Improvements to a Response Surface Thermal Model for Orion

Stephen W. Miller
NASA Johnson Space Center, Houston, TX 77058

William Q. Walker
West Texas A&M University, Canyon, TX 79016

ABSTRACT

A study was performed to determine if a Design of Experiments (DOE)/Response Surface Methodology could be applied to on-orbit thermal analysis and produce a set of Response Surface Equations (RSE) that predict Orion vehicle temperatures within ±10 °F. The study used the Orion Outer Mold Line model. Five separate factors were identified for study: yaw, pitch, roll, beta angle, and the environmental parameters. Twenty-three external Orion components were selected and their minimum and maximum temperatures captured over a period of two orbits. Thus, there are 46 responses. A DOE case matrix of 145 runs was developed. The data from these cases were analyzed to produce a fifth order RSE for each of the temperature responses. For the 145 cases in the DOE matrix, the agreement between the engineering data and the RSE predictions was encouraging with 40 of the 46 RSEs predicting temperatures within the goal band. However, the verification cases showed most responses did not meet the ±10 °F goal. After reframing the focus of the study to better align the RSE development with the purposes of the model, a set of RSEs for both the minimum and maximum radiator temperatures was produced which predicted the engineering model output within ±4 °F. Therefore, with the correct application of the DOE/RSE methodology, RSEs can be developed that provide analysts a fast and easy way to screen large numbers of environments and assess proposed changes to the RSE factors.

INTRODUCTION

This study is an extension of previous work[1] to evaluate the applicability of Design of Experiments (DOE)/Response Surface Methodology to on-orbit thermal analysis. The goal was to determine if the methodology could produce a Response Surface Equation (RSE) that predicted the thermal model temperature results within ±10 °F. An RSE is a polynomial expression that can be used to predict temperatures for a defined range of factor combinations. Based on suggestions received from the previous work, this study used a model with simpler geometry, considered polynomials up to fifth order, and evaluated orbital temperature variations to establish a minimum and maximum temperature for each component.

The concept of the Design of Experiments is over a century old, but not well known by many engineers. The foundation of DOE is the statistical variation of variables, or factors, between their defined upper and lower limits and the observation of the system response to this variation. This paper will not attempt to give a full mathematical background for DOE, but there is published literature on the subject[2]. Once the combinations of factors and responses have been obtained, there are several commercially available computer packages which perform a regression fit of the responses based on the interaction of the factors. These interactions range from linear variations with a single factor, up to *n*-level interactions of all identified factors. The regressions produce a series of coefficients which are then coupled to the appropriate terms to produce a polynomial Response Surface Equation. This RSE can then be used to predict a response for any combination of factor values, provided the values are within the defined factor limits. Extrapolation outside of the factor limit is not recommended. An example of a DOE/RSE implementation is shown in Figure 1.

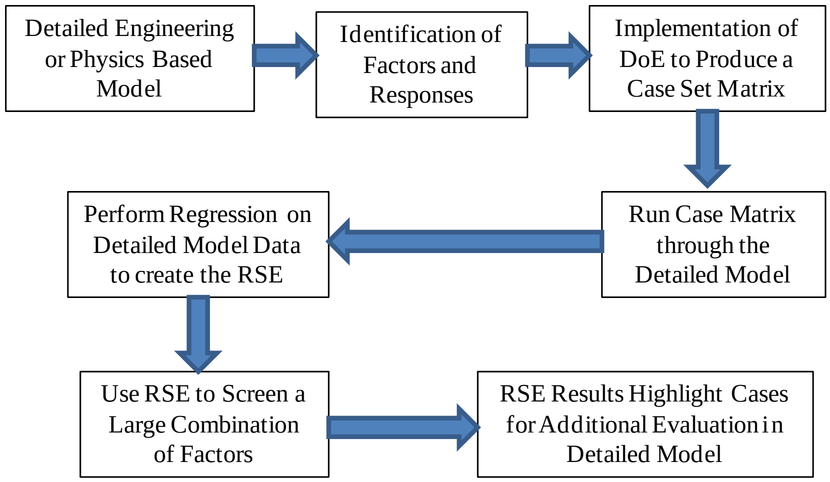

Figure 1. Flowchart example of DOE/RSE implementation.

DOE has been used in thermal analysis previously as part of an aerobreaking study on the Mars Reconnaissance Orbiter (MRO)[3,4,5]. The MRO analysts used DOE to produce a set of RSEs to predict solar array temperatures based on factors such as atmospheric density, drag pass duration, and material properties. The resulting thermal model was able to predict solar array temperatures for a wide combination of factors. The model results were compared against flight data and showed that only a few data points fell outside of the $\pm 3\sigma$ error bands applied to the predictions.

ORION MODEL OVERVIEW

For this study, the authors made use of the Orion Outer Mold Line (OML) thermal model in a free-flying configuration, *i.e.*, not mated with another spacecraft. The Orion OML was created by Lockheed Martin as part of the Constellation Program/Orion Project. This model is a simplified representation of the Orion spacecraft intended to perform screening analyses to locate hot/cold environments for the radiators. Once the extreme environments are located, the more detailed Orion Integrated Thermal Model can be run in those environments. The model's main features are the radiators, solar arrays, propulsion thrusters, communications antennae, and the crew module outer surface (see Figure 2). The model contains detailed geometry to represent the radiators. The radiators consist of diffusion nodes that have user logic to represent the active thermal control system (a pumped fluid loop). The solar arrays are also diffusion nodes that also have properties and logic to represent the complex, partially transparent panels. Additionally, the solar arrays are allowed to articulate to track the sun in defined heating cases. The remaining model components consist mainly of arithmetic nodes and are meant to serve as blocking surfaces. They are not as detailed because they do not have a large effect on the radiator environment.

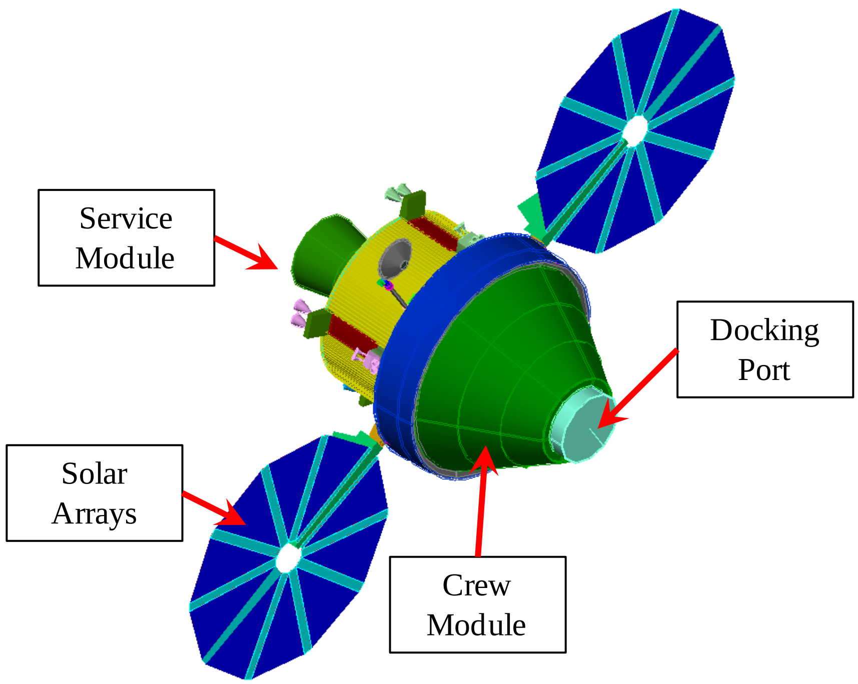

Figure 2. Orion Outer Mold Line Model.

RSE DEVELOPMENT

The first step in creating RSEs is to determine the factors to use in the DOE. For the Orion model, a natural choice for factors are the yaw, pitch, and roll, which define the vehicle's on-orbit attitude, and the beta angle and natural environment, which determine the external heating. For this particular exercise, other variables such as the vehicle power level, were held constant. Table 1 shows the selected factors, low, nominal, and high limits.

Table 1. Orion/ISS Variables for Creating RSEs

Variable	Low Value	Mid Value	Upper Value
Yaw	-15°	0°	15°
Pitch	-20°	-2.5°	15°
Roll	-15°	0°	15°
Beta Angle	0°	37.5°	75°
Environment	-1	0	1

The environment variable is a combination of the altitude, solar constant, albedo, and planetary infrared radiation. The hot/cold values for each of these values were normalized between a value of -1 and +1. Table 2 contains the dimensional values for each of these parameters, taken from the Orion-to-International Space Station Interface Requirements Document[6]. The Environment variable was +1 in the hot case and -1 in the cold case. Values were varied linearly between the upper and lower extremes.

Table 2. Environmental Constants

Parameter	Hot Case	Cold Case
Solar	451 BTU/(hr-ft^2)	419 BTU/(hr-ft^2)
Albedo	0.53	0.20
Planetary IR	110.7 BTU/(hr-ft^2)	48.5 BTU/(hr-ft^2)
Altitude	173 miles	286 miles

The next step was to determine which responses were to be measured from the model. Since this activity was a demonstration of the DOE/RSE approach, nodes were not selected with regard to temperature limits or sensitivity to a particular mission. Rather, the authors chose 23 components located at various points around the model. In order to provide a more representative temperature for each component, several nodes were used to characterize each component. A simple min/max survey of all the nodes for a component was performed in order to produce a minimum and maximum temperature for each component. The component names and the number of nodes in the response are provided in Table 3 and shown in Figure 3. In an actual design, the selected responses could be critical component temperatures, heater power, or any other model output of interest to the analyst.

Table 3. Component Names and Number of Nodes Feeding Response

Component	# of Nodes in Response	Component	# of Nodes in Response
CM Backshell 1	3	Comm Antenna 1	5
CM Backshell 2	6	Comm Antenna 2	5
CM Backshell 3	3	Comm Antenna 3	5
CM Backshell 4	6	Comm Antenna 4	5
Radiator 1	32	RCS Thruster 1	12
Radiator 2	32	RCS Thruster 2	12
Radiator 3	32	RCS Thruster 3	12
Radiator 4	32	RCS Thruster 4	12
Solar Array 1	40	Aux Thruster 1	11
Solar Array 2	40	Aux Thruster 2	11
High Gain Antenna	13	Aux Thruster 3	11
		Aux Thruster 4	11

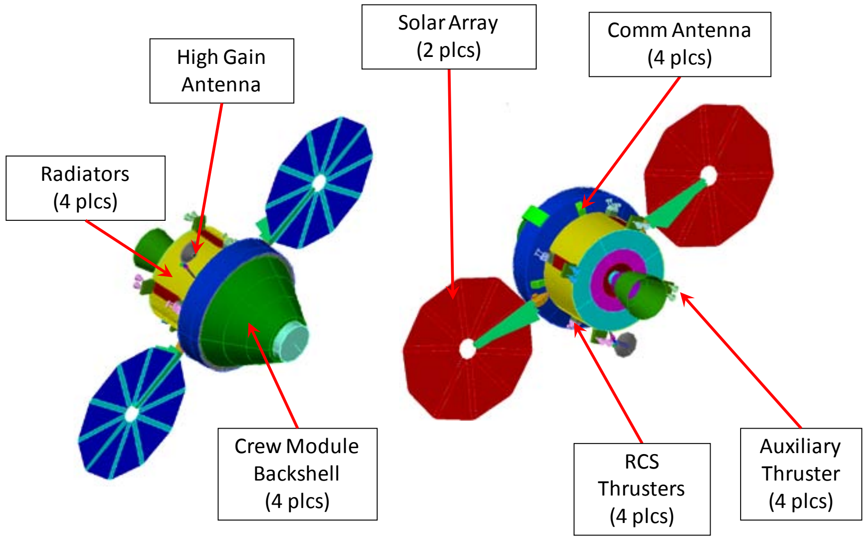

Figure 3. Location of various Orion components.

With the Factors and Responses defined, a DOE case matrix can be produced. One useful recommendation is to non-dimensonalize all factors to a -1 to +1 range. This allows the same DOE matrix to be used, even if the factor ranges change. Using the 5 factors, the following test points were selected: vertices, centers of edges, axial checkpoints and the overall centroid. Vertices represent the "corners" of the 5-dimensional space where all factors have values of either +1 or -1 (32 cases). Centers of edges have 4 of the 5 factors equal to +1 or -1 and the fifth factor equal to 0 (80 cases). The Axial Checkpoints provide cases within the design space and all Factors have values or either 0.5 or -0.5 (32 cases). The overall centroid provides an anchor in the middle of the design space with all factors equal to 0 (1 case). Figure 6 provides a visual representation of where these test points occur for a 2-Factor design. With these selections made, the DOE package Design-Expert 8 (DX8) recommended a set of 145 cases. The DOE case matrix was run in Thermal Desktop using the OML model. For each of the 145 cases, a full radiation analysis for heating rates and radiation to space was conducted (100,000 rays shot for each radiation task) and the model was solved using a steady state solution solver and then a transient solver for 4 orbits. Data was captured over the last two orbits and the min/max temperature pair for each response was output.

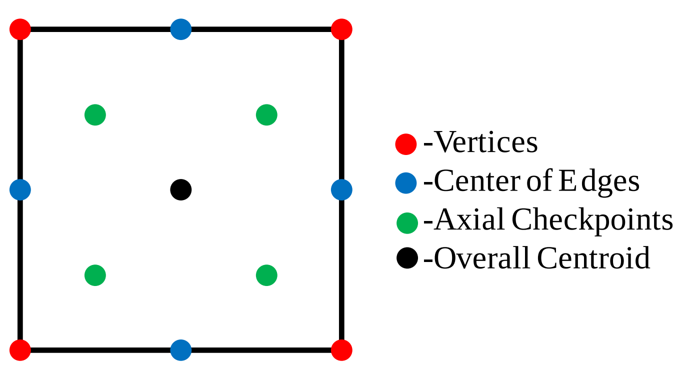

Figure 4. Illustration of test point locations.

After completing the analysis runs with the OML model, the temperature data were entered back into Design-Expert 8 in order to produce the RSEs. One of the choices the analyst can make is the level of interactions between factors to be considered. Because of the complex nature of many engineering problems, the interaction of factors can play a significant role in determining the response. For the current study, a cubic, quartic, and a fifth order polynomial were all evaluated to determine which produced the best fit. These equations take the general form in equation 1.

$$F(x) = C_0 + \sum_{i=1}^{5} C_i X_i + \sum_{i=1}^{5}\sum_{j=1}^{i} C_{ij} X_i X_j + \sum_{i=1}^{5}\sum_{j=1}^{i}\sum_{k=1}^{j} C_{ijk} X_i X_j X_k + \sum_{i=1}^{5}\sum_{j=1}^{i}\sum_{k=1}^{j}\sum_{l=1}^{k} C_{ijkl} X_i X_j X_k X_l + \sum_{i=1}^{5}\sum_{j=1}^{i}\sum_{k=1}^{j}\sum_{l=1}^{k}\sum_{m=1}^{l} C_{ijklm} X_i X_j X_k X_l X_m \quad [1]$$

Each of the 46 temperature predictions will have its own unique RSE. Therefore, the DOE code will produce 46 RSEs, each with different coefficients for the interaction terms defined in equation 1. There are 56 coefficients for each RSE with the cubic interactions. For a fifth order equation, there are 252 possible terms. So the complexity of the RSE must be weighed against the desired accuracy of the response. Additionally, not all terms are significant contributors to the overall response. Therefore, some terms can be ignored. Finally, as the number of terms increases, aliasing is possible. This means that the effects of one term include the effects of one or more other terms. This may or may not be a problem depending on if the aliased terms are significant.

The goal of this study was to create RSEs that agreed with the engineering model within ±10 °F. To determine if the RSE met this goal, a simple statistical analysis was performed using the difference between the RSE prediction and the OML model output. The error values are shown in Table 4 for the three levels of polynomials considered. Note that for the quartic and 5th order RSEs, the majority of the $\pm 3\sigma$ values are within the desired ±10 °F goal. Also, as additional interactions are included, the $\pm 3\sigma$ value decreases. In the current study, the 5th order RSEs were selected for further use because it was determined that it provided the most accurate results. Although the Design Expert 8 software cautioned that some aliasing may be present, it was decided that the aliased interactions did not affect the overall goal of the RSE, which was to produce temperature predictions. All subsequent discussions will refer to results based on the 5th order RSEs. Forty of the 46 responses had a $\pm 3\sigma$ value at or below the desired 10 °F value. While not all responses are within the desired criteria, this is a significant improvement over the previous work.

Table 4. Temperature Response 3σ Values

Response	±3σ – Cubic Min / Max (°F)	±3σ – Quartic Min / Max (°F)	±3σ – 5th Order Min / Max (°F)
CM Backshell 1 Min/Max	12.9 / 3.0	5.5 / 1.4	2.7 / 0.6
CM Backshell 2 Min/Max	16.6 / 3.2	8.5 / 1.6	4.5 / 0.9
CM Backshell 3 Min/Max	10.3 / 2.7	4.9 / 1.5	1.9 / 0.5
CM Backshell 4 Min/Max	22.9 / 10.9	7.7 / 4.4	3.4 / 1.0
Radiator 1 Min/Max	0.7 / 1.9	0.2 / 1.1	0.2 / 0.3
Radiator 2 Min/Max	0.6 / 0.4	0.2 / 0.2	0.2 / 0.1
Radiator 3 Min/Max	0.5 / 0.5	0.1 / 0.2	0.1 / 0.1
Radiator 4 Min/Max	1.1 / 0.6	0.3 / 0.4	0.1 / 0.1
Solar Array 1 Min/Max	34.7 / 18.4	11.6 / 4.1	5.1 / 2.4
Solar Array 2 Min/Max	19.0 / 6.8	6.3 / 3.2	3.2 / 1.3
High Gain Antenna Min/Max	50.8 / 3.9	31.7 / 2.8	21.3 / 1.9
Comm Antenna 1 Min/Max	34.0 / 25.9	6.2 / 3.8	3.3 / 1.8
Comm Antenna 2 Min/Max	13.1 / 11.4	6.9 / 4.9	4.9 / 2.4
Comm Antenna 3 Min/Max	11.4 / 4.3	5.4 / 1.7	2.2 / 1.0
Comm Antenna 4 Min/Max	64.8 / 5.6	41.4 / 3.9	27.9 / 2.1
RCS Thruster 1 Min/Max	41.7 / 46.5	14.6 / 9.4	5.3 / 11.0
RCS Thruster 2 Min/Max	43.0 / 47.6	15.2 / 11.8	3.6 / 13.3
RCS Thruster 3 Min/Max	37.3 / 65.3	12.0 / 11.8	5.2 / 12.6
RCS Thruster 4 Min/Max	39.8 / 57.9	12.6 / 10.1	2.8 / 12.7
Aux Thruster 1 Min/Max	22.5 / 9.9	11.7 / 1.8	6.5 / 0.7
Aux Thruster 2 Min/Max	28.4 / 10.5	12.1 / 1.9	4.2 / 0.4
Aux Thruster 3 Min/Max	23.1 / 12.5	6.4 / 1.4	3.7 / 0.8
Aux Thruster 4 Min/Max	20.1 / 12.4	9.5 / 1.0	2.2 / 0.4

RESULTS

With the RSEs now available, twenty cases were developed to verify the predictive power of the RSEs. The value for each of the five factors was generated using the random number generator function in Excel. The factor values were input into the RSEs and the temperature predictions were complete within a matter of seconds. The Thermal Desktop runs were executed as described above (number of rays, solution routines, etc.). The Thermal Desktop model run took approximately 20 hours on a dual quad-core processor with 8GB of RAM for all 20 cases.

After all runs were complete, the data was collected in a spreadsheet and the RSE predictions were compared against the Thermal Desktop output by evaluating the absolute value of the difference between the RSE prediction and the Thermal Desktop output. Table 5 shows the largest discrepancy between the RSE and the OML. Values that are within the desired 10 °F range are not colored. Values that are between 10 and 20 °F are colored yellow. Values above 20 °F are colored red. The first observation to make after looking at the table is the large number of red values. This is especially true for the minimum temperature predictions where 16 of the 23 responses are over 20 °F off. Indeed, for the minimum temperatures, only the four radiator responses had all 20 cases within the desired 10 °F range. Results are better for the maximum temperatures, were only 6 of the 23 responses are red. Twelve of the maximum temperature responses were within the 10 °F goal for all 20 cases. This was quite unexpected given the excellent correlations achieved as part of the RSE development. To confirm these results, an additional 50 random cases were generated and run through both the RSEs and Thermal Desktop model. These results are also shown in Table 5. Virtually the exact same breakdown of prediction agreement is present as in the 20-case run.

Examining the results closer revealed that the responses with the largest deviations are mostly arithmetic nodes. This means that these components will be especially sensitive to sudden changes in the environment (i.e., shadow to full-sun). It is postulated that these sudden changes make the min/max temperature behavior erratic and more difficult to predict. Therefore, the RSEs do not perform as well for these components.

Table 5. 20-Case and 50-Case Verification Results

Component	20-Case Results Largest |RSE-TD| Value (°F)		50-Case Results Largest |RSE-TD| Value (°F)	
	Min Temp Predictions	Max Temp Predictions	Min Temp Predictions	Max Temp Predictions
CM Backshell 1	21.5	4.2	21.6	3.5
CM Backshell 2	23.8	5.5	29.9	2.2
CM Backshell 3	19.1	2.6	23.2	2.9
CM Backshell 4	32.4	16.4	28.2	15.8
Radiator 1	3.2	1.8	3.5	1.3
Radiator 2	2.7	0.4	2.0	0.3
Radiator 3	2.1	0.2	0.9	0.3
Radiator 4	2.7	0.7	2.5	0.7
Solar Array 1	90.8	27.2	100.3	20.6
Solar Array 2	96.4	3.7	121.8	6.1
Comm Antenna 1	74.3	30.7	42.2	27.4
Comm Antenna 2	21.4	12.3	27.8	10.5
Comm Antenna 3	14.6	5.1	18.9	4.3
Comm Antenna 4	109.2	7.8	111.3	9.1
High Gain Antenna	101.5	5.7	116.1	7.6
Aux Thruster 1	25.0	12.2	33.7	12.5
Aux Thruster 2	51.4	11.5	69.3	10.9
Aux Thruster 3	67.1	11.1	36.5	9.8
Aux Thruster 4	17.0	8.5	28.5	9.1
RCS Thruster 1	120.5	42.3	120.8	53.6
RCS Thruster 2	96.8	69.1	96.4	49.4
RCS Thruster 3	67.7	78.2	57.3	63.5
RCS Thruster 4	109.5	79.5	112.4	55.6

From these two data sets, four general findings can be drawn:

1. With the exception of the 4 radiator temperatures, the RSEs do not predict the minimum temperature Thermal Desktop results with any degree of accuracy that instills confidence.
2. The RSEs for the four RCS thrusters, Solar Array 1, and Comm Antenna 1 do not predict the Thermal Desktop results for either the minimum or maximum temperatures.
3. The RSEs provide a reasonable prediction for the remaining 17 component maximum temperatures.
4. The RSEs for the four radiators show excellent agreement with the Thermal Desktop predictions in all cases.

Given the above findings, it was decided to continue the evaluation using only the RSEs developed for the maximum temperature responses since they produced results that agreed best with the Thermal Desktop output. The next step was to evaluate the RSEs in a large number of cases and determine the combinations of factors that produced the hottest temperatures. To this purpose, a matrix of 59,045 cases was developed by varying each of the 5 factors from -1 to +1 in 0.25 increments. These factor combinations were then evaluated in each of the maximum temperature RSEs using an Excel macro. It took approximately 15 minutes on a dual quad-core processor with 8GB of RAM to evaluate all 59,045 cases. From these cases, the absolute maximum predicted temperature for each component was identified. All cases that produced a maximum temperature within 5 °F of this absolute maximum temperature were noted. The authors then filtered through the cases manually using the criteria of searching for cases that had multiple high maximum temperatures, while ensuring that all components were identified in at least once case. This produced a set of 55 cases that produced temperatures at or near the absolute maximum predicted temperature for all components. These 55 cases were then run in Thermal Desktop. The results are shown in Table 6. Given the trends found in the two sets of verification runs, the results in Table 6 will come as no surprise. Indeed the exact same findings can be drawn.

An alternative method to screening would be to use a feature in the DOE software to look for an optimized solution. In this case, the RSEs would be optimized to produce the maximum temperature for each component. The parameters that are needed to create those predictions can then be run in Thermal Desktop. The advantage of this approach is that the analyst can claim to have found the actual “worst case” for each response. The disadvantage is that the RSEs are only approximations of the model. By screening a large number of cases, the analyst can better understand the sensitivity of the components to changes in the factors.

Table 6. Results from Selected 55 Hottest Cases

Component	55-Case Results Largest |RSE-TD| Value (°F)
CM Backshell 1	5.0
CM Backshell 2	4.1
CM Backshell 3	2.5
CM Backshell 4	13.7
Radiator 1	1.8
Radiator 2	0.6
Radiator 3	0.6
Radiator 4	1.0
Solar Array 1	28.3
Solar Array 2	9.2
Comm Antenna 1	23.9
Comm Antenna 2	9.1
Comm Antenna 3	7.2
Comm Antenna 4	9.7
High Gain Antenna	8.4
Aux Thruster 1	18.9
Aux Thruster 2	14.3
Aux Thruster 3	17.8
Aux Thruster 4	16.0
RCS Thruster 1	65.6
RCS Thruster 2	53.4
RCS Thruster 3	84.1
RCS Thruster 4	73.6

REFRAMING THE QUESTION

Based on the results that have been presented above, it would seem very difficult to argue that the DOE/RSE application has been shown to be applicable to on-orbit thermal analysis. Indeed, the authors were puzzled as to how the minimum temperature RSEs could be so wretchedly wrong. An additional complexity was developing a logical explanation why some of the maximum temperature RSEs performed rather well and why some were just as awful as the minimum temperature RSEs. The key to explaining the problem lies in how the original question was posed. Initially, the goal was to take a working model and attempt to develop RSE that could reliably predict the thermal model output within ±10 °F. However, what the authors neglected to consider was the purpose for which the original model was developed.

Recall that the main purpose of the Orion OML thermal model is to predict the thermal environments for the radiators. To that purpose, the radiators were the most detailed components in the OML and contained additional logic designed to ensure they mimicked the radiator responses in the Orion Integrated Thermal Model. The remaining components were modeled only to the level of detail needed to support the radiators. Therefore, it may not be reasonable to try to develop RSE for OML components other than the radiators. Indeed, it would seem unreasonable to expect otherwise. From the beginning, the real focus of this work should have been to use the DOE/RSM approach to produce RSEs that predict the radiator temperatures produced by the OML within ± 10 °F.

Using this reframed question, the radiator data is now presented by itself. First, consider the selection of the appropriate RSE. All three RSEs perform quite well. Indeed, if this was the data initially considered, a strong case could be made to select the simpler 3rd order equation and still have confidence in its accuracy.

Table 7. Reframed Temperature Response 3σ Values

Response	±3σ – Cubic (°F)	±3σ – Quartic (°F)	±3σ – 5th Order (°F)
Radiator 1 Min/Max	0.7 / 1.9	0.2 / 1.1	0.2 / 0.3
Radiator 2 Min/Max	0.6 / 0.4	0.2 / 0.2	0.2 / 0.1
Radiator 3 Min/Max	0.5 / 0.5	0.1 / 0.2	0.1 / 0.1
Radiator 4 Min/Max	1.1 / 0.6	0.3 / 0.4	0.1 / 0.1

Second, re-examine the two sets of verification runs (Table 8). Note that while the maximum observed deviations from the OML output are significantly larger than the 3σ values shown in Table 7, all of them are well within the ± 10 °F goal identified. Considered in this light, the two verification sets confirm the performance of the radiator RSEs.

Table 8. Reframed 20-Case and 50-Case Verification Results

Component	20-Case Results Largest |RSE-TD| Value (°F)		50-Case Results Largest |RSE-TD| Value (°F)	
	Min Temp Predictions	Max Temp Predictions	Min Temp Predictions	Max Temp Predictions
Radiator 1	3.2	1.8	3.5	1.3
Radiator 2	2.7	0.4	2.0	0.3
Radiator 3	2.1	0.2	0.9	0.3
Radiator 4	2.7	0.7	2.5	0.7

And finally, revisit the results of the 55-cases selected from the 59,045 screening cases. These data show that the RSEs were able to identify the absolute hottest radiator environments and predict the OML temperature results with excellent accuracy.

Table 9. Reframed Results from Selected 55 Hottest Cases

Component	55-Case Results Largest |RSE-TD| Value (°F)	
	Min Temp Predictions	Max Temp Predictions
Radiator 1	1.3	1.8
Radiator 2	1.0	0.6
Radiator 3	0.5	0.6
Radiator 4	1.4	1.0

CONCLUSIONS, COMMENTS, AND FUTURE WORK

Based upon the reformulated purpose of the study, it can be concluded that DOE/RSM can indeed be successfully applied to on-orbit thermal analysis. However, several caveats should be noted. First, as demonstrated by this paper, the analyst must carefully consider the appropriate responses in the thermal model. A model that is meant to be used to predict on-orbit radiator temperatures should not be expected to accurately predict temperatures for other components not adequately modeled. All thermal models are built with the purpose of producing data to characterize a particular component. A small model may focus on a single component with limited operational modes, while a large integrated may contain tens of thousands of nodes, utilize multiple power levels and operational states, and be intended to produce data in a wide range of environments and configurations. Knowing how to intelligently frame the question and use an engineering model built to answer that question will produce RSEs capable of emulating the engineering model.

Second, RSEs are not meant to replace a detailed engineering model. Indeed, the RSE development is completely dependent on having a well built engineering model to supply the initial data for correlation and to verify the results. Additionally, since RSE are merely polynomial equations based of correlation, they are not capable of the intricate calculations performed by engineering models. The experienced thermal analyst will be well aware that shadowing and solar entrapment can occur within very narrow boundaries. The RSEs will not be able to predict these "singularities." Therefore, it is up to the author to be vigilant about accounting for these phenomena. Once found, the RSEs can be developed around these points.

Third, as developed in this instance, the RSEs provide an excellent means of screening large combinations of factors that would otherwise prove time prohibitive using more detailed, but slower, engineering models. Analysts can uses this fast turnaround time to be responsive to proposed changes to the identified factors, so long as the proposed changes are within the bounds originally defined. Additionally, the RSE can be used to fulfill requirements verification tasks that require large numbers of analyses to be performed. The RSE results would not be the only data, but they can help provide confidence that the vehicle or component functions within the defined parameters. Lastly, RSE's can be used during initial design phases to assess various thermal design options. For instance, an analyst could develop and RSE that looks at the relative merits of component heaters vs. a radiant heater environment. RSEs can also be developed to assess the sensitivities to optical coatings or contact conductance.

Future work in this area is to continue to prove the applicability of DOE/RSM by using it on either more detailed thermal models (such as the Orion Integrated Thermal Model) or on a different spacecraft. In doing so, more thermal analysts will become familiar with the concepts and uses of DOE/RSM and be more likely to implement it on future projects.

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