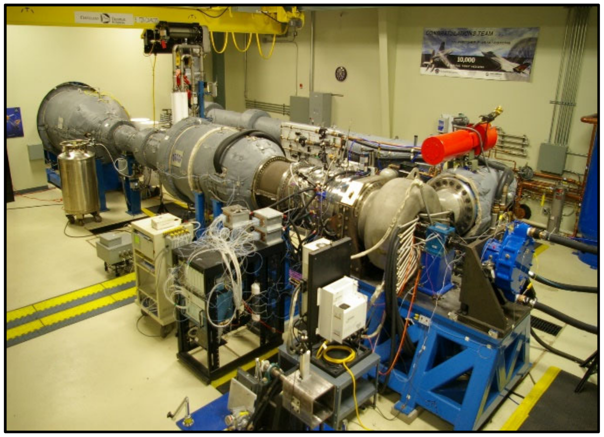
START: Advanced Cooling Design Studies and Turbine Rim Seal Results

Karen A. Thole

November 2018



Atul Kohli
and many others

Brian Knisely, Ivan Monge-Concepcion, Shawn Siroka, Jacob Snyder
Mike Barringer, Reid Berdanier, Jeremiah Bunch,
Scott Fishbone, and Karen Thole

Patcharin Burke
Richard Dennis
Doug Straub
and many others

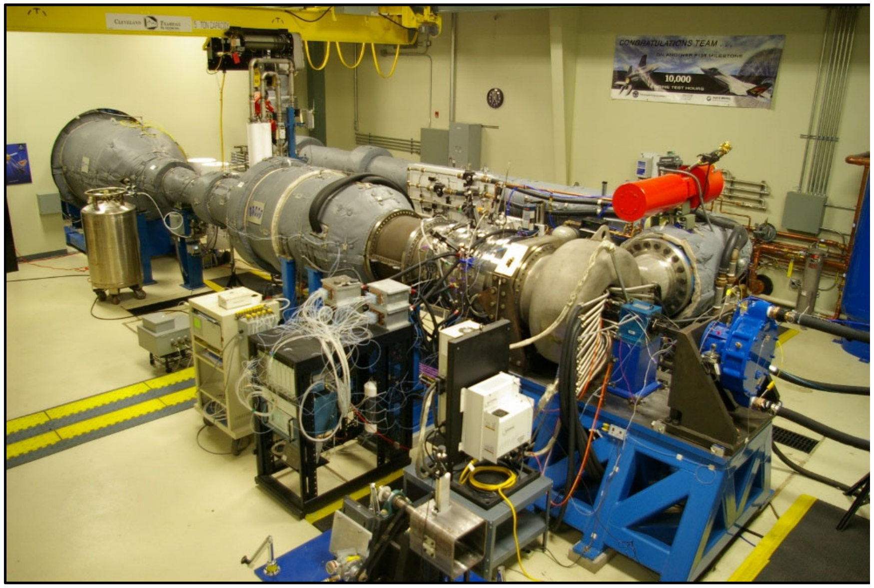
This presentation will provide updates in three tasks

Progress on DOE cooled blade study

Underplatform sealing results with and without vane trailing edge flow

Progress on heat flux gauge manufacturing

Latest additive manufacturing results

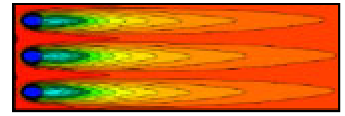
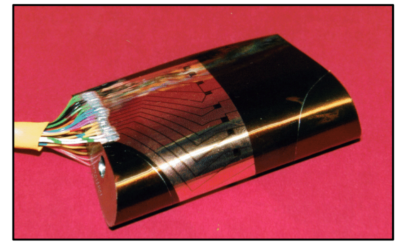


START

The Penn State START laboratory is founded on four pillars of research emphasis to benefit the gas turbine community

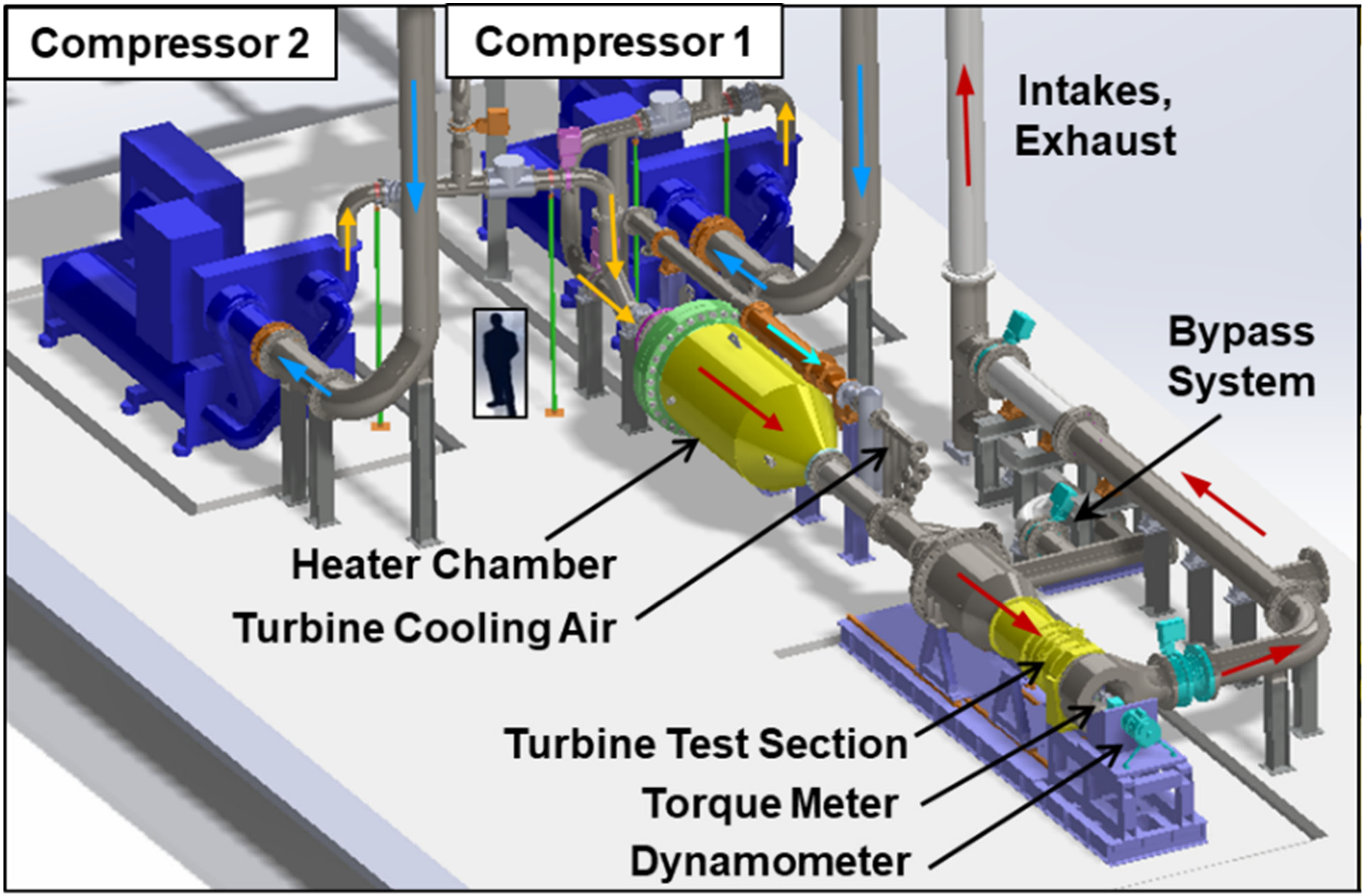




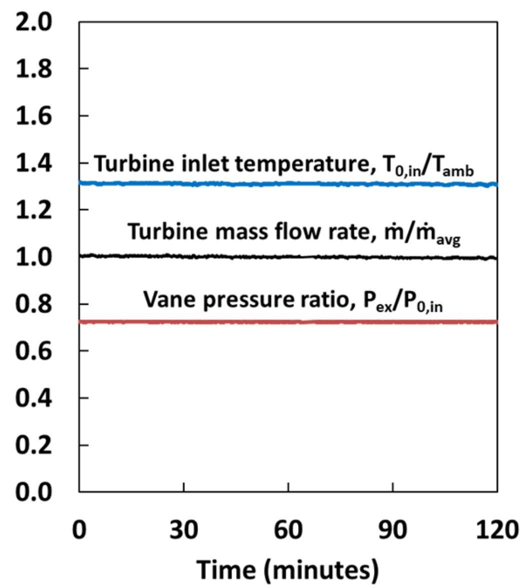


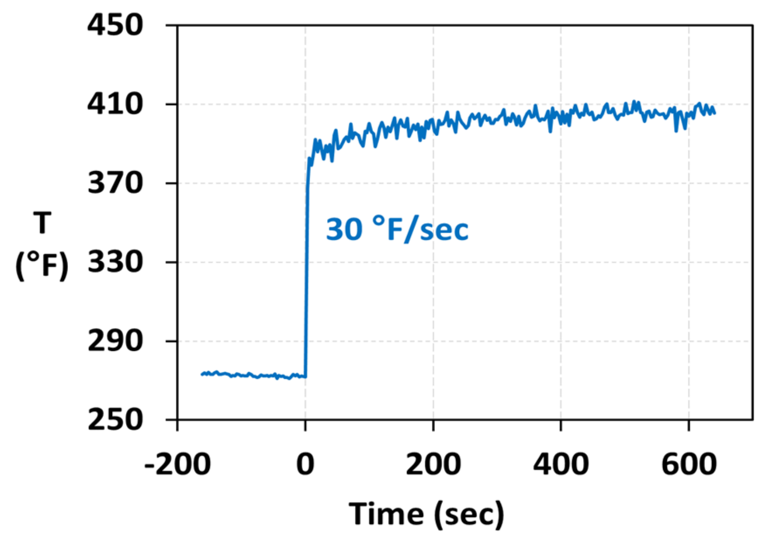
START


Compressor 2
Compressor 1
Intakes, Exhaust
Bypass System
Heater Chamber
Turbine Cooling Air
Turbine Test Section
Torque Meter
Dynamometer

Several flow conditions in the main gas path and secondary air system are matched to engine relevant parameters

Parameter at Blade Inlet		Turbine	START
Coolant-to-Mainstream Density Ratio	ρ_c/ρ_∞	2.0	1.0 - 2.0
Stage Pressure Ratio	$P_{0,in}/P_{0,exit}$	2	1.5 – 2.5
Rotational Reynolds Number	Re_ϕ	2.0 x 10^7 +	$\leq$ 2 x 10^7
Mass flow rate	lb_m/s	25+	25
Pressure	PSIA	100's	60-80
Axial Reynolds Number	Re_x	3 x 10^5	3 x 10^5
Turbine Inlet Temp Secondary Coolant Temp	°F	~ 2500 ~ 1000	750 40

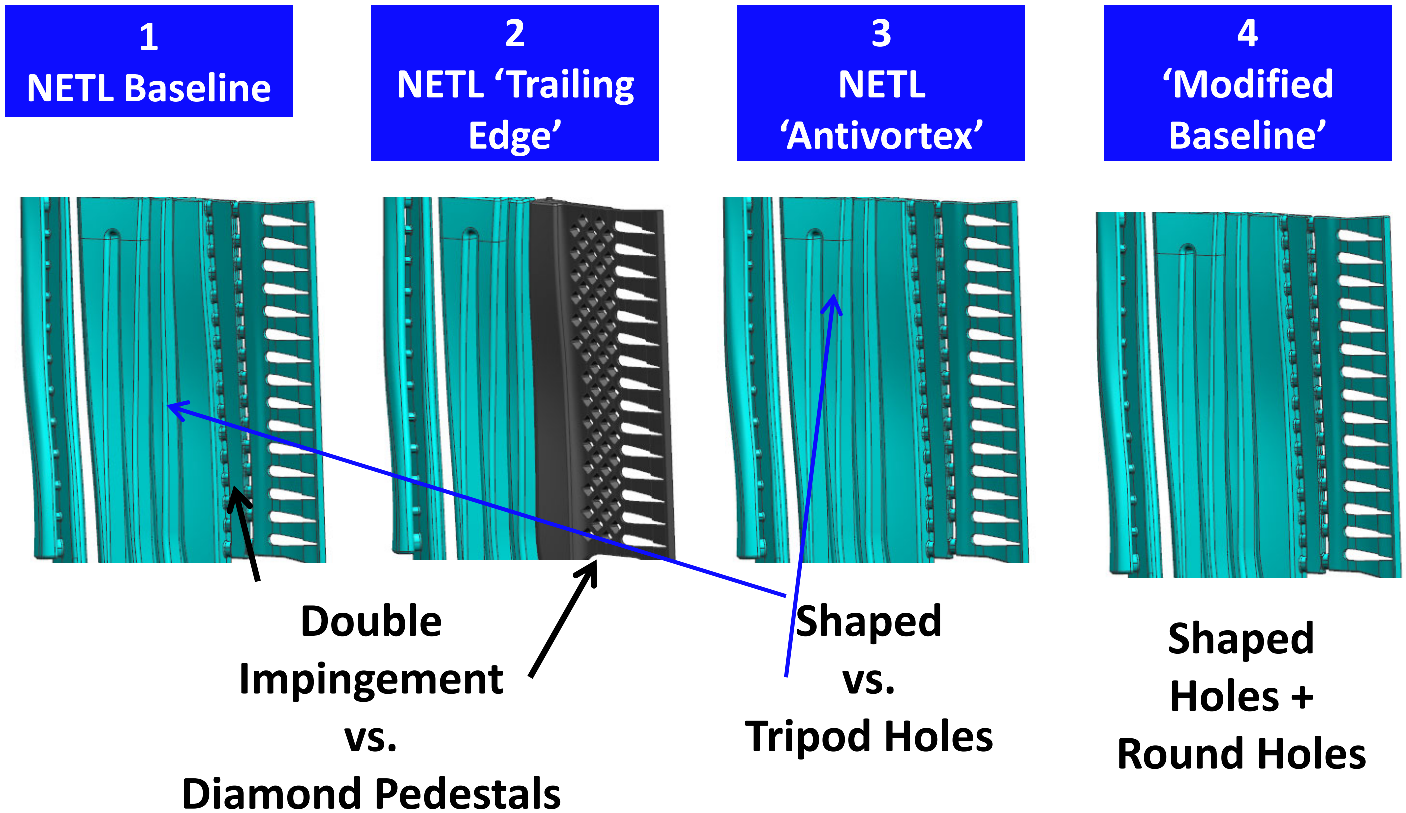




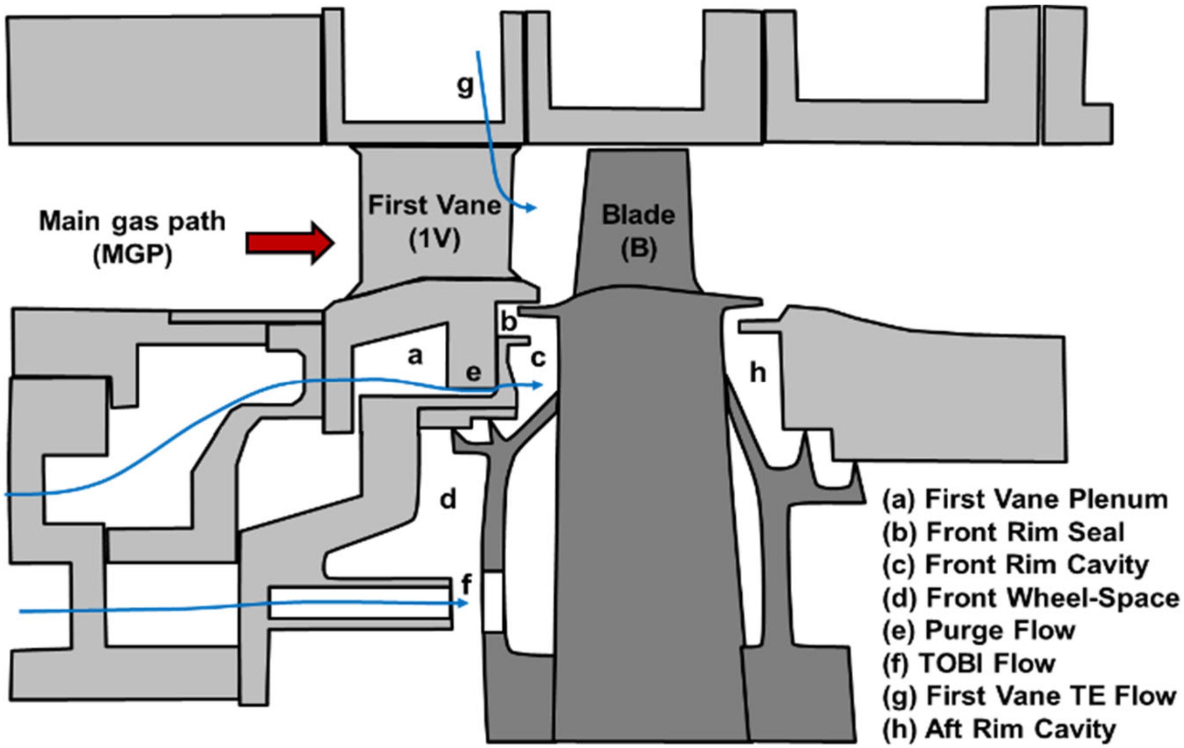
The primary goal of this project is to evaluate public cooling technologies in a 'rainbow' wheel in the START turbine

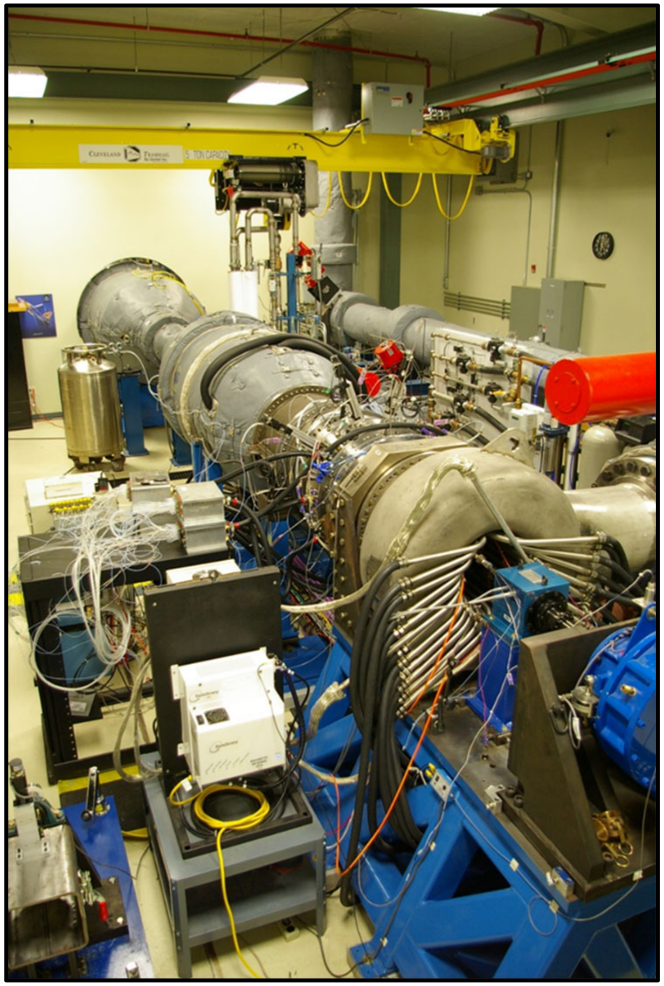
		1 Baseline	2 'Trailing Edge'	3 'Anti-Vortex'	4 Modified Baseline
Leading Edge	Internal	Impingement cooling	Impingement cooling	Impingement cooling	Impingement cooling
	External	Showerhead	Showerhead	Showerhead	Showerhead
Pressure Surface	Internal	Serpentine with 'V' Discrete Trip Strips	Serpentine with 'V' Discrete Trip Strips	Serpentine with Discrete 'V' Trip Strips	Serpentine with 'V' Discrete Trip Strips
	External	7-7-7 Shaped Hole	7-7-7 Shaped Hole	Shaped Antivortex Tripod Hole	Shaped + Round Holes
Suction Surface	Internal	Serpentine with 'V' Discrete Trip Strips	Serpentine with 'V' Discrete Trip Strips	Serpentine with 'V' Discrete Trip Strips	Serpentine with 'V' Discrete Trip Strips
	External	7-7-7 Shaped Hole	7-7-7 Shaped Hole	Shaped Antivortex Tripod Hole	Shaped + Round Holes
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
	External	Diffused Partitioned Pressure Side Cut	Diffused Partitioned Pressure Side Cut	Diffused Partitioned Pressure Side Cut	Diffused Partitioned Pressure Side Cut

PW subcontract status: internal core design for all blades completed, thermal and structural assessments completed



This past year's study was to evaluate rim sealing effectiveness in the presence of vane trailing edge (VTE) flow

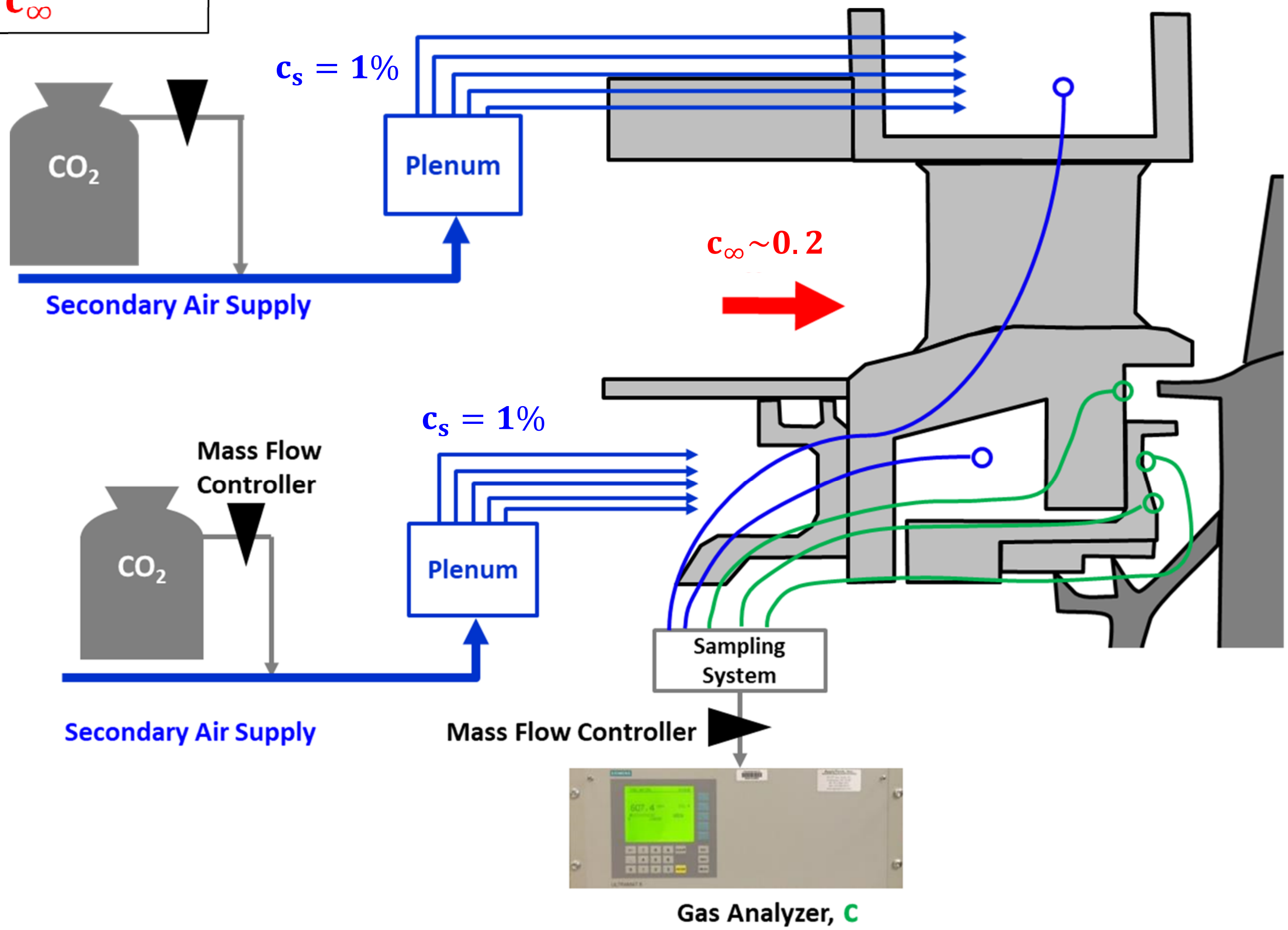




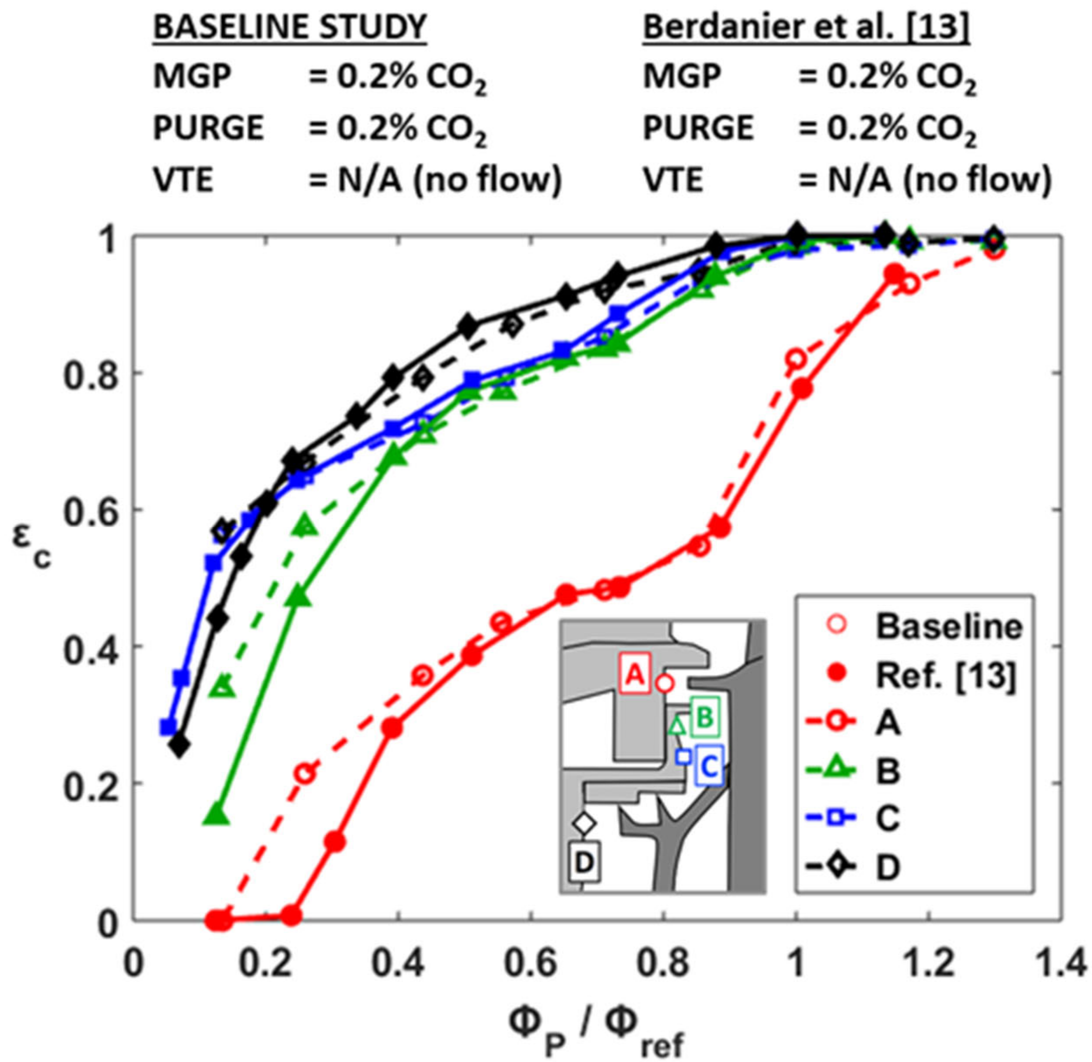
CO_2 seeding was used for tracing the various purge and vane trailing edge (VTE) flows to determine rim sealing

Concentration Effectiveness

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



A baseline study was repeated for rim sealing effectiveness without vane trailing edge flow to ensure repeatability

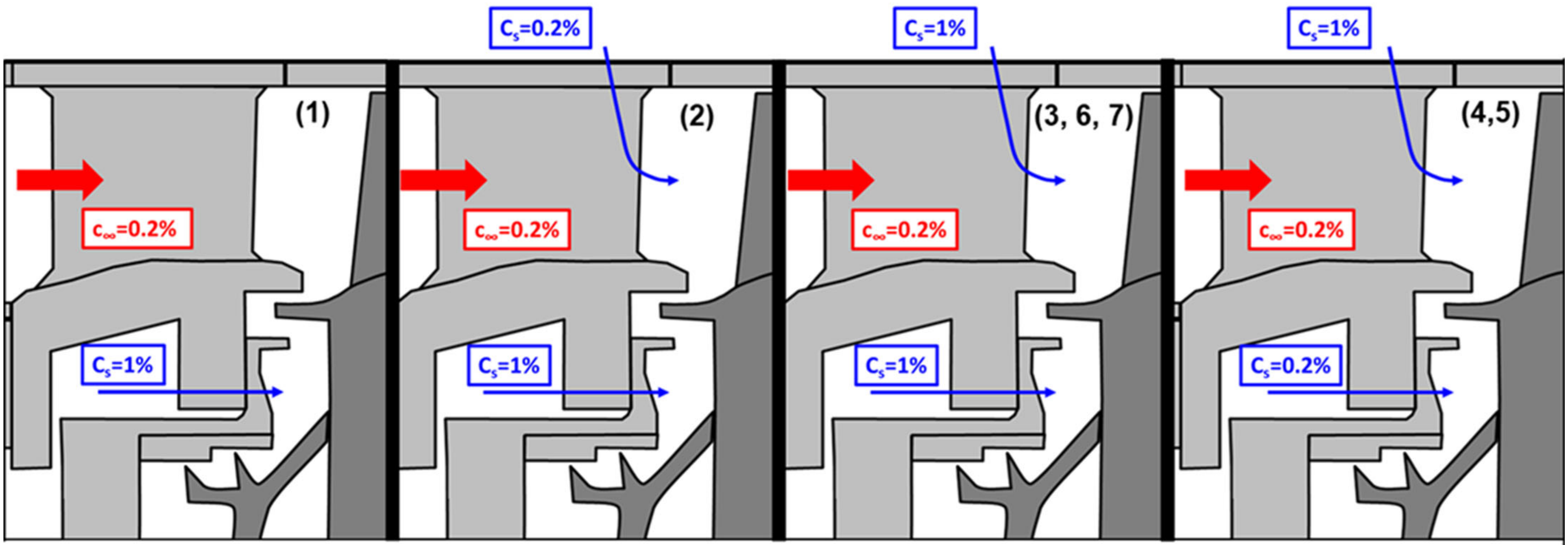


Multiple teardowns and re-assemblies over a one year period

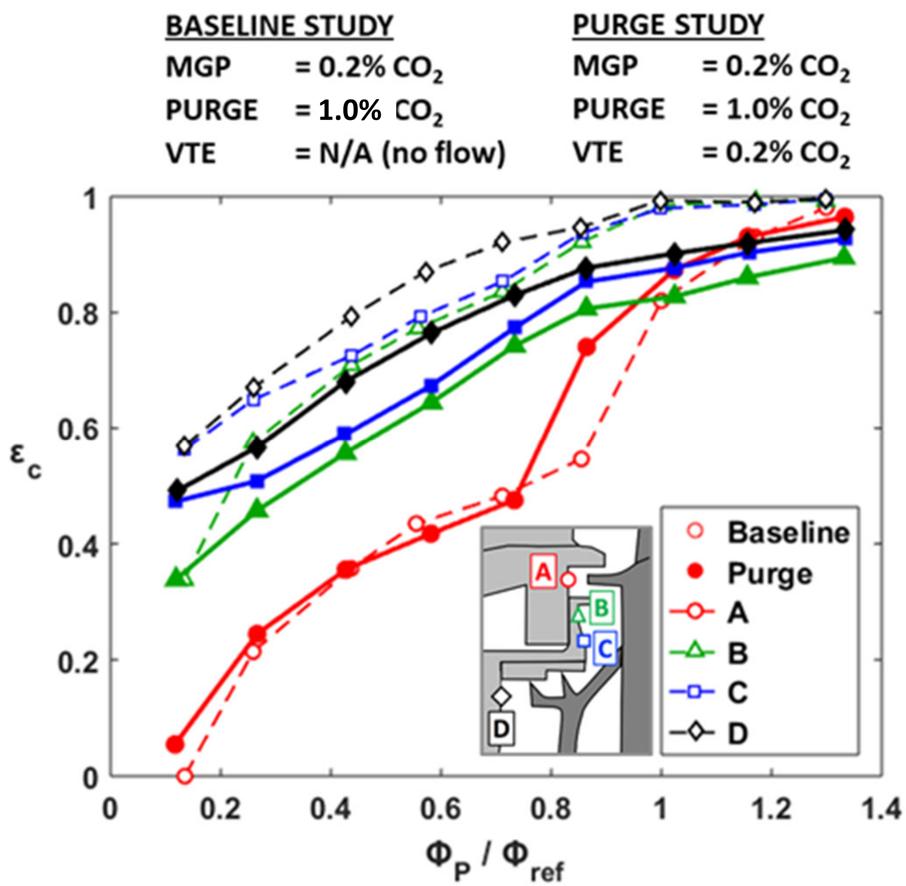
Berdanier et al., 2018, "Scaling Sealing Effectiveness in a Stator-Rotor Cavity for Differing Blade Spans", GT2018-77105

Various CO_2 seeding strategies were developed to independently track purge and VTE flows in the rim seal

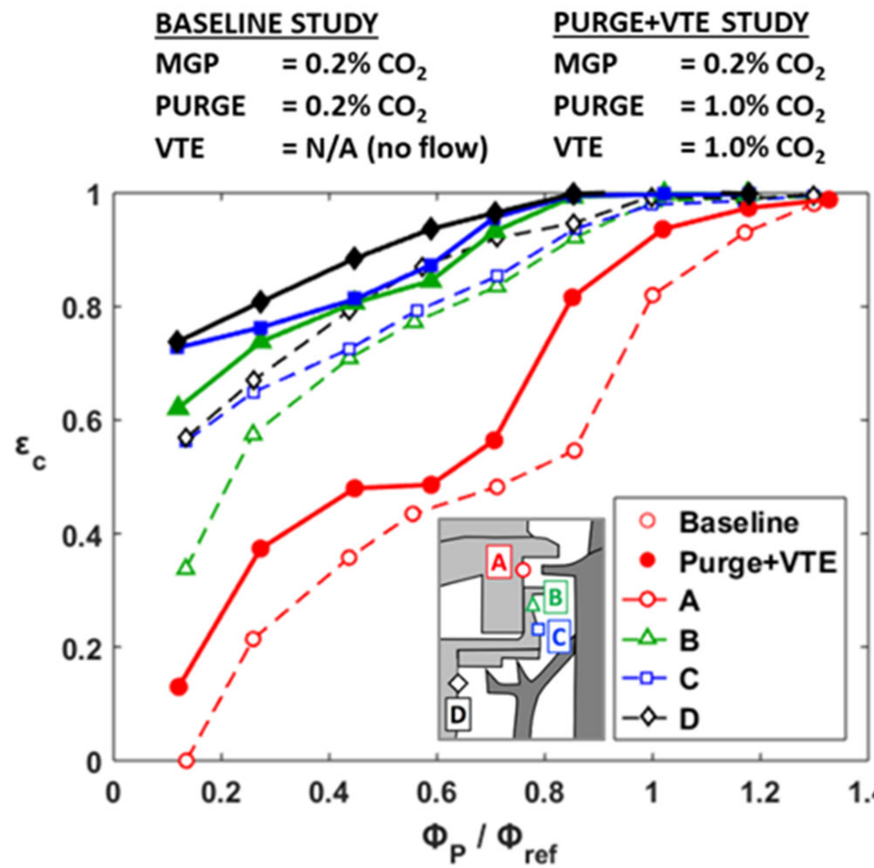
CO_2 Seed Configuration	MGP Background CO_2 Level	Purge Flow CO_2 Level	VTE CO_2 Level	Φ_P / Φ_{ref}	Φ_{VTE} / Φ_{ref}
(1) Baseline	0.2%	1.0%	No Flow	0.1 – 1.3	No Flow
(2) Purge	0.2%	1.0%	0.2%	0.1 – 1.3	0.4
(3) Purge+VTE	0.2%	1.0%	1.0%	0.1 – 1.3	0.4
(4) VTE1	0.2%	0.2%	1.0%	0.1 – 1.3	0.4
(5) VTE2	0.2%	0.2%	1.0%	0.4	0.1 – 0.7
(6) VTEMigration	0.2%	1.0%	1.0%	1.2	0 – 0.7
(7) PurgeMigration	0.2%	1.0%	1.0%	0.3 – 1.2	0.4



Two CO_2 configurations showed VTE flow is entrained into the wheelspace cavity with positive effectiveness results

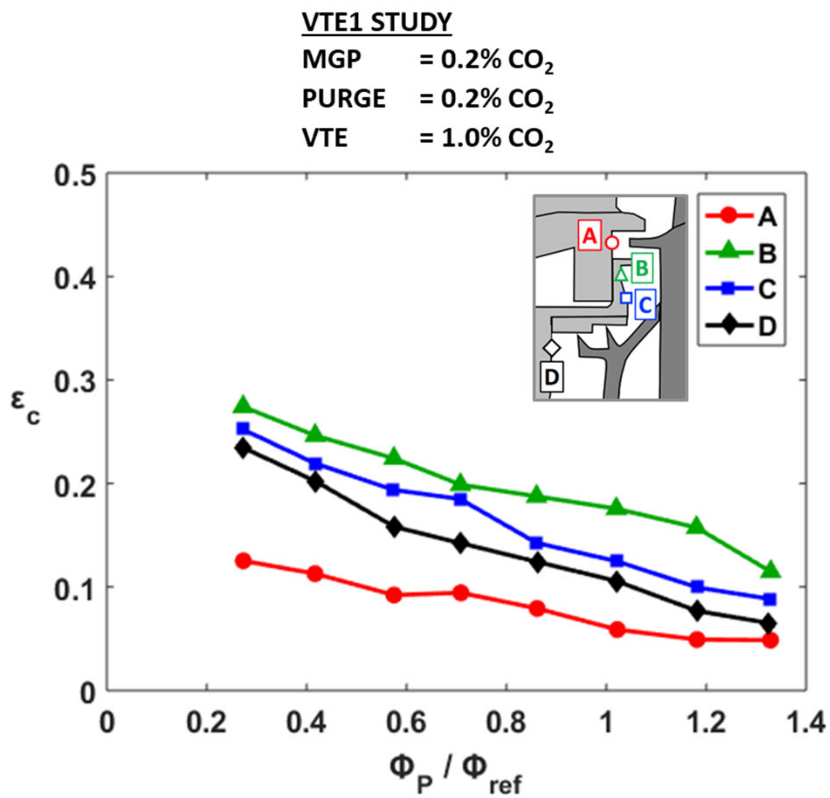


Location A was found to be the least affected by the presence of VTE flow.

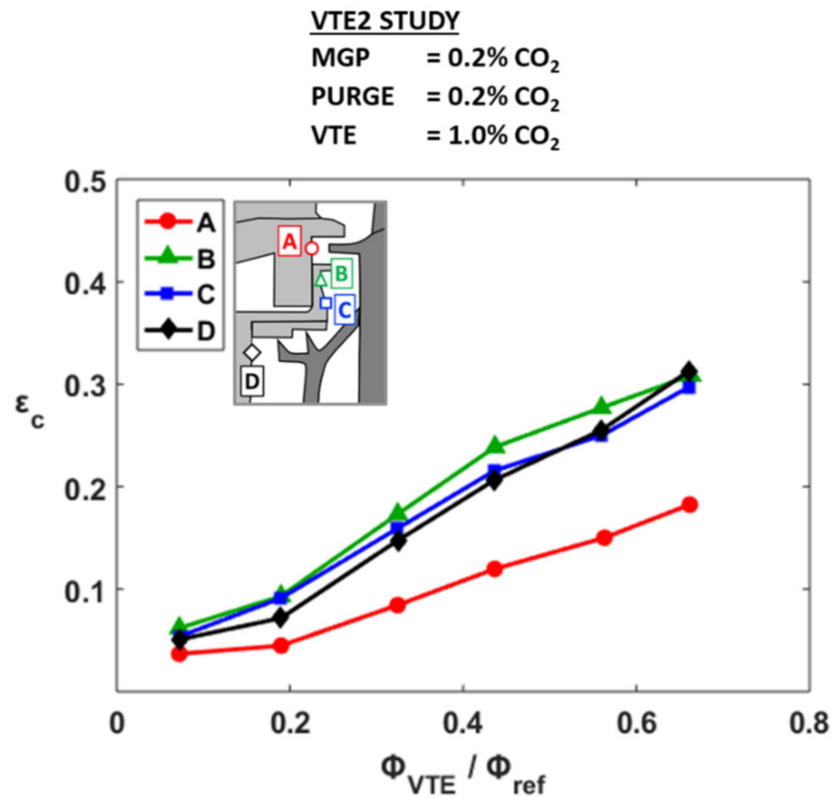


When seeding both purge and VTE flow, it was found that there is an increase of sealing effectiveness.

Sole VTE seeding was performed to study the independent effect of VTE flow in rim sealing effectiveness

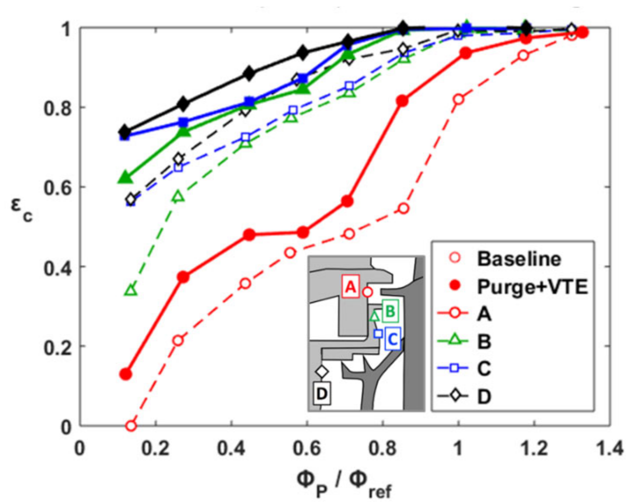


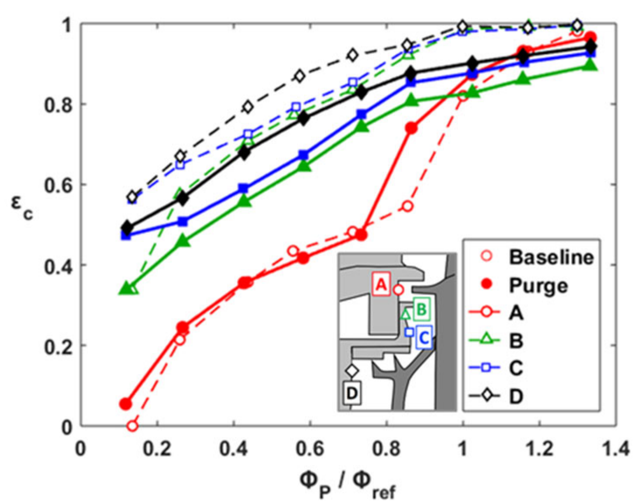
By holding the VTE flow fixed while varying purge flow, it was found that VTE influence decreased as purge flow increased.



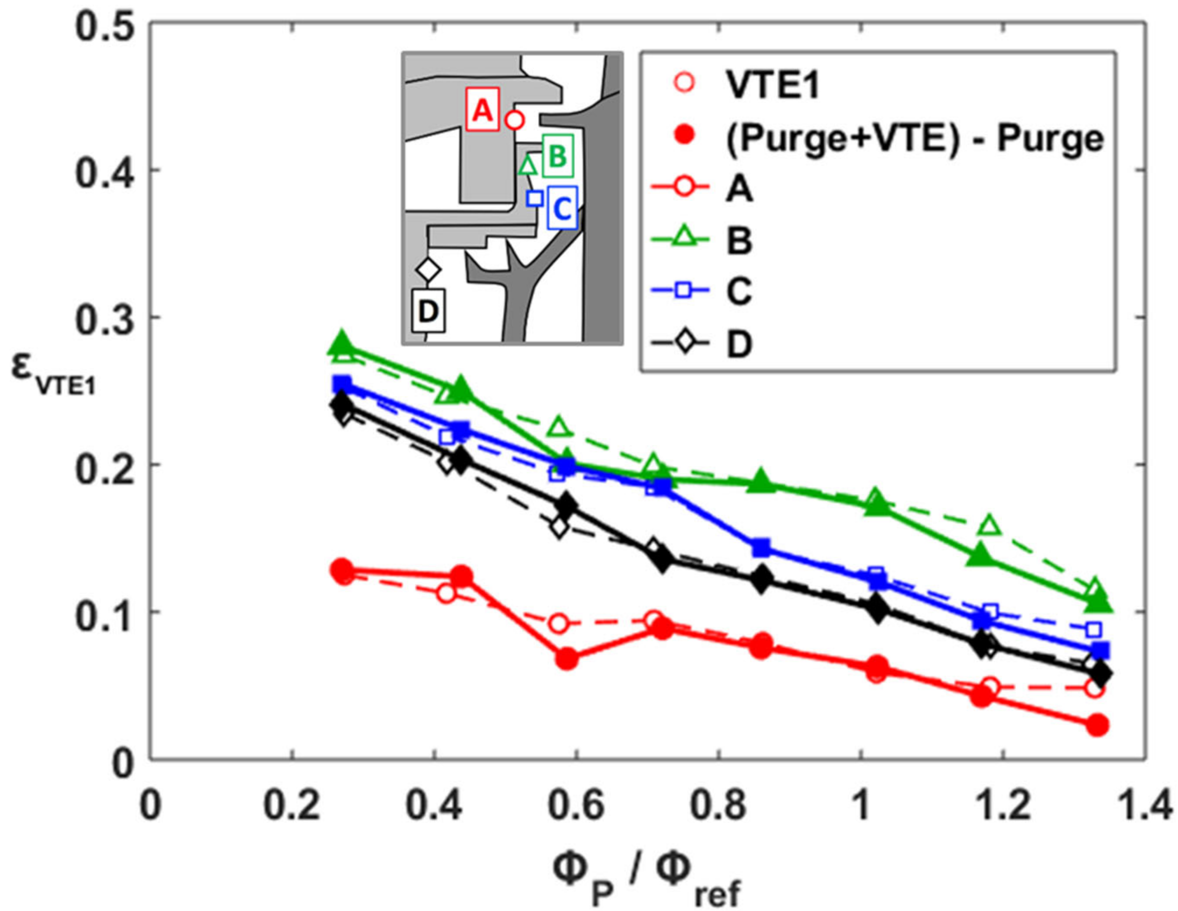
By holding the purge flow fixed while varying VTE flow, it was found that VTE influence in the wheelspace increased as VTE flow increased.

With VTE and purge, superposition predicted rim sealing effectiveness



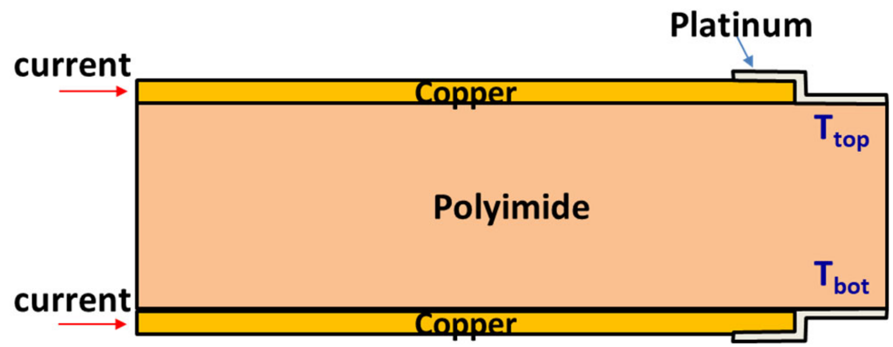


Superposition Results

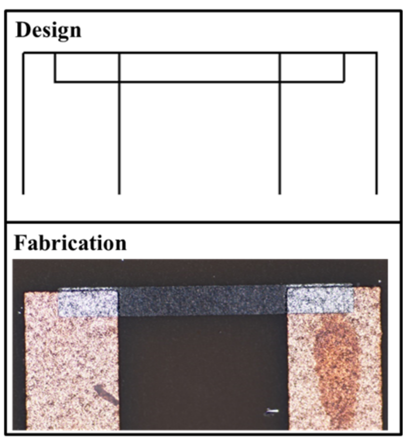


Elongated test times combine with elevated temperatures lead to instrumentation challenges in steady facilities

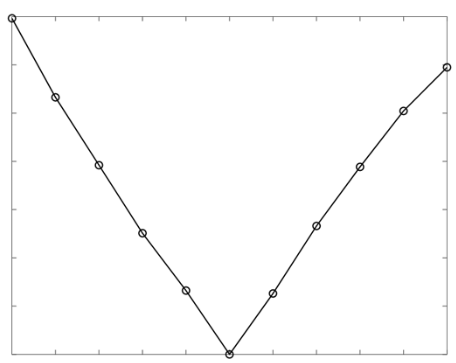
Facility	Length of Test [s]	Tests Per Day	Cumulative 20 year Test Time [hrs]
OSU TTF	0.120	3	0.730
MIT	0.200	3	1.217
Oxford OTRF	0.500	3	3.042
VKI	0.500	3	3.042
AFRL	2.500	3	15.208
Penn State	8 [hrs]		



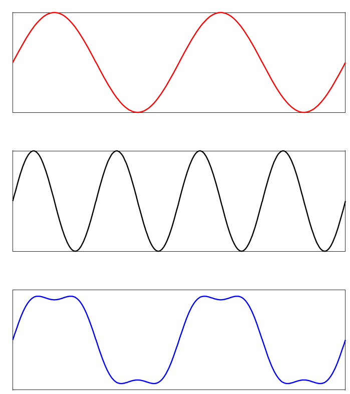
Fabrication



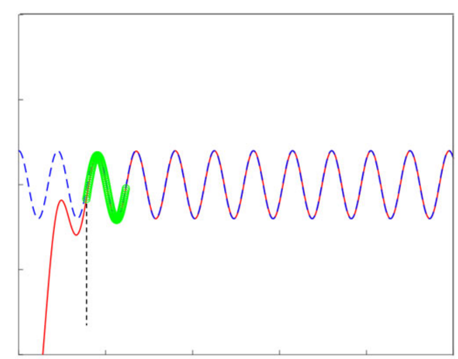
Thermal Property Determination



In-Situ Calibration

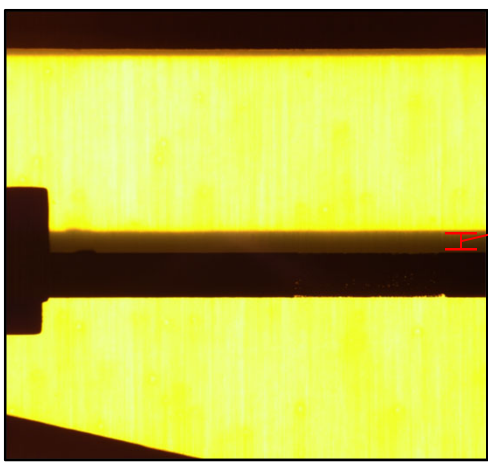


Post Processing Method



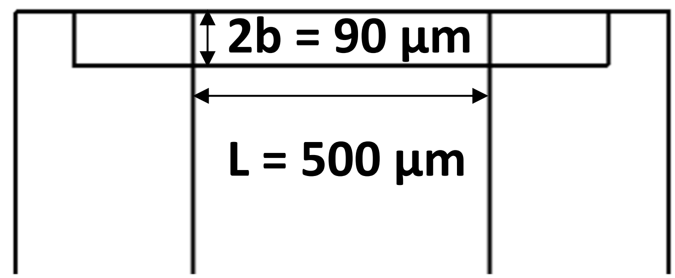
Must be modified for steady operation

Using the Penn State Nanofabrication Lab, thin film HFGs can be made to fine specifications

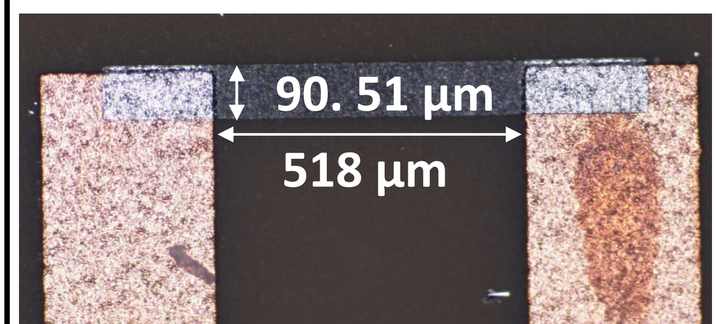


Alignment to within 5 µm

Design



Fabrication



Thermal property determination has been achieved over a range of temperatures, necessary for accurate results

Specific Heat

Direct Scanning Calorimetry

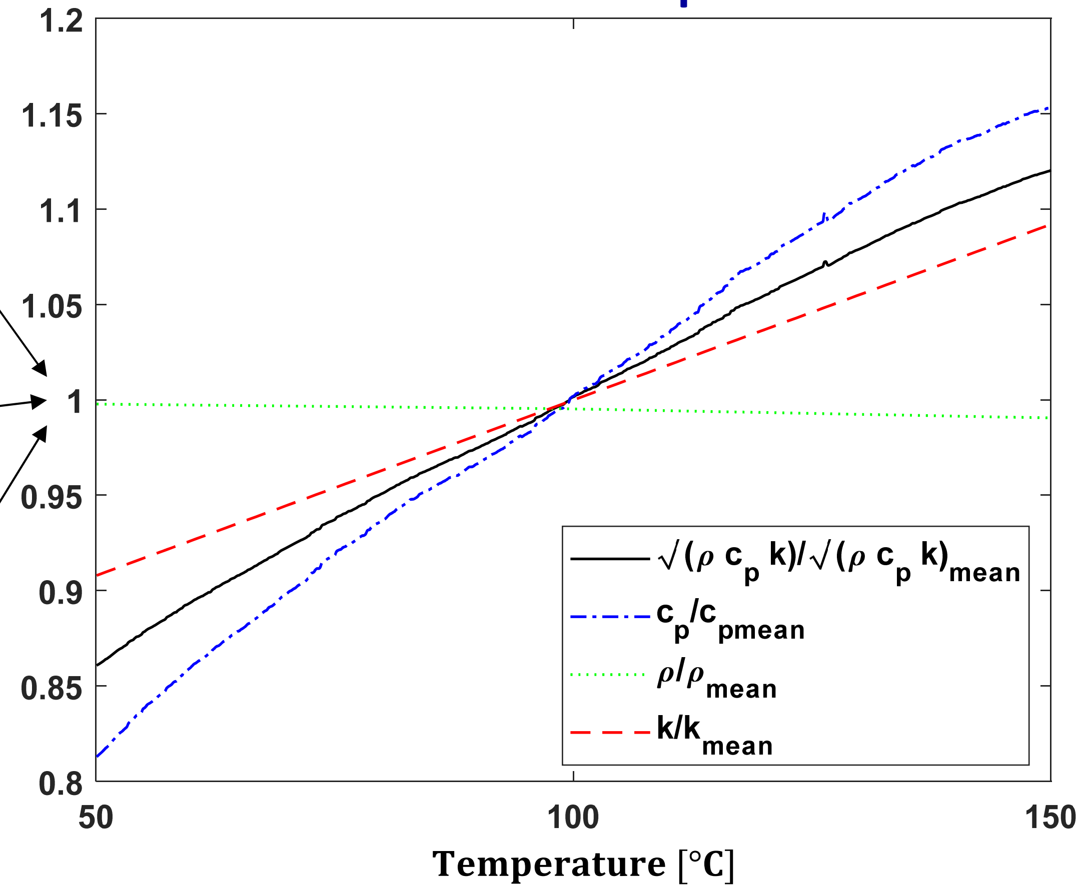
Density

Helium Pycnometry

Thermal Conductivity

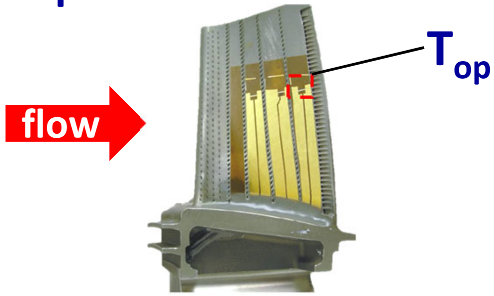
Transient Plane Source

Thermal Properties as a Function of Temperature

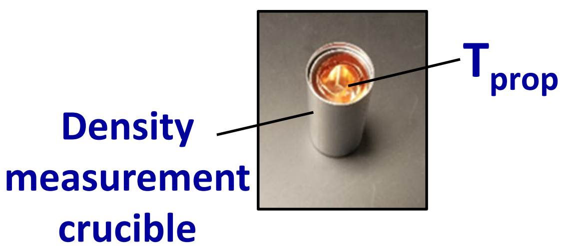


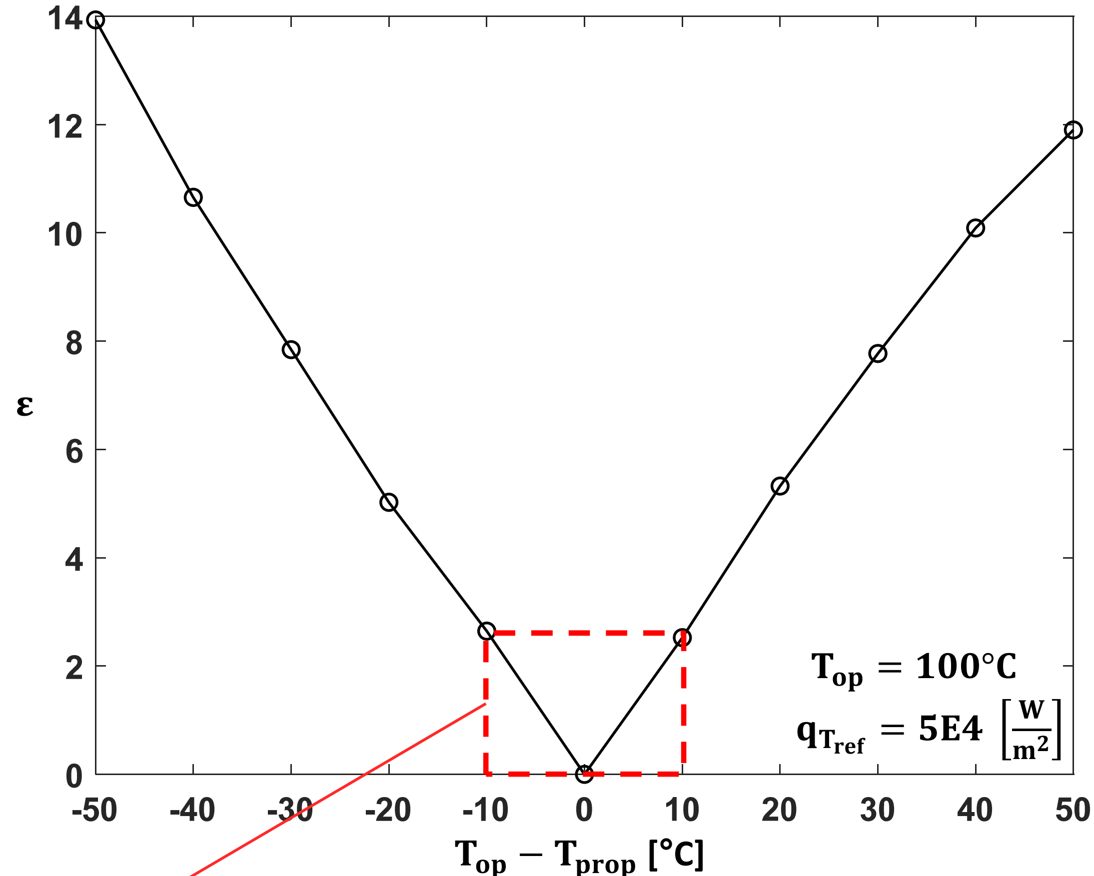
The experimental and property evaluation temperatures are not always equal, leading to errors in the measurement

Experimental Conditions



Property Evaluation Conditions

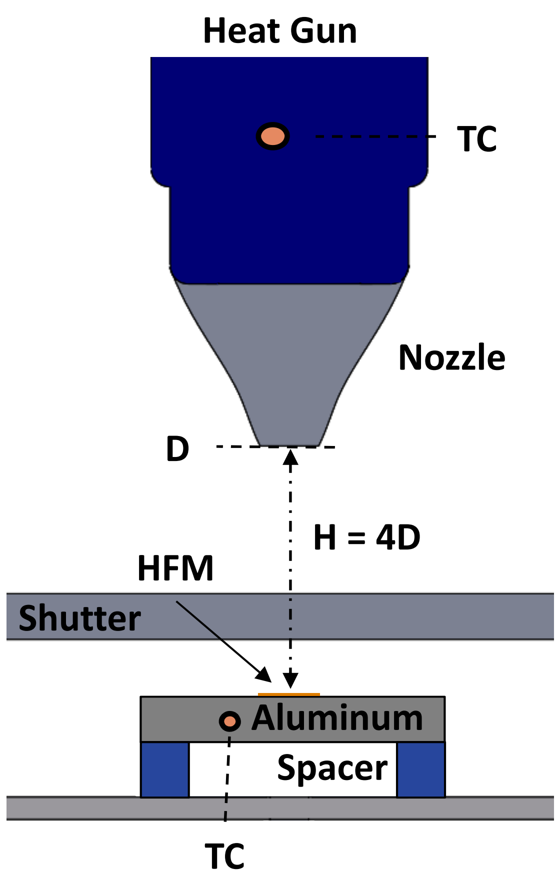


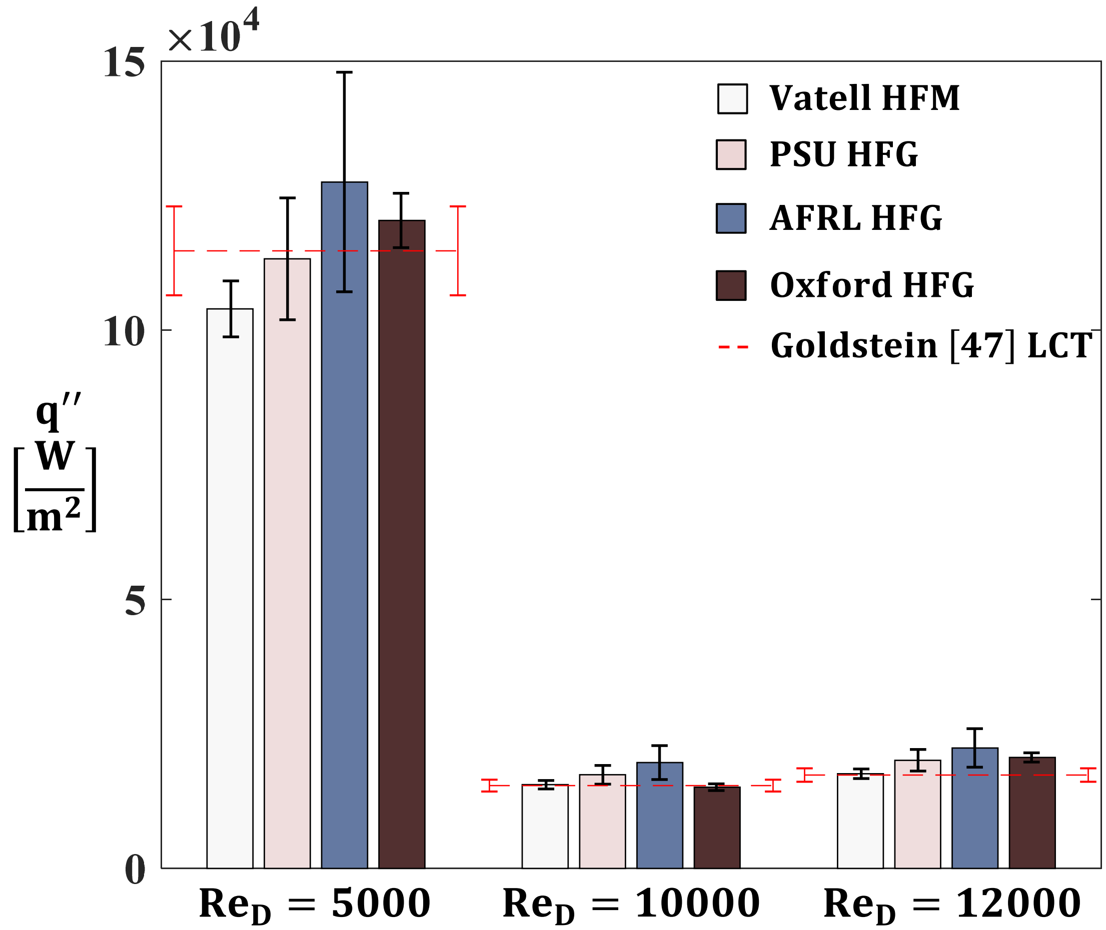


Error is 3% at 10°C Temperature Difference

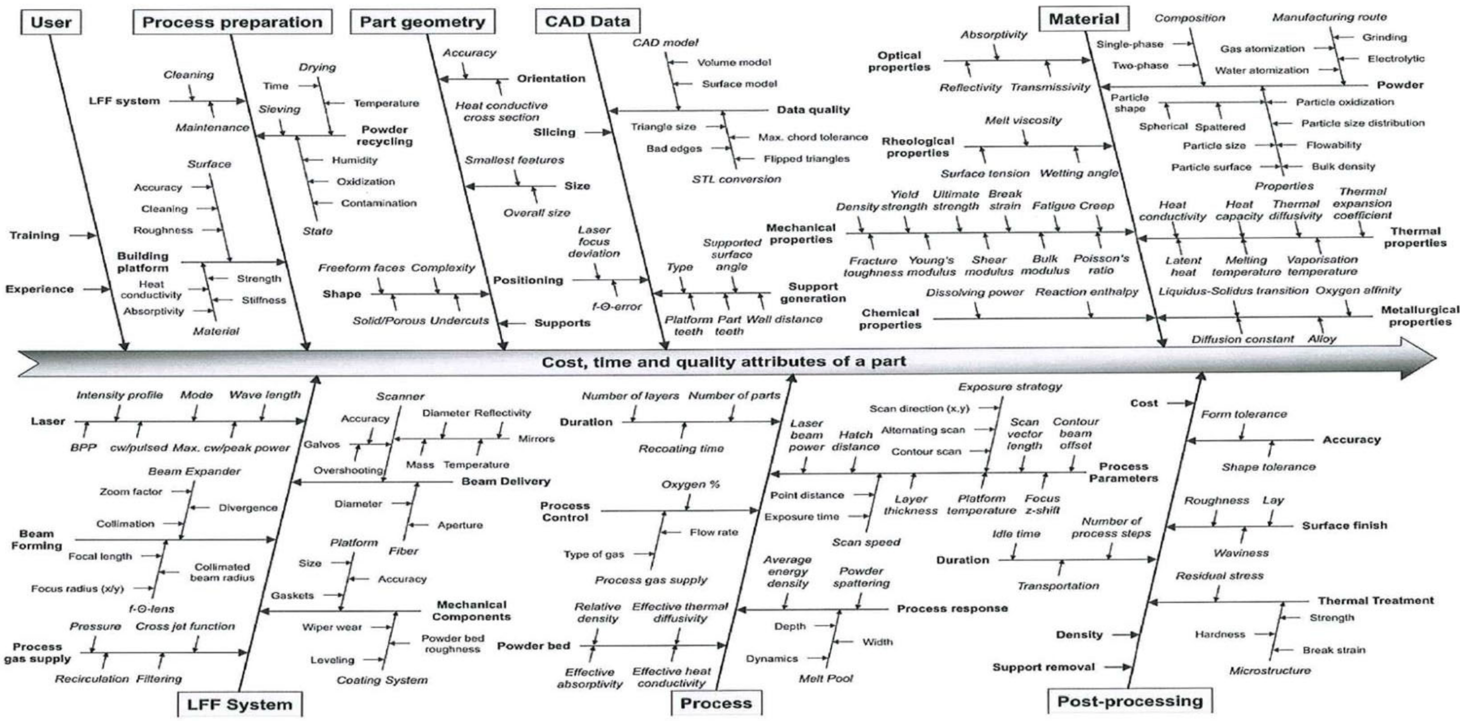
The results from an impinging jet show good agreement with sensors fabricated at different institutions

Experimental Set-up





Part quality is associated with build direction, laser power, machine, and powder variables—many choices to make



Laser Variables

- Power
- Scan Speed
- Spot size/focus
- Hatch spacing
- Beam offset
- Contouring

Machine Variables

- Material scaling
- Beam offset
- Recoater type
- Location on build plate
- Orientation on build plate
- Gas flow rate/direction

Powder Variables

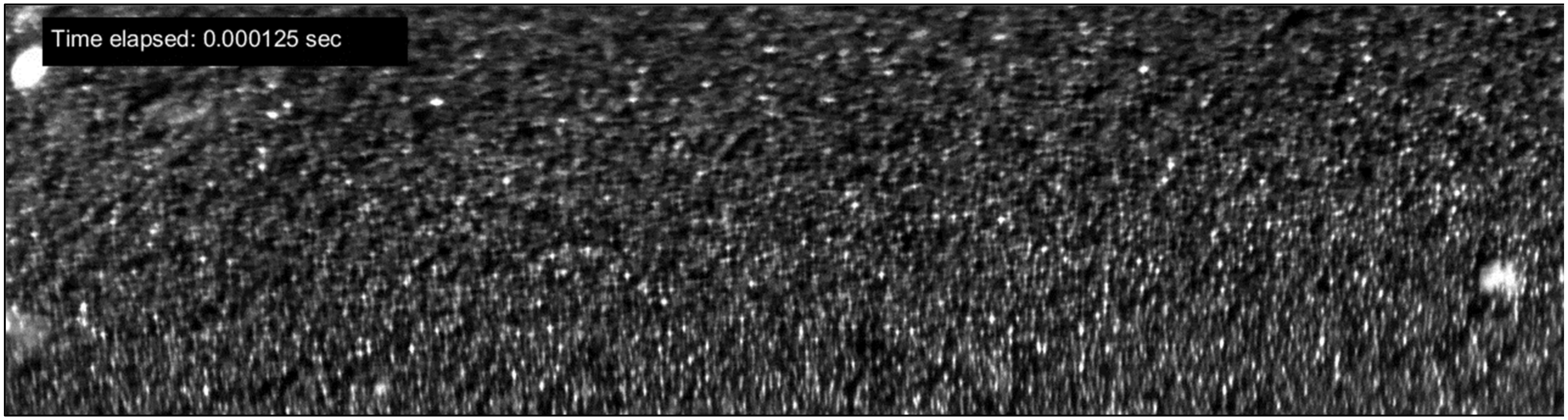
- Mean particle size
- Particle size distribution
- Powder compaction
- Powder reuse rate

Build Direction

Post-processing

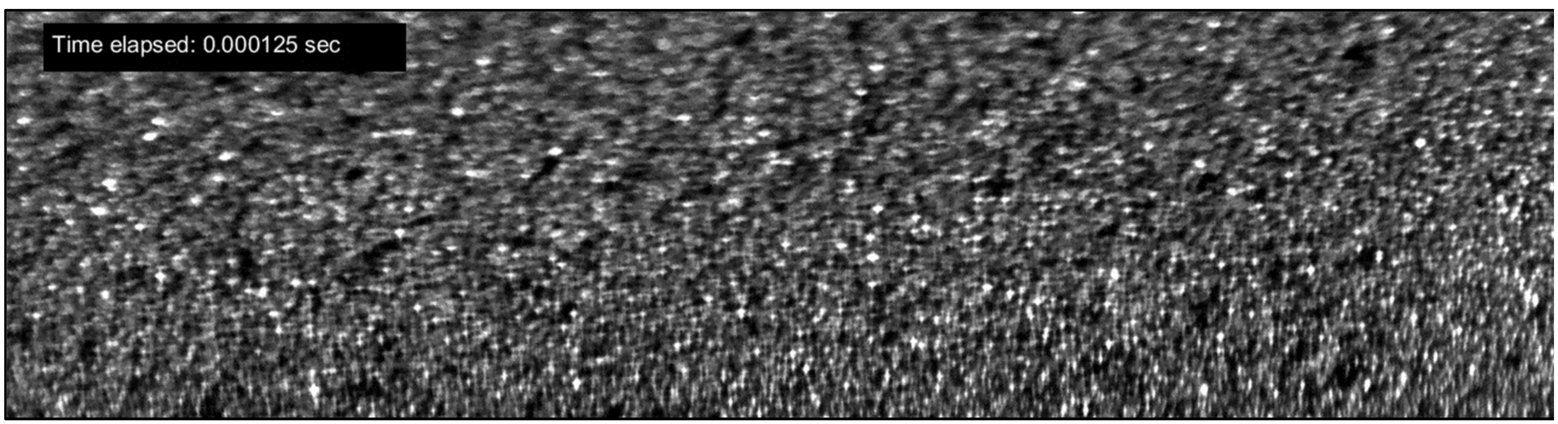
Slow Scanning Speed, Low Power

Stable melt pool, neighboring powder entrained



High Scanning Speed, High Power

Unstable melt pool, neighboring powder repelled



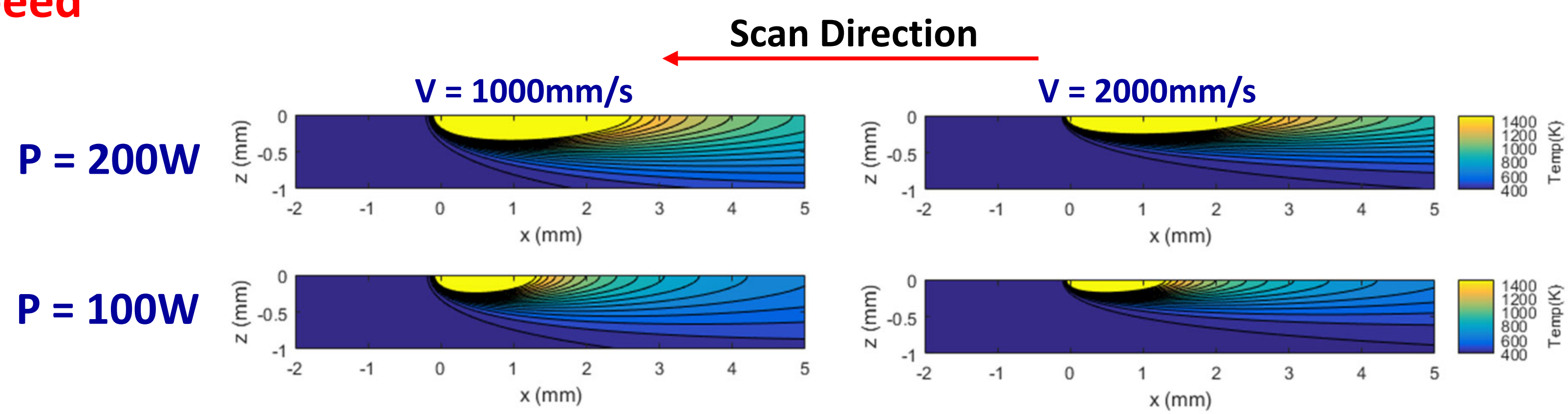
[Bidare et al. 2018]

The laser power and scanning speed as well as scan strategy were investigated

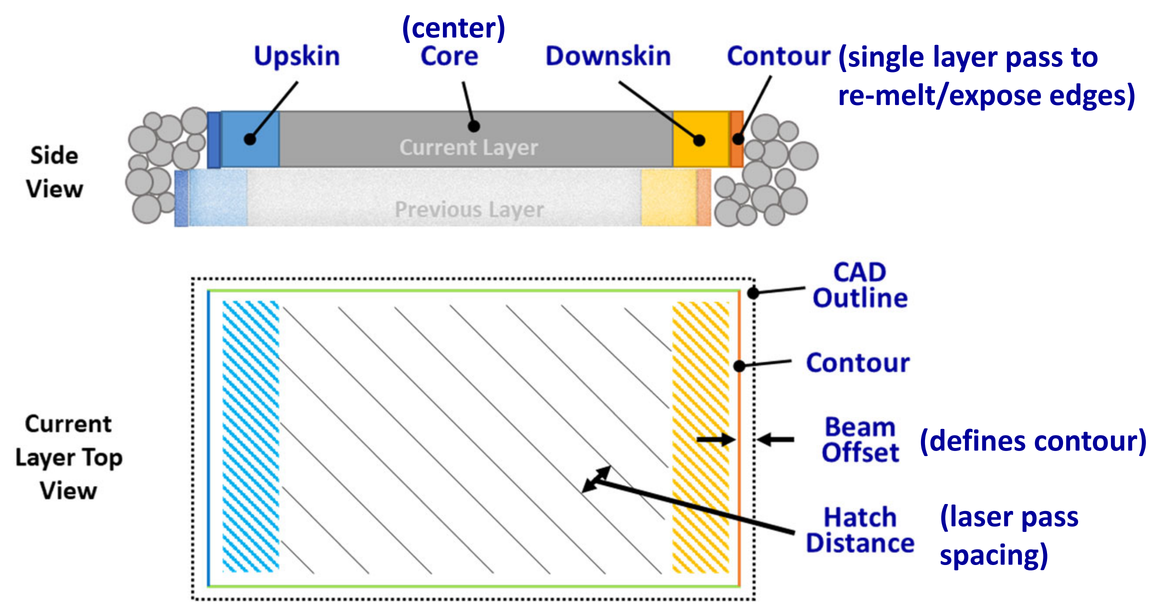
Power

Scan Speed

$$LHI = \frac{\text{Laser Power}}{\text{Scan Speed}}$$

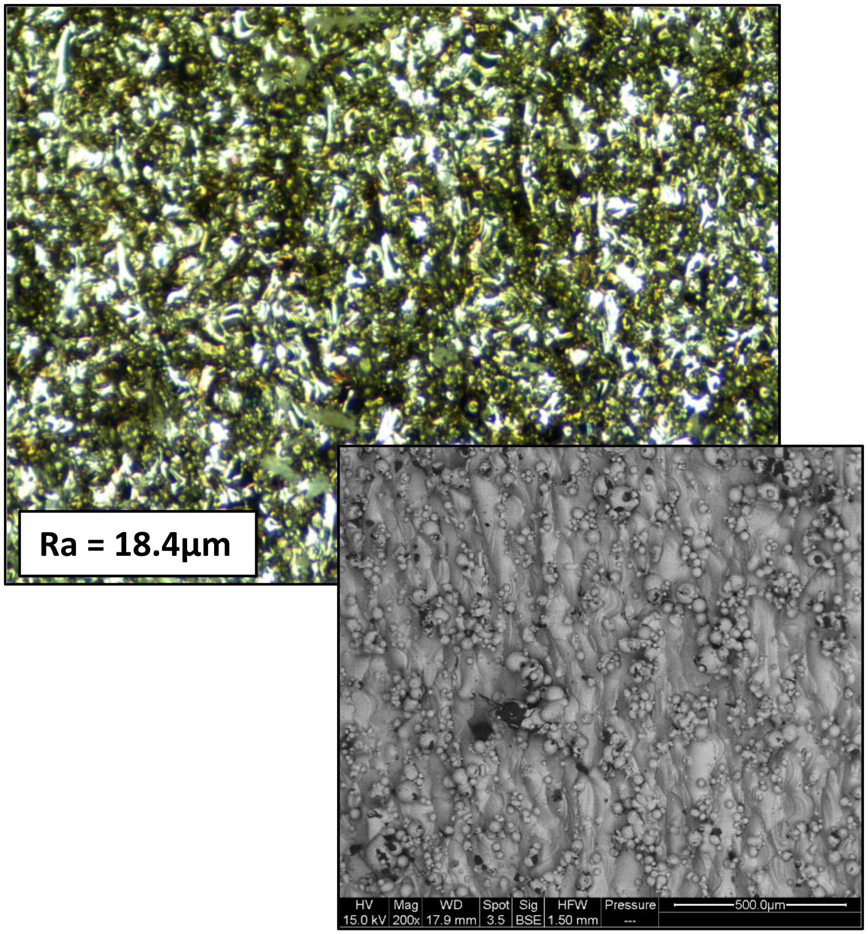


Scan Strategy

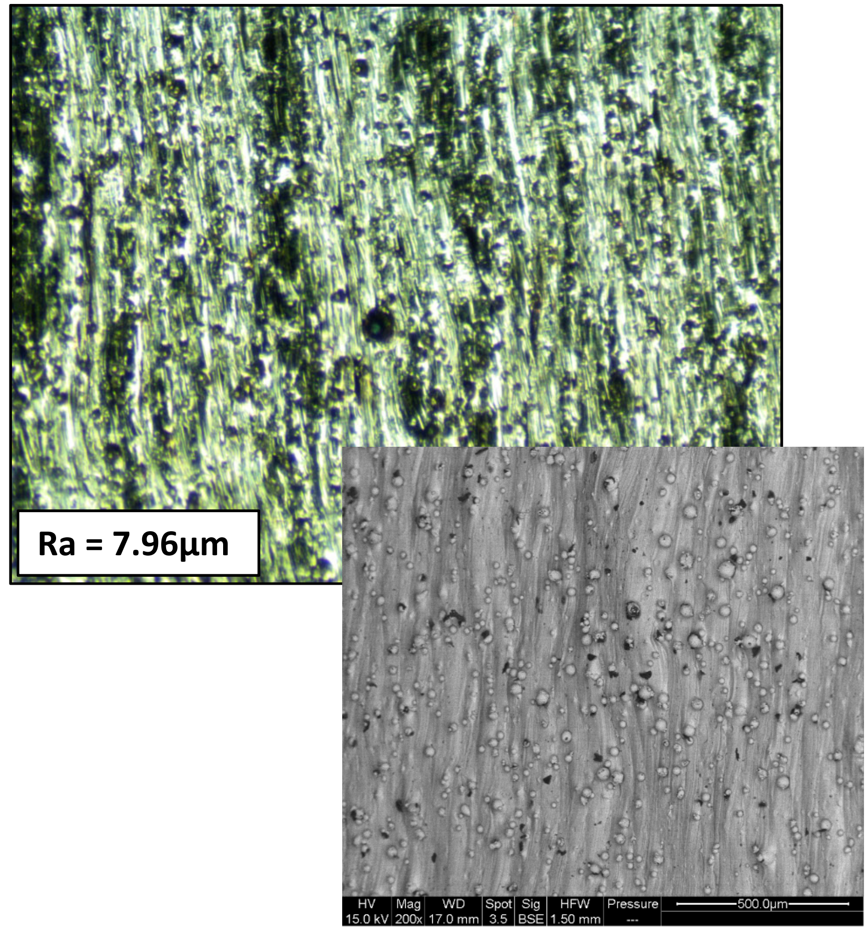


Adding a contour scan significantly decreases roughness to an upskin

LHI = 0.13 J/mm

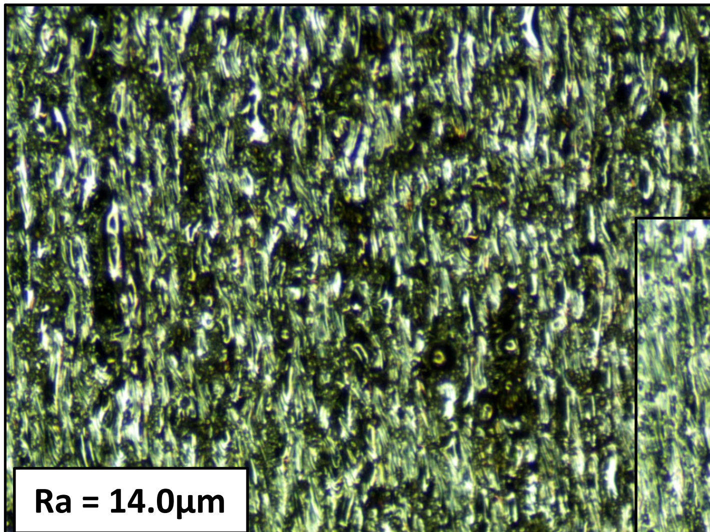


LHI = 0.13 J/mm + Contour LHI = 0.33 J/mm

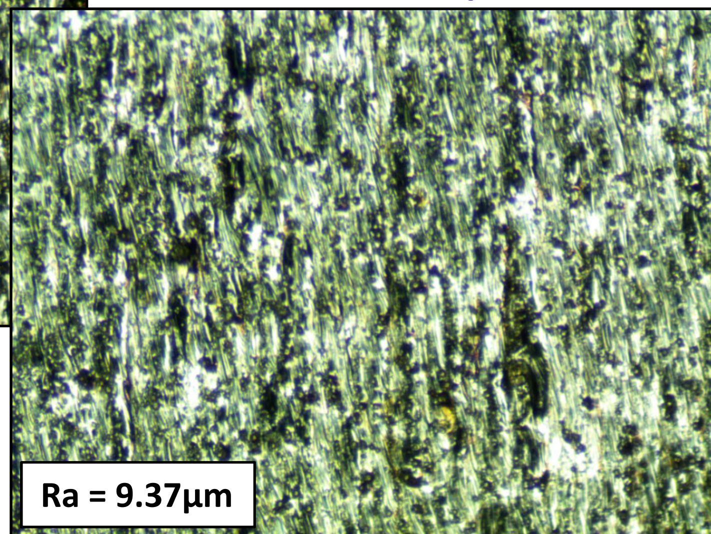


Increasing contour laser power to scan speed ratios decrease surface roughness

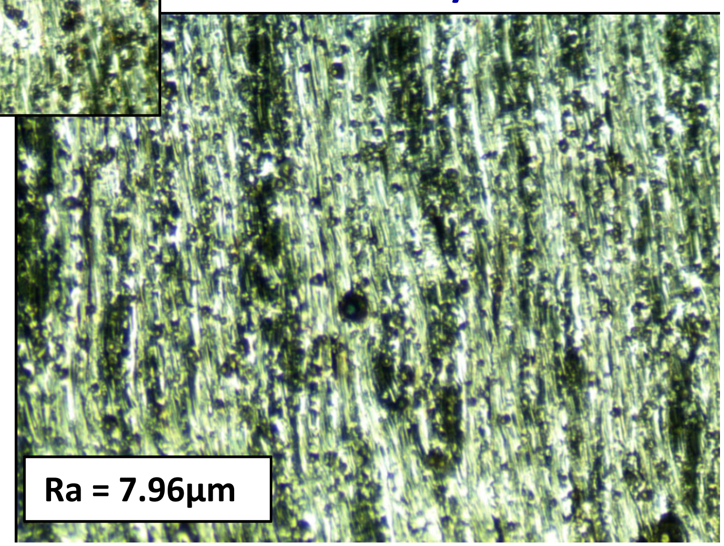
LHI = 0.13 J/mm



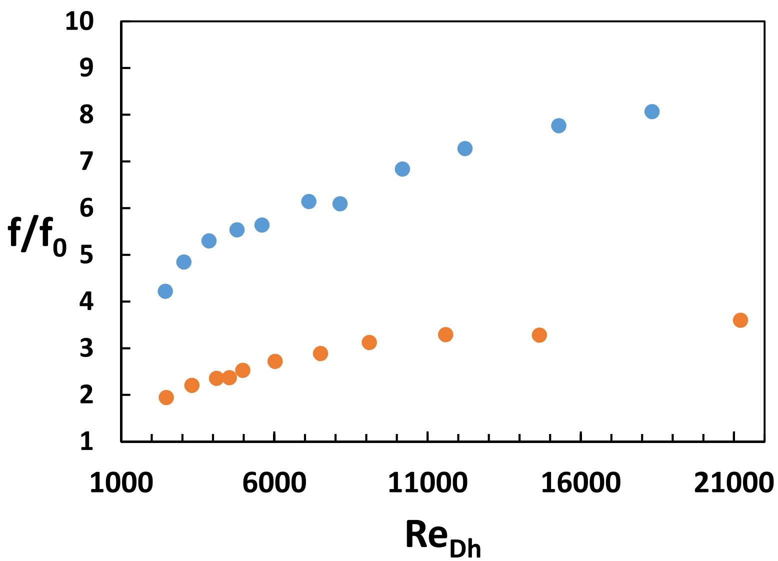
LHI = 0.26 J/mm



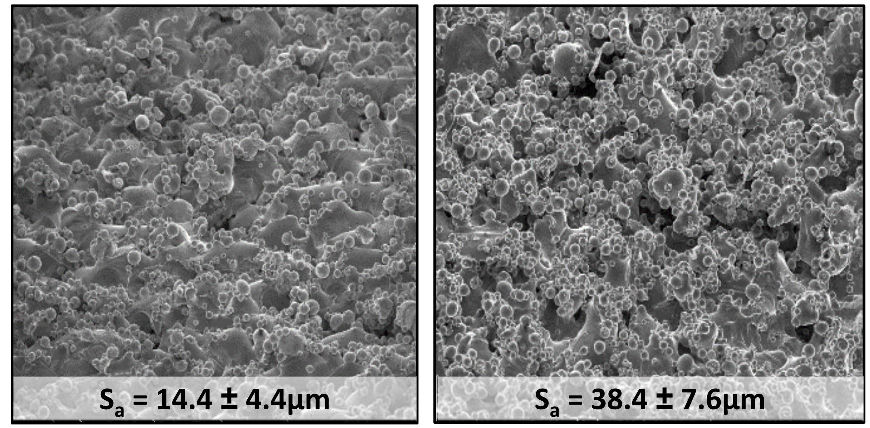
LHI = 0.33 J/mm

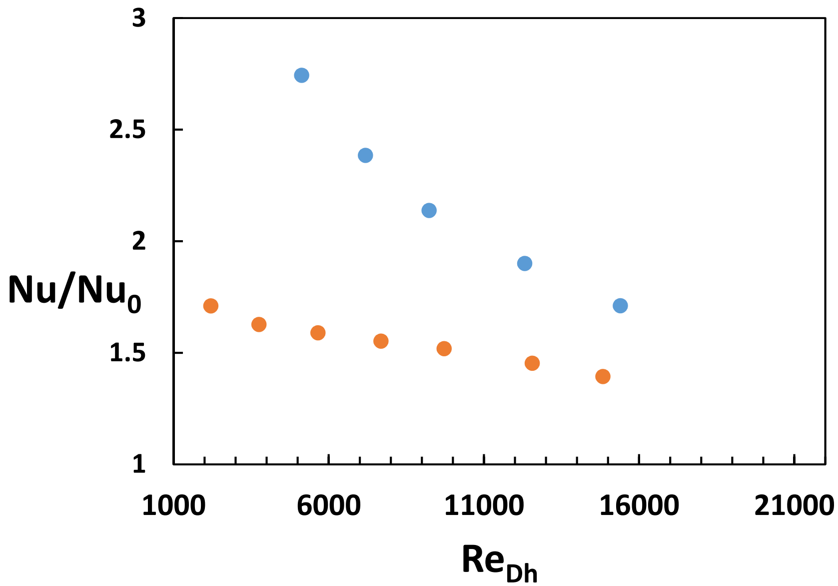


As contouring is added, a dramatic effect results in microchannel performance

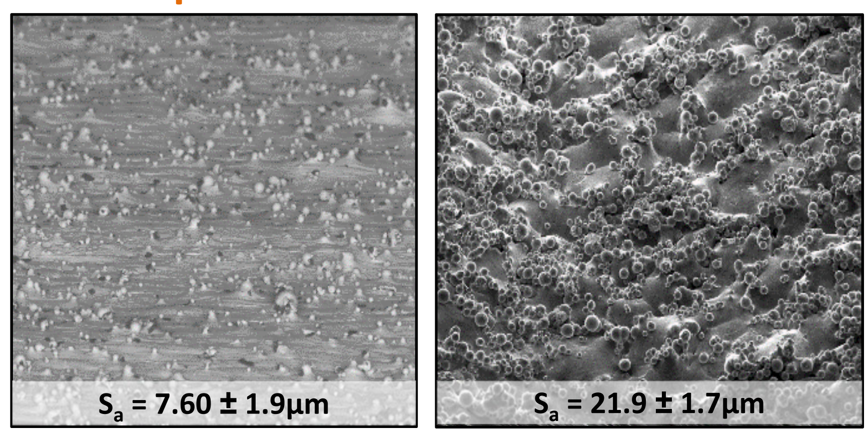


Upskin Downskin

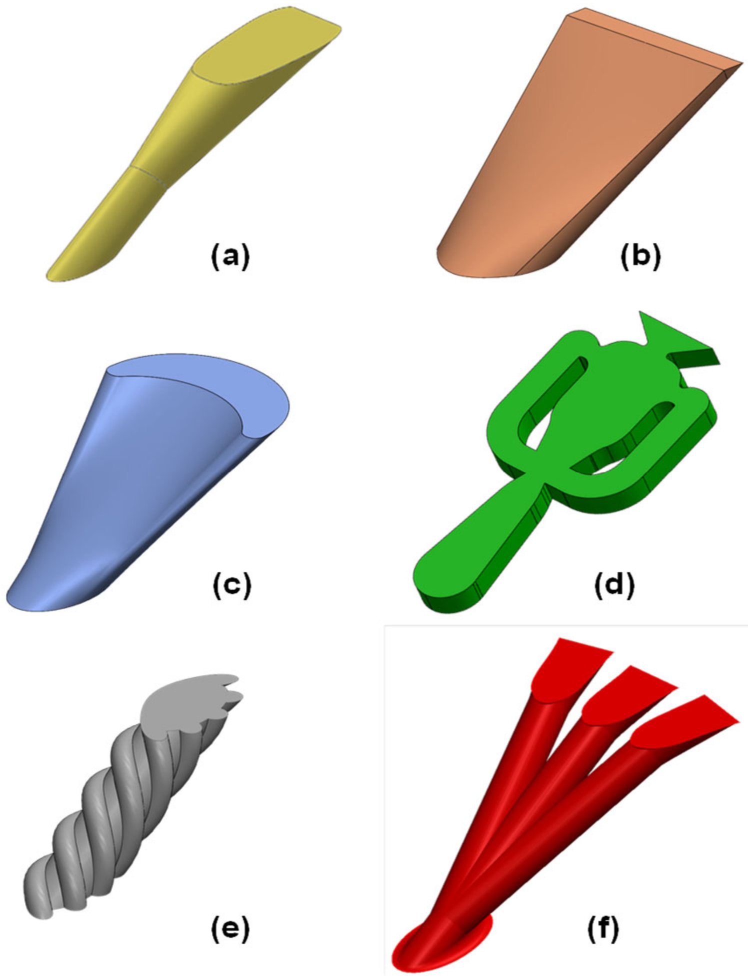


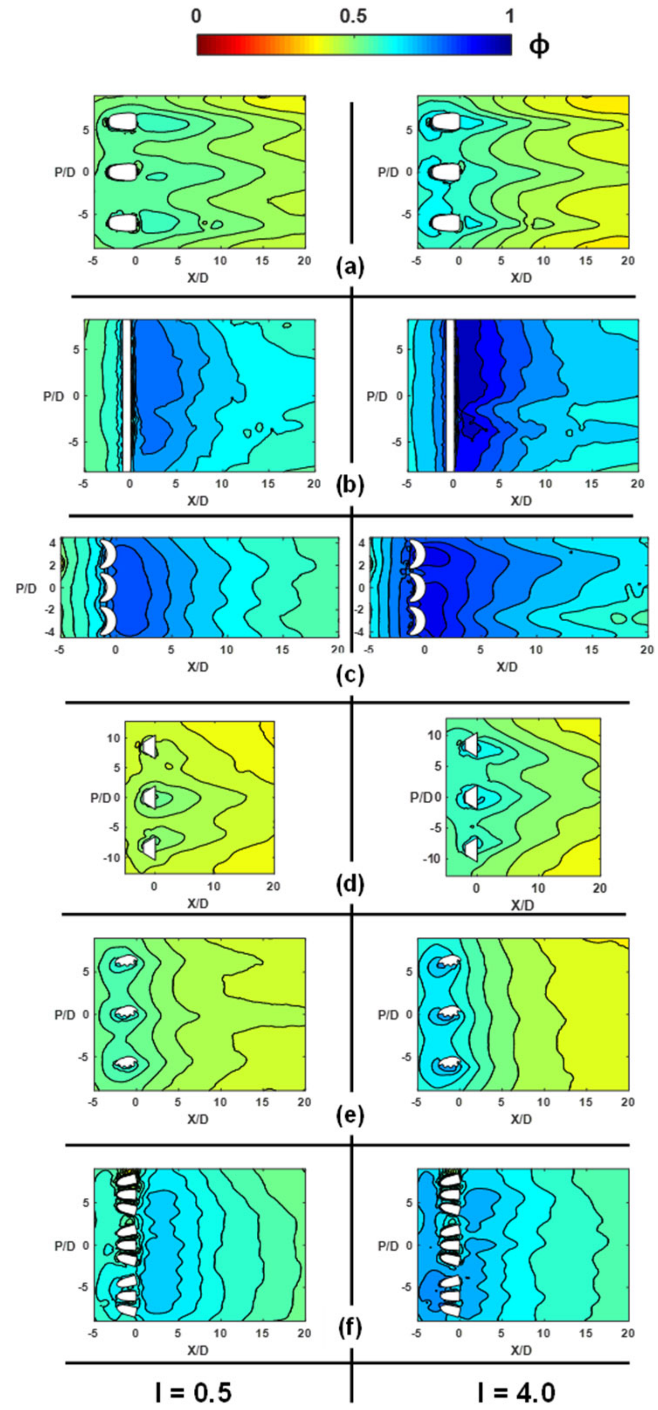


Upskin Downskin



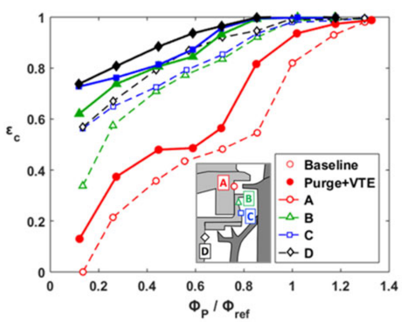
In-progress is overall effectiveness comparisons of AM public film holes



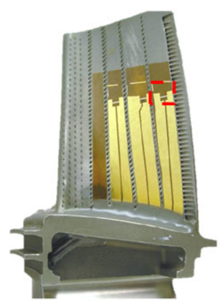


This past year's work identified several key findings and progress towards studying the cooled blades

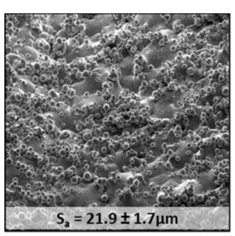
Cooled blade designs have been completed and now need to be manufactured



Vane Trailing Edge flow has a positive effect on the overall rim sealing effectiveness



Heat flux gages for use in a steady facility have been evaluated.



Additive manufacturing process parameters have promise in altering surface roughness.

QUESTIONS