Re-Architecting the NASA Wire Derating Approach

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Disclaimer

This presentation discusses work in progress.

All results are considered preliminary and subject to change and should not be used for engineering analysis

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Team

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Background

- Design of wiring for aerospace vehicles relies on an understanding of “ampacity,” which refers to the current carrying capacity of wires, individually or in wire bundles.

- Designers rely on standards to derate allowable current flow to prevent exceedance of wire temperature limits due to resistive heat dissipation within the wires or wire bundles. Designers select wire sizing and circuit protective device settings/sizing based on the standards.

- Exceeding the wire temperature rating can result in electrical, physical, and/or chemical degradation of the wiring insulation and conductor which could lead to a catastrophic failure.

- These standards can add considerable margin, in some cases underestimate the margin and are based on empirical data that is no longer available for review.

Background

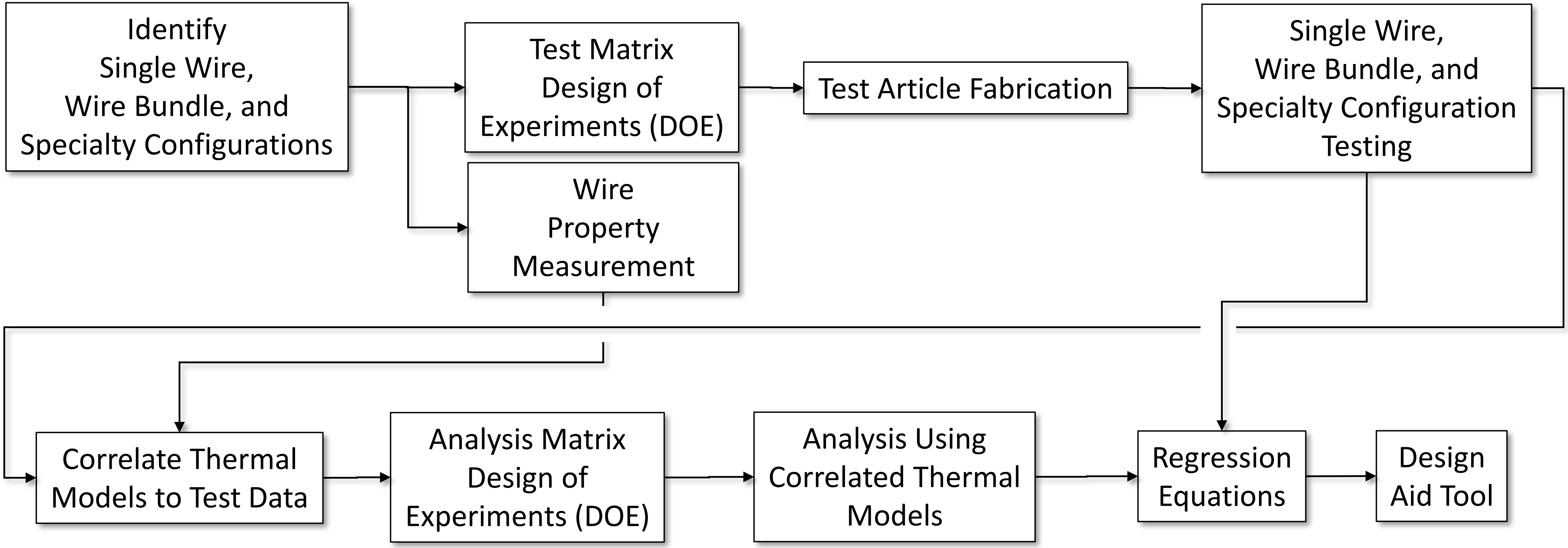
- Wire and wire bundle testing were performed during a previous NESC-led pathfinder assessment [Ref. 1] resulting in data to inform thermal models developed as a predictive tool to aid in ampacity determination. The results were encouraging and suggested, with further development, models may become sufficiently mature to supplant the long-held practice of using published wire derating standards. Derating standards use of tables limits designers' options and, in some cases, drive conservative designs. Tables are limited and can not address range of parameters that can impact design.

- A follow-on assessment was approved and started in Spring, 2021 and expands upon the testing and analysis performed during the pathfinder study.

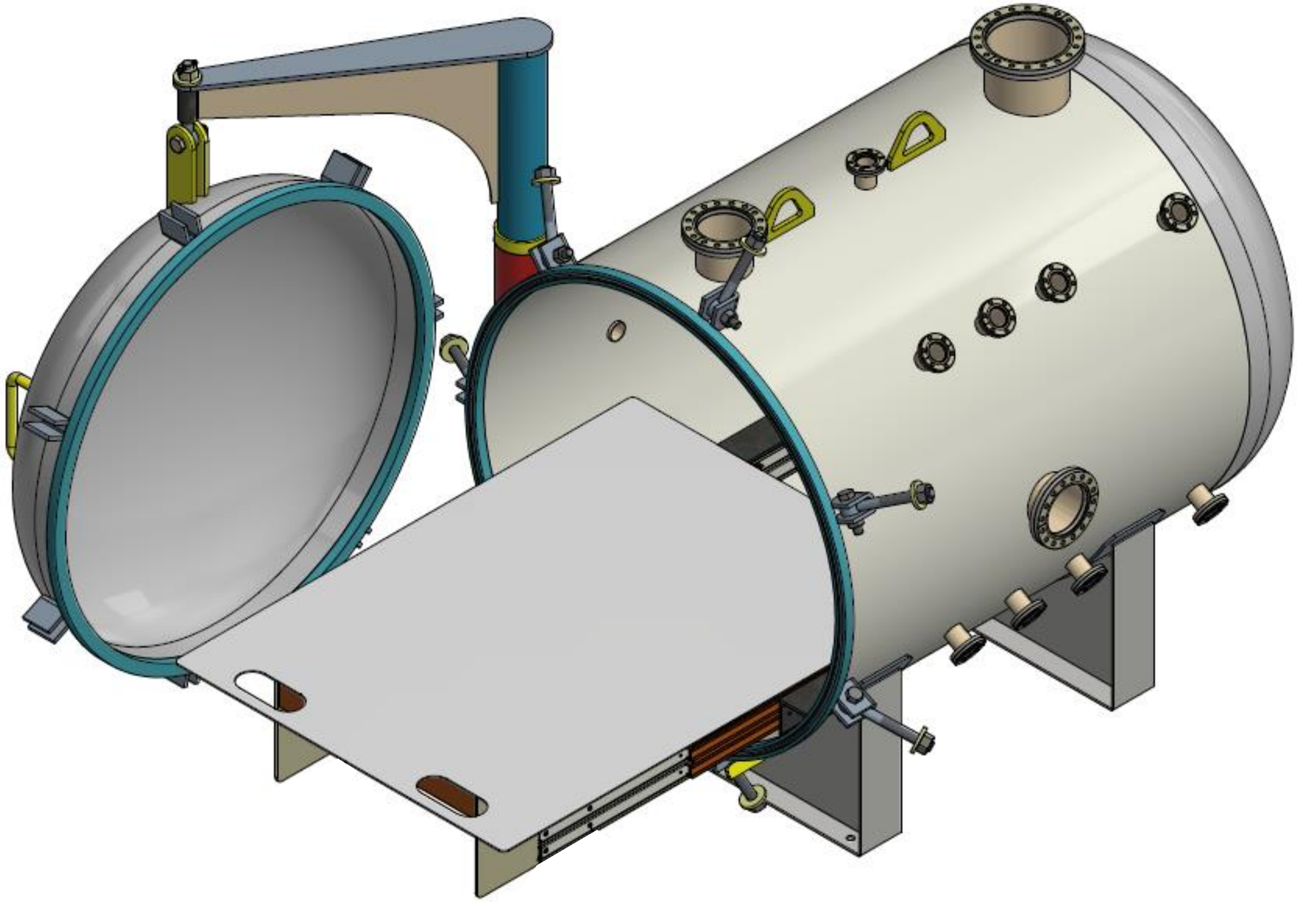
Scope of New Assessment

- Design of experiments (DOE) techniques are used to formulate the test matrix including single wires, wire bundles, and specialty configurations.
- The test apparatus is modified to improve application of boundary conditions on test articles.
- Wire data are being collected for use in thermal models including: conductor radius, outer jacket radius, resistance per unit length and a reference temperature, temperature coefficient of resistance, jacket infrared transmissivity, jacket infrared emissivity.
- Thermal models have been reconfigured to accommodate large quantities of analysis runs.
- A design aid tool is being developed to aid the user community in wire bundle sizing.
- Regression equations, based on DOE cases, will be derived from, both, test data and analytical models for use in the design aid tool.
- The model will be validated using wire sizes 26 to 4 using modern wire constructions with bundles as large as 149 wires and under sea level to vacuum conditions over the operating range of the wiring.

Overall Study Architecture



Test Apparatus



Vacuum Chamber Configuration

Chamber at JPL

Test Apparatus

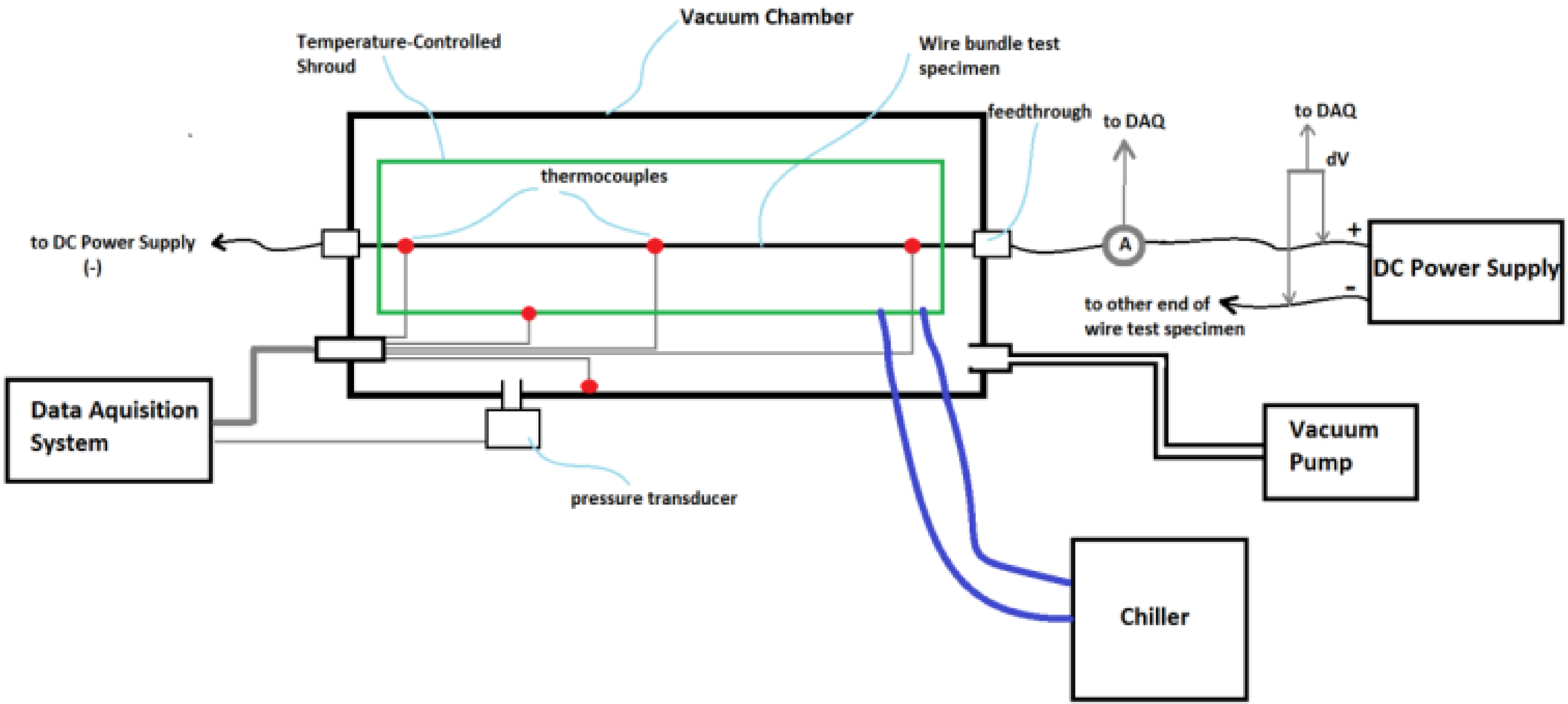
Shroud with Lid (Old Design)

Old Routing

New Routing

Temperature Controlled Shroud with Wire Bundle Test Article

Test Apparatus



Schematic of Test Configuration (PRELIMINARY)

Thermal Modeling – Single Wire Model

The single wire model is composed of a system of equations:

$$I^2 R_{L0}[1+\alpha(T_c-T_0)] = 2\pi r_s f_h h(T_s-T_e) + 2\pi r_s \sigma\varepsilon(T_s^4-T_e^4) + 2\pi r_c \sigma\tau(T_c^4-T_e^4)$$

$$I^2 R_{L0}[1+\alpha(T_c-T_0)] = \frac{2\pi k_w (T_c-T_s)}{\ln(r_s/r_c)} + 2\pi r_c \sigma\tau(T_c^4-T_e^4)$$

where…

R_{L0}	Resistance/length at a reference temperature
T_0	Reference temperature
α	Temperature coefficient of resistance
r_c	Conductor radius
r_s	Jacket radius
k_w	Jacket effective thermal conductivity
I	Current flow
ε	Jacket infrared emissivity
τ	Jacket infrared transmissivity
h	Convective heat transfer coefficient
f_h	Convection coefficient scaling
T_c	Conductor temperature
T_s	Jacket surface temperature
T_e	Environment temperature
σ	Stefan-Boltzmann constant

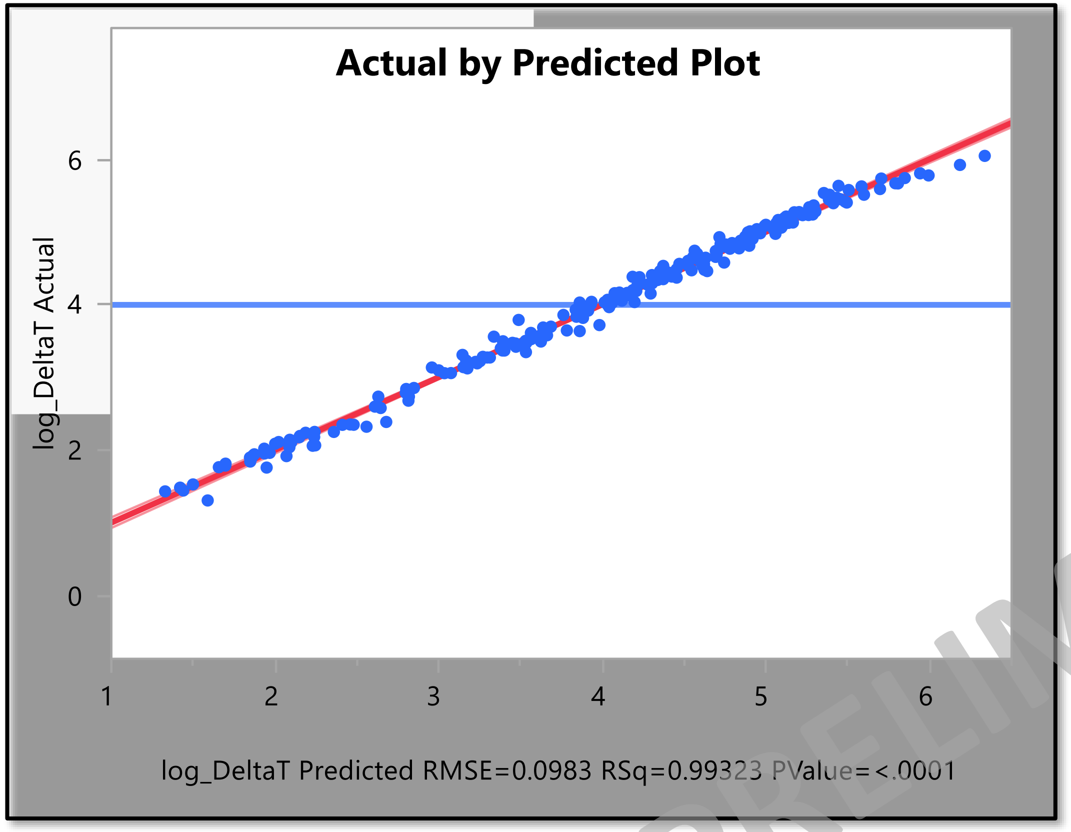
Thermal Modeling – Single Wire Model

R_{L0}	Resistance/length at a reference temperature
T_0	Reference temperature
α	Temperature coefficient of resistance
r_c	Conductor radius
r_s	Jacket radius
k_w	Jacket effective thermal conductivity
I	Current flow
ε	Jacket infrared emissivity $(1-\tau-\rho)$
τ	Jacket infrared transmissivity
ρ	Jacket infrared reflectance (not used directly in model)
h	Convective heat transfer coefficient
f_h	Convection coefficient scaling
T_c	Conductor temperature
T_s	Jacket surface temperature
T_e	Environment temperature
σ	Stefan-Boltzmann constant

Key

- Measured Parameter
- Calculated Parameter
- Test Parameter
- Constant Parameter
- Correlation Parameter

Thermal Modeling – (Uncorrelated) Single Wire Regression Model



Summary of Fit

RSquare	0.993228
RSquare Adj	0.992911
Root Mean Square Error	0.098305
Mean of Response	3.995573
Observations (or Sum Wgts)	225

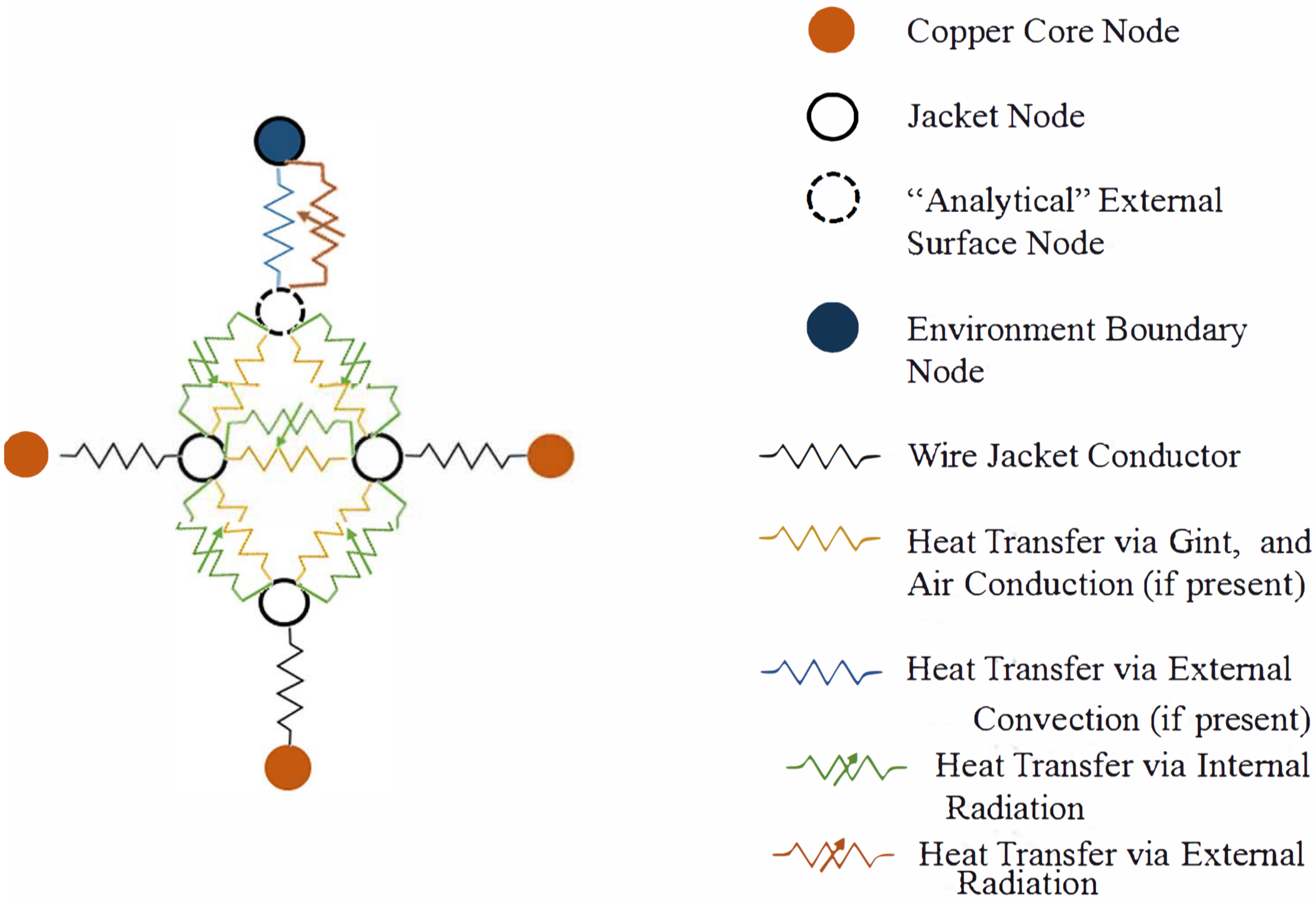
Effect Summary

Source	LogWorth	PValue
log_Current	225.719	0.00000
igauge	185.891	0.00000
pamb	153.109	0.00000
pamb*pamb	68.535	0.00000
Wire Conductor	41.607	0.00000
pamb*tamb	37.013	0.00000
pamb*log_Current	31.885	0.00000
insul	31.687	0.00000
tamb	21.296	0.00000 ^

Prediction Expression

$$
\begin{aligned}
\mathrm{Ln}(\Delta T) = & -7.357259335 \\
& + 0.3236247525 \cdot \mathrm{igauge} \\
& + \mathrm{Match}(\mathrm{insul}) \begin{pmatrix} 1 & \Rightarrow 0.2857404512 \\ 2 & \Rightarrow -0.285740451 \\ \mathrm{else} & \Rightarrow . \end{pmatrix} \\
& + -0.012069208 \cdot \mathrm{pamb} \\
& + -0.001464096 \cdot \mathrm{tamb} \\
& + 1.8789611792 \cdot \mathrm{log\_Current} \\
& + \mathrm{Match}(\mathrm{Wire\ Conductor}) \begin{pmatrix} \text{"Cu"} & \Rightarrow 0.3465408316 \\ \text{"HSCu"} & \Rightarrow -0.118142685 \\ \text{"UHSCu"} & \Rightarrow -0.228398147 \\ \mathrm{else} & \Rightarrow . \end{pmatrix} \\
& + (\mathrm{pamb} - 50.6625) \cdot ((\mathrm{pamb} - 50.6625) \cdot 0.0001443914) \\
& + (\mathrm{pamb} - 50.6625) \cdot ((\mathrm{tamb} - 13.333333333) \cdot 0.0000510758) \\
& + (\mathrm{pamb} - 50.6625) \cdot ((\mathrm{log\_Current} - 2.8360369257) \cdot 0.0021659511)
\end{aligned}
$$

Thermal Modeling – Wire Bundle Models



Wire Bundle Thermal Model Schematic (Partial)

Thermal Modeling – Wire Bundle Models

R_{L0}	Resistance/length at a reference temperature
T_0	Reference temperature
α	Temperature coefficient of resistance
r_c	Conductor radius
r_s	Jacket radius
k_w	Jacket effective thermal conductivity
I	Current flow
ε	Jacket infrared emissivity
h	Convective heat transfer coefficient
f_h	Convection coefficient scaling
T_c	Conductor temperature
T_s	Jacket surface temperature
T_e	Environment temperature
σ	Stefan-Boltzmann constant
G_{int}	Wire jacket to wire jacket interface conductance

Key

Measured Parameter

Calculated Parameter

Test Parameter

Constant Parameter

Correlation Parameter

Test Design

- Design of Experiments (DOE) techniques used to formulate test single wire and wire bundle test matrices.

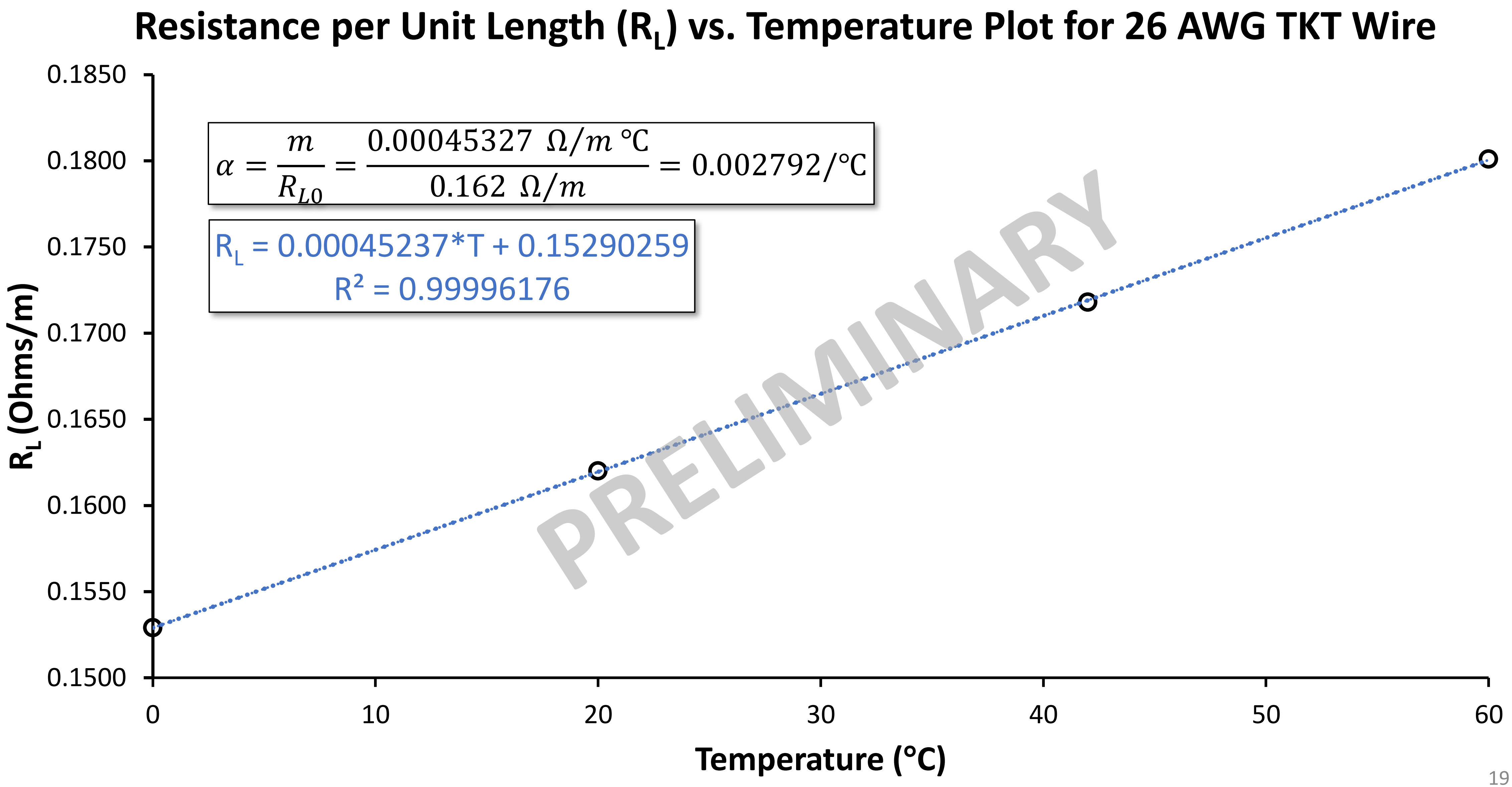
Test Article	WPB	AWG	Insul_Wt	Insul_Type	Conductor	Plating	Pressure_atm	Shroud Temp	Status
1	1	20	LW	ETFE	CuHS	Ag	0	-50	Completed
1	1	20	LW	ETFE	CuHS	Ag	0	70	Completed
1	1	20	LW	ETFE	CuHS	Ag	1	20	Completed
2	32	20	LW	ETFE	CuHS	Ag	0	20	Completed
2	32	20	LW	ETFE	CuHS	Ag	1	70	Completed
2	32	20	LW	ETFE	CuHS	Ag	1	-50	Completed
				⋮	⋮	⋮	⋮		
27	149	22	LW	ETFE	Cu	Ni	0	70	New
27	149	22	LW	ETFE	Cu	Ni	1	20	New
28	149	26	NW	TKT	CuHS	Ag	0.5	-50	New
28	149	26	NW	TKT	CuHS	Ag	1	70	New
28	149	26	NW	TKT	CuHS	Ag	0	20	New
29	10	8	NW	ETFE	Cu	Ag	1	70	New
29	10	8	NW	ETFE	Cu	Ag	0	-50	New
29	10	8	NW	ETFE	Cu	Ag	0.5	70	New

Obtaining Key Test Data

- Wire resistance per unit length as a function of temperature is determined using an oil bath technique.
- Data collected are used to determine the temperature coefficient of resistance.

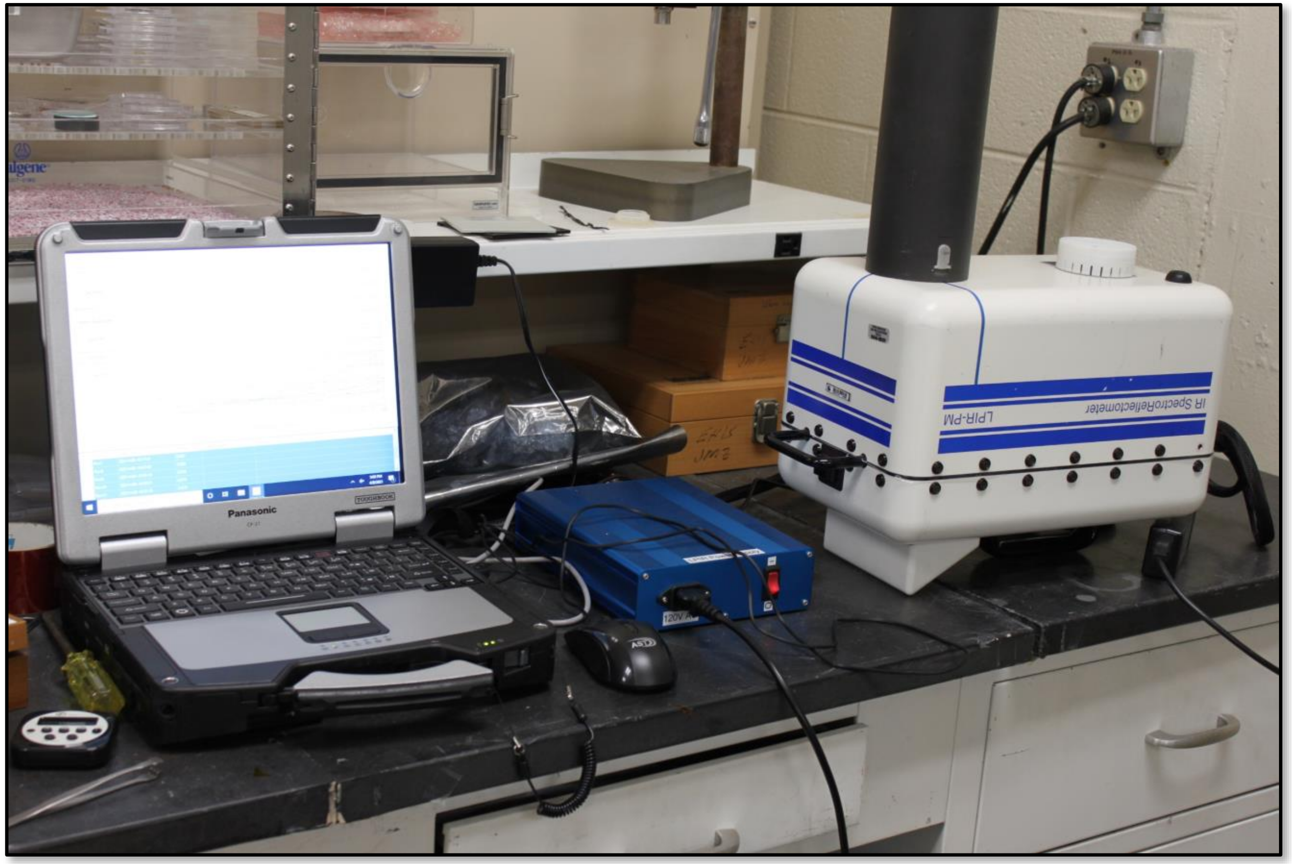
Polyscience Temperature Bath

Obtaining Key Test Data



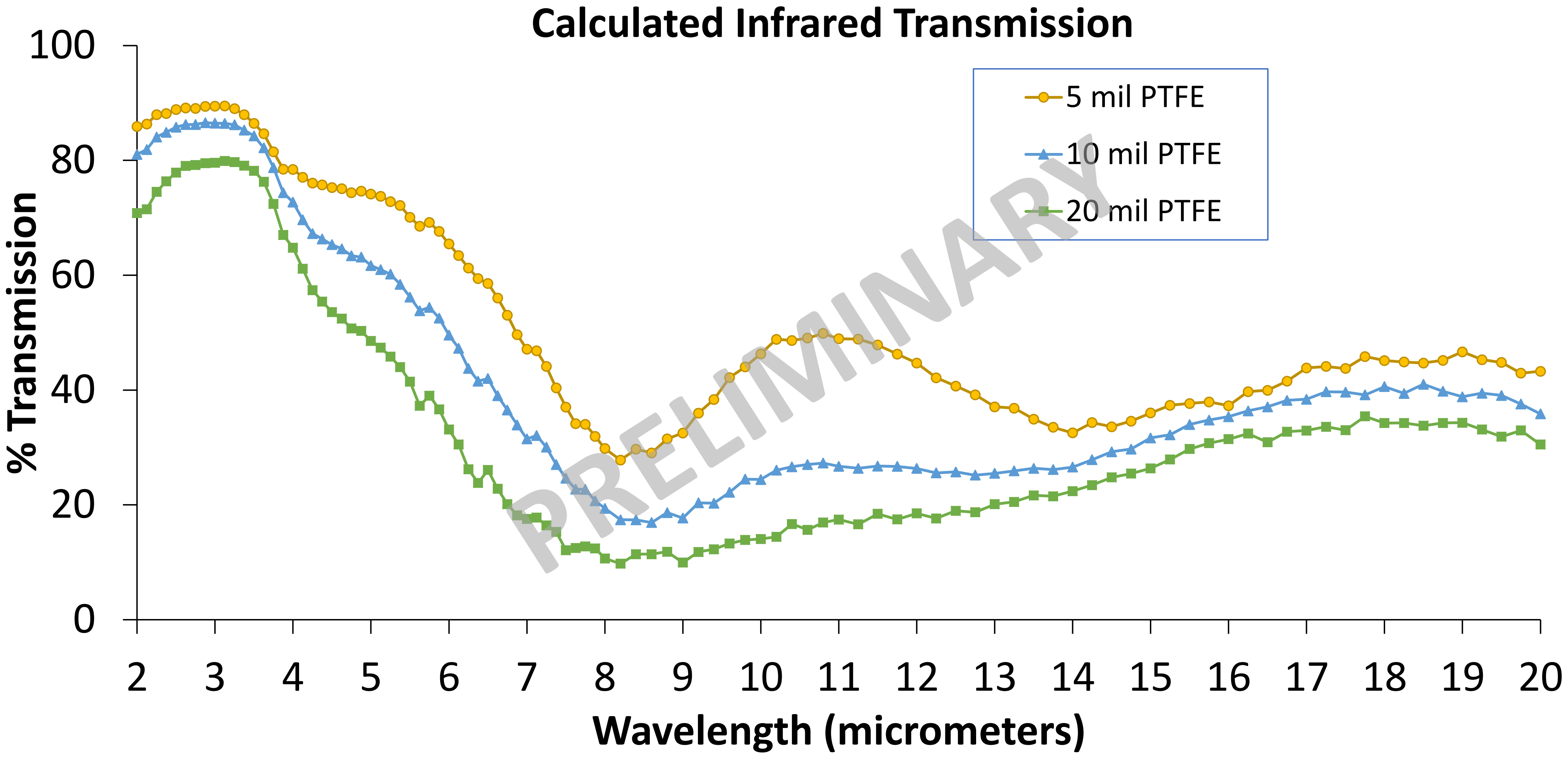
Obtaining Key Test Data

- Infrared reflectance measurements using the AZ Technology Laboratory Portable Spectroreflectometer (LPIR), with both gold and blackbody backgrounds and calculating the transmission per NASA/TP-2019-220552.
- Will develop IR transmissivity as a function of temperature for use in single wire model.



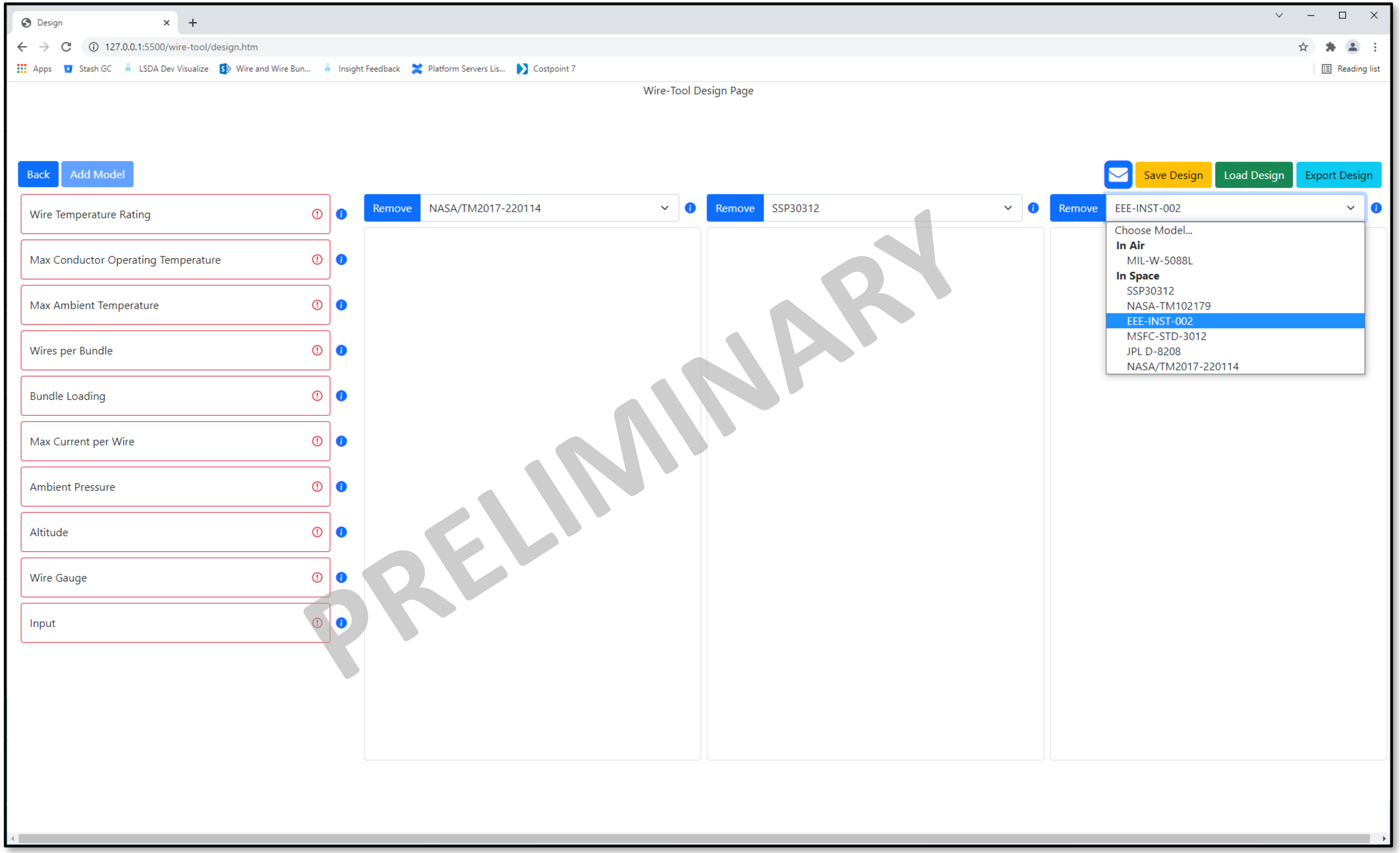
LPIR with blackbody over sample

Obtaining Key Test Data



Design Aid Tool

- Design Aid Tool envisioned to allow users opportunity to size bundles based on predictions from assessment models and various standards.



Current Status

- Vacuum chamber fabricated.
- Chamber shroud modifications completed.
- Test matrices defined using Design of Experiments (DOE)
- Wire materials ordered and some have arrived.
- Test article fabrication underway.
- Wire property data collection in progress.
- Analytical models updated and pre-test analysis is completed.
- Analysis case DOE developed and cases run – used for initial regression models.
- Design Aid Tool requirements are complete and initial coding is underway.

Forward Work

- Complete wire property measurements
- Set up test chamber
- Conduct single wire and wire bundle testing
- Correlate thermal models to test data
- Run DOE model cases using correlated model and generate regressions
- Complete Design Aid Tool

Reference

1. Rickman, Steven L., et al., Re-Architecting the NASA Wire Derating Approach for Space Flight Applications, available from: https://ntrs.nasa.gov/citations/20180007922

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