Optimizing Thermal Radiator Designs Using the Veritrek Software

Lina L. Maricic & R. Scott Miskovish
(ATA Engineering, Inc.)
Jacob A. Moulton & Derek W. Hengeveld
(LoadPath, Inc.)

Presented By
Lina L. Maricic
Jacob Moulton

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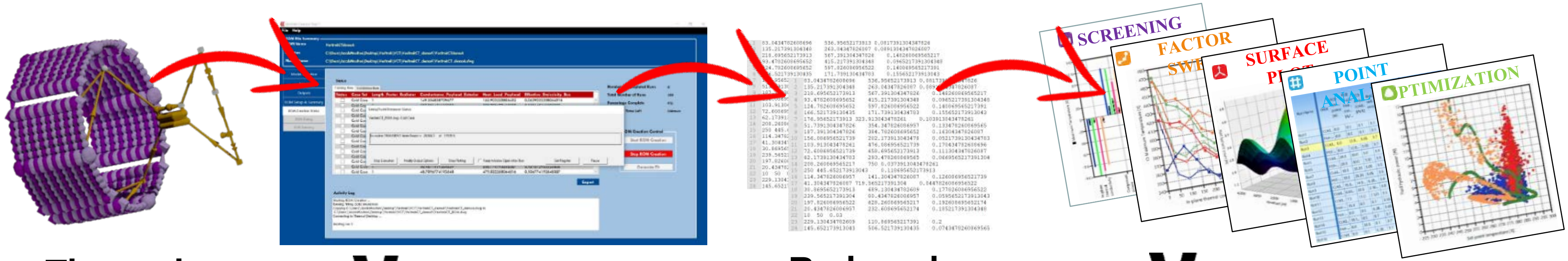
Objectives

- Find an alternative method to design thermal radiators of a spacecraft
  - Traditional method: numerous simulations using detailed thermal math models
  - Alternative method: machine learning to create reduced-order models
- One alternative method: using the Veritrek software to optimize thermal radiator designs
  - Using Veritrek to create a reduced-order model (ROM) and explore thermal design space
  - Find optimal design solutions or radiator sizes

Veritrek Software Overview

- Veritrek is a reduced-order thermal modeling software suite built to work with Thermal Desktop®
  - Creation Tool: allows you to easily create a ROM directly from a Thermal Desktop® model
  - Exploration Tool: uses the ROM, and allows for rapid thermal analysis and easy results viewing



Thermal Desktop®

VERITREK CREATION TOOL

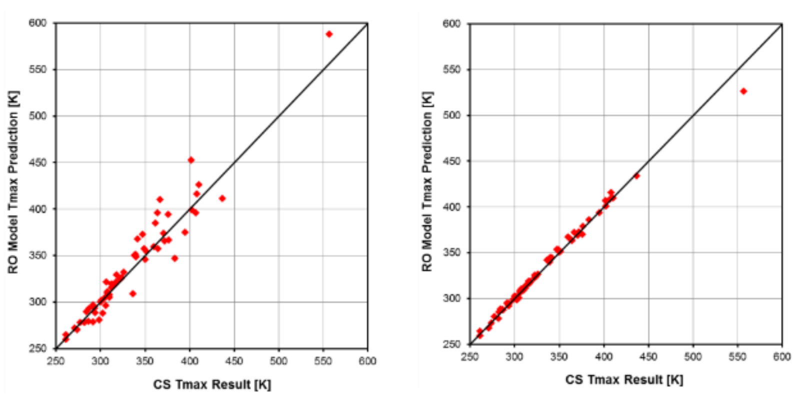
Reduced-Order Model

VERITREK EXPLORATION TOOL

Veritrek's Reduced-order Model

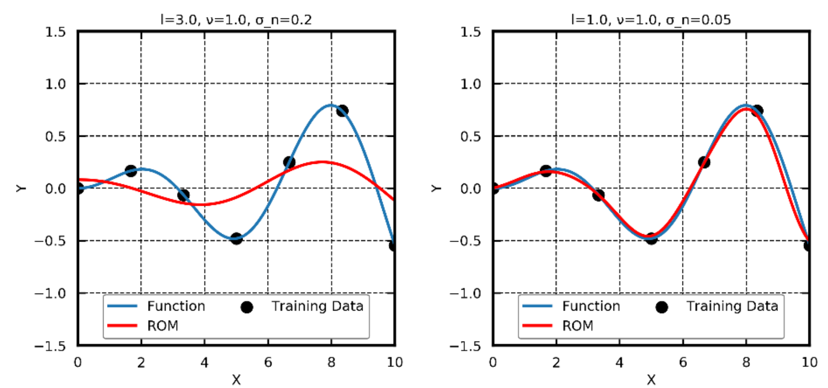
- A ROM is an accurate surrogate of a high-fidelity model (References 1, 2, and 3)
- Acts as a statistical emulator constructed from high resolution simulations
- Based on intelligent design space sampling and robust data fitting

Latin Hypercube Sampling



Sampling size of 64 ($2^8/4$) and 512 ($2*2^8$)

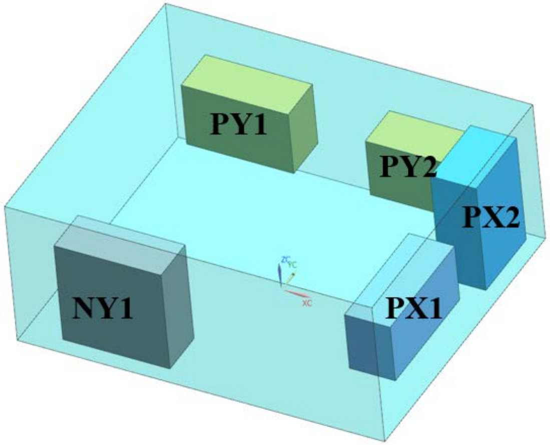
Gaussian Process Data-fitting



Variation of hyperparameters

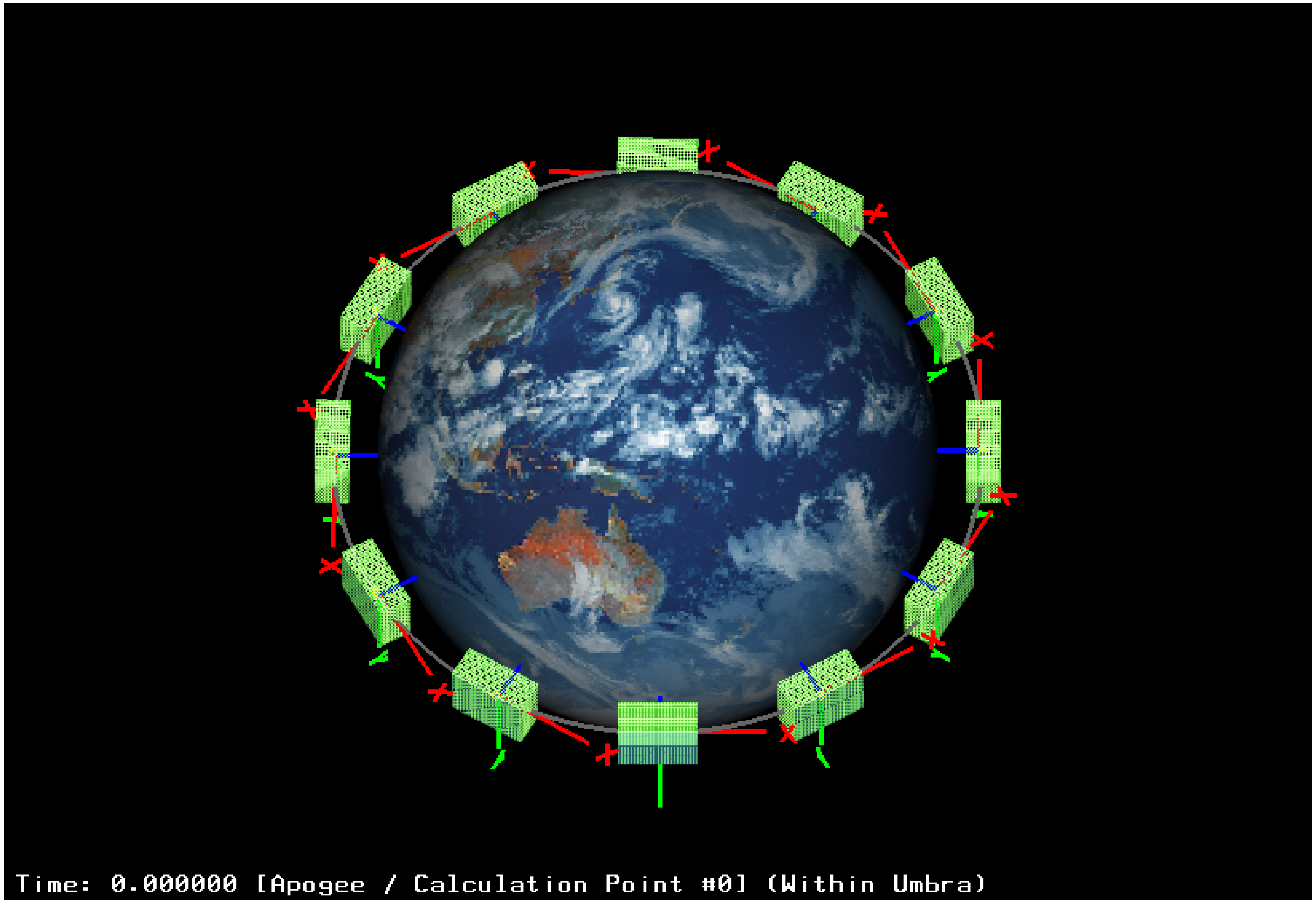
Problem Presented

- A six-sided box representing a generic spacecraft orbiting on low earth orbit (LEO)
  - Large box made of aluminum honeycomb sandwich panels
  - Small boxes representing electronics made of aluminum
- Spacecraft orbiting parameters:
  - Orbit Planet: earth
  - Orbit Type: beta (β) angle
  - Orbit Period: 6,298 seconds
  - Orbit Altitude: 1,000 km



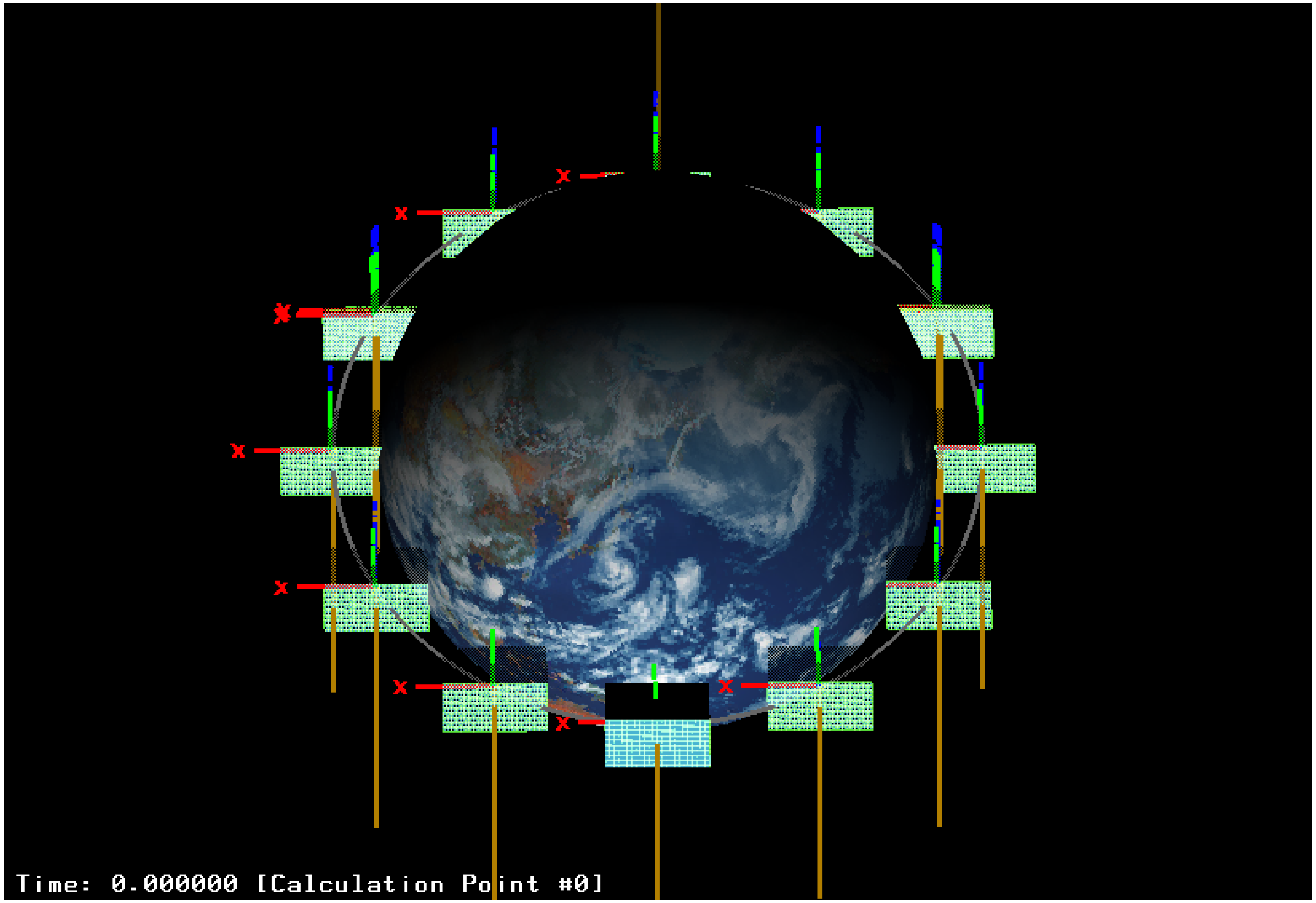
- Worst Case Hot (WCH): Nadir +Z, Velocity +X, $\beta = 60^\circ$
- Worst Case Cold (WCC): Sun –Z, North +Y, $\beta = 0^\circ$
- All solutions solved in Thermal Desktop® (TD)

Worst Hot Case: Nadir +Z, Velocity +X, β = 60



Nadir +Z, Velocity +X, β = 60, No Eclipse.
Solar Flux = 1414 W/m^2. Earth IR Flux = 263. Albedo = 0.35.

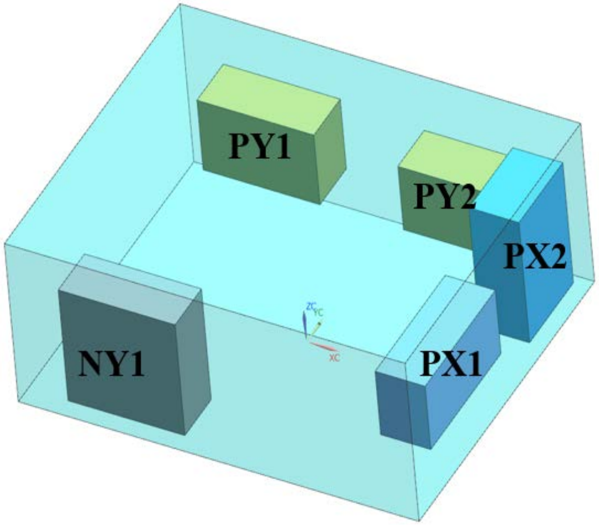
Worst Cold Case: Sun –Z, North +Y, β = 0

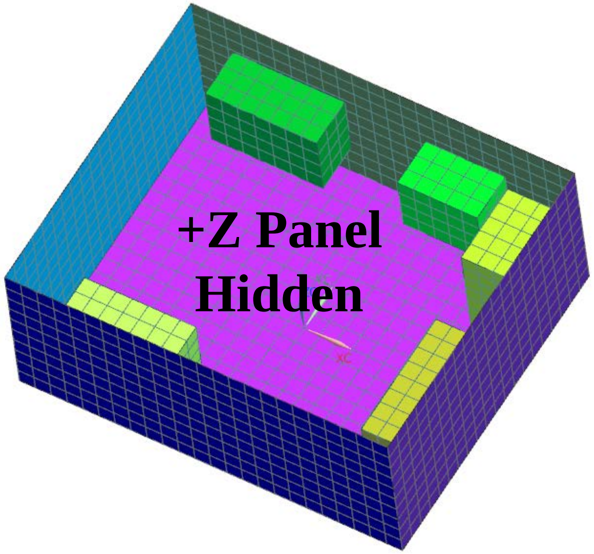


Sun –Z, North +Y, β = 0.
Solar Flux = 1318 W/m^2. Earth IR Flux = 215. Albedo = 0.25.

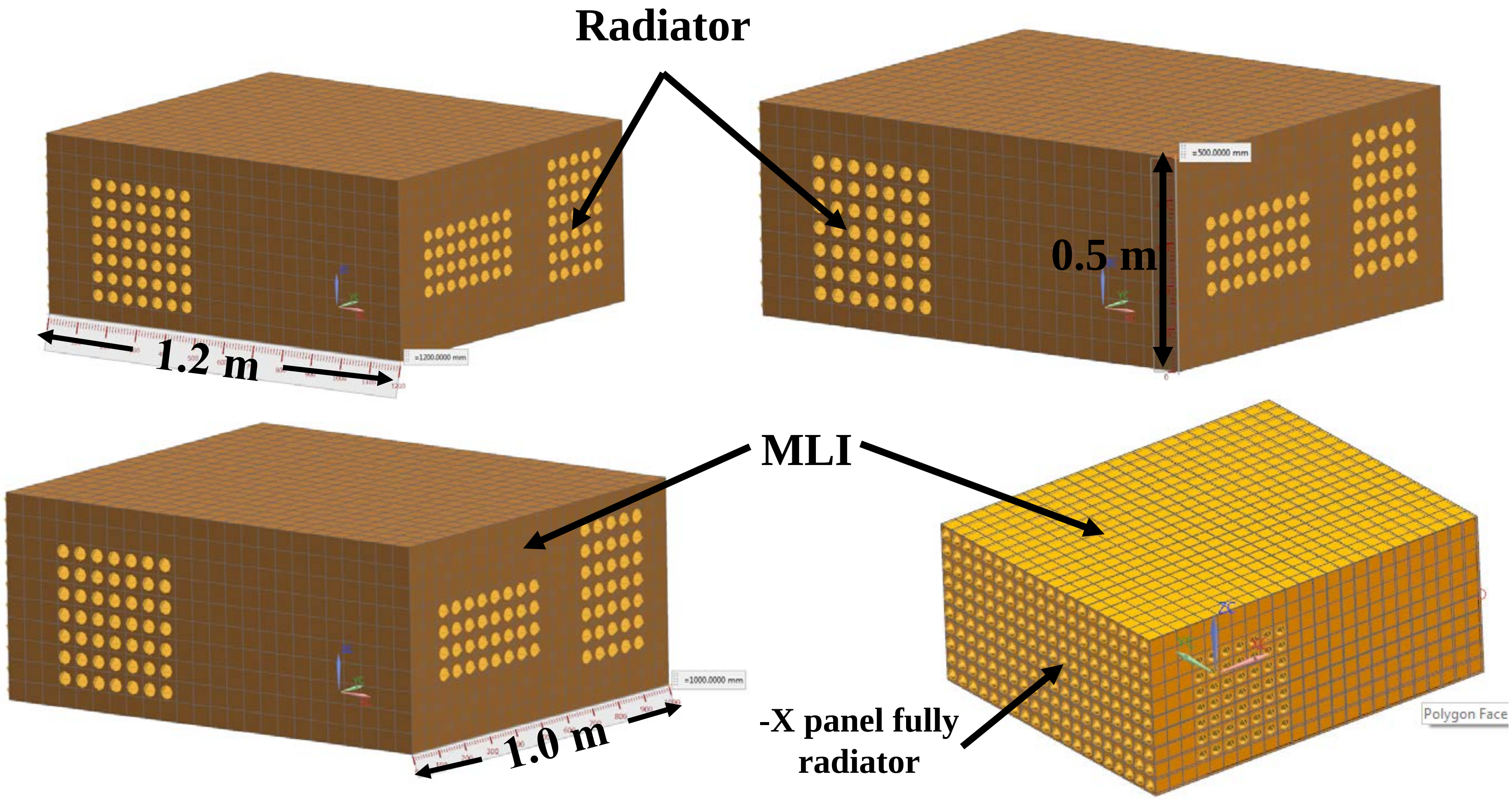
Thermal Design Constraints

- Maximum temperatures of electronics in worst case hot (WCH) environment cannot exceed maximum allowable flight temperatures (AFTs) of 40 °C
- Duty cycles of survival powers used to maintain electronics above minimum AFTs in worst case cold (WCC) environment cannot exceed 80%





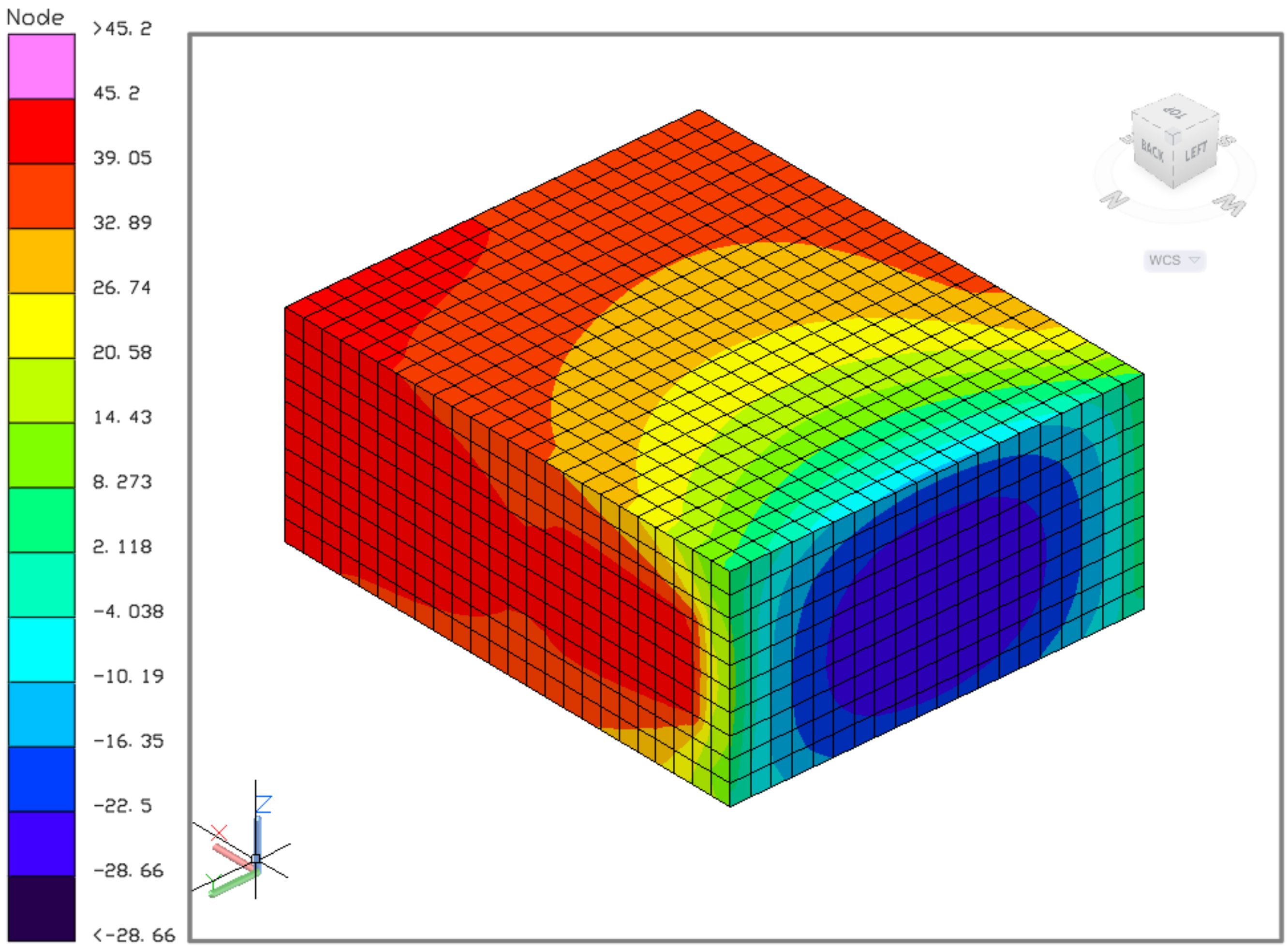
Nominal Radiator Size (Electronic Box Footprint)



Each radiator's length is a variable. Radiator's height-to-length ratio is the same as the electronic box footprints.

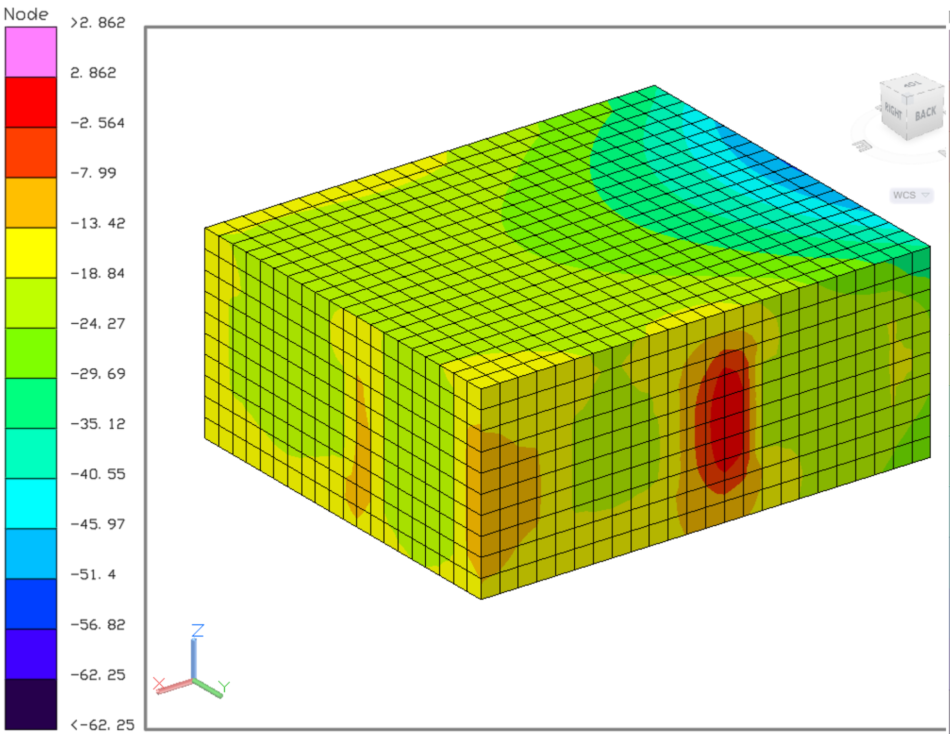
WCH, Steady State Solution, Nominal Radiators

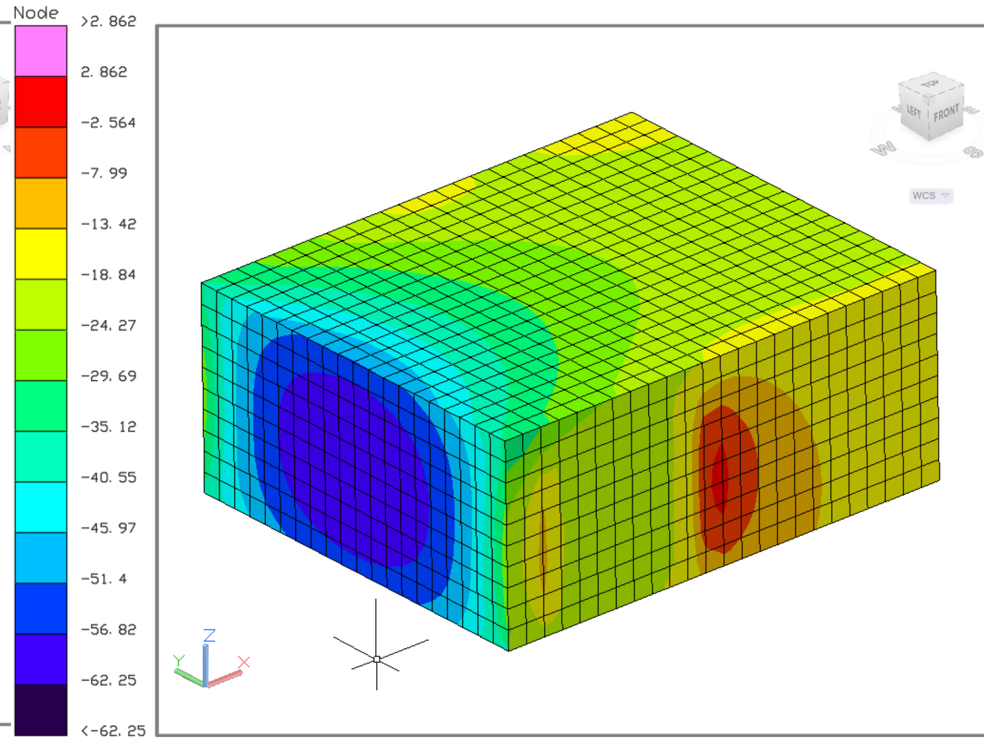
- Maximum temperature is above AFT limit of 40 °C with nominal radiator size



WCC, Steady State Solution, Nominal Radiators

- Minimum temperature without heaters is below AFT limit of -20 °C. Survival heaters needed to keep temperatures above AFT min limit.





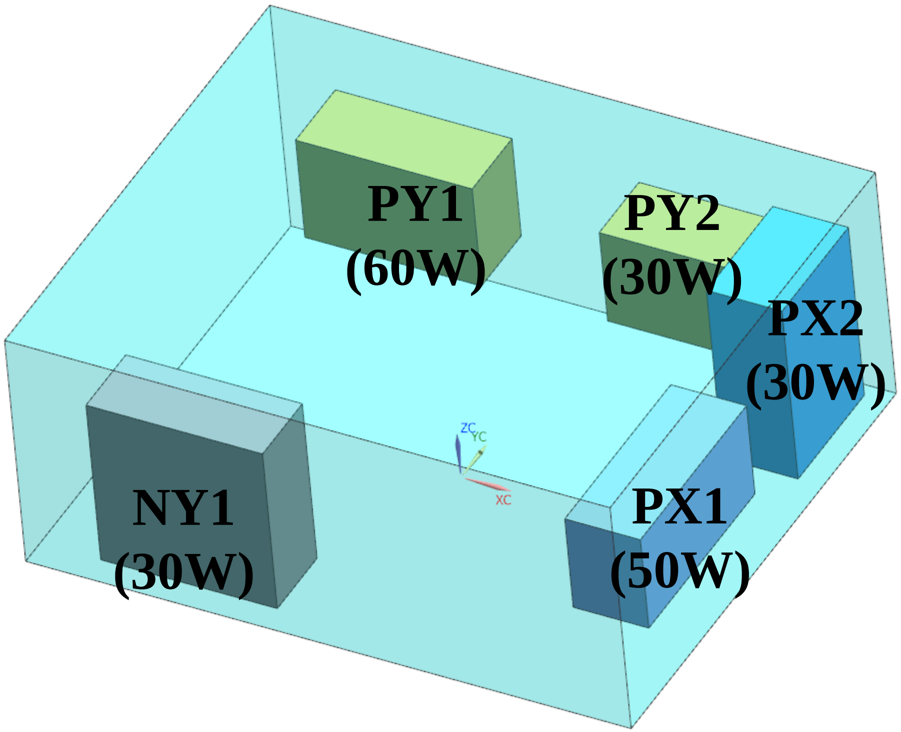
WCC Heater Powers and WCH Heat Loads

WCC Heater Powers

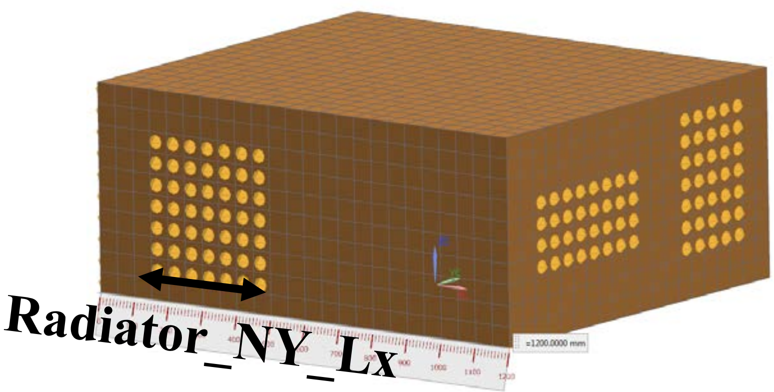
Thermostat ID/Name	Heater Power (W)	T, Cut-in (°C)	T, Cut-out (°C)	T,set-in (°C)
PY1	55	-21	-19	-20
PY2	40	-21	-19	-20
NY1	55	-21	-19	-20
PX1	80	-21	-19	-20
PX2	20	-21	-19	-20

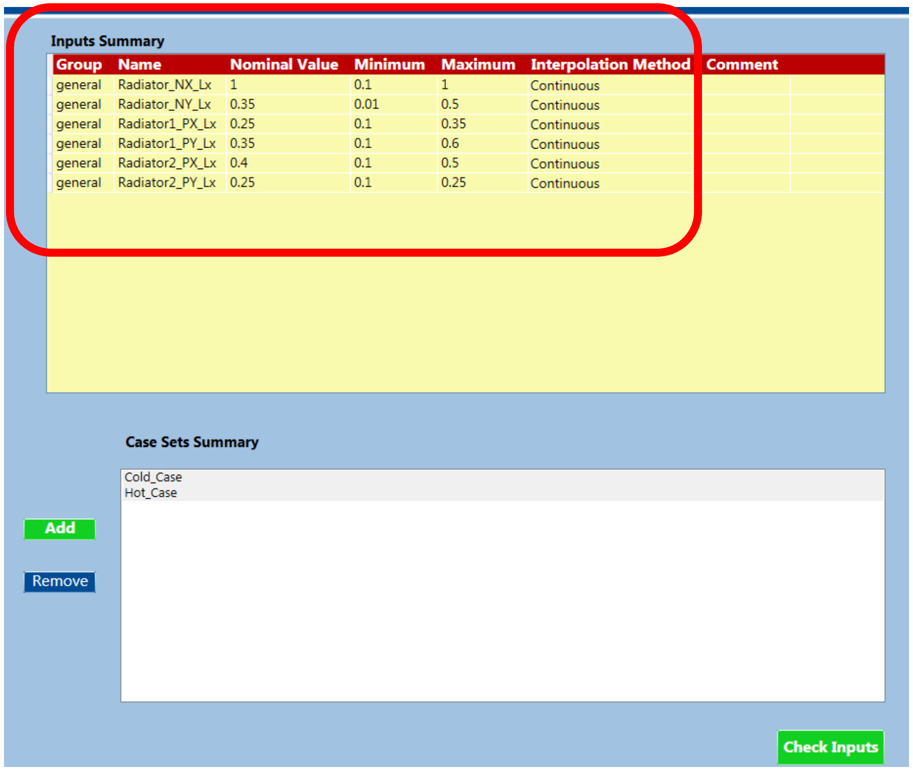
WCH Heat Load

Electronics	Heat Load (W)
PY1	60
PY2	30
NY1	30
PX1	50
PX2	30
Total	200



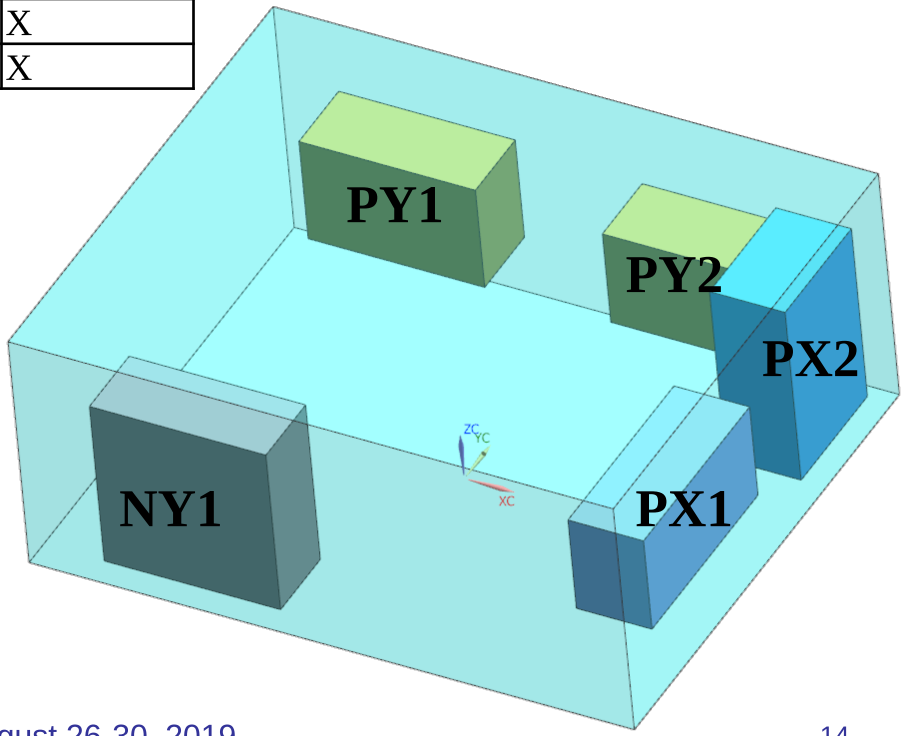
Input Variable Name	Description
Radiator NX Lx	Size of the radiator on the –X face of the spacecraft. Ranges from 0.1 to 1.
Radiator NY Lx	Size of the radiator on the –Y face of the spacecraft. Ranges from 0.01 to 0.5.
Radiator1 PX Lx	Size of the first radiator on the +X face of the spacecraft. Ranges from 0.1 to 0.35.
Radiator1 PY Lx	Size of the first radiator on the +Y face of the spacecraft. Ranges from 0.1 to 0.6.
Radiator2 PX Lx	Size of the second radiator on the +X face of the spacecraft. Ranges from 0.1 to 0.5.
Radiator2 PY Lx	Size of the second radiator on the +Y face of the spacecraft. Ranges from 0.1 to 0.25.





Output Responses for the Veritrek Creation Tool

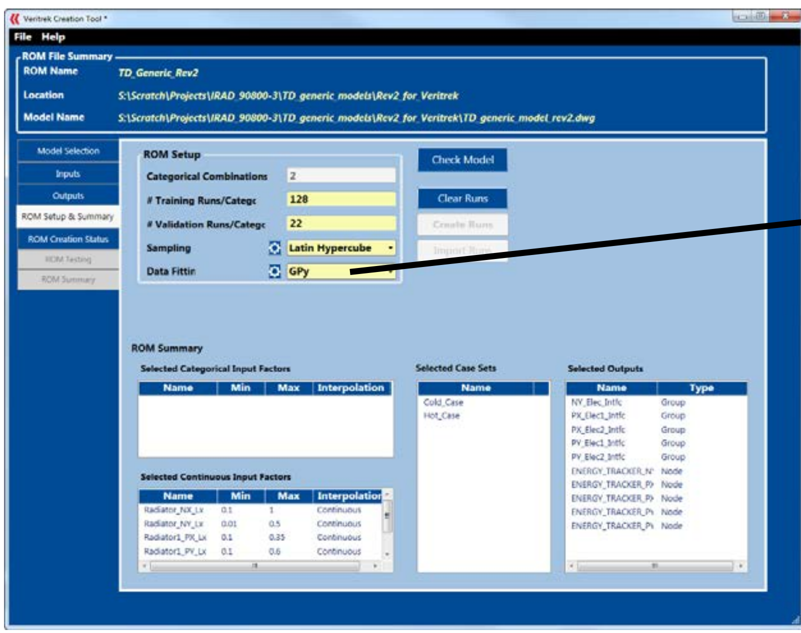
Output Response Name	Single Node	Node Group	Max Value
NY Elec Intfc Max Temperature (–Y Face)		X	X
PX Elec1 Intfc Max Temperature (+X Face)		X	X
PX Elec2 Intfc Max Temperature (+X Face)		X	X
PY Elec1 Intfc Max Temperature (+Y Face)		X	X
PY Elec2 Intfc Max Temperature (+Y Face)		X	X
Heater NY1.1 Max Power (–Y Face)	X		X
Heater PX1.1 Max Power (+X Face)	X		X
Heater PX2.1 Max Power (+X Face)	X		X
Heater PY1.1 Max Power (+Y Face)	X		X
Heater PY2.1 Max Power (+Y Face)	X		X

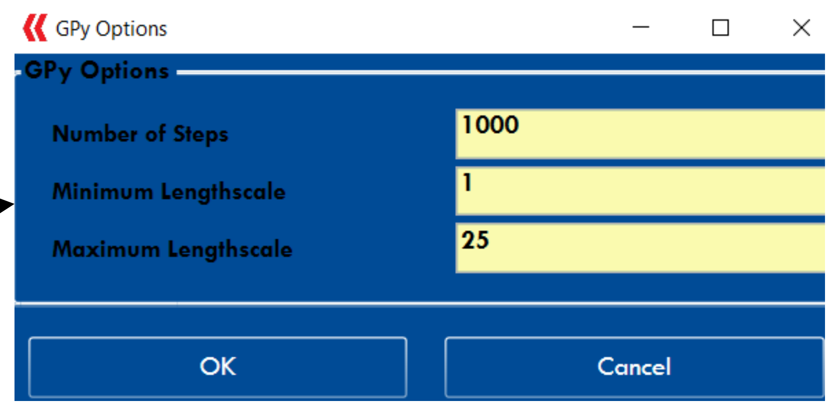


Computation Time for ROM Creation Iterations

ROM Creation Iteration	# Training Runs	Time to Generate Training Data*	Time to Test the ROM	Total Time for ROM Creation
1	66	17 hours	4 hours	~ 1.0 days
2	128	32 hours	4 hours	~ 1.5 days
3	256	64 hours	8 hours	~ 4.0 days

* The system used to generate the ROM was a Windows 7 HP Z440 workstation running AutoCAD 2018 and Thermal Desktop® 6.0 Patch 21. The processor on this system was a 12-core Intel Xeon CPU at 3GHz

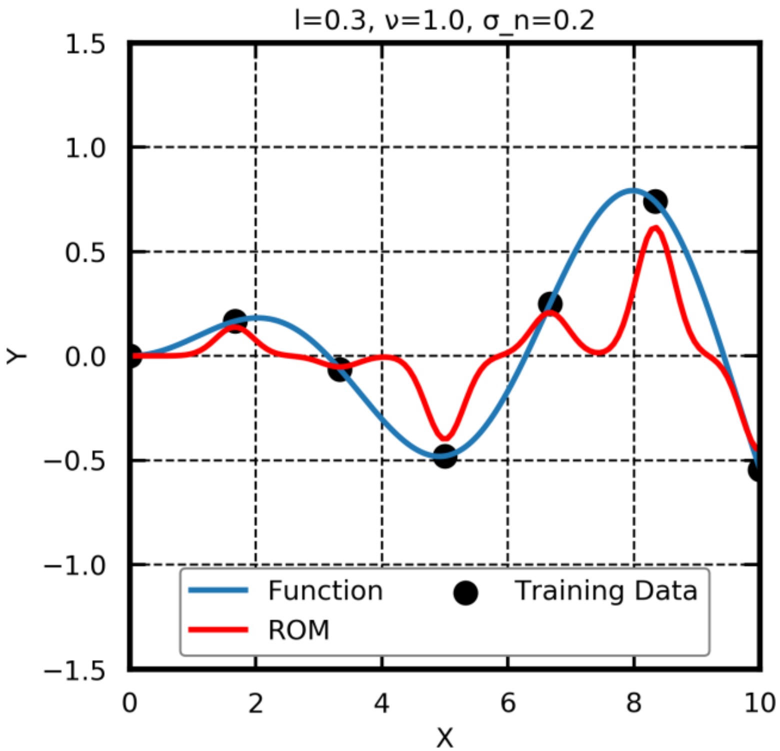


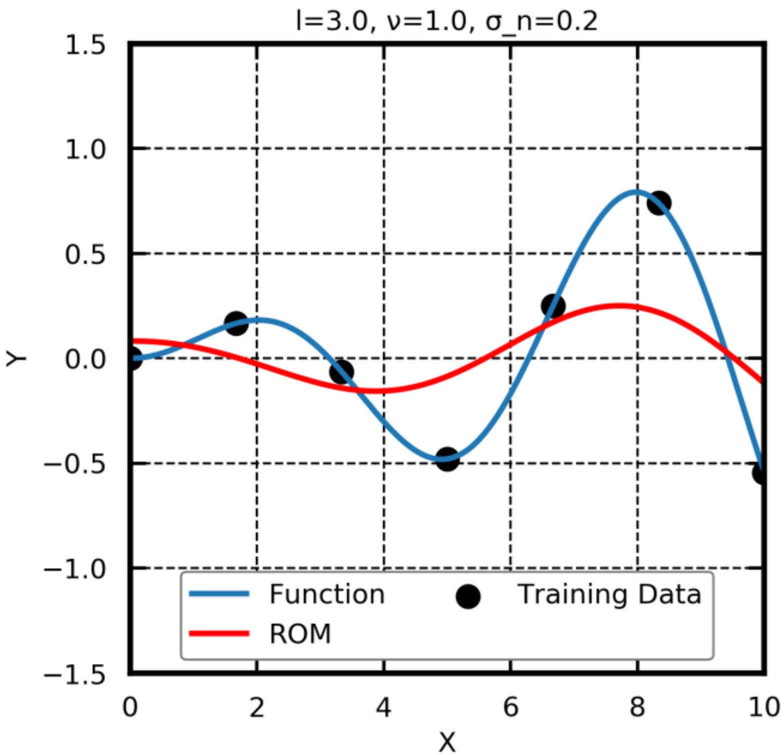


GPy Options can be altered to improve the ROM data-fitting

Explanation of GPy Parameters

Lengthscale parameter (l) controls the smoothness of the fitting function

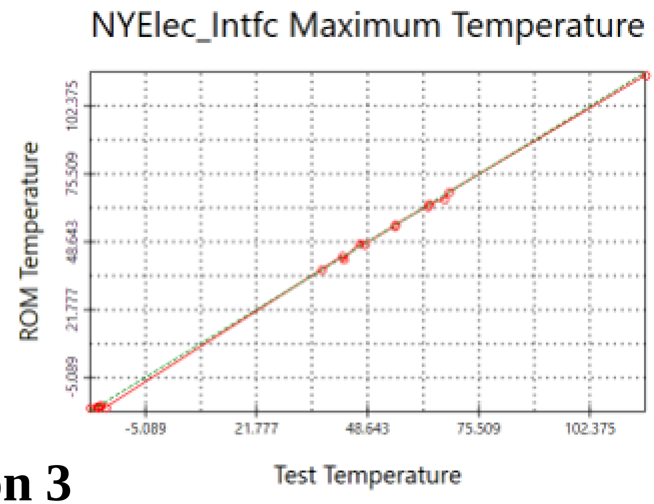


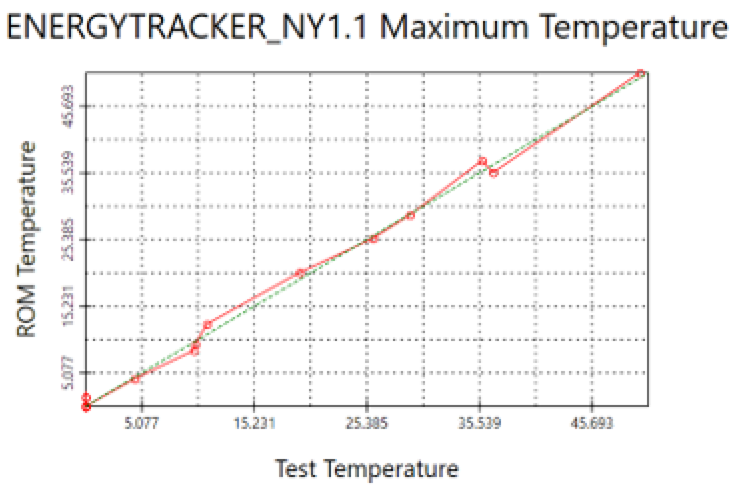


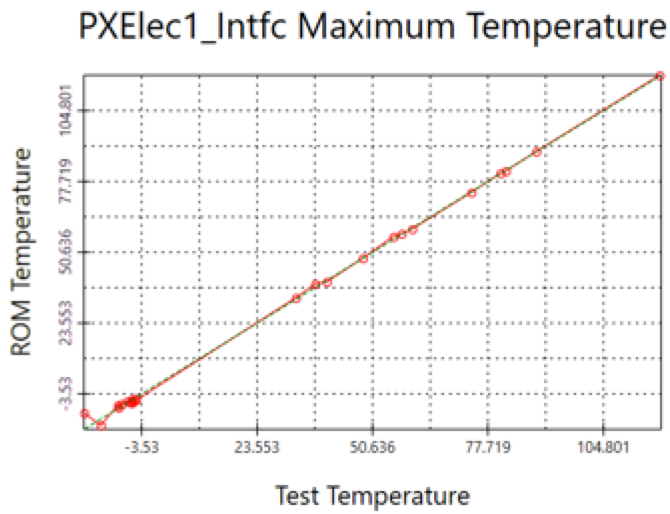
Veritrek's data-fitting algorithm automatically optimizes the model parameters, but provides user options for setting the range of lengthscales and number of steps within that range to evaluate.

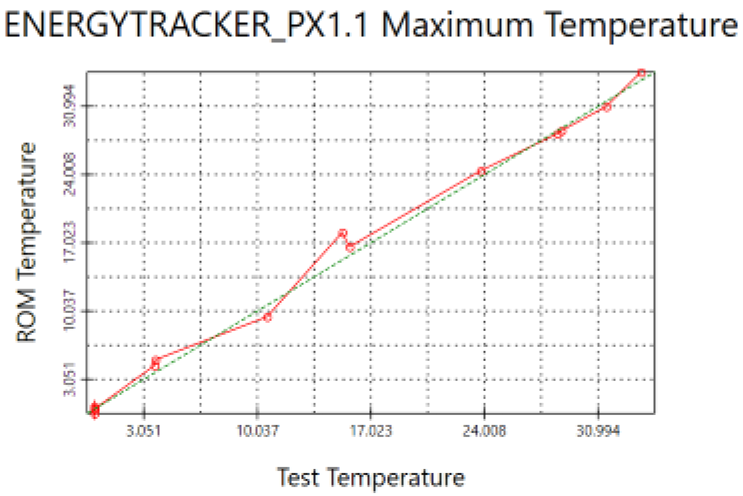
ROM vs. TD Output Prediction Comparison

Iteration 3 ROM

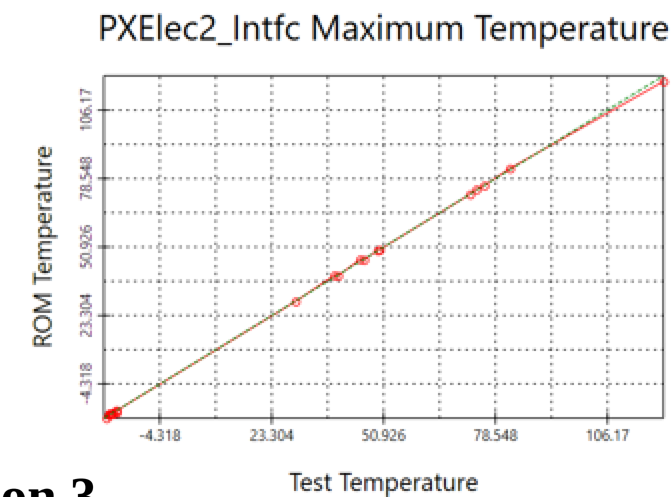


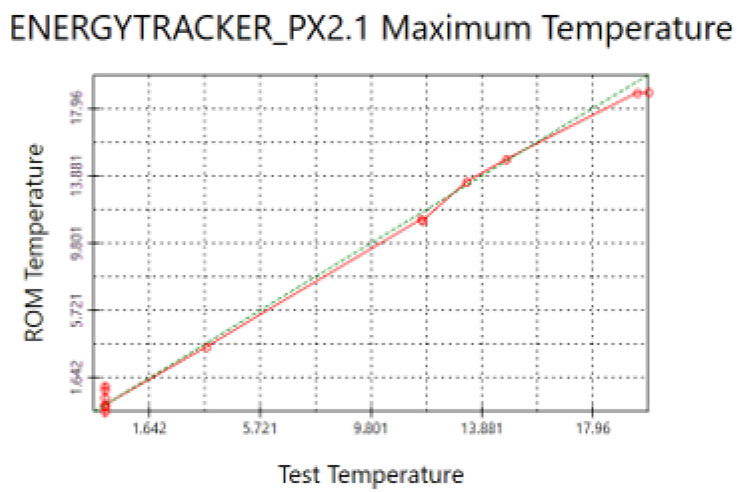




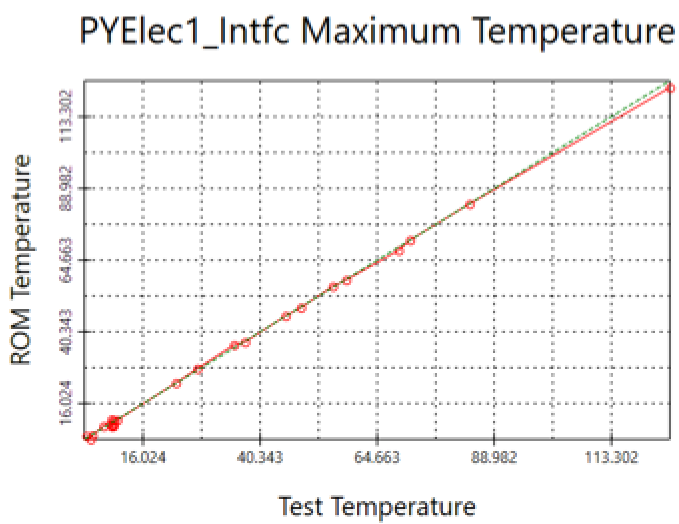


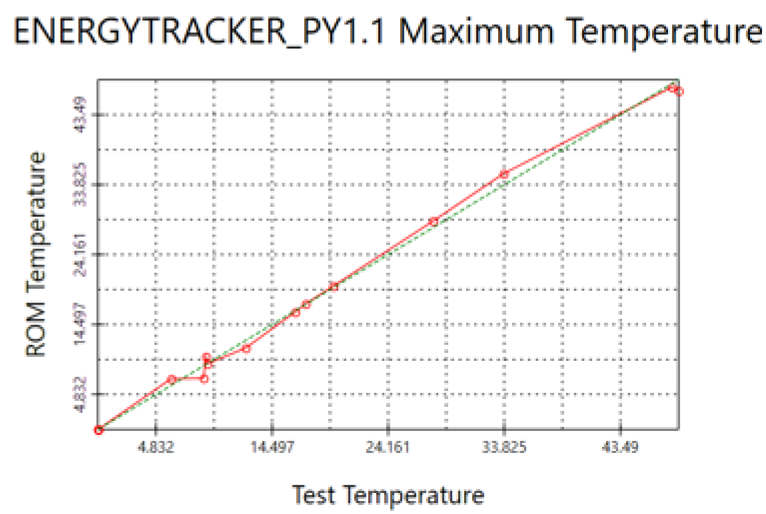
ROM vs. TD Output Prediction Comparison





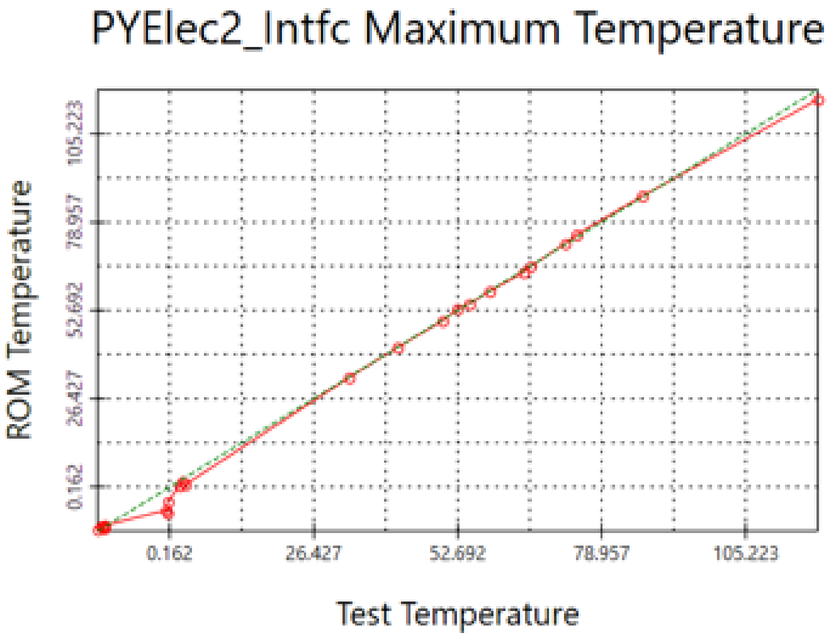
Iteration 3 ROM

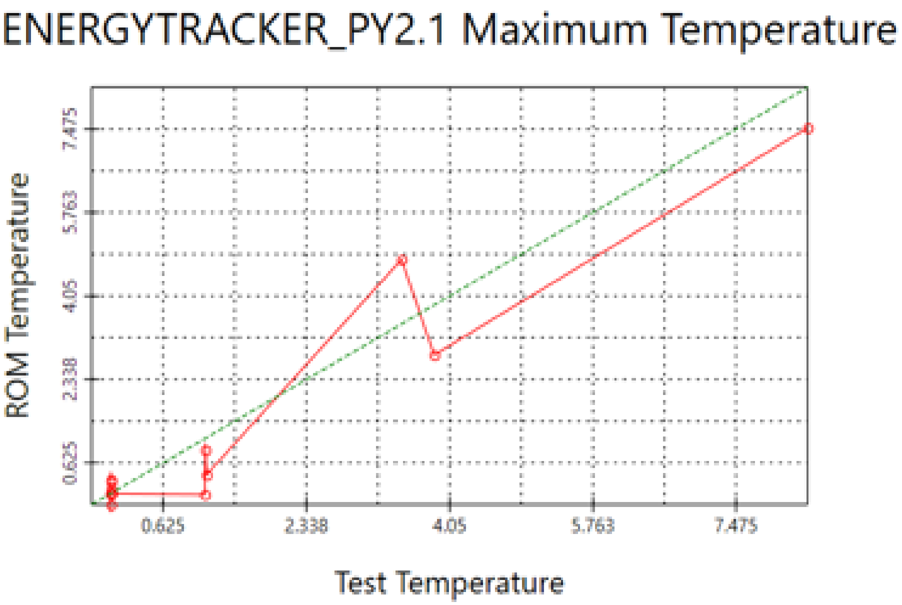




ROM vs. TD Output Prediction Comparison

Iteration 3 ROM





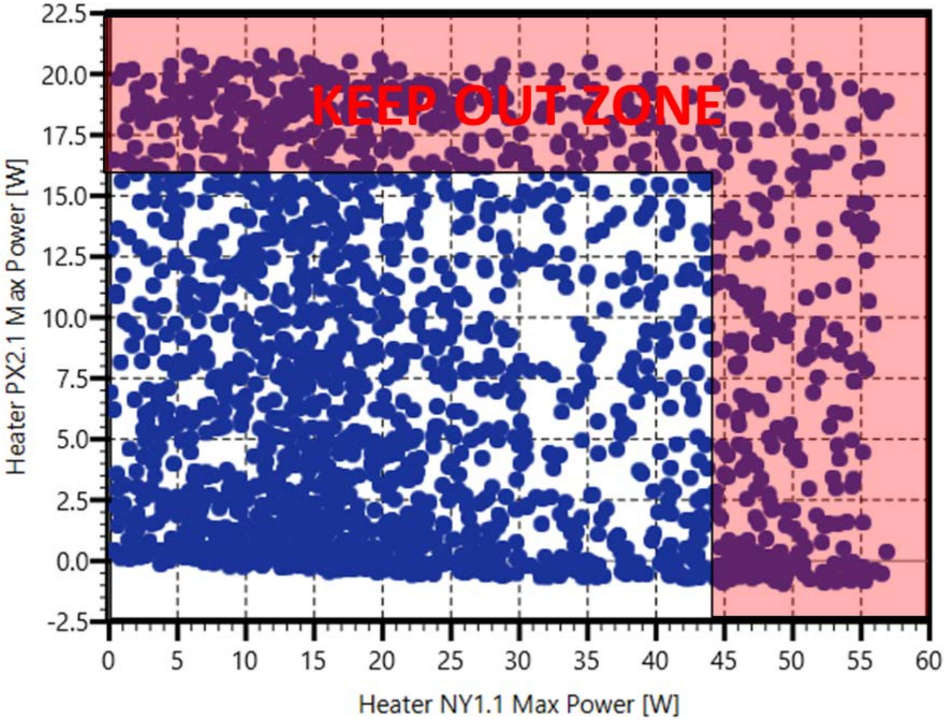
Residuals between ROM and TD Predictions (24 Test Runs)

< 1 C (or W)   < 3 C (or W)

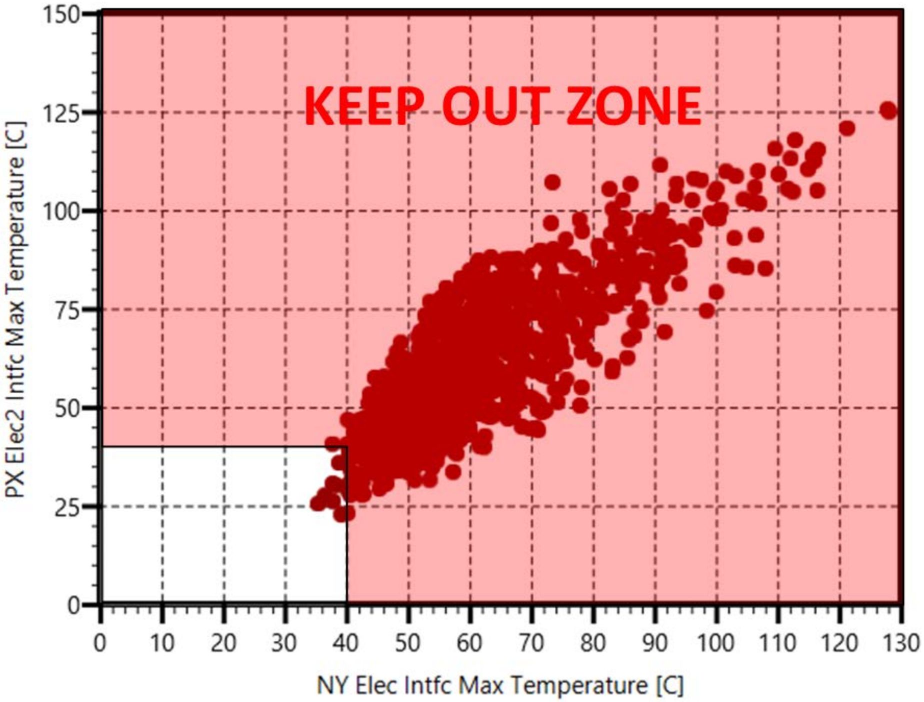
Output Response Name	Mean of the Residual	Standard Deviation of the Residual
NY Elec Intfc Max Temperature (–Y Face)	-0.133 °C	0.764 °C
PX Elec1 Intfc Max Temperature (+X Face)	0.287 °C	1.496 °C
PX Elec2 Intfc Max Temperature (+X Face)	-0.019 °C	0.615 °C
PY Elec1 Intfc Max Temperature (+Y Face)	-0.197 °C	0.832 °C
PY Elec2 Intfc Max Temperature (+Y Face)	-0.928 °C	2.109 °C
Heater NY1.1 Max Power (–Y Face)	0.178 W	0.742 W
Heater PX1.1 Max Power (+X Face)	0.204 W	0.746 W
Heater PX2.1 Max Power (+X Face)	-0.021 W	0.443 W
Heater PY1.1 Max Power (+Y Face)	-0.007 W	0.710 W
Heater PY2.1 Max Power (+Y Face)	-0.094 W	0.476 W

Note: Different number of test runs may produce slightly different numerical residual metrics, but the ROM does not change. Differing residuals in this case, is a symptom of testing closer to the edges of the design space.

Cold Case Max Power Results
for
PX2 and NY1 Heaters



Hot Case Max Temperature Results
for
PX2 and NY1 Electronics



Filtered Optimized Solution(s)

ATA Preliminary Optimal Design

Radiator Name	Optimal Size (m)	Allowable Tolerance
Radiator NX Lx	0.898	+/-0.05
Radiator NY Lx	0.262	+/-0.05
Radiator1 PX Lx	0.327	+/-0.02
Radiator1 PY Lx	0.462	+/-0.03
Radiator2 PX Lx	0.440	+/-0.06
Radiator2 PY Lx	0.249	+/-0.001

Filtered through 30,000 design points using a Python script

LoadPath Preliminary Optimal Design

Radiator Name	Optimal Size (m)	Allowable Tolerance
Radiator NX Lx	0.950	+/- 0.050
Radiator NY Lx	0.320	+/- 0.060
Radiator1 PX Lx	0.330	+/- 0.020
Radiator1 PY Lx	0.435	+/- 0.025
Radiator2 PX Lx	0.410	+/- 0.030
Radiator2 PY Lx	0.250	+/- 0.005

Filtered through 150,000 design points using combination of Excel and Veritrek Exploration Tool

These two optimal designs are essentially the same.

Preliminary Optimal Design, Veritrek vs. TD

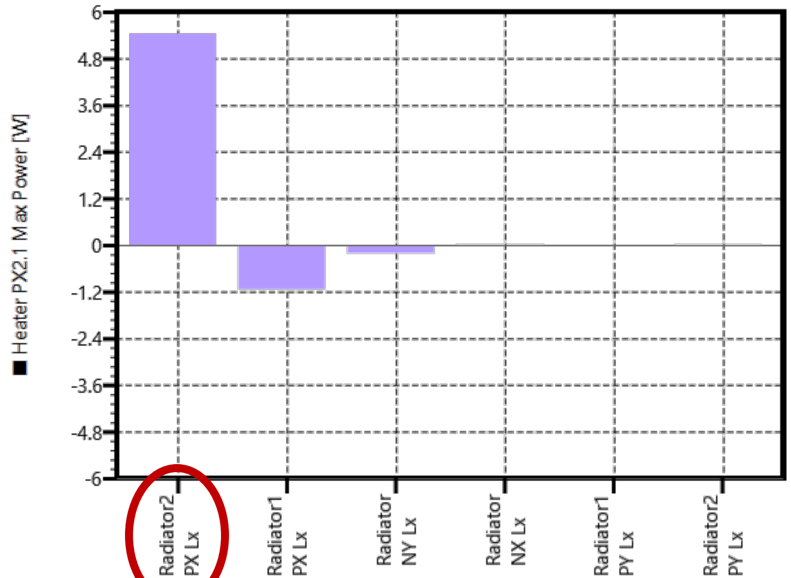
All design requirements were met except for PX2 survival power duty cycle is larger than 80%

Optimal Design	**NY Elec Intfc Max Temp (-Y Face)**	**PX Elec1 Intfc Max Temp (+X Face)**	**PX Elec 2 Intfc Max Temp (+X Face)**	**PY Elec1 Intfc Max Temp (+Y Face)**	**PY Elec2 Intfc Max Temp (+Y Face)**
Hot Case Veritrek Predict	39.3 °C	30.6 °C	28.4 °C	28.5 °C	33.8 °C
Hot Case TD Predict	36.8 °C	28.7 °C	27.9 °C	25.2 °C	33.0 °C
Difference	2.5 °C	1.9 °C	0.5 °C	3.3 °C	0.8 °C
Optimal Design	**Heater NY1.1 Max Power**	**Heater PX1.1 Max Power**	**Heater PX2.1 Max Power**	**Heater PY1.1 Max Power**	**Heater PY2.1 Max Power**
Cold Case Veritrek Predict	26.6 W	31.2 W	14.9 W	41.8 W	2.3 W
Cold Case TD Predict	26.3 W	23.1 W	19.6 W	35.9 W	9.7 W
Difference	0.3 W	8.1 W	-4.7 W	5.9 W	-7.4 W
Optimal Design	**Duty Cycle**				
Cold Case Veritrek Predict	48.4%	39.0%	74.5%	76.0%	5.8%
Cold Case TD Predict	47.8%	28.9%	97.8%	65.2%	24.4%
Difference	1%	10%	-23%	11%	-19%

Violation of duty cycle due to ROM under-estimating PX2's survival energy

Further Veritrek Analysis Provides Final Optimal Design

Screening Analysis shows we only needed to slightly alter Radiator2 PX Lx to find final optimal design



Orbits	Radiator NX Lx	Radiator NY Lx	Radiator1 PX Lx	Radiator1 PY Lx	Radiator2 PX Lx	Radiator2 PY Lx	NY Elec Intfc Max Temp... [C]	PX Elec1 Intfc Max Temp... [C]	PX Elec2 Intfc Max Temp... [C]	PY Elec1 Intfc Max Temp... [C]	PY Elec2 Intfc Max Temp... [C]	Heater NY1.1 Max Power [W]	Heater PX1.1 Max Power [W]	Heater PX2.1 Max Power [W]	Heater PY1.1 Max Power [W]	Heater PY2.1 Max Power [W]
Cold Case	0.95	0.32	0.33	0.435	0.38	0.25	-15.709	-8.291	-15.189	7.868	-1.675	32.408	33.037	9.309	39.276	2.816
Hot Case	0.95	0.32	0.33	0.435	0.38	0.25	40.248	32.459	34.327	32.631	36.209	0.000	0.000	0.000	0.000	0.000

Point Analysis allows instant execution of design change

Final Optimal Design

Radiator Name	Optimal Size (m)	Allowable Tolerance
Radiator NX Lx	0.950	+/- 0.050
Radiator NY Lx	0.320	+/- 0.060
Radiator1 PX Lx	0.330	+/- 0.020
Radiator1 PY Lx	0.435	+/- 0.025
Radiator2 PX Lx	0.380	+/- 0.030
Radiator2 PY Lx	0.250	+/- 0.005

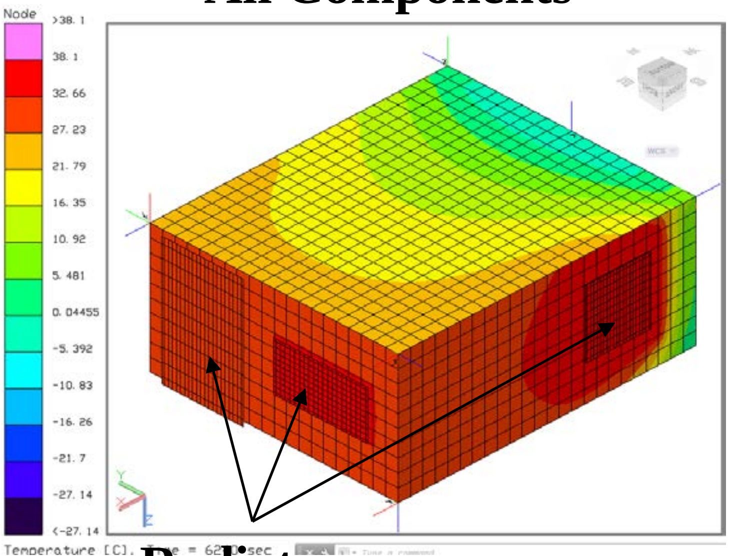
Final Optimal Design Meets All Requirement

Design points filtering process should have given a small tolerance beyond requirement or included design points that are slightly above maximum temperature of 40 ℃

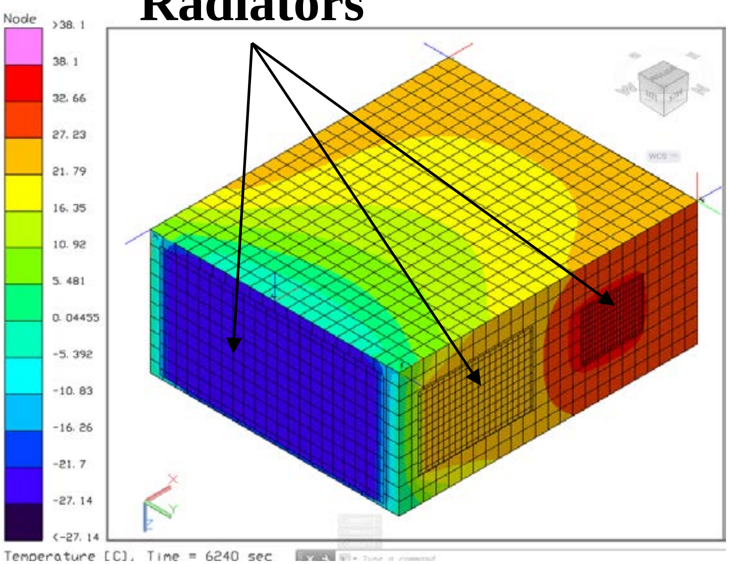
Optimal Design	NY Elec Intfc Max Temp (-Y Face)	PX Elec1 Intfc Max Temp (+X Face)	PX Elec 2 Intfc Max Temp (+X Face)	PY Elec1 Intfc Max Temp (+Y Face)	PY Elec2 Intfc Max Temp (+Y Face)
Hot Case Veritrek Predict	40.2 °C	32.6 °C	34.3 °C	32.6 °C	36.2 °C
Hot Case TD Predict	38.1 °C	30.6 °C	33.1 °C	26.2 °C	34.4 °C
Difference	2.2 °C	2.0 °C	1.2 °C	6.4 °C	1.8 °C
Optimal Design	**Heater NY1.1 Max Power**	**Heater PX1.1 Max Power**	**Heater PX2.1 Max Power**	**Heater PY1.1 Max Power**	**Heater PY2.1 Max Power**
Cold Case Veritrek Predict	32.4 W	33.0 W	9.3 W	39.3 W	2.8 W
Cold Case TD Predict	26.4 W	23.9 W	14.7 W	35.9 W	9.8 W
Difference	6.0 W	9.1 W	-5.4 W	3.4 W	-7.0 W
Optimal Design	**Duty Cycle**				
Cold Case Veritrek Predict	58.9%	41.3%	46.5%	71.5%	7.0%
Cold Case TD Predict	48.0%	29.9%	73.5%	65.3%	24.5%
Difference	10.9%	11.4%	-27%	6.2%	-17.5%

WCH Temperature Contours with Final Optimal Design

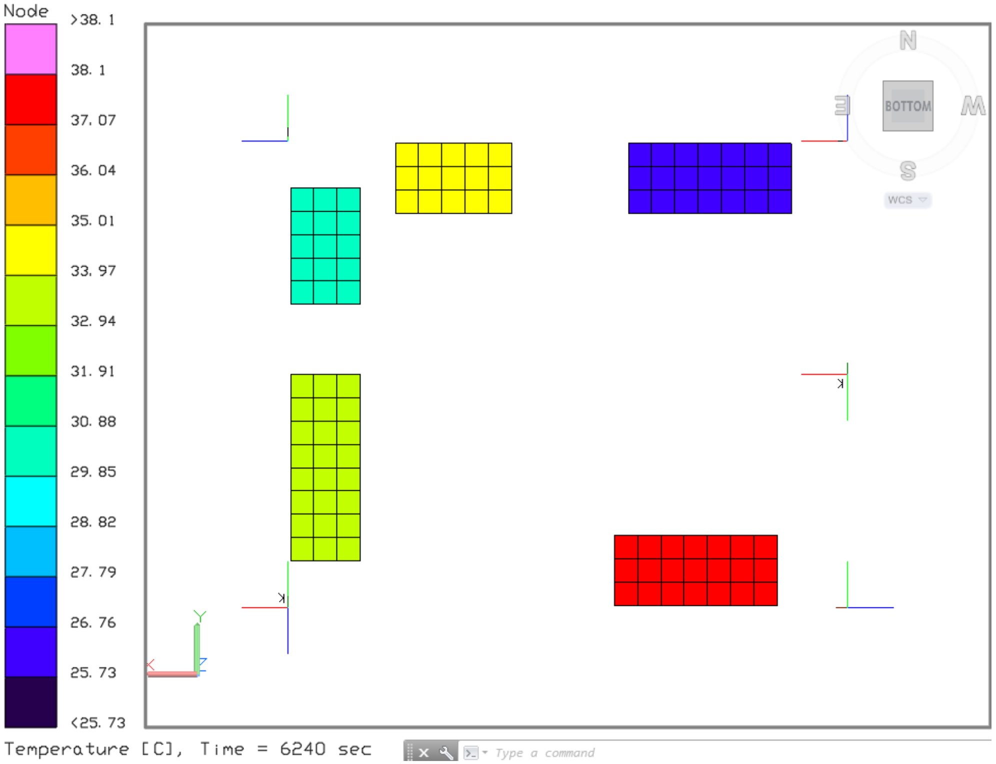
All Components



Radiators



Electronics Only



Conclusions

- ATA explored an alternative design method to find optimal radiator size
- ATA created a reduced-order model (ROM) using Veritrek, and tested this ROM to verify its accuracy
- Fidelity of the ROM depends on number of training data simulations, such that a higher fidelity ROM requires more computation time
- Design and verification of the thermal system in a variable environment was executed in real time in Veritrek Exploration Tool
- An optimal design solution was reached in about five days using Veritrek, compared to a month using traditional thermal analysis techniques

References

1. Hengeveld, D. W., & Biskner, A. (2017). Enhanced data exploration through Reduced-Order Models. *47th International Conference on Environmental Systems.* Charleston, SC.

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3. Tyler M. Schmidt, S. C. (2018). Thermal Design of a Mars Helicopter Technology Demonstration Concept. *ICES 2018.* Albuquerque.

Questions?