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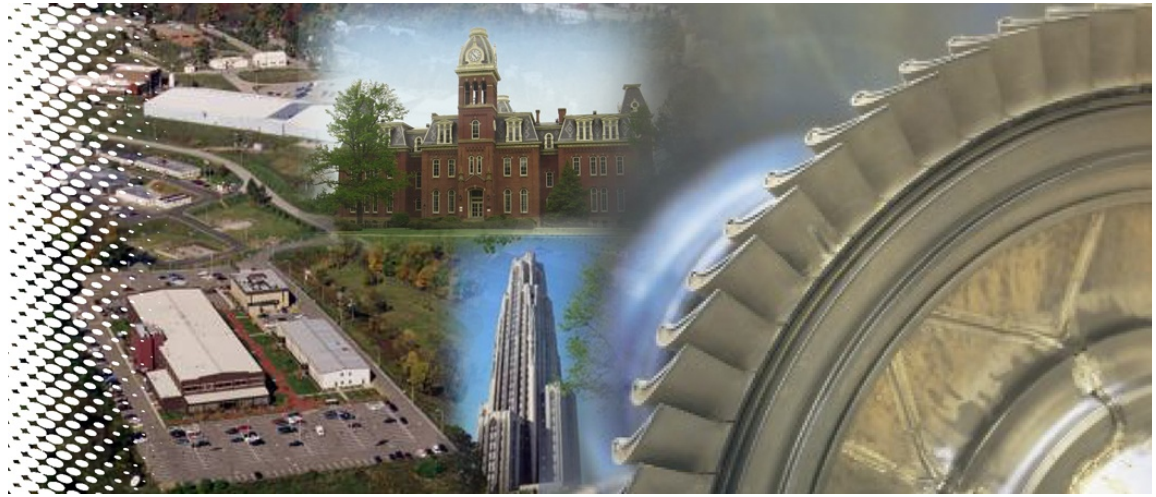

Overview of NETL Heat Transfer Studies in a High Temperature Test Rig

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National Energy Technology Laboratory

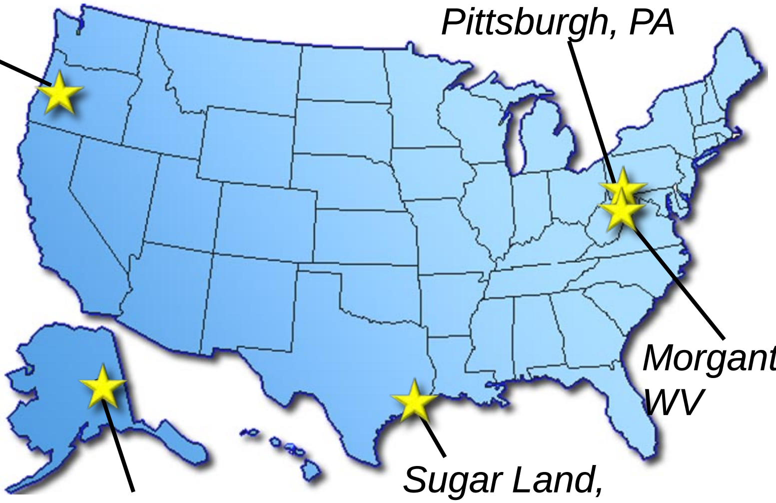
2012 UTSR Workshop

October 2-4, 2012

Irvine, CA

National Energy Technology Laboratory

MISSION
Advancing energy options to fuel our economy, strengthen our security, and improve our environment



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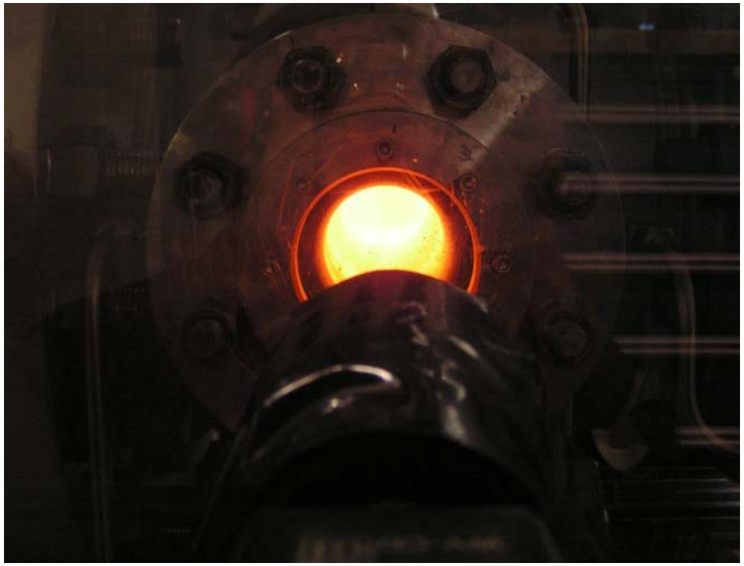
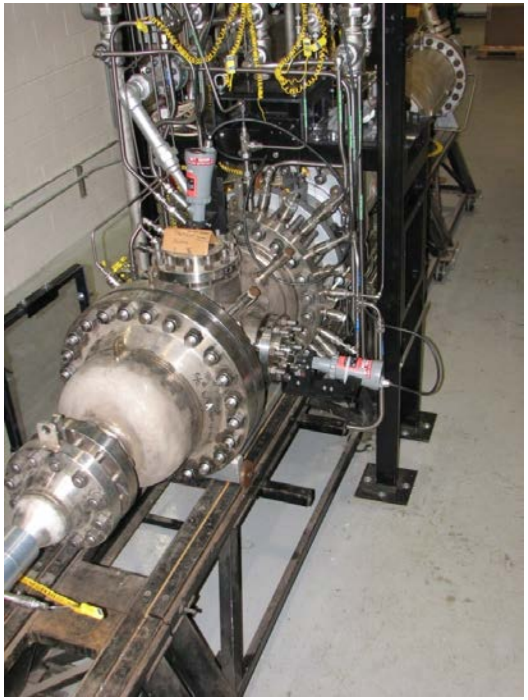
University of Pittsburgh

Leveraging National Lab and University-Based Scientific and Engineering Assets to Address Significant National Energy Issues

Outline

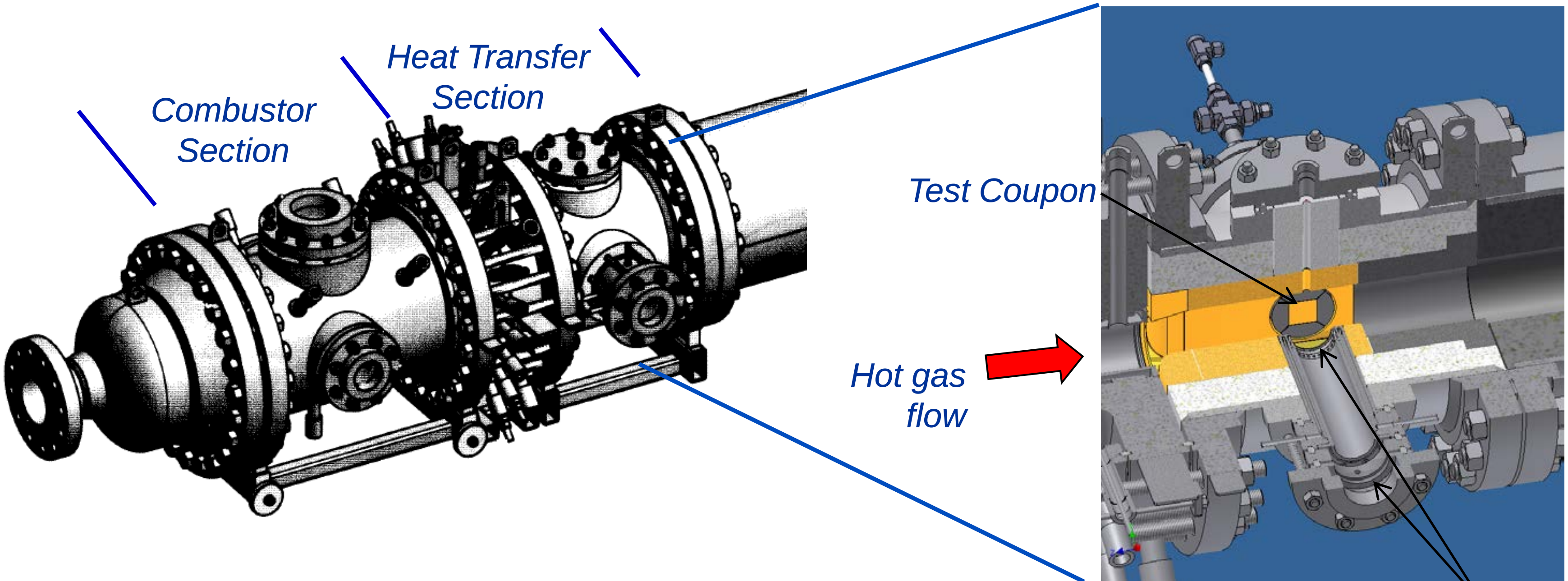
- **Overview high temperature/high pressure test facility**
  - Hardware and facility capabilities
- **Overview results since last UTSR Workshop**
  - Rig validation efforts
  - 3D CFD and conjugate heat transfer results





Project Background

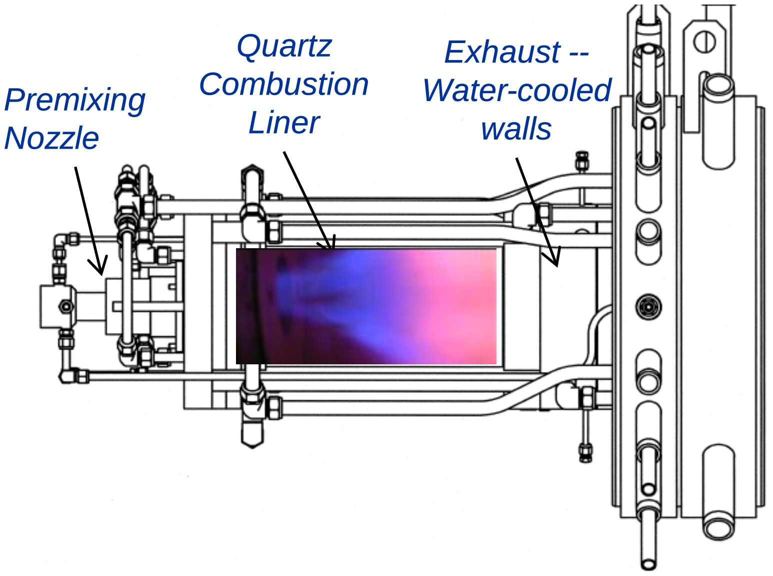
- **Modify an existing high pressure combustion rig**



- **Provide “realistic” hot gas path conditions for collaborative efforts**
- **“Proof-of-concept” testing for cooling and sensors**

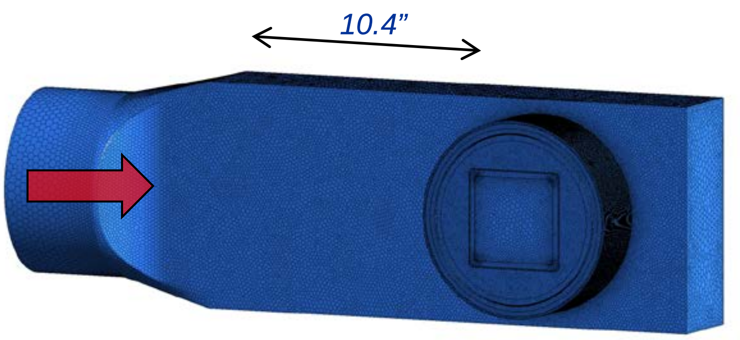
Facility and Rig Capabilities

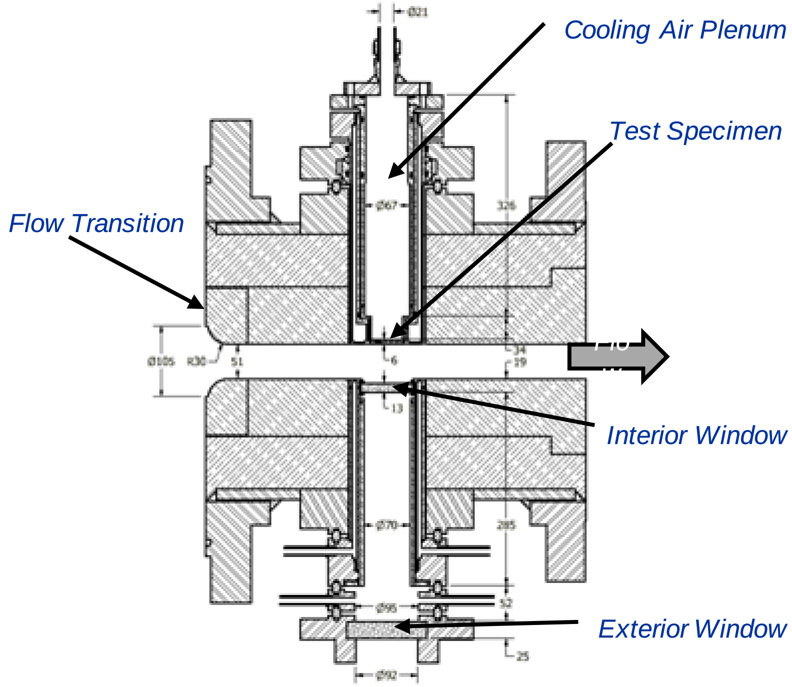
- **Facility capabilities**
  - 2 lb/s air flow @ 700 psi
  - 800-900 F air preheat (independent control)
- **Rig capabilities**
  - 2 lb/s air flow @ 10 atm
  - Max inlet air temperature (800F)
  - Natural gas or hydrogen fuels
- **Combustor design**
  - Swirl-stabilized
  - Lean premixed gaseous fuel
  - Diffusion pilot (12 jets)
  - Quartz combustor liner
    - No dilution cooling jets
    - No upstream film cooling



Experimental Setup – Detailed Description

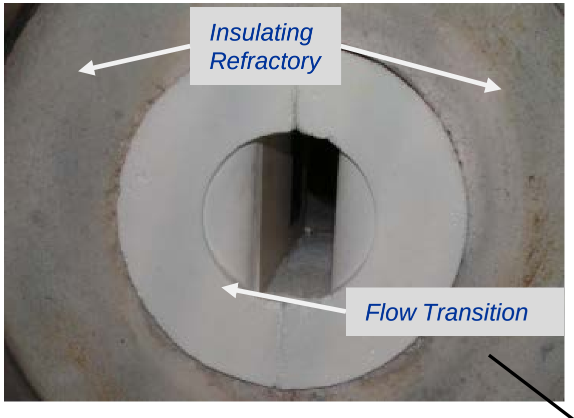
- **Heat transfer section**
  - Refractory lined walls
  - Transition to rectangular cross-section
    - Nominal 4” ID to 5”x 2” flow channel
  - Test samples – flat plates
    - Haynes 230 coupons
      - 2” x 2” x 0.25” thick
    - Flush with interior walls
  - External viewport
    - Commercial quartz flange
  - Internal viewport
    - 3” OD x ½” thick quartz
    - Flush with inner wall



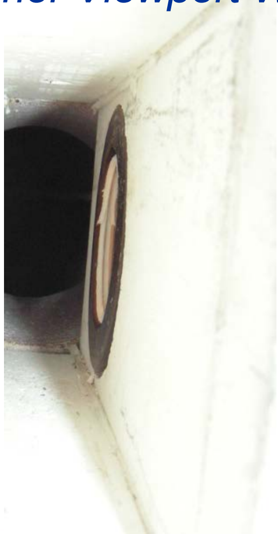


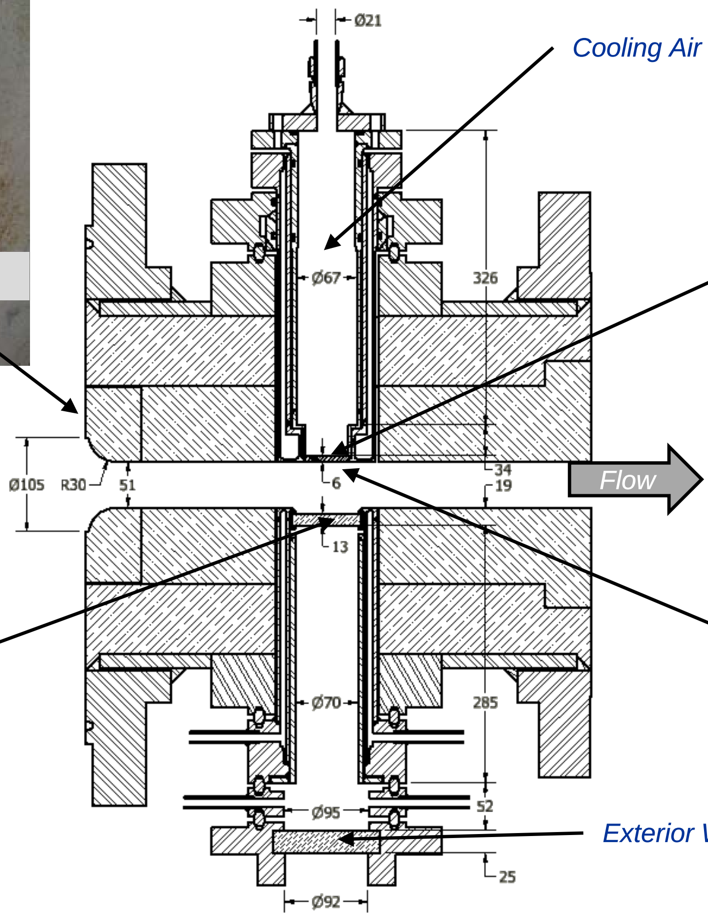
Experimental Setup -- Overview
(Film Cooling Test Section; dimensions in mm)

Inlet Flow Transition



Flow Channel Showing Interior Viewport Window





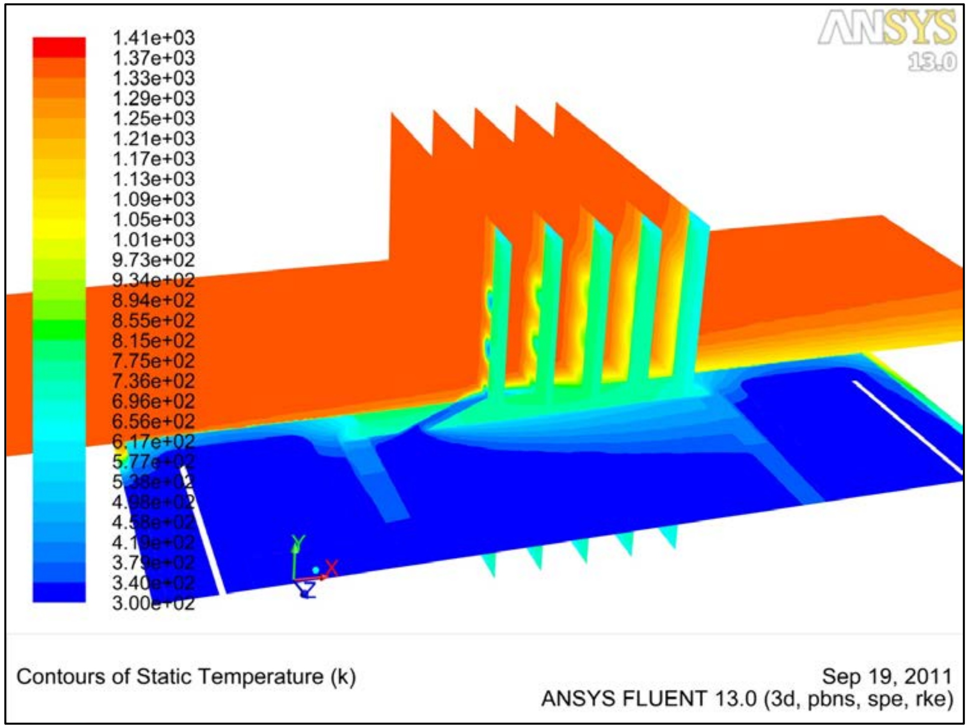
Top View
(a)

Flat Plate Test Specimen (50 x 50 x 6 mm)

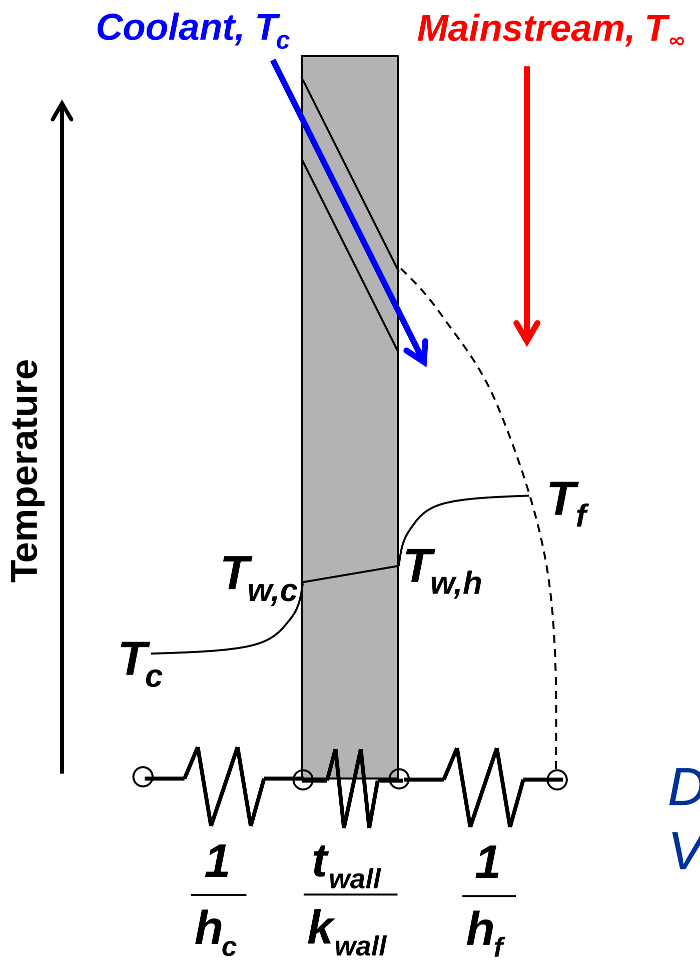
Test Specimen and Holder From Viewport Perspective

What Variables Can We Control?

- **Operating pressure (1-10 atm)**
- **Free-stream temperature (1000 - 1300C)**
- **Free-stream velocity (30-100 m/s)**
  - Limited by flashback and blowoff in combustor
- **Cooling air flowrate**
  - Blowing ratio
- **Film cooling design**
  - Without TBC
  - With TBC



What Variables Are We Measuring?



Heat Flux to Wall (neglecting radiation)

Without Coolant

$$q''_0 = h_0\left(T_\infty - T_w\right)$$

With Coolant

$$q''_f = h_f\left(T_f - T_w\right)$$

Net Heat Flux Reduction

Dependent Variable →

$$\Delta q''_r = \frac{q''_0 - q''_f}{q''_0}$$

$$\Delta q''_r = 1 - \frac{h_f}{h_0}\left(1 - \frac{\eta}{\phi}\right)$$

Dependent Variable →

$$\phi = \frac{T_\infty - T_w}{T_\infty - T_c}$$

$$\eta = \frac{T_\infty - T_f}{T_\infty - T_c}$$

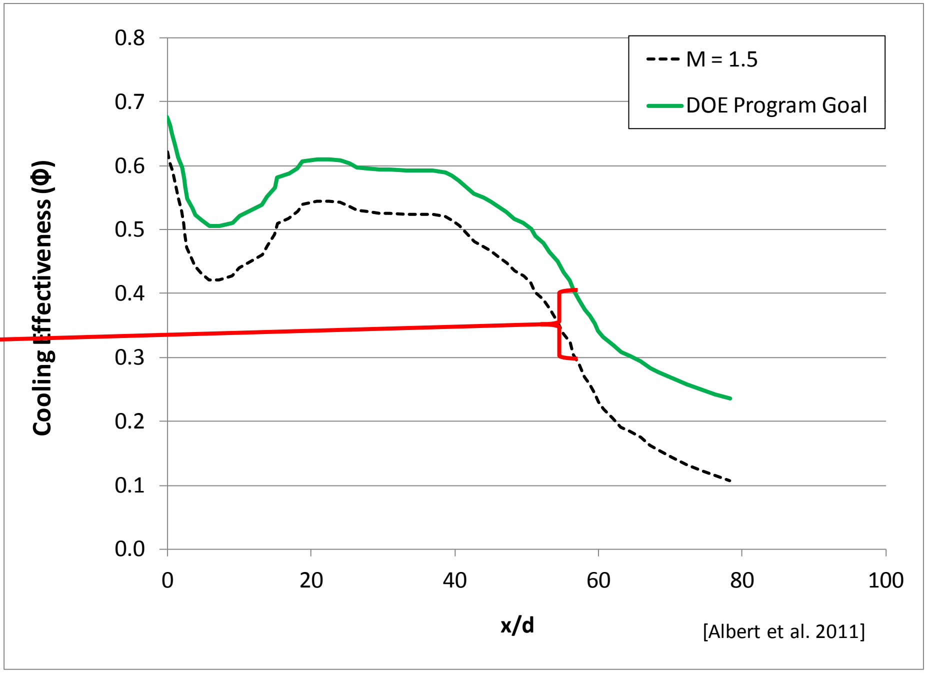
What Is The Basis For Our Uncertainty Goals?

- **Overall Cooling Effectiveness**
  - Increase gas temperature
  - Maintain same metal temp
  - Maintain same coolant temp

$$\phi = \frac{T_\infty - T_w}{T_\infty - T_c}$$

- **Area-averaged improvement to achieve program goal is approximately 0.10**

- **Experimental uncertainty must be significantly smaller than this value**
  - Similar argument for heat flux reduction

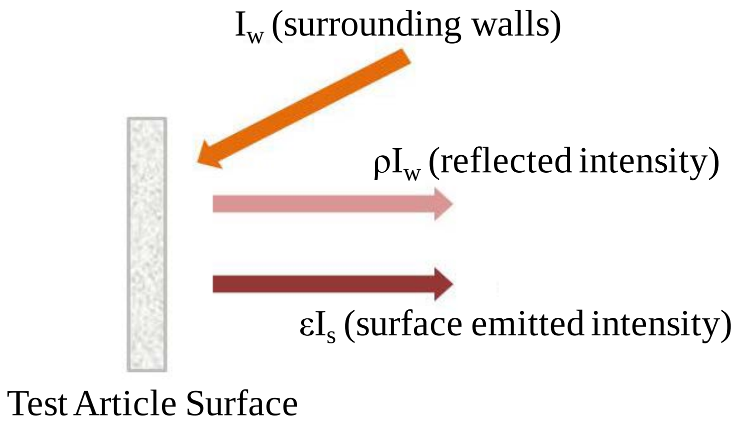


What Are Reasonable Uncertainty Goals For NETL's High Temperature Test Rig?

Dependent Variable	Uncertainty Goals: Less than . . .	
	Local	2D Image
ϕ Overall Effectiveness	$\pm$ 0.03	$\pm$ 0.06
$\Delta q''_r$ Net Heat Flux Reduction	$\pm$ 0.06	$\pm$ 0.12

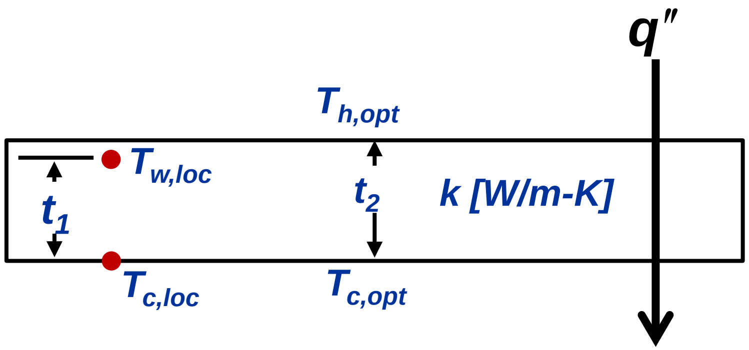
IR Thermography With Significant Ambient Interference
(i.e., Hot Wall Effects)

- **Optical approach cannot differentiate between reflected and emitted photons**
  - Design of a multi-color probe (Apogee Scientific)
  - Develop single wavelength approach using in-house expertise



$$I_{cam} = \varepsilon I_s + \rho I_w$$

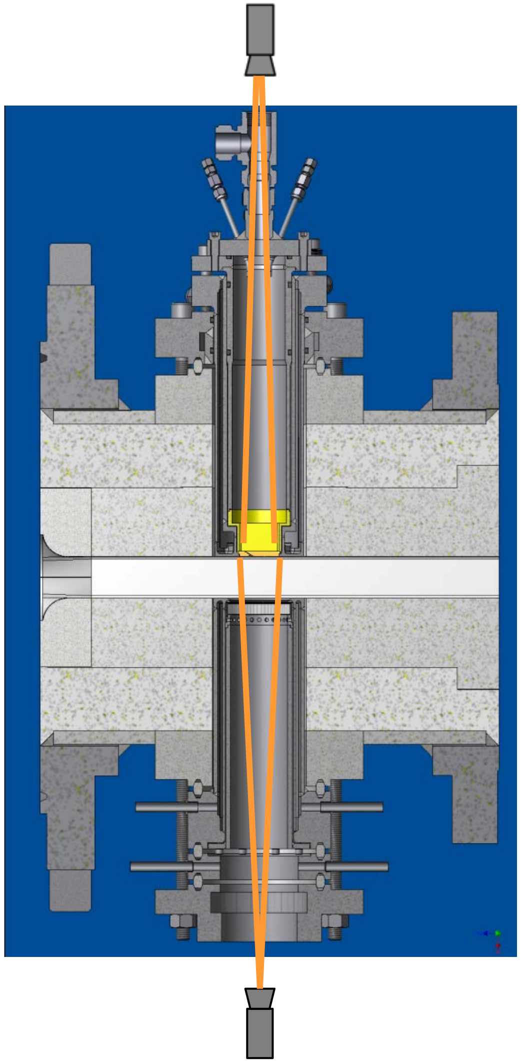
Optical Measurements Validated Against Local Thermocouple Measurements



$$q''_{loc} = \frac{k}{t_1}\left(T_{w,loc} - T_{c,loc}\right)$$

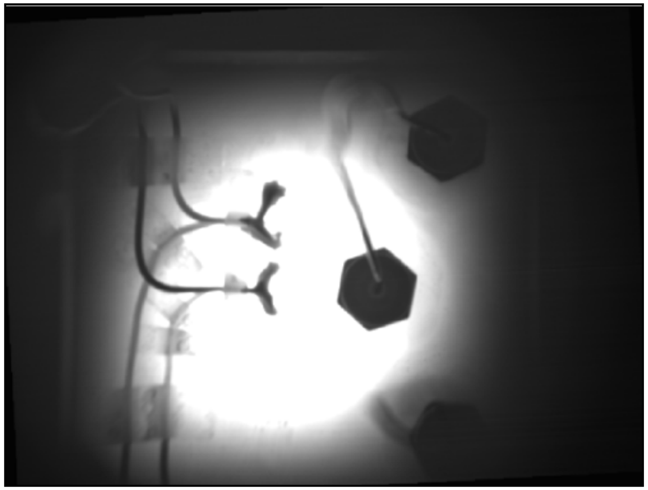
$$q''_{opt} = \frac{k}{t_2}\left(T_{w,opt} - T_{c,opt}\right)$$

Compare q”$_{loc}$ to q”$_{opt}$ to validate measurements

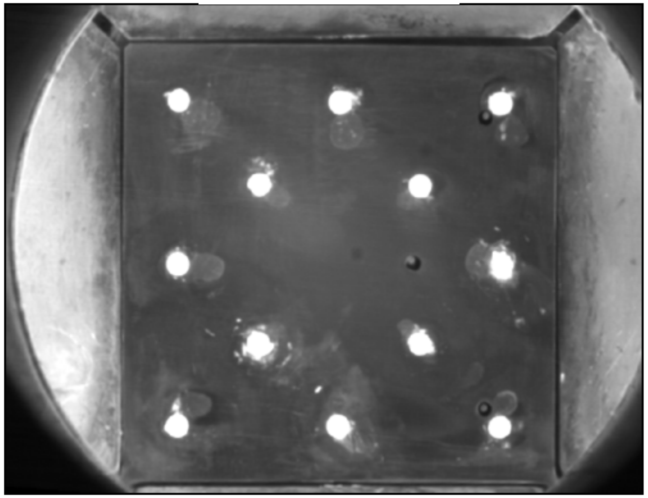


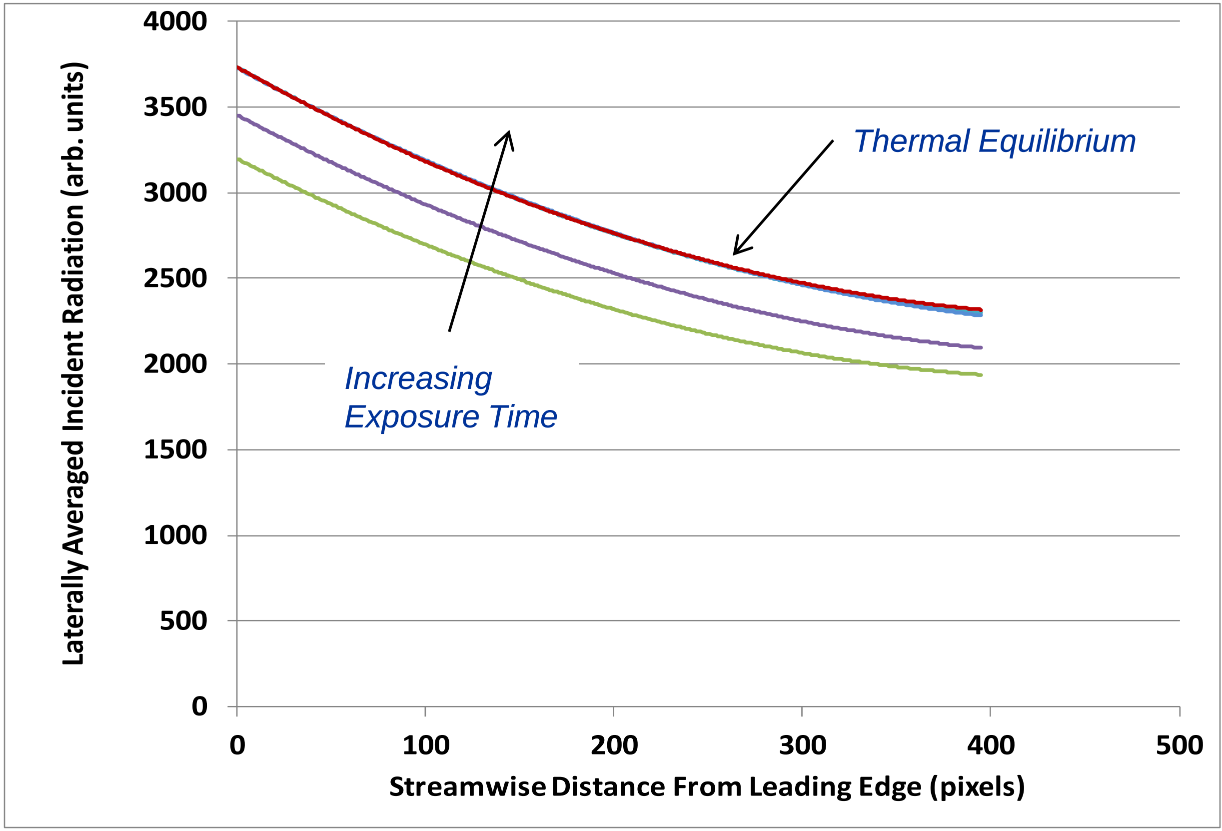
Test to Assess Variations With Location and Time

Cold Side Image



Hot Side Image

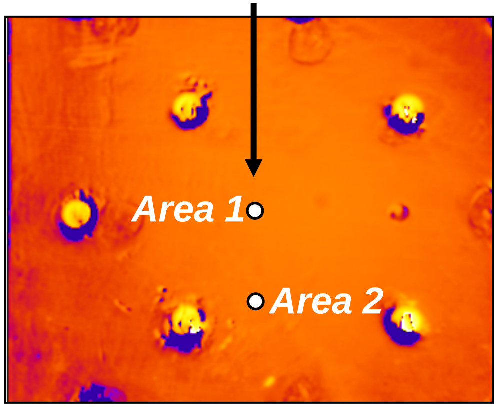




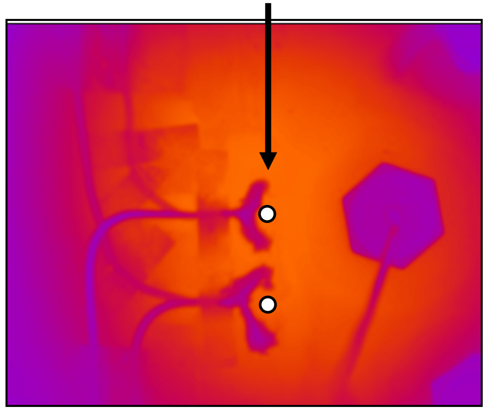
Results From Reference Test Specimen
(no film cooling)

Temperature Contours

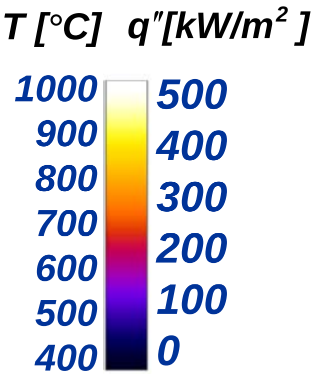
Embedded TC Locations *Cold Surface TC Locations*



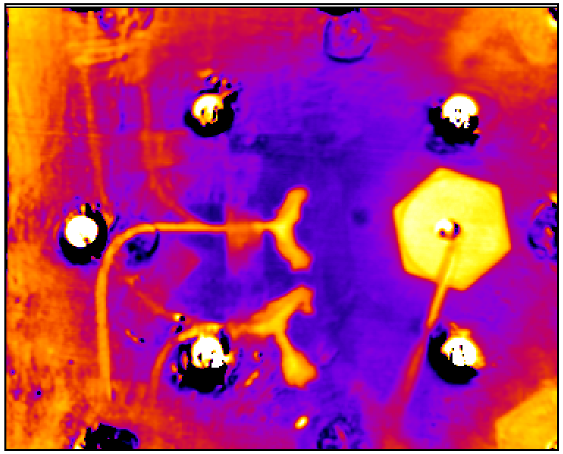
Hot Side



Cold Side



Heat Flux Contour



$P_\infty = 3$ bar

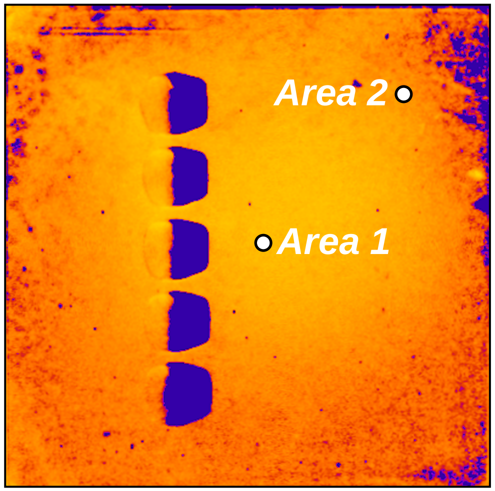
	Area 1				Area 2			
	Thermocouple	Optical	Residual	Residual %	Thermocouple	Optical	Residual	Residual %
Hot Side Temp [C]	747.80	751.60	3.80	0.51	730.63	742.40	11.77	1.61
Cold Side Temp [C]	720.72	722.83	2.11	0.29	705.65	708.60	2.94	0.42
Overall Effectiveness	0.351	0.349	0.00	0.81	0.367	0.360	0.01	1.92
Heat Flux [kW/m²]	72.94	77.49	4.55	6.24	67.28	91.05	23.78	35.34

Experiments Were Conducted Using A Coupon With Fan Shaped Film Cooling Holes

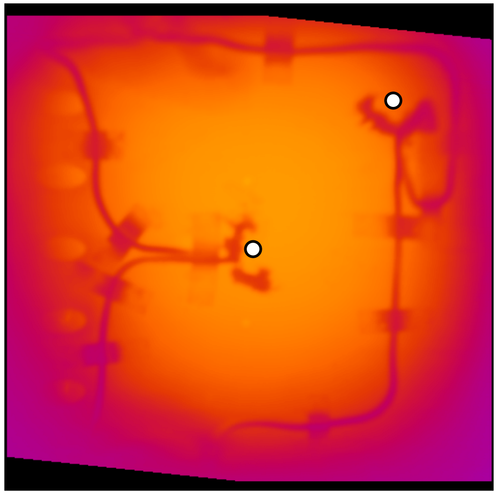
$M = 1.0$, $P_\infty = 5.1$ Bar, $T_\infty = 1145°C$

Temperature Contours

Embedded TC Locations

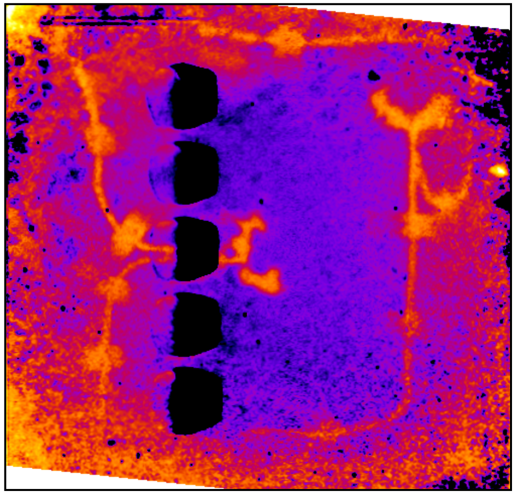


Cold Surface TC Locations



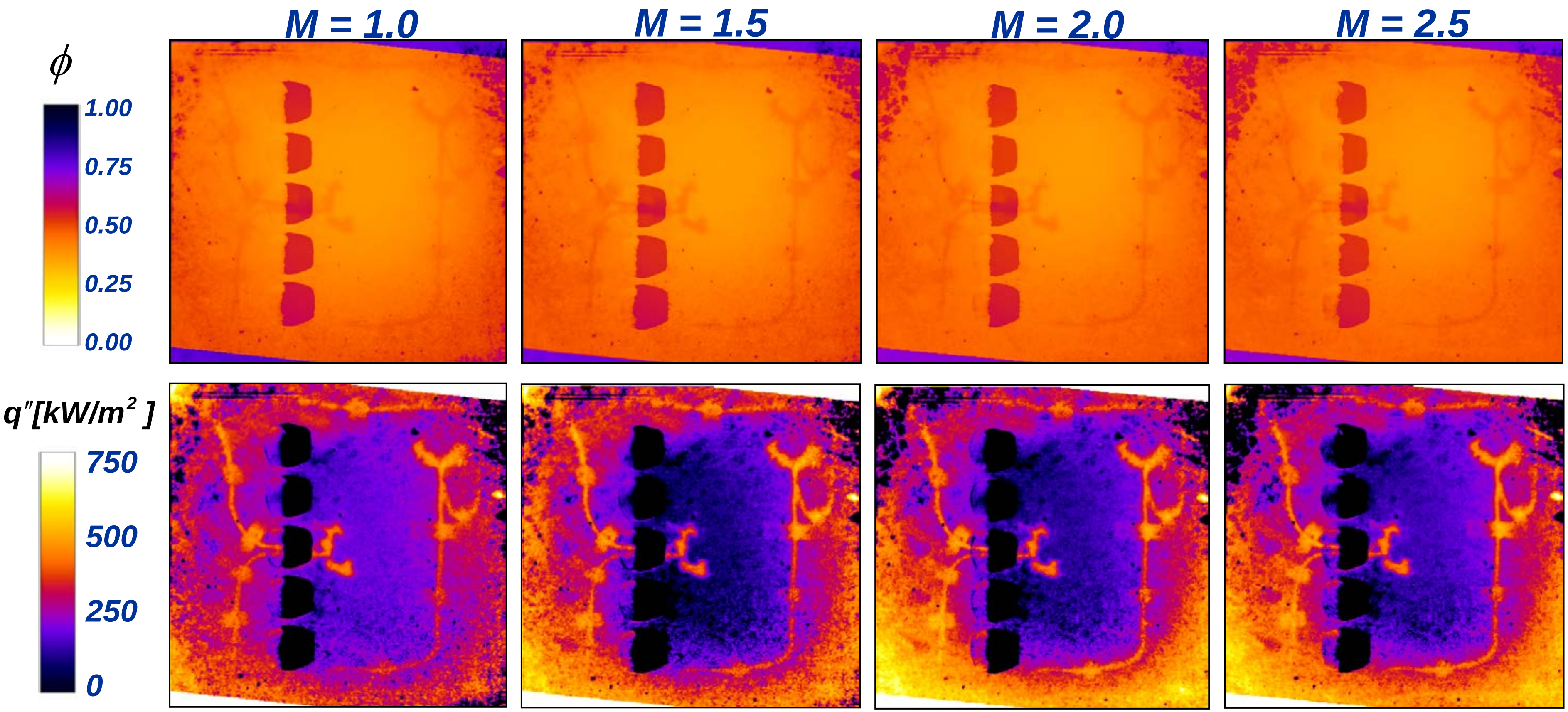
T [°C] *q″[kW/m²]*

Heat Flux Contour



	Area 1				Area 2			
	Thermocouple	Optical	Residual	Residual %	Thermocouple	Optical	Residual	Residual %
Hot Side Temp [°C]	816.63	825.80	9.17	1.12	785.99	776.20	9.79	1.25
Cold Side Temp [°C]	775.86	777.90	2.04	0.26	737.44	711.70	25.74	3.49
Overall Effectiveness	0.368	0.362	0.01	1.62	0.405	0.424	0.02	4.66
Heat Flux [kW/m^2]	127.21	149.47	22.27	17.50	151.51	201.27	49.76	32.84

Overall Effectiveness And Heat Flux Contours Were Generated For Four Blowing Ratios



Data From NETL Test Rig Can Achieve Desired Uncertainty Goals

Dependent Variable	Uncertainty Goals -- Less than . . .	
	Local	2D Image
ϕ Overall Effectiveness	$\pm$ 0.03 $\pm$ 0.02	$\pm$ 0.06[1]
$\Delta q''_r$ Net Heat Flux Reduction	$\pm$ 0.06 $\pm$ 0.04	$\pm$ 0.12[2]

[1] Contour maps compare to within $\pm$0.02 of the local effectiveness measurements (so far)

[2] May require larger temperature difference (higher temperature/pressure test conditions/higher cold side heat transfer coefficient). Both options are possible with current test rig.

CFD Modeling

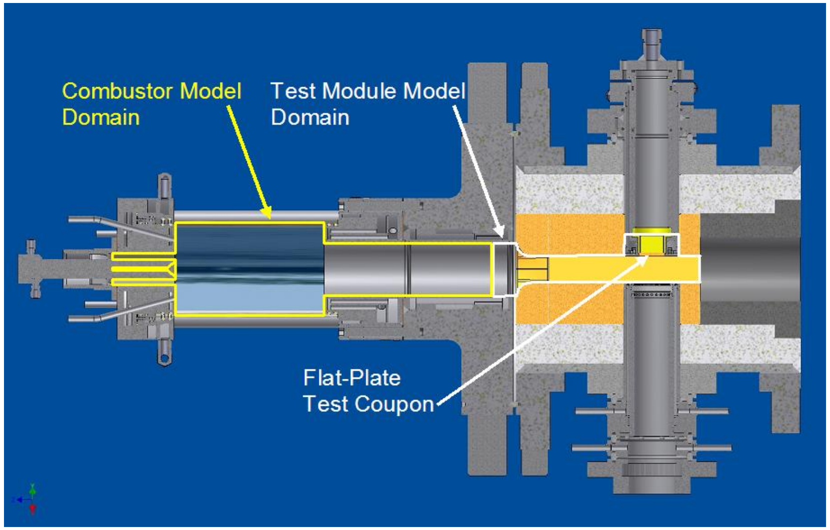
Goals

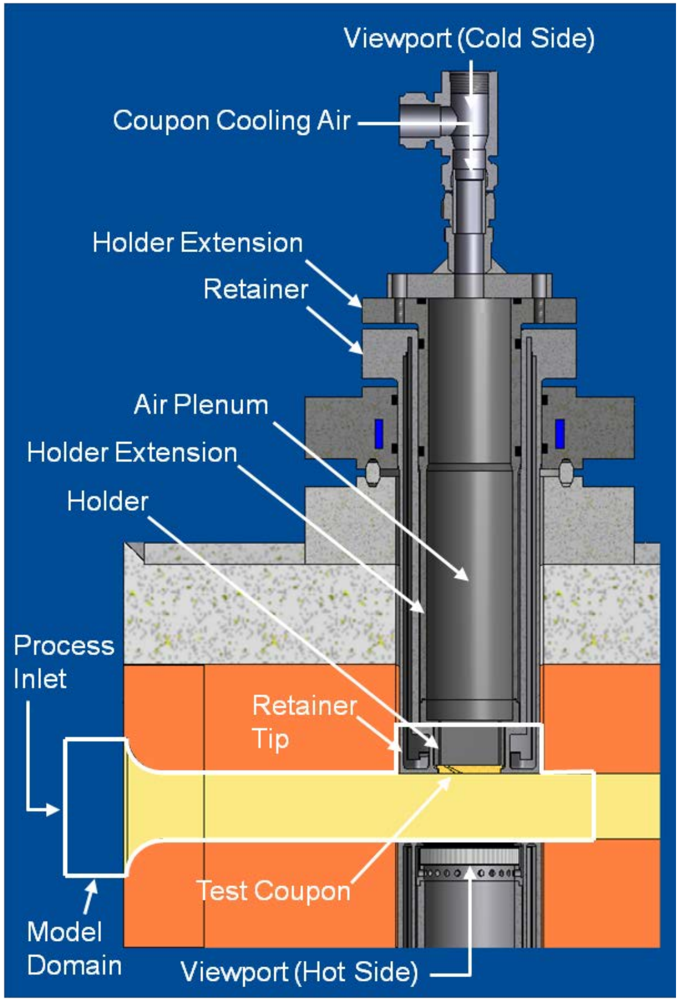
- Assist refinement of the surface temperature measurement techniques being developed and validated experimentally under this task by performing conjugate heat transfer (CHT) modeling of the aerothermal test module
- Develop predictive capability to assist with evaluation of film cooling designs

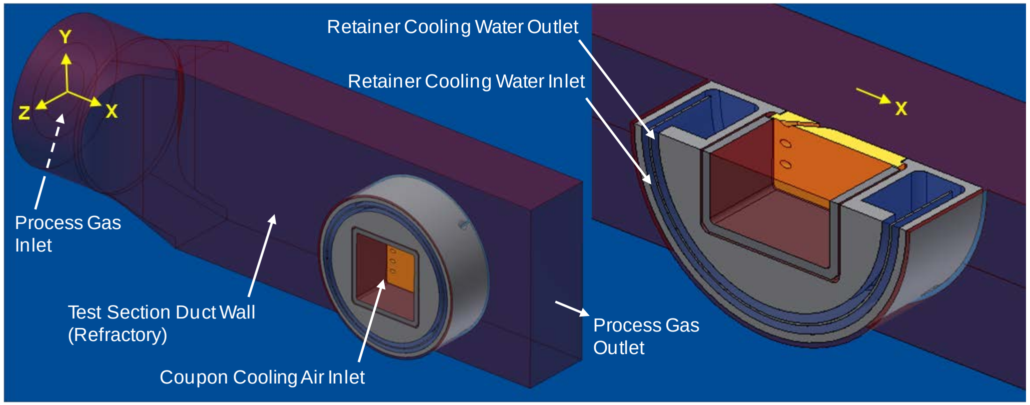
Overview

- o Modeling of combustor
- o Modeling of test module
  - Three cooling geometries
    - o Round holes, round holes with trench, laidback fan-shaped holes
  - Coarse meshes with standard wall functions
- FY12
  - o Modeling of test module
    - One cooling geometry (laidback fan-shaped hole)
    - Improved convective heat transfer predictions
      - o Wall model, turbulence model, mesh refinement, discretization order
    - Radiative heat transfer study planned

Combustor and Test Section Geometries and Model Domains







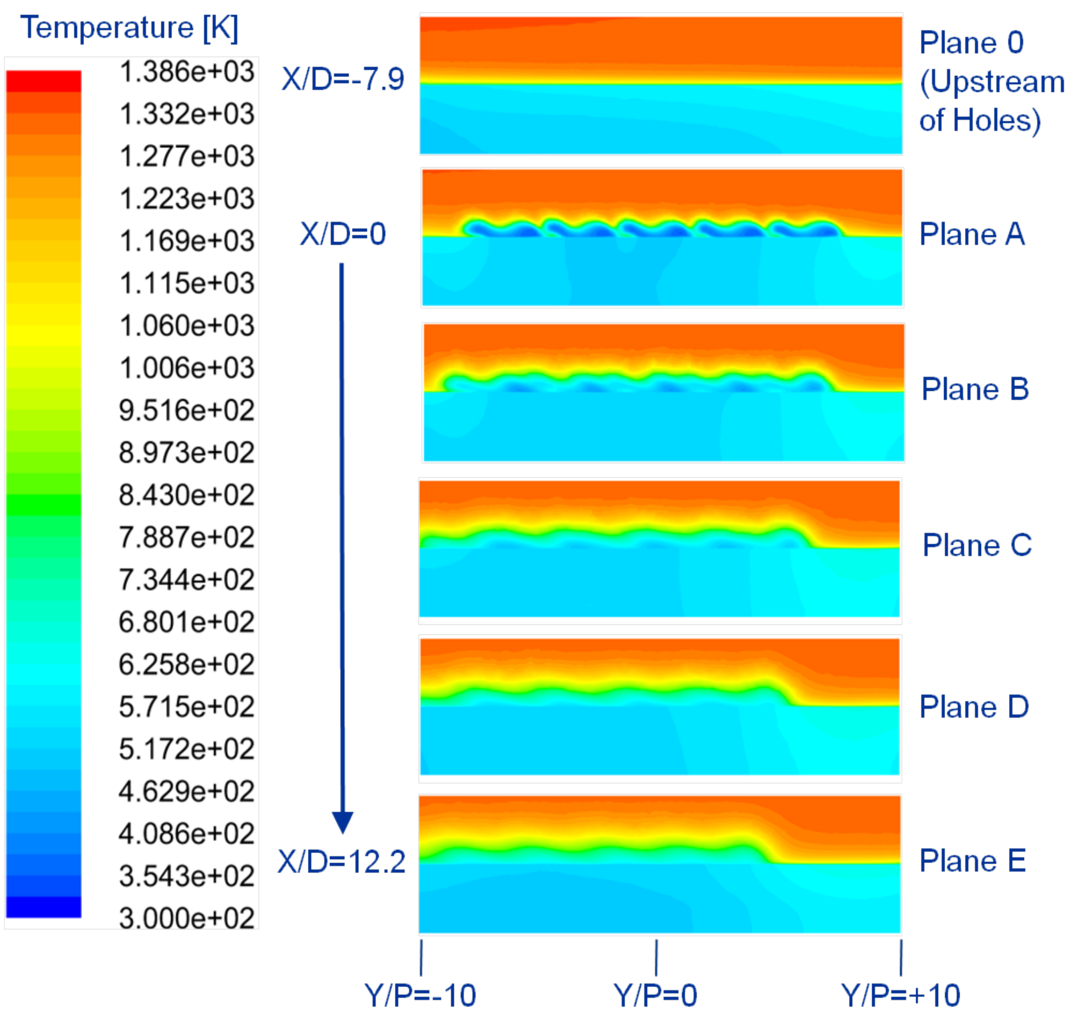
CHT Modeling with Convective and Conductive Heat Transfer

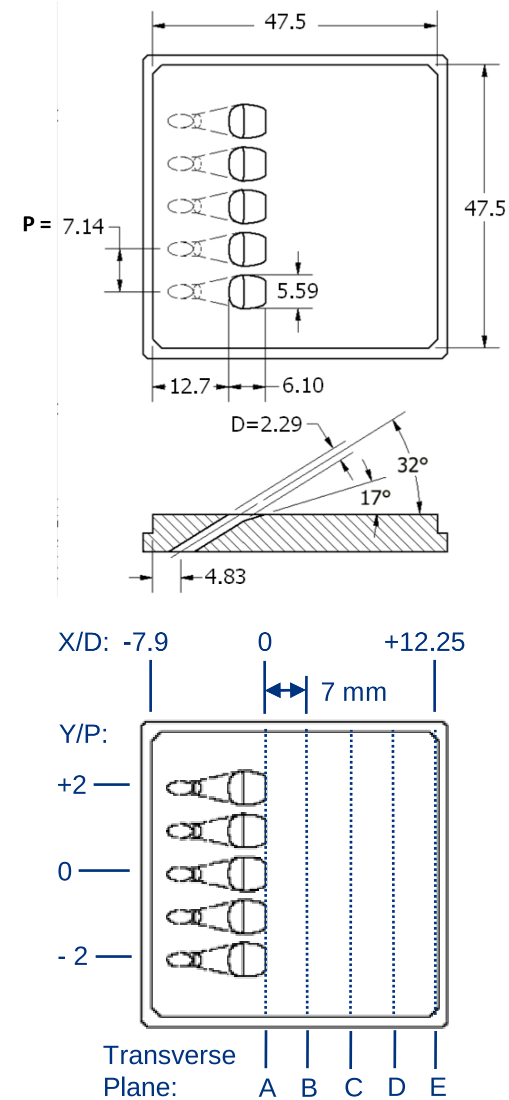
- Sensitivity of convective HT to select model parameters
  - Turbulence model (Re k-ε and SST k-ω)
  - Discretization order (1st and 2nd)
  - Mesh (three cases – fine, intermediate, coarse)
  - Coupon-retainer coupling (effect of finite thermal contact resistance)
- Simulation cases:

Model Case	Turbulence Model	Solution Order	Mesh Case	Coupon Cooling Flow	Coupon-Retainer Coupling	Radiation
1	Re k-ε	1st	1	Y	Y	N
1A	Re k-ε	2nd	1	Y	Y	N
1B	Re k-ε	2nd	3	Y	Y	N
1C	Re k-ε	2nd	1	Y	N	N
1D	Re k-ε	2nd	3	Y	N	N
1E	Re k-ε	2nd	2	Y	Y	N
2	SST k-ω	1st	1	Y	Y	N
2A	SST k-ω	2nd	1	Y	Y	N
2B	SST k-ω	2nd	3	Y	Y	N
2C	SST k-ω	2nd	1	Y	N	N
2D	SST k-ω	2nd	3	Y	N	N
2E	SST k-ω	2nd	2	Y	Y	N
2F	SST k-ω	2nd	1	N	Y	N
2G	SST k-ω	2nd	1	N	N	N

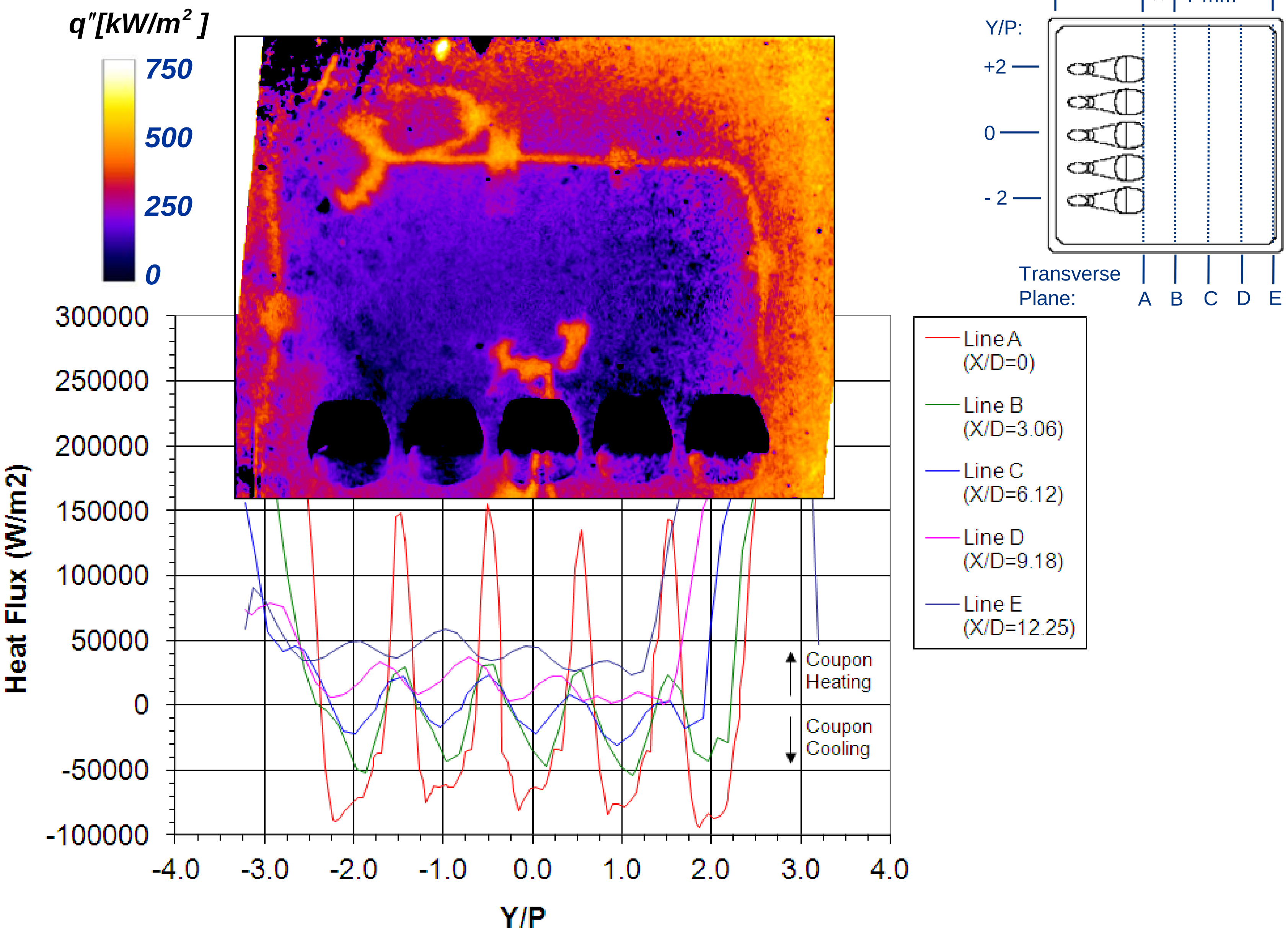
<u>Mesh Case 1</u>: 4.3×10^6 Cells, 1st Layer Thickness = 0.025 mm, Total Layers = 12
<u>Mesh Case 2</u>: 6.9×10^6 Cells, 1st Layer Thickness = 0.020 mm, Total Layers = 13
<u>Mesh Case 3</u>: 8.5×10^6 Cells, 1st Layer Thickness = 0.014 mm, Total Layers = 15

Temperature Contours on Transverse Planes (Case 2A)

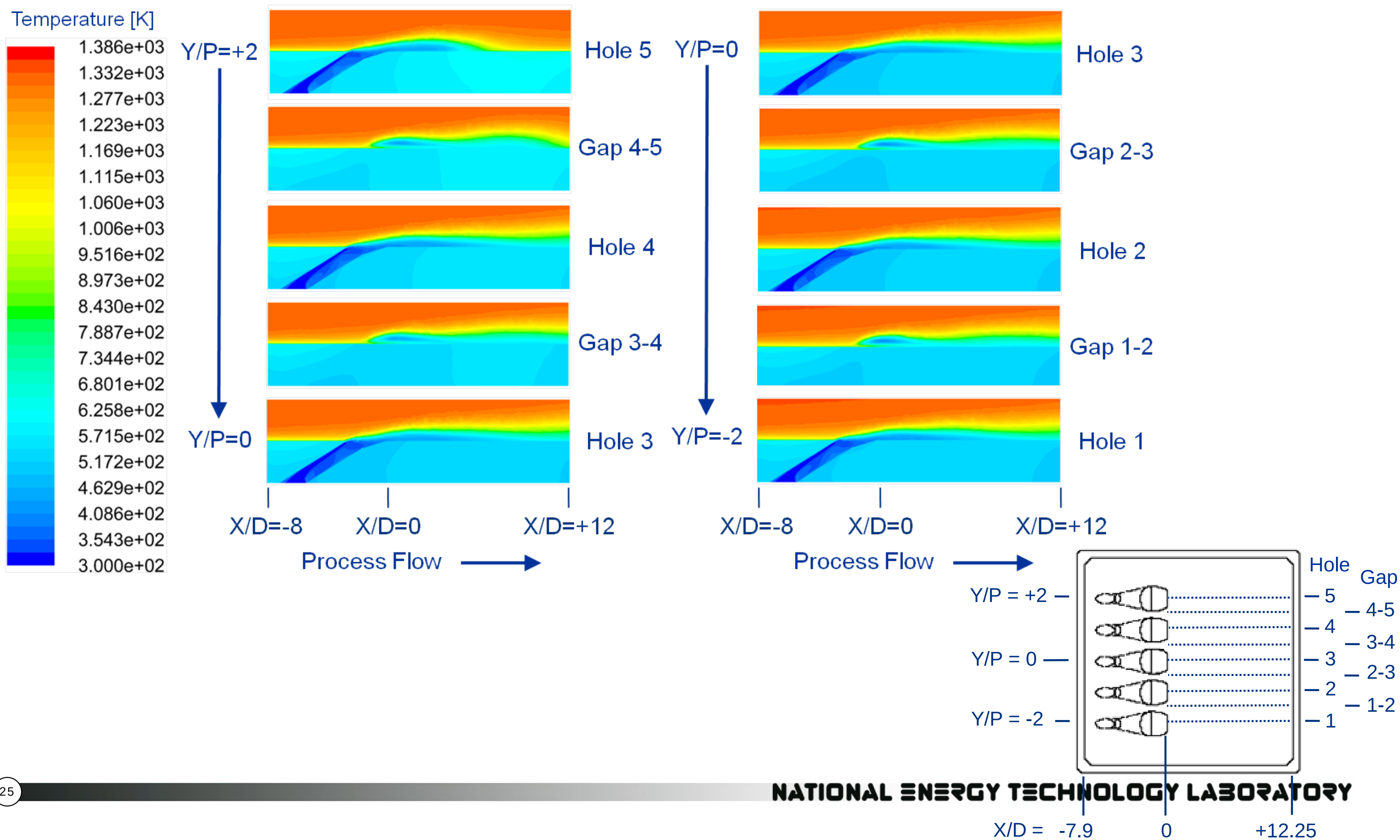




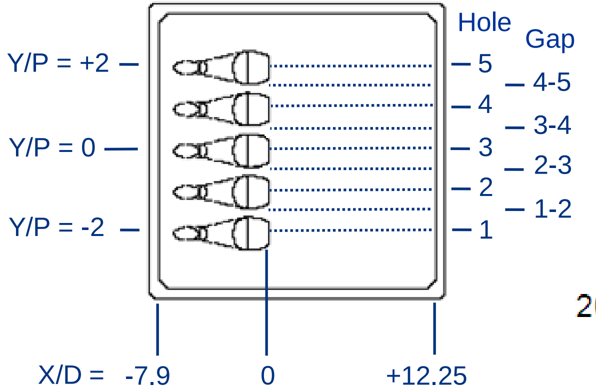
Transverse Heat Flux Profiles

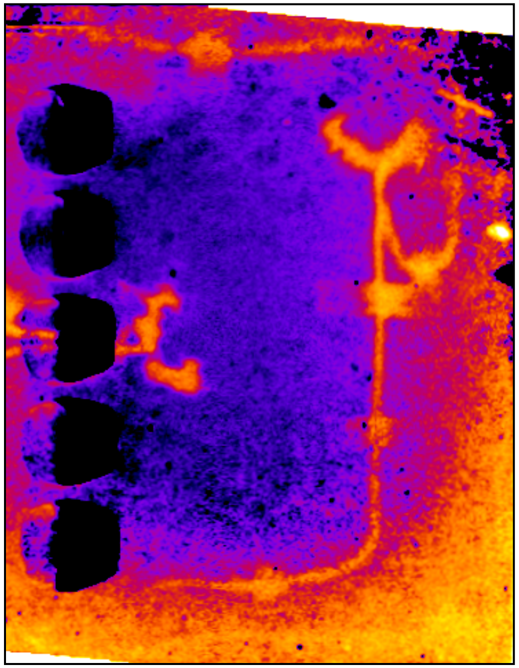


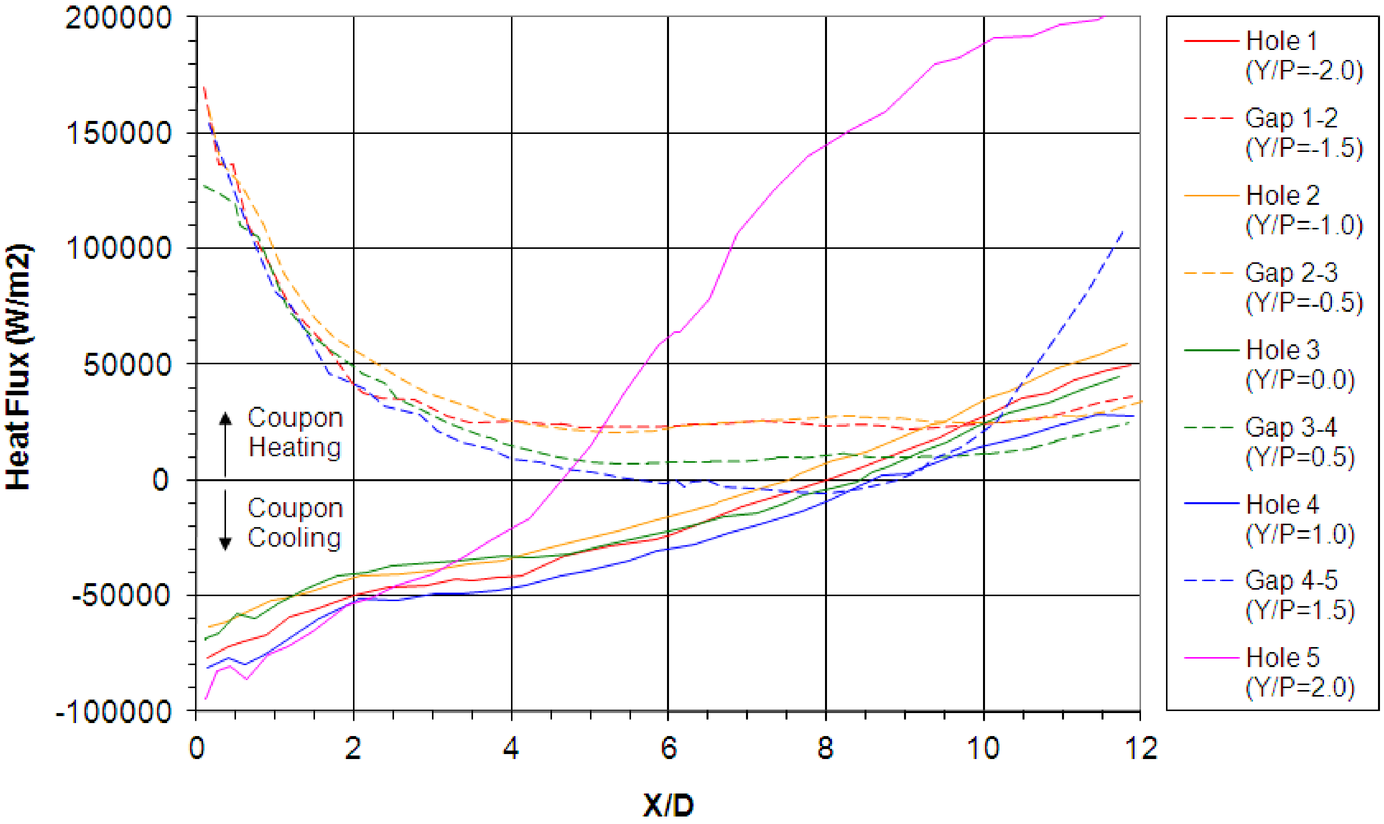
Temperature Contours on Axial Planes (Case 2A)



Test Coupon Axial Heat Flux Profiles (Case 2A)







Summary

- **NETL test rig validation**
  - Significant improvement in IR temperature measurements
  - Achieved uncertainty goals for measuring overall film cooling effectiveness and local heat flux reduction
  - Very close to achieving uncertainty goals for 2D heat flux reduction contours

- **Conjugate heat transfer CFD modeling**
  - Completing grid sensitivity studies
  - Radiative heat transfer study (not yet completed)
    - Realistic comparison with measured metal temperatures

- **University and industrial collaboration is encouraged**

Acknowledgments

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