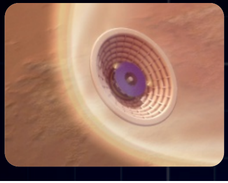

Flexible Thermal Protection System Design and Margin Policy

Anthony M. Calomino[1], John A. Dec[1], and Joseph A. Del Corso[1]
Roy M. Sullivan[2], Eric H. Baker[2] and Peter J. Bonacuse[2]

(1)NASA Langley Research Center, MS 431 Hampton VA 23681, USA
Anthony.M.Calomino@nasa.gov, John.A.Dec@nasa.gov, Joseph.A.Delcorso@nasa.gov
(2)NASA Glenn Research Center, MS 49-3, Cleveland OH 44135, USA
Roy.M.Sullivan@nasa.gov, Eric.H.Baker@nasa.gov, Peter.J.Bonacuse@nasa.gov

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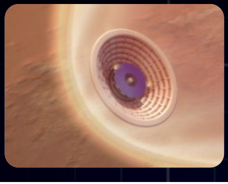
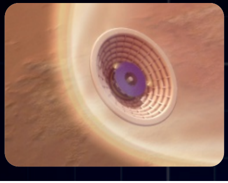


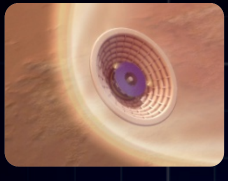
Introduction

- Design of Thermal Protection System (TPS) is critical to successful planetary atmospheric entry.
- Design of a TPS depends on several analysis stages having inherent and unavoidable uncertainty
  - Prediction of aerothermal environment
  - Prediction of material thermal properties
  - Prediction of material response to environment.
- Uncertainty conventionally handled with stacked, conservative margins that are often overly conservative.
- Conservative margin policies lead to increased TPS mass.
- Improved modeling and increased understanding with rational uncertainty treatment can result in TPS mass fraction reduction.

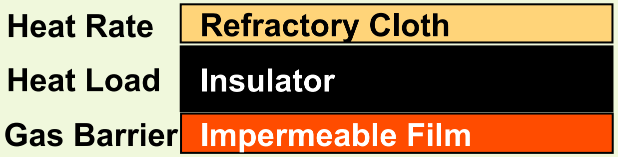


Thermal Margin Policy Objectives

- Investigate and reliably model the thermal management mechanisms for f-TPS using physics based formulations.
- Establish a margins policy for f-TPS that treats model and response uncertainty using a Monte Carlo methods.
- Couple f-TPS sizing to trajectory dispersion analysis.
- Predict temperature profile distributions that can be used to establish reliability intervals.



HIAD f-TPS Development

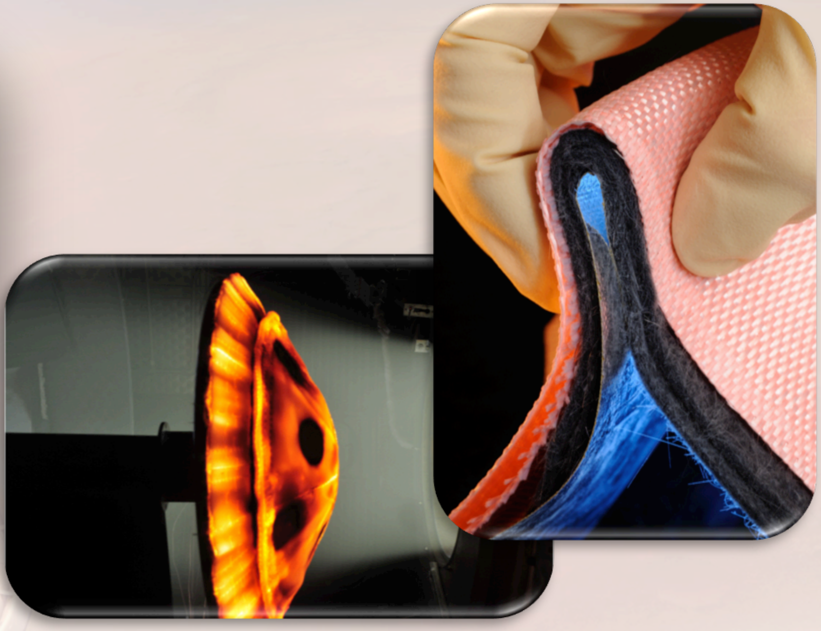


Heat Rate | **Refractory Cloth**

Heat Load | **Insulator**

Gas Barrier | **Impermeable Film**

Modular design using functional layers



Gen 1 TPS

Arc-jet Testing

Class & Size	**Capability**	**TPS Performance**
1st Generation	***30 Watts/cm2, 5000 Joules/cm2 class***	***1350°C Aluminosilicate refractory cloth and Pyrogel insulator layer at 5kg/m^2 areal weight***
2nd Generation	***50 Watt/cm^2, 7500 Joules/cm^2 class***	***1650°C Silicon carbide cloth and insulator layers at 4kg/m^2 areal weight***

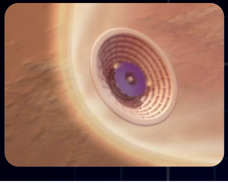
Flexible Heat Shield Concept

- Material selected based on temperature, stowage, and handling capability.
- Capability to manufacture large-scale, >6 m, f-TPS.
- Utilize commercial manufacturing base with acceptable quality control.

3-m IRVE-3 f-TPS

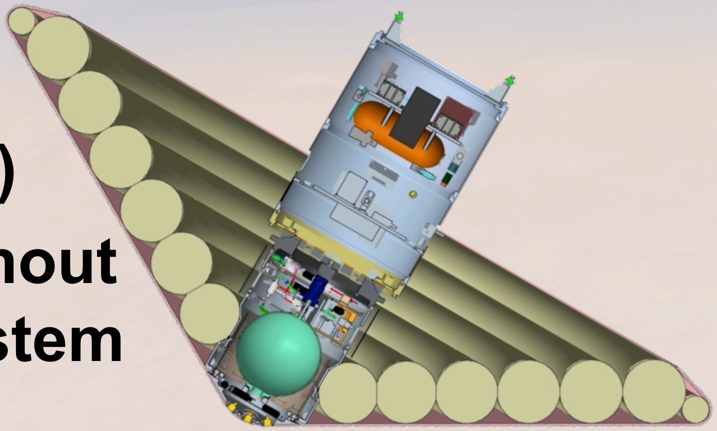
Packed 3-m f-TPS

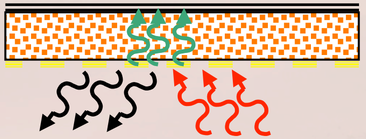
Integrated 3-m f-TPS



Soft-good Materials

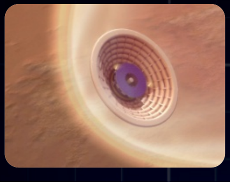
- Allow aeroshell to be packed to relatively high density (400 kg/m^3)
- Allow tight folds and creases without damage to thermal protection system
- Allow for accurate and reliably prediction of thermal response.
- Deploy after stowage without significant detriment to thermal response.





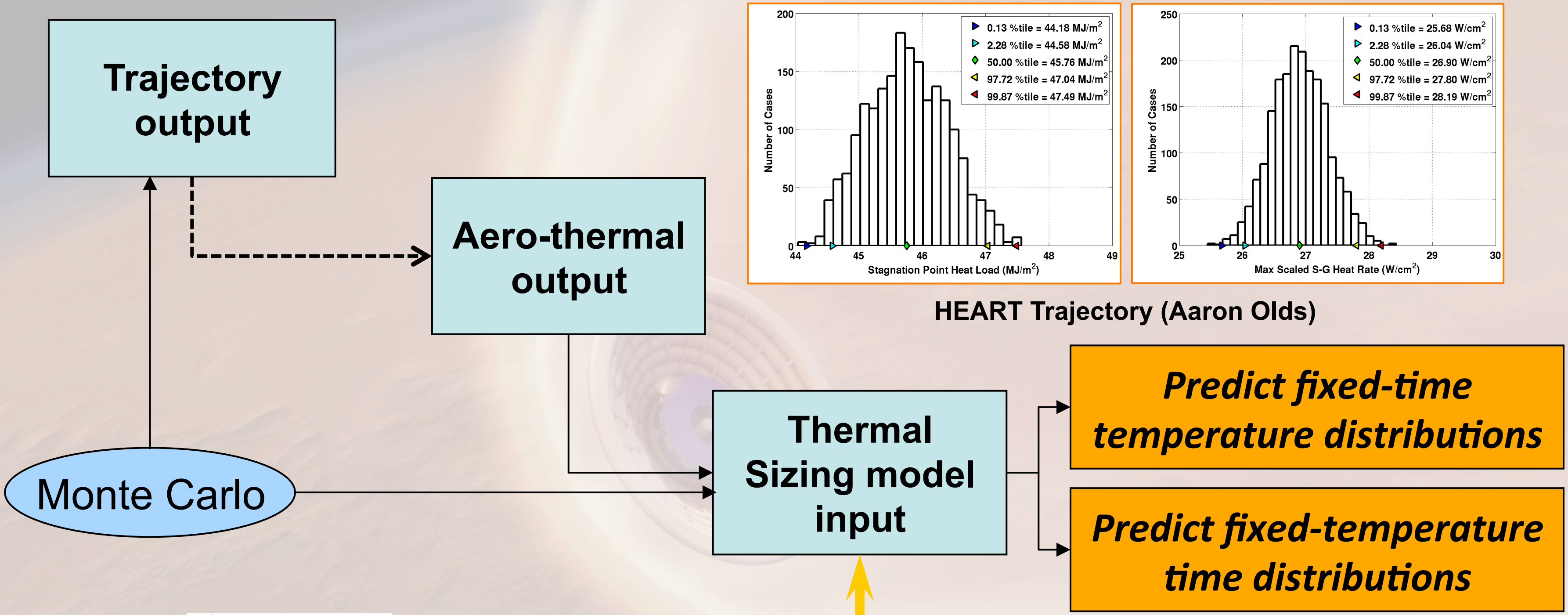
Thermal Protection Layer

Materials:
Aluminosilicate and silicon carbide cloth, fibrous insulators, aerogels, opacifiers, thin film polyimides



f-TPS Margins Policy Approach

f-TPS sizing pipelined within trajectory and aerothermal dispersion analysis



Trajectory output

Aero-thermal output

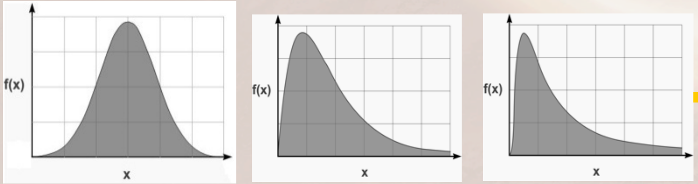
Monte Carlo

Thermal Sizing model input

Predict fixed-time temperature distributions

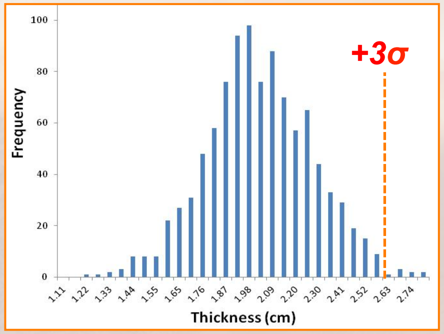
Predict fixed-temperature time distributions

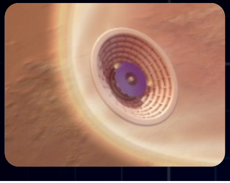
HEART Trajectory (Aaron Olds)



Normal Gamma Lognormal

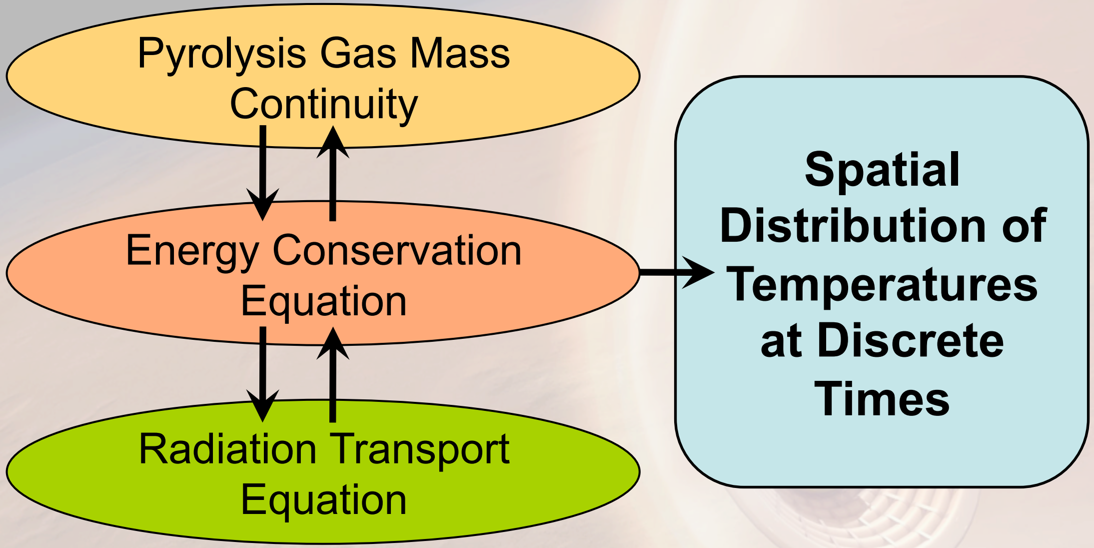
f-TPS Key Property Distribution

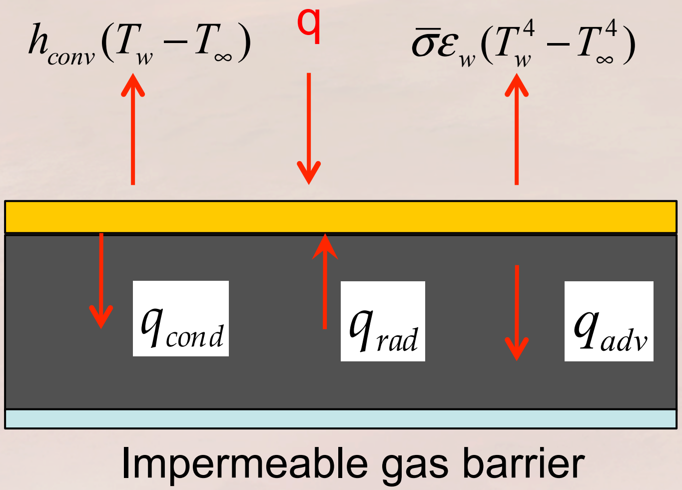




f-TPS Thermal Model

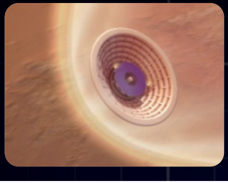
High fidelity thermal model of flexible f-TPS materials under development using COMSOL





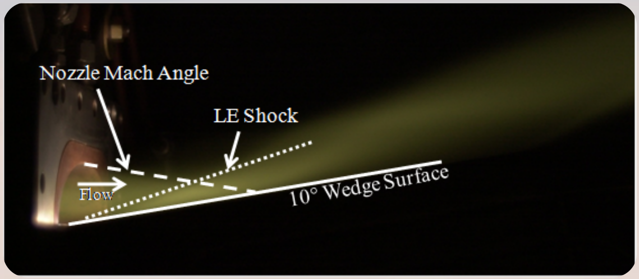
$$\underbrace{\left((1-\phi)\rho_s C_{p_s} + \phi\rho_g C_{p_g}\right)\frac{\partial T}{\partial t}}_{\textbf{Capacitance}} - \underbrace{\frac{\partial}{\partial x}\left(\left((1-\phi)K_s + \phi\, K_g\right)\frac{\partial T}{\partial x}\right)}_{\textbf{Conduction}} + \underbrace{\frac{\partial}{\partial x}\left(\rho_g h_g v_g\right)}_{\textbf{Advection}} + \underbrace{h_R \frac{d\rho_s}{dt}}_{\textbf{Pyrolysis}} - \underbrace{\frac{\partial q_{rad}}{\partial x}}_{\textbf{Radiation}} = 0$$

Thermal model requires the simultaneous, time-accurate solution of three coupled differential equations:



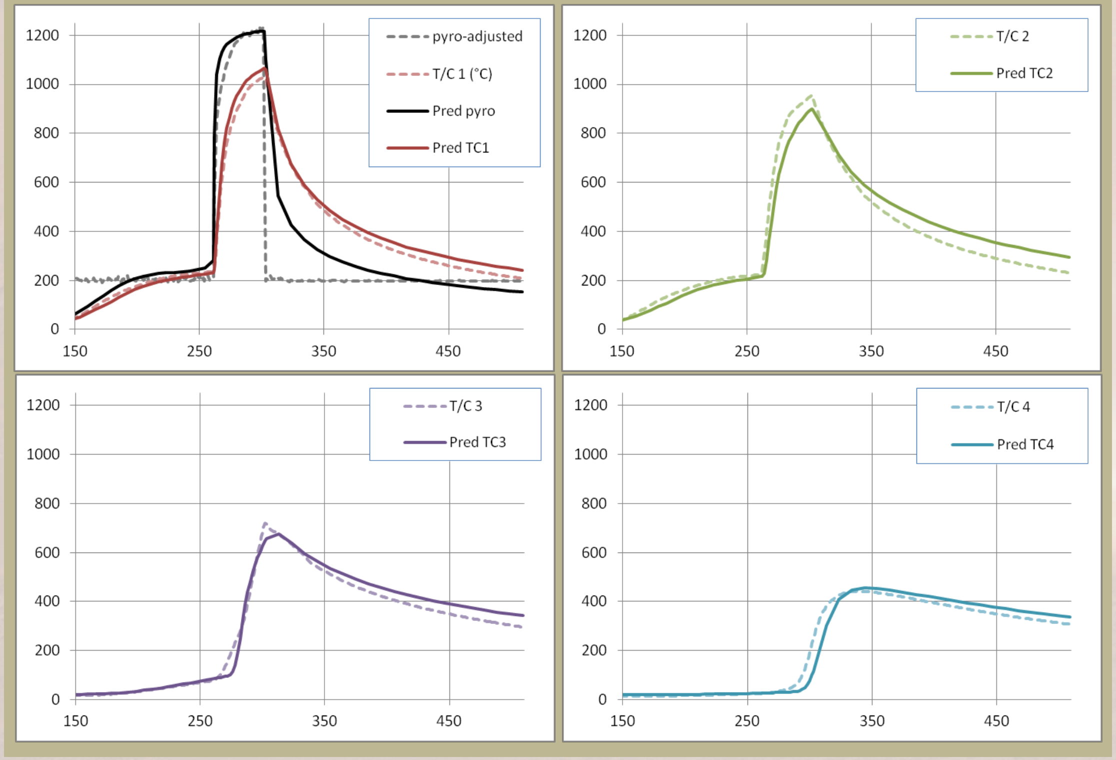
Thermal Model Response

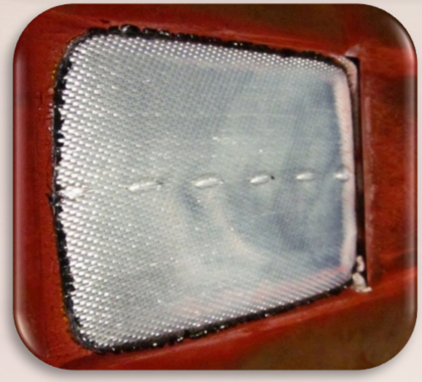
- **Thermal model validation and verification through ground based arc-jet tests**
  - **Shear coupons**
  - **Stagnation coupons**



Arc-jet Shear Testing

Model Shear Predictions (IRVE-3) ***Temp. (°C) vs. time (s)***

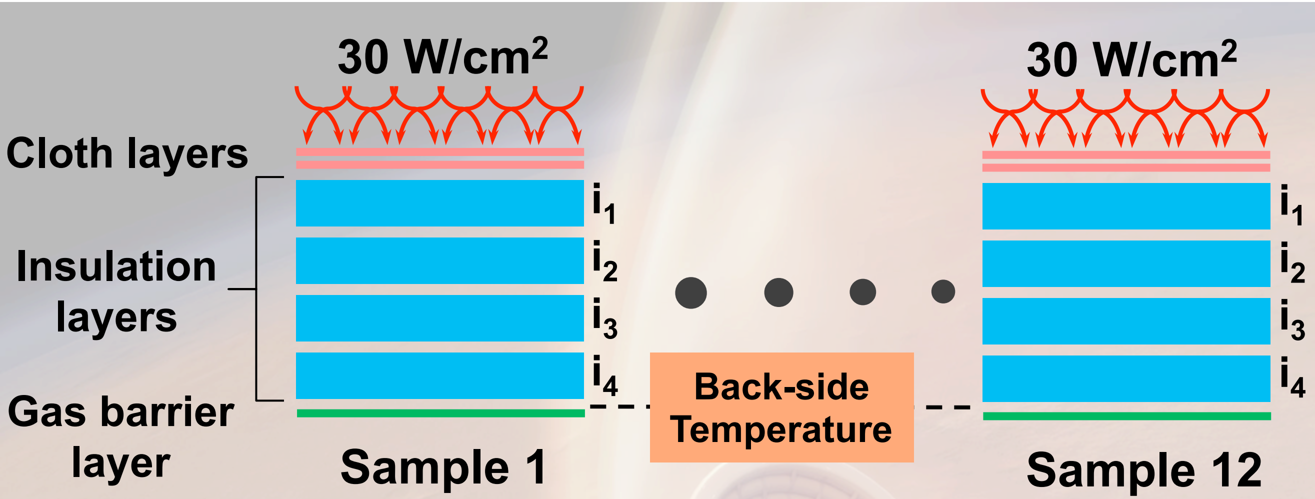


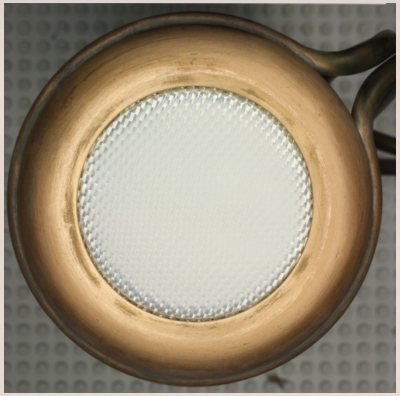


Post-test Sample

Instrumentation

Thermal Model Validation Study

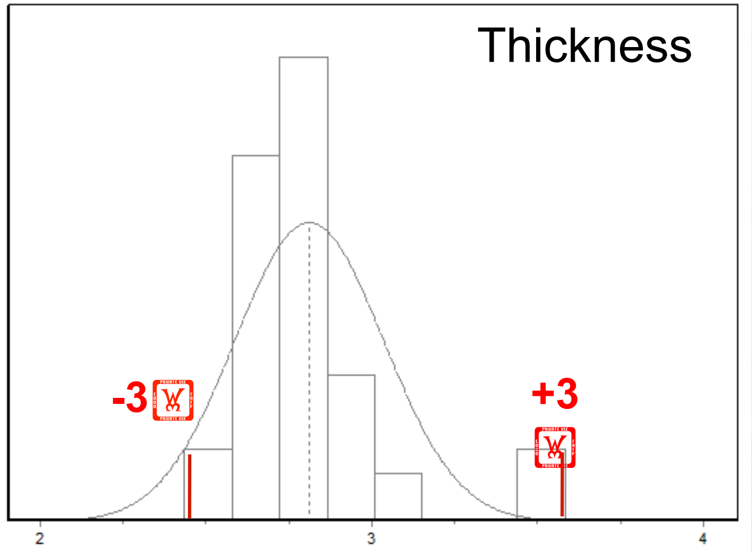


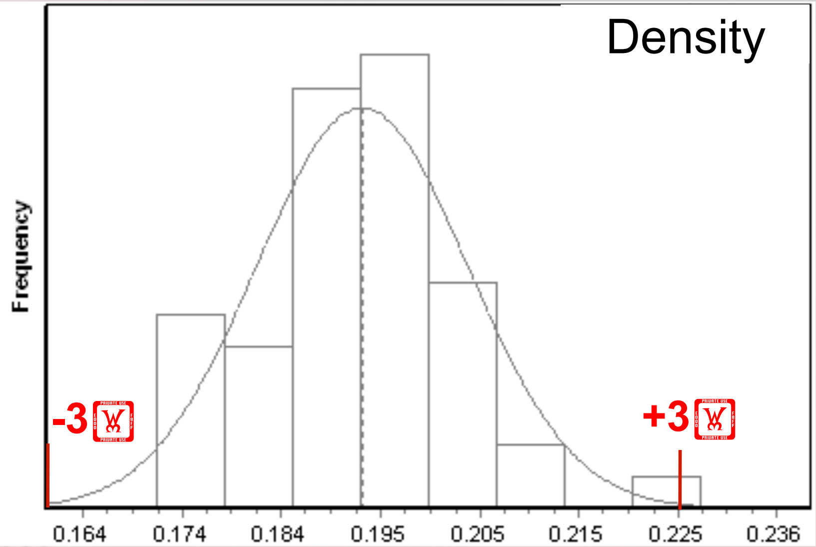


50 mm Stagnation Test

- Total test sample size of 50.
- Insulation layer weight independent random variable.
- Assembled 2 light- and 2 heavy-weight samples to investigate distribution tails.
- 12 nominally identical samples selected at random from remaining pool of 46 samples.
- Exposure time to a backside temperature of 300°C defined as dependent random variable.

Thickness and Density Distributions



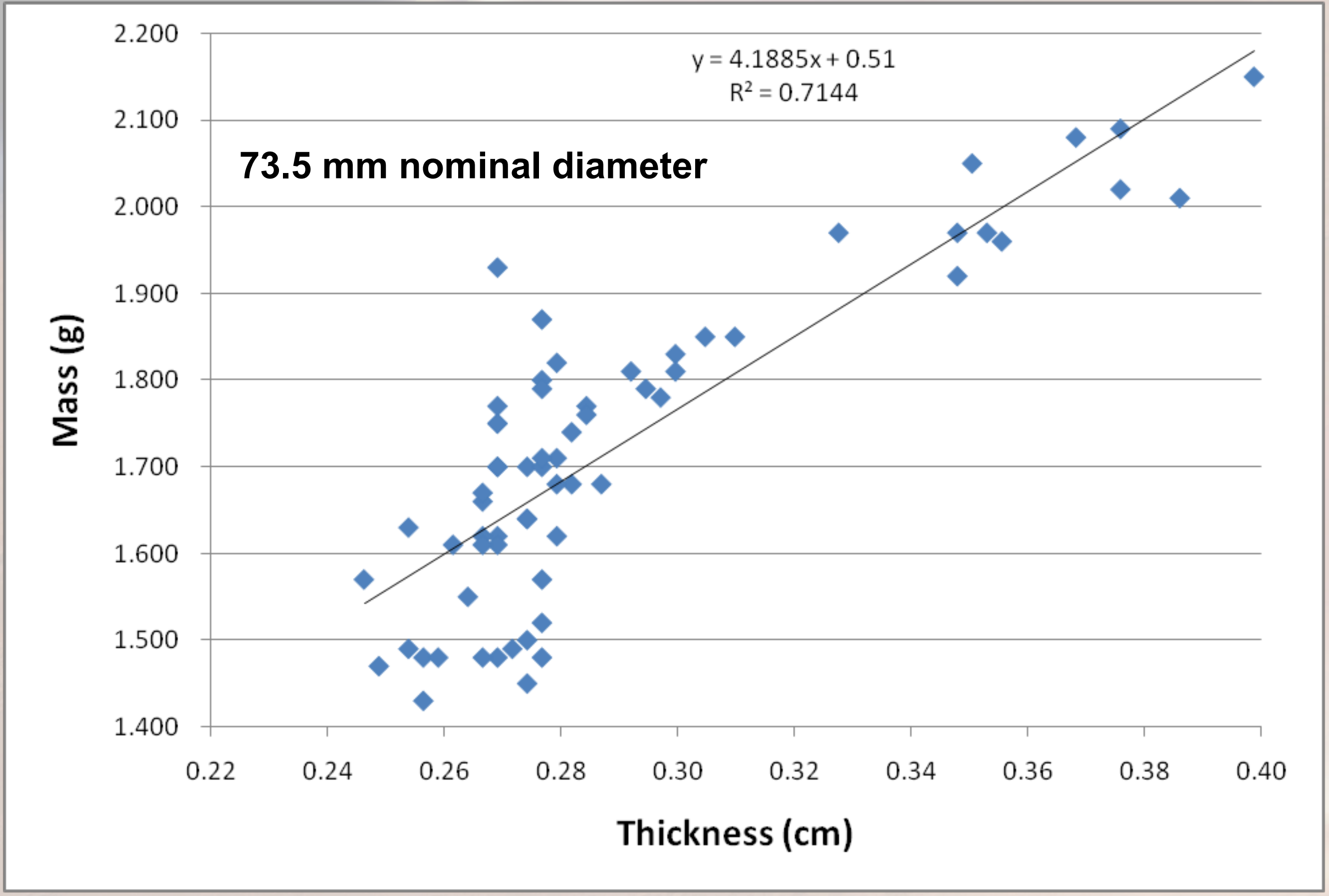


	Thickness	Density
	mm	g / cm^3
MIN	2.464	0.173
MAX	3.556	0.226
MEAN	2.813	0.193
STDEV	0.224	0.011
$\mu-3\sigma$	2.140	0.160
$\mu+3\sigma$	3.485	0.225

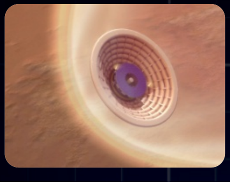
Distributions derived from measurements on 16 specimens (48 layers)

Specimens Weight vs. Thickness

64 Layers from 12 Random, 2 Light and 2 Heavy Specimens

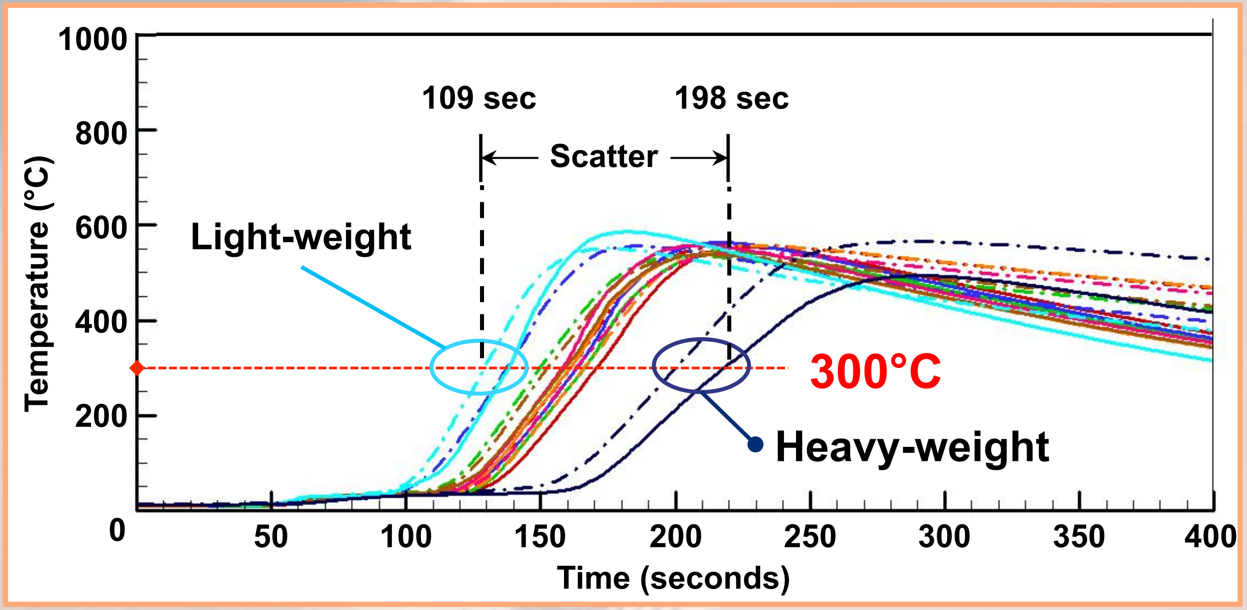


Apparent correlation between thickness and areal weight



Thermal Model Validation Results

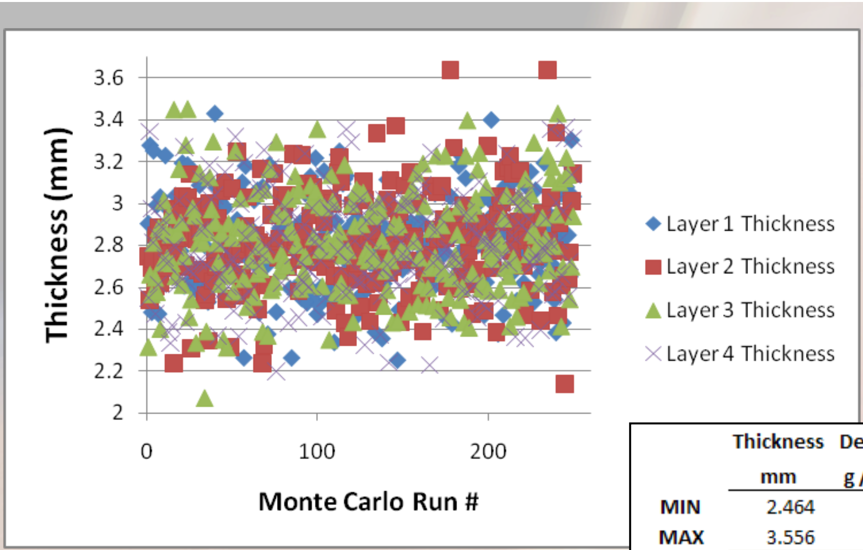
Back-side temperature-time profile (all samples)

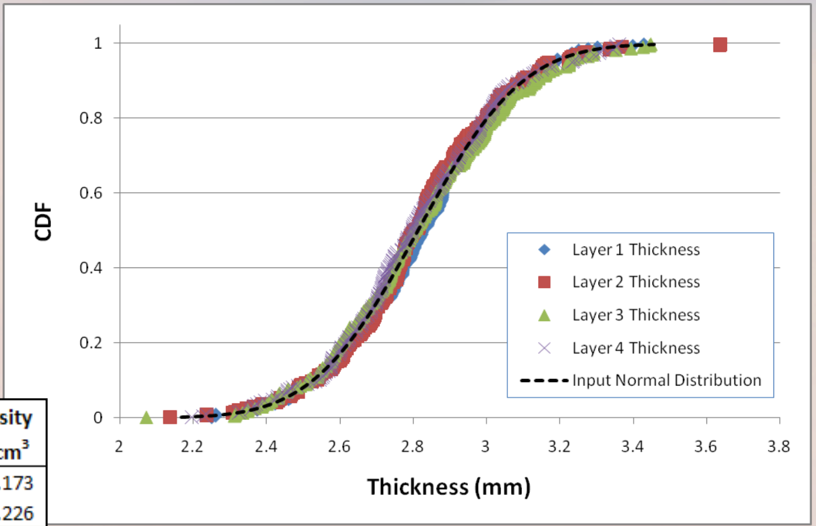


142 seconds average time to a back-side temperature of 300°C
76-second -3 time to a back-side temperature of 300°C

- Back-side temperature shows strong correlation with weight.
  - Lightweight → shortest time and heavyweight → longest time
- Nominally identical samples weighted toward lightweight result.

Randomly Generated Layer Thickness





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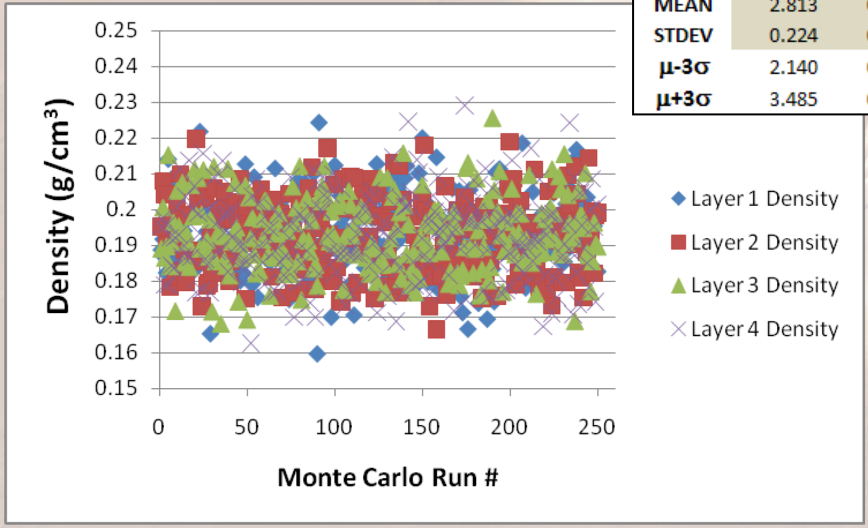
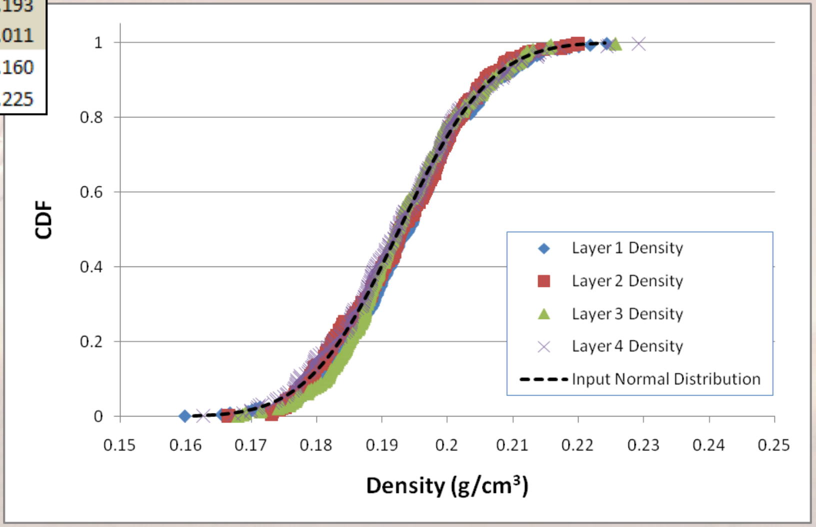
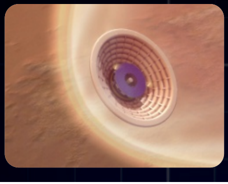






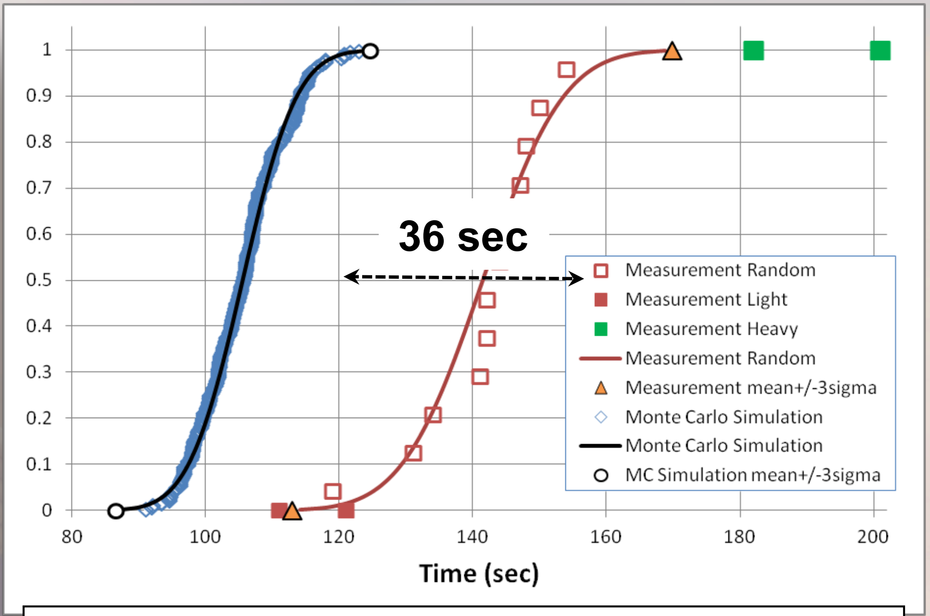
Gas Barrier Time to 300°C

Key Difference

- **Analysis used previous insulator properties**
- **Current insulator similar chemistry/structure but must be characterized.**

Model Physics

- **Sample compression effect**
- **Gas advection**
- **Pyrolysis/decomposition.**
- **Permeability/Diffusivity changes**

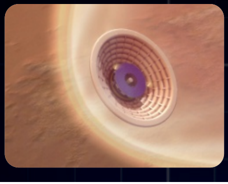


	Measurement	Prediction	Difference	Relative Difference
COUNT	12	250		
MIN	119.00	91.02	-27.98	-23.5%
MAX	154.00	123.02	-30.98	-20.1%
MEAN	141.42	105.54	-35.88	-25.4%
STDEV	9.50	6.36	-3.14	-33.1%
$\mu-3\sigma$	112.91	86.47	-26.45	-23.4%
$\mu+3\sigma$	169.92	124.61	-45.31	-26.7%
Thin	116.00	97.80	-18.20	-15.7%
Thick	191.50	152.71	-38.79	-20.3%

250 virtual samples analyzed

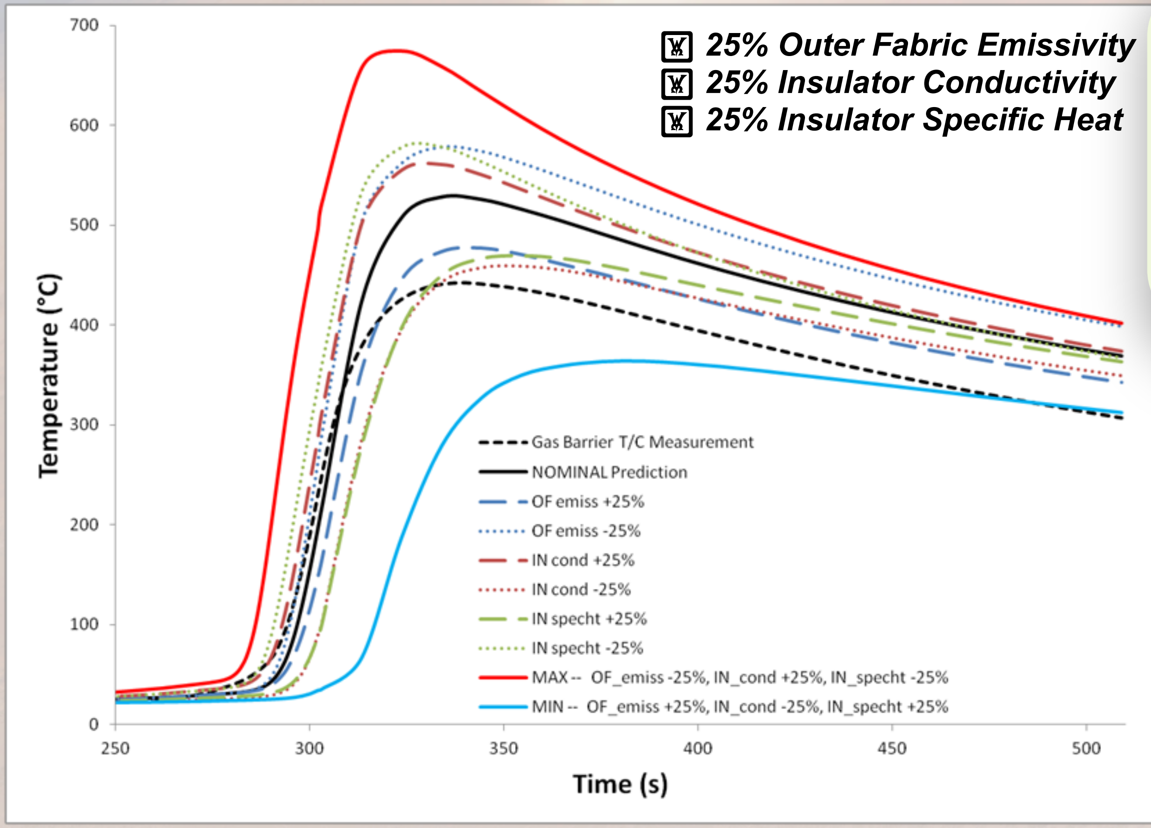
Conclusions

- A margin policy assembled for f-TPS that addresses response uncertainty using Monte Carlo techniques.
- f-TPS thermal response model has been coded within COMSOL using a physics-based formulations.
- Thermal model shows good correlation with Gen-1 f-TPS response **under** shear aerothermal loading.
- Gen-1 f-TPS validation data set will be examined to improve understanding and modeling capability.
- Additional material measurements are required to improve the fidelity:
  - Acquire properties for new insulator
  - Permeability/diffusivity
  - Pyrolysis/decomposition

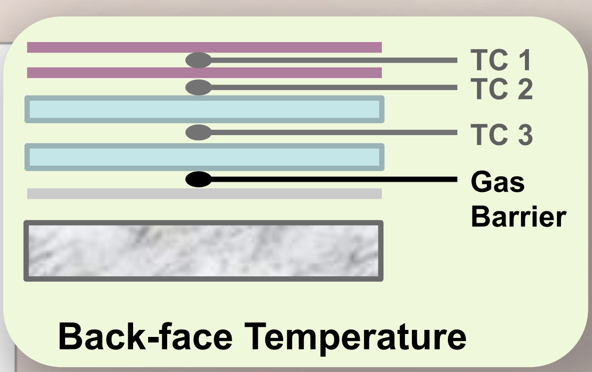


Thermal Model Sensitivity

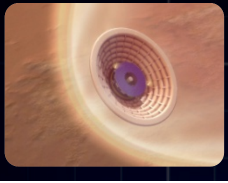
- **Each parameter varied independently of the other two**
- **One case where all three were set to generate the highest thermal profile**
- **Variation of ± *25% completely arbitrary (material characterization on-going)***



± 25% Outer Fabric Emissivity
± 25% Insulator Conductivity
± 25% Insulator Specific Heat



Back-face Temperature



Insulation Layer Measured Properties

	LCAT Run Number	LCAT Sample Name	Pre-Test Thickness (mm)				Pre-Test Mass (g)				Pre-Test Density (g/cm^3)			
			Layer 1	Layer 2	Layer 3	Layer 4	Layer 1	Layer 2	Layer 3	Layer 4	Layer 1	Layer 2	Layer 3	Layer 4
RANDOM	2337	STAG-8C	2.769	2.743	2.794	2.845	1.87	1.64	1.82	1.77	0.213	0.189	0.206	0.196
	2337	STAG-8G	2.692	2.692	3.099	2.769	1.70	1.61	1.85	1.79	0.199	0.189	0.189	0.204
	2338	STAG-9C	2.464	2.692	3.048	2.769	1.57	1.75	1.85	1.70	0.201	0.205	0.192	0.194
	2338	STAG-9G	2.997	2.819	2.769	2.616	1.83	1.68	1.80	1.61	0.193	0.188	0.205	0.194
	2339	STAG-10C	2.794	2.667	2.946	2.794	1.71	1.62	1.79	1.62	0.193	0.192	0.192	0.183
	2339	STAG-10G	2.743	2.718	2.540	2.845	1.50	1.49	1.49	1.76	0.173	0.173	0.185	0.195
	2340	STAG-11C	3.480	2.692	2.692	2.667	1.92	1.93	1.70	1.67	0.174	0.226	0.199	0.198
	2340	STAG-11G	2.921	2.769	3.556	2.819	1.81	1.52	1.96	1.74	0.196	0.173	0.174	0.195
	2341	STAG-12C	2.997	2.692	2.642	2.540	1.81	1.77	1.55	1.63	0.191	0.208	0.185	0.203
	2341	STAG-12G	2.692	3.531	2.667	2.972	1.62	1.97	1.66	1.78	0.190	0.176	0.197	0.189
	2342	STAG-13C	2.870	2.743	2.743	2.769	1.68	1.70	1.64	1.71	0.185	0.196	0.189	0.195
	2342	STAG-13G	2.769	2.692	2.794	2.667	1.57	1.75	1.68	1.61	0.179	0.205	0.190	0.191
LIGHT	2343	STAG-14C	2.565	2.489	2.667	2.769	1.48	1.47	1.48	1.48	0.182	0.186	0.175	0.169
	2343	STAG-14G	2.692	2.565	2.591	2.743	1.48	1.43	1.48	1.45	0.174	0.176	0.180	0.167
HEAVY	2344	STAG-15C	3.759	3.759	3.277	3.683	2.09	2.02	1.97	2.08	0.176	0.170	0.190	0.178
	2344	STAG-15G	3.480	3.988	3.861	3.505	1.97	2.15	2.01	2.05	0.179	0.170	0.164	0.185

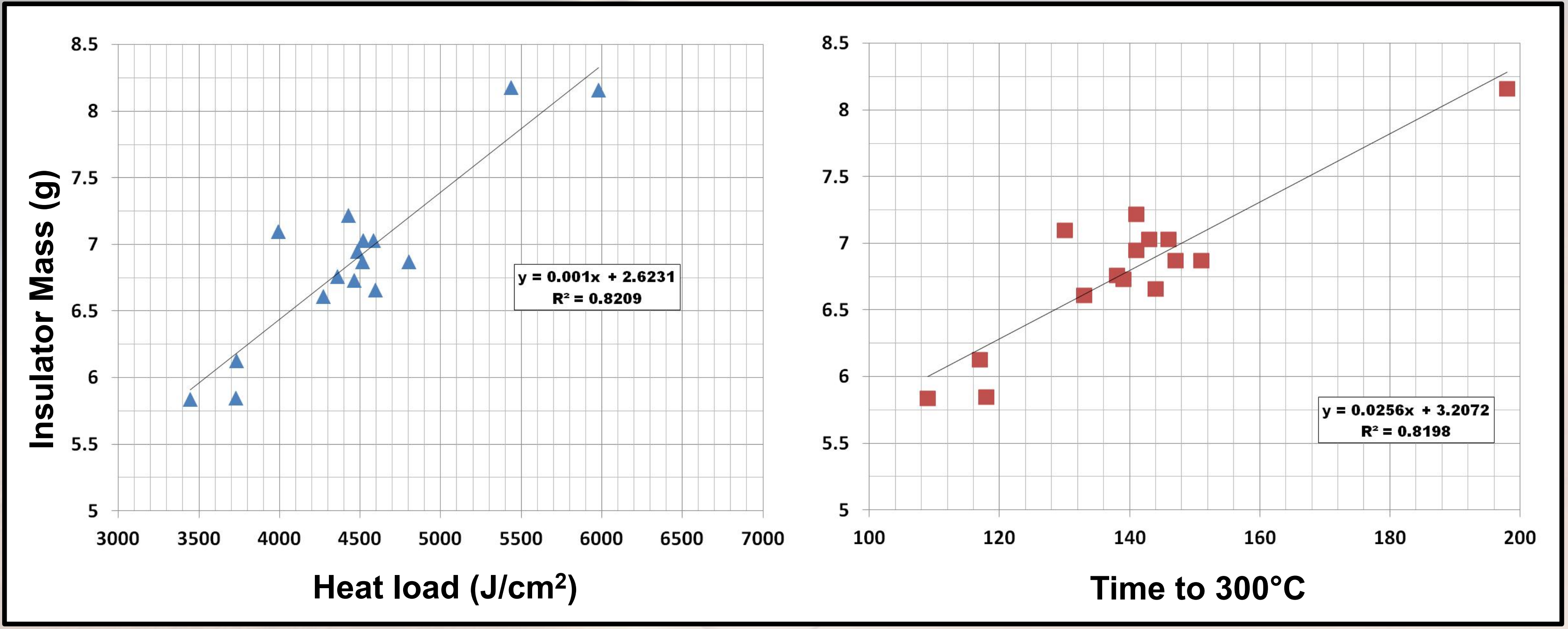
	Mean	StDev
RANDOM	2.813	0.224
LIGHT	2.635	0.098
HEAVY	3.664	0.230

	Mean	StDev
RANDOM	1.713	0.121
LIGHT	1.469	0.019
HEAVY	2.043	0.063

	Mean	StDev
RANDOM	0.193	0.011
LIGHT	0.176	0.007
HEAVY	0.176	0.008

Nominal Acreage Diameter: _2.5 in_

Insulator Weight Dependence



Heat load and time to 300°C show good dependence on total insulator weight