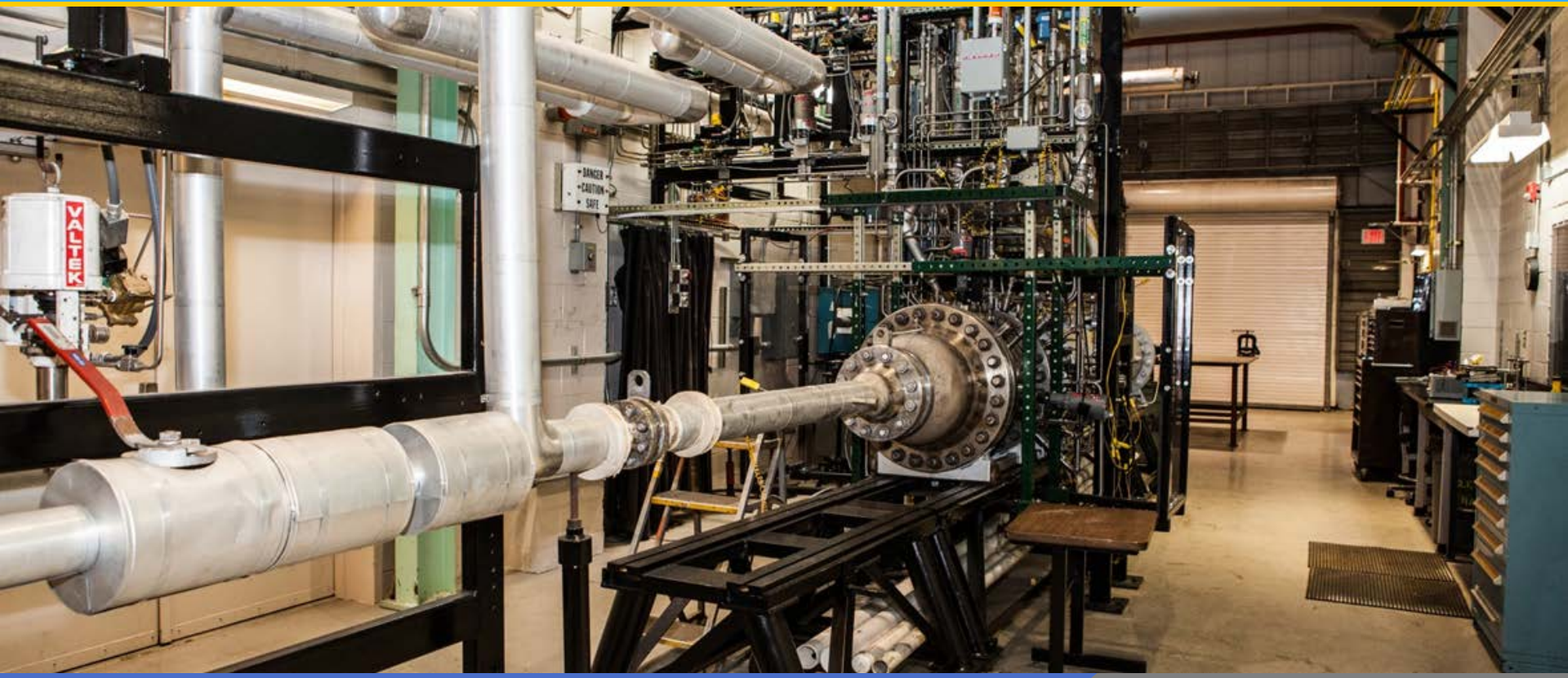
Driving Innovation ♦ Delivering Results



Film and Internal Cooling Testing at NETL

Jim Black, Doug Straub, Ed Robey, and Sridharan Ramesh

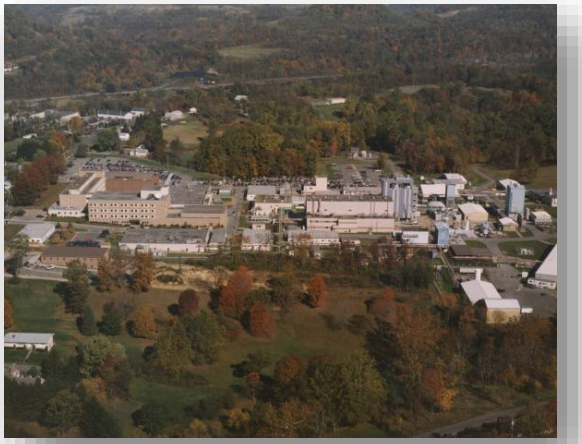
2015 UTSR Workshop
November 4, 2015

NETL Overview

- Full service DOE national laboratory
- Dedicated to energy RD&D, domestic energy resources
- Fundamental science through technology demonstration
- Unique industry – academia – government collaborations

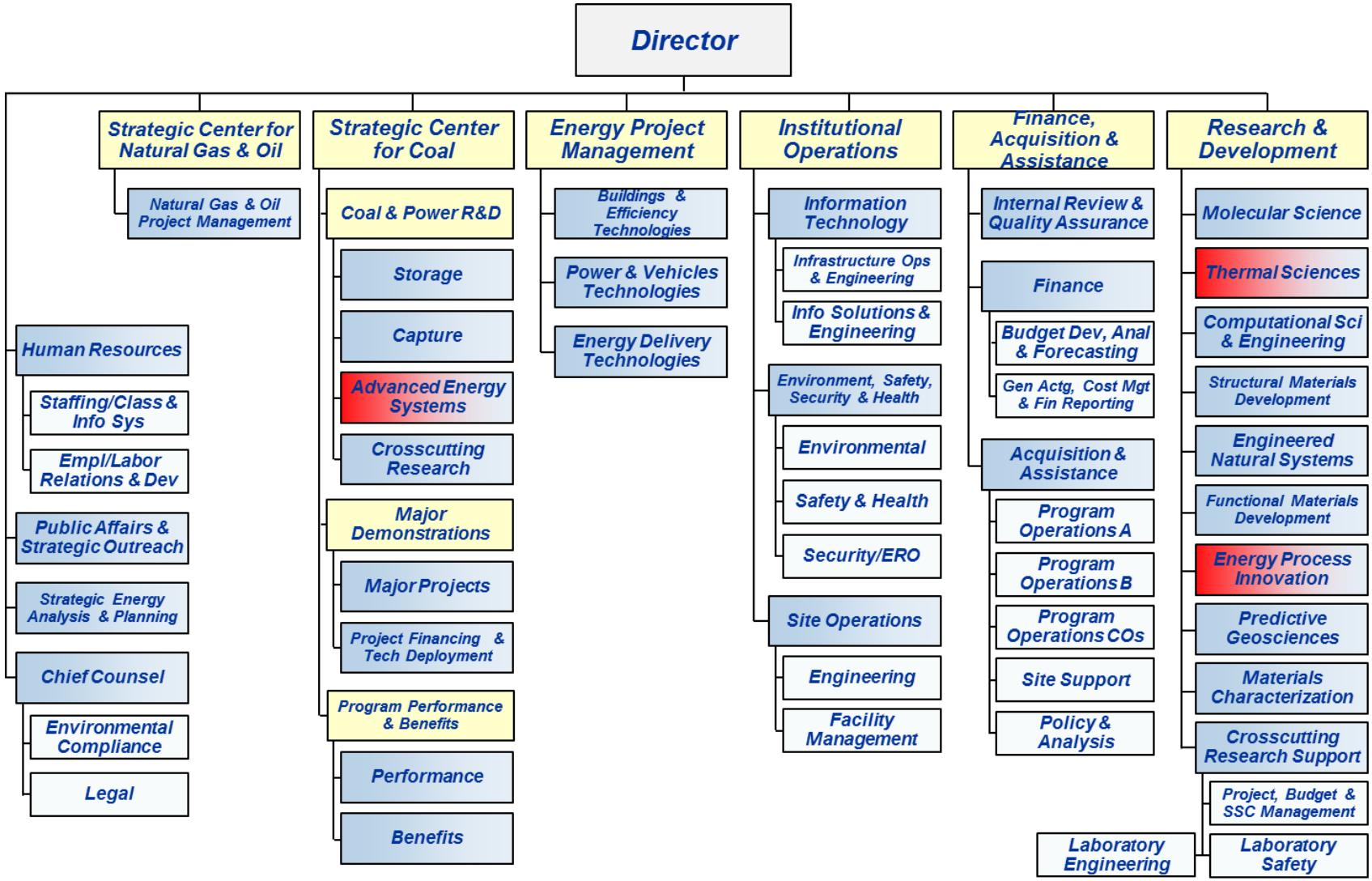
Oregon

Pennsylvania



West Virginia

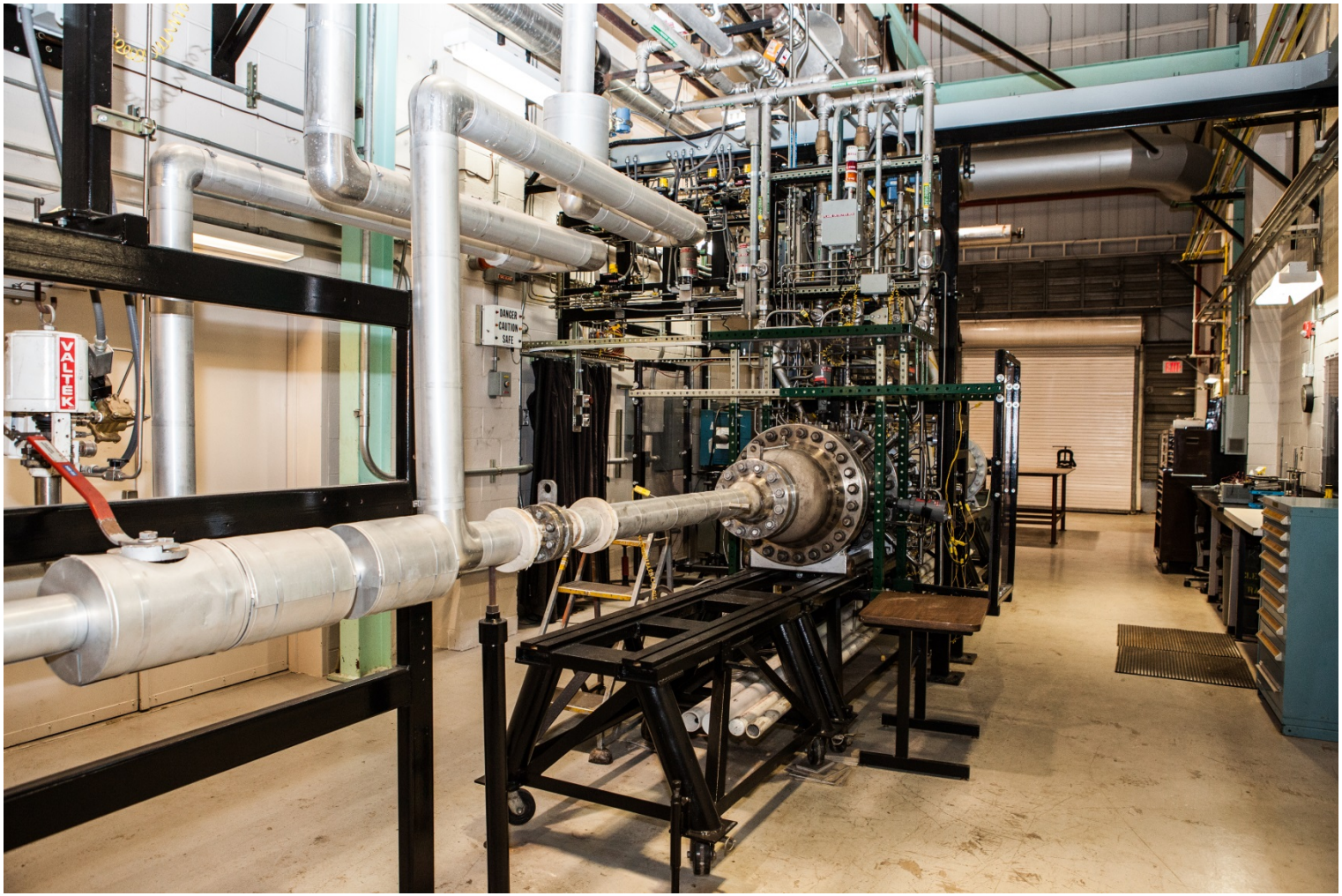
NETL Organizational Structure



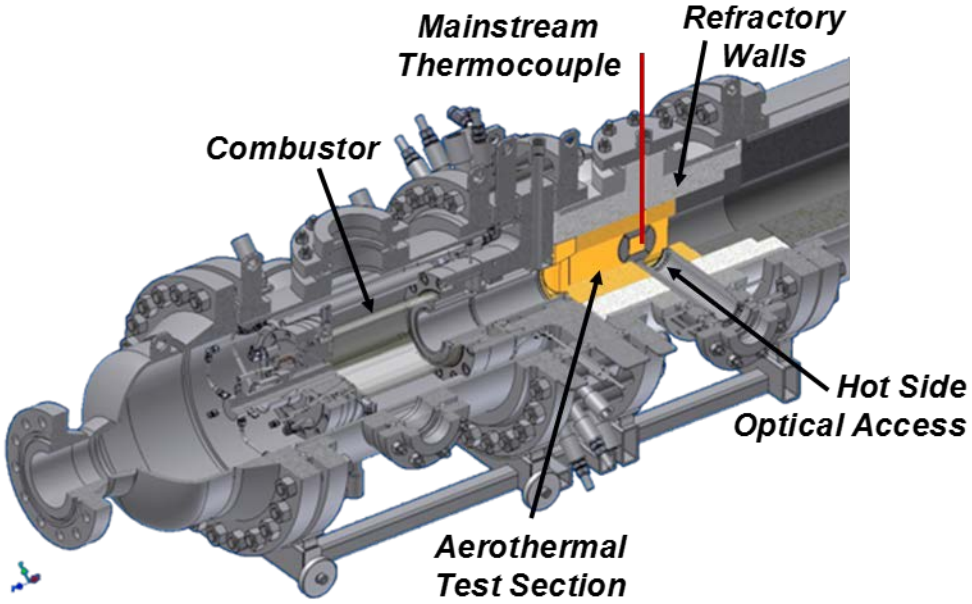
Presentation Overview

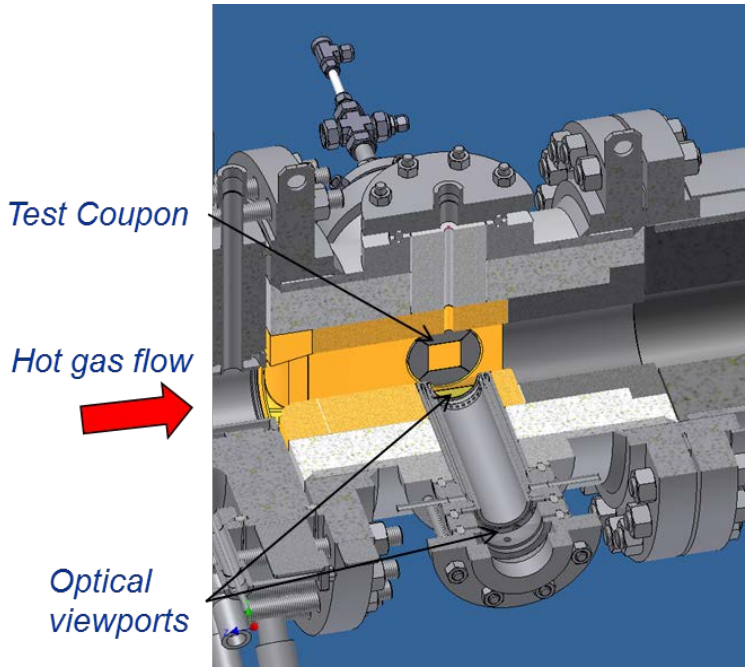
- Overview high temperature/high pressure test facility and setup
- Film cooling test results
- Internal cooling test results
- Future work

NETL's High Temperature and High Pressure Aerothermal Test Facility



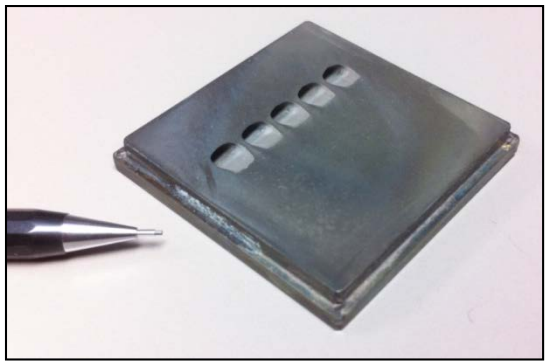
Test Articles Located Downstream of NG Swirl-Stabilized Combustor

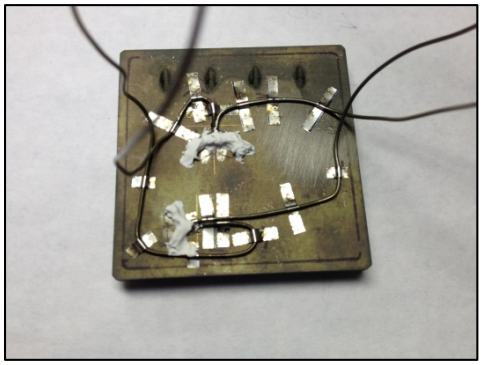




Hot Gas Path Capabilities

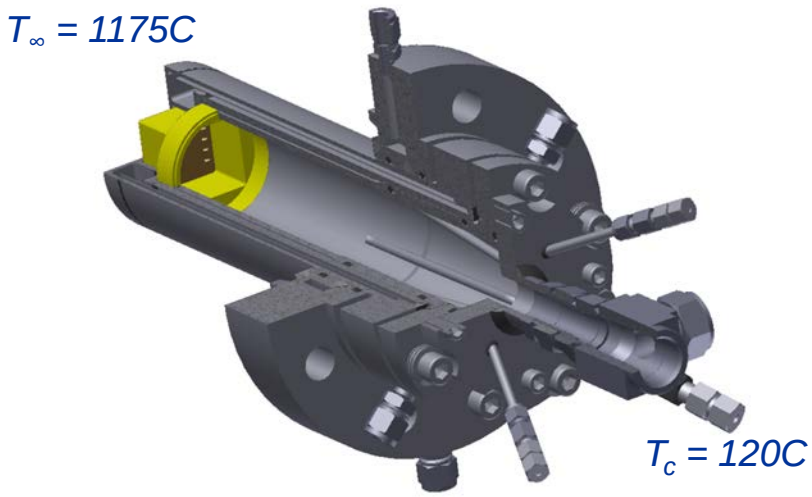
- ~70 m/s @ Tu ~ 15-20%
- 1000-1200°C
- 1 – 10 bar





Experimental Setup – Coupon Holder

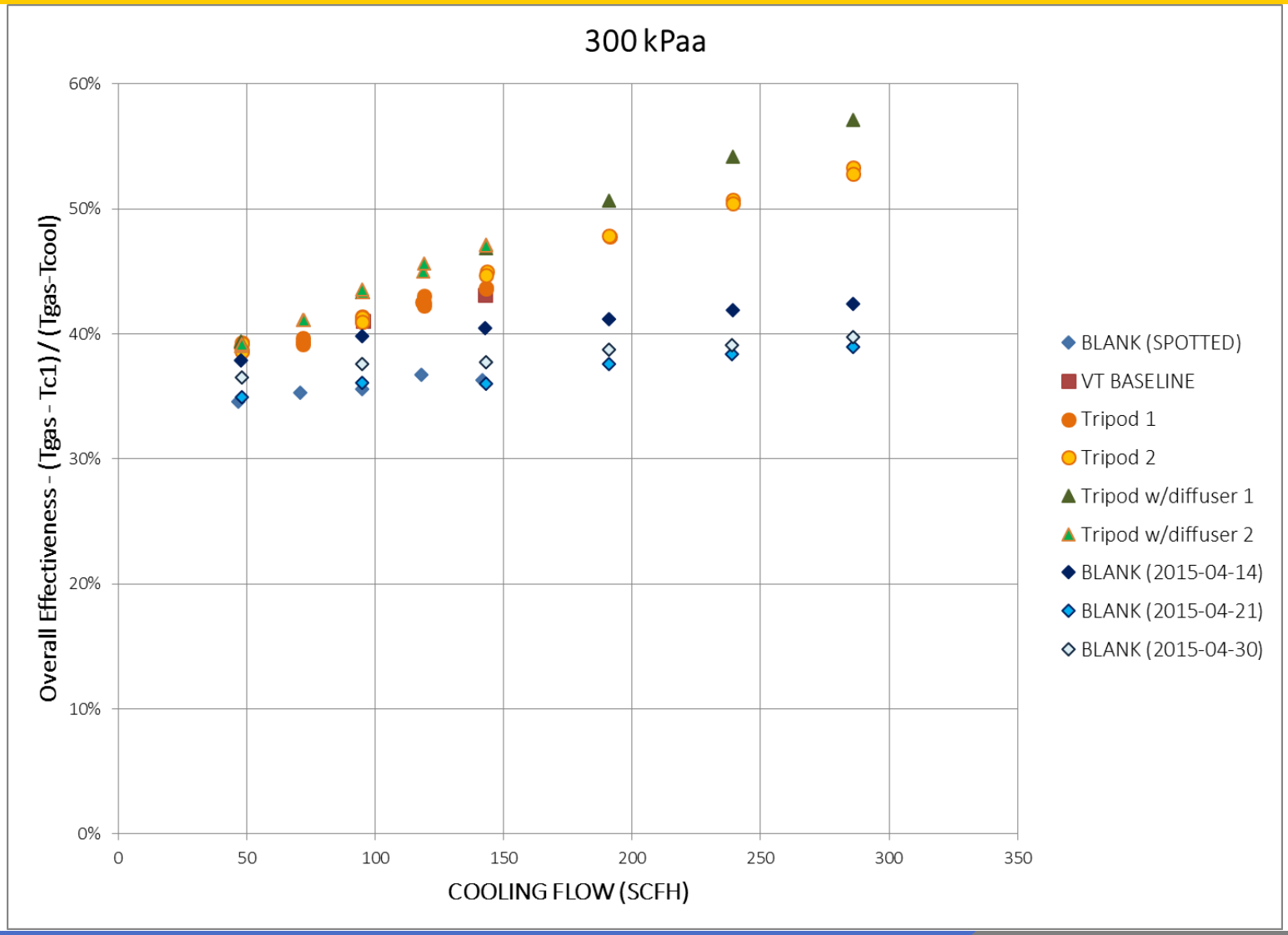
- **Flat plate test articles**
  - 2” x 2” x ¼” Haynes 230
  - Installed flush with walls
- **Different cooling schemes can be evaluated**
- **IR imaging on hot and cold side of test article**
  - Direct measurement of thermal gradient
  - Heat flux is estimated assuming 1-D conduction



Coolant Gas Path Capabilities

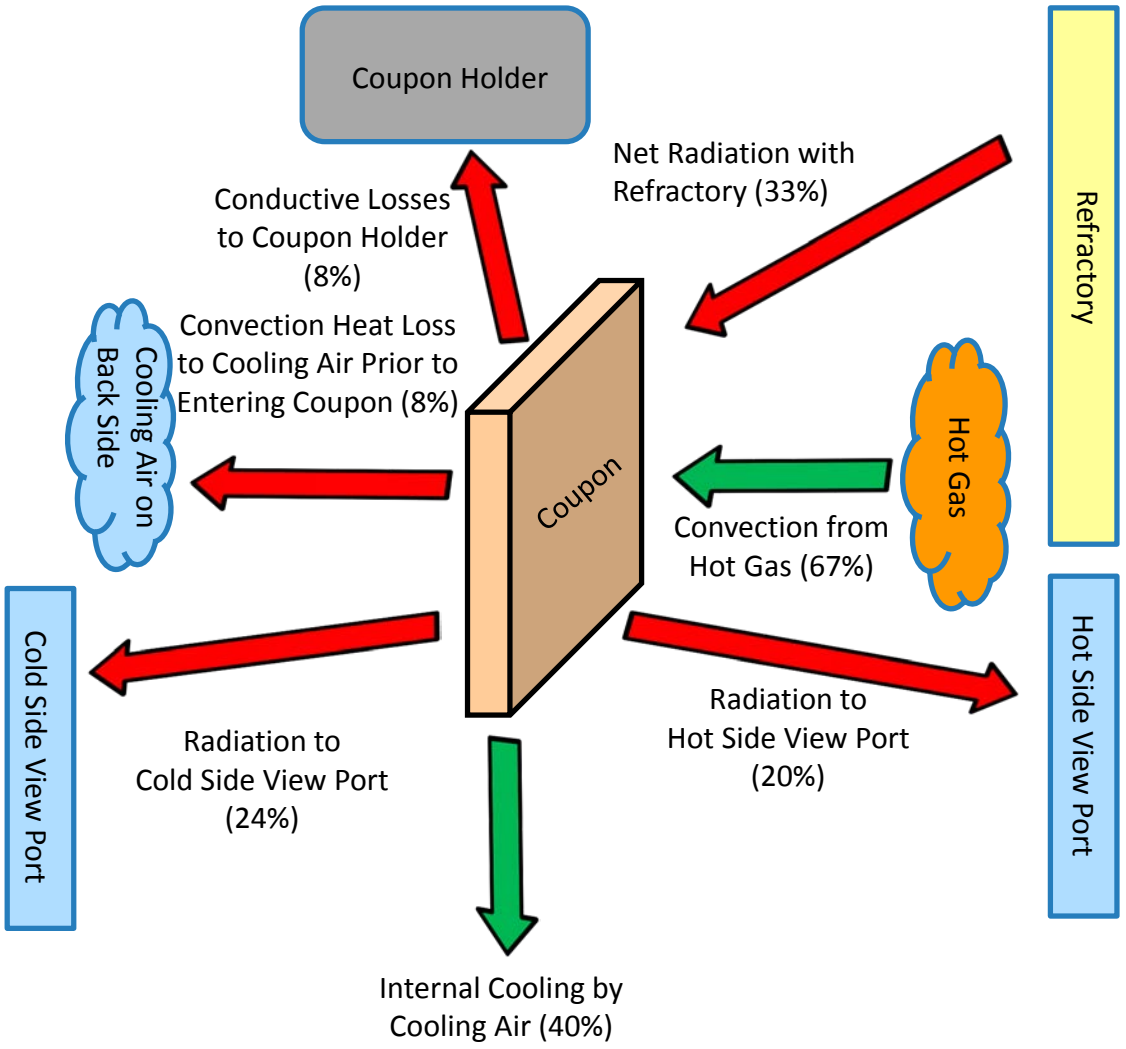
- Ambient → ~300°C
- 0.5 → 5 gm/sec

Va Tech Film Cooled Coupons



Coupon Energy Balance

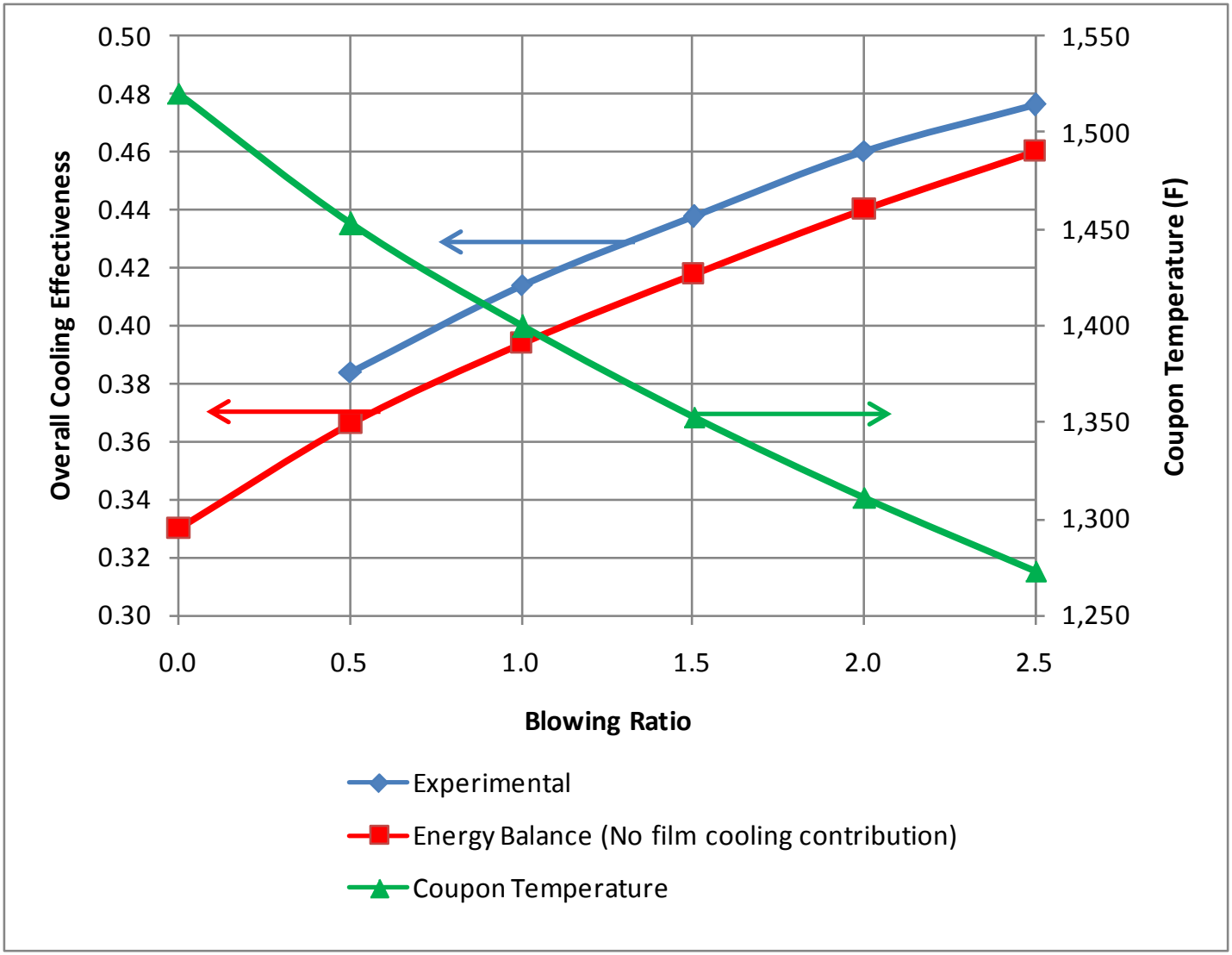
- **Desired heat transfer modes indicated with green arrows**
- **In an ideal test rig, convective heating by hot gas would equal internal cooling by cooling air – heat transfer represented by red arrows would be zero.**
- **Qualitative discussion**
  - Improved film cooling will decrease Convection from Hot Gas causing coupon temperature to drop
  - Lower coupon temp decreases all of the 'heat loss' components
  - Film cooling improvement (reduction in Convection from Hot Gas) must overcome these reductions in heat loss. The apparent impact of film cooling improvement is under-predicted when looking at overall cooling effectiveness.
- **Reference blowing ratio – 1.5, coupon temp ~ 1,300°F (700°C)**



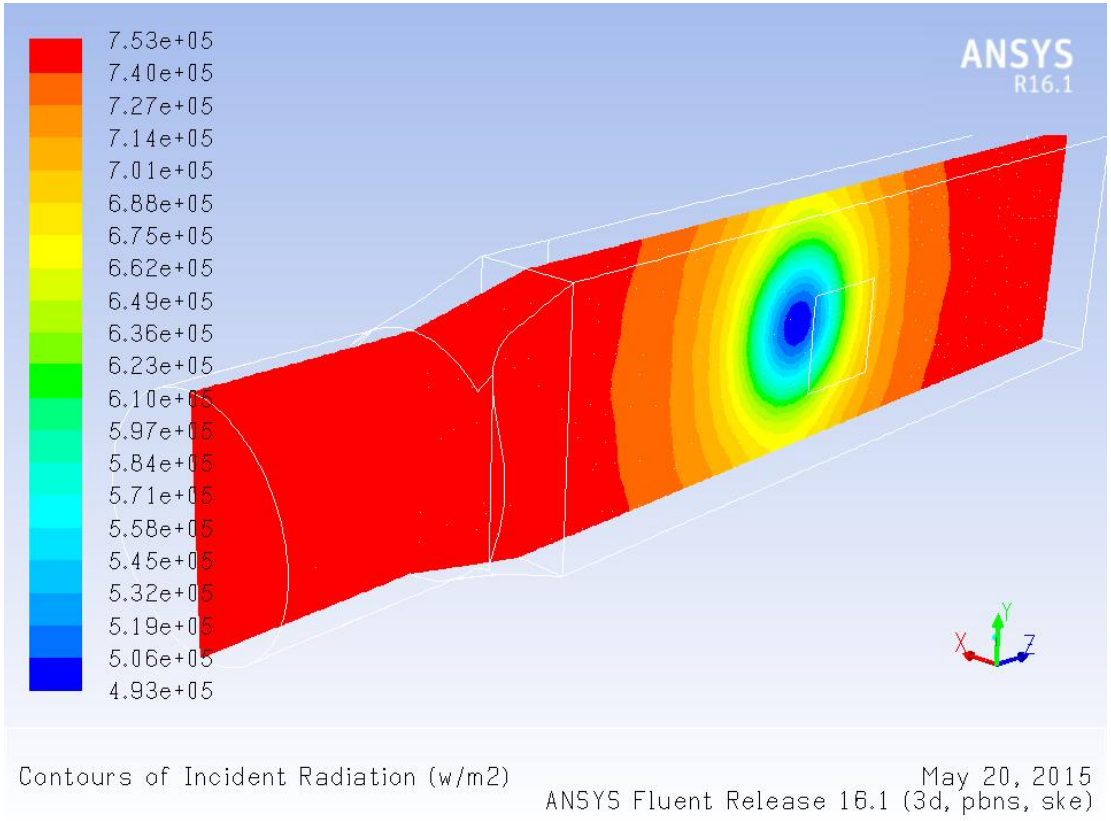
Energy Balance Assumptions

- Assume that the coupon is at a uniform temperature.
- Convective heating of the coupon is calculated by modeling as flow across a flat plate and assuming the boundary layer begins to develop at the leading edge of the coupon.
- No effort is made to account for the effect of the film cooling in this model.
- Make simplifying assumptions with regard to geometry to enable calculations of radiation shape factors, conduction, etc.
- Order of magnitude type analysis.

Overall Cooling Effectiveness



Radiation Modeling of Aerothermal Rig



- **3D modeling of radiation to assess amount of radiation from walls reflecting off of coupon surface.**
- **Walls typically 200-300K above coupon temperature.**
- **Simulations indicate that IR measured coupon temperatures are 50-150K over actual temperature due to reflected radiation.**
- **Consistent with experimental measurements.**

General Testing Objectives

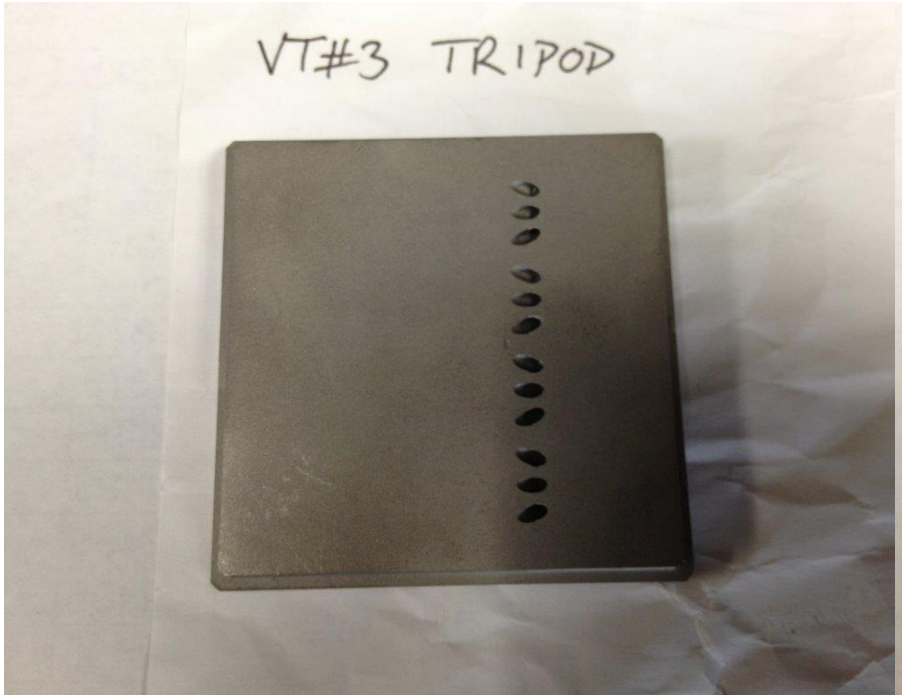
- Perform comparison of different film and internal cooling configurations under engine-like conditions
- Provide experimental data for CFD model validation at engine-like conditions
- Validate scaling parameters by comparing with result obtained from test rigs operating at different process conditions
- Provide correlations for blade and vane design

Comparison of NETL and Va Tech Film Cooling Tests

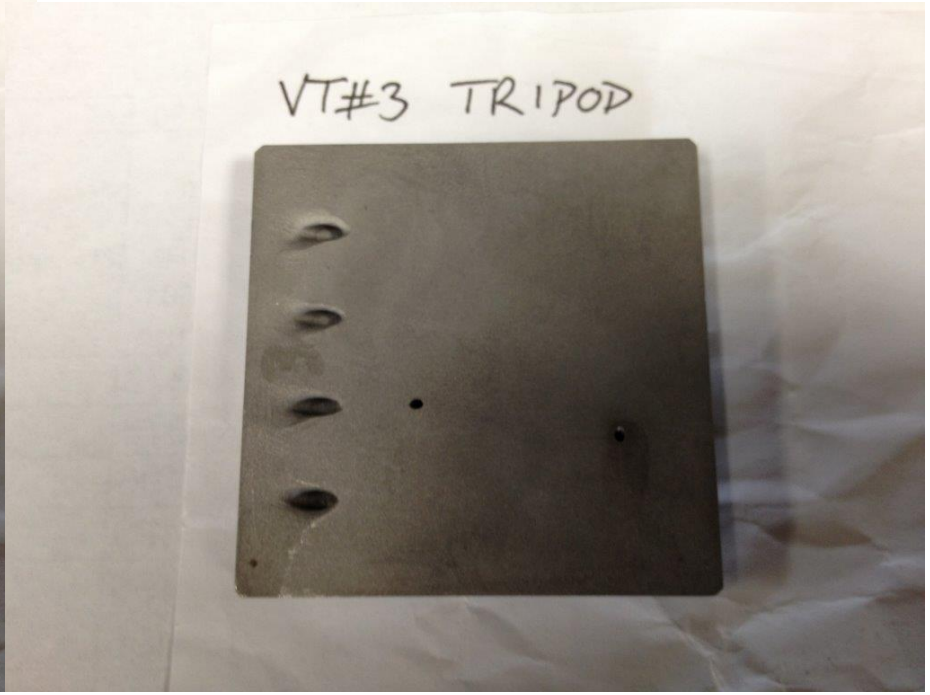
	NETL	Va Tech
Hot Gas	Flue Gas	Air
Hot Gas Temp	2,100 – 2,200°F (1,150-1,200°C)	122°F (50°C)
Hot Gas Pressure	30 and 60 psig (300 and 500 kPa_a)	Atmospheric
Hot Gas Velocity	230 ft/s (70 m/s)	26 ft/s (8 m/s)
Cooling Gas	Air	Air
Cooling Gas Temp	250°F (120°C)	72 and 122°F (22 and 50°C)
Density Ratio - Cooling Gas to Hot Gas	3.7	1.1
Coupon Material / Thermal Conductivity	Haynes 230 -15 Btu/hr-ft-°F (26 W/m-°C) and CM 247 LC – 12 Btu/hr-ft-°F (21 W/m-°C)	ABS Plastic - 0.11 Btu/hr-ft-°F (0.187 W/m-°C)
Film cooling hole diameter	0.067 inches (1.7 mm)	0.25 inches (6.35 mm)
Coupon Surface Roughness	???	???
Coupon Temperature Measurements	Thermocouples and IR Imaging	IR Imaging
Test Technique	Steady State	Transient
Heat Source	2 MW NG swirl-stabilized combustor	25 kW electric SS mesh heater
Turbulence	15-20%	0.47 cm trip rod 5 cm upstream of coupon on base plate to make boundary layer turbulent
Results	Hot side temp, overall effectiveness, and heat flux	Film cooling (adiabatic) effectiveness and heat transfer coefficient

VA Tech Tripod Coupon

Hot Side

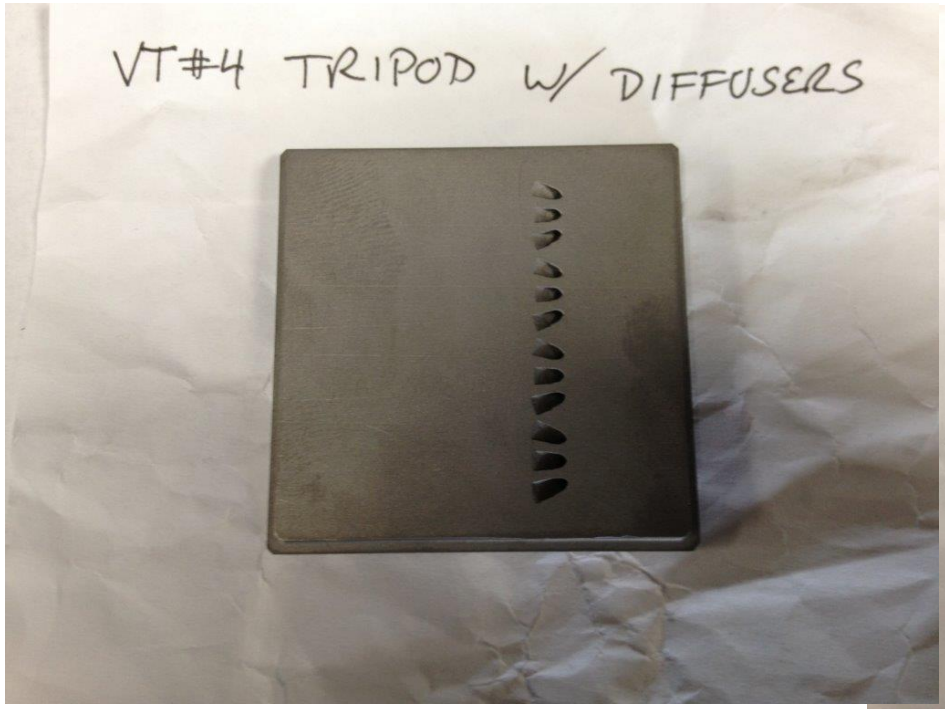


Cold Side

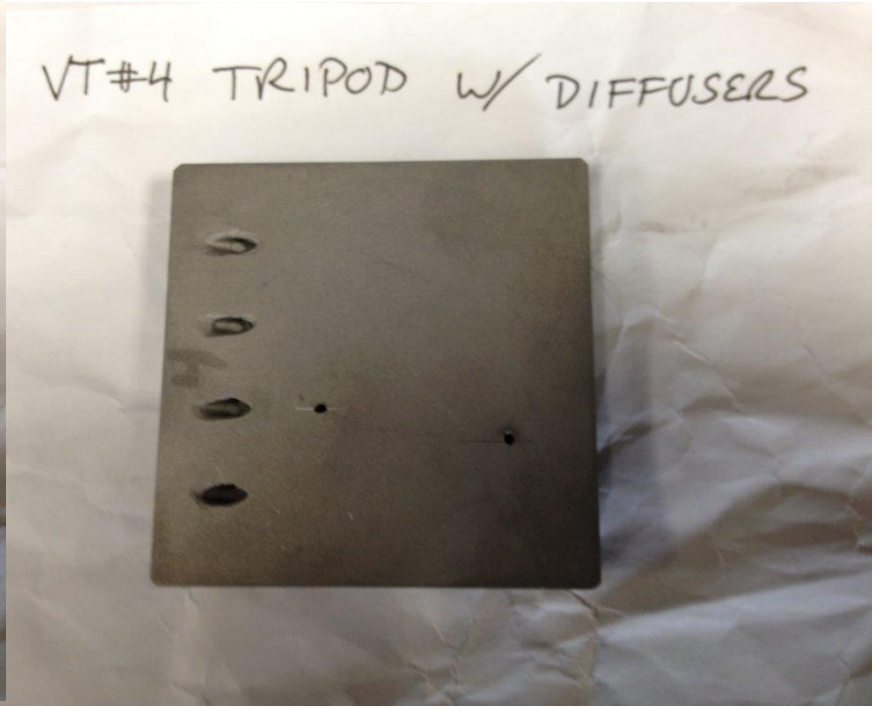


VA Tech Tripod Coupon w/Diffusers

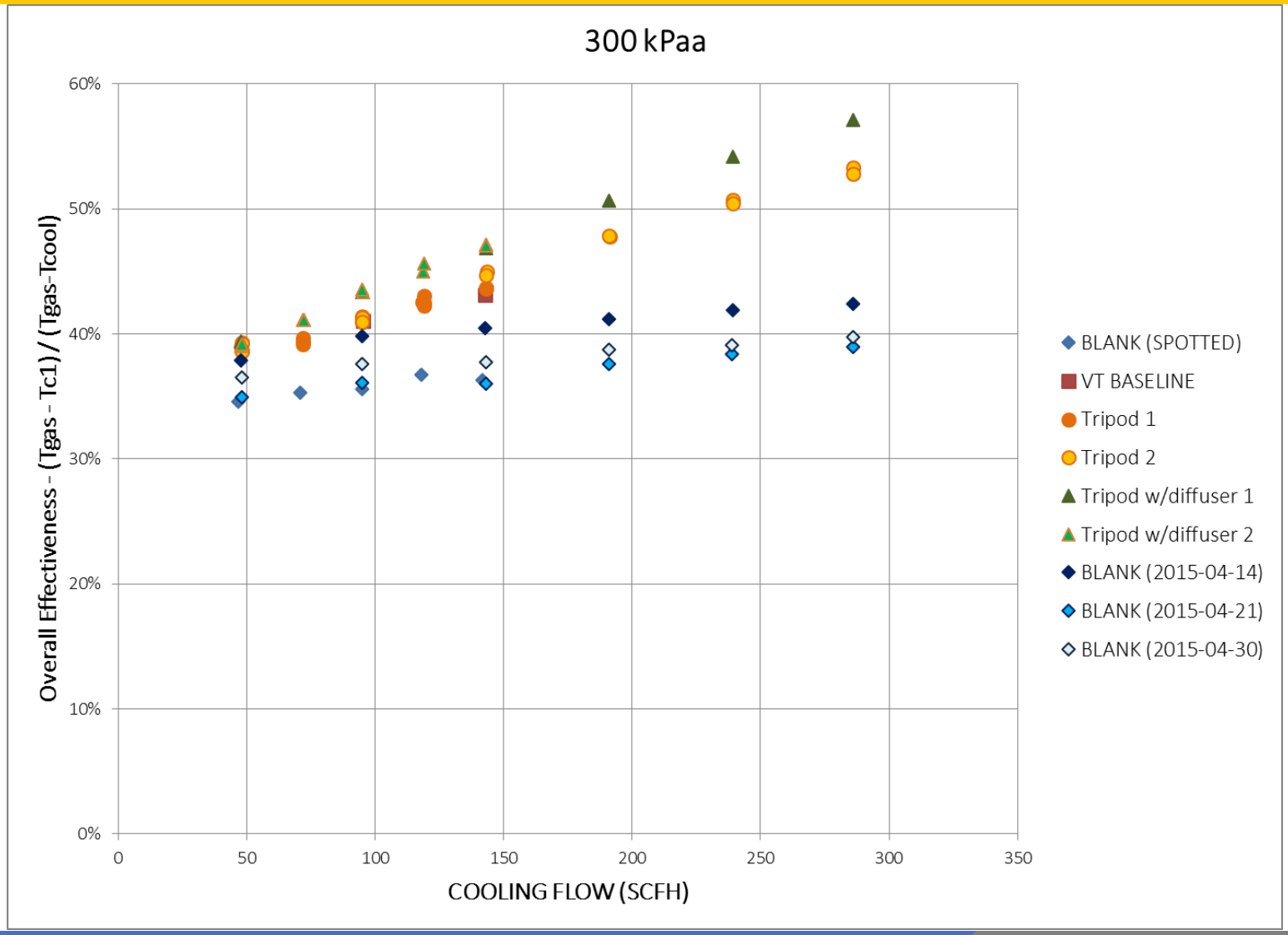
Hot Side



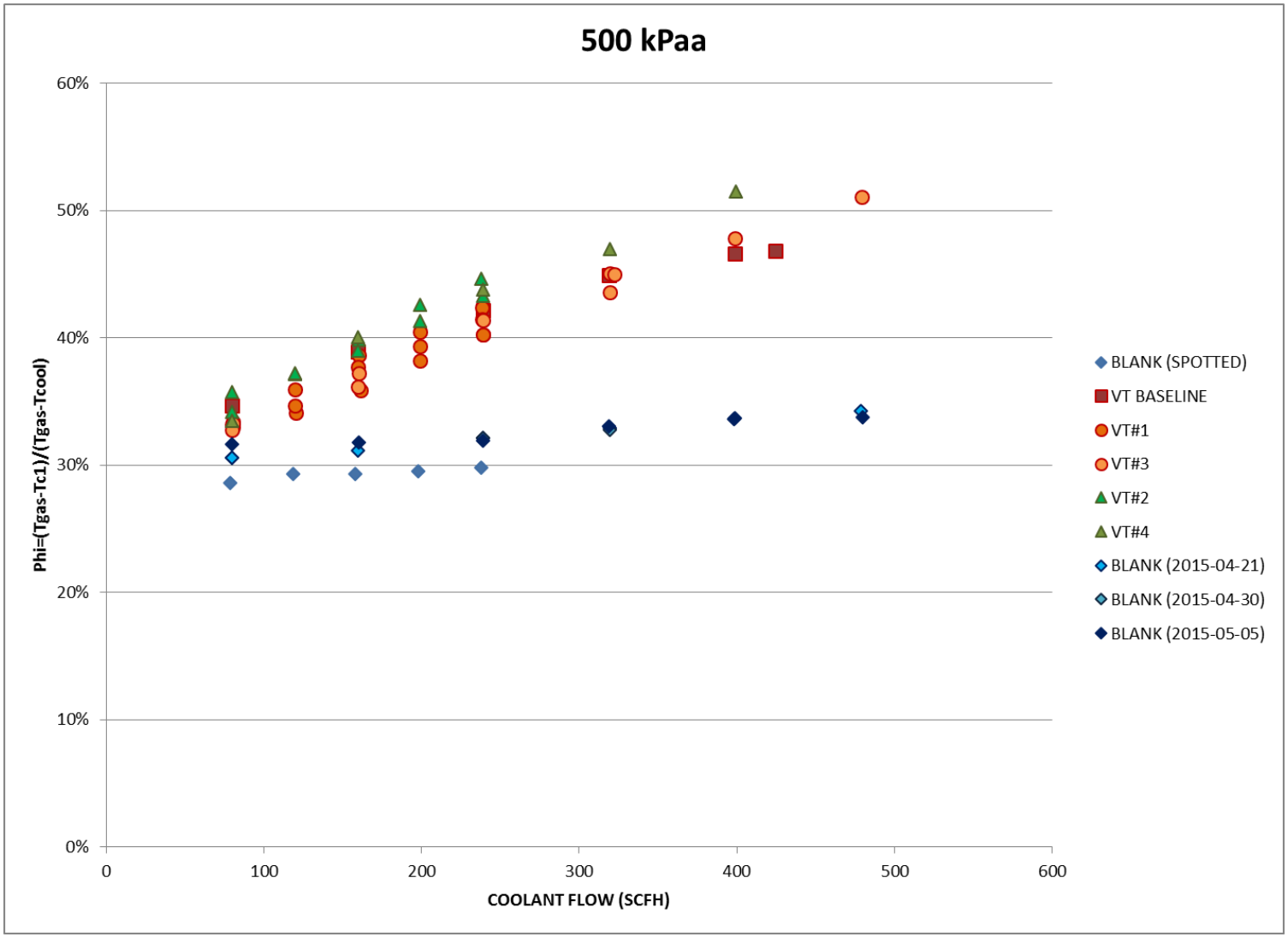
Cold Side



Va Tech Film Cooled Coupons



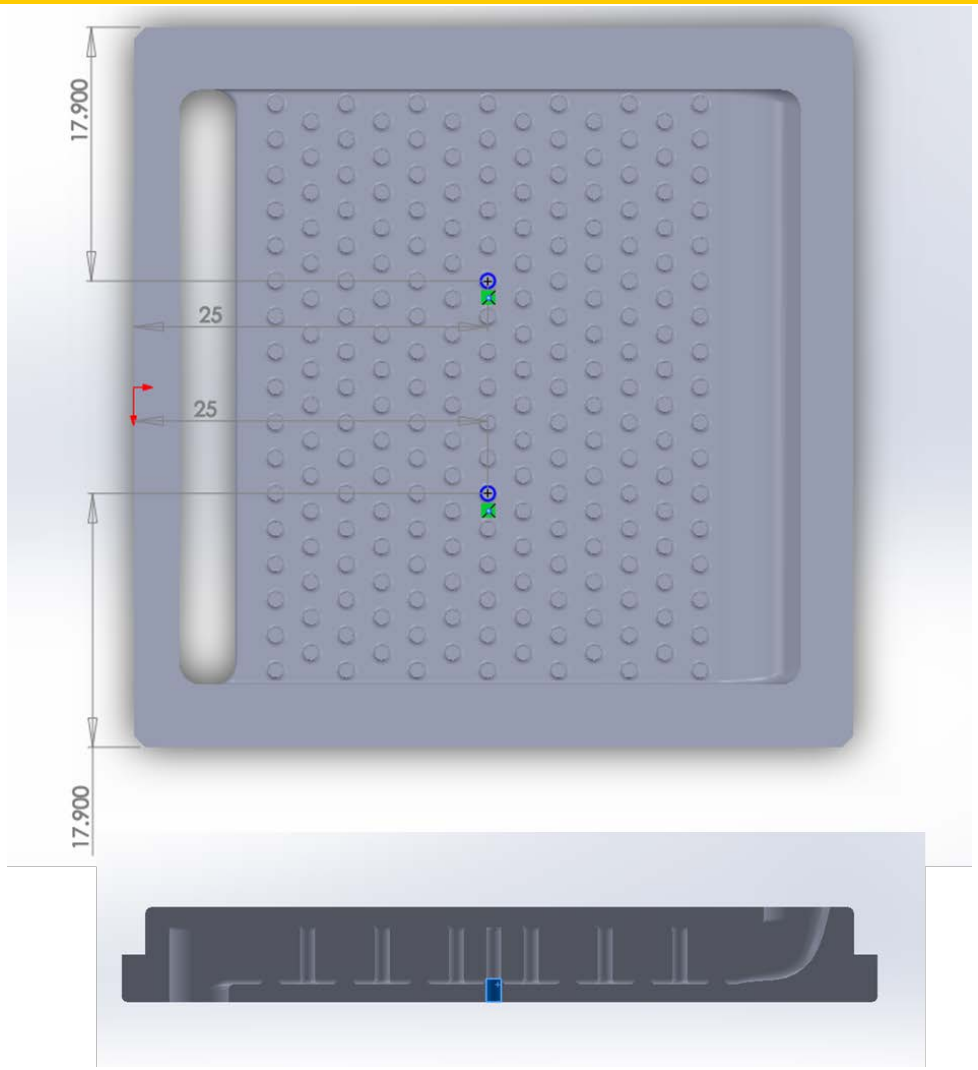
Va Tech Film Cooled Coupons



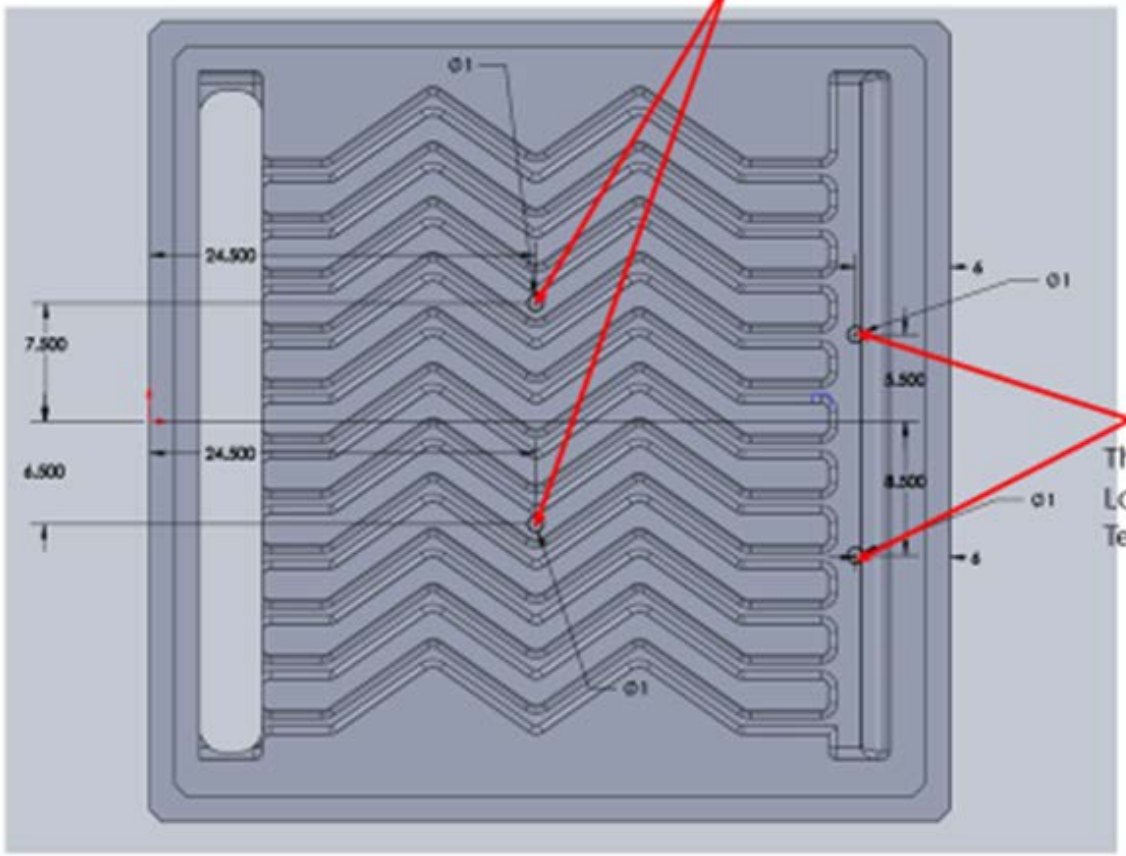
Va Tech Film Cooled Coupon Test Results

- **Film cooled coupons with tripod and tripod with shaped hole configurations indicated a continuous increase in cooling effectiveness with cooling flow rate over the range studied.**
- **Overall effectiveness does not approach zero at zero cooling flow rate. This is a characteristic of the test rig.**
- **Blank coupon test results indicate a cooling effectiveness of ~30% for the test rig alone.**
- **Other data reduction approaches are being investigated to circumvent the impact of the rig cooling effectiveness .**

Pitt Fully-Bridged Pin-Fin Internally Cooled Coupon

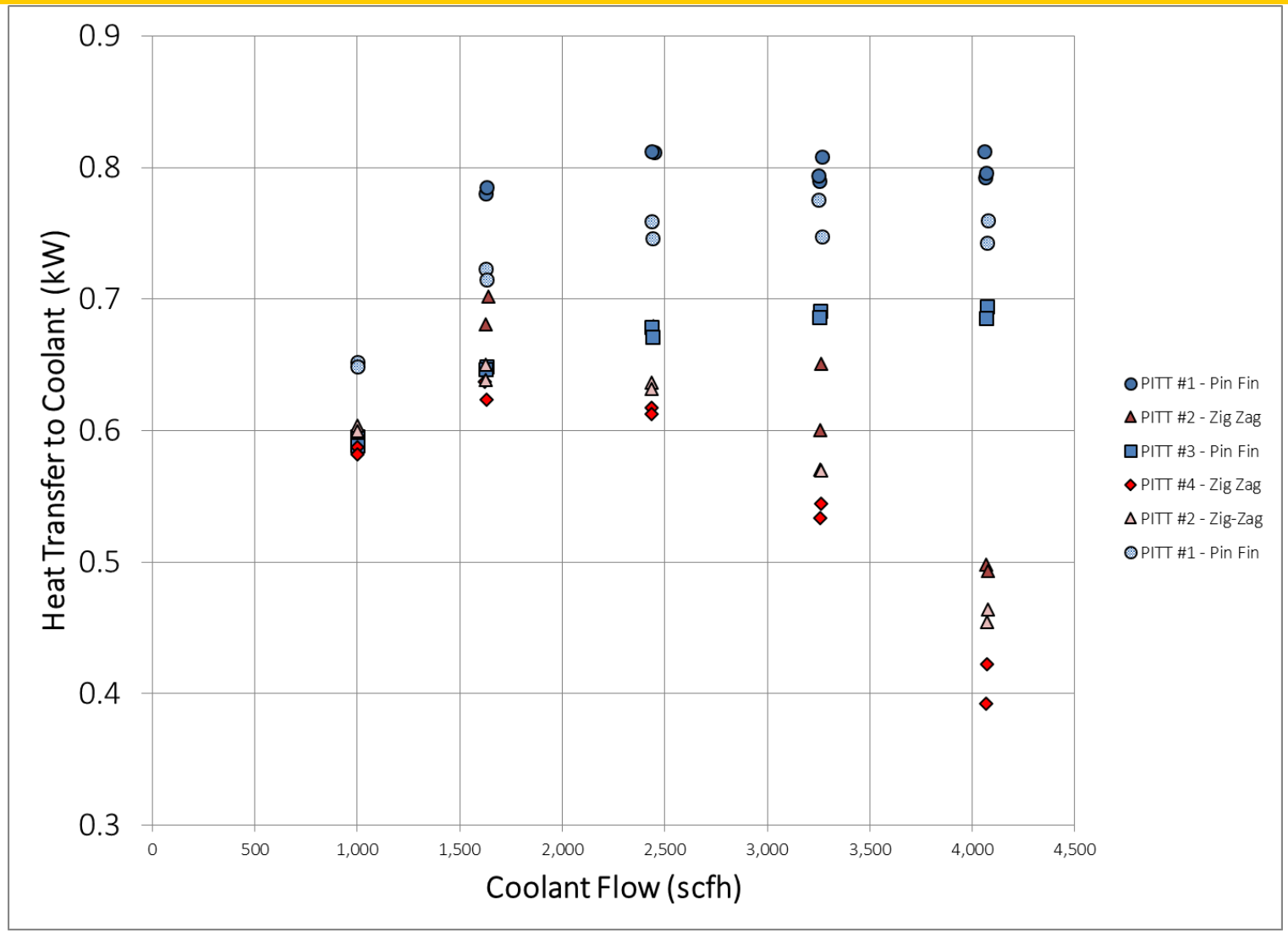


Pitt Zig-Zag Internally Cooled Coupon

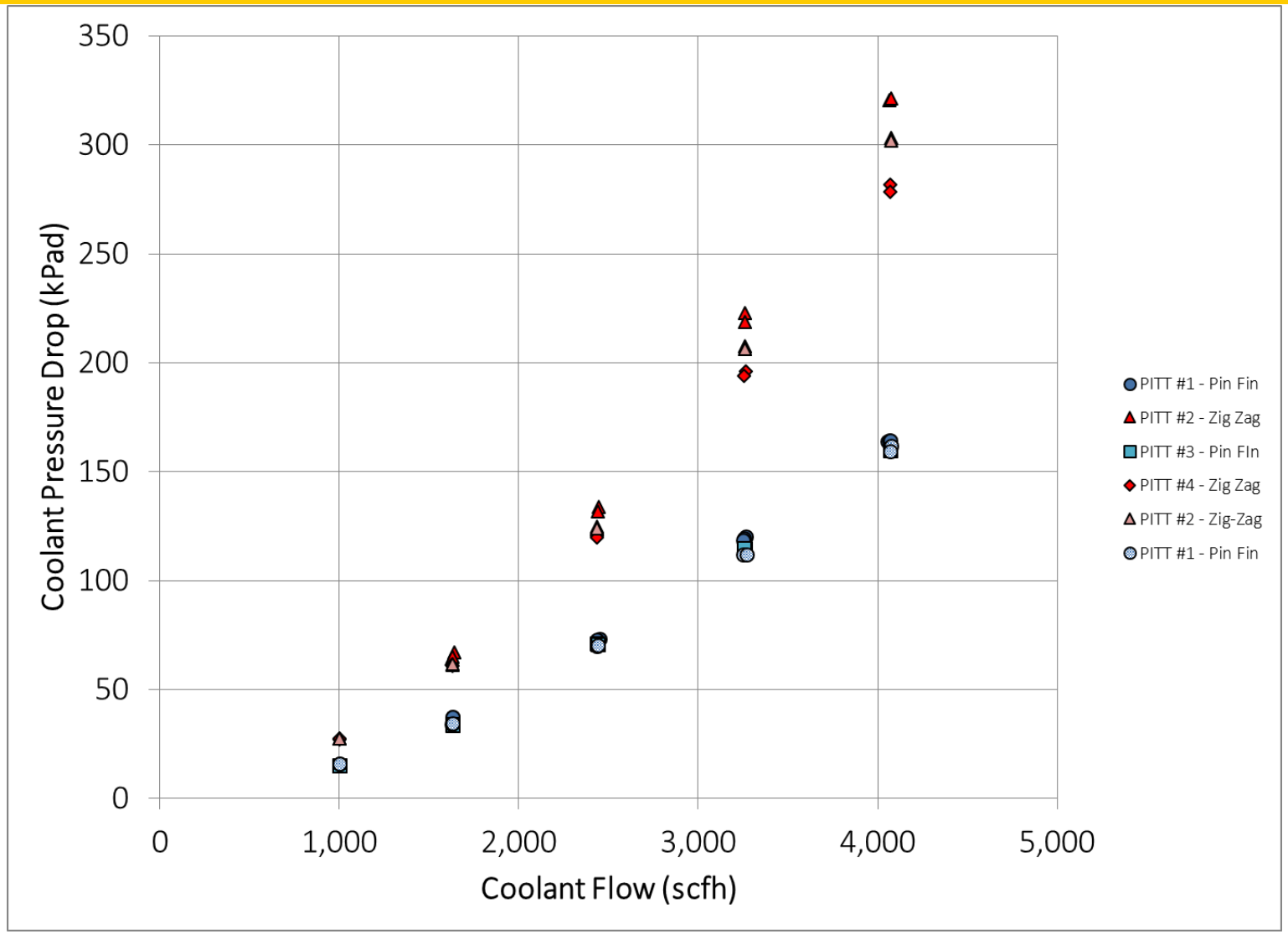


*All dimensions are in mm.

Pitt – Internally Cooled Coupons



Pitt – Internally Cooled Coupons



Internally Cooled Coupon Summary

- **Performance of coupons with ‘pin fins’ was better (lower pressure drop with the same or more heat transfer) than the zig zag configuration.**
- **Flow rates (and resulting pressure drops) were significantly higher than typical for film cooling coupons.**

Future Work

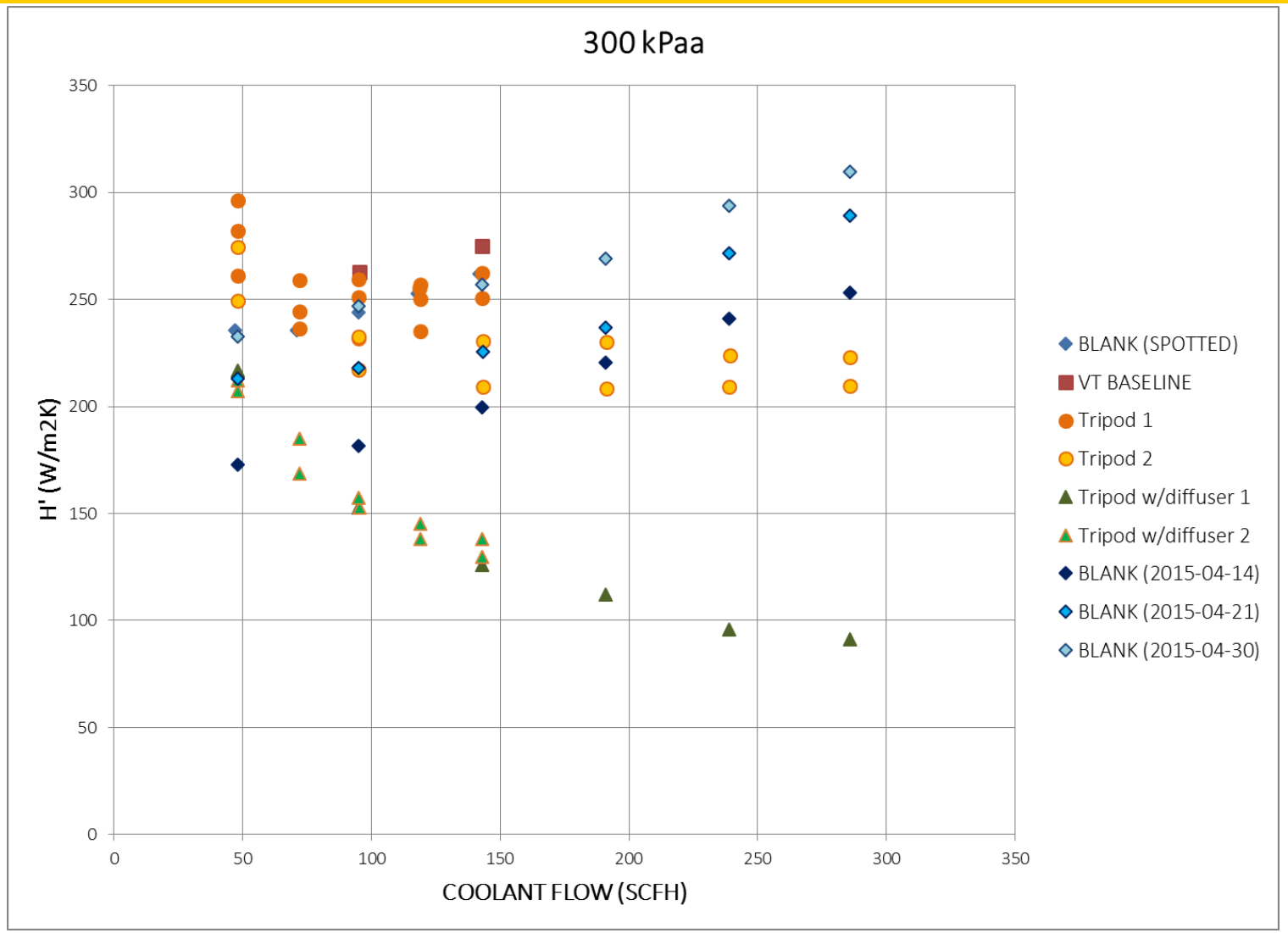
- Quantify rig heat losses using a combination of experimental, analytical, and numerical calculations
- Redesign of test section to eliminate or reduce unwanted heat losses
- Investigate other methods of optical temperature that are not impacted by reflected radiation, e.g. two-color or RAMAN pyrometry
- Repeat turbulence measurements with seed material injected into combustor. CFD modeling indicates seed material is not uniformly distributed using current injection point.

Acknowledgements

- Rich Dennis and Dr. Patcharin (Rin) Burke at NETL for their support
- Mark Tucker and Jeff Riley for setting up and performing experiments

Backup slides

Va Tech Film Cooled Coupons



Va Tech Film Cooled Coupons