can be made that this method performs slightly better than Method 1, while having an outlier with radiation.

C. Modeling Method 3

Method 3 is a relatively simple method that aims to use the LDES ϵ_{eff} as ϵ^* is used in theory. ϵ^* is often a value found through physical testing and is a simpler way to define the effectiveness of MLI, merging the radiative and conductive components into a single value. Thermal analysts will frequently utilize this ϵ^* value within a layer of arithmetic insulation. This means that the layer will be “massless”, with TD ignoring any specific heat or density inputs, so it will respond instantaneously to any change in energy balance. Analysts can also choose not to include thermal conductivity in the property card, and the result of choosing to model MLI in this way greatly assists in reducing computational power and model runtime, especially with large, detailed models.

Therefore, in this method, the LDES ϵ_{eff} value will be input into the insulation property card's ϵ^* box without any dust thermophysical properties, and this insulation layer will be defined as arithmetic. Optics will be modified based on equations (4) and (5). Appropriate values for optics and ϵ_{eff} are input for each dust density level. An example of the heat flow path represented in a resistance network is shown in Figure 10. Results are shown in Table 4 below, and percent errors exceeding +/-10% are flagged in red for ease of comparison, and is an arbitrary cutoff.

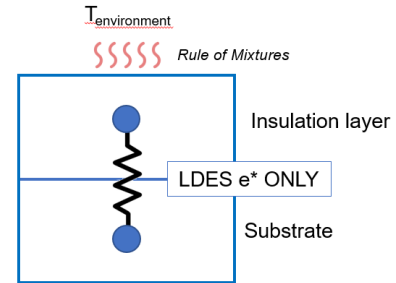


Figure 10. Method 3 Resistance Network

Table 4. Percent Error of Data vs Model Comparisons for Low, Medium, and High Dust Densities.

Power and Radiation Comparisons - Percent Error					
Modeling Method			Dust Density (mg/cm ²)		
			0.25	1.18	2.07
Power	White Paint	Main Heater	-46.50	-42.85	-34.07
		Guard Heater	-20.68	-34.27	-37.03
	Rough Aluminum	Main Heater	-22.90	-31.28	-25.65
		Guard Heater	-14.64	-30.64	-31.95
	Silver Teflon	Main Heater	-42.79	-38.23	-28.18
		Bottom Heater	-16.05	-32.03	-35.19
Radiation	White Paint		4.35	4.71	4.36
	Rough Aluminum		5.14	4.86	5.03
	Silver Teflon		4.32	4.34	4.57

This method does not appear to work as well Methods 1-2, and it is clear that only having a layer of insulation with an ϵ^* equivalent to an LDES ϵ_{eff} value does not reflect the complete heat transfer path through the dust layer. The TD model heavily underestimates the heater power needed to keep the coupon setpoint, meaning that this method models dust as much more insulative than reality. Though the radiation comparisons are still within +/-10%, this method will not be considered due to consistently high errors.

D. Modeling Method 4

This is the simplest method considered, as it involves simply replacing the ϵ within the TD optics card of the dusted surface with the LDES ϵ_{eff} value. This was intended to integrate the LDES team's equation flow back into the test system to see if it behaves as expected from the test data. Theoretically, the calculated ϵ_{eff} value represents the combined heat path through the dust and radiation to the shroud, similar to how emissivity radiates off of a surface to the environment. Appropriate values for the ϵ_{eff} values are input for each dust density level. An example of the heat flow path represented in a resistance network is shown in Figure 11. Results are shown in Table 5 below, and percent errors exceeding +/-10% are flagged in red for ease of comparison, and is an arbitrary cutoff.

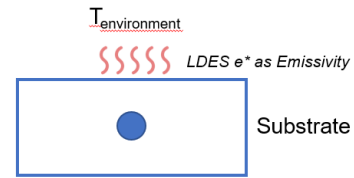


Figure 11. Method 4 Resistance Network

Table 5. Percent Error of Data vs Model Comparisons for Low, Medium, and High Dust Densities.

Power and Radiation Comparisons - Percent Error					
Modeling Method			Dust Density (mg/cm ²)		
			0.25	1.18	2.07
Power	White Paint	Main Heater	-7.45	-6.21	-1.87
		Guard Heater	-0.80	-18.58	-22.03
	Rough Aluminum	Main Heater	-3.62	-1.39	3.17
		Guard Heater	3.52	-12.72	-12.72
	Silver Teflon	Main Heater	-4.72	-5.64	1.93
		Guard Heater	1.93	-14.05	-16.06
Radiation	White Paint		0.52	0.62	1.18
	Rough Aluminum		4.30	1.73	2.01
	Silver Teflon		0.83	1.12	1.60

This method appears to work very well for all coupons and dust densities for the main heater, as well as for lower dust densities for the guard heater. For medium and high dust densities for the guard heater, the model underpredicts heater power and errors exceed +/-10%. Radiation comparisons are all within +/-5%.

E. Results Summary

A summary of all errors for heater power and radiation to the shroud for all four methods can be seen below. Values exceeding +/-10% are again flagged in red for ease of comparison, and is an arbitrary cutoff.

Table 6. Percent Error Summary for all Modeling Methods

Coupons			Method 1			Method 2			Method 3			Method 4		
			Dust Density (mg/cm ²)											
			0.25	1.18	2.07	0.25	1.18	2.07	0.25	1.18	2.07	0.25	1.18	2.07
White Paint	Heater Power	Main	-11.95	-16.97	-7.10	-13.65	-16.19	-3.42	-46.50	-42.85	-34.07	-7.45	-6.21	-1.87
		Guard	2.53	-11.04	-15.10	7.11	-9.57	-13.84	-20.68	-34.27	-37.03	-0.80	-18.58	-22.03
	Radiation		3.42	1.92	-0.30	0.01	-1.35	-1.94	4.35	4.71	4.36	0.52	0.62	1.18
Rough AL	Heater Power	Main	69.73	14.13	14.22	64.86	13.11	16.76	-22.90	-31.28	-25.65	-3.62	-1.39	3.17
		Guard	9.85	-4.94	-8.11	14.70	-3.10	-6.51	-14.64	-30.64	-31.95	3.52	-12.72	-12.72
	Radiation		5.50	2.85	1.92	0.05	-3.20	-3.50	5.14	4.86	5.03	4.30	1.73	2.01
Silver Teflon	Heater Power	Main	-1.43	2.74	19.07	-3.55	1.39	19.47	-42.79	-38.23	-28.18	-4.72	-5.64	1.93
		Guard	10.44	-5.07	-11.27	15.46	-3.07	-9.43	-16.05	-32.03	-35.19	1.93	-14.05	-16.06
	Radiation		4.01	4.20	3.07	-0.14	-1.92	-3.25	4.32	4.34	4.57	0.83	1.12	1.60

All four methods show mixed error comparison results. Method 4 correlates to the main heater for all 3 coatings without exceeding the +/-10% error, but error increases at higher dust coverages for the guard heater. Method 2 has a mix of high and low errors but clearly does not correlate well to the rough aluminum coating's main heater at low dust coverage. However, Method 2 does provide lower error percentages for almost all test coupons' guard heaters at

medium and high dust coverage. Method 1 also provides a mix of high and low errors but generally performs similar to Method 2 with the exception of reduced error for most heater power comparisons at the low dust density. In theory, Method 1, which aimed to recreate the test setup as accurately as possible without including the LDES ϵ_{eff} values, should have also seen power usage that is consistent with the test data. Lastly, Method 3 has consistently high errors of ~15% to ~45% across the board.

V. Conclusion

Out of all modeling methods studied previously and within this analysis, it appears that the best performing modeling method using all of the most up-to-date data is Method 4. This method is by far the simplest to implement and has very low error for the main focus of the correlation effort – the main heater. However, it does simply reflect the ϵ_{eff} value calculated using the test data and then reintroduces it into the test setup as an emissivity, reflecting almost exactly how it was calculated. This data series also comes with the stipulation that only one “test point” was obtained – this being one specific coupon temperature and one specific sky (or shroud) temperature used for all testing series. There was no solar simulator used in the test and the only reliable correlation metric was heater power for the main heater, so not only is it unknown how a dusted coating would react at a hotter or colder setpoint, but it is also unknown how the system will behave when a solar influence is added.

Therefore, a preliminary prediction on how dust will affect coatings that face deep space within the infrared spectrum and without any solar/UV influence is provided. To accurately model dusted surfaces over a large range of surface and environmental temperatures, though, additional testing would likely be needed to get ϵ_{eff} values that span possible operational scenarios. Because of these points, no method is recommended to be adopted for general analysis at this time until desired future work can be completed.

This desired forward work would be to make an equation-based curve fit of the data for public use. In addition, the LDES team also tested the NU-LHT-4M simulant, which produced another set of ϵ_{eff} versus dust density data. The correlation of this data and comparison of results to this analysis would be a significant factor in proving or disproving Method 4 as the best modeling method. Also, another testing series at a different temperature setpoint would be desired, as well as testing series that utilize an IR camera or have a solar simulator integrated onto the TVAC chamber. These additional testing points and correlation metrics would provide a more complete look at how the dust layer and the underlying coating behave, as well as providing another point on the LDES ϵ_{eff} curves.

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