AN IMPROVED THERMAL MODEL CORRELATION PROCESS USING VERITREK'S REDUCED-ORDER MODELING SOFTWARE

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ABSTRACT

Engineering computer-aided design models are often based on an assortment of estimated input parameters. Specifically for thermal models, this may include handbook conductance values, or vendor specified optical or thermophysical property values, to name a few. It can be challenging to determine a combination of model parameter values that accurately predict reality; and to remedy this, engineering teams go through a process of correlating the model to measured test data obtained in the lab. Often, model correlation processes involve institutional knowledge and an iterative "guess and check" method that can become time-consuming and costly. Veritrek's Correlation Analysis feature provides a new approach to correlating thermal models to test data by using reduced-order modeling to explore thousands of parameter combinations in a few seconds. By first creating a reduced-order form of the high-fidelity model, the reduced-order model (ROM) can be used to quickly find multiple solutions that match model outputs to test data; thus, providing a way to intelligently improve the accuracy of the high-fidelity model, and leading to a deeper understanding of the relationship between model inputs and outputs.

Engineers at Ball Aerospace used the Veritrek software to help determine key parameter values that made model outputs match test data for an Internal Research and Development (IRAD) effort involving cryo instruments. Tasked to correlate a Thermal Desktop® model to ten unique test configurations, Veritrek's Correlation Analysis feature was used to quickly find multiple solutions that met Ball's correlation criteria (+/- 3K for ambient sensors and +/- 0.5K for cryo sensors) and provided insight into the best combination of parameter values to use. The correlation effort was split into three different sections to correlate the temperatures of 15 sensors and heat flow calculations. By splitting the correlation effort into three sections and using Veritrek, results could be focused, ROM generation time could be reduced, and additional exploration of each section's sensitivities could be performed. With Veritrek, over 20,000 combinations of parameter values were quickly explored and produced a few dozen viable solutions for correlating the Thermal Desktop® model. These viable solutions were then independently evaluated to determine the best solution to use. The final selected values allowed the correlated thermal model to meet the goal criteria for all test configurations. In total, this model correlation effort would have typically taken an estimated 3-4 weeks to

complete; but with Veritrek, a best solution was determined in an automated and repeatable fashion within a few days. Not only did the Veritrek approach save time, but it provided much more confidence in the chosen best solution.

NOMENCLATURE, ACRONYMS, ABBREVIATIONS

FOP	Factor of Performance
GFAC	Conductance factor applied to thermal joints
GFOP	Group Factor of Performance
Htr	Heater
IRAD	Internal Research and Development
QFAC	Heater power factor applied to ambient shroud heaters
ROM	Reduced-Order Model
RSS	Root sum square
TD	Thermal Desktop®
ε^*	Effective emissivity of multilayer insulation

INTRODUCTION

Uncorrelated thermal models are often based on an assortment of uncertain input parameters. Examples include interface conductance based on handbook values and estimated insulation ε^* values. Because of this, it is hard to know which combination of parameter values accurately predict reality. To overcome this, thermal model correlation uses test results to better estimate and validate these uncertain inputs. This process commonly involves institutional knowledge and an iterative method that quickly becomes time-consuming and costly. The process of performing a thermal model correlation to test data can be an intricate and arduous task. Frequently, the number of parameters that must be adjusted to match model outputs to measured values can be quite large and determining the interrelated impacts of these parameters on the output relies more on intuition and guess-and-check methodologies rather than systematic variation.

To overcome these challenges, reduced-order models (ROMs) can be used. ROMs provide computationally efficient surrogates of high-fidelity thermal models (e.g., Thermal Desktop® models). The Veritrek software is a commercially available solution for developing and using ROMs. Specifically, the Veritrek correlation routine has recently been made available, and can be used to define the desired model outputs and automatically suggest various combinations of input parameters to meet these conditions. An approach for creating these surrogates using efficient sampling and data fitting was developed and successfully applied to a Ball cryogenic thermal model. This approach provides numerous benefits including computational speed and greater confidence in final solutions. Leveraging this speed, ROMs can be used to calibrate thermal model parameters to experimental test data using an automated, repeatable, and simple methodology. This paper provides a real-world example of using the Veritrek software to correlate a Thermal Desktop® (TD) model to a Ball Aerospace test set up.

THERMAL MODEL AND TEST SETUP

At Ball Aerospace in Boulder, CO, an independent research and development (IRAD) test was performed to measure temperature and heat transport capabilities of a cryogenic configuration. Simultaneously, a Thermal Desktop® model of the test set up was created to provide additional insight into the configuration's performance and its applicability to existing and future programs. One goal of the IRAD project was to correlate the thermal model to various test configurations, thereby gaining confidence that the model was an accurate indicator of real-world performance. The test set up consisted of a thermal vacuum chamber with an actively controlled ambient shroud that served as the effective sink environment (Figure 1). Several test components were then assembled to transition from ambient conditions to an intermediate shroud, and finally to a cryogenic area covered with multilayer insulation.

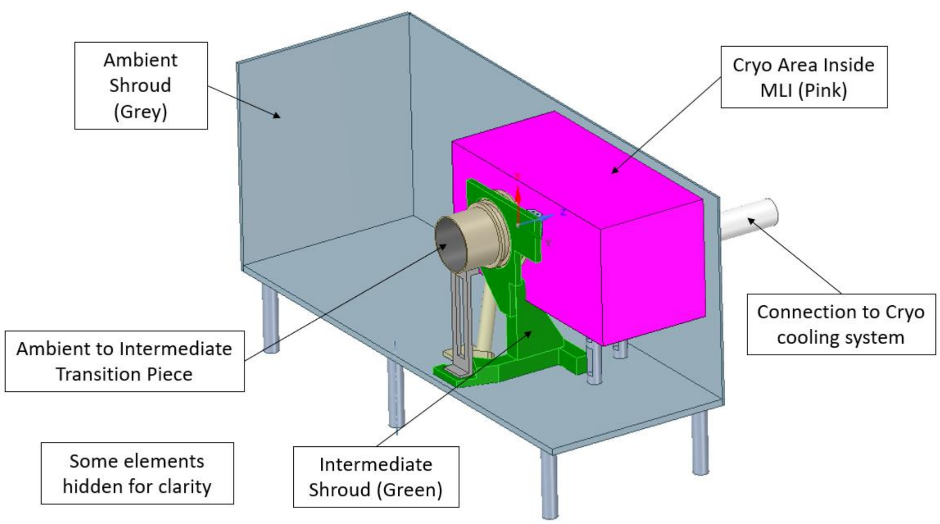


Figure 1. Ball Aerospace IRAD Test Configuration.

During the test execution, 10 different test cases were defined, as outlined in Table 1. Due to proprietary concerns, detailed test values and data have been replaced with generic or normalized values. Data collected from the various test points served as the measured or calculated test output which the thermal model needed to faithfully reproduce after correlation. Table 2 contains a listing of the pertinent data values, both measured (14 temperatures) and calculated (1 heat rejection rate).

Table 1. Ball Aerospace IRAD Test Cases

Case Designator	Cryo Setting	Intermediate Shroud	Ambient Shroud	Htr #1	Htr #2
Test_Case_01	Low	Point #1	Low	Low	Low
Test_Case_02	Low	Point #2	Low	Low	Low
Test_Case_03	Low	Point #3	Low	Low	Low
Test_Case_04	Low	Point #4	Low	Low	Low
Test_Case_05	Low	Point #2	Low	Low	Low
Test_Case_06	Low	Point #2	Low	High	Low
Test_Case_07	High	Point #2	Low	Low	Low
Test_Case_08	Low	Point #2	Low	Low	High
Test_Case_09	High	Point #1	Low	Low	Low
Test_Case_10	Low	Point #2	High	Low	Low

Table 2. Ball Aerospace IRAD Test Data

Data Name	Description
Htr #1 Temp 1, 2	Temperature sensors controlling heater #1 (only 1 used for ROM generation)
Htr #2 Temp	Temperature sensor controlling heater #2
Ambient Shroud Temp 1, 2, 3	Temperature sensors on ambient shroud
Intermediate Shroud Temp 1, 2	Temperature sensors on intermediate shroud
Cryo Temp 1 thru 6	Temperature sensors in the cryogenic area
Heat Rejection Rate	Calculated heat rejection rate through cryo system

The thermal model was created in Thermal Desktop®, Version 6.1. Model elements consisted of both TD primitives and meshed elements using TD Direct. Due to testing schedules and personnel availability, the thermal model was created after the test set up was complete and preliminary testing started. While not the preferred order, this sequence allowed the thermal model to accurately locate test sensors, heater elements, and other boundary conditions used during testing. The final model consists of 39 submodels, 4126 nodes, and the various heaters, heat loads, contactors, and conductors to thermally connect the model elements. The model run time for a steady state solution was less than 5 minutes.

The goal of the correlation was for the thermal model to recreate the test cases to within:

- Ambient Temp Sensors (> 200 K, qty. 8): within ± 3 K
- Cryogenic Sensors (< 200 K, qty. 6): within ± 0.5 K
- Calculated Heat Rejection Rate: within ± 10%

ROM DEVELOPMENT

ROMs provide computationally efficient surrogates of high-fidelity thermal models (e.g., Thermal Desktop® models). ROMs are often built for a singular reason: reducing development cycle times and costs; however, methods for building ROMs vary considerably. Methods include those that reduce the dimension of the underlying high-fidelity model. Examples include: projection-based methods [1, 2] and nodal reduction through lumped parameter methods [3]. Alternatively, ROMs can be built by interrogating the high-fidelity model, generating training data, and then creating a metamodel or statistical emulator by interpolating the observed data [4, 5]. An approach for creating a statistical emulator using efficient sampling and Gaussian process data fitting was developed and successfully applied to a broad range of spacecraft applications [6-10]. Called Veritrek, the developed approach provides numerous benefits, including computational speed and greater confidence in final solutions. Leveraging their speed, ROMs can be a useful tool for thermal model correlation.

The first step to successfully use Veritrek is to thoroughly understand the thermal model and its sensitivities related to the desired measured value. The Veritrek program offers a tremendous amount of power and insight, but an in-depth understanding of model hierarchy, functionality, and sensitivity is the cornerstone of a successful correlation effort. Therefore, the user needs to run various test cases to determine which model parameters cause the greatest amount of change in a desired output, and the appropriate ranges to generate the output values of interest. Without this level of understanding, the analyst will not be able accurately identify the appropriate input/output relationships for the correlation to succeed. Implementing the above philosophy, the start of the Ball IRAD correlation began with an overall inspection of the model and consideration of how the model and test data aligned. Because the test cases were held until steady state conditions were reached, it was unnecessary to run the thermal model in a transient solution mode, greatly reducing the model run time. Additionally, there were no moving or articulating components in the test set up and the same set up was used in all 10 test cases. This implies that a single set of radiation conductors can be calculated and applied to all the cases (i.e., optical property variation was not used as an input factor). After running several test cases and discussing results, other patterns emerged which helped to guide the correlation effort. Namely, that the model could be broken into three distinct sections. Each section could be studied sequentially and then built upon for the next correlation effort.

- Cryogenic area
- Intermediate shroud
- Ambient shroud

The rationale for this breakdown is that the cryogenic area is protected by high performance multilayer insulation and supported by low thermal conductivity materials from the remaining test set up. Therefore, the external conditions can be treated as constant boundary conditions while the cryogenic thermal interactions are studied. While these boundary conditions may vary for different test conditions, how those boundary conditions vary is not important to the cryogenic area. Once the cryogenic area is functional, the intermediate shroud area can be studied in the same manner, using the cryogenic results and holding the ambient shroud at fixed value. Finally, the ambient shroud can be addressed. The authors also postulate that the inverse approach can be used (start with the ambient shroud and work in towards the cryogenic area). Another reason for splitting up the correlation effort into three sub-efforts is to expedite the run time in Veritrek and TD. Because the number of Veritrek ROM training runs generally increases with 2^n, where n is the number of input variables, focusing on a smaller number of input variables allows faster completion times when creating the ROM. As detailed below, a total of 13 input parameters were eventually selected, which may have required thousands of training runs to obtain an accurate ROM. By understanding the model and subdividing the correlation effort into three individual chunks, the largest number of training runs executed was 128.

<u>Sub-effort 1: Cryogenic Area ROM Creation</u>

The first area for study was the cryogenics area. In this section, there were five temperature measurements identified as outputs, and six joints as inputs (Figure 2). The temperature sensors were located at various points to monitor heat flow through the system and calculate the heat rejection rate into the cryogenic cooler system. Within the model, specific thermal nodes were selected to represent the sensor locations. The overall heat rejection rate to the cryogenic system was also of interest but was not selected as an output because if the temperature values could be reliably predicted by the thermal model, then the resulting heat rejection rate should fall out from resulting calculations.

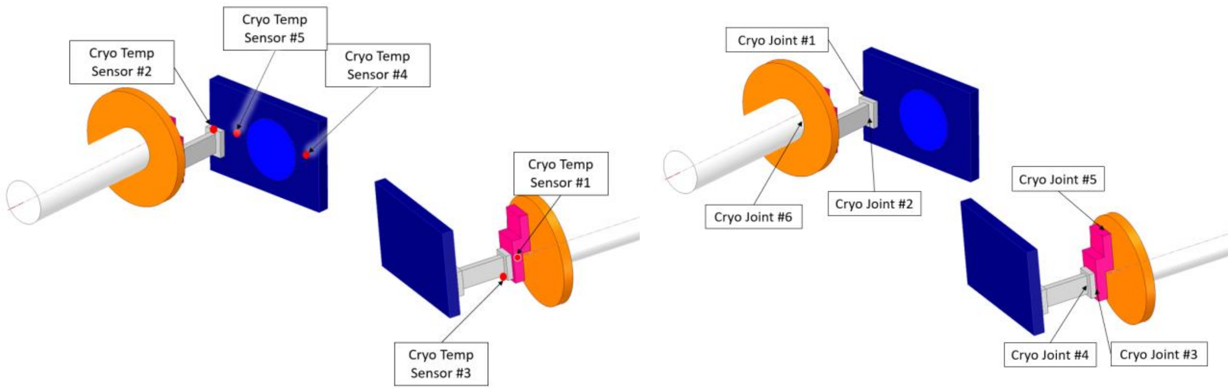


Figure 2. Cryogenic Area Output and Input Locations.

Knowing the areas of the model where the correlation would be focused, the model was then inspected to determine what parameters would influence these predictions. In between the heat source and the cryogenic sink, a total of 6 bolted joints were identified as critical to the heat path. These joints were dry joints with no thermal interface material or thermal grease to enhance heat transfer. Initial model runs were conducted using standard conductance values based on the size and quantity of fasteners used. An individual conductance factor (GFAC) was then applied to each interface which allowed that joint's overall conductance to be manipulated by Veritrek as an input. Additional test runs were conducted to determine the range of the GFACs for each joint and establish an estimate of a midpoint. This is an important step because the Veritrek ROM will be most accurate near the center of the input factor range and less accurate near the edges of the design space. By seeding the model with factors centered near the suspected answer and making the factor range wide enough to cover the known test conditions, the final correlation values will be much easier to obtain. Table 3 contains a listing of inputs and outputs used in the cryogenic area.

Table 3. Cryogenic Area Inputs and Outputs

Input	Description	Nominal	Min	Max
Cryo_GFAC1	Unitless scaling factor on cryo joint #1 conductance	0.1	0.01	1.00
Cryo_GFAC2	Unitless scaling factor on cryo joint #2 conductance	1.0	0.1	1.5
Cryo_GFAC3	Unitless scaling factor on cryo joint #3 conductance	1.0	0.1	1.5
Cryo_GFAC4	Unitless scaling factor on cryo joint #4 conductance	3.0	1.0	5.0
Cryo_GFAC5	Unitless scaling factor on cryo joint #5 conductance	2.0	1.0	4.0
Cryo_GFAC6	Unitless scaling factor on cryo joint #6 conductance	3.0	1.0	5.0
Output	**Description**	**Units**		
Cryo_Temp_1	Cryo area sensor #1	K		
Cryo_Temp_2	Cryo area sensor #2	K		
Cryo_Temp_3	Cryo area sensor #3	K		
Cryo_Temp_4	Cryo area sensor #4	K		
Cryo_Temp_5	Cryo area sensor #5	K		

With the inputs and outputs defined, the Veritrek Creation Tool can now be engaged. Following the Creation Tool user's guide, a ROM was designed using the defined parameters. For the outputs, the mean temperature value option was selected since only steady state runs were performed. Because the ROM used 6 input parameters, Veritrek recommended 64 training cases be created. However, the analyst elected to increase this number to 128 to provide additional data for ROM generation. Since the thermal model is relatively small, this number of cases was easily run overnight, and the ROM generated the following day. Figure 3 shows the results from the ROM testing performed in the Creation Tool (temperature values have been normalized). The ROM predictions were deemed acceptable, and no additional ROM improvement was performed.

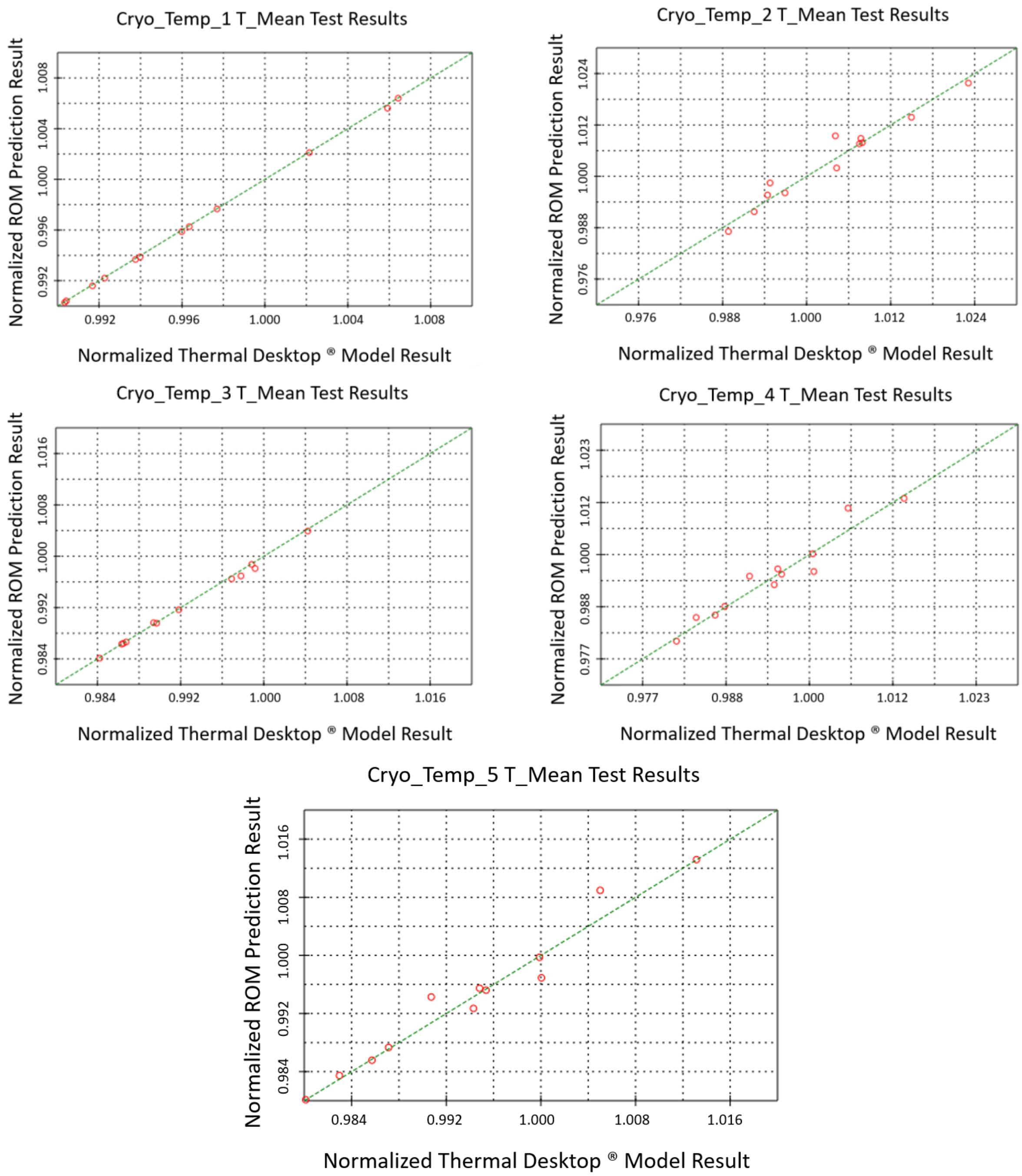


Figure 3. Cryo Area Veritrek Output Test Results.

<u>Part 2: Intermediate Shroud ROM Creation</u>

A similar process was followed to create the ROM for the intermediate shroud. Figure 4 shows the relevant components for this part of the model and identifies the main bolted joints that provided the thermal connections between the elements. As in the previous case, a GFAC variable was applied to the nominal conductance value based on the size and quantity of fasteners used.

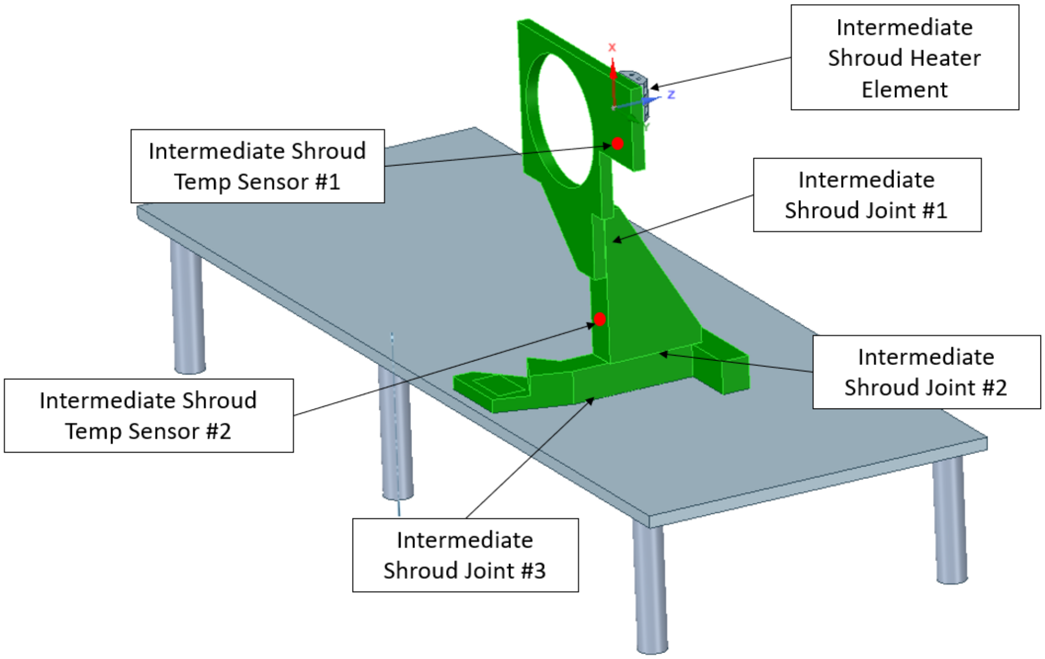


Figure 4. Intermediate Shroud Input and Output Locations.

An important difference for the intermediate shroud is the presence of a heater block on the upper plate. This heater was used to drive the intermediate shroud to different test conditions (see Table 4), and the heater power level at each test point was recorded as part of the test. While the heater power itself could have been selected as a variable in the ROM, it was decided to used test cases 2, 3, and 4 as individual cases with the measured heater power applied to the appropriate case. While this decision triples the number of cases needed to be run in the ROM training phase, this was considered better than the 2^n increase when adding the additional variable. The two temperature sensors located on the intermediate shroud were selected as the ROM outputs. Table 4 lists the relevant inputs and outputs for this ROM.

Table 4. Intermediate Shroud Inputs and Outputs

Input	Description	Nominal	Min	Max
Int_Shroud_GFAC1	Unitless scaling factor on intermediate shroud joint #1 conductance	0.5	0.1	1.0
Int_Shroud_GFAC2	Unitless scaling factor on intermediate shroud joint #2 conductance	0.5	0.1	1.0
Int_Shroud_GFAC3	Unitless scaling factor on intermediate shroud joint #3 conductance	0.35	0.1	1.0
Test Case	Selection of 3 test cases with different intermediate shroud heater power levels	02	03	04
Output	**Description**	**Units**		
Int_Sheild_Temp_1	Intermediate shroud area sensor #1	K		
Int_Sheild_Temp_2	Intermediate shroud area sensor #2	K		

A total of 16 ROM training cases were defined in the Creation Tool for training purposes. This was double the number of suggested cases ($2^n = 8$), but the extra run time was acceptable due to the model performance. Since there were 3 different cases selected, the total number of training cases run was 48 since each of the 16 cases was run in each of the 3 test conditions. Results from the ROM testing are shown in Figure 5 and no additional ROM optimization was considered necessary.

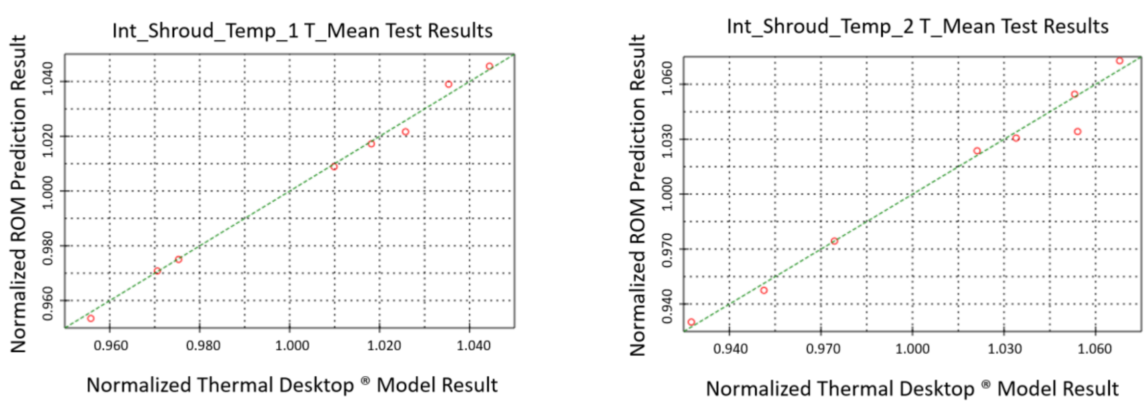


Figure 5. Intermediate Shroud Veritrek Output Test Results.

Part 3: Ambient Shroud ROM Creation

The final section considered for ROM creation was the ambient shroud. The ambient shroud temperature is controlled by several heaters on the system. Unlike the previous ROMs, the inputs varied for this ROM were the heater powers applied to the heater elements. This approach was selected since the test value heater powers were not directly recorded for these heater elements. However, applying the correct amount of heat input at the correct location is needed to drive the ambient shroud to its correct temperature readings and gradient. Test runs using the thermal model were conducted to determine appropriate baseline heater powers and QFACs (heater power scaling factor) for each heater element. The ROM creation set up for the ambient shroud consisted of 4 different QFAC input factors, and 5 different output factors. These are shown in Figure 6 and listed in Table 5.

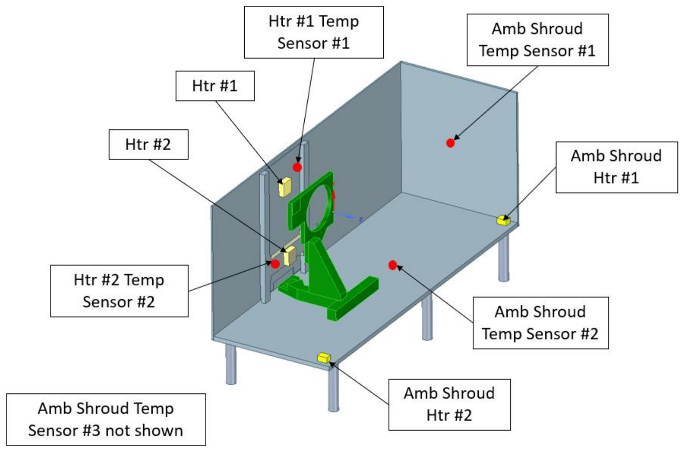


Figure 6. Ambient Shroud Input and Output Locations.

Table 5. Ambient Shroud Inputs and Outputs

Input	Description	Nominal	Min	Max
Amb_Shroud_QFAC1	Unitless scaling factor on ambient shroud heater #1 power	1.0	0.6	1.4
Amb_Shroud_QFAC2	Unitless scaling factor on ambient shroud heater #2 power	1.0	0.6	1.4
Amb_Shroud_QFAC3	Unitless scaling factor on heater #1 power	1.0	0.9	1.1
Amb_Shroud_QFAC4	Unitless scaling factor on heater #2 power	1.0	0.8	1.7
Output	**Description**	**Units**		
Amb_Shroud_Temp1	Ambient shroud sensor #1	K		
Amb_Shroud_Temp2	Ambient shroud sensor #2	K		
Amb_Shroud_Temp3	Ambient shroud sensor #3	K		
Htr#1_Temp1	Heater #1, Sensor #1	K		
Htr#2_Temp1	Heater #2 sensor	K		

A total of 32 ROM training cases were defined in the Creation Tool for training purposes. This was double the number of suggested cases ($2^n = 16$), but the extra run time was acceptable due to the model performance. Results from the ROM testing are shown in Figure 7, and no additional ROM optimization was considered necessary.

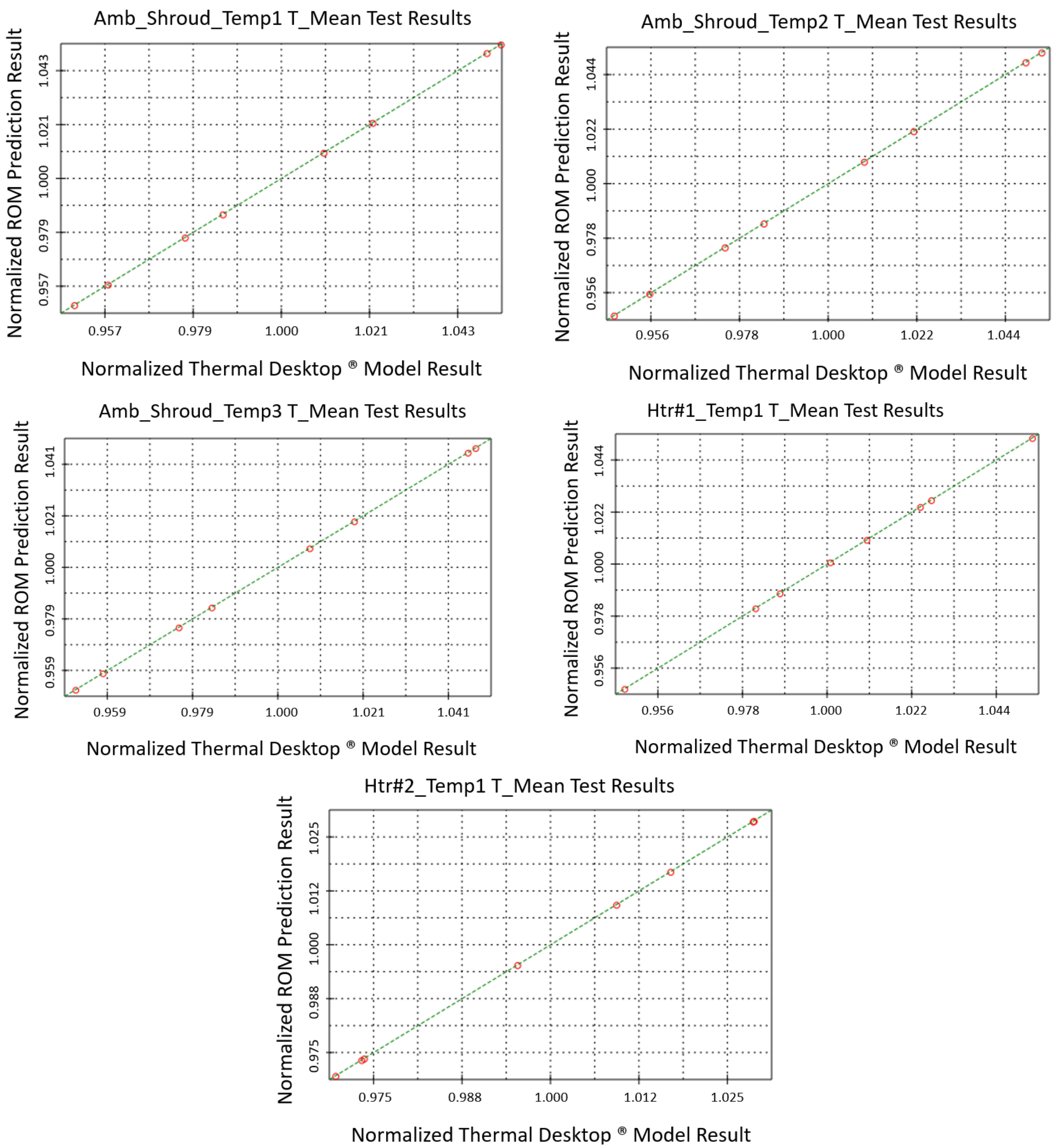


Figure 7. Ambient Shroud Veritrek Output Test Results.

RESULTS

The thermal model correlation method in this paper essentially takes the traditional thermal model correlation approach and leverages the speed of ROMs to iterate thousands to millions of times in seconds. The Veritrek thermal model correlation approach can be applied to most any thermal model assuming you can appropriately convert it into a ROM and requires just a few simple steps. This approach can also be used to correlate against a collection of test results (e.g., hot-soak, cold-soak, etc.).

First, ROM inputs are identified as either fixed or correlation factors. Fixed input factors are those that remain static during a given test (e.g., hot soak heater power) and are therefore given a test-specific value during correlation. Correlation input factors are those that are uncertain, and we want to correlate. These input factors are given a range for us to correlate within across all test results. Next, ROM output responses are selected that will be correlated to. For each ROM output response and test case, both measured values and margins are allowed. Margins can be used to help filter out solutions.

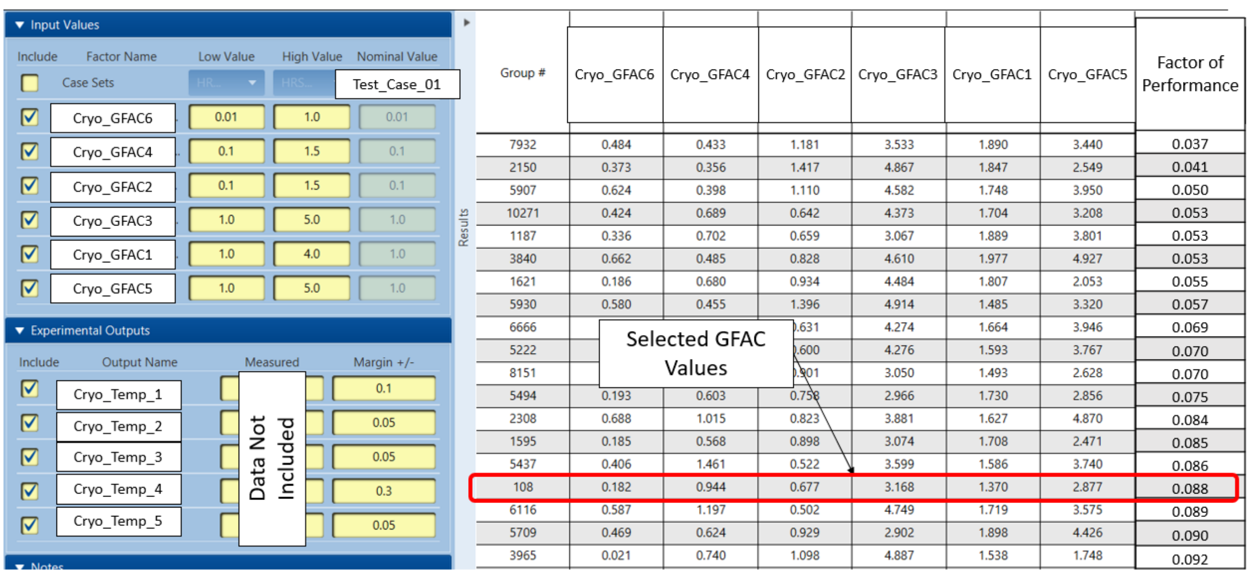
Once inputs and outputs are setup, the iterative correlation process can begin. For each iteration, a random set of input factors is selected and quickly processed using the ROM. ROM outputs are provided and compared against measured values for all test cases. A performance metric is calculated by taking the root sum square (RSS) of the difference between measured and ROM values. A Group Factor of Performance (GFOP) metric for the trial is calculated by summing the RSS values (root sum square between ROM and Measured values) across all output responses and tests (Equation 1). Currently, the GFOP equally weights the contributions from all outputs and tests. For example, cold- and hot-tests contribute the same to GFOP although hot-tests typically provide richer test information.

$$GFOP = \sum_{t}^{Test} \sum_{o}^{Output} \sqrt{(ROM_{t,o} - Measured_{t,o})^2} \qquad 1$$

Leveraging the speed of ROMs, this process can be repeated very quickly. In fact, thousands to millions of iterations can be completed in just a few seconds using typical laptop/desktop processing power. This method then provides not just one but a collection of viable solutions, each with a unique GFOP. The solutions with the lowest GFOP could be considered the 'best' although the collection of solutions provide opportunity for more advanced correlation analysis and better understanding.

The advantage of the Veritrek thermal model correlation approach is its ability to systematically identify viable solutions that meet correlation requirements. Further, this method provides not just a single, but a collection of viable solutions. Additionally, this method takes very little user intervention; both ROM creation and model correlation are relatively 'hands-off'. The most significant disadvantage is the computational expense of ROM creation. As model complexity grows, so does this expense and in some cases could make this method too costly. In many cases though, the Veritrek thermal model correlation can provide time savings; however, the biggest value comes from having a collection of viable solutions which provides more insight, confidence, and reduced risk.

With the three Ball IRAD ROMs created, they can now be analyzed in Veritrek's Exploration tool, specifically using the Correlation Analysis feature described above. The first ROM analyzed was the cryogenic area. In the first attempt, results for all 5 cryo area temperature sensors in Test_Case_01 were entered into the Correlation Analysis tool and all 6 GFAC inputs were left active. Recall that the goal was to correlate all cryogenic sensors within ±0.5 K. Therefore, this was the margin applied to all sensors and 20,000 ROM simulations were added to the correlation run. This produced over 5,000 results. In other words, for the given sensor and margin values, there were over 5,000 combinations of the 6 conduction factors that the 20,000 ROM simulations found that met those conditions. At this point, an assessment of the relative importance of each sensor value was made and margins were decreased until results were narrowed down. This is another benefit of understanding the model, which sensors/sensitivities are most important, and how to tailor the Veritrek analysis based on this level of model knowledge. After tweaking the allowed sensor margins, the Correlation Analysis tool produced 18 different combinations of GFAC values that met correlation goal (Figure 8).



Group #	Cryo_GFAC6	Cryo_GFAC4	Cryo_GFAC2	Cryo_GFAC3	Cryo_GFAC1	Cryo_GFAC5	Factor of Performance
7932	0.484	0.433	1.181	3.533	1.890	3.440	0.037
2150	0.373	0.356	1.417	4.867	1.847	2.549	0.041
5907	0.624	0.398	1.110	4.582	1.748	3.950	0.050
10271	0.424	0.689	0.642	4.373	1.704	3.208	0.053
1187	0.336	0.702	0.659	3.067	1.889	3.801	0.053
3840	0.662	0.485	0.828	4.610	1.977	4.927	0.053
1621	0.186	0.680	0.934	4.484	1.807	2.053	0.055
5930	0.580	0.455	1.396	4.914	1.485	3.320	0.057
6666	[illegible]	[illegible]	.631	4.274	1.664	3.946	0.069
5222	[illegible]	[illegible]	.600	4.276	1.593	3.767	0.070
8151	[illegible]	[illegible]	.901	3.050	1.493	2.628	0.070
5494	0.193	0.603	0.758	2.966	1.730	2.856	0.075
2308	0.688	1.015	0.823	3.881	1.627	4.870	0.084
1595	0.185	0.568	0.898	3.074	1.708	2.471	0.085
5437	0.406	1.461	0.522	3.599	1.586	3.740	0.086
108	0.182	0.944	0.677	3.168	1.370	2.877	0.088
6116	0.587	1.197	0.502	4.749	1.719	3.575	0.089
5709	0.469	0.624	0.929	2.902	1.898	4.426	0.090
3965	0.021	0.740	1.098	4.887	1.538	1.748	0.092

Figure 8. Cryogenic Area Veritrek Correlation Analysis Results.

These combinations were then inspected to determine if any trends or groupings could be identified. This inspection led to general groups of GFAC values being run in the TD model. The TD model outputs for the nodes representing the test temperatures were then compared against the measured test data. The final set of selected GFAC values most closely aligns with Group #108, which had a Factor of Performance (FOP) of 0.088. Although this was not the lowest FOP of the possible solutions, these GFAC values produced consistently accurate TD model results for all 10 test cases. In fact, the TD model output temperatures are all meet the correlation goal of ±0.5 K, apart from one test point. Investigation revealed this point to be a data acquisition error. The final GFAC values are shown in Table 6 and the sensor error for all 10 test cases is plotted in Figure 9.

Table 6. Cryogenics Area Selected GFACs

Factor	Value
Cryo_GFAC1	1.37
Cryo_GFAC2	0.68
Cryo_GFAC3	3.17
Cryo_GFAC4	0.94
Cryo_GFAC5	2.88
Cryo_GFAC6	0.18

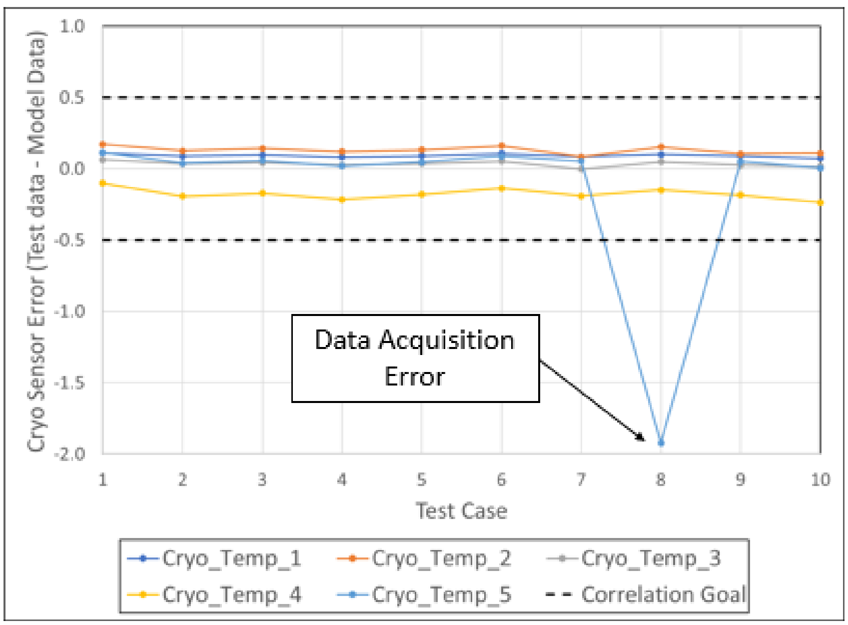


Figure 9. Cryogenic Sensor Error for All Test Cases.

The Correlation Analysis process was next repeated for the intermediate shroud. The main difference is that 3 different test cases were used as correlation runs in the Veritrek Exploration tool, rather than a single case. This was to align the data from the three different test cases with the three separate model cases used in the ROM development. The correlation goal for the intermediate shroud area was ±3 K. Data from each test case were added to the appropriate correlation run and 20,000 ROM simulations were performed. The correlation tool suggested over 4,500 GFAC combinations which would meet the correlation goals. Once again, the margin was narrowed until only 12 combinations remained. All were evaluated in the TD model and a preferred set of GFAC values was selected (Figure 10).

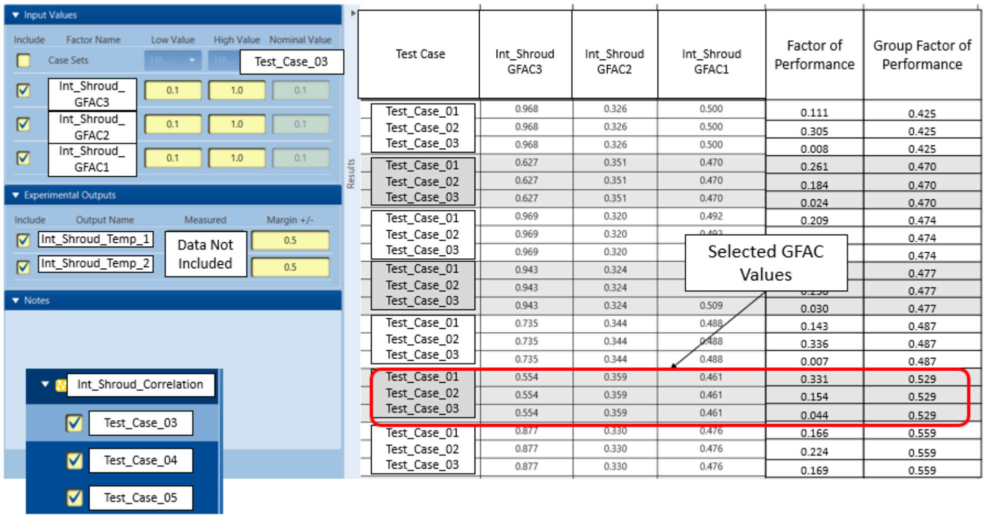


Figure 10. Intermediate Shroud Veritrek Correlation Analysis Results.

These GFAC values (Table 7) were run in all 10 test cases and the difference between the test and model data are shown in Figure 11. The model predictions are within ±1 K, which is well within the ±3 K goal value. Once again, the selected set of factors did not have the highest GFOP or individual FOP, yet the results within TD and discussion with other team members lead these values to be implemented.

Table 7. Intermediate Shroud Selected GFACs

Factor	Value
Int_Shroud_GFAC1	0.461
Int_Shroud_GFAC2	0.359
Int_Shroud_GFAC3	0.554

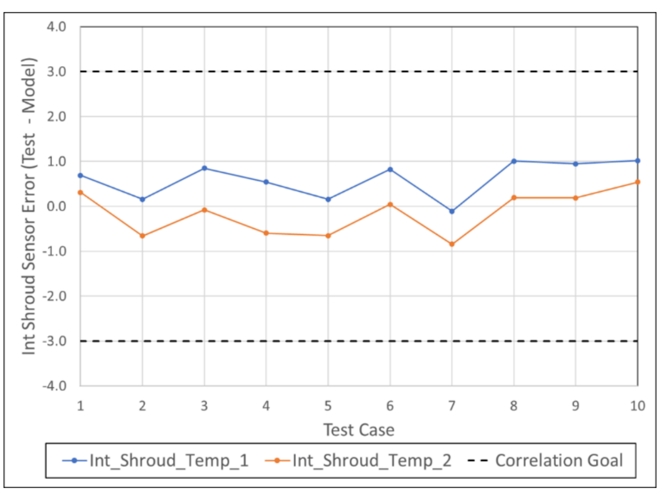


Figure 11. Intermediate Shroud Sensor Error for All Test Cases.

Finally, the ambient shroud ROM was evaluated in the Exploration Tool's Correlation Analysis. Unlike the previous two examples, this correlation resulted in different QFAC values for the various test cases. However, this was expected since the heater power needs to change in each configuration in order to meet the measured test temperatures. In retrospect, this ROM could have been more accurately created to replicate the test conditions. Hence, the ambient shroud correlation effort in Veritrek served as a guide to determine QFAC values for the 10 different test cases. While not as precise as the correlation efforts for the cryogenic area and the intermediate shield, the Veritrek tool did help to understand the interactions between the different QFAC values, which greatly facilitated the final QFAC value selections (Table 8). The TD model predictions for all 10 cases is shown in Figure 12 and meet the ±3 K goal value.

Table 8. Ambient Shroud Selected QFACs

Test	Amb_Shd QFAC1	Amb_Shd QFAC2	Amb_Shd QFAC3	Amb_Shd QFAC4
01	1.035	1.050	0.959	1.000
02	0.800	0.800	0.920	1.000
03	0.650	0.700	0.920	1.000
04	0.550	0.550	0.897	1.000
05	0.800	0.800	0.920	1.000
06	0.750	0.750	1.480	1.000
07	0.800	0.800	0.920	1.000
08	0.775	0.775	0.920	1.000
09	0.775	0.775	0.897	1.000
10	1.300	1.300	0.739	1.000

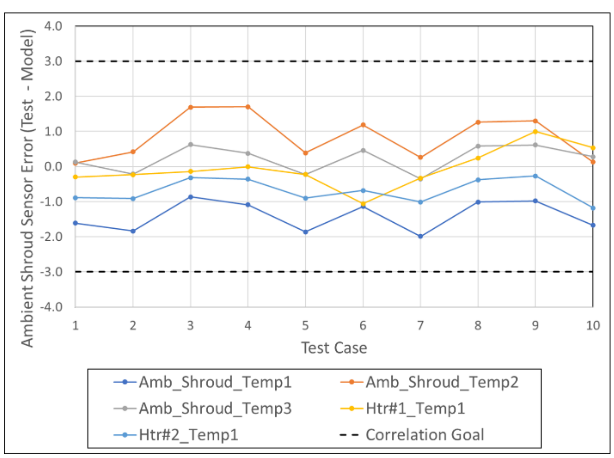


Figure 12. Ambient Shroud Sensor Error for All Test Cases.

A final comparison of the heat rejection rate was also performed. This was to determine the amount of energy removed from the test system by the cryogenic cooling equipment. Because of the excellent cryogenic area temperature correlation, the heat rejection rate was able to easily meet the ±10% goal, with predictions within ±3% of the value calculated based on test data (Figure 13). This provided additional confidence that the final TD model configuration was an accurate representation of the test set up.

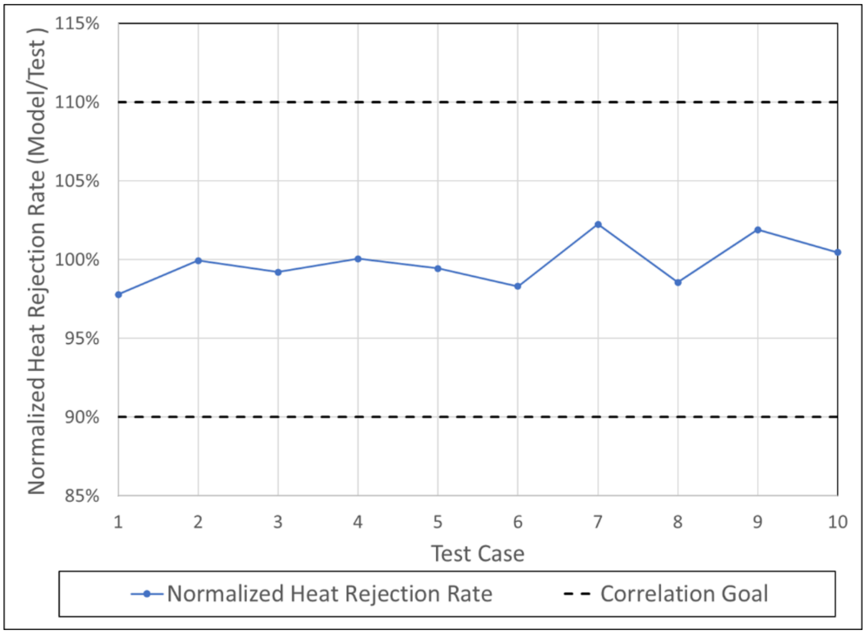


Figure 13. Normalized Cryogenic Heat Rejection Rate for All Test Cases.

Not discussed above was the timeframe over which these correlation efforts occurred. Each individual ROM creation and Correlation Analysis effort took on the order of 1-2 days. The overall correlation effort lasted over a period of weeks, but the speed with which the ROMs were created and analyzed in the Exploration tool enabled more in-depth understanding of the interactions of the various input parameters. It is estimated that each individual correlation effort could have taken 3-4 weeks if traditional guess-and-check approaches were used.

It is also noteworthy that in none of the correlation efforts above was the “best” solution recommended by Veritrek (per the FOP and/or GFOP) used as the final implemented values in the TD model. This is because all results were scrutinized to determine which values best worked in the TD model itself to accurately reproduce the test data. Future users are cautioned that they should similarly evaluate results and be cognizant of model performance and personal biases. Discussing the Veritrek and TD results with peers and having an intimate knowledge of the model hierarchy will greatly enhance the odds of success.

CONCLUSIONS

In conclusion, engineers at Ball Aerospace successfully used the Veritrek software to help correlate their thermal model, for an Internal Research and Development (IRAD) effort involving cryo instruments, to test data. By splitting the correlation effort into three sections and using Veritrek, results could be focused, ROM generation time could be reduced, and additional exploration of each section's sensitivities could be performed. With Veritrek, over 20,000 combinations of parameter values were quickly explored and produced a few dozen viable solutions for correlating the Thermal Desktop® model. These viable solutions were then independently evaluated to determine the best solution to use. The final selected values allowed the correlated thermal model to meet the goal criteria for all test configurations. In total, this model correlation effort would have typically taken an estimated 3-4 weeks to complete; but with Veritrek, a best solution was determined in an automated and repeatable fashion within a few days. Not only did the Veritrek approach save time, but it provided much more confidence in the chosen best solution.

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