Development of a Response Surface Thermal Model for Orion Mated to the International Space Station

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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 accurately predict vehicle temperatures. The study used an integrated thermal model of the International Space Station and the Orion Outer mold line model. Five separate factors were identified for study: yaw, pitch, roll, beta angle, and the environmental parameters. Twenty external Orion temperatures were selected as the responses. A DOE case matrix of 110 runs was developed. The data from these cases were analyzed to produce an RSE for each of the temperature responses. The initial agreement between the engineering data and the RSE predictions was encouraging, although many RSEs had large uncertainties on their predictions. Fourteen verification cases were developed to test the predictive powers of the RSEs. The verification showed mixed results with some RSE predicting temperatures matching the engineering data within the uncertainty bands, while others had very large errors. While this study to not irrefutably prove that the DOE/RSM approach can be applied to on-orbit thermal analysis, it does demonstrate that technique has the potential to predict temperatures. Additional work is needed to better identify the cases needed to produce the RSEs

Nomenclature

C_x = Coefficient
X_i = Variable
σ = Standard deviation
i, j, k = Summation integers

I. Introduction

The goal of this study was to apply a Design of Experiments (DOE)/Response Surface Methodology to on-orbit thermal analysis and determine if the resulting Response Surface Equations (RSEs) could predict temperatures within a defined error band. As detailed thermal models continue to increase in complexity, the time required to run them also increases. This limits the number of runs that an analysis team can practically perform in a given design cycle. This study explored using a DOE to define a set of detailed model runs, from which a RSE could be created for various temperature responses. An RSE is a polynomial expression that can then be used to predict temperatures for a wide range of variable combinations. The RSE is then solved to determine a grouping of extreme high and low temperature predictions. The conditions which cause these temperatures can then be entered into the detailed thermal model for a more thorough analysis.

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

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and the observation of the system response, or responses, to this variation. This paper will not attempt to give a full mathematical background for DOE, but there is published literature on the subject. [1]. 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.

DOE has been used in thermal analysis previously as part of an aerobreaking study on the Mars Reconnaissance Orbiter (MRO) [2, 3, 4]. 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.

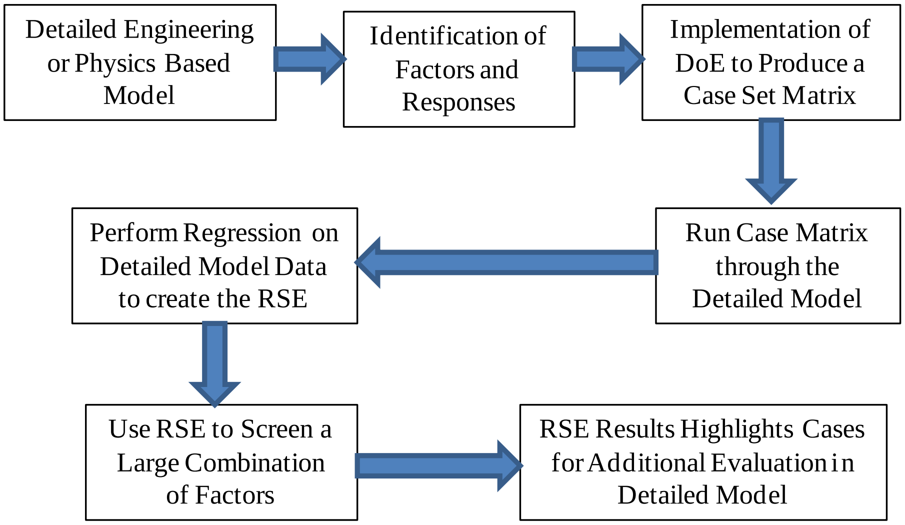

Figure 1. Flowchart Example of DOE/RSE Implementation

II. Orion and ISS Model Overview

For this study, the authors made use of the Orion Outer Mold Line (OML) model, integrated with the simplified International Space Station (ISS) thermal model. 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 conditions in which the more detailed Orion Integrated Thermal Model can be run. The model's main features are the radiators, solar array, propulsion modules, and crew module outer surface (see Figure 2). It consists of a geometric model for radiation heat transfer and lumped capacitance nodalized thermal model.

The ISS thermal model used was the V6R1 ISS thermal model provided by Boeing, as shown in Figure 3. The geometric model is used to calculate radiation heat transfer and a lumped thermal capacitance nodalized model is used to calculated temperatures. Figure 4 shows the Orion OML model placed at the Forward Node 2 port location. The combined model contains approximately 3200 nodes.

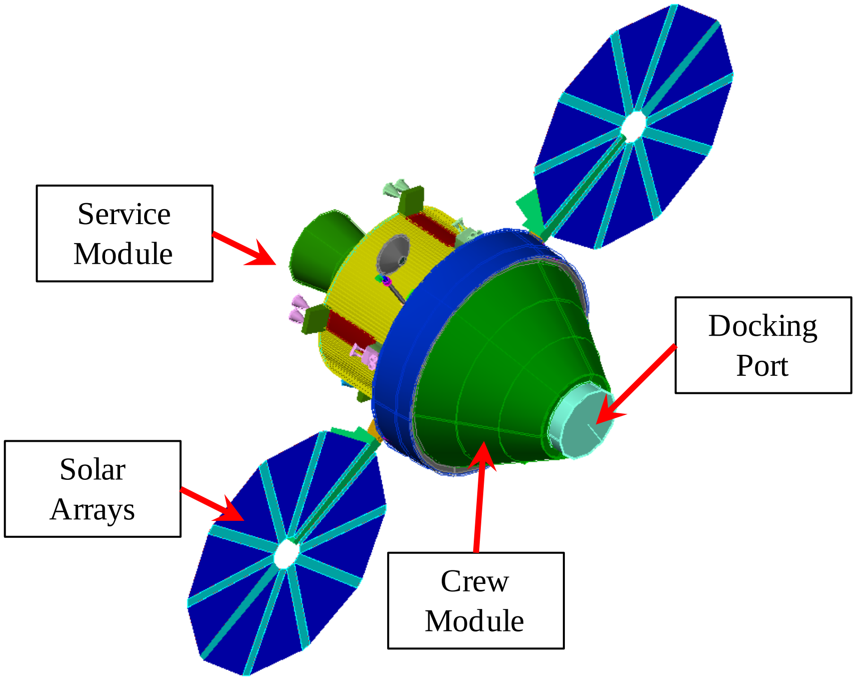

Figure 2. Orion Outer Mold Line Model

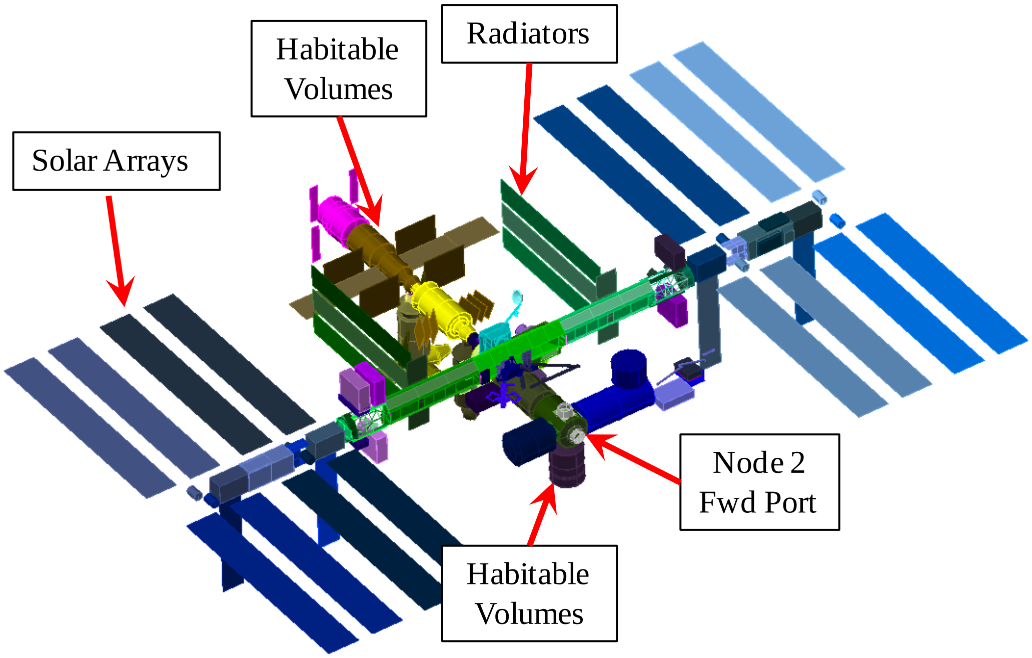

Figure 3. ISS Thermal Model

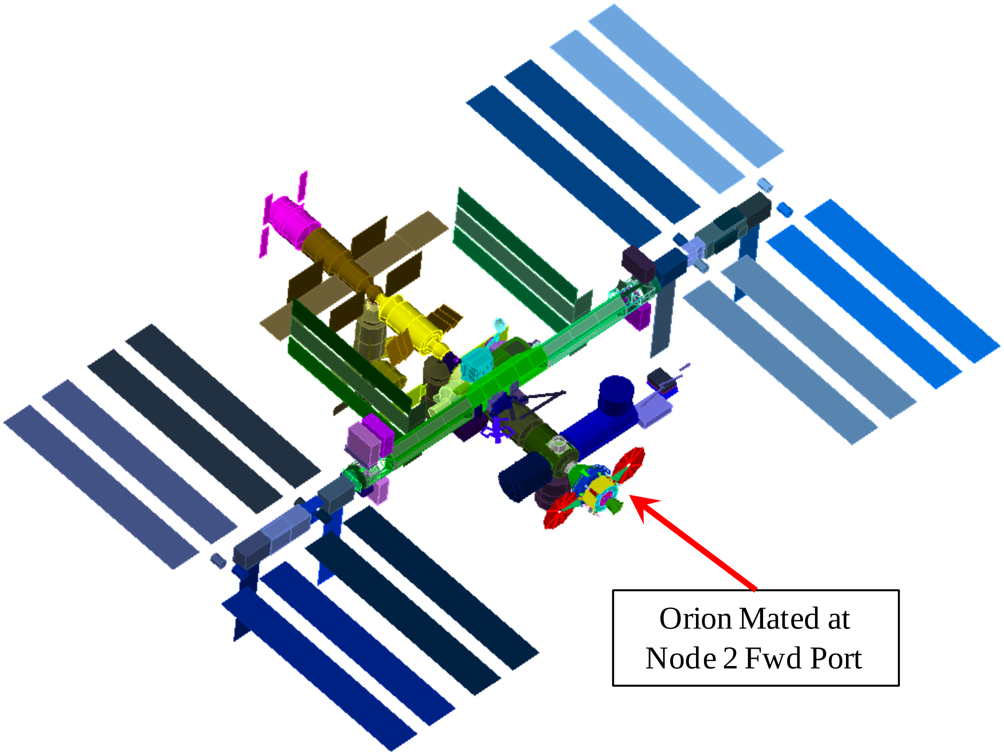

Figure 4. Orion Outer Mold Line Model Mated to the ISS thermal Model

III. Orion/ISS RSE Development

The first step in creating RSEs is to determine the factors to use in the DOE. For the Orion/ISS 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 levels were held constant. In the case of articulating surfaces, they were allowed to rotate per their defined algorithms, and were not locked in any particular position. Table 1 shows the selected variables, uncertainly values, low, nominal, and high limits. The uncertainty levels were based on an engineering estimate.

Table 1. Orion/ISS Variable for Creating RSEs

Variable	Uncertainty	Low Value	Mid Value	Upper Value
Yaw	10%	-15°	0°	15°
Pitch	10%	-20°	-2.5°	15°
Roll	10%	-15°	0°	15°
Beta Angle	2%	0°	37.5°	75°
Environment	5%	-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-ISS Interface Requirements Document [5]. The Hot Case values were used when the Environment variable was +1 and the Cold Case values when it was -1. Values were varied linearly between the upper and lower extremes.

Table 2. Environmental Constants

Parameter	Hot Case	Cold Case
Solar	1423 W/m^2	1321 W/m^2
Albedo	0.53	0.20
Planetary IR	349 W/m^2	153 W/m^2
Altitude	278 km	460 km

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 the particular mission. Rather, the authors chose 20 nodes located at various points around the model. The locations of these points are show in Figure 5 and listed in Table 3. It should be noted that any of the model nodes could serve as a response and an RSE developed. 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. Temperature Responses

Node # (Submodel.###)	Component	Node # (Submodel.###)	Component
SOLARDEP.1014	Solar Array, Sun Facing	SR4D1.30000	Service Module Auxiliary Thrusters
SOLARDEP.2014		SR4D2.30000	
SOLARDEP.1114	Solar Array, Space Facing	SR4D3.30000	
SOLARDEP.2114		SR4D4.30000	
SMCOMM.11	Service Module Communication Antennas	SRCS1.4000	Service Module Reaction Control thrusters
SMCOMM.21		SRCS2.60000	
SMCOMM.31		SRCS3.50000	
SMCOMM.41		SRCS4.2000	
SMHGA.11	High Gain Antenna	SMSADA1.7042	Solar Array Gimbal Mechanisms
CMBKSHL.1004	Crew Module Backshell	SMSADA2.7002	

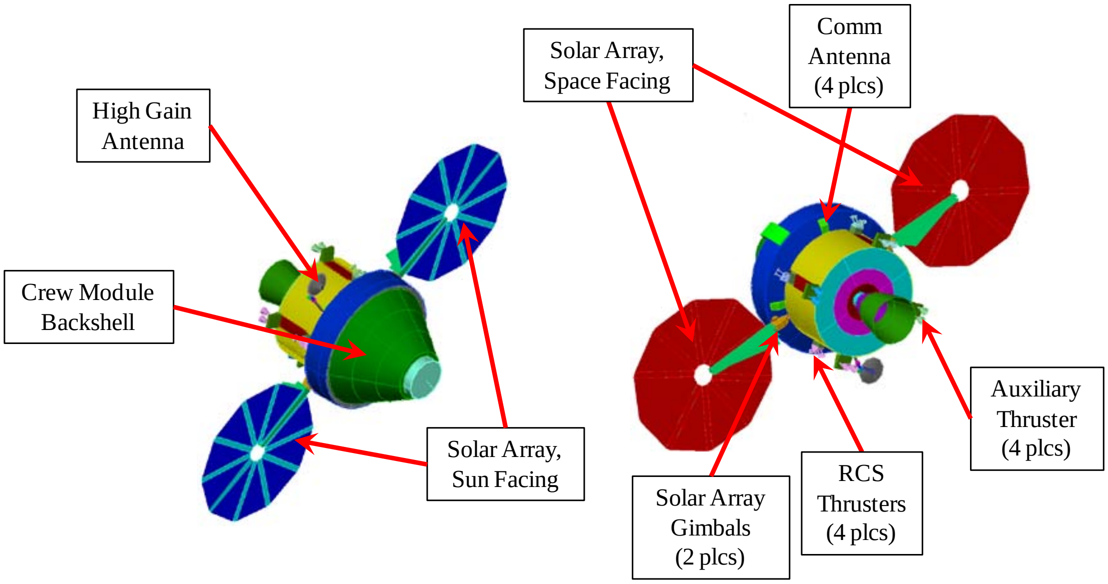

Figure 5. Orion Outer Mold Line Model

With the Factors and Responses defined, a DOE case matrix can be produced. Using the 5 factors and a face-centered central composite design, the DOE package recommended a set of 64 cases to be run. An additional 10 cases at the center point of each factor were run to help anchor the model. These runs are known as replicate runs. After some initial trials, it was decided to add an additional 36 cases to the matrix. This enabled the program to better fit the RSEs to the measured responses. In total, 110 runs were performed. One useful recommendation is to non-dimensonalize all variables to a -1 to +1 range. This allows the same DOE matrix to be used, even if the factor ranges change. The DOE case matrix was run in Thermal Desktop. For each of the 100 cases, a full radiation analysis for heating rates and radiation to space was conducted (25,000 rays shot for each radiation task) and the model was solved using a steady state solution solver. Therefore, the temperatures reported are orbit average temperatures. Note that if an analyst is interest in minimum or maximum temperatures, a transient run could be performed and the data scanned for the desired local min/max values.

After completing the analysis runs with the detailed thermal model, the temperature data were entered back into the DOE software tool in order to produce the RSEs. One of the choices the analyst can make is the level of interactions to be considered. For example, a first order, or linear, regression would only produce a polynomial equation with an intercept and one term representing each of the factors (yaw, pitch, roll, beta angle, and environment in this case). This RSE would not serve as a good predictor for the response because it cannot account for the complexity of interacting factor effects.

[1]

Because of the complex nature of many engineering problems, the interaction of factors can play a significant role in predicting the response. For a problem of 5 factors, the maximum number of interactions would be a 5th order polynomial. However, a polynomial of that degree is not necessarily required. The DOE software performs an analysis of the data and recommends the highest level of interactions needed before the interaction effects become confounded, or aliased. For the current study, a cubic polynomial was recommended. This equation takes the form:

[2]

Each of the 20 separate temperature predictions will have its own unique RSE. Therefore, the DOE code will produce 20 RSEs, each with different coefficients for the interaction terms defined in equation 2 above. There are 56 coefficients for each RSE with the cubic interactions. An example of the RSE for the temperature of node SOLARDEP.1014 is given in equation [3].

[3]

Where:

Y = Yaw, normalized between -1 and +1.
P = Pitch, normalized between -1 and +1.
R = Roll, normalized between -1 and +1.
B = Beta Angle, normalized between -1 and +1.
E = Environment, normalized between -1 and +1.

One important consideration is the accuracy of the RSE. To establish a $\pm 3\sigma$ value for the predictions, the RSE prediction was subtracted from the engineering model output. Assuming a normal distribution, a one σ value can be found using statistics. The error values are shown in Table 4. One of the facts that leaps from the table is the wide spread in 3σ values. Some of the variation is as low as 3.5 °F, while others range up to 47 °F. This implies that additional cases may be needed for those responses to better characterize the response surface. Also, it is doubtful that an uncertainty as large of 40 °F would be useful to a thermal analyst. Figure 6 shows that all of the engineering model data falls within the RSE prediction error band for the 100 DOE cases. This is not entirely unexpected since these cases were used to create the RSEs themselves. Nevertheless, it is useful to see that even for an RSE with a wide 3σ value, the general agreement between the RSE prediction and the engineering model is within 20 °F. Note that for perfect agreement, the data points would lie along the "truth line," indicating that the RSE and Thermal Desktop models were predicting the same temperature.

Table 4. Temperature Response 3σ Values

Node # (Submodel.###)	3-σ Value (Deg F)	Node # (Submodel.###)	3-σ Value (Deg F)
SOLARDEP.1014	25.0	SR4D1.30000	38.6
SOLARDEP.2014	17.7	SR4D2.30000	33.5
SOLARDEP.1114	28.7	SR4D3.30000	36.1
SOLARDEP.2114	13.1	SR4D4.30000	39.1
SMCOMM.11	14.0	SRCS1.4000	32.0
SMCOMM.21	3.5	SRCS2.60000	47.1
SMCOMM.31	16.9	SRCS3.50000	38.2
SMCOMM.41	27.3	SRCS4.2000	10.2
SMHGA.11	11.1	SMSADA1.7042	4.1
CMBKSHL.1004	29.7	SMSADA2.7002	5.3

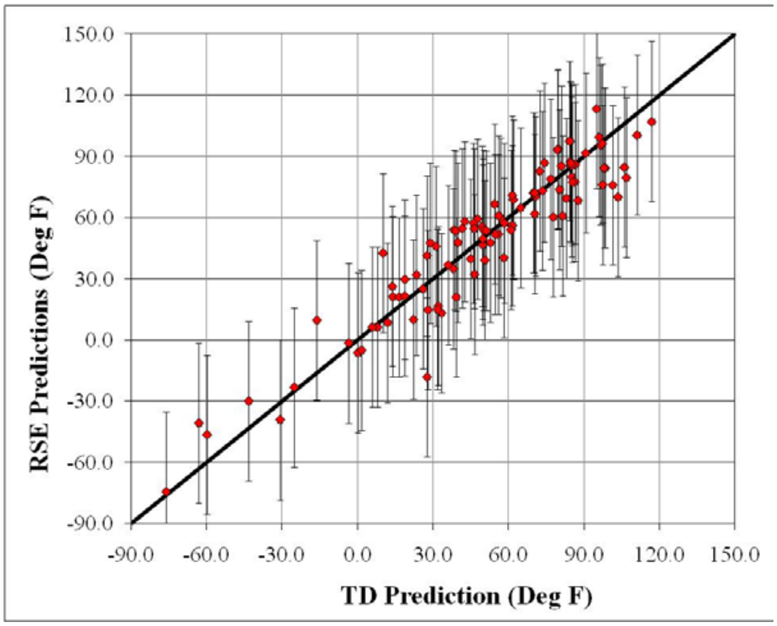

Figure 6. Comparison of Engineering Data to RSE Prediction for Node SR4D4.30000

IV. Results

With the RSEs now in hand, fourteen verification cases were run to test the predictive power of the RSEs. These cases were selected to provide a wide range of factor combinations that had not been run previously (see Table 5). The RSE predictions were complete within a matter of seconds. The Thermal Desktop runs took longer to complete. Like the previous runs, the Thermal Desktop runs performed a radiation analysis using 25,000 rays per node and a steady-state solution routine. One change was to shoot and additional 100,000 rays from the RCS and Auxiliary thruster submodels. This change was made based on feedback from an initial data review with the model developers that the additional rays would provide a better temperature response for those nodes. The Thermal Desktop model run took approximately 6 hours on a dual quad-core processor with 8GB of RAM.

Table 5. 14-Case Verification Matrix
Note that all values are normalized.

Case #	Yaw	Pitch	Roll	Beta	Env
1	1.00	1.00	1.00	1.00	0.80
2	0.20	0.60	1.00	0.40	-0.80
3	0.20	0.20	1.00	1.00	0.60
4	0.00	0.80	0.00	1.00	-1.00
5	0.00	0.60	0.80	0.20	-0.40
6	-0.20	0.20	0.20	0.00	0.60
7	-0.40	0.80	0.20	0.00	-0.60
8	-0.40	0.40	-0.80	0.20	0.20
9	-0.40	0.40	-1.00	-0.20	0.40
10	-0.60	0.80	-0.80	0.60	-0.60

The results show varying degrees of agreement. In some instances, both the RSE and Thermal Desktop predictions are nearly identical, while in other instances the predictions are off by up to 100 °F. It is obvious that a 100 °F error is completely unacceptable. However, in most cases, the disagreement is < 20 °F on average. Figure 7 shows an example of one node where the RSE performed particularly well. Note that all but one of the cases lie within the $\pm 3\sigma$ value. This is encouraging given the fact that the RSE predictions at the hot and cold extremes match quite well with the Thermal Desktop predictions.

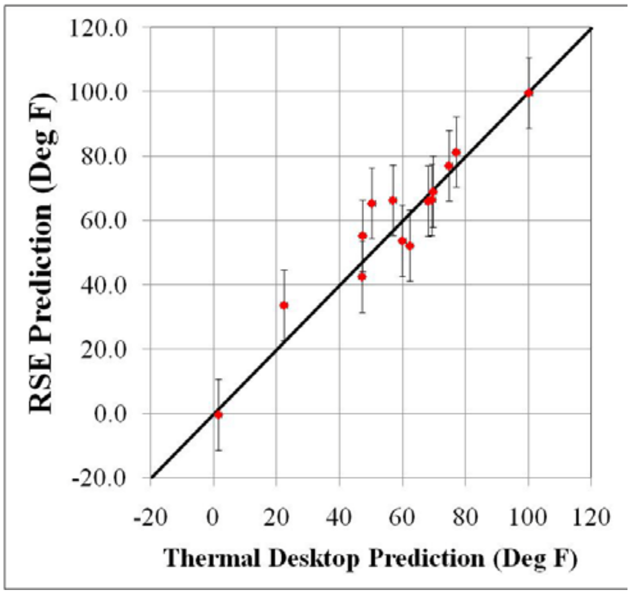

Figure 7. Comparison of Thermal Desktop Prediction to RSE Prediction for Node SMHGA.11 for the 14 Checkout Cases

Figure 8 shows one of the cases with a large disagreement (~80 °F) for one of the data points. This particular node also has several instances where the Thermal Desktop prediction does not fall with the RSE predictions $\pm 3\sigma$ value.

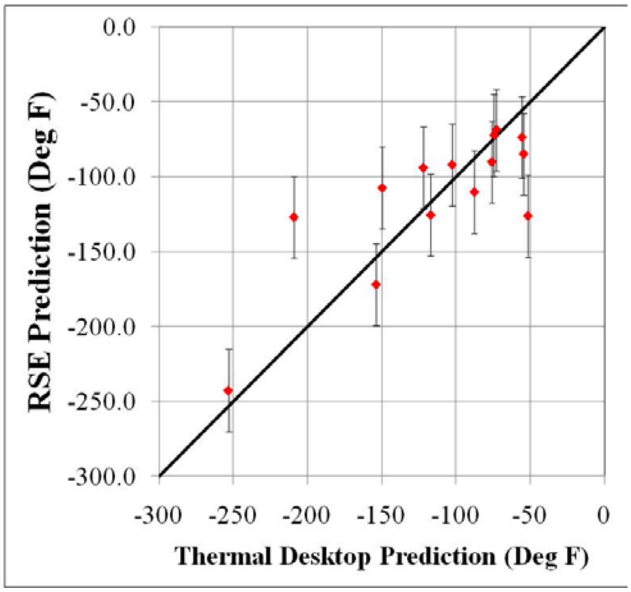

Figure 8. Comparison of Thermal Desktop Prediction to RSE Prediction for Node SMCOMM.41 for the 14 Checkout Cases

V. Conclusions & Additional Work

The above work does not irrefutably prove that the DOE/RSM approach can be applied to on-orbit thermal analysis. However, it does show the potential that this technique can be used successfully. Further work is needed to refine the development of the RSEs to ensure that they are valid over the entire range of factor combinations. The initial agreement of the RSEs with the DOE data is very promising, although the lack of consistent agreement with the verification cases is disappointing.

Preliminary reviews of this work reveal several areas for improvement and additional work. These include performing transient runs of the system to measure orbital minimum and maximum temperatures for an entire submodel rather than a specific node. This may lead to better RSE agreement. Also, a suggestion was made to shoot a larger number of rays to ensure the proper radiation heat exchange is accounted for. Finally, the integrated ISS and Orion models represent a very complex vehicle. Applying this technique to a simpler spacecraft design may also improve the RSE performance.

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