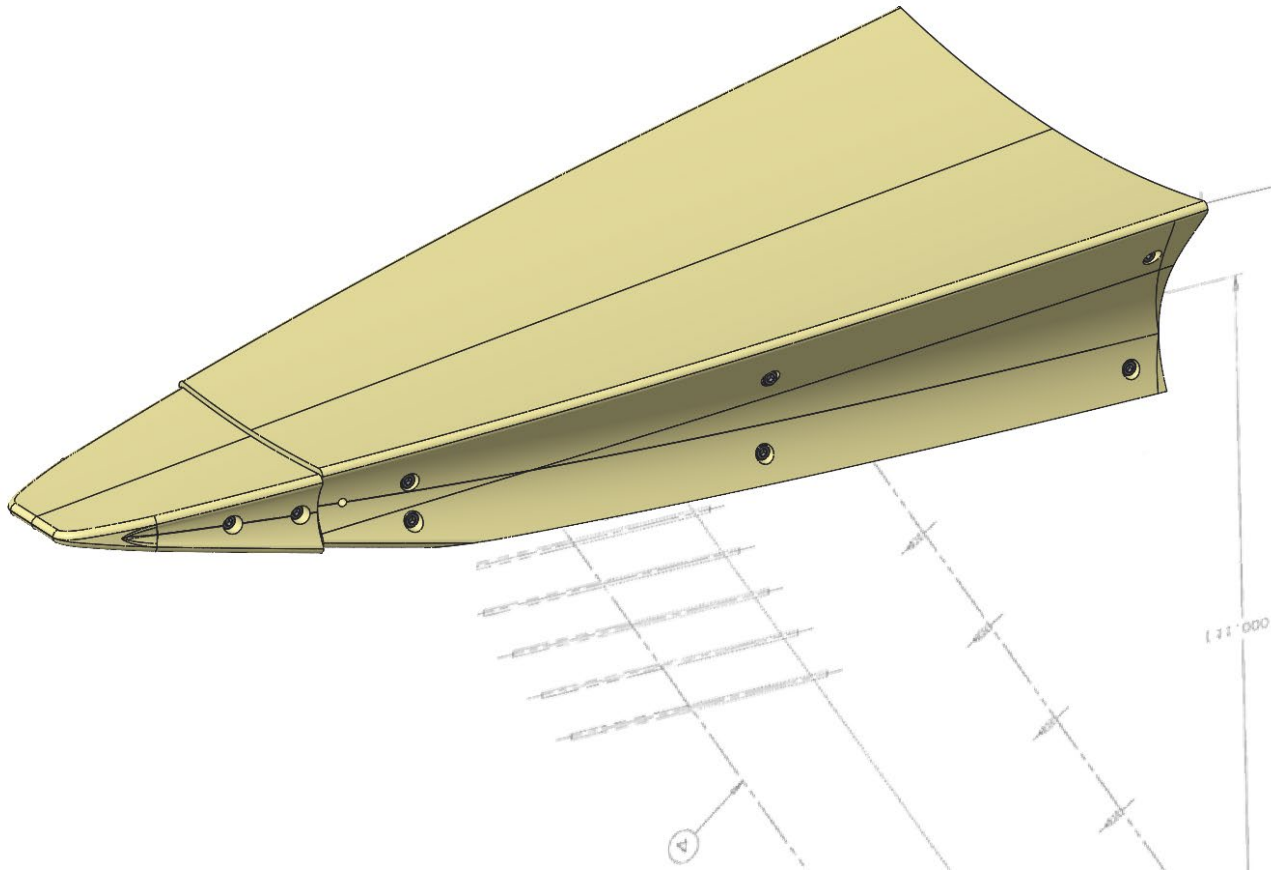


Presented to:
AIAA Aviation
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NASA Langley Research Center

Kevin Basore & Stefan Wernz
Raytheon

➤ Project Overview

- ❑ Test Methodology
- ❑ Preliminary Results
- ❑ Discussion
- ❑ Future Work

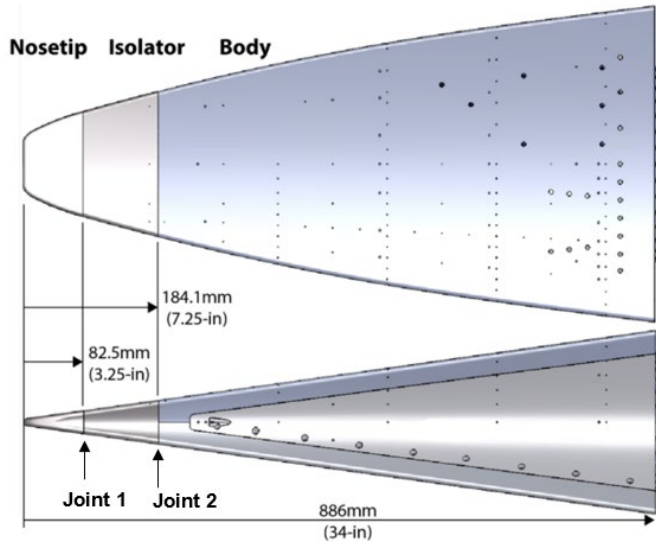


Figure 1. BOLT I Flight Vehicle Design.

BOLT: BOundary Layer Transition Hypersonic Flight Test

AFOSR funded study of hypersonic boundary layer transition in simple conical shapes to develop new physics-based transition prediction tools.

Why BOLT Step Test?

- The Boundary Layer Transition (BOLT I) flight test article was designed with 2 different joints near the nose to accommodate the TPS and isolator materials.
- There are differences in the CTE of the material on either side of the joint.
- The difference in CTE is expected to cause a 2-dimensional step at the joint locations.
- The step on the flight test article was designed to be rearward facing (RF).

The goals of this test include:

- ✓ Demonstration of a quantitative infrared thermographic test technique at LaRC.
- ✓ Complete a parametric study of forward and rearward facing 2-dimensional steps and their impact on the chord-wise transition location (x/L) of the boundary layer from laminar to turbulent in Mach 6 flow by varying flow conditions and step height, k .

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Model Design Concept:

- The BOLT Step Test (BST) model utilized an aluminum 'strongback' for the main body and nose with a PEEK OML for the outer mold line (OML).
- The nose was built as a separate piece with a set of slotted spacers to create offsets for the forward-facing (FF) or rearward-facing (RF) step configurations.

BST Assembly:

- PEEK OML
- Al strongback
- Al nose spacers (multiple)
 - Creates steps in OML
 - Center slot offsets
 - 0.005" increments
 - 1 spacer = 2 steps(+/-)

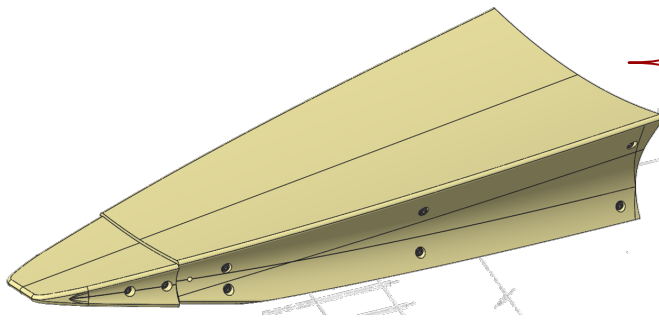


Figure 2. BST Model Design.

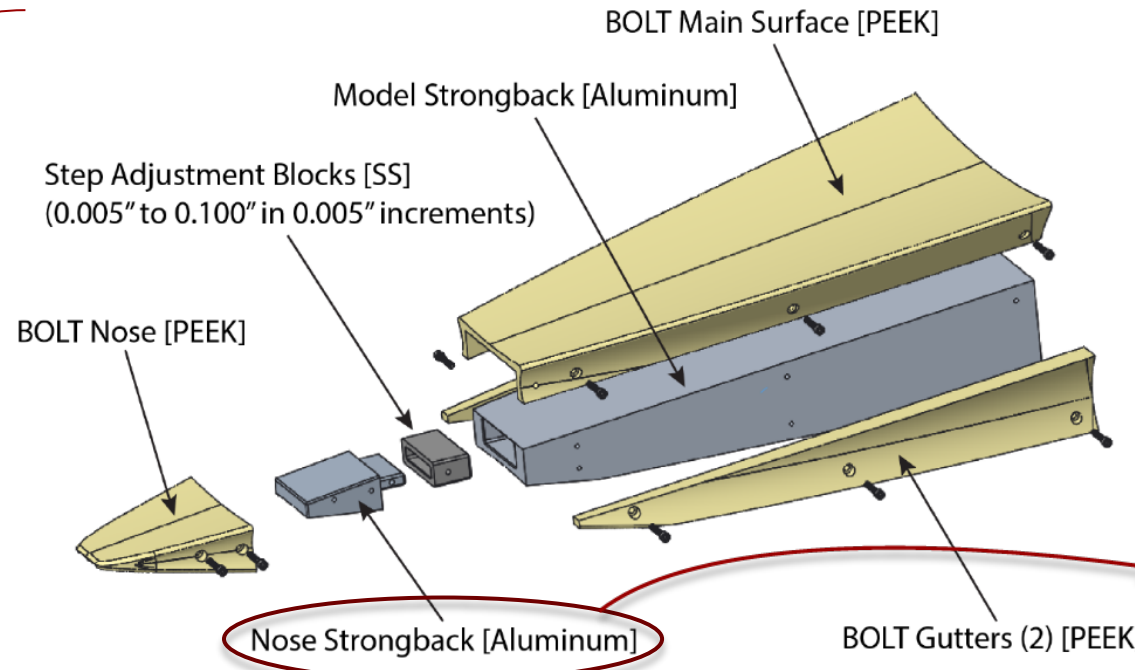


Figure 3. BST Model Exploded View

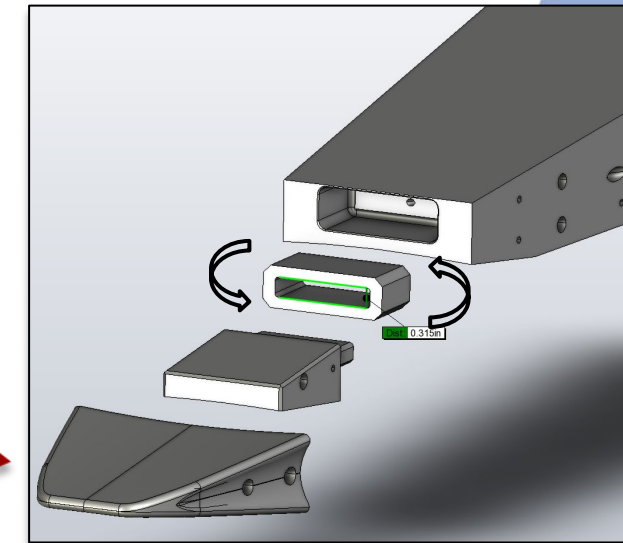


Figure 4. BST Nose and 0-Step Insert



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Model Configuration Values:

- A single insert produced 2 step configurations by rotating the slotted inserts by 180° in roll axis. *All step height measurements was along the model centerline.*
- Resulting step heights were scanned using an optical scanning microscope which lists a height measurement precision of 3.94×10^{-5} inches.
- Significant deviation in as-built results from designed step heights. Primarily due to PEEK OML deformation in thin regions.

Closest to a
no-step case

Table 2. Step Height Values for As-Built Configurations

BST Insert	Step Direction	k_{Measured}		Baseline % ($k_B=0.005\text{-in}$)
		(mm)	(in)	
IR-21b	RF	1.718	0.0676	13.5 k_B
IR-11b	RF	1.101	0.0433	8.7 k_B
IR-06b	RF	0.438	0.0172	3.5 k_B
IR-02b	FF	0.076	0.0030	-0.5 k_B
IR-01a	FF	0.089	0.0035	-0.7 k_B
IR-01b	FF	0.157	0.0062	-1.2 k_B
IR-02a	FF	0.272	0.0107	-2.1 k_B
IR-06a	FF	0.777	0.0306	-6.1 k_B
IR-11a	FF	1.409	0.0554	-11 k_B
IR-21a	FF	2.033	0.0800	-16 k_B

Note: Negative values denote FF steps.

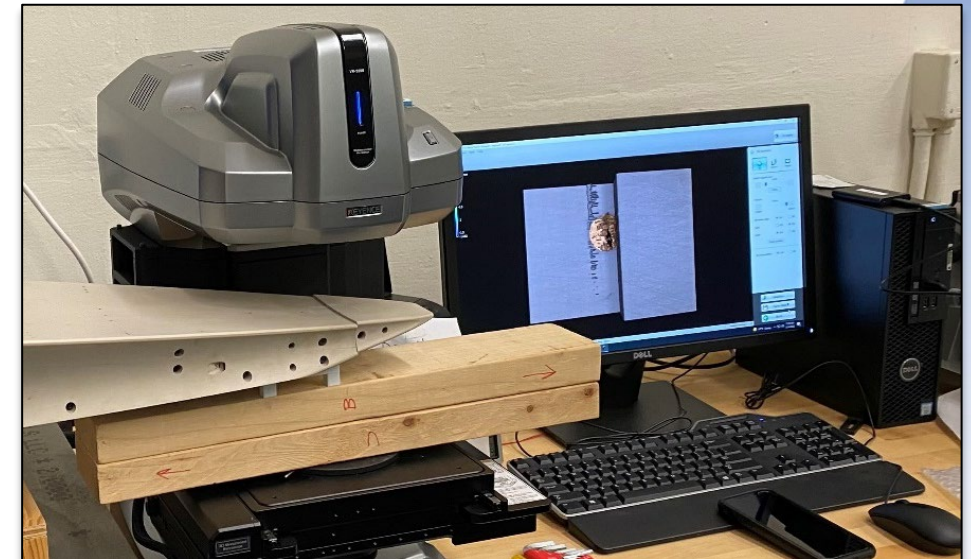


Figure 5. BST Model on Optical Scanner Bench



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Langley Aerothermodynamic Laboratory (LAL):

- Average run time for this test was 10 seconds.
- Reynolds number sweeps from 1.05×10^6 /ft to 7.97×10^6 /ft were conducted for 10 step heights.

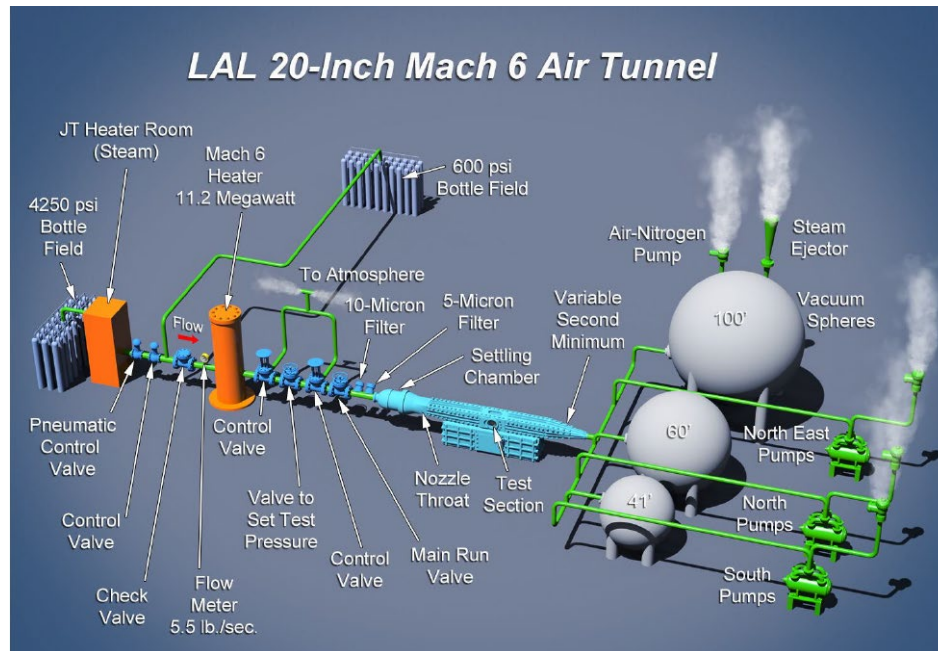


Figure 6. LAL 20-Inch Mach 6 facility in Hampton, VA. [1]

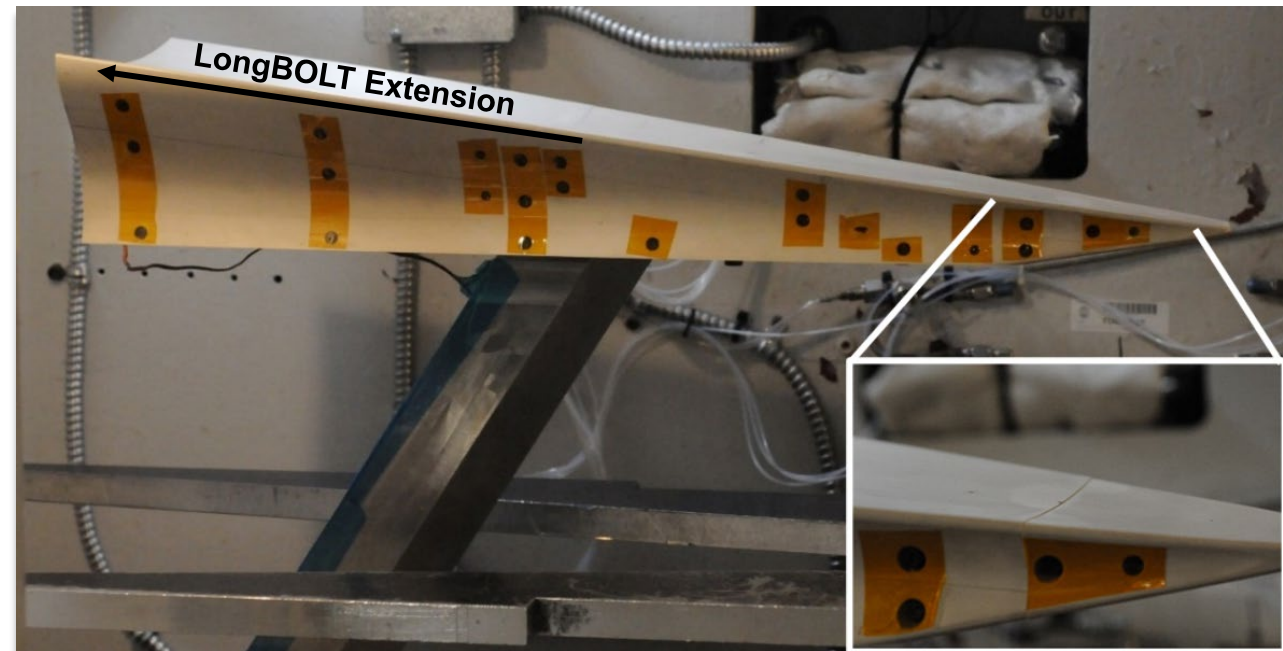


Figure 7. BST Model in the test section. LongBOLT configuration is ~170% BOLT I length.

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IR Thermography Workflow:

- 1) Define calibration coefficients of the Sakuma-Hattori equation for a single integration time of the camera over the range of expected temperatures.
- 2) Export the raw counts from the IR software for a pre-run frame and at frame 300 during the test entry.
- 3) Apply calibration equation to all pixels to get the transfer from Counts > Temp(K) > Temp(C) then export as .csv files.
- 4) Import the temperature .csv files to IHEAT for processing to heat transfer and non-dimensionalize by Fay-Riddell film coefficient reference values.
- 5) Extract line cuts along regions of interest using the built-in IHEAT profiling tool.

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IR Camera System Specs:

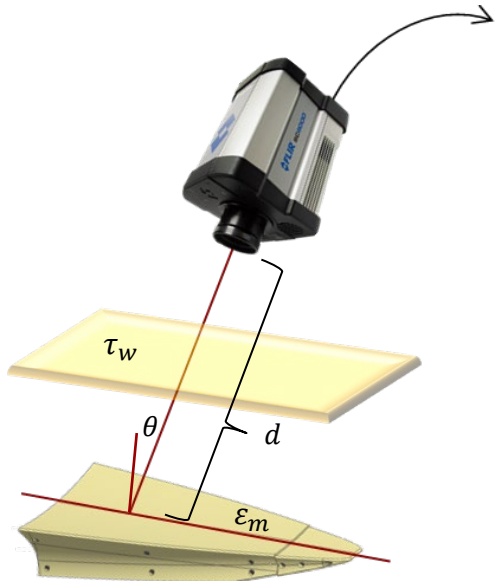
- FLIR SC6701 SLS (LWIR)
- FLIR 50mm Ge lens
- 11-in x14-in AR coated ZnSe Window
- Integration time = 0.038 ms
- Frame rate = 60 Hz

Infrared Thermography Test Technique

- Model temperature range (no-wind vs. wind-on) required custom radiometric calibration and temperature retrieval methodology.
- Use Planckian version of Sakuma-Hattori equation as a basis for Signal to Temperature transfer function.

$$S_{tot} = S_a^0 + S_w + S_m = F(T_{app})$$

$$S(T) = \frac{C}{e^{\left(\frac{c_2}{AT+B}\right)} - 1} + G \Rightarrow T_m(S) = \frac{B}{\ln\left(\frac{\epsilon_m \tau_{win} C}{S_m - G} + A\right)}$$



$$d < 1.0\text{m} \therefore S_a \approx 0$$

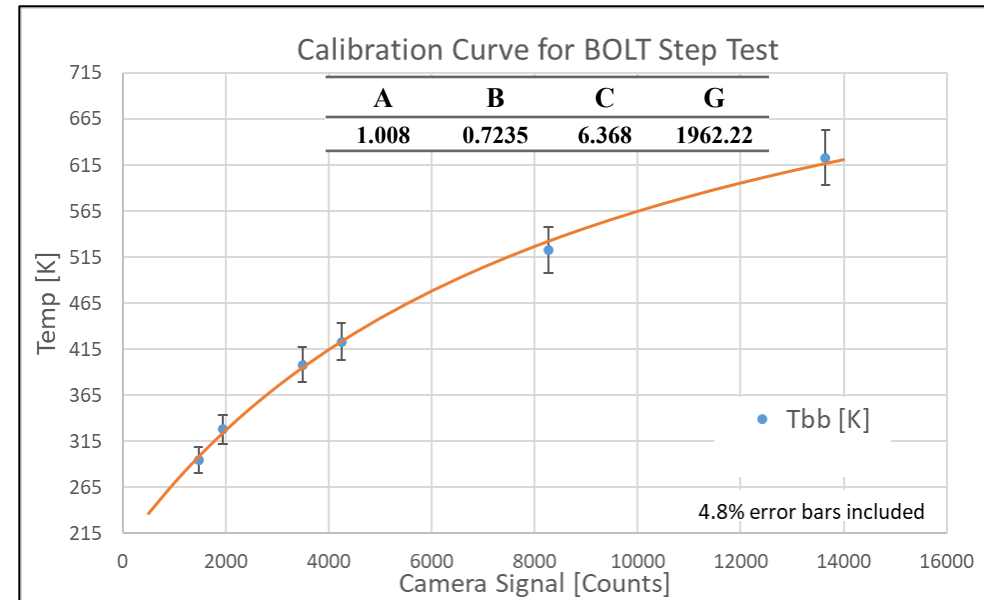
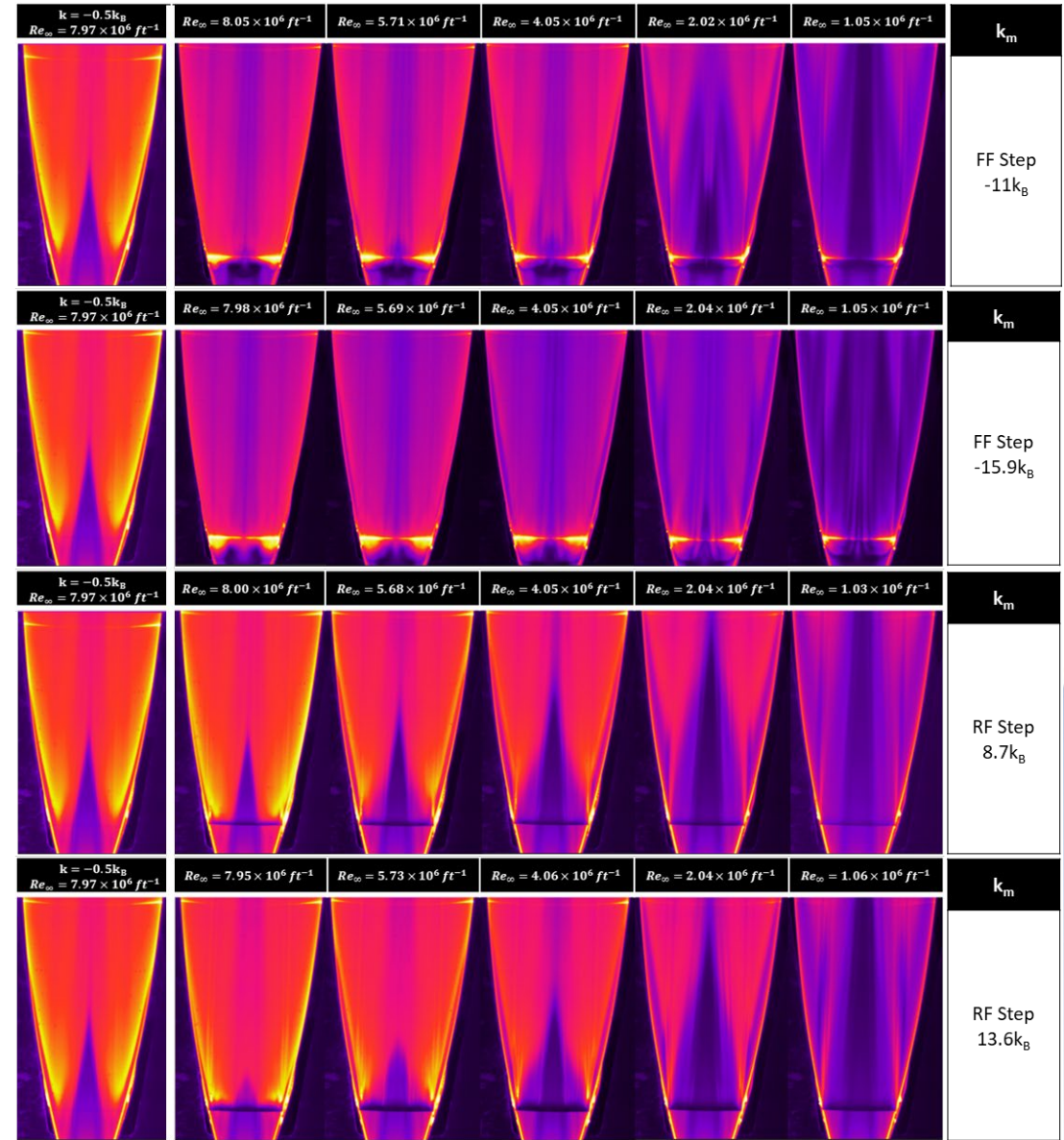
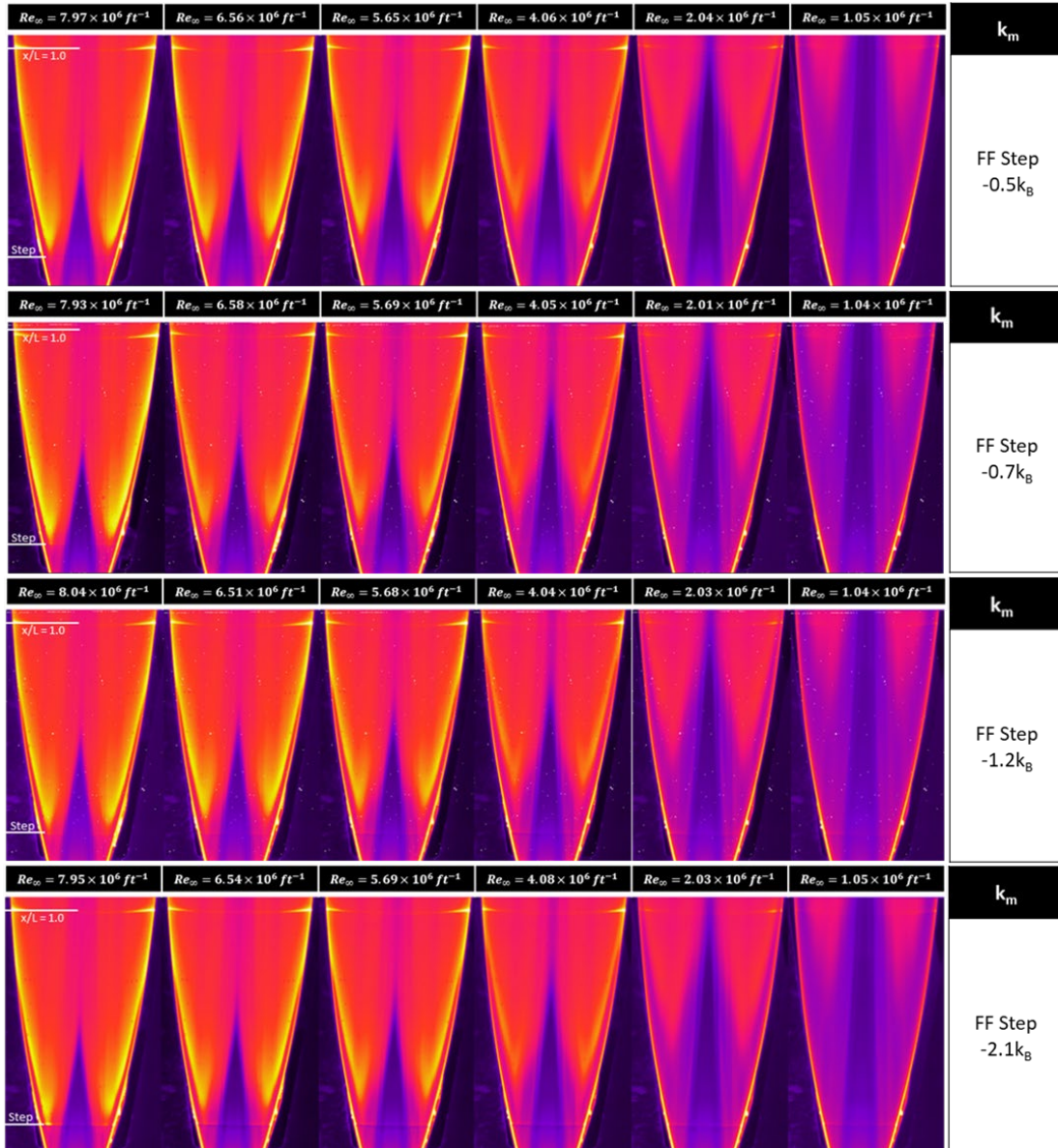


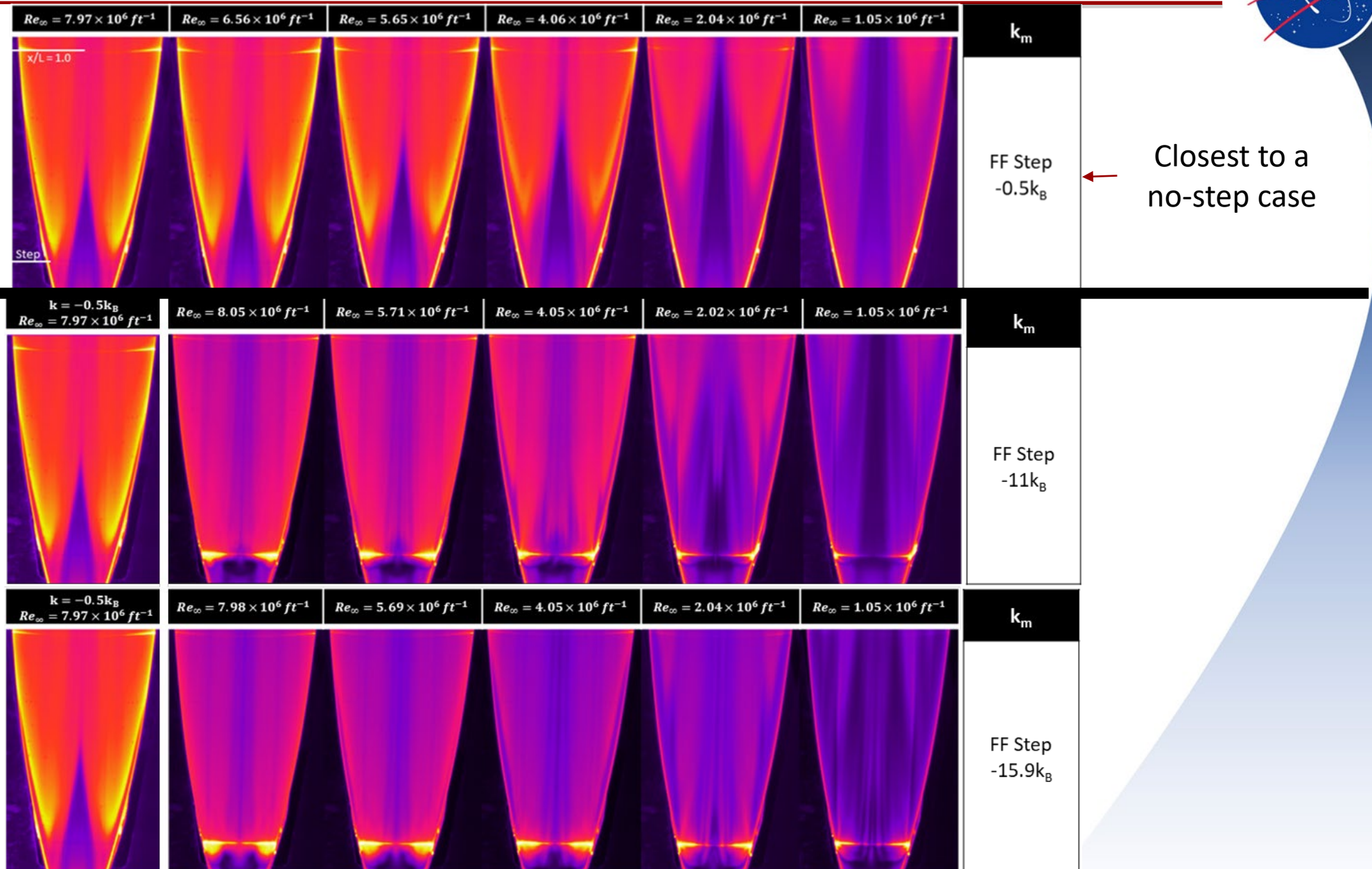
Figure 8. Temperature retrieval calibration curve provides greater dynamic range while imaging

Raw IR Data – 83 Rotal Runs



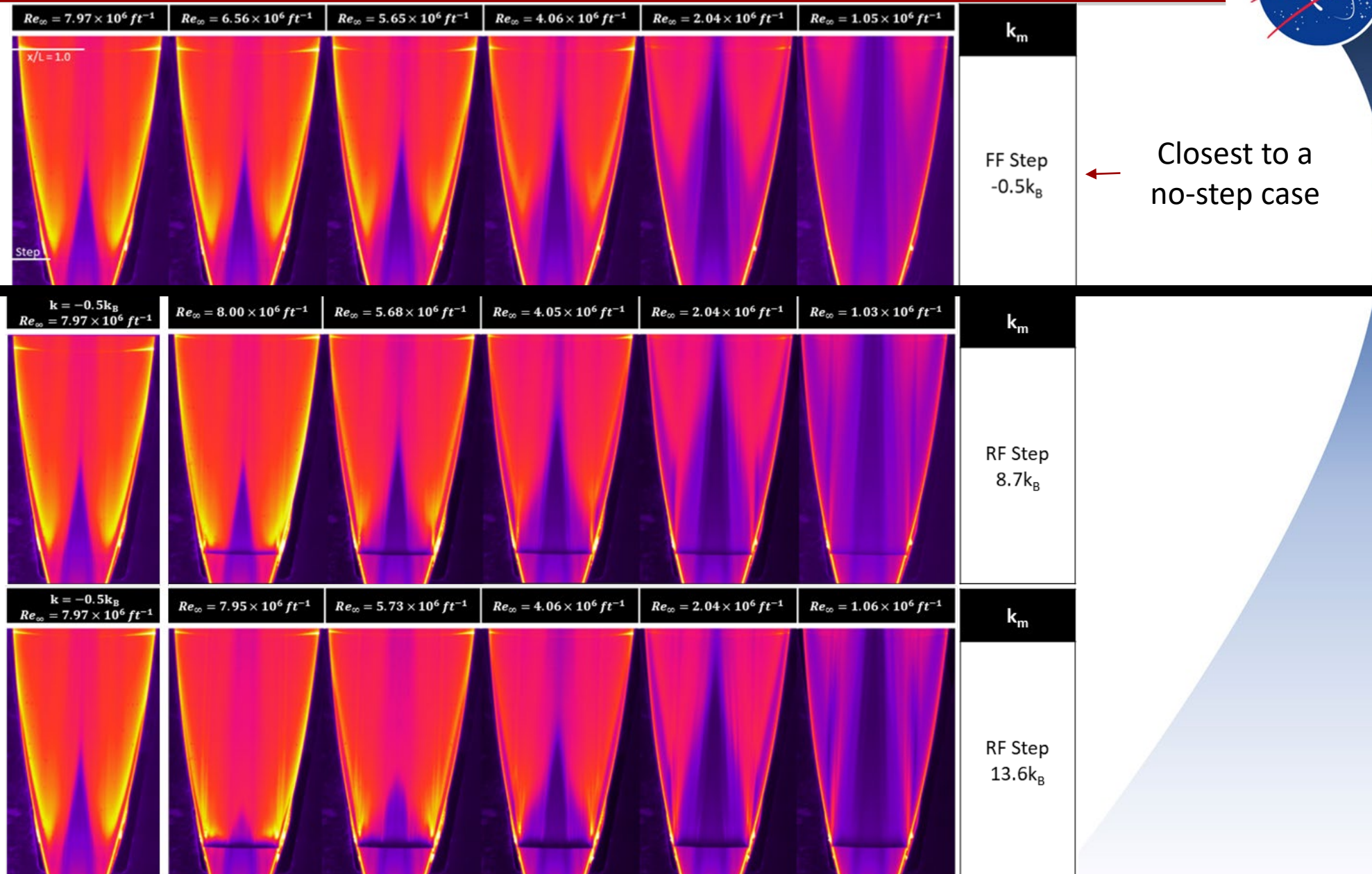
Raw IR Data – Baseline vs. Large FF Steps

Baseline step height:
 $k_B = 0.005$ inches



Raw IR Data – Baseline vs. Large RF steps

Baseline step height:
 $k_B = 0.005$ inches



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IHEAT Data Analysis Software

- Aerothermal data processing package developed at LaRC.
- Details of the **IHEAT** software are given by Mason, et al. [2]
- Inputs to heat transfer calculations are given by Merski [3]
- One-dimensional heat transfer results are output as heat transfer images.

Convective heating film coefficient is represented by h in **IHEAT** output, definition is:

$$h \equiv \frac{q_{conv}}{(H_{AW} - H_w)} \cong \frac{q_{conv}}{(H_0 - H_w)} = \text{film coefficient in } \left(\frac{kg}{m^2 \cdot s} \right), \text{ where } q_{conv} = \text{convective heat flux } \left(\frac{W}{m^2} \right)$$

$$H_w = \text{wall enthalpy } \left(\frac{J}{kg} \right), H_{AW} \cong H_0 \equiv c_p T_\infty + \frac{U_\infty^2}{2}, \text{ where } c_p = \text{specific heat } \left(\frac{J}{kg \cdot K} \right) \text{ and}$$

$$T_\infty = \text{free stream temperature (K)}$$

Local value of h is computed by **IHEAT** for all pixels from temperature-time history $(T_{Run} - T_{PRun})$.

Local values are normalized by the Fay-Riddell correlation for stagnation point heat flux:

$$\left(\frac{h}{h_{FR}} \right) \equiv \left[\frac{h(x, y, z, Re, t, T_w)}{h_{FR}(R_n, Re, T_{300K})} \right]$$

$$h_{FR} \equiv \frac{q_{FR,300K}}{(H_0 - H_{w,300K})}$$

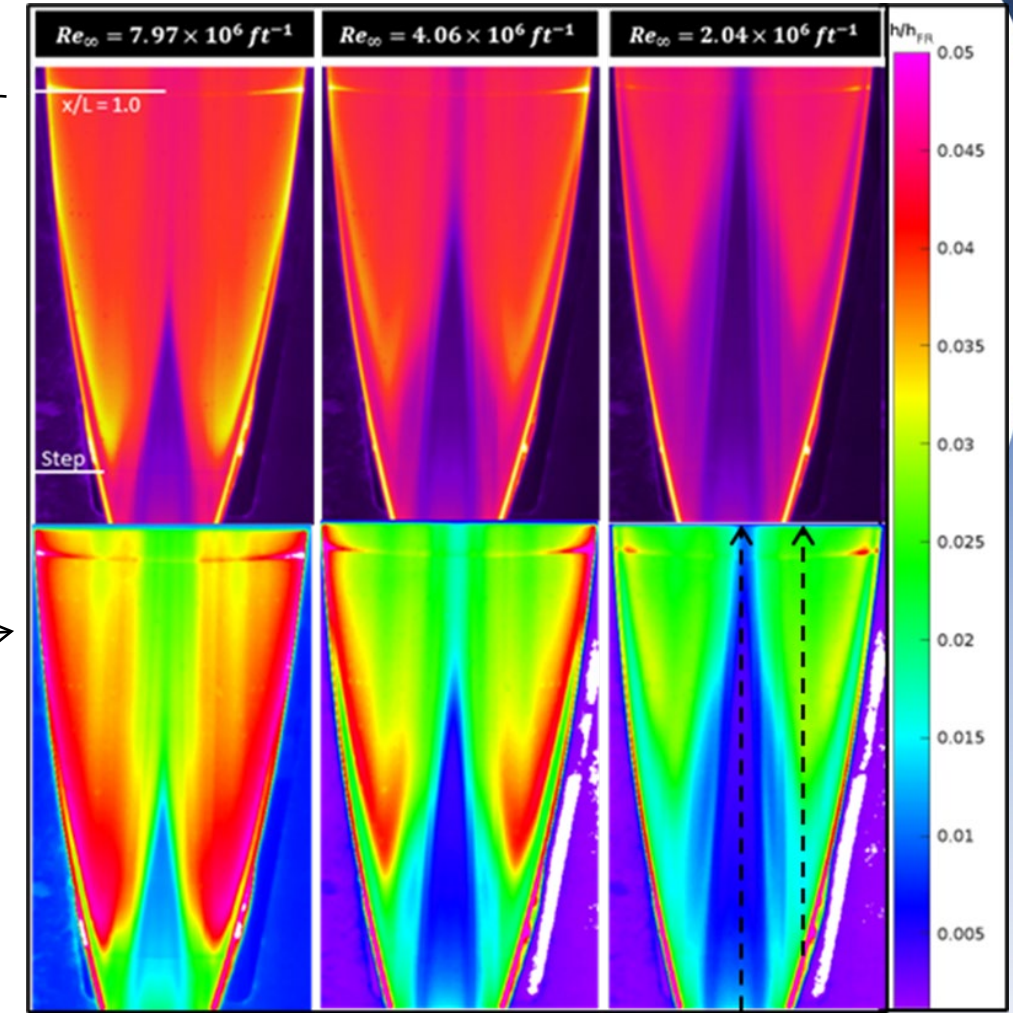


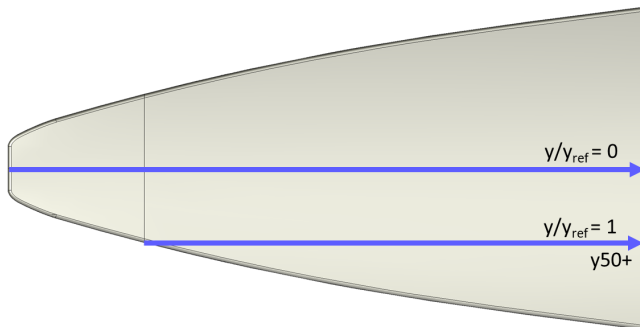
Figure 11. Raw IR images (top) and the resulting heat transfer images (bottom) for $Re_\infty \approx 8, 4, 2 \times 10^6 \text{ ft}^{-1}$ runs with $k = -0.5k_B$.

Note: Color bar values are for the heat transfer images only (bottom row).

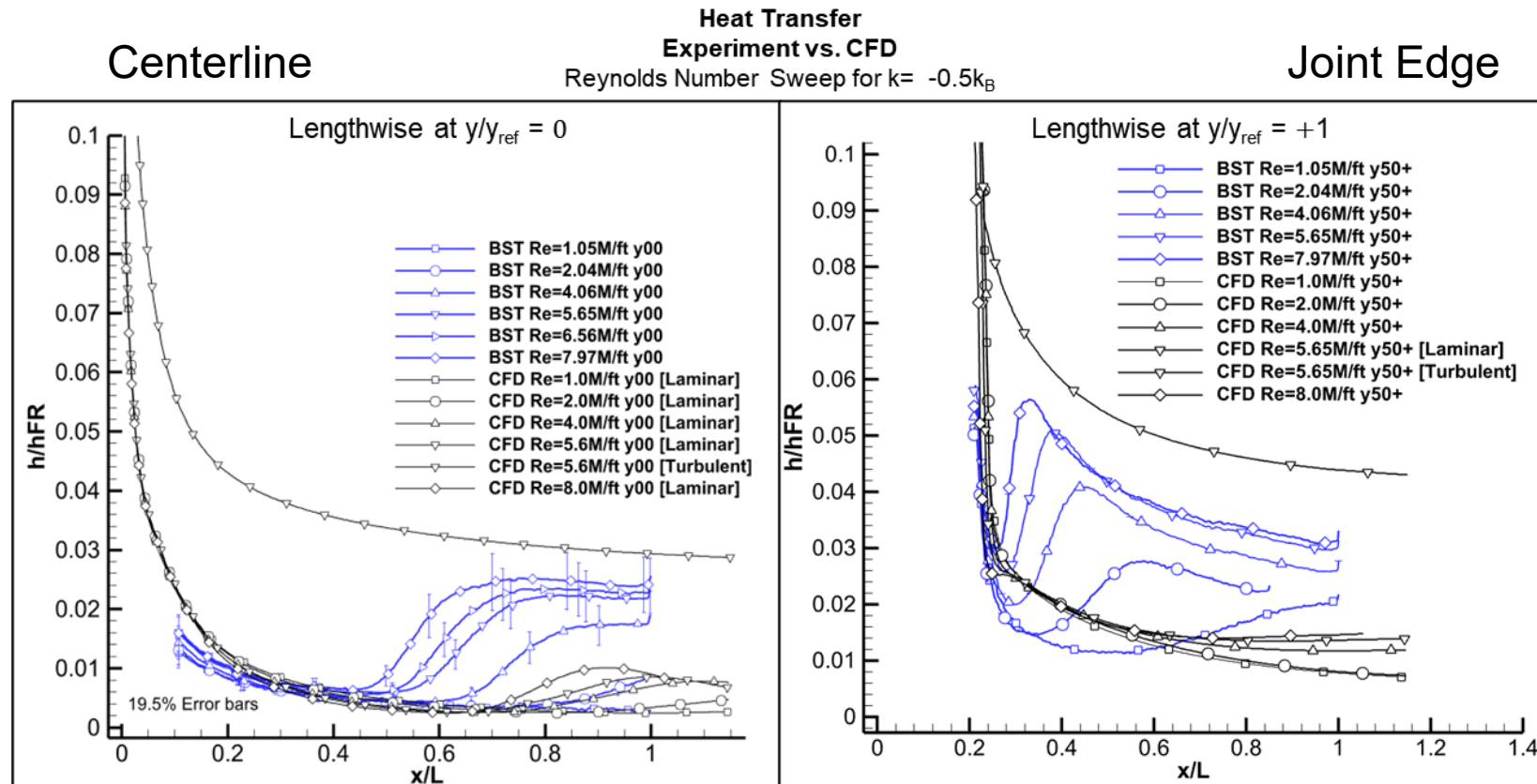
- ✓ Project Overview
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Qualitative Technique Validation

- Smooth OML (no step) cases were run for $Re_\infty = 1, 2, 4, 5.6, \text{ and } 8 \times 10^6 / \text{ft}$ and used as a basis for comparison of the IR test technique with LAURA CFD solutions.
- Line cuts were extracted and plotted against the wind tunnel results using h/h_{FR} .



Baseline step height:
 $k_B = 0.005$ inches



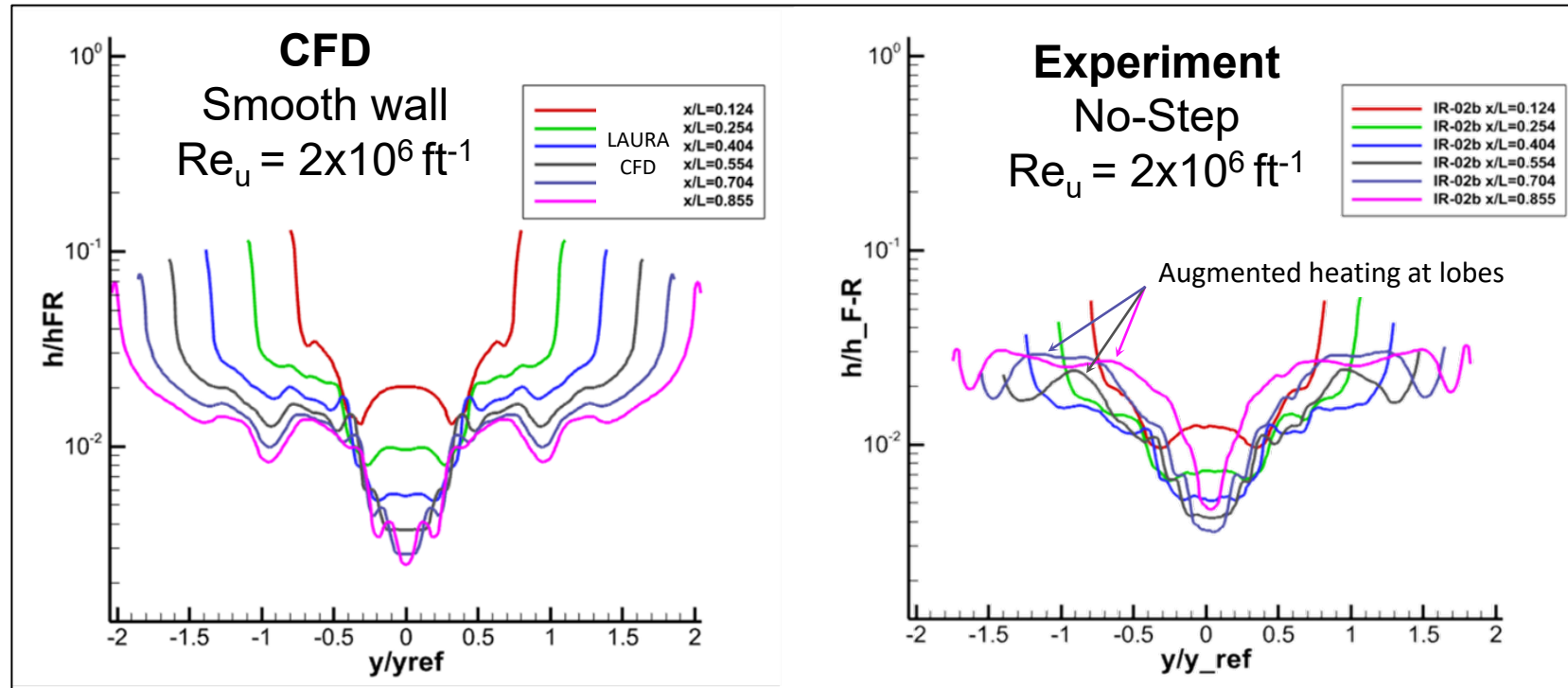
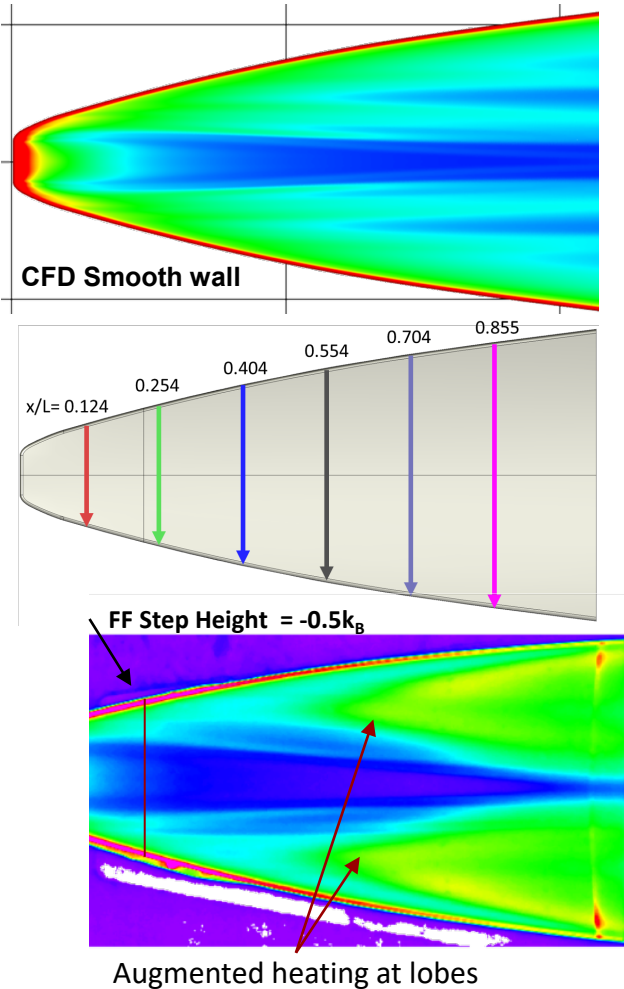


Comparison with CFD – Spanwise Cuts for $Re_u = 2 \times 10^6 \text{ ft}^{-1}$

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Qualitative Technique Validation

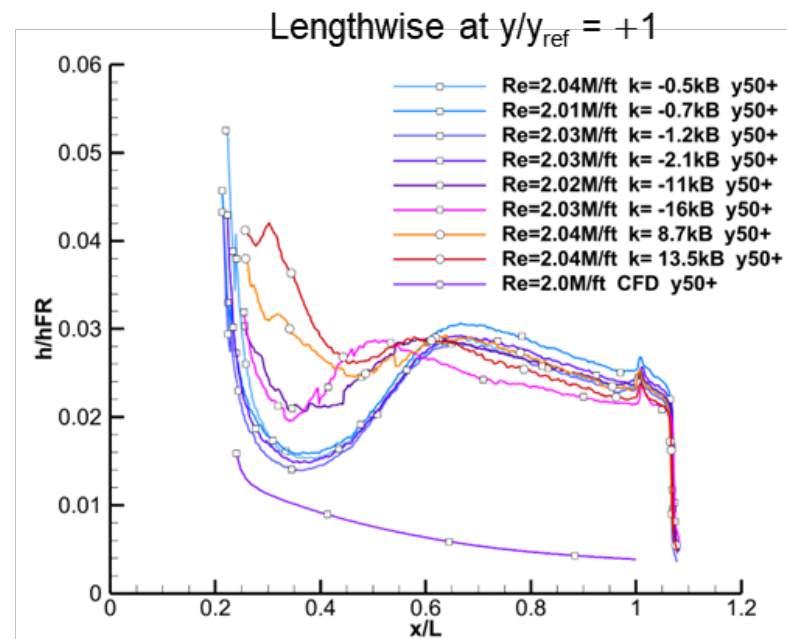
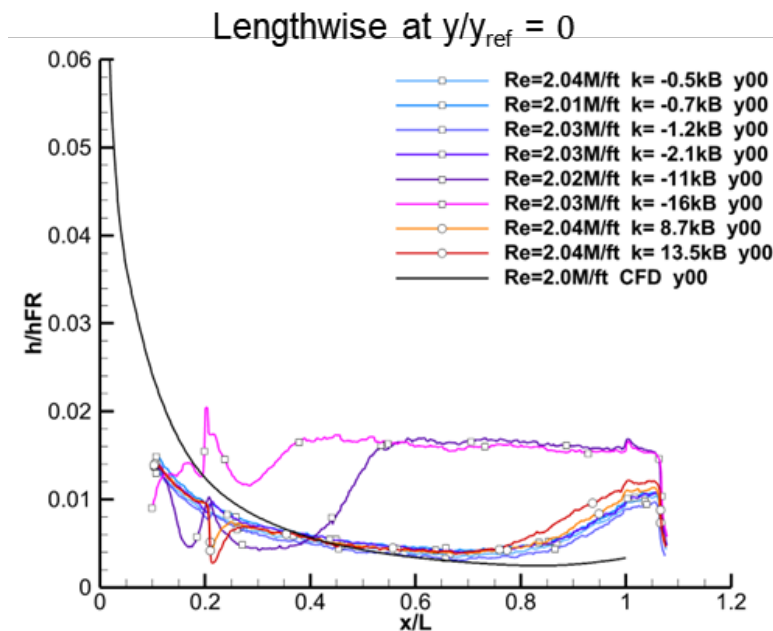
- Smooth-wall CFD solutions are used as a basis for data validation.
- Line cuts were extracted and plotted against the wind tunnel results using h/h_{FR} .
- Spanwise cuts shown here show the augmented heating at the lobes.



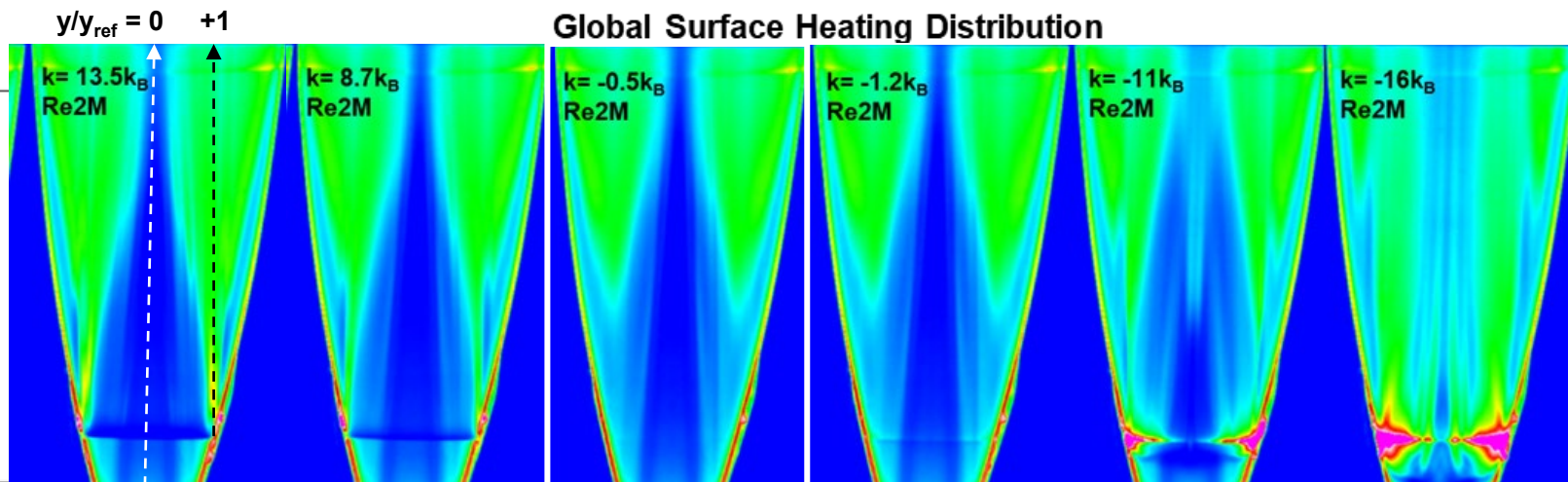
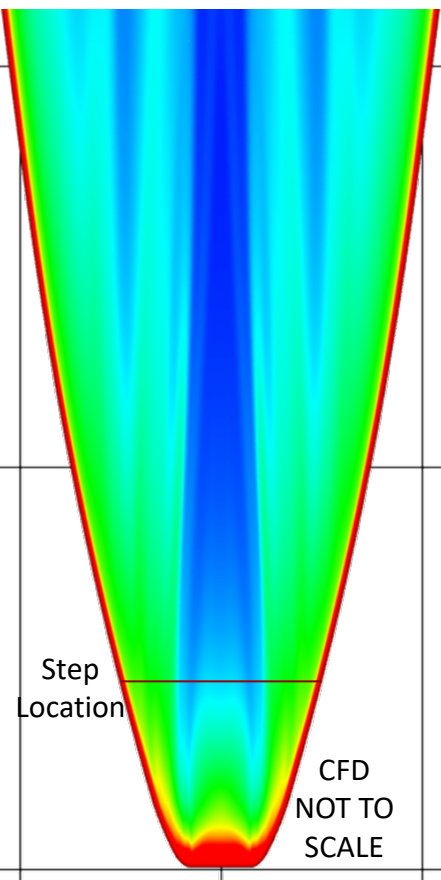
Heat Transfer Data – Constant Re, Variable Step Height

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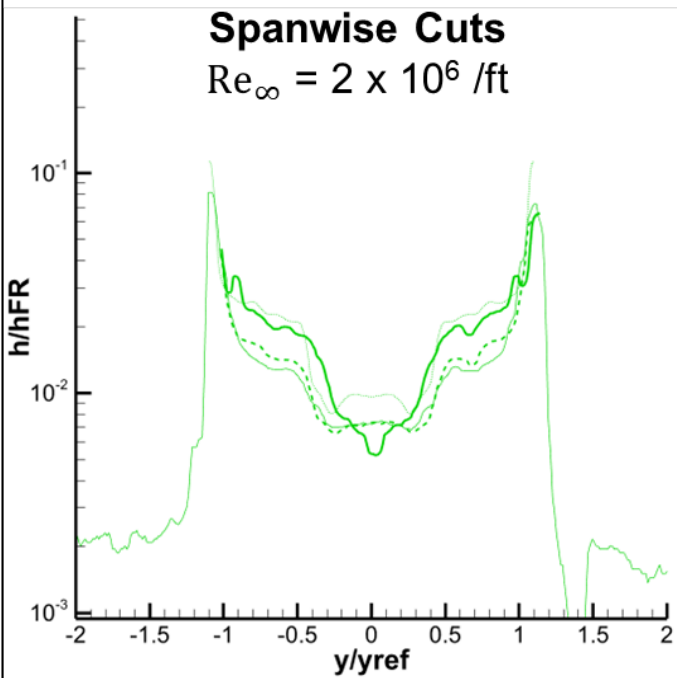
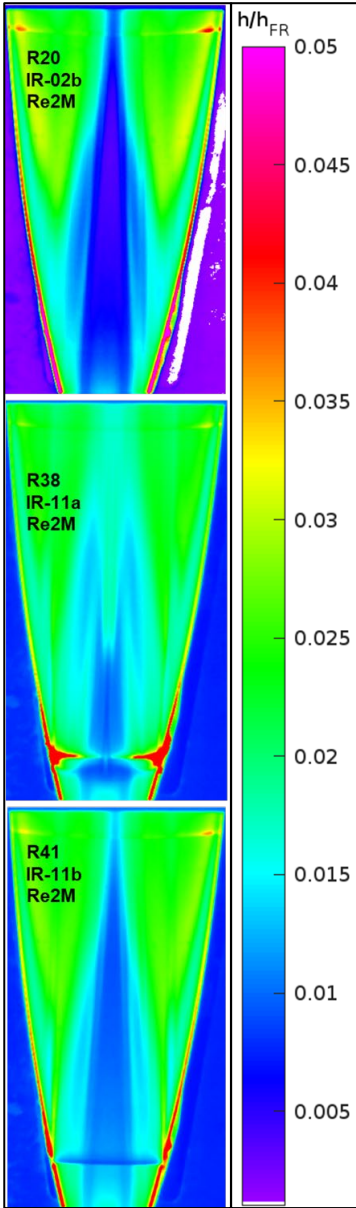
$$Re_u = 2 \times 10^6 / ft$$



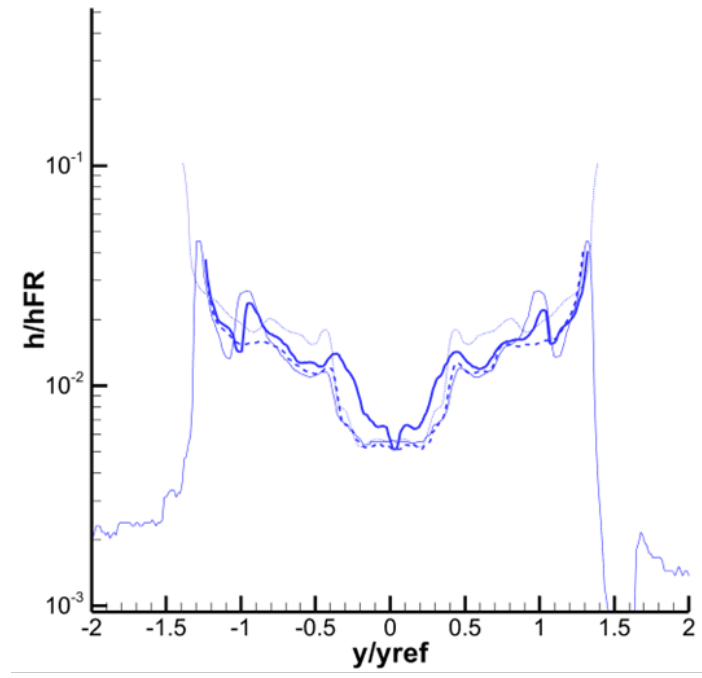
CFD Smooth Wall



Spanwise Cuts - Constant Re, Variable Step Height

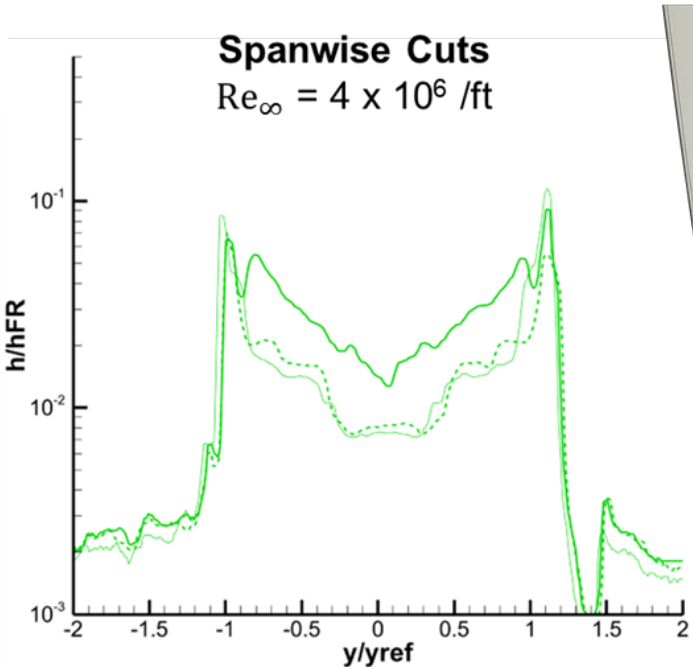
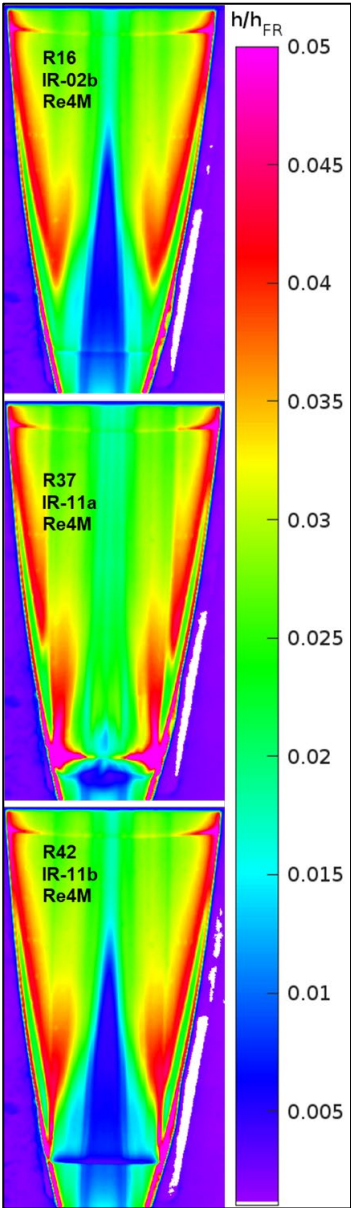


- LAURA CFD $x/L=0.254$
- - - IR-02b $x/L=0.254$
- IR-11a $x/L=0.254$
- IR-11b $x/L=0.254$

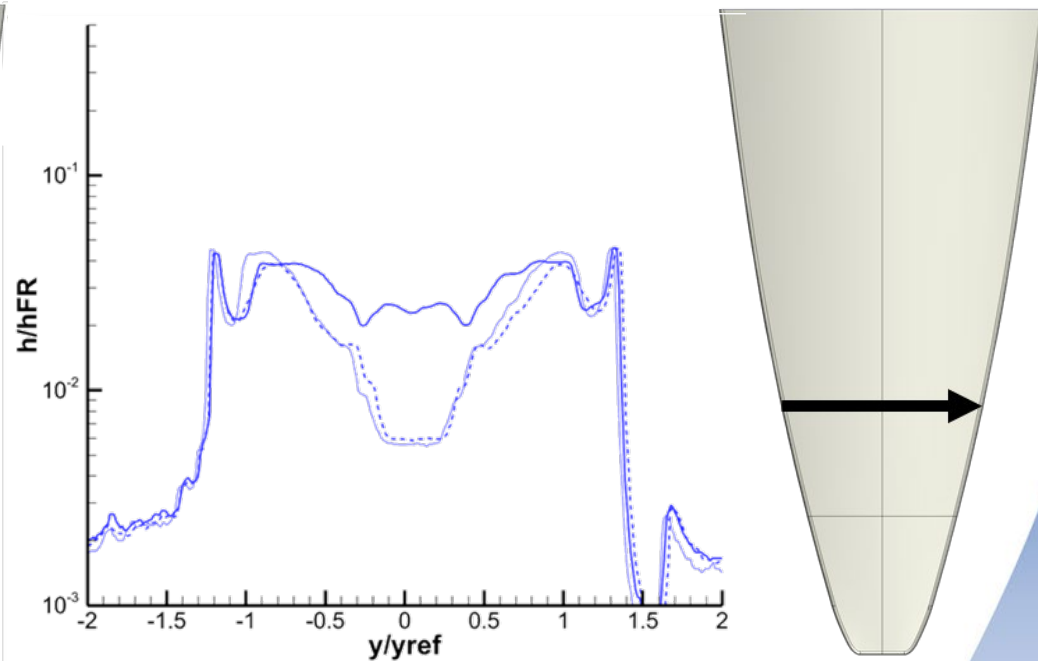


- LAURA CFD $x/L=0.404$
- - - IR-02b $x/L=0.404$
- IR-11a $x/L=0.404$
- IR-11b $x/L=0.404$

Spanwise Cuts - Constant Re, Variable Step Height



- IR-02b $x/L=0.254$
- IR-11a $x/L=0.254$
- IR-11b $x/L=0.254$



- IR-02b $x/L=0.404$
- IR-11a $x/L=0.404$
- IR-11b $x/L=0.404$

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Quantitative IR Thermography:

- Significant forward progress was made toward quantitative IR thermographic test technique development at LAL.
- This measurement technique offers potential cost, manufacturability, and supply chain benefits over the legacy phosphor thermography technique, but with previously undetermined accuracy.

BOLT Step Effects:

- Forward-facing steps significantly disrupt the boundary layer, causing augmented heating forward of the step boundary, and more evenly distributed surface heating downstream.
- Rearward-facing steps show reduced heating immediately downstream, suggesting boundary layer separation immediately aft of the step.
- Observations suggest the region near the leading edge and the joint is highly sensitive to step effects.

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BOLT Step Effects:

- Continue data processing for additional Reynolds numbers and measure step heights near leading edge.
- Investigate additional BOLT-derivative designs (i.e., Flat-BOLT, various nose shapes).
- Explore use-cases for BST and BST-derivative models in other flow conditions.

Table 3. Approximate transition onset locations for $k = -0.5k_B$ as a function of Reynolds number.

Re_∞ $\times 10^6 \text{ ft}^{-1}$	CL x/L	y50
7.98	0.47	0.26
6.56	0.52	
5.65	0.57	0.28
4.06	0.66	0.3
2.04	0.85	0.34
1.05		0.56

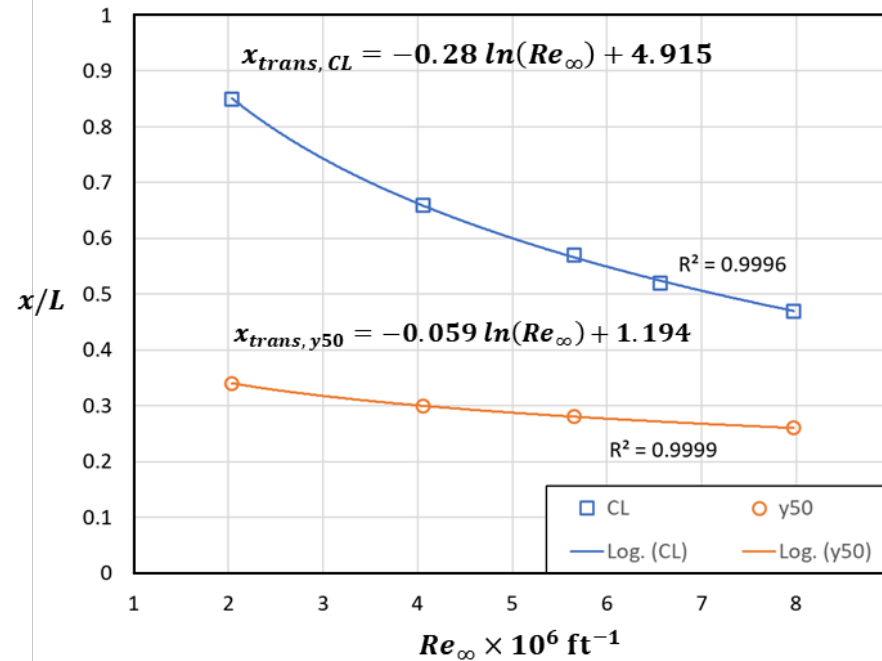


Figure 12. ‘No-step’ transition data will be used as a baseline for comparing step effects for different configurations.

Goal: Develop a step height vs transition onset correlation model for BOLT geometry.

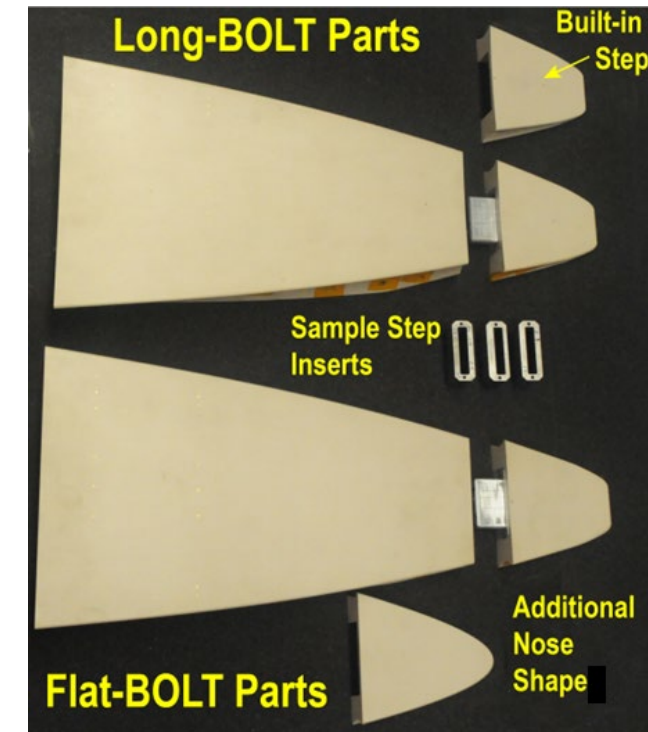
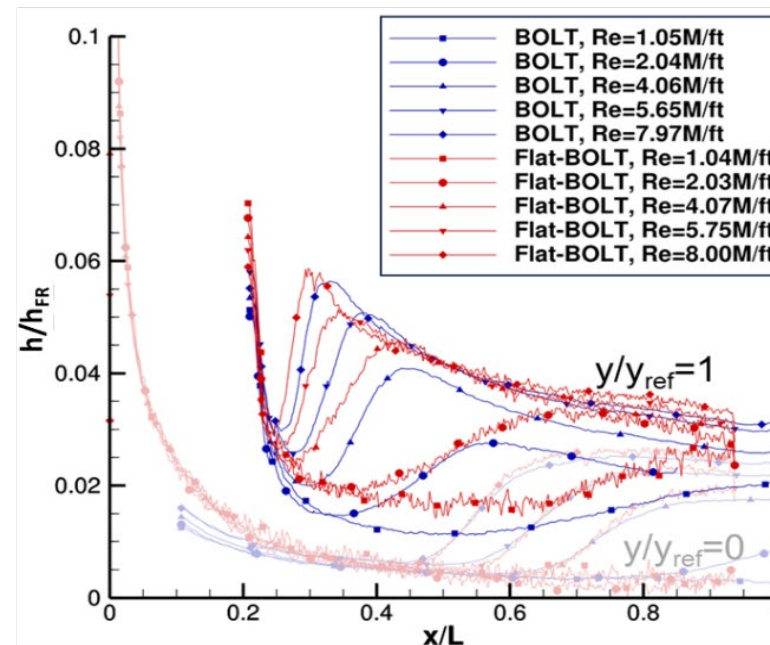
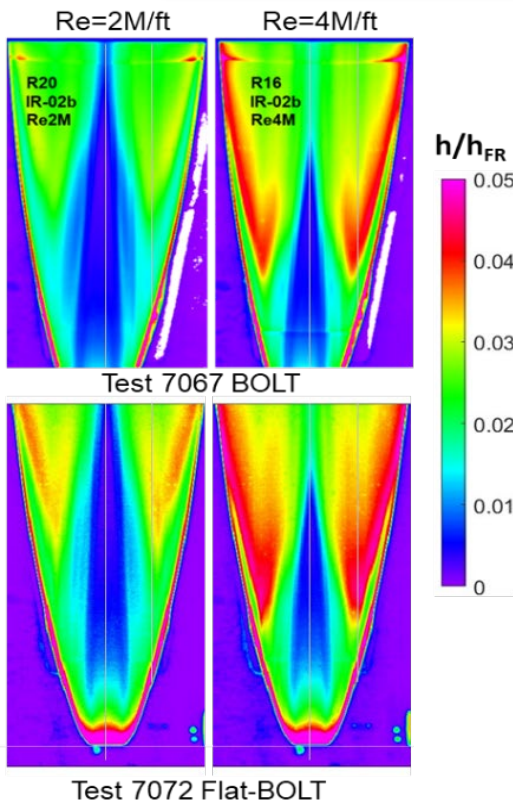
2D Step / Transition Correlation Model:

$$\frac{k}{\delta} = \frac{Re_\theta}{M_E} \cdot F_C$$

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Benefits of Flat-BOLT Design:

1. Isolates the effect of the planform shape on leading-edge and acreage heating.
2. Permits optical measurements of the boundary layer such as Focused Schlieren and Focused Laser Differential Interferometry (FLDI).
3. Flat-BOLT acreage can host standard flat material coupons for testing



References:

- [1] NASA Langley Hypersonic Experimental Aerothermodynamic Capabilities and Recent Contributions, AIAA Aviation 2024
- [2] Mason, M. L. and Rufer, S. J., "Features of the Upgraded Imaging for Hypersonic Experimental Aeroheating Testing (IHEAT) Software," AIAA 2016-4322, Jun. 2016. doi:10.2514/6.2016-4322.
- [3] Merski, N., "Reduction and Analysis of Phosphor Thermography Data with the IHEAT Software Package," presented at the 36th AIAA Aerospace Sciences Meeting and Exhibit, Reno,NV,U.S.A., 1998. <https://doi.org/10.2514/6.1998-712>



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Background

- This investigation is focused on the 2-dimensional step at the joint between the stainless-steel isolator and the aluminum body (Joint 2). [Figure 1]
- The BOLT Step Test (BST) model utilized a nose step location that accurately represents the step location on the BOLT I flight geometry. [Figure 2]
- The intent of the present experiment is to provide a controlled data set to assist in flight test data analyses and provide data for future design considerations.
- Additional comparisons to other BOLT-derivative geometries (i.e. Flat-BOLT) were conducted using similar model design principles and are presented in later sections for reference.

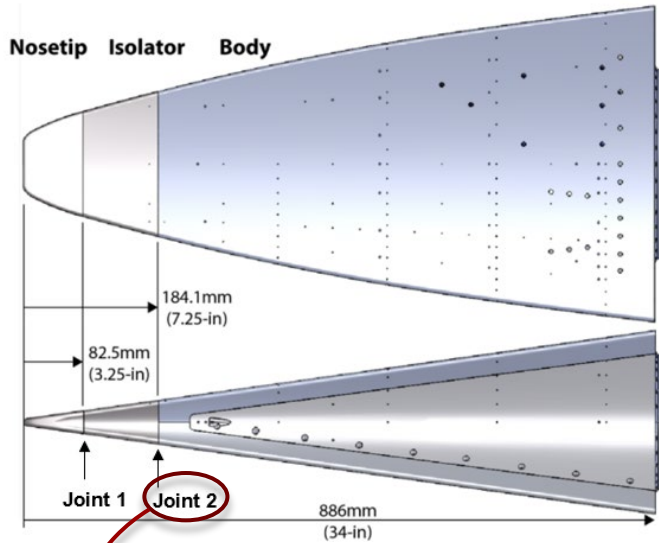


Figure 1. BOLT I Flight Vehicle Design.

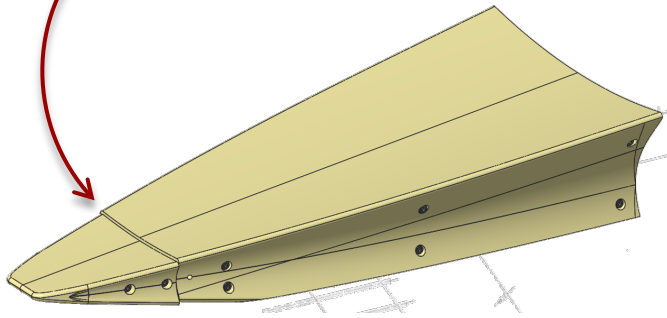


Figure 2. BST Model Design.

Table 1. 20-Inch Mach 6 Air Tunnel Test Conditions

Re_{∞} (1/ft)	P_{t1} (psia)	T_{t1} (°R)	P_{∞} (psia x 10 ⁻²)	T_{∞} (°R)	V_{∞} (ft/s)	M_{∞}
1.05	60	885	4.25	110.62	3039	5.89
2.03	125	910	8.12	111.66	3086	5.96
4.05	250	930	16.19	110.82	3092	6.01
5.69	365	935	23.11	112.98	3132	6.03
7.97	475	875	30.05	105.43	3012	6.02

The BOLT Step Test (BST) was conducted at the 20-Inch Mach 6 Tunnel at NASA LaRC.

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			Uncertainty Quantification:		Temperature					
Value Ranges:						(H-L)/2	Ui / u	(ui/xi)	coverage factors:	
Variable	xi	ui distribution type	u-factor	Low	High	Ui	ui	ui (%)		k = 1.96
$\epsilon(\theta)$	0.91	log-Norm for θ : 0 to 30 de	2.375	0.898	0.920	0.011	0.004631579	0.51%		2- σ
τ_{window}	0.975	Square for xlow-xhigh	1.732050808	0.962	0.989	0.014	0.007881585	0.81%		95% C-I
A	1.00083	Triangle: xi $\pm$ 2%	2.449489743	0.976	1.026	0.025	0.010214641	1.02%		
B	0.72984	Triangle: xi $\pm$ 2%	2.449489743	0.712	0.748	0.018	0.007448905	1.02%		k = 3
C	6.28236	Triangle: xi $\pm$ 2%	2.449489743	6.125	6.439	0.157	0.064119081	1.02%		3- σ
G	1962.19041	Triangle: xi $\pm$ 2%	2.449489743	1913.136	2011.245	49.055	20.02652204	1.02%		99.7% C-I
S	Var(T)	Gaussian: use 3-sigma	3	uncertainty $\Delta S(T)$:		0.313%	k * std(S):	0.94%		
						Combined std Uc:		2.44%	2- σ Ue: 4.79%	

Uncertainty Quantification:				Heat Transfer			
iHEAT Value Ranges:				or		Bounding %	
Variable	xi or xavg	Δxi or std(xi)	ui distribution type	u-factor	k-value	Ui	ui
k_PEEK (Elora)	0.28462	0.03514	Uniform u=sqrt(3)	1.732050808	1.96	12.35%	13.973%
Cp_PEEK	1.60944	0.09880	Uniform u=sqrt(3)	1.732050808	1.96	6.14%	6.947%
dT (Ttr-Tpr)	2*Ue(T)	0.04785	Combo (see above)		1.96	9.57%	9.571%
H_aw		6.00%	Normal		1.96	6.00%	6.000%
t_eff		2.50%	Uniform u=sqrt(3)		1.96	2.50%	2.500%
F-R coefficient	3.76%	0.101%	Uniform u=sqrt(3)	1.732050808	1.96	0.06%	0.115%
2- σ Combined Standard Uc:							19.43%

Total Combined Standard Uncertainty with 95% confidence interval:

$$\text{Temperature Uncertainty} \Rightarrow \left(\frac{\Delta T_m}{T_m} \right)^2 = \left(\frac{\Delta S}{S} \right)^2 + \left(\frac{\Delta \epsilon}{\epsilon} \right)^2 + \left(\frac{\Delta \tau_{win}}{\tau_{win}} \right)^2 + \left(\frac{\Delta A}{A} \right)^2 + \left(\frac{\Delta B}{B} \right)^2 + \left(\frac{\Delta C}{C} \right)^2 + \left(\frac{\Delta G}{G} \right)^2 \Rightarrow 4.79\% (2\sigma)$$

$$\text{Heat Transfer Uncertainty} \Rightarrow \left(\frac{\Delta h/h_{FR}}{h/h_{FR}} \right)^2 = \left(\frac{\Delta dT_m}{dT_m} \right)^2 + \left(\frac{\Delta k_{PEEK}}{k_{PEEK}} \right)^2 + \left(\frac{\Delta C_{pPEEK}}{C_{pPEEK}} \right)^2 + \left(\frac{\Delta H}{H} \right)^2 + \left(\frac{\Delta h_{FR}}{h_{FR}} \right)^2 + \left(\frac{\Delta t_{eff}}{t_{eff}} \right)^2 \Rightarrow 19.43\% (2\sigma)$$

Figure 6. LAL 20-Inch Mach 6 facility in Hampton, VA.

- ✓ Project Overview
- **Test Methodology**
- ❑ Preliminary Results
- ❑ Discussion
- ❑ Future Work

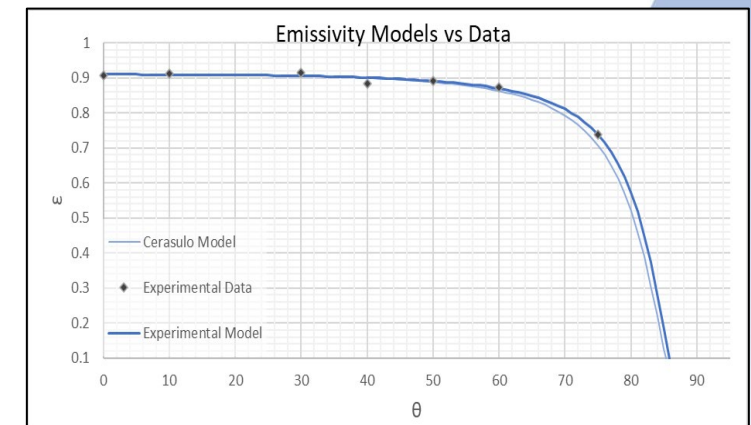
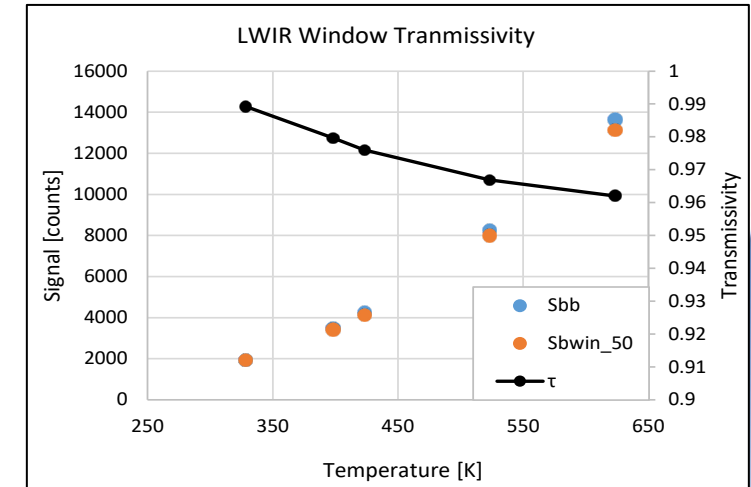
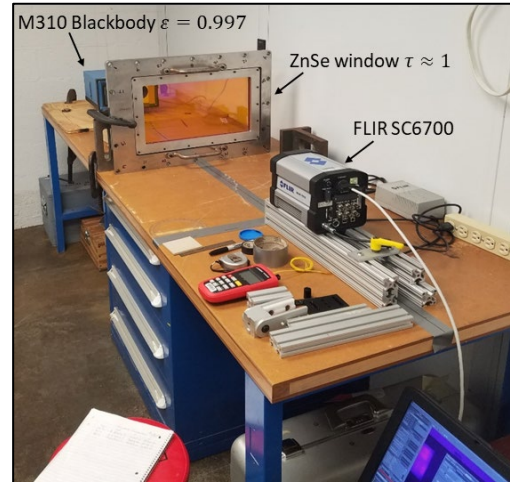
Infrared Thermography Test Technique

- Empirical measurements made for window transmission and PEEK emissivity values.

$$T_m(S) = \frac{B}{\ln\left(\frac{\varepsilon_m \tau_{win} C}{S_m - G} + A\right)}$$

$$\tau_{win} = \frac{S_{bb}(T_i)_{win}}{\varepsilon_{bb} \cdot S_{bb}(T_i)}$$

$$\varepsilon_m(\theta) = \varepsilon_n \cos(\theta)^{\frac{\hat{\alpha}}{\cos(\theta\hat{\beta})}}$$



$$\hat{\alpha} = 0.0255 \text{ \& } \hat{\beta} = 1.3345$$

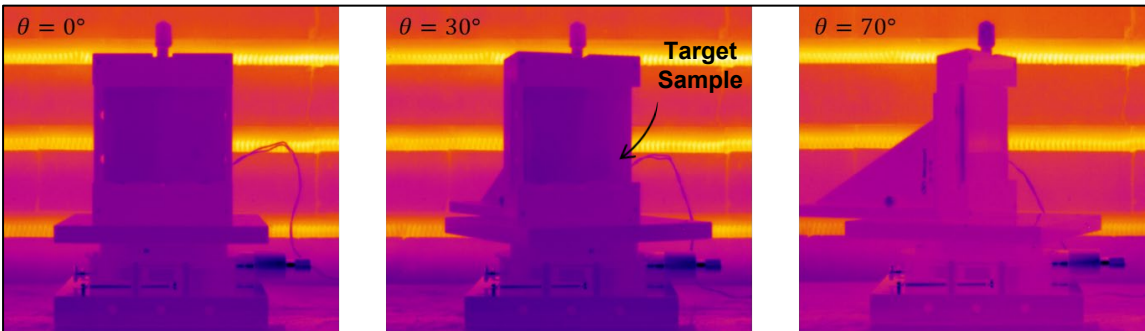
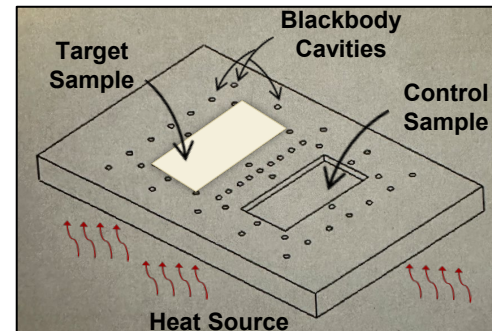


Figure 9. Two methods of emissivity measurement were used. Convective and conductive heating methods provided data for ratio method of determination. Black electrical tape was used as a control.

Figure 10. Window transmissivity and directional emissivity measurements help quantify uncertainty in T .



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Quantitative IR Thermography:

- Inputs to the governing equations for temperature extraction and heat transfer are treated as type B uncertainties.
- Uncertainty distributions & coverage factors are assigned conservatively.
- Uncertainty input terms are the normalized standard deviations ($\Delta x_i / x_i$), for each measured variable in percentage units.
- All uncertainties are treated independently (no covariance is assumed).

Total Combined Standard Uncertainty with 95% confidence interval:

$$\text{Temperature Uncertainty} \Rightarrow \left(\frac{\Delta T_m}{T_m} \right)^2 = \left(\frac{\Delta S}{S} \right)^2 + \left(\frac{\Delta \varepsilon}{\varepsilon} \right)^2 + \left(\frac{\Delta \tau_{win}}{\tau_{win}} \right)^2 + \left(\frac{\Delta A}{A} \right)^2 + \left(\frac{\Delta B}{B} \right)^2 + \left(\frac{\Delta C}{C} \right)^2 + \left(\frac{\Delta G}{G} \right)^2 \Rightarrow \mathbf{4.79\% (2\sigma)}$$

$$\text{Heat Transfer Uncertainty} \Rightarrow \left(\frac{\Delta h/h_{FR}}{h/h_{FR}} \right)^2 = \left(\frac{\Delta dT_m}{dT_m} \right)^2 + \left(\frac{\Delta k_{PEEK}}{k_{PEEK}} \right)^2 + \left(\frac{\Delta C_{pPEEK}}{C_{pPEEK}} \right)^2 + \left(\frac{\Delta H}{H} \right)^2 + \left(\frac{\Delta h_{FR}}{h_{FR}} \right)^2 + \left(\frac{\Delta t_{eff}}{t_{eff}} \right)^2 \Rightarrow \mathbf{19.43\% (2\sigma)}$$