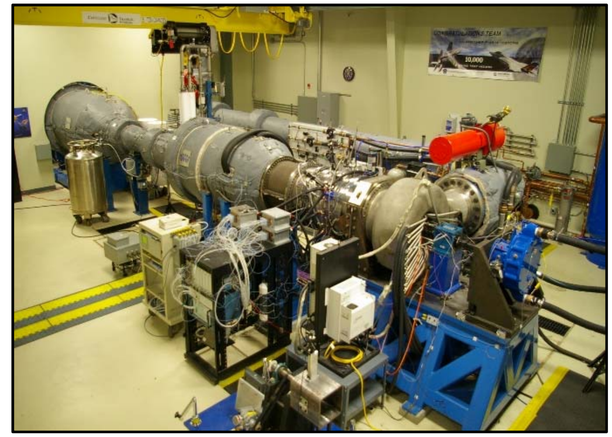
START: Advanced Cooling Design Studies and Turbine Rim Seal Results

November 2017

Atul Kohli
and many others

Brian Knisely, Ivan Monge-Concepcion, Shawn Siroka
Mike Barringer, Reid Berdanier, Jeremiah Bunch,
David Johnson, Jeremy Neal, and Karen Thole

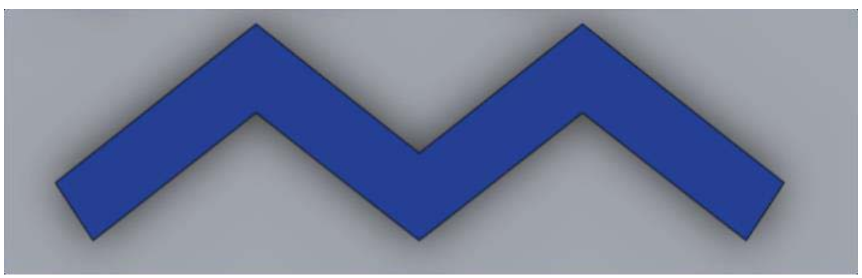
Patcharin Burke
Richard Dennis
and many others

The overall goal of the DOE project is to advance cooling of turbine components with the aim of improving efficiencies and lowering costs

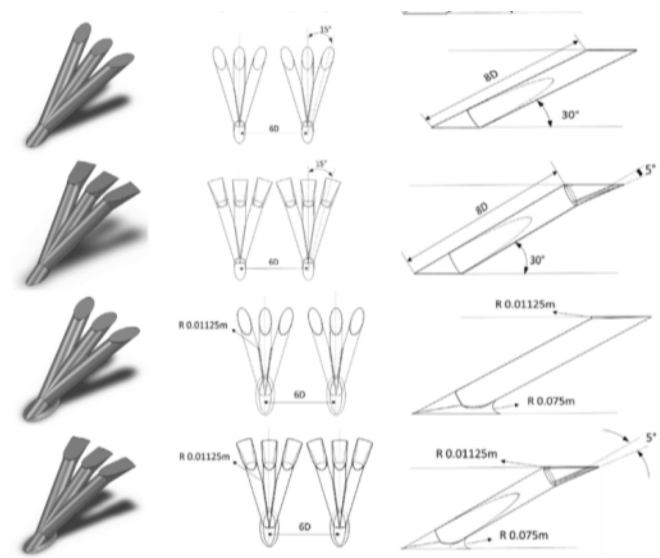
Specific goals include:

1) demonstrate increased turbine efficiency by reducing cooling flow to the turbine through the systematic studies of Reynolds number, cooling flowrates, and airfoil cooling designs;

2) determine the appropriate scaling parameters for different testing environments including Virginia Tech, U Pitt, and DOE-NETL.



Siw, Chyu, and Alvin, 2015



Ramesh, Ramirez, Ekkad, Alvin, 2016

U.S. DEPARTMENT OF ENERGY | Fossil Energy

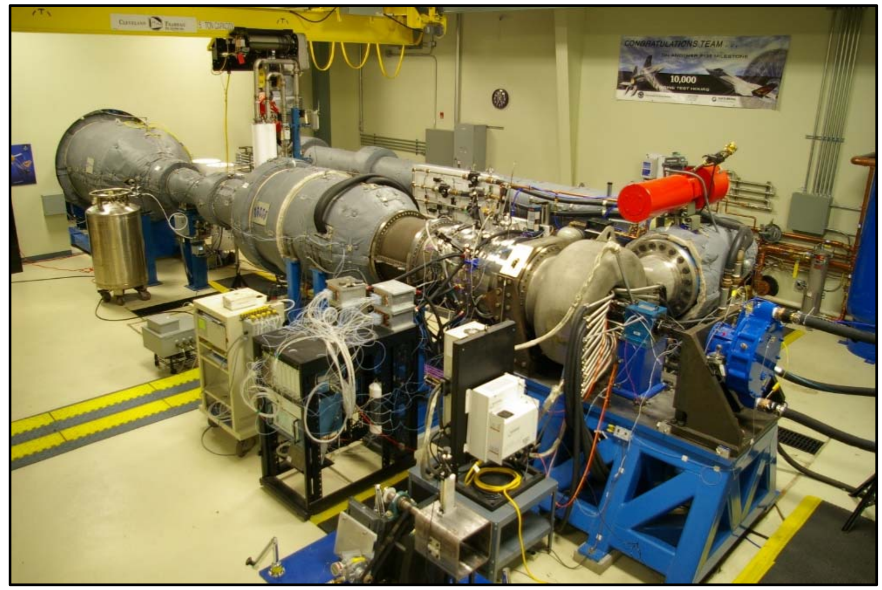
Progress to Date

DOE Project Status

- **Task 2 – Facility Upgrade**
- **Task 3 – Cooled Blade Design**
- **Task 4 – Instrumentation**
- **Task 6 – Advanced Manufacturing**

Turbine Sealing Test Results

Full Span vs Partial Span



There are six specific tasks for: *Improving Turbine Efficiencies through Heat Transfer and Aerodynamics Research in START*

Task 1.0 –Project Management, Planning and Reporting

Task 2.0 – Facility Upgrade Planning and Execution
Second compressor and heater integration

Task 3.0 – Cooled Blade Design and Manufacturing
--A cooled blade airfoil design will be completed by Pratt & Whitney
-- Rainbow blade ring to include baseline and five configurations

Task 4.0 – Instrumentation Upgrades and Validation
--Unsteady pressures; rotating data acquisition; long wave infrared radiation detection

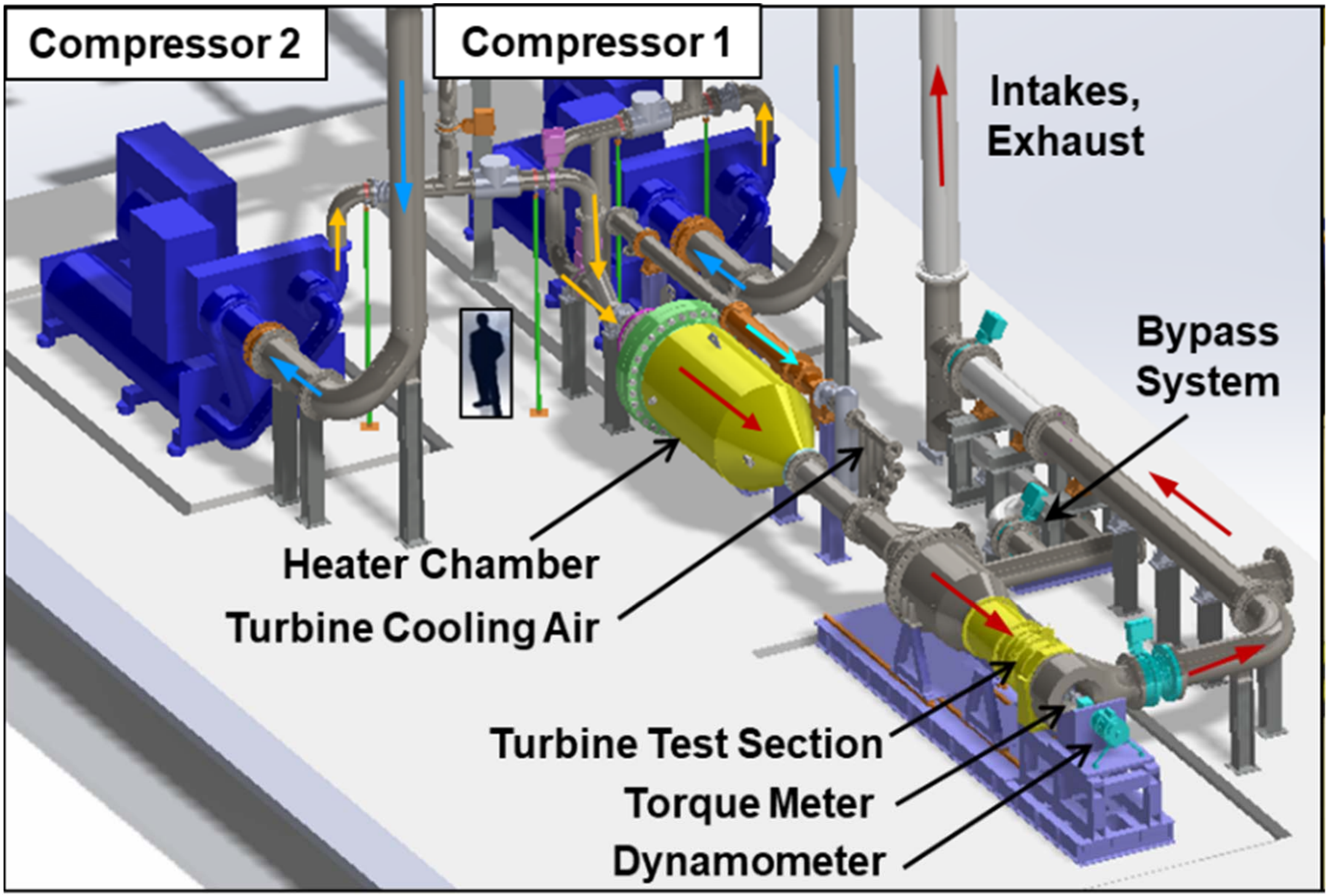
Task 5.0 Cooled Blade Testing
-- Testing will be done on the full blade ring containing five different cooling configurations different cooling flow rates, Reynolds numbers, Mach numbers and other relevant parameters for each of the five configurations.

Task 6.0 Evaluation of Advanced Manufacturing Methods

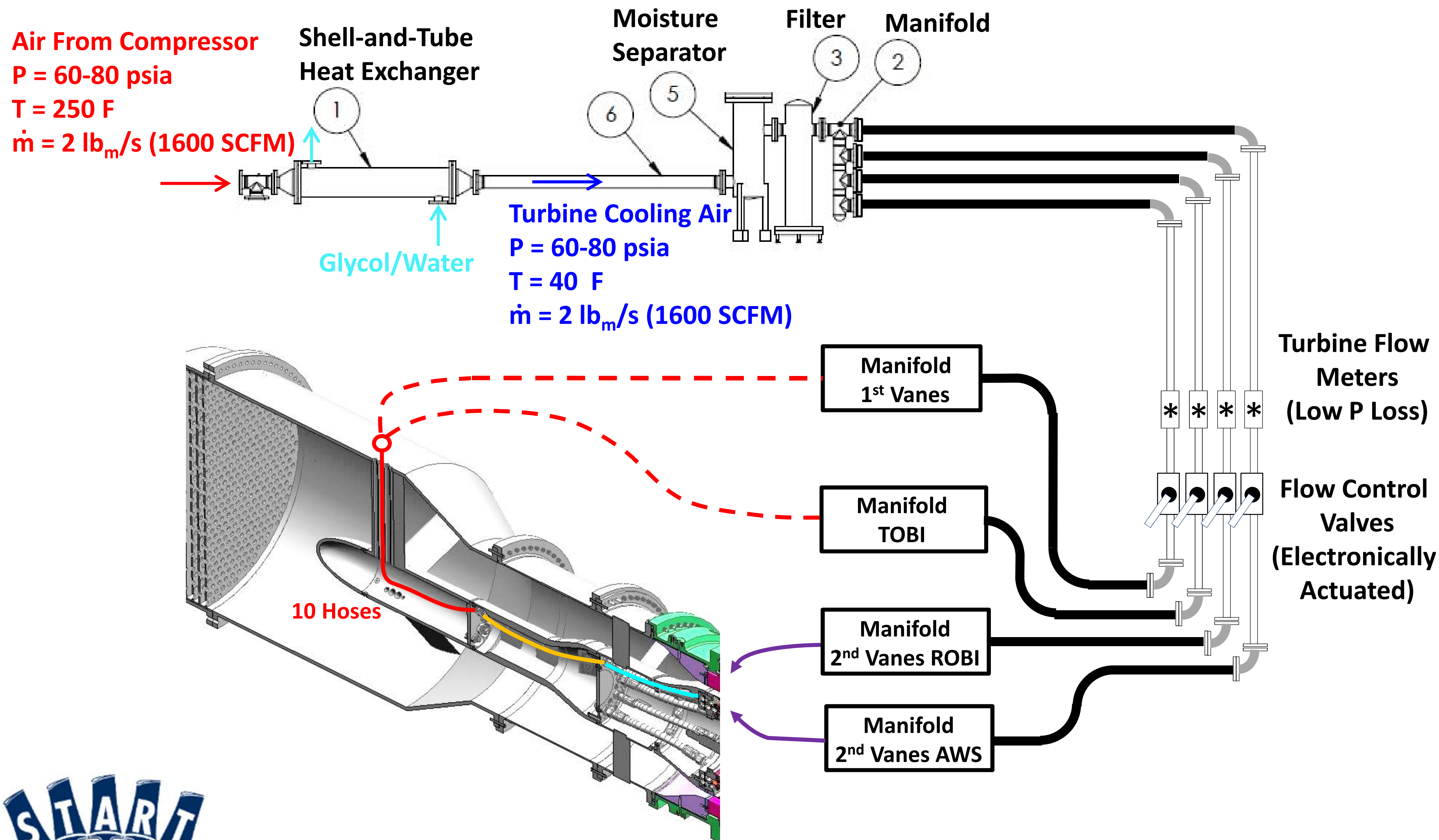
Several important flow conditions in the turbine main gas path and secondary air system are at engine relevant scaling parameters

Parameter at Blade Inlet		Aero Engine	START (I) Single Compressor (2014-2015)	START (II) Two Compressors (2016)
Coolant-to-Mainstream Density Ratio	ρ_c/ρ_∞	2.0	1.0 - 1.3	1.0 - 2.0
Stage Pressure Ratio	$P_{0,in}/P_{0,exit}$	2	1.5 - 2.5	1.5 – 2.5
Rotational Reynolds Number	Re_ϕ	2.0 x 10^7 +	$\leq$ 1 x 10^7	$\leq$ 2 x 10^7
Rotational Speed	rpm	15000+	$\leq$ 11000	$\leq$ 11000
Mass flow rate	lb_m/s	25+	12.5	25
Pressure	PSIA	100's	60-80	60-80
Axial Reynolds Number	Re_x	3 x 10^5	3 x 10^5	3 x 10^5
Vane Exit Mach Number	Ma	0.7	0.7	0.7
Airfoil Geometry (True Engine Scale)	Span	Full	Half	Full
Turbine Inlet Temp Secondary Coolant Temp	°F	~ 2500 ~ 1000	250 40	750 40

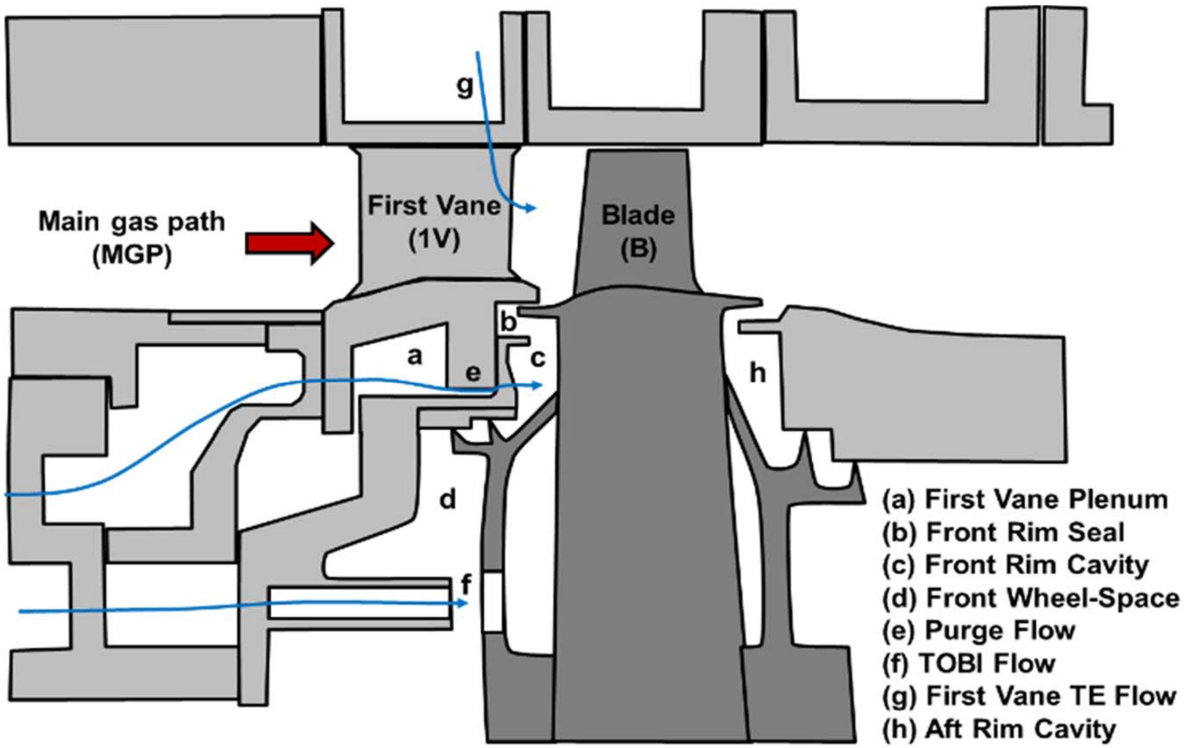
The facility upgrades were completed and benchmarked in spring 2017

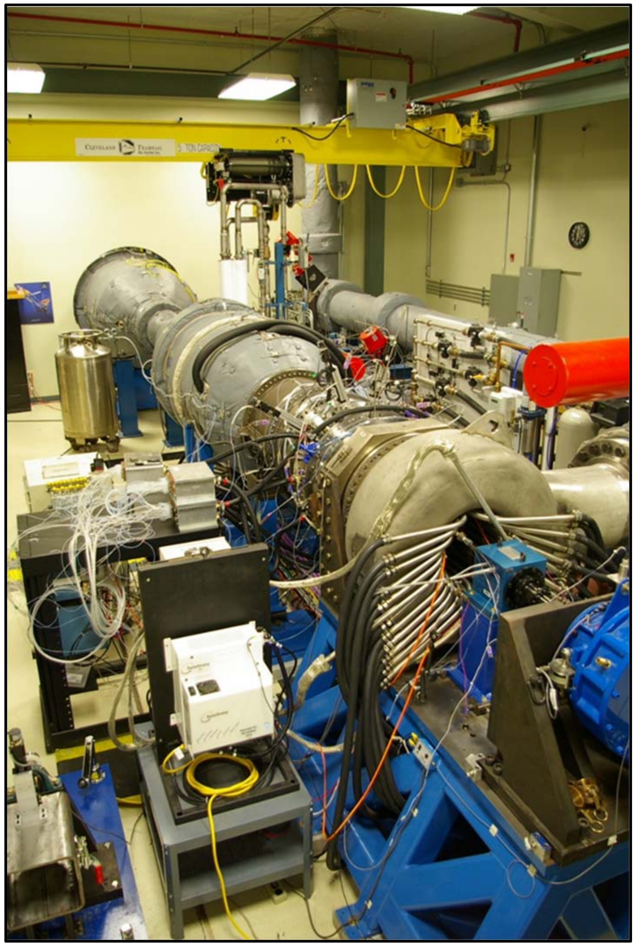


The delivery system for the turbine cooling air includes a heat exchanger, moisture separator, filter, and manifold system

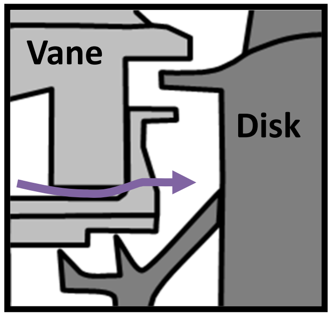


Full-span vanes and blades were installed by increasing the main gas path area





The Phase 1 turbine was a 1.5 stage design while the Phase 2 is a 1.0 stage design including the following features

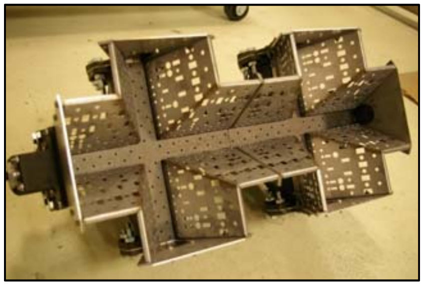


Parameter	Phase 1	Phase 2
Turbine Stage	1.5	1.0
Blade Tip Clearance (τ/S [%])	3.8	3.3, 5.8
Vane - Rim Seal Design	Double Overlap	Double Overlap
Vane - Rim Cavity Purge Holes	150	150

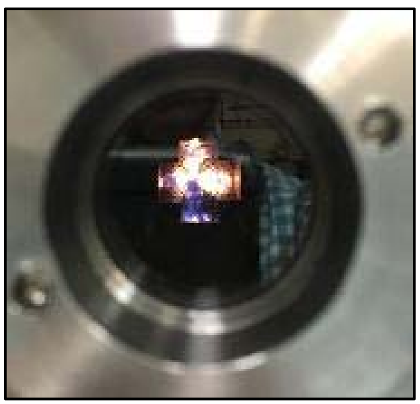
GEOMETRY FEATURE	VANES		BLADES	
	Phase 1	Phase 2	Phase 1	Phase 2
Span	Half	Full	Half	Full
Manufacturing	Additive	Cast/Machined	Cast/Machined	Cast/Machined
Mate Face Gaps	Sealed	Sealed	Dampers	Dampers
Film Cooling Holes	None	Airfoil/Platform = Sealed Trailing Edge = Open	None	All Open

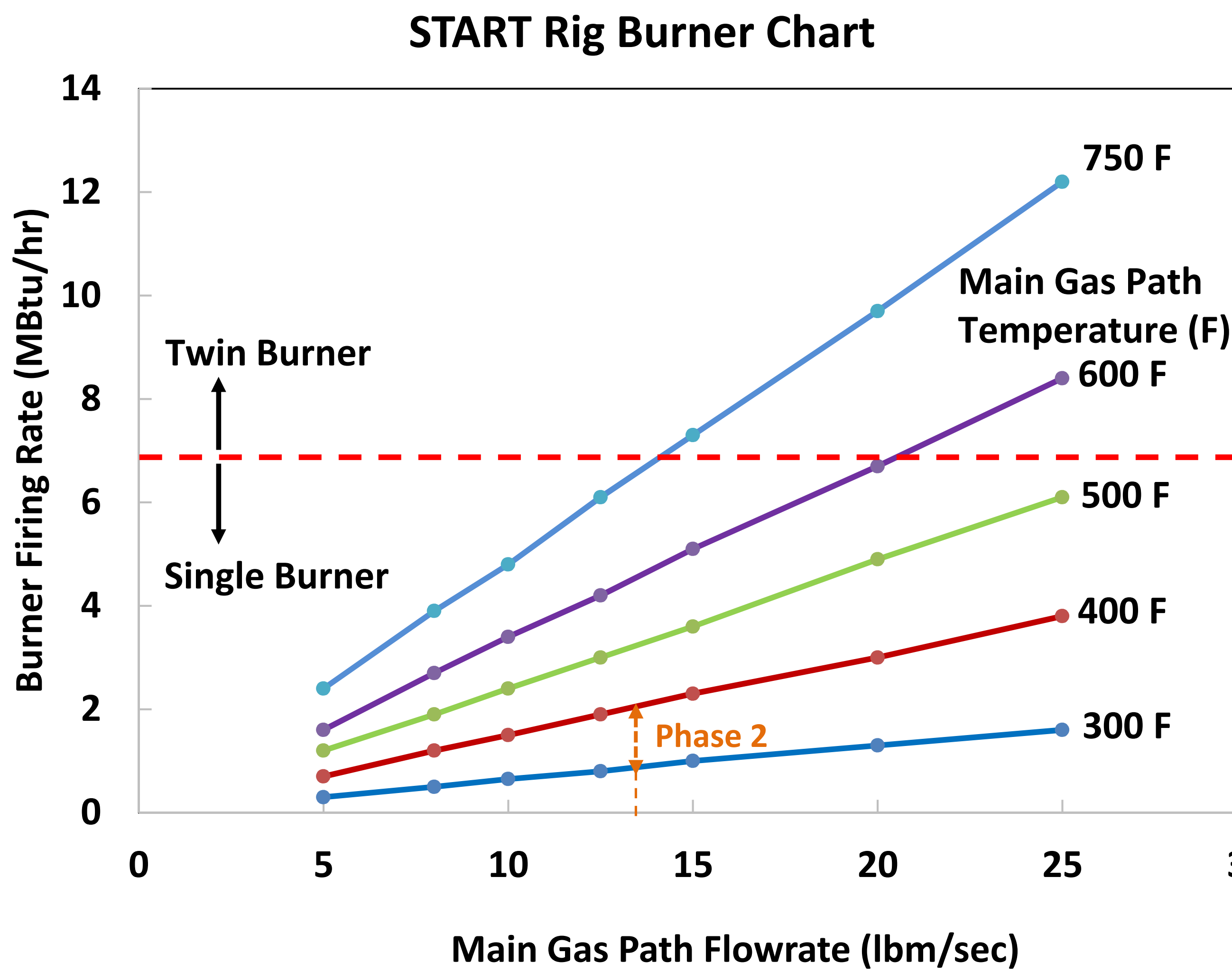
The new combustion heater is currently configured for DOE testing using a single burner

Single Burner



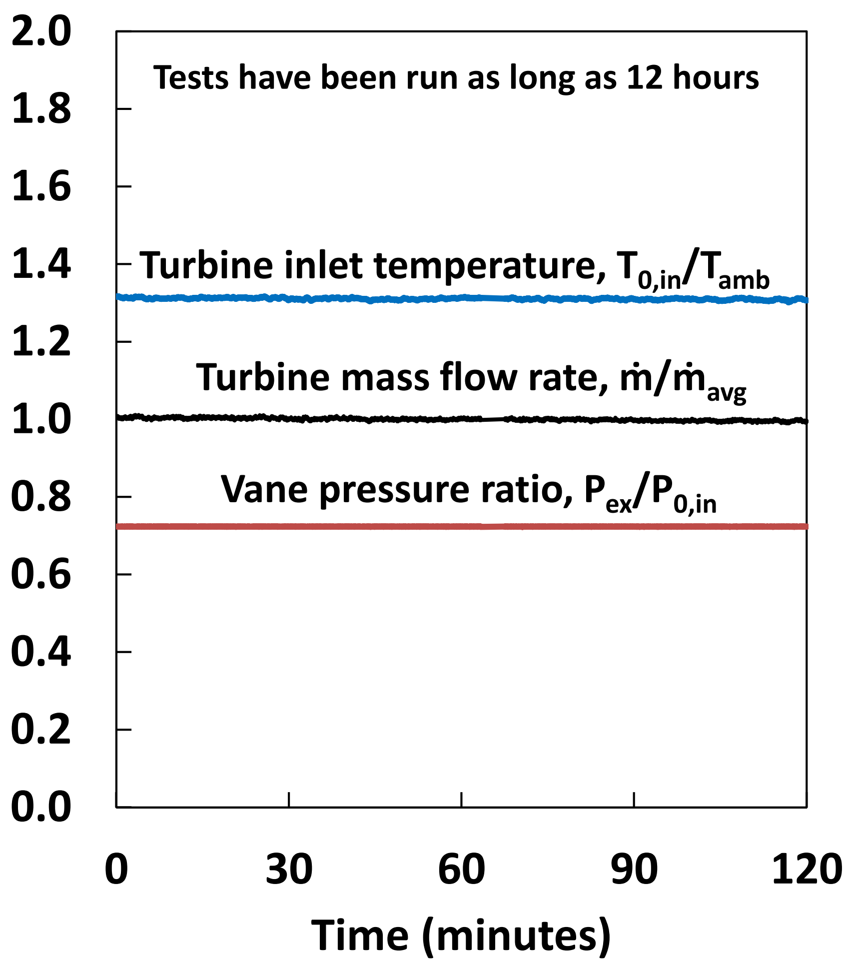
Chamber Sight Port

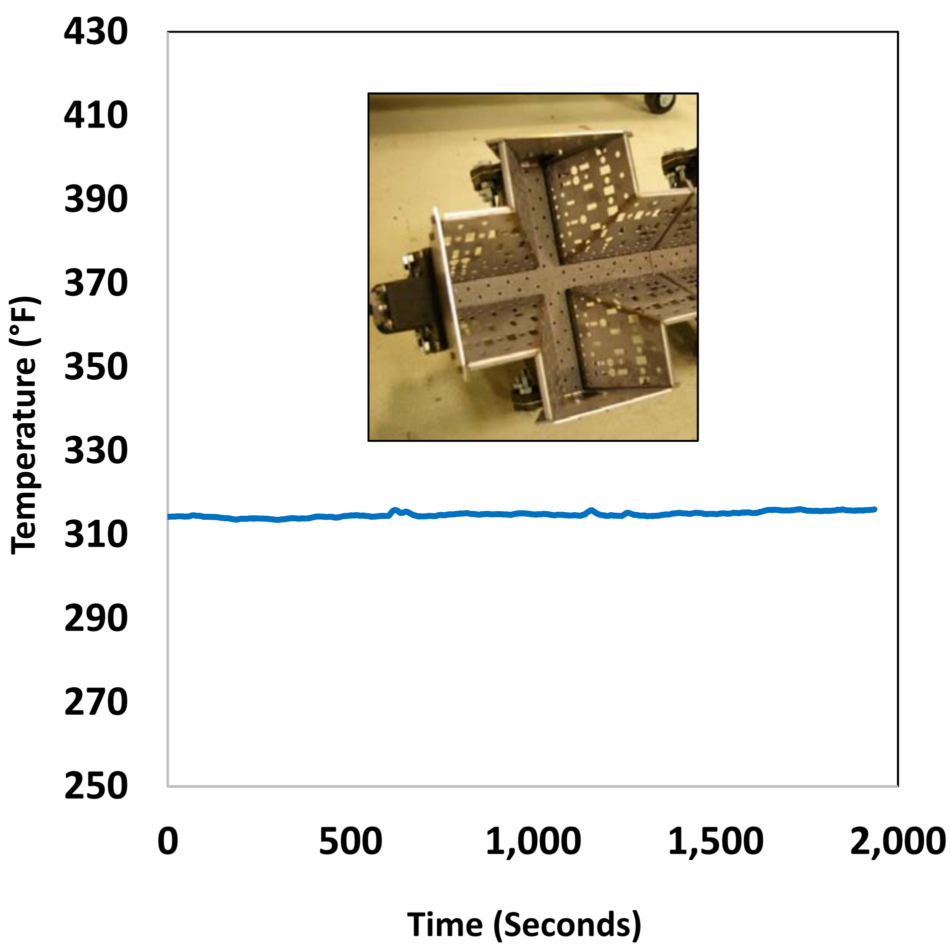




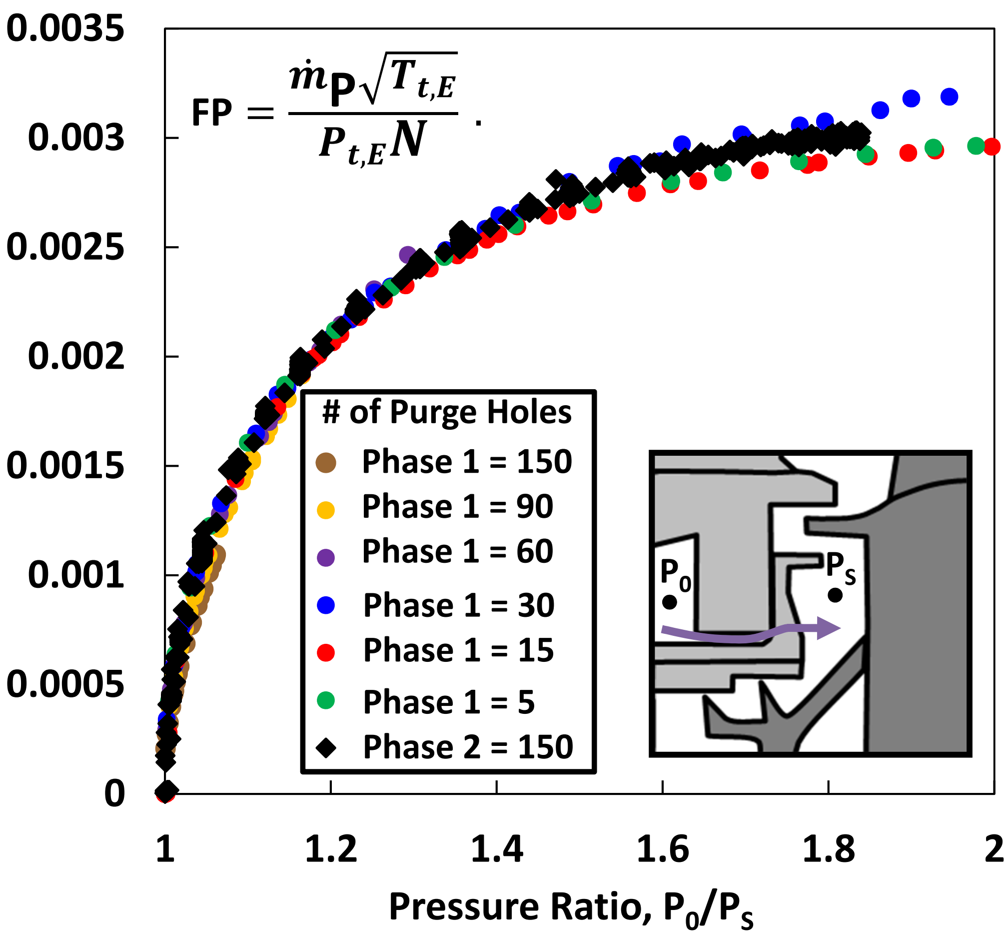
The new combustion heater was successfully commissioned for both long-duration steady thermal tests and transient ramp tests

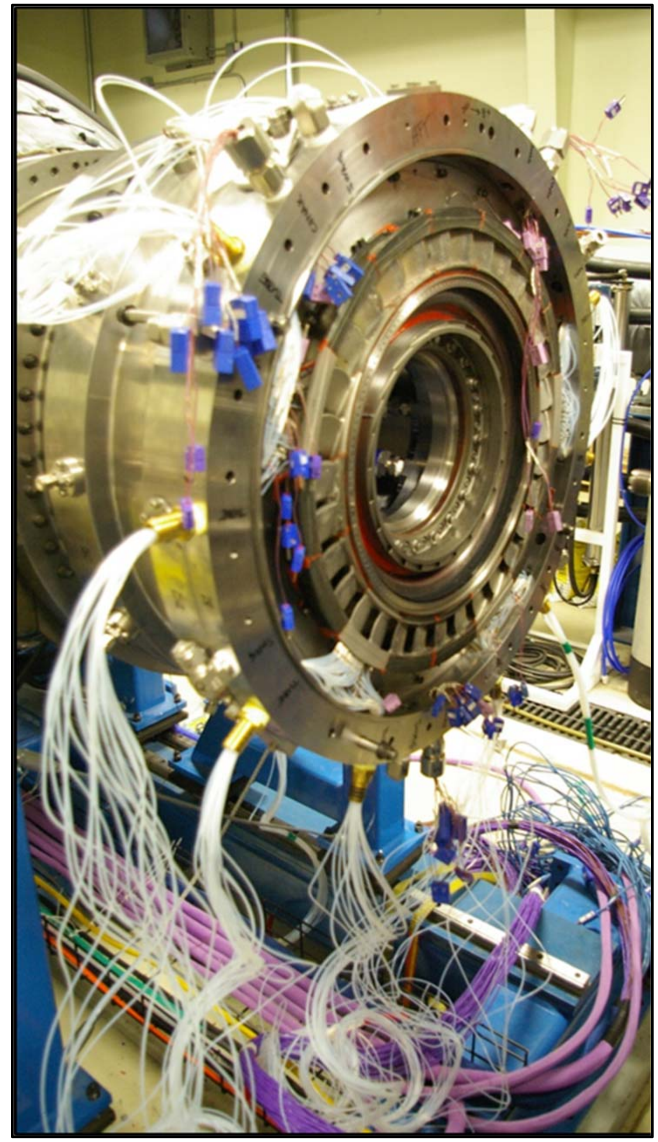
Long Duration Steady Tests





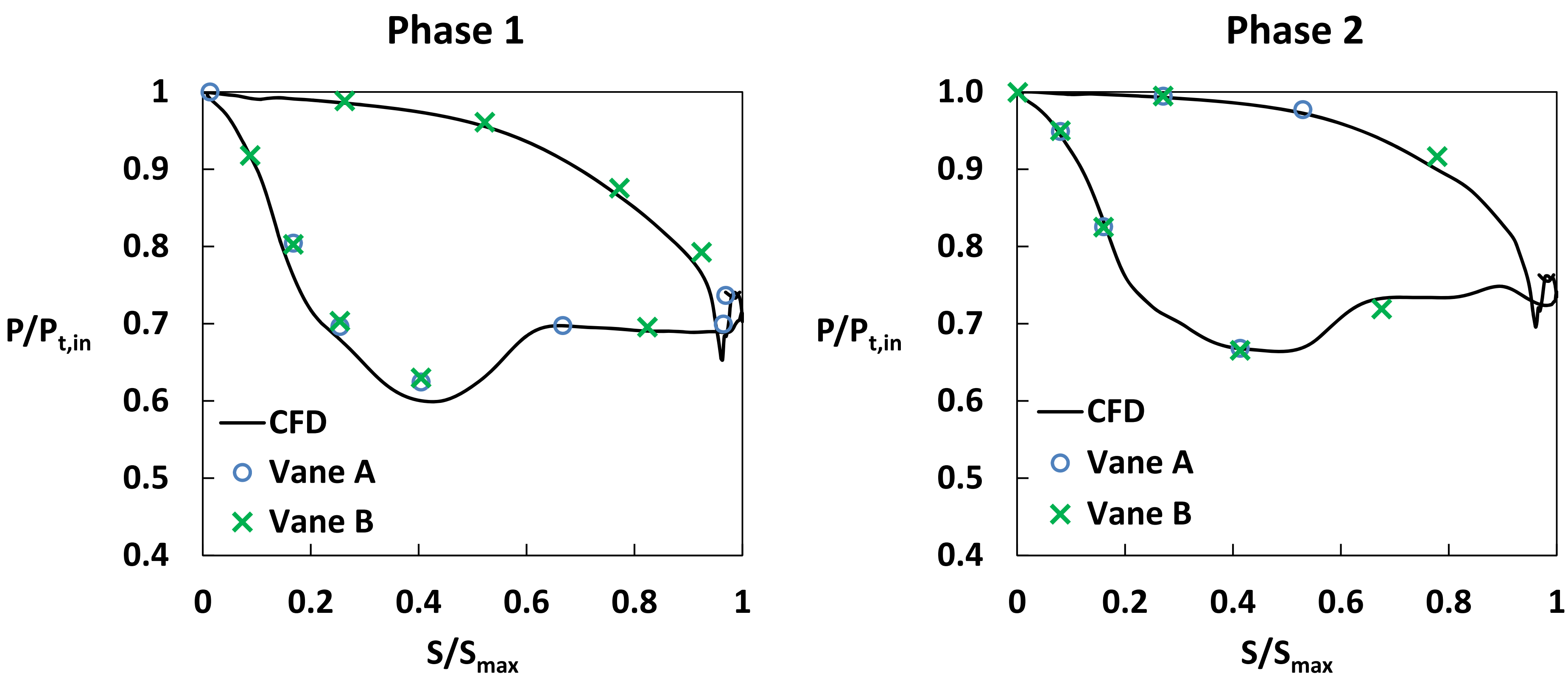
After installation of new capabilities, numerous experiments were conducted to ensure accurate measurements





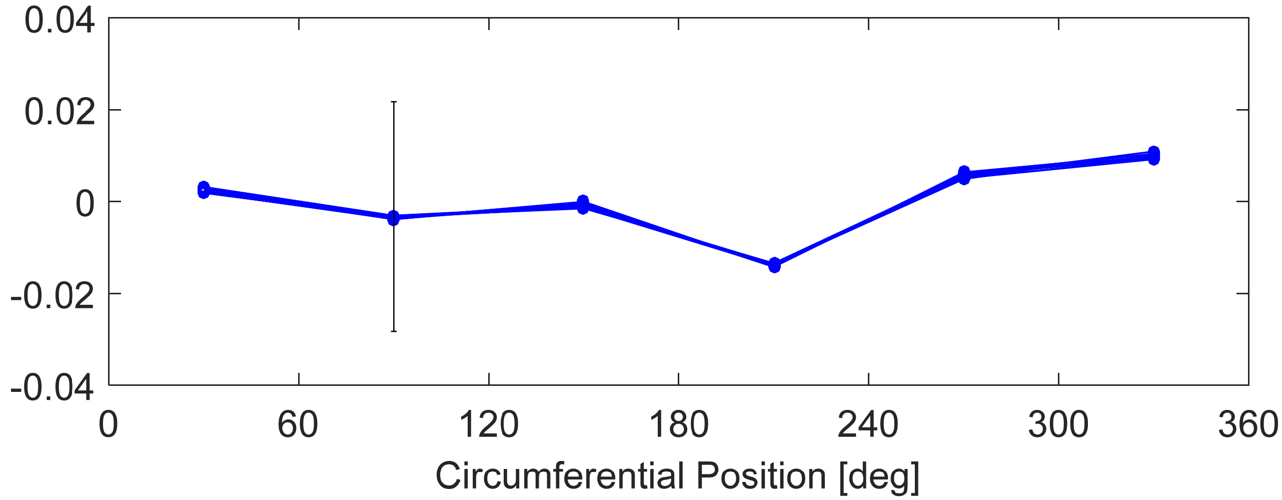
FP / N = Mass Flow Parameter Per Hole = $\frac{lb_m \cdot R^{0.5}}{s \cdot psia \cdot \#holes}$

Shakedown testing included measuring the aerodynamic loading on the 1st Vane airfoil surfaces and good agreement was found to CFD

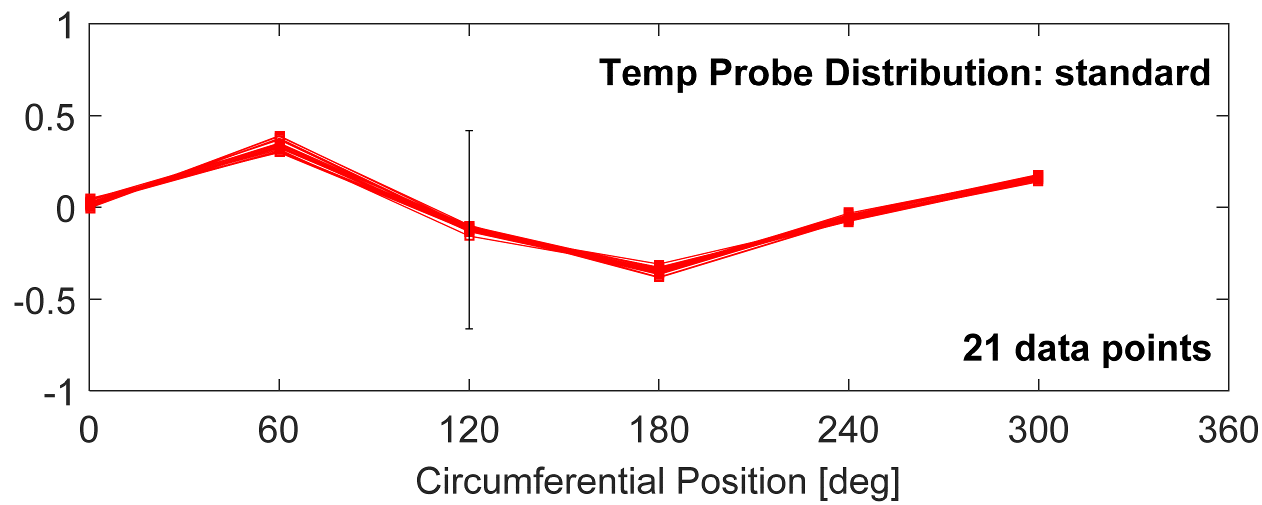


The turbine inlet pressure and thermal fields were also surveyed using multiple circumferential Kiel probes and thermocouples

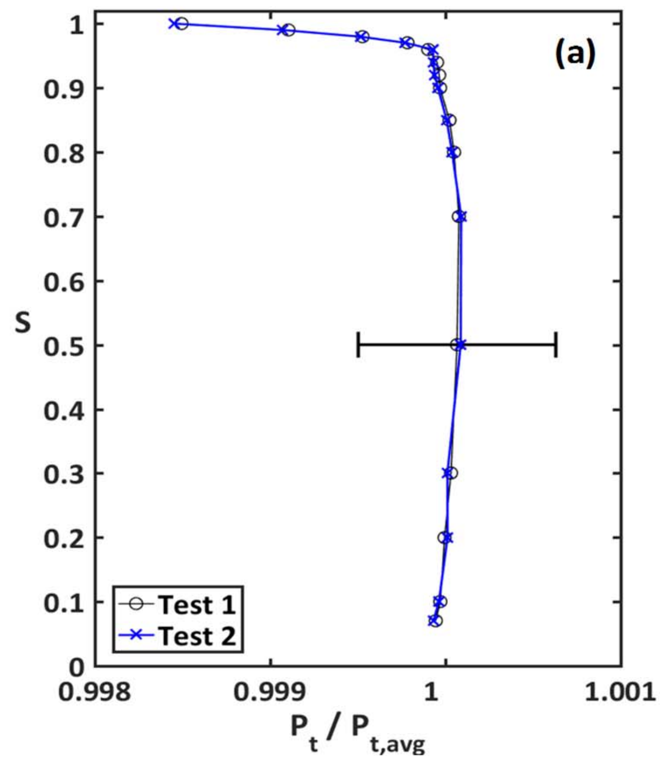
Pressure Variation Relative to Average (PSIG)

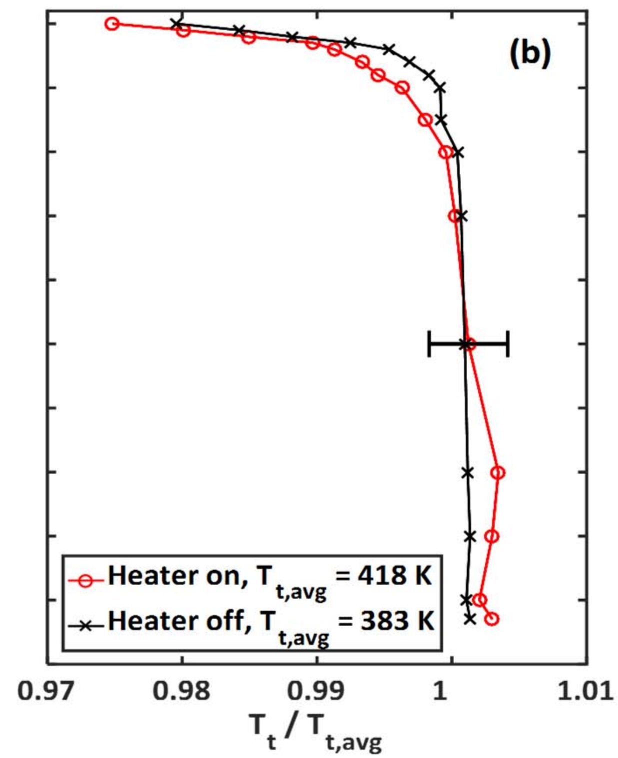


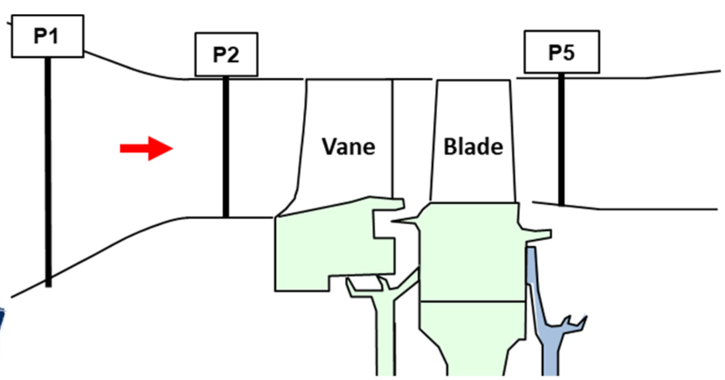
Temperature Variation Relative to Average (°F)



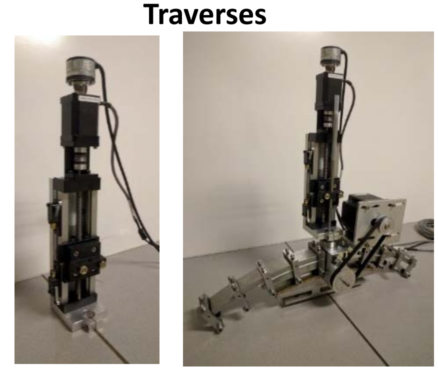
The turbine inlet pressure and thermal fields were surveyed using multiple radial traverses with Kiel probes and thermocouples







Three Radial Traverses



One Radial-Circumferential Traverse

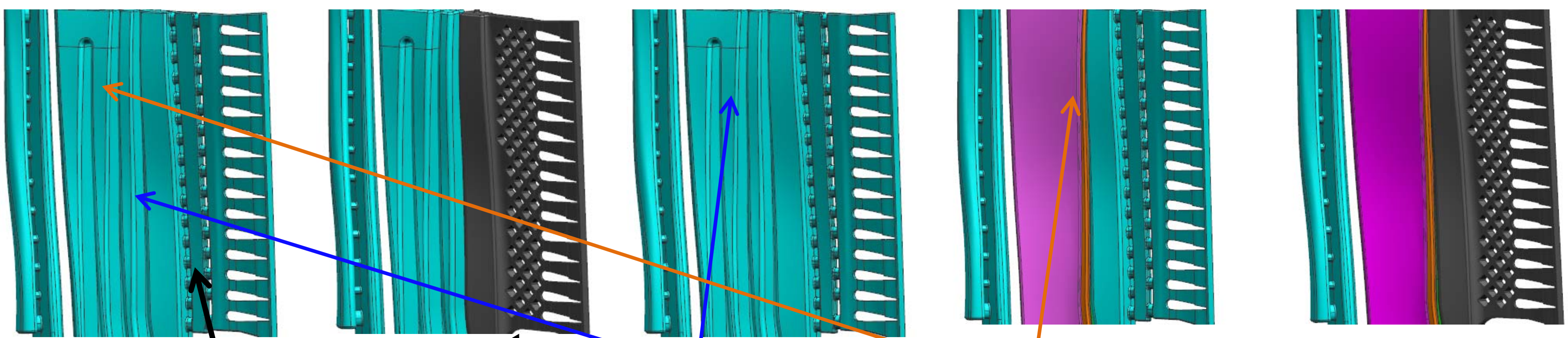
Task 3.0 – Cooled Blade Design and Manufacturing

		1 NETL Baseline	2 NETL 'Trailing Edge'	3 NETL 'Antivortex'	4 NETL 'Double Wall'	5 NETL 'TrEAD'
Leading Edge	Internal	Impingement cooling	Impingement cooling	Impingement cooling	Impingement cooling	Impingement cooling
	External	Showerhead	Showerhead	Showerhead	Showerhead	Showerhead
Pressure Surface	Internal	Serpentine with 'V' Discrete Trip Strips	Serpentine with 'V' Discrete Trip Strips	Serpentine with Discrete 'V' Trip Strips	Partially Bridged Pedestal Double Wall	Partially Bridged Pedestal Double Wall
	External	7-7-7 Shaped Hole	7-7-7 Shaped Hole	Shaped Antivortex Tripod Hole	7-7-7 Shaped Hole	Shaped Antivortex Tripod Hole
Suction Surface	Internal	Serpentine with 'V' Discrete Trip Strips	Serpentine with 'V' Discrete Trip Strips	Serpentine with 'V' Discrete Trip Strips	Partially Bridged Pedestal Double Wall	Partially Bridged Pedestal Double Wall
	External	7-7-7 Shaped Hole	7-7-7 Shaped Hole	Shaped Antivortex Tripod Hole	7-7-7 Shaped Hole	Shaped Antivortex Tripod Hole
Trailing Edge	Internal	Triple Chamber, Double Impingement, Trip Strips, and Pedestals	High Solidity Diamond Pedestal Array	Triple Chamber, Double Impingement, Trip Strips, and Pedestals	Triple Chamber, Double Impingement, Trip Strips, and Pedestals	High Solidity Diamond Pedestal Array
	External	Diffused Partitioned Pressure Side Cut	Diffused Partitioned Pressure Side Cut	Diffused Partitioned Pressure Side Cut	Diffused Partitioned Pressure Side Cut	Diffused Partitioned Pressure Side Cut

Courtesy of D. Straub, DOE-NETL

PW subcontract status: internal core design for all blades complete, thermal and structural assessments in progress

1 NETL Baseline	2 NETL 'Trailing Edge'	3 NETL 'Antivortex'	4 NETL 'Double Wall'	4 NETL 'TrEAD'



Double Impingement vs. Diamond Pedestals

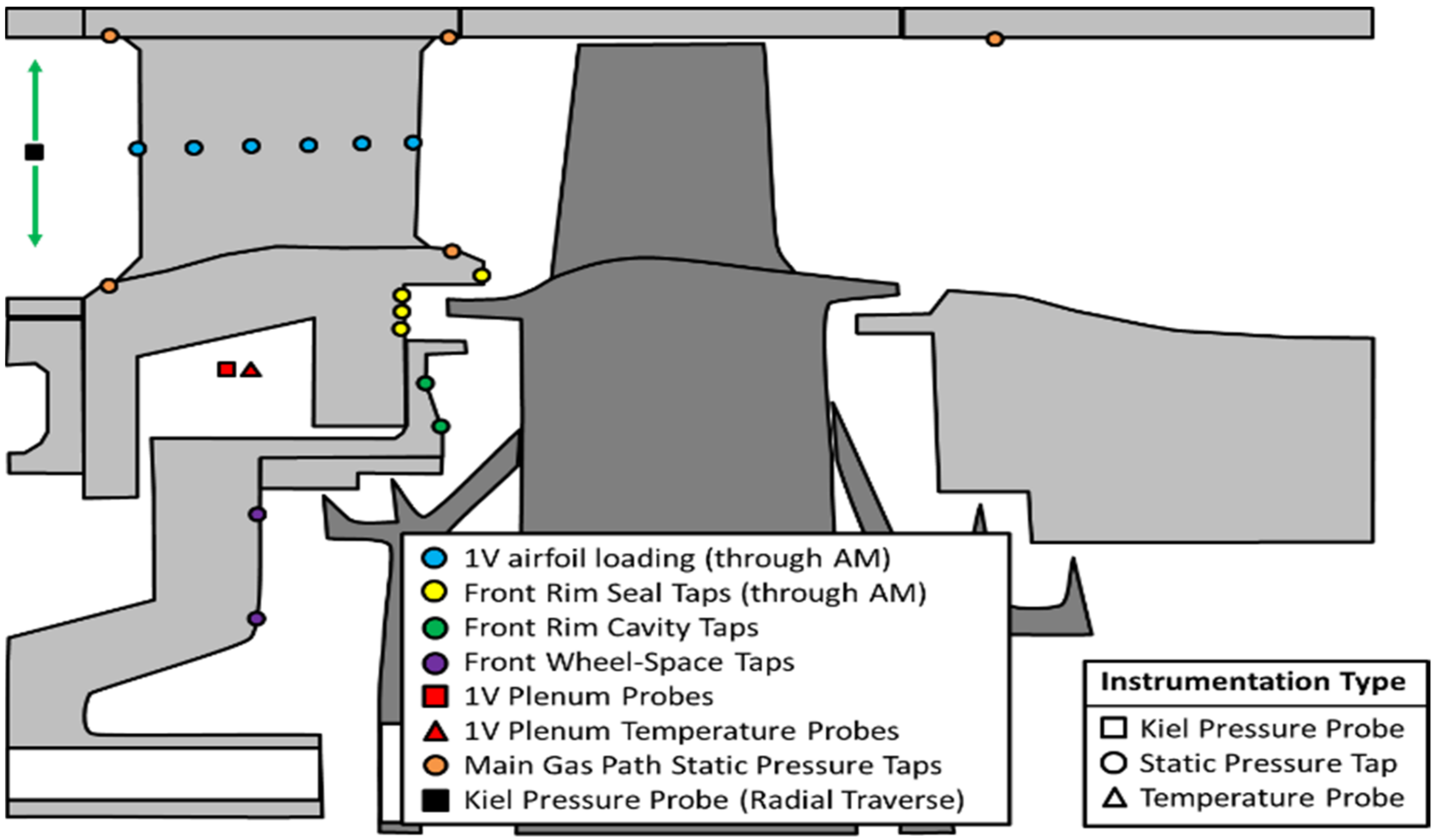
Shaped vs. Tripod Holes

Serpentine vs. Double Wall

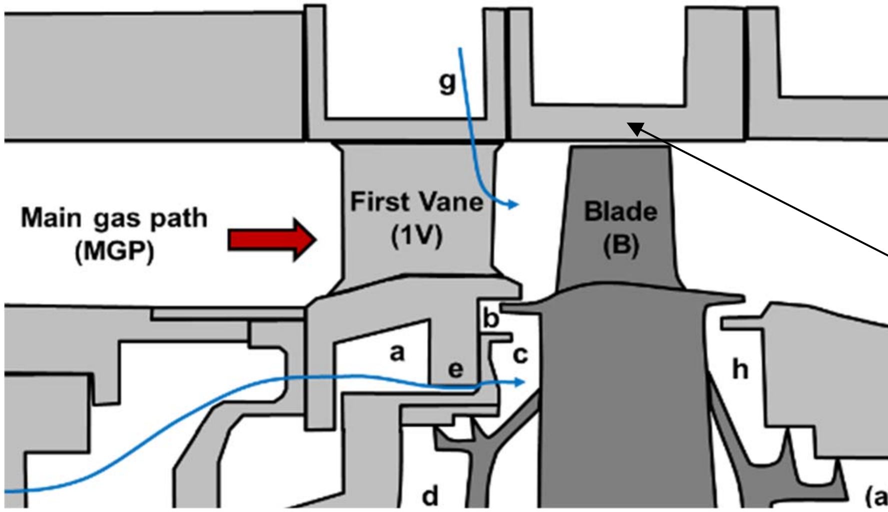
Baseline vs. Advanced

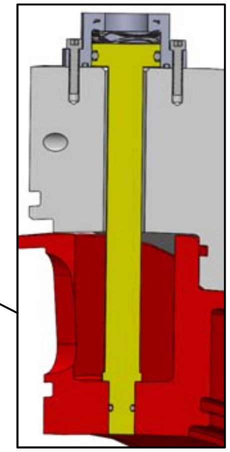
Approved for public release

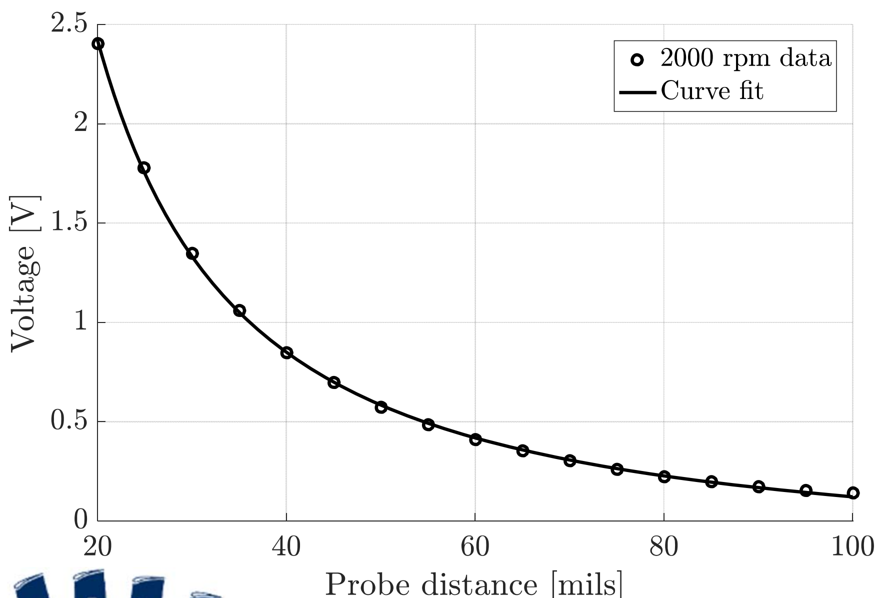
Task 4.0 – Instrumentation Upgrades and Validation

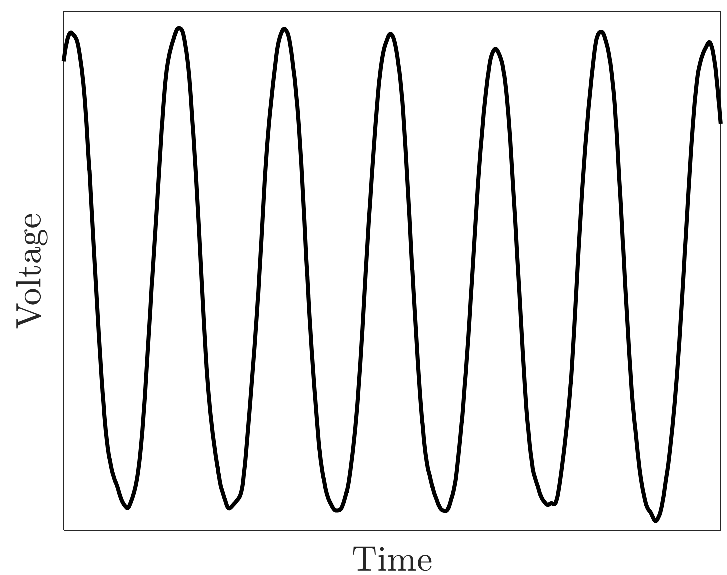


Blade tip clearance probes were installed and calibrated

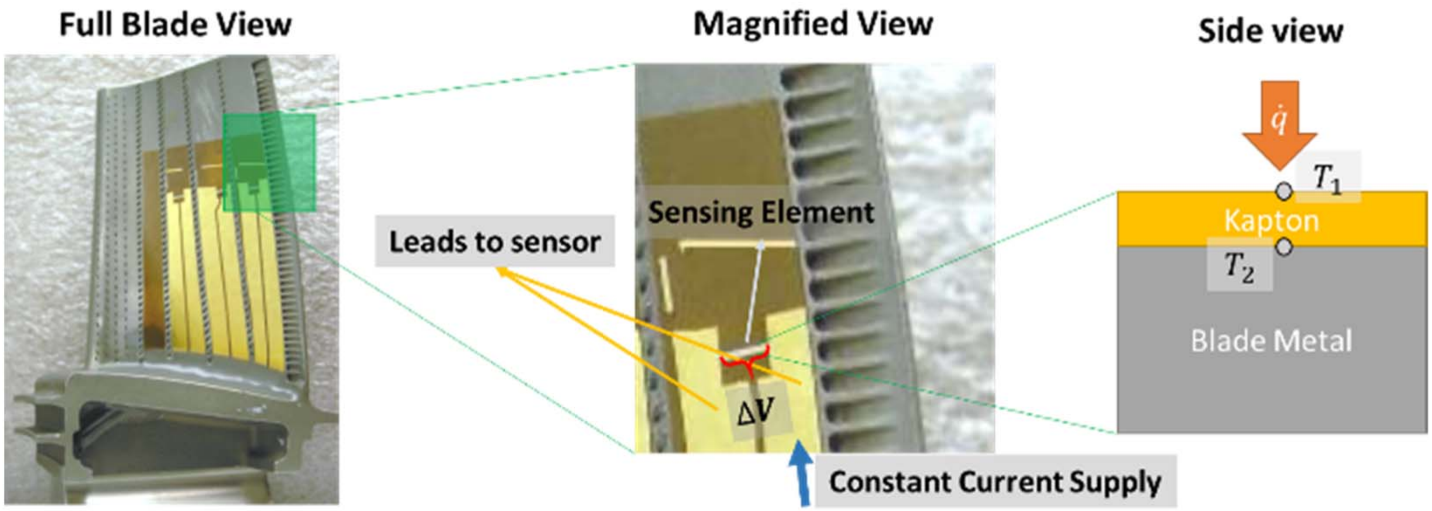




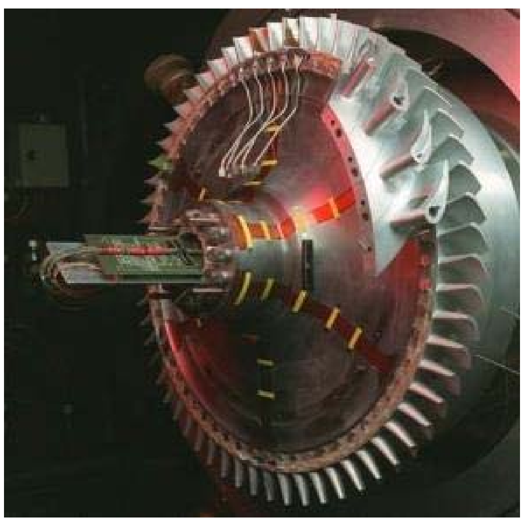




Heat transfer into the blades will also be measured using thin film heat flux gauges both purchased and manufactured in-house at PSU



Anthony et al. 2011



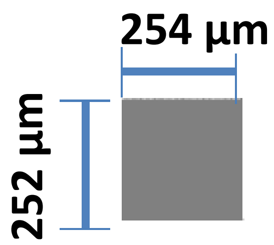
Courtesy of PrOXisense

Digital telemetry hardware will allow HFG operation

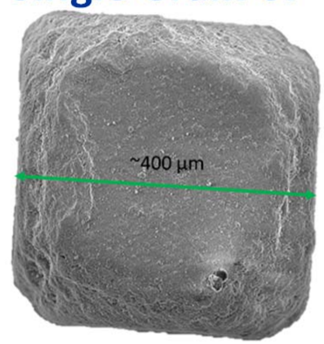
Gages will be procured from Oxford University (PrOXisense) and manufactured at PSU

HFG sensing elements are being made smaller with increased sensitivity using modern fabrication technology

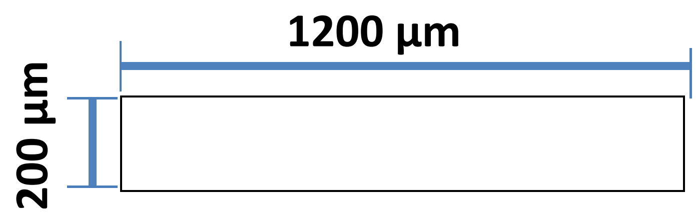
Penn State Design



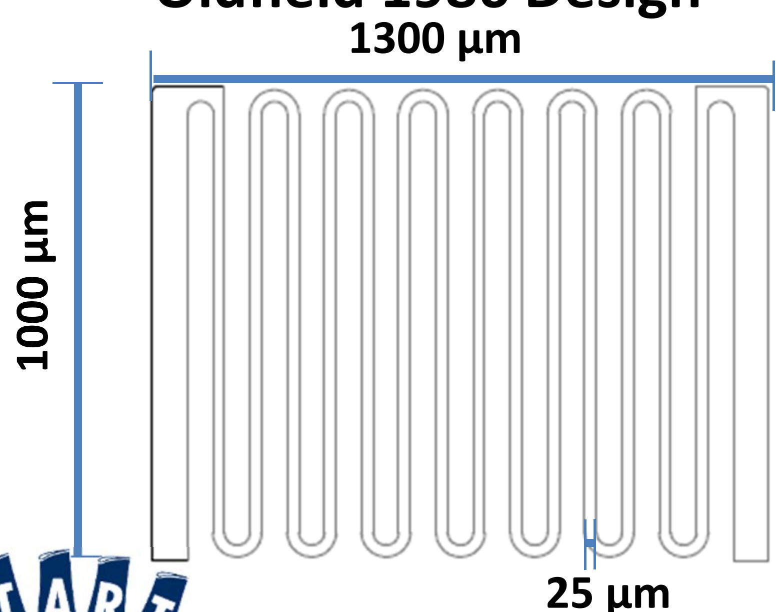
Single Grain of



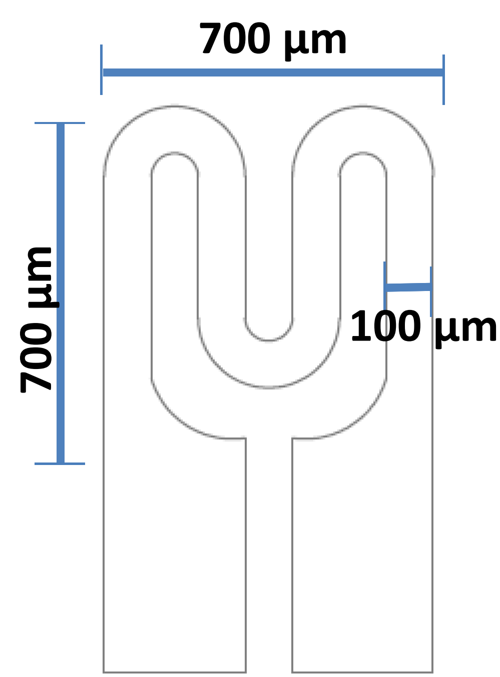
AFRL 2016 Design



Oldfield 1986 Design

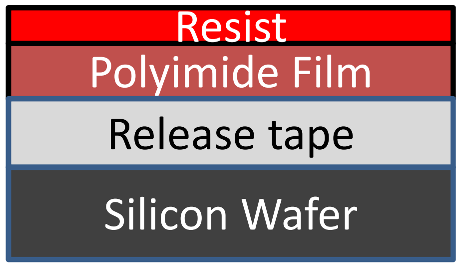


Oxford 2015 Design

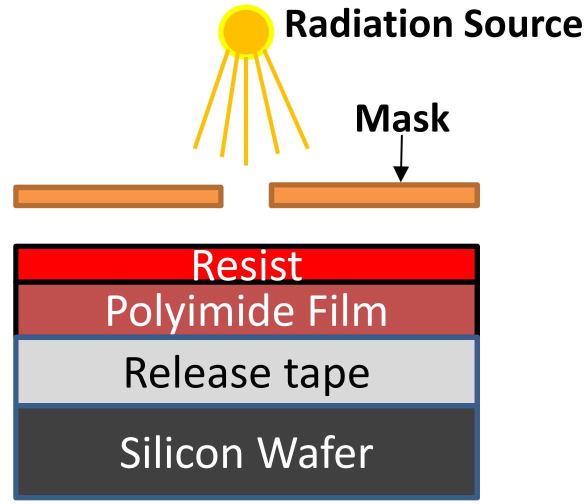


Penn State's Nano Fabrication Lab will provide the equipment to make the complex heat flux gauges

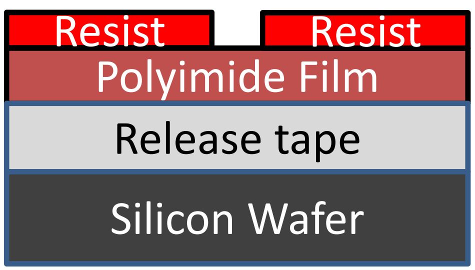
1. Adhere Polyimide to Silicon wafer and prepare surface



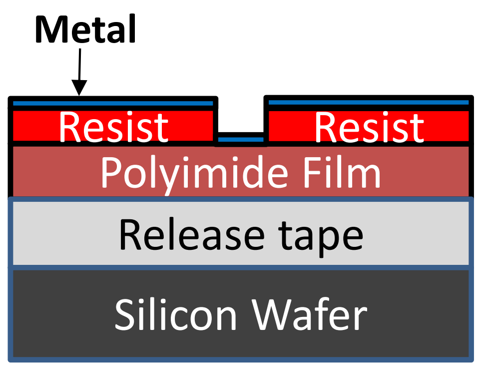
2. Spin coat a chemical resist to the surface



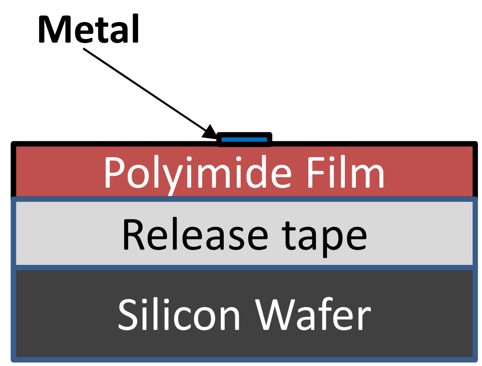
3. Develop resist



4. Prepare to deposit metal



5. Sputter metal of sensor material

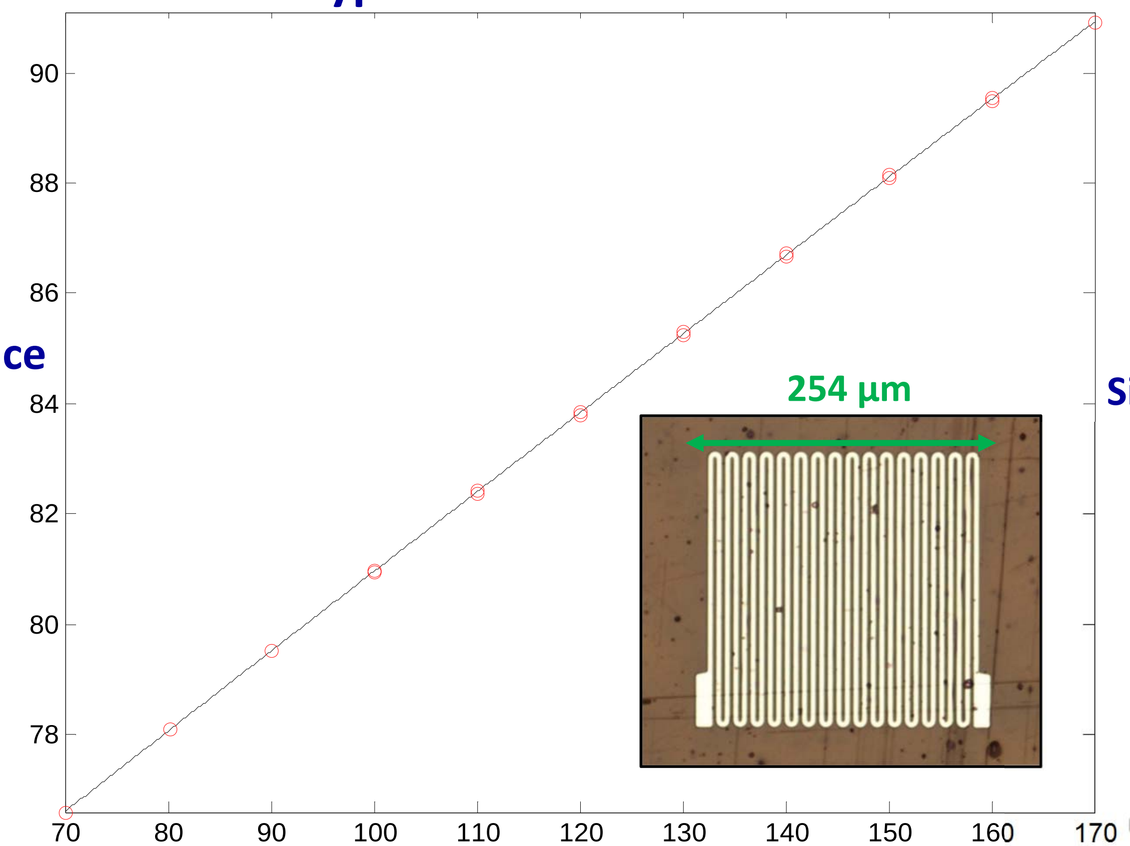


6. Strip resist, leaving the final metal

The HFG sensing elements are each calibrated to within 0.05°C

Typical Calibration Curve

Resistance Ω

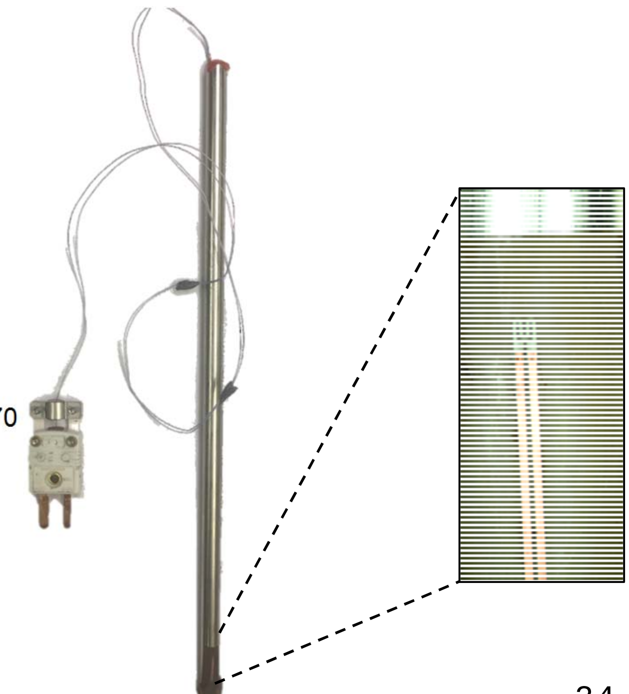


Temperature °C

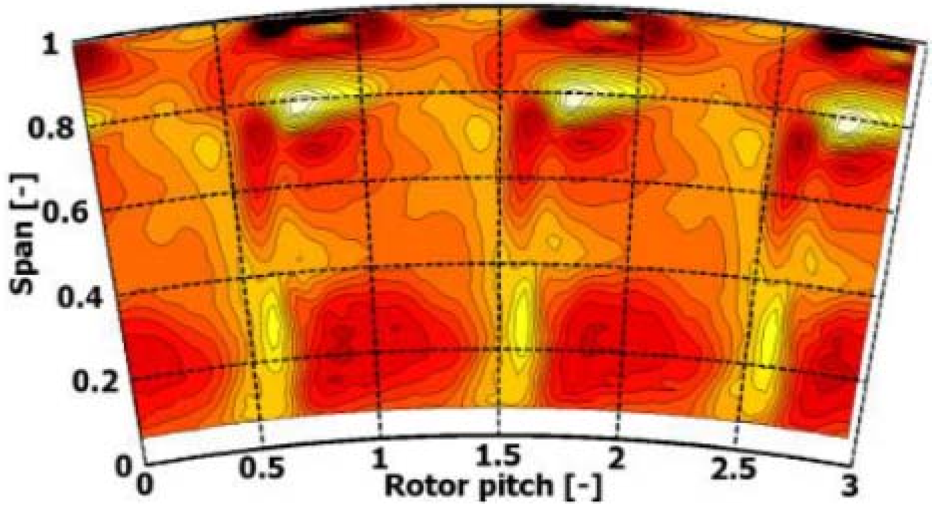
Fluke Calibration Oil Bath

0.05°C Accuracy

Single Sided Heat Flux Gauge Probe

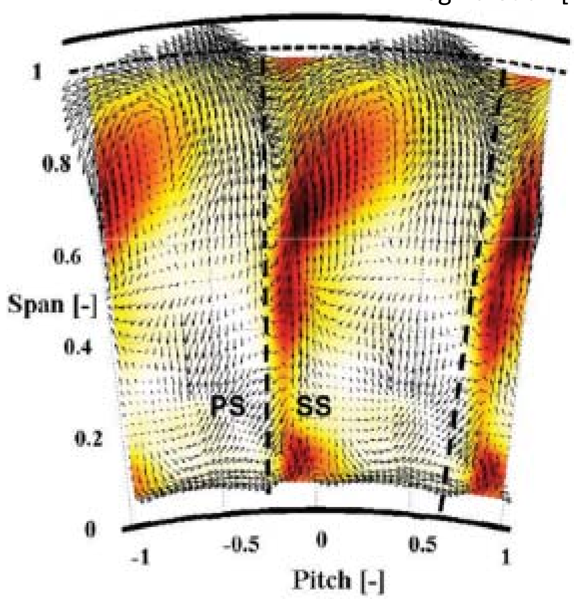


The new high frequency response aero-probe and data acquisition system arrive soon and allow time resolved spatial maps of pressure



Regina et al. [2014]

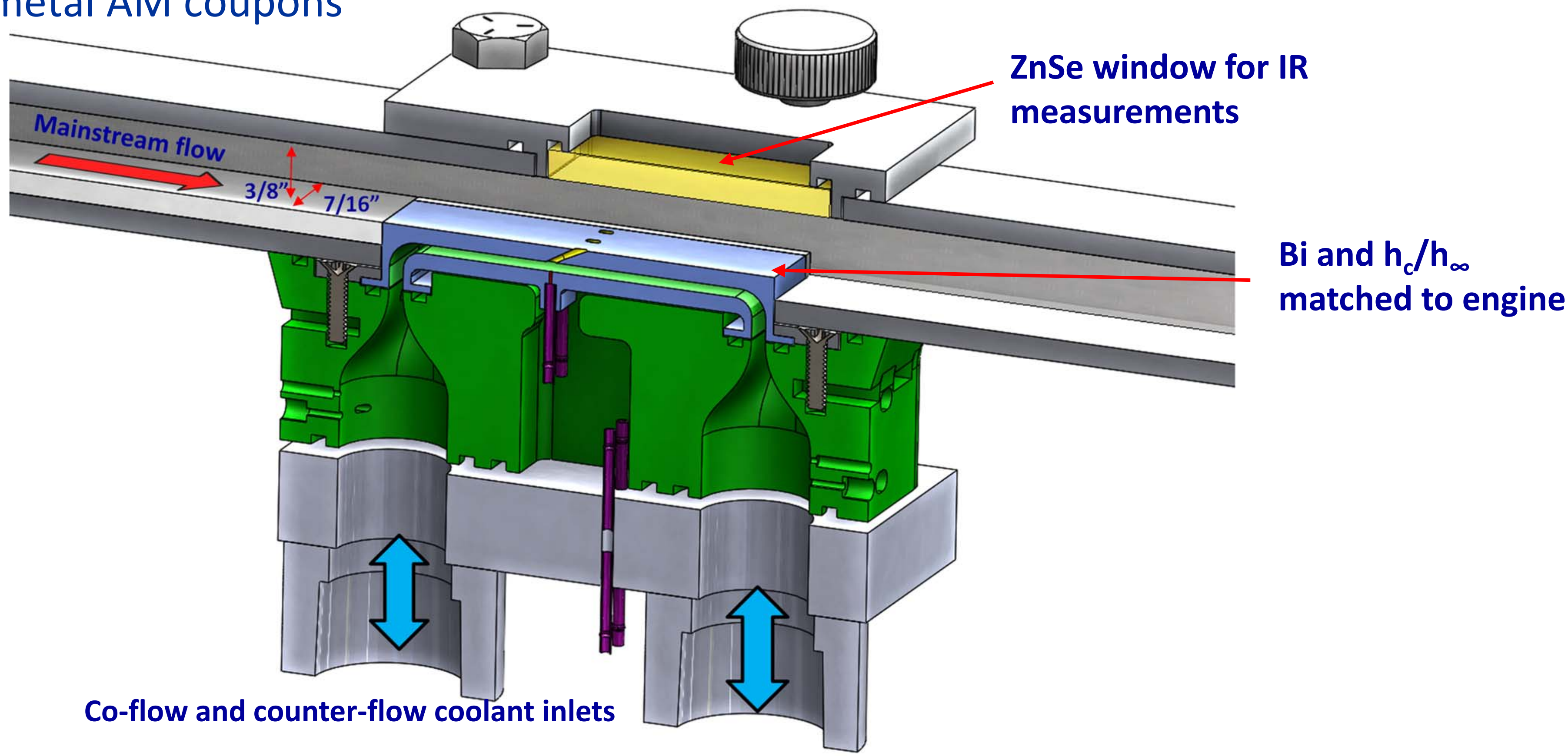
Courtesy of Limmat Scientific

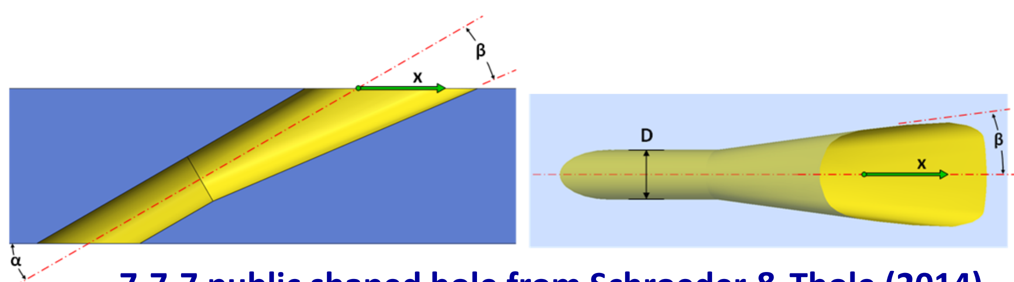


Porreca et al. [2007]

Task 6.0: Evaluation of Advanced Manufacturing Methods

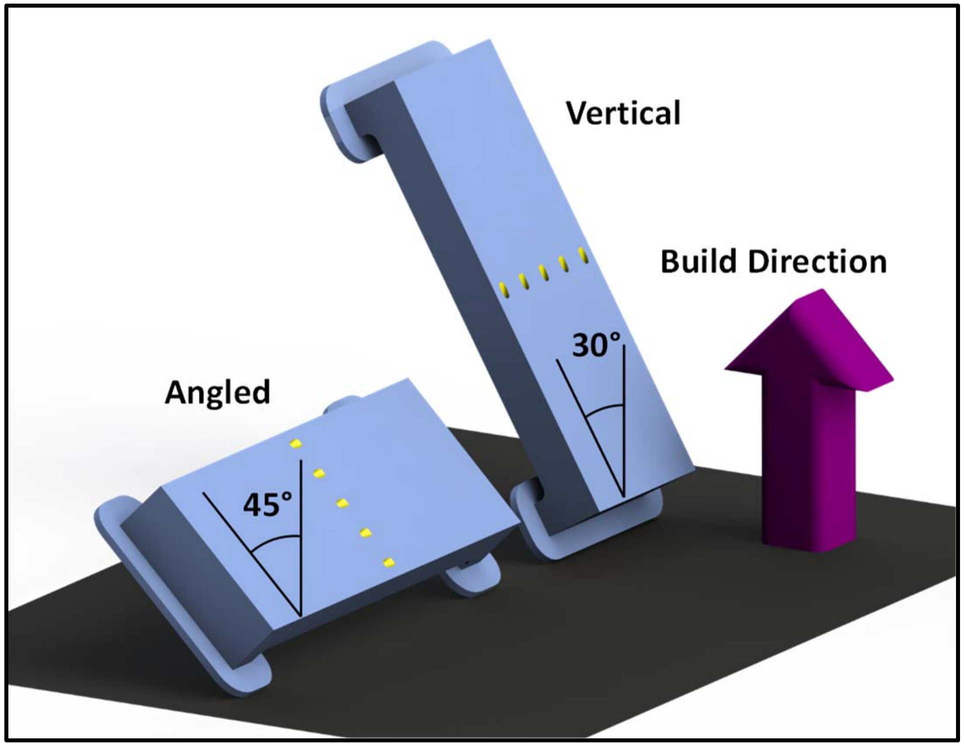
Public film cooling configurations are being tested in a engine scale test rig with metal AM coupons

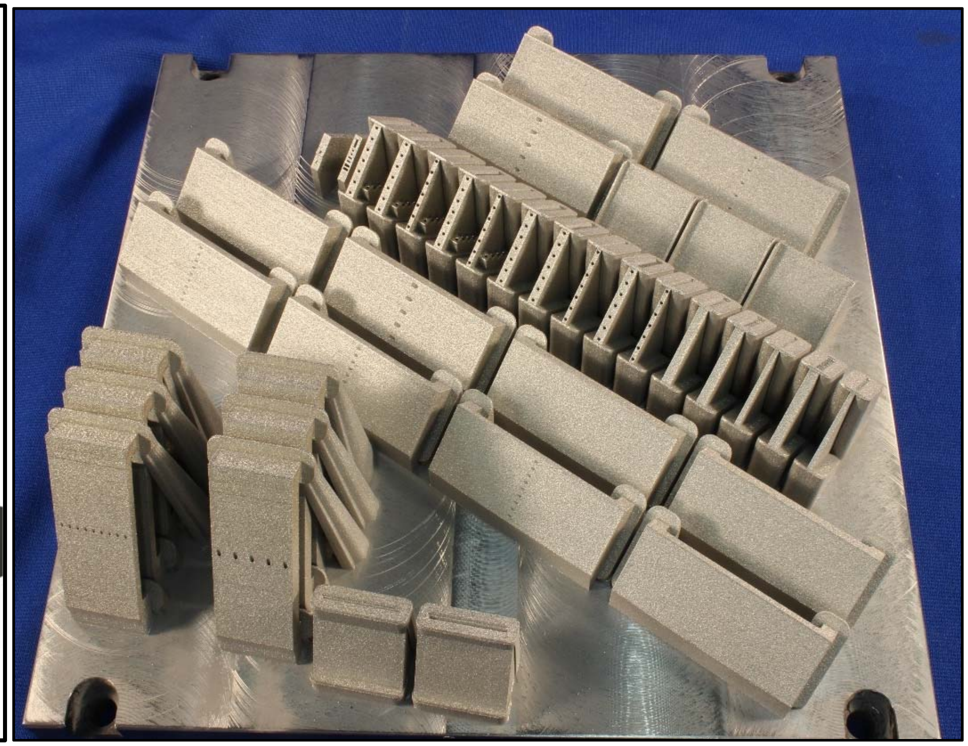




7-7-7 public shaped hole from Schroeder & Thole (2014)

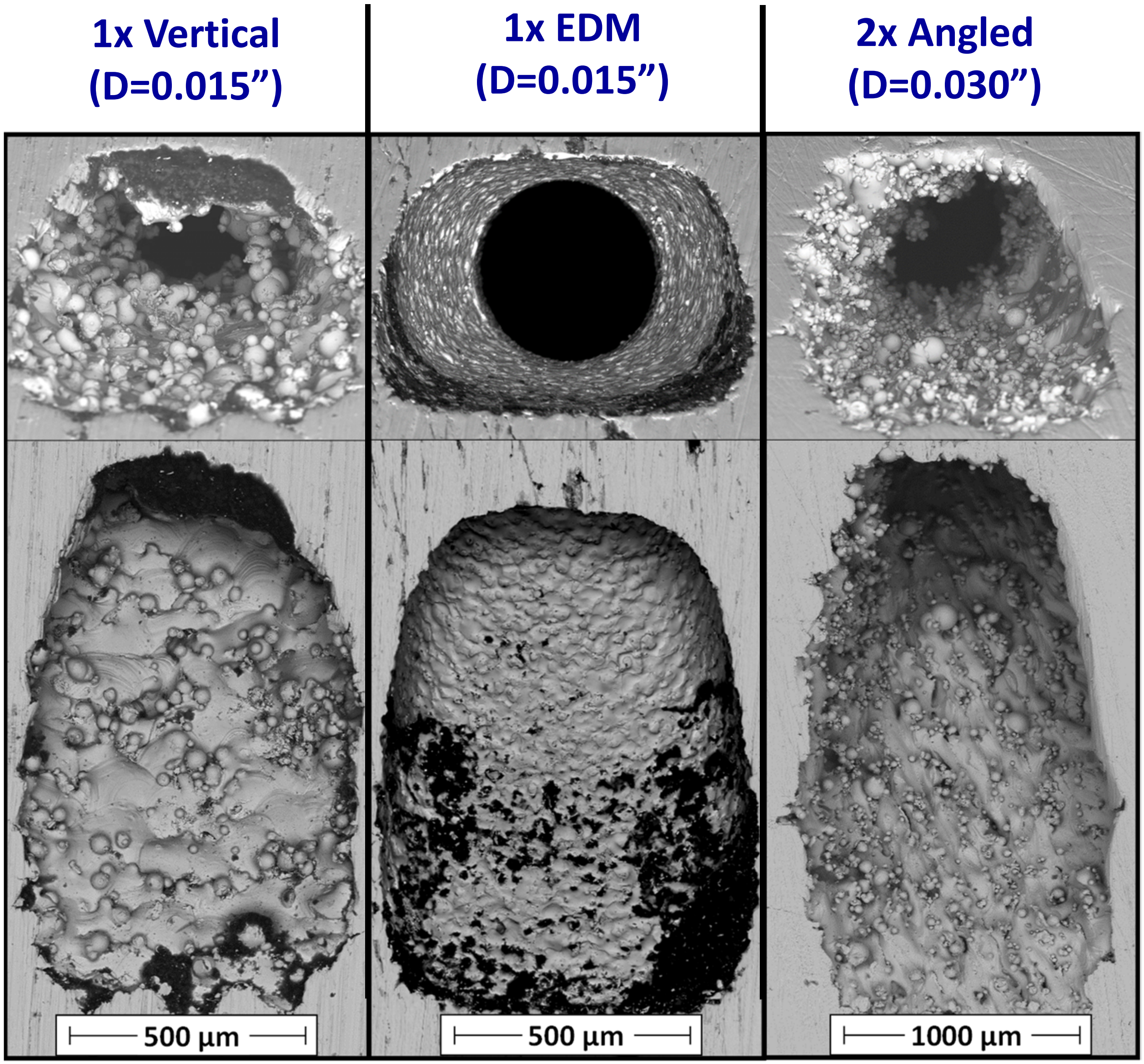
Film cooling coupons were manufacture using laser powder bed fusion in two different build orientations





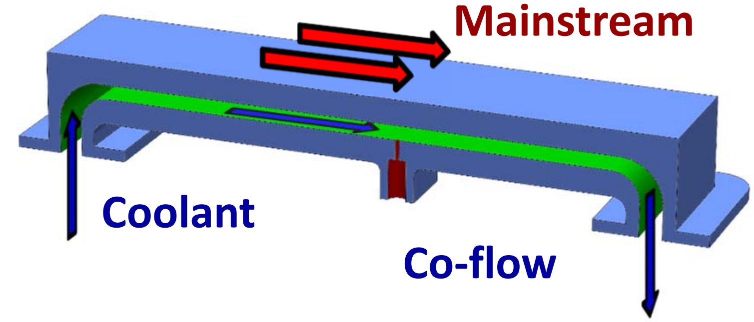
Material: Hastelloy® X
Machine: EOS M280 DMLS machine

SEM micrographs show high levels of roughness in the diffuser and metering section of AM film holes

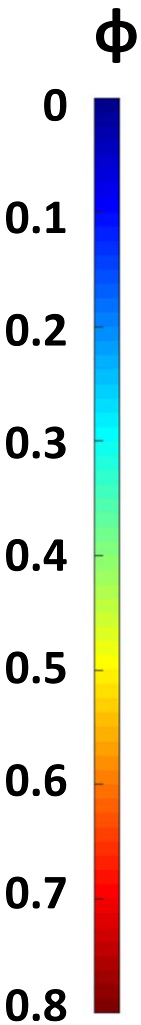


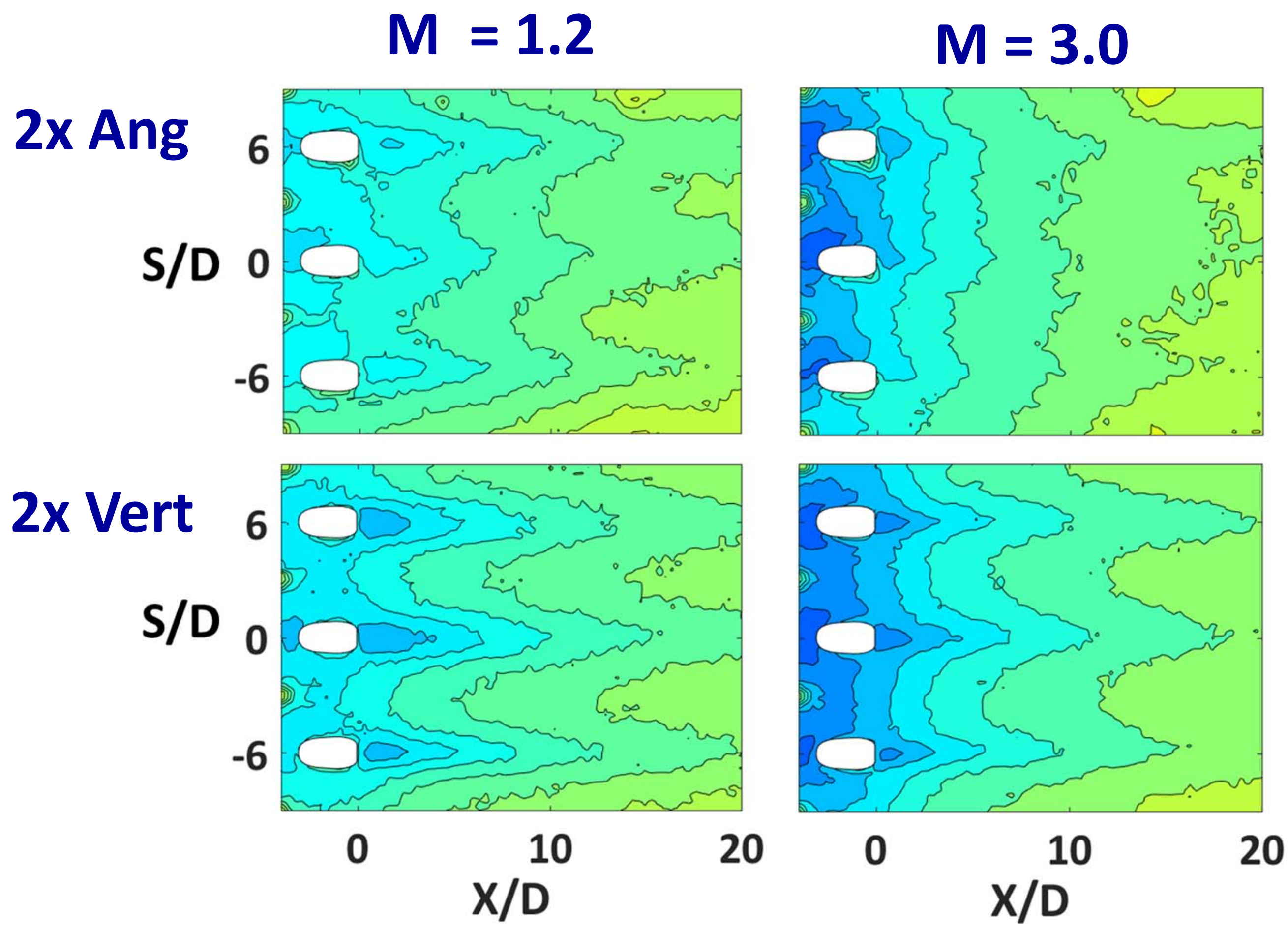
(black regions on surfaces are paint)

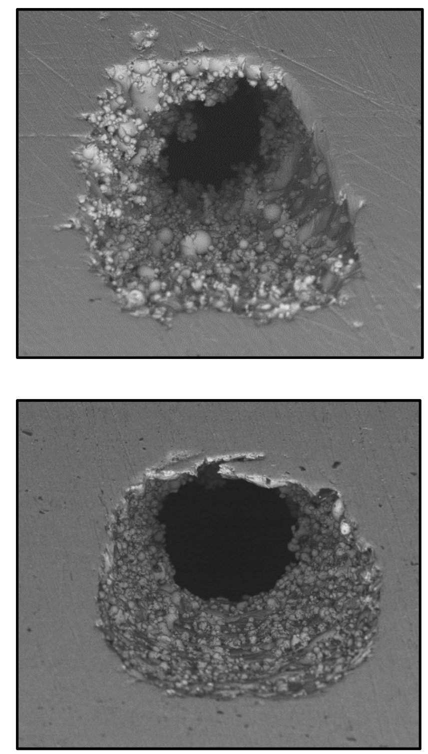
The build direction affects the type of roughness in the hole, which affects film performance



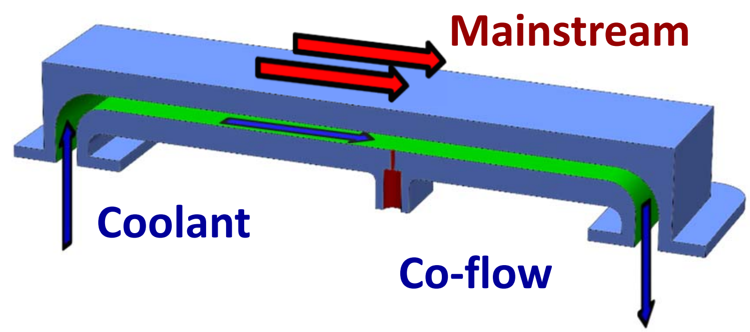
Hole Scale	Build Dir	Chan Height	Mfg Method	R_a/D^*
2x	Ang	1.7D	AM	0.02
2x	Vert	1.7D	AM	0.01



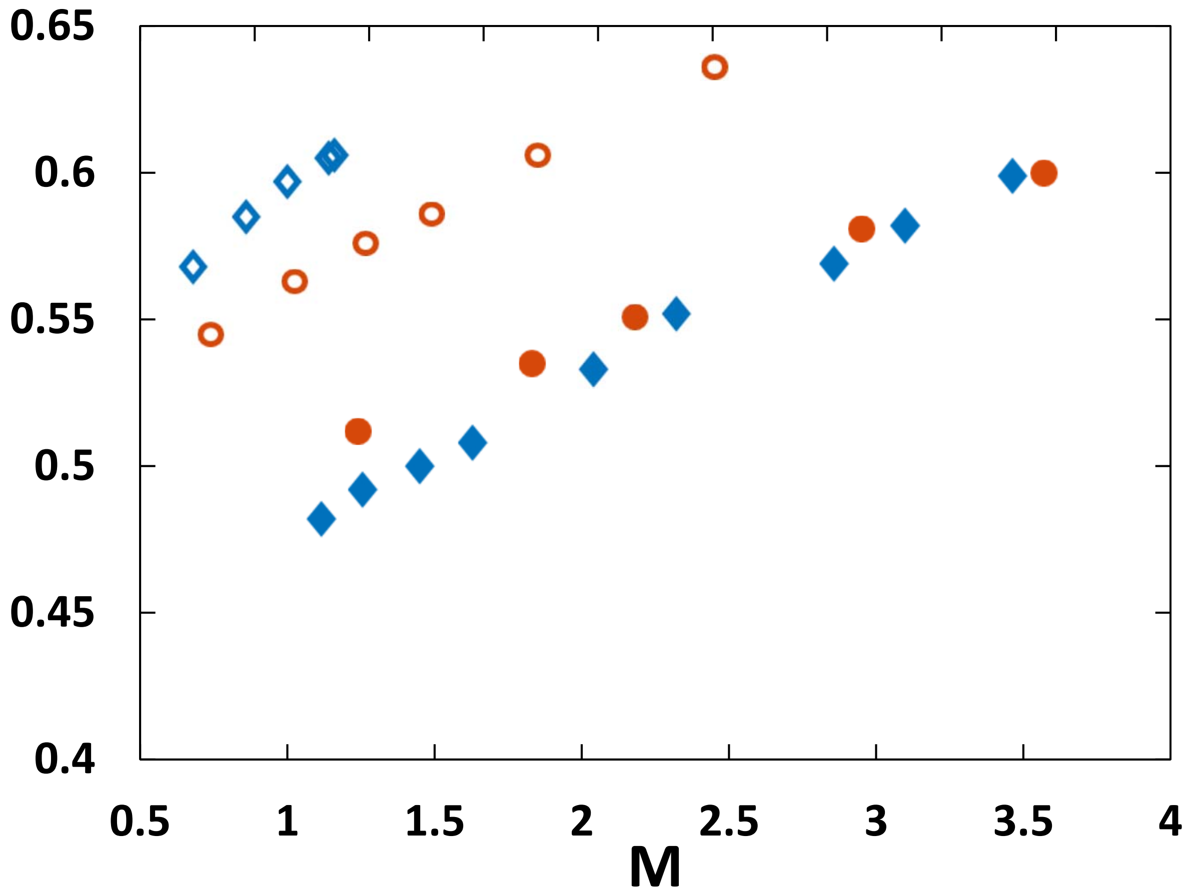


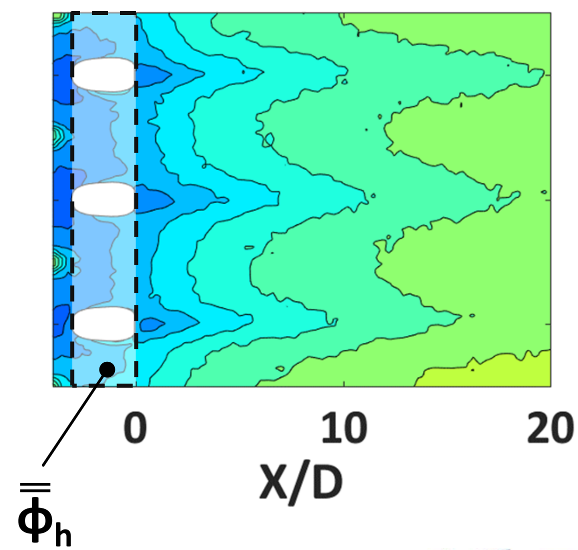


In-hole convection dominates overall effectiveness near the exit of the hole

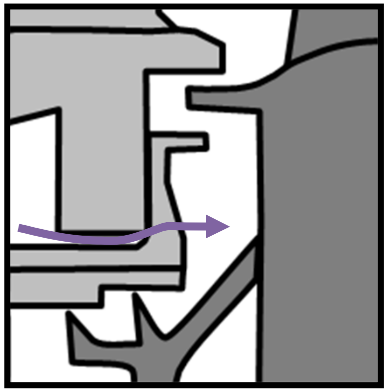


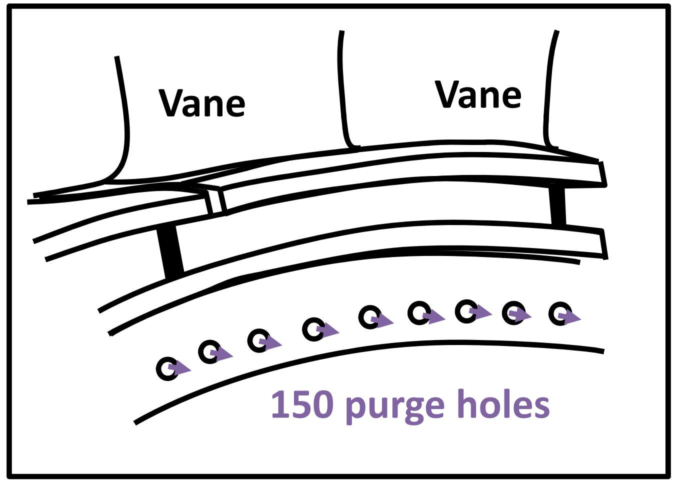
	Hole Scale	Build Dir	Chan Height	Mfg Method	R_a/D^*
◇ (open blue diamond)	1x	Ang	1.7D	AM	0.04
○ (open orange circle)	1x	Vert	1.7D	AM	0.02
◆ (filled blue diamond)	2x	Ang	1.7D	AM	0.02
● (filled orange circle)	2x	Vert	1.7D	AM	0.01

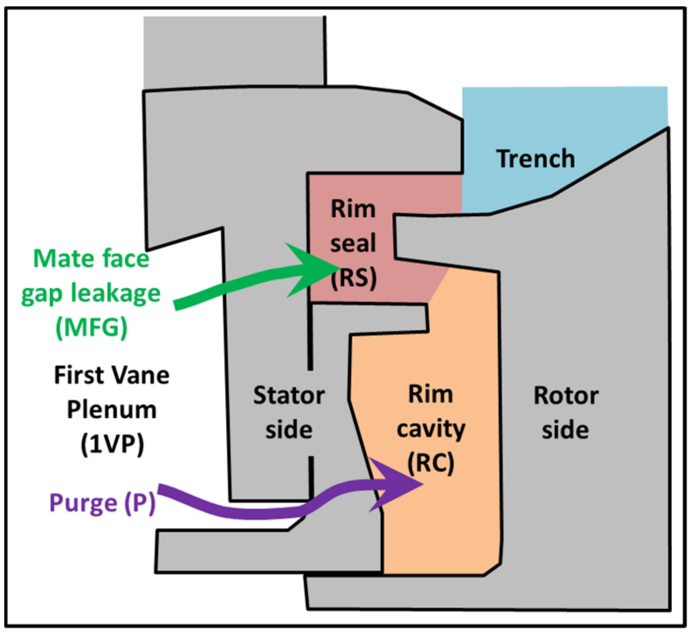




The first test campaign after the facility upgrades were completed was to compare full and partial span turbine sealing results





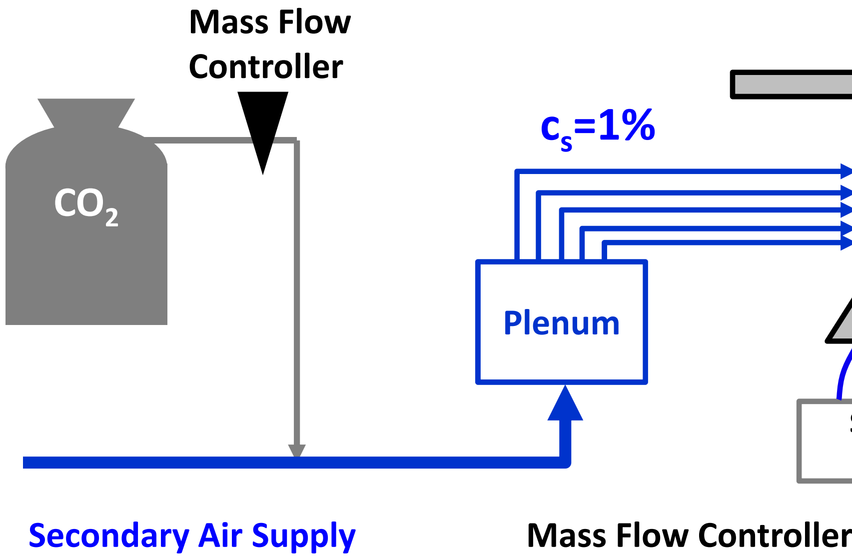


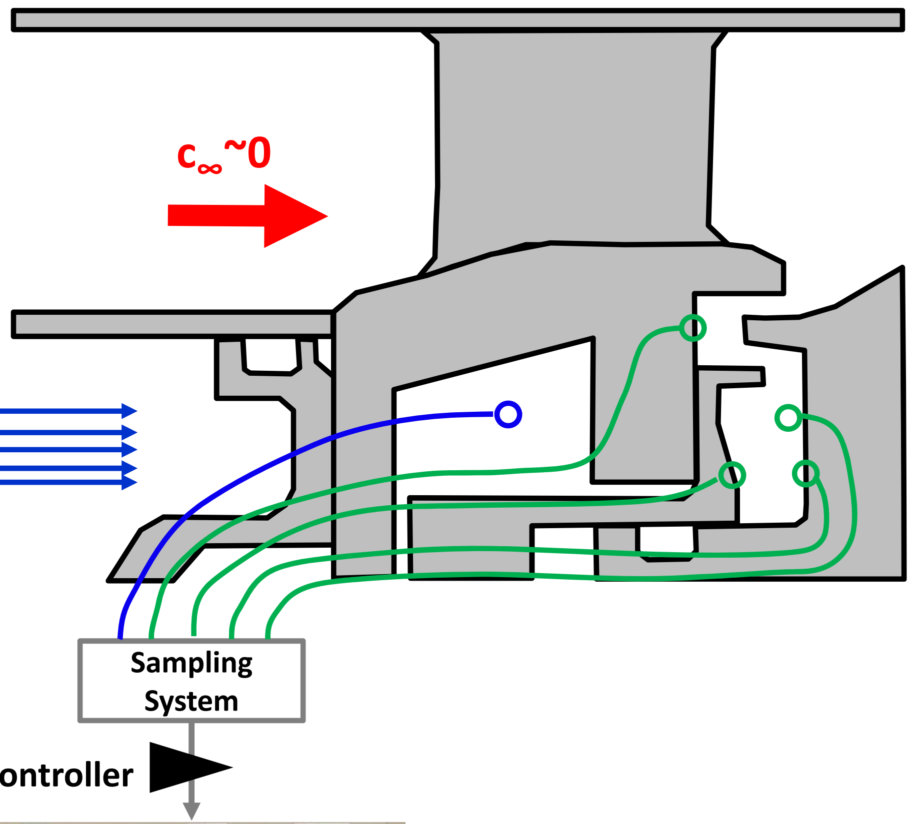
CO_2 concentration measurements are made through static pressure taps using a gas analyzer, sampling system, and mass flow controllers

Concentration Effectiveness

$$\varepsilon_c = \frac{c - c_\infty}{c_s - c_\infty}$$

Alicat

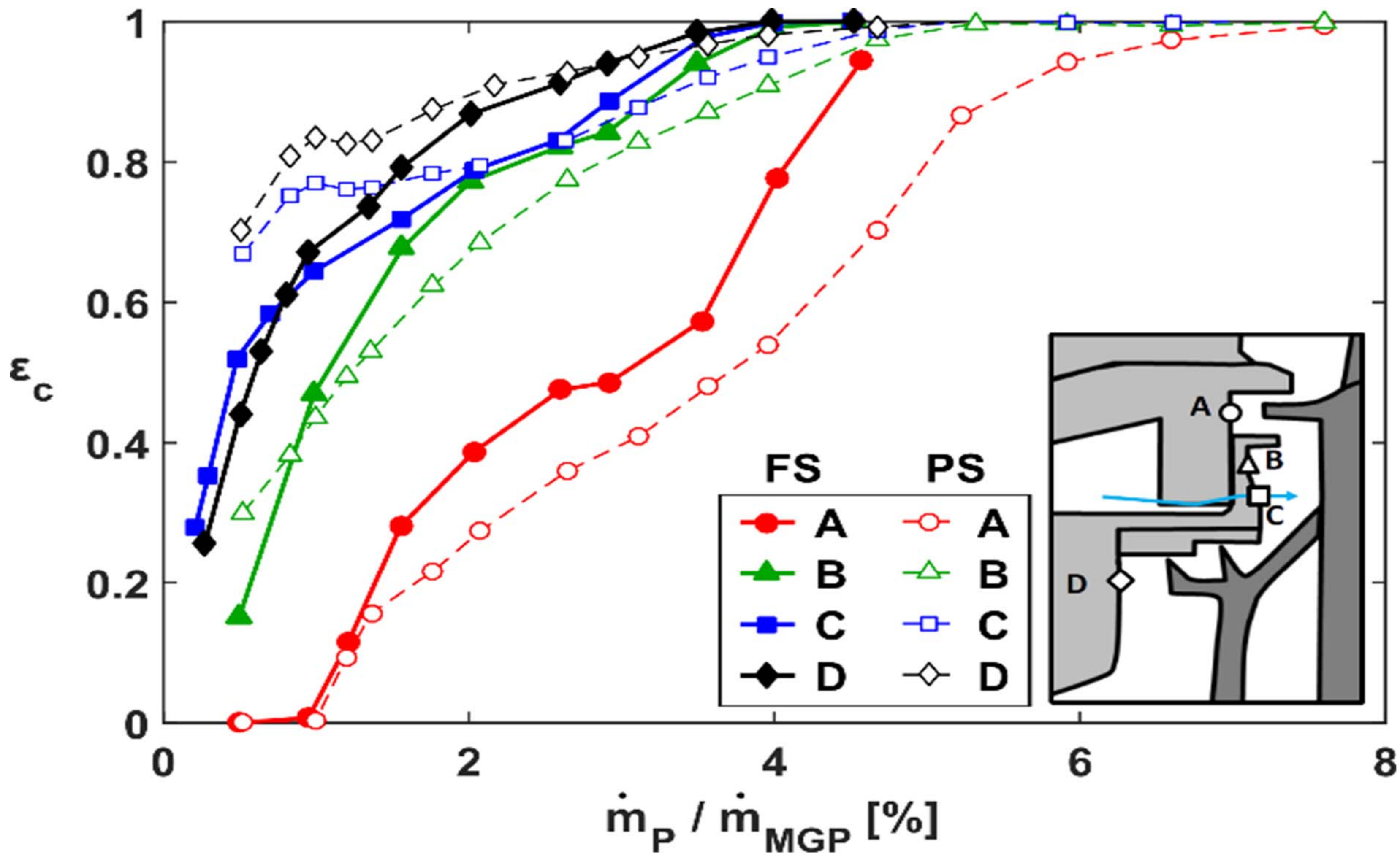




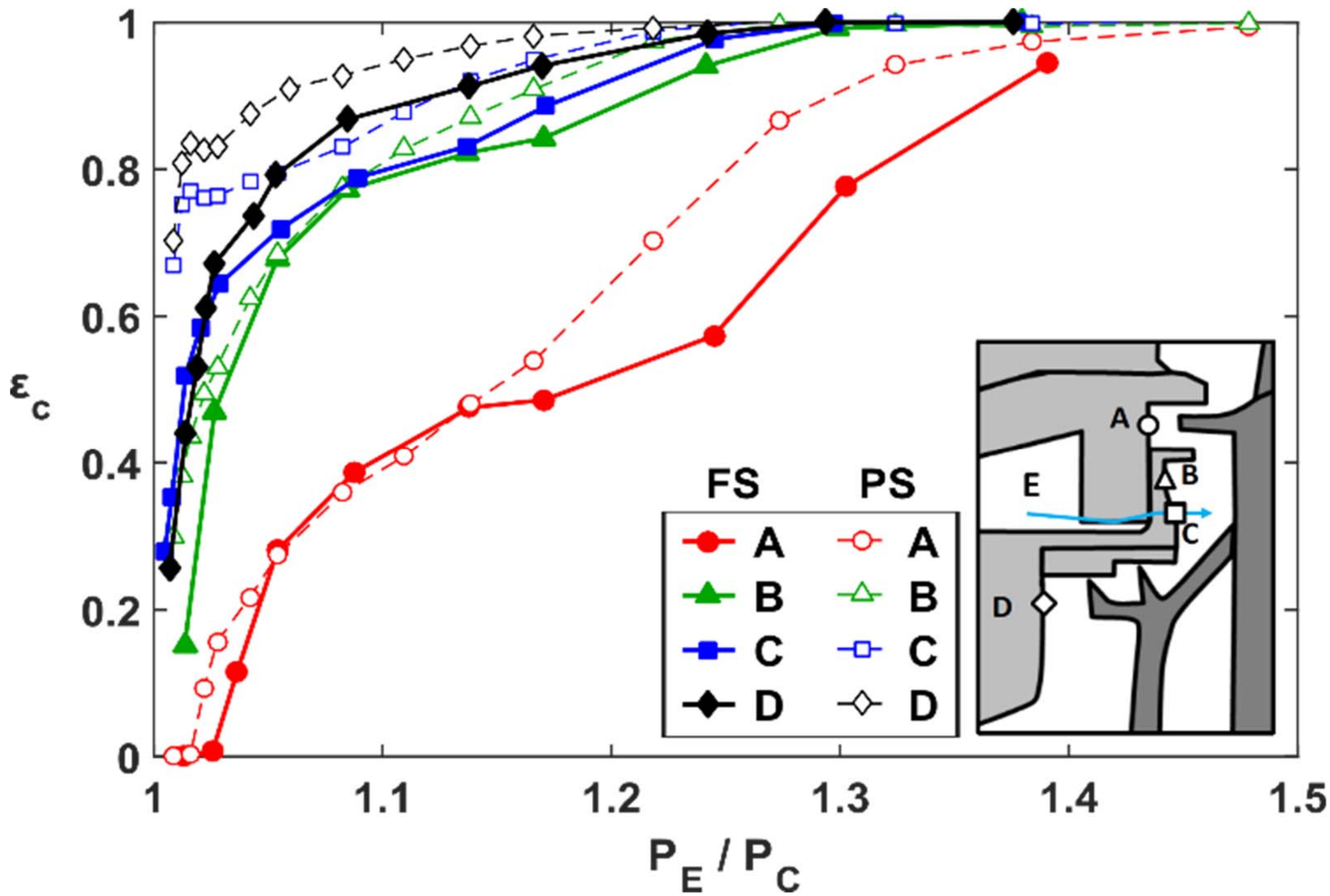
Siemens Ultramat 6

Gas Analyzer, c

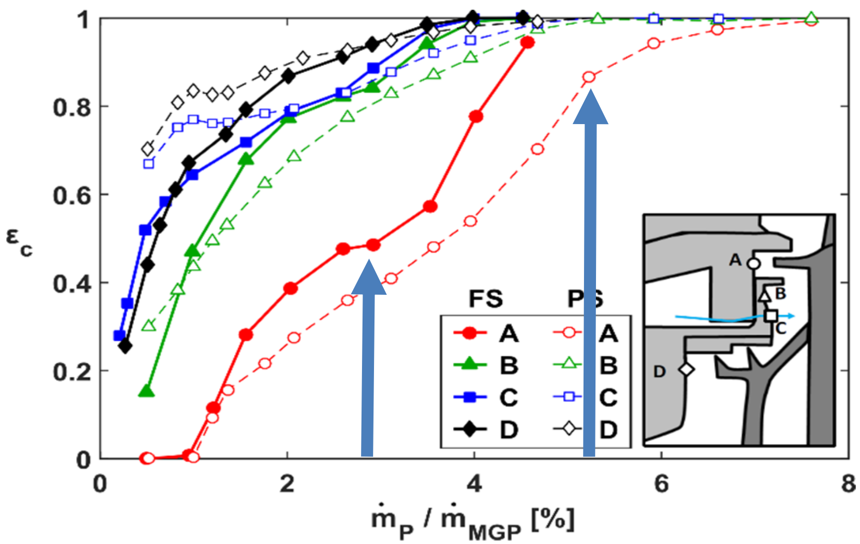
Sealing effectiveness does not scale with purge-to-main gas path flow ratios

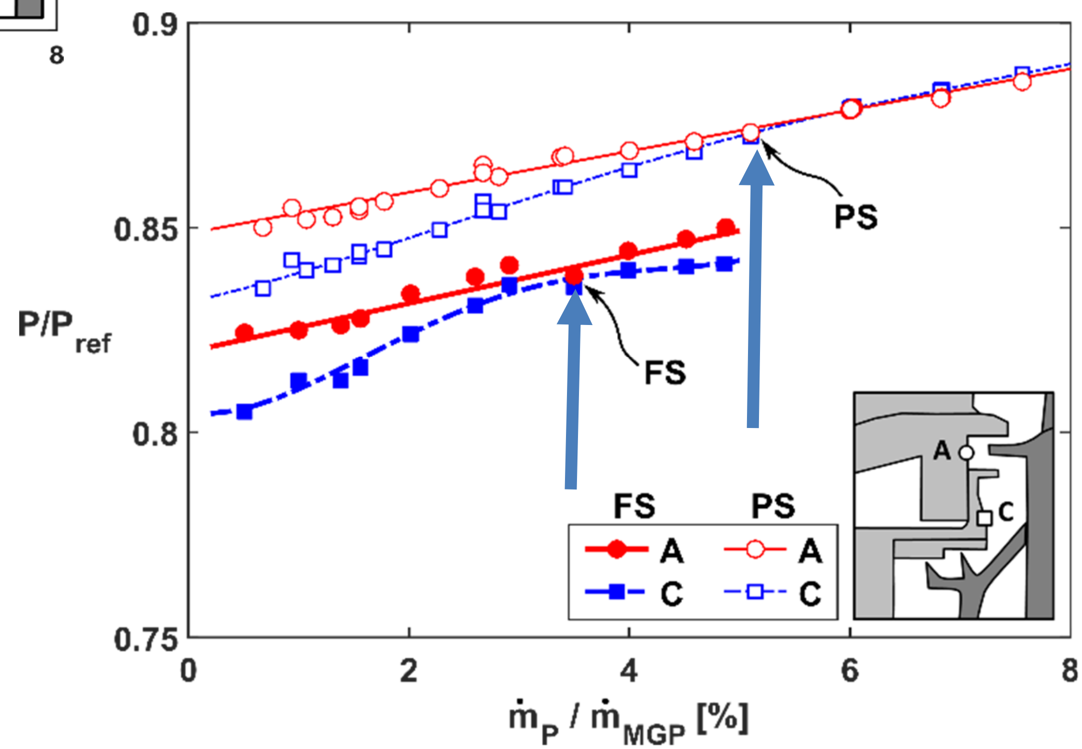


Sealing effectiveness levels at low purge flows scale better with pressure ratio across the purge holes (similar to momentum flux ratio)



Inflection point in the data was detected in sealing effectiveness, which occurred when rim seal and rim cavity pressures agreed



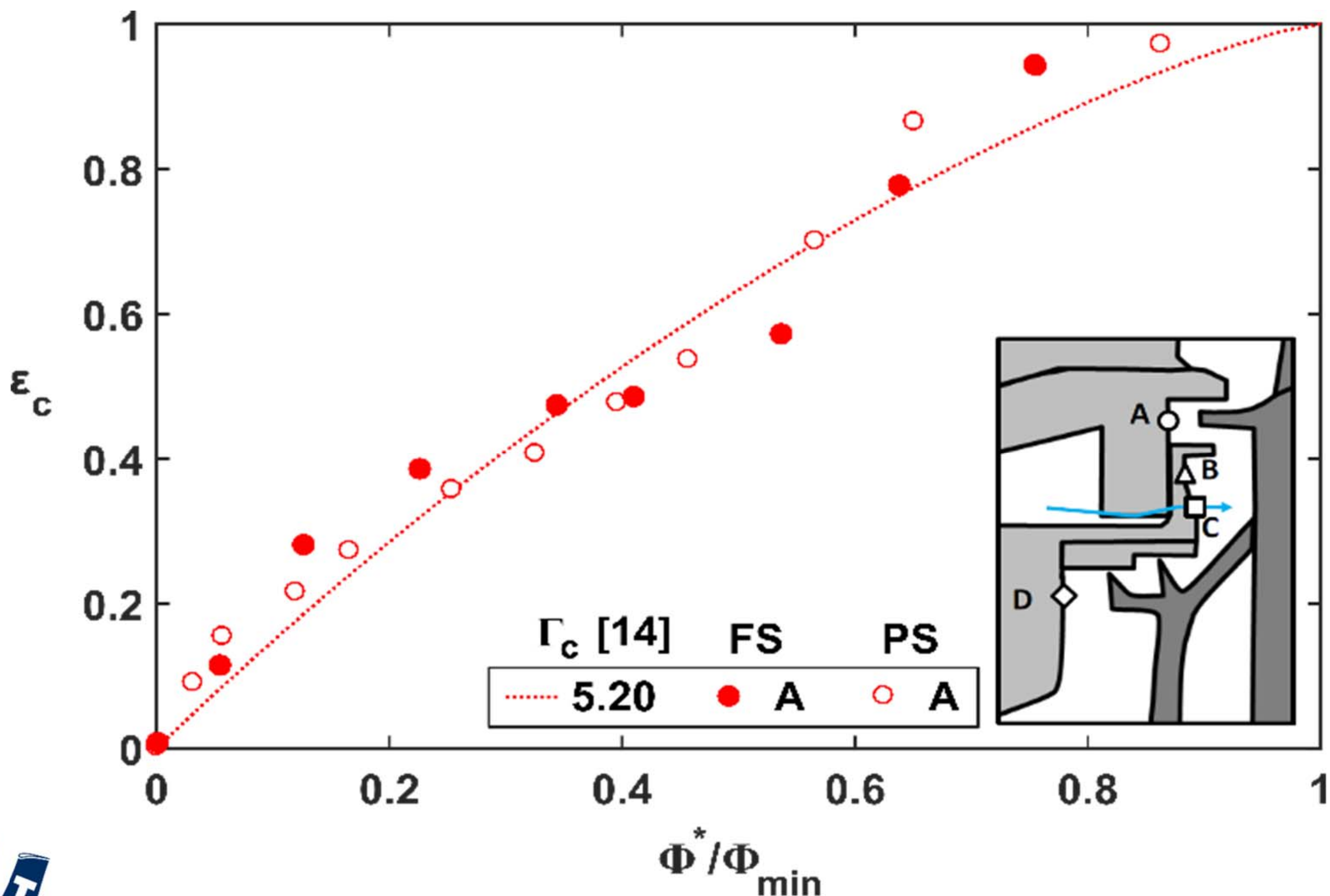


The normalizing parameter proposed by Owen et al. [2012] showed good scaling of the data but does not agree with theoretical model

$$\frac{\phi^*}{\phi_{min}} = \frac{\varepsilon}{\left[1 + \Gamma_c^{-2/3}(1-\varepsilon)^{2/3}\right]^{3/2}}$$

$$\phi^* = \phi - \phi_0$$

ϕ_{min} = ϕ where ε = 0



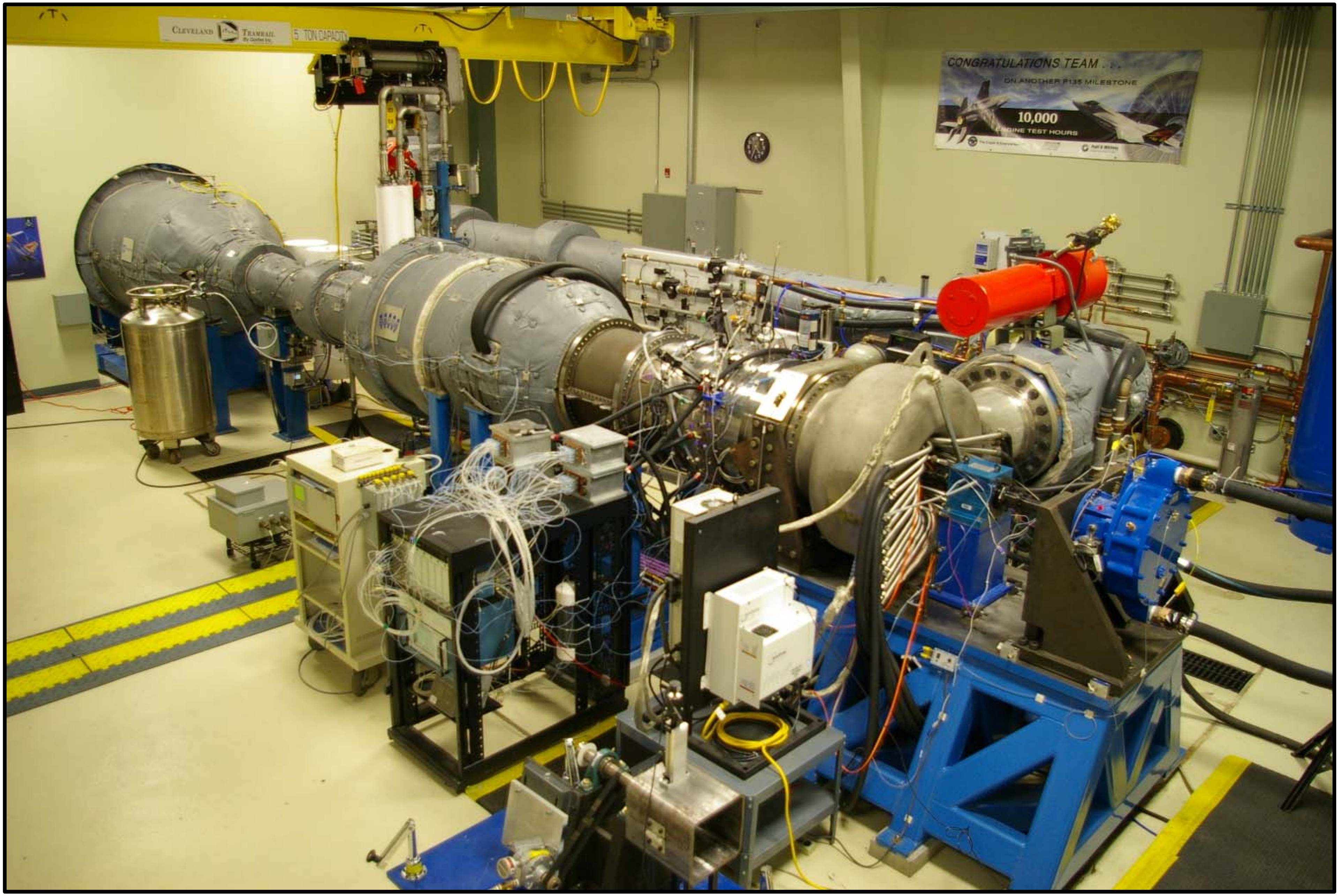
Key Findings to Date

The START facility has been upgraded to integrate the second compressor and combustor; benchmarking of the facility with the full span airfoils are complete; significant instrumentation upgrades have been completed and are continuing

Design for the turbine airfoils integrating the baseline and advanced cooling configurations are progressing

Comparison of sealing effectiveness levels for full-span and partial-span airfoils have been made; purge flow-to-main gas path flow ratios do not scale the effectiveness

Questions?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