# Cooling Strategies for Vane Leading Edges in a Syngas Environment Including Effects of Deposition and Turbulence

UTSR Workshop – Aerodynamics/Heat Transfer Breakout

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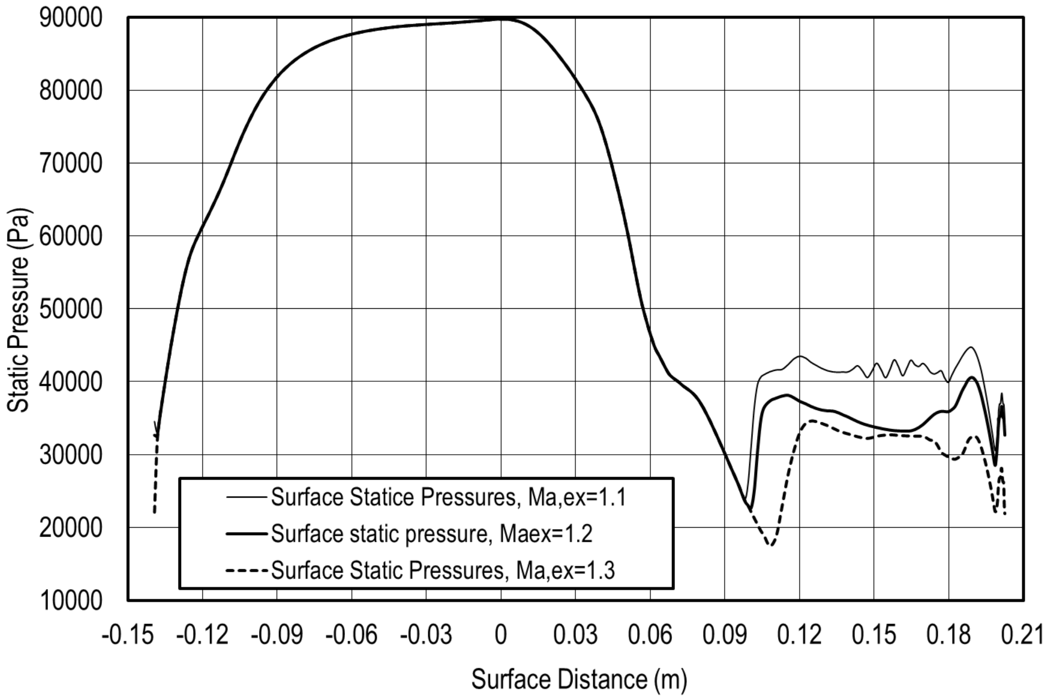
# Motivation and Conceptual Approach

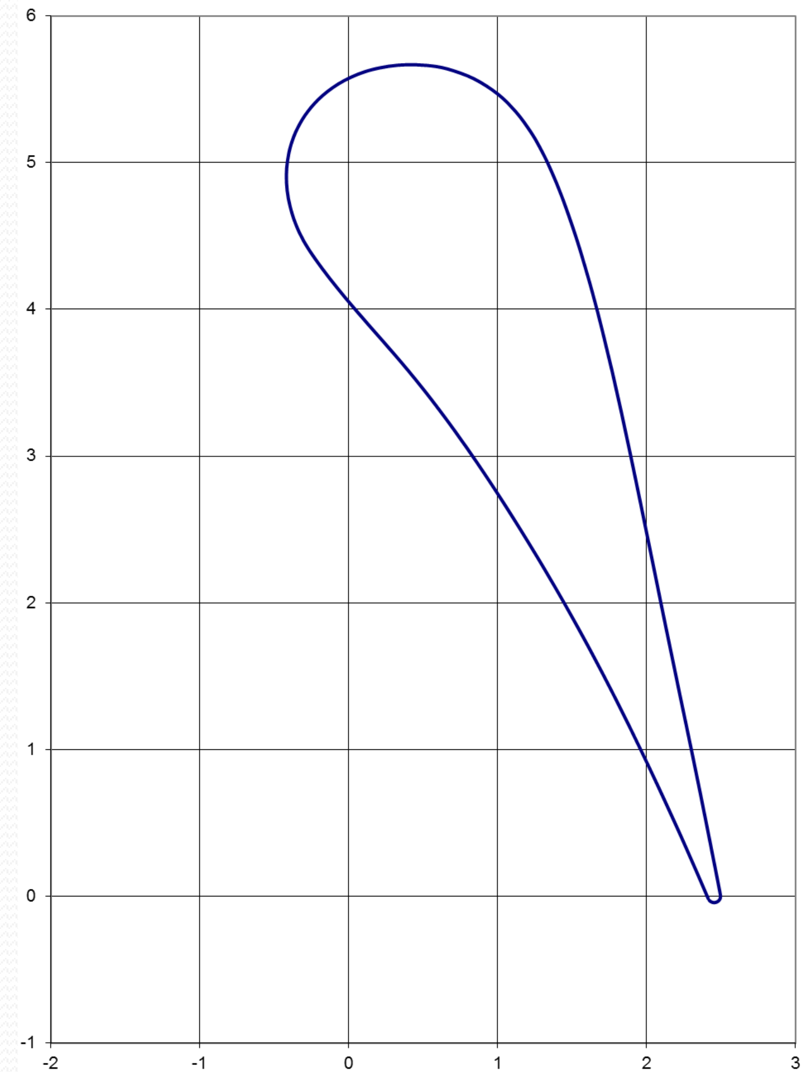
- Land based gas turbines for IGCC cycles run at high Reynolds numbers and often see very high inlet turbulence levels from combustion systems
- Increasing the leading edge diameter can significantly reduce leading edge heat transfer levels which can allow internal cooling methods in combination with TBC rather than less efficient showerhead cooling.
- The combination of high turbulence and large leading edge Reynolds numbers require improved understanding of heat transfer mechanisms.
- Ideal internal cooling systems maximize thermal cooling potential of air then discharge spent air onto surfaces on lower velocity regions (before throat) in a full coverage film.
- Leading edge regions in IGCC cycles have the potential to experience deposition causing roughness which can lead to early transition and possibly increase stagnation region heat transfer in some cases.
- Deposition may possibly lead to clogging of coolant holes and the combination of realistic roughness and turbulence has an adverse affect on film cooling effectiveness

Vanes with larger diameter leading edge regions will not only have lower heat transfer levels but they will also have larger regions where the surface static pressure is high. This means that internal cooling methods ideally will need to cool significant surface arc around the leading edge without discharge.

Downstream regions should be protected from deposition buildup to ensure the passage throat area and geometry are preserved.

Testing at OSU will look at the potential for full coverage film cooling to protect downstream pressure surfaces from deposition buildup.



# *Key Ongoing Experimental Tasks*

- Assessing the response of high intensity turbulence to large stagnation regions.
- Investigation of stagnation region boundary layer development with high intensity turbulence.
- Internal cooling approaches for large radius stagnation regions.
- Investigation of the influence of high intensity turbulence on full coverage film cooling effectiveness and downstream heat transfer.

# *Future Experimental Tasks*

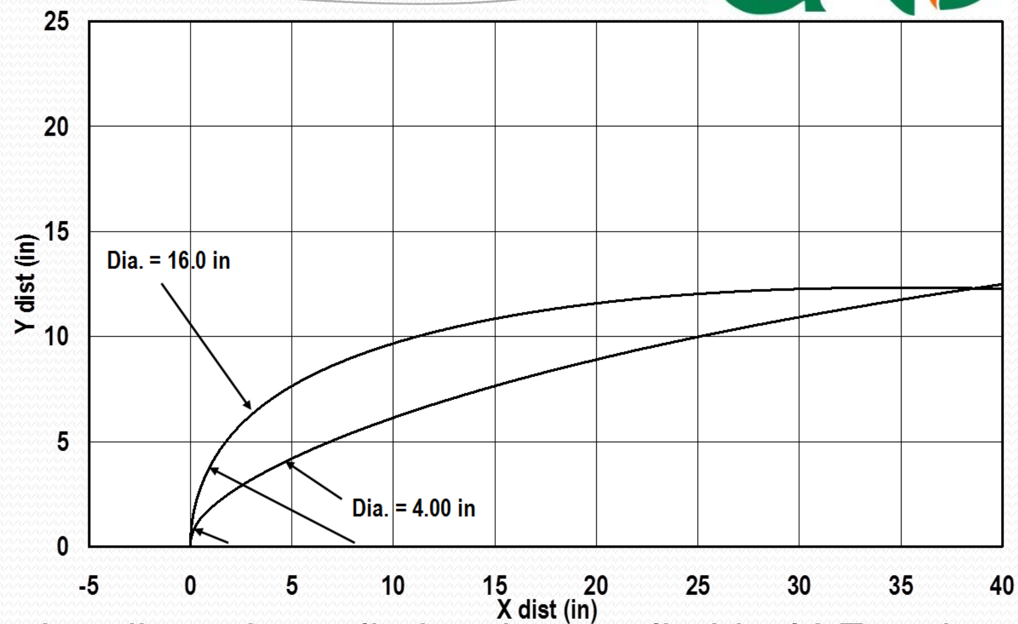
- Assessing the combined response of realistic roughness and high intensity turbulence on large stagnation region heat transfer.
- Investigation of stagnation region boundary layer development with realistic roughness and high intensity turbulence.
- Investigation of the influence of realistic roughness and high intensity turbulence on full coverage film cooling effectiveness and downstream heat transfer.

# *Research Approach for Internal Cooling*

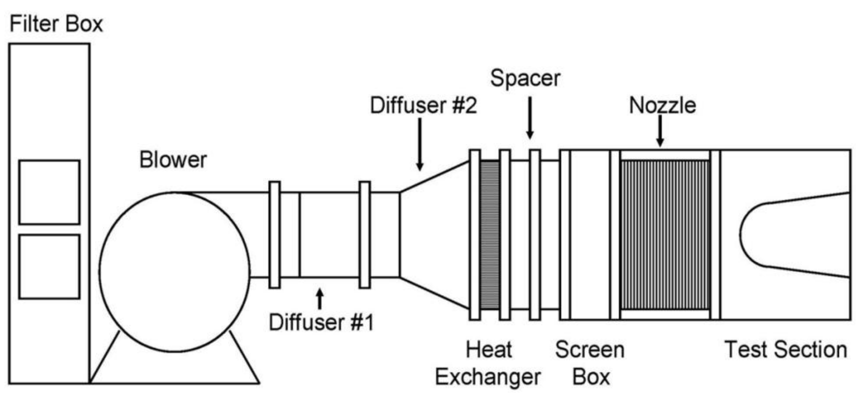
- Development of high solidity internal cooling arrays with cooling air renewal.
- Screening of internal cooling geometries using RANS calculations
- Design of high solidity internal cooling geometries with cooling air renewal for heat transfer tests.
  - **Row by row thermal isolation of rows**
  - **Heating and instrumentation approach**
- Renovation of bench scale internal cooling rig.
- Constant temperature testing of internal cooling.
- Assessment of the potential of internal cooling methods for cooling enhanced diameter leading edge regions of vanes, with and without the help of TBCs.

# Heat transfer and film cooling measurements using UND's big cylinder rig.

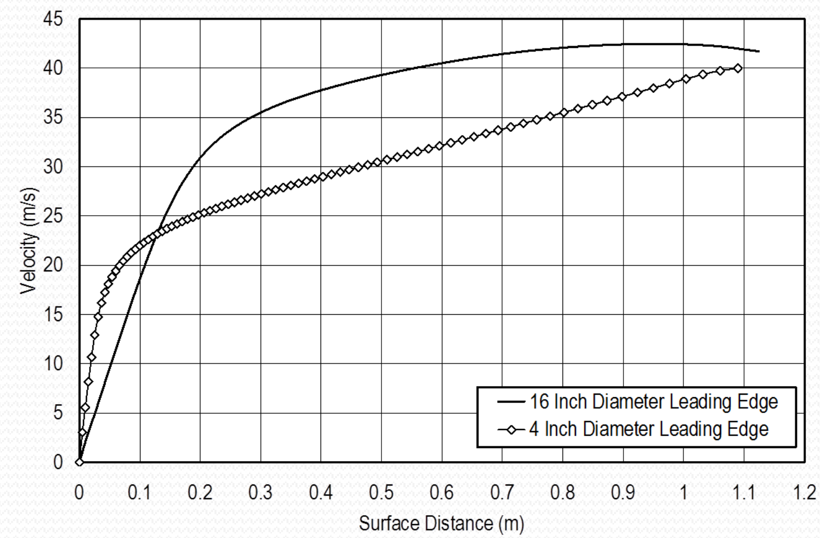
The general approach to investigate leading edge heat transfer and downstream film cooling is to develop leading edge cylinders with a constant radius stagnation regions and an accelerating flow downstream. Leading edge regions of 10.16 cm and 40.64 cm diameters were developed. The downsteam afterbodies were designed to provide a continued acceleration.




Leading edge cylinders have cylindrical LE regions




UND's large scale turbine vane cascade wind tunnel is used with large cylinder test section.

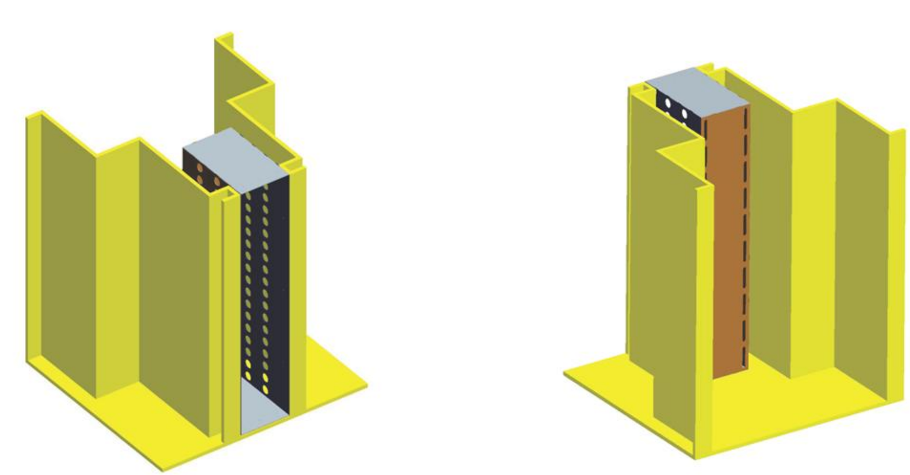


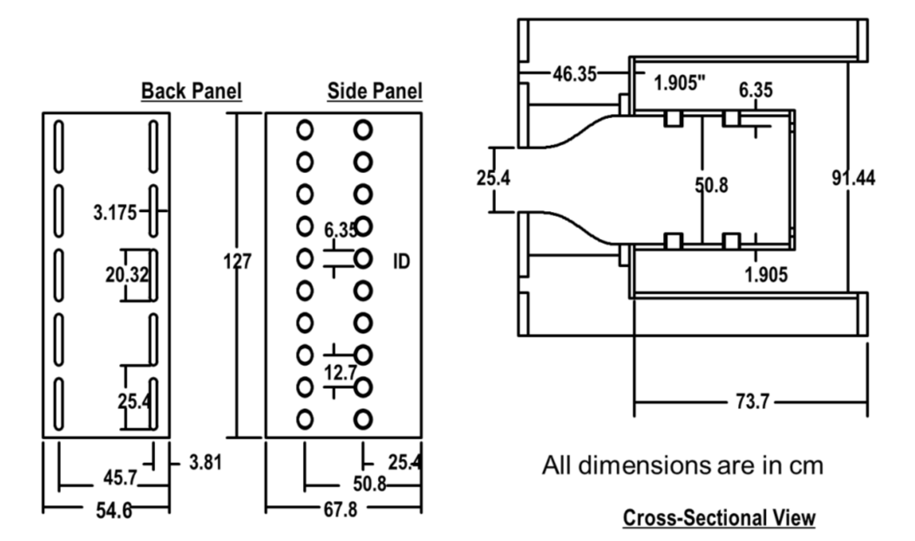

Afterbodies shaped to provide accelerating flow

A range of turbulence conditions are being generated for the heat transfer and film cooling study. These conditions include a low turbulence condition, three grid generated turbulence conditions and three aerocombustor turbulence conditions.

Grid turbulence are being generated with a small and a large grid. Both grids are positioned 10 mesh lengths upstream from the cylinder leading edge. The small grid is also positioned about 30 mesh lengths upstream to produce a lower level turbulence.

Aero-combustor turbulence is being generated with the existing mock combustor which has a 2 to 1 contraction nozzle. A second level is being generated using this mock combustor with a decay spool. A third level will be generated with a new smaller mock combustor with no contraction.



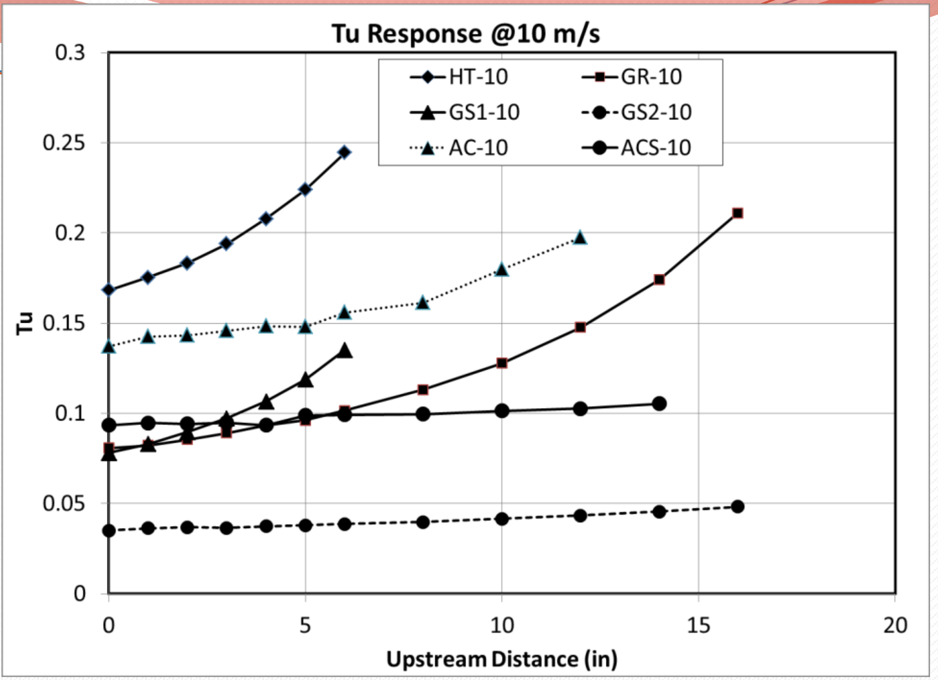


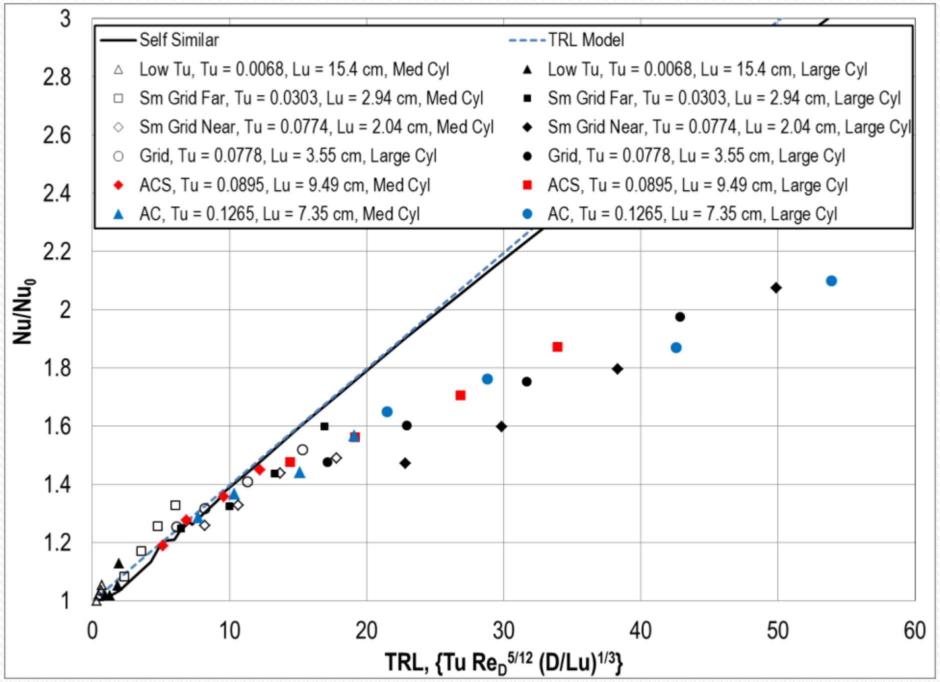

| Turb. System | Tu | Lu (cm) |
|---|---|---|
| New Aero Comb. | 0.1686 | 4.34 |
| Grid, M = 6.35 cm | 0.0815 | 3.25 |
| Grid, M = 3.125 cm | 0.0794 | 1.87 |
| Grid, Sm, Far | 0.0361 | 3.30 |
| Aero Comb. | 0.1425 | 6.80 |
| Aero Comb. w/Spl | 0.0953 | 9.37 |

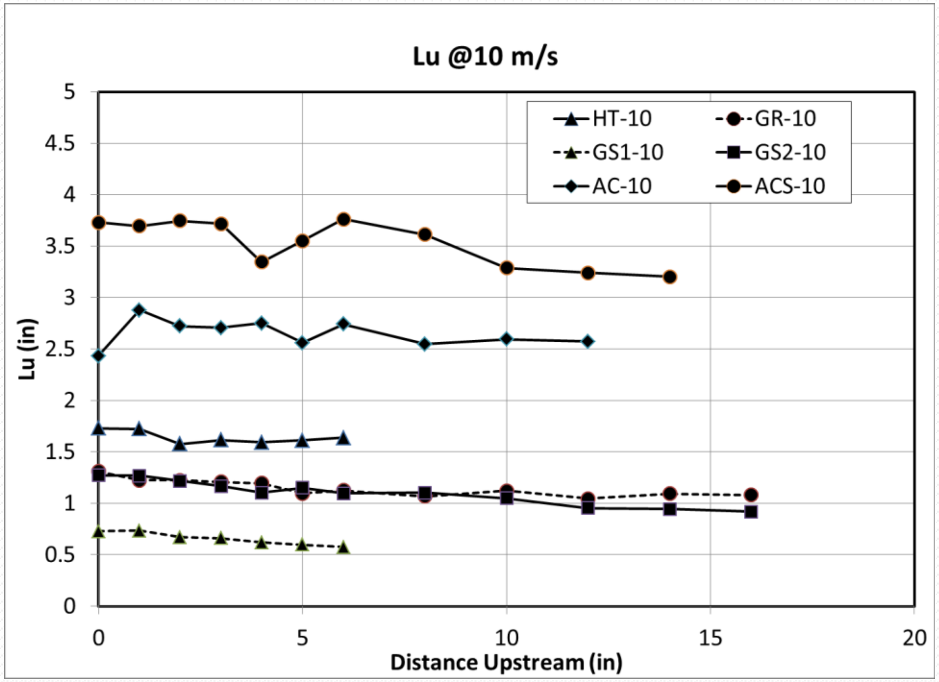
Initial stagnation region heat transfer data from UND’s Large Cylinder Rig show new trends compared with conventional studies. These trends need to be studied to understand how turbulence responds in the presence of these large cylinders

Initially, the decay of turbulence without the cylinders present has been studied.

We expect to begin investigating the response with the cylinders in place.

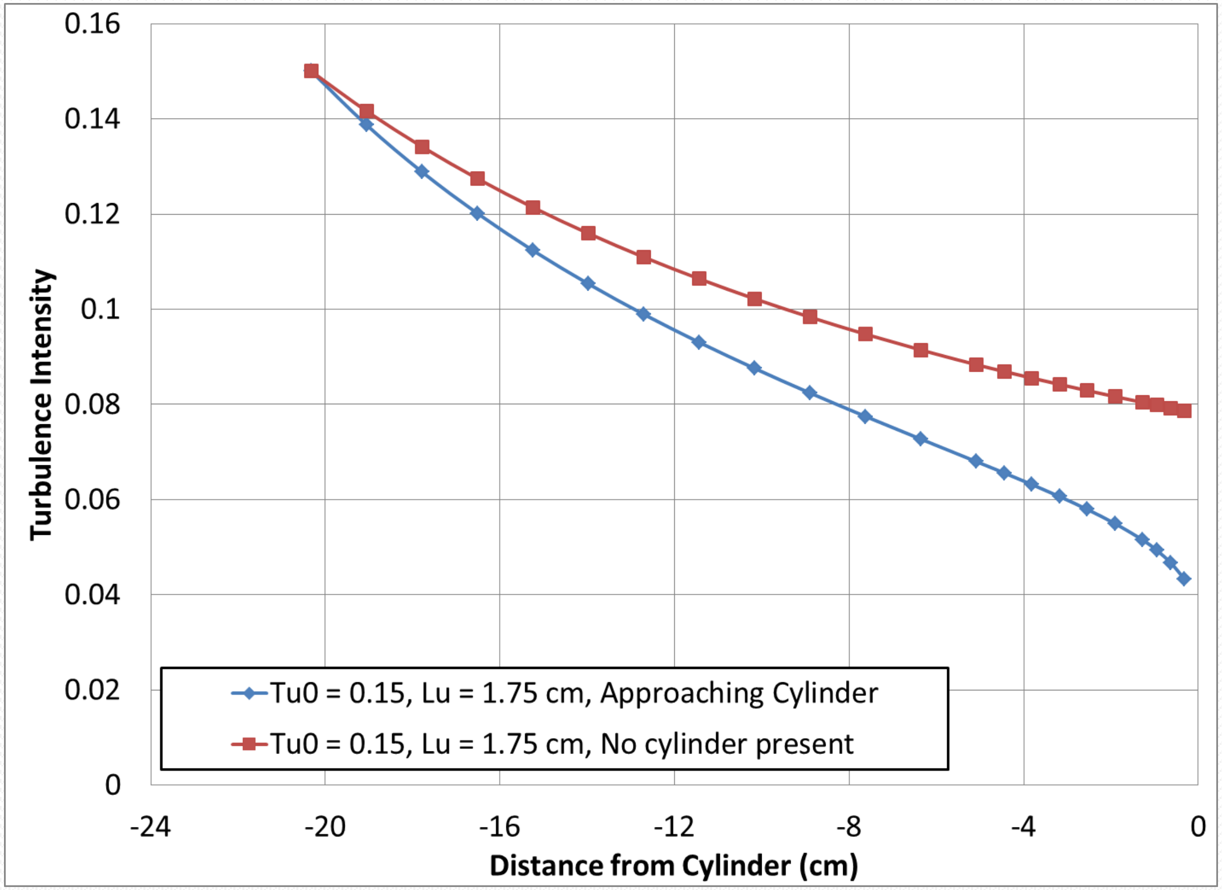


# Small Scale Turbulence Decay in the Presence of the Large Cylindrical Leading Edge

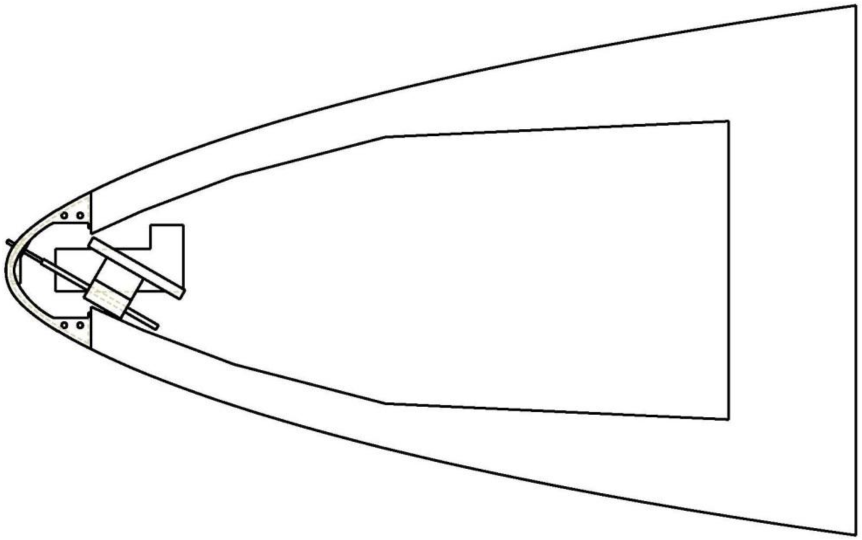
One issue in trying to correlate the influence of turbulence is related to turbulence decay particularly in the presence of the large diameter leading edge cylinder.  The large cylinder significantly increases the convection time for the flow approaching the stagnation region. For relatively small scale turbulence this can make a significant difference in the level of turbulent kinetic energy convected into the boundary layer.



# Turbulence response measurements in the vicinity of the stagnation region and boundary layer measurements

**The intensification of turbulence in the vicinity of a stagnation region has previously been documented. However, turbulence seems to be unaffected along the pressure surface of a vane where the strain rate is smaller. Recent heat transfer measurements have suggested that turbulence may not be significantly intensified in the presence of large stagnation regions, which are becoming a more popular design for first vanes. Current work is focused on documenting the response of turbulence to large leading edge regions. We are also integrating a traversing system into our large cylinders to investigate boundary layers.**

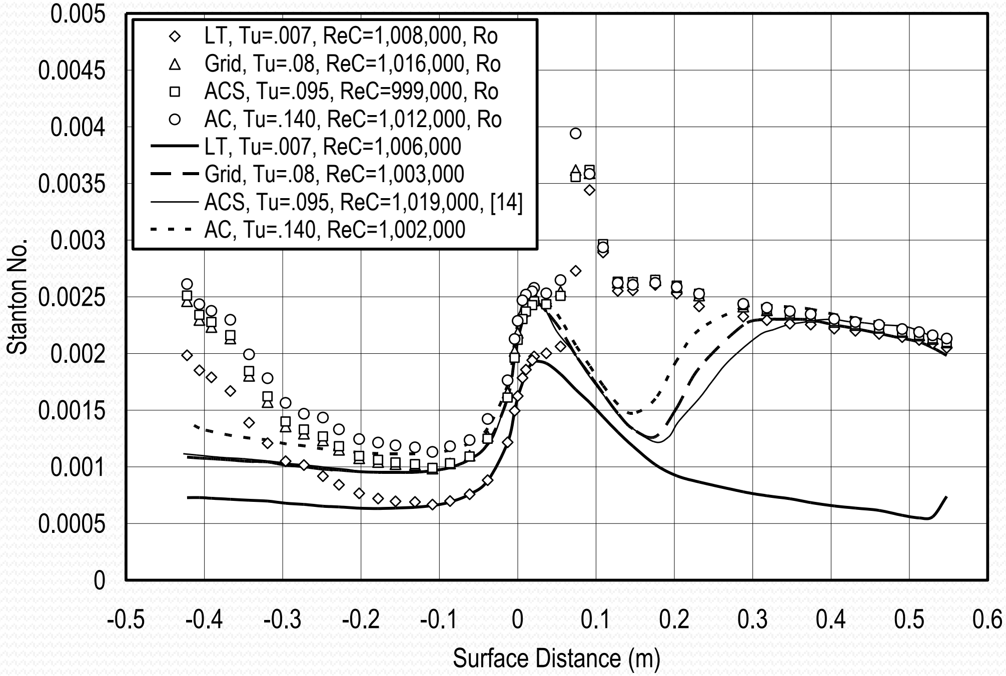
Turbulence decay measurements began without the cylinder in place.

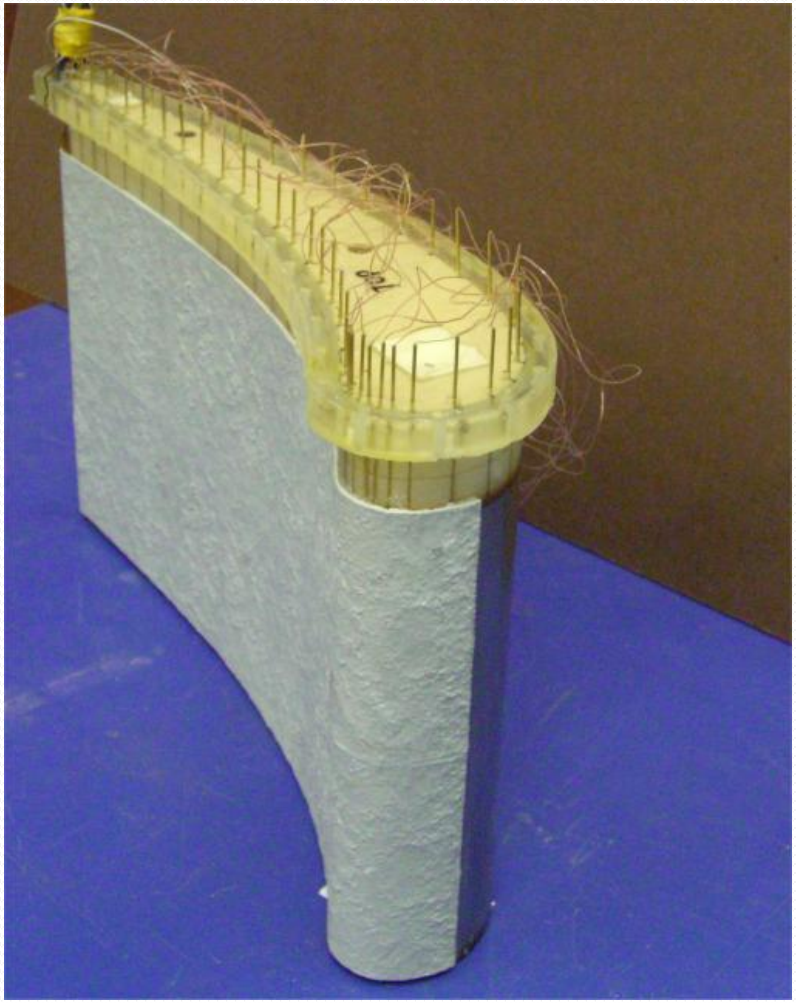


Leading edge cylinders were designed and are being fabricated to incorporate boundary layer and approach turbulence measurements

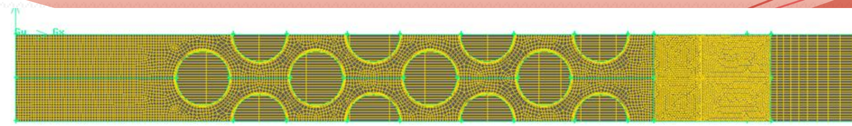
Geometrically scaled rough surfaces can be cast using stereo lithography molds to replicate TuRFR facility surfaces and then applied to heat transfer foils as shown pictured right.

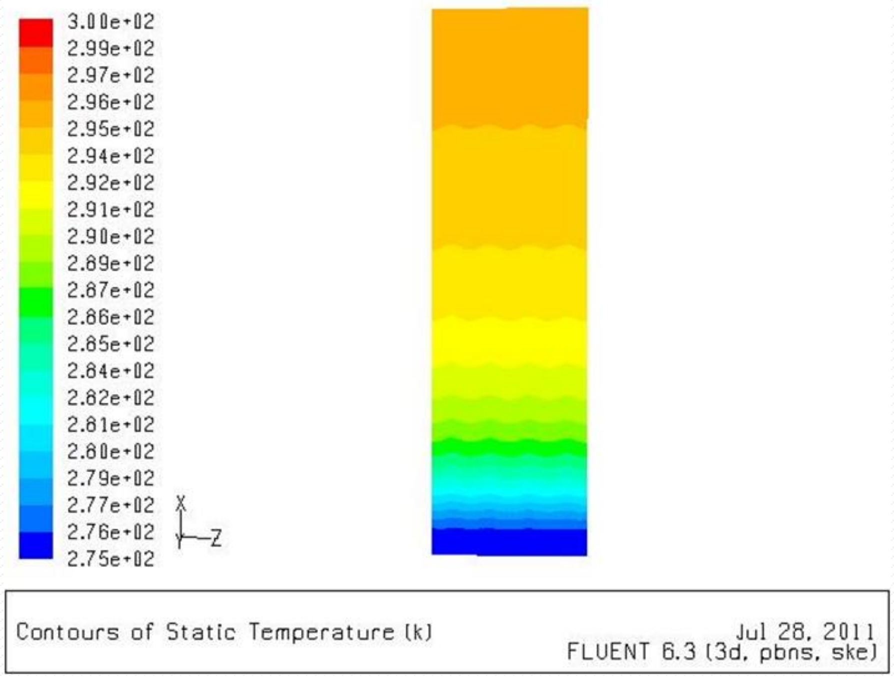
Vane surface Stanton number data show that roughness causes early transition but in this case has no impact before transition. Literature data (Bunker) show direct augmentation on leading edge at high Reynolds numbers.

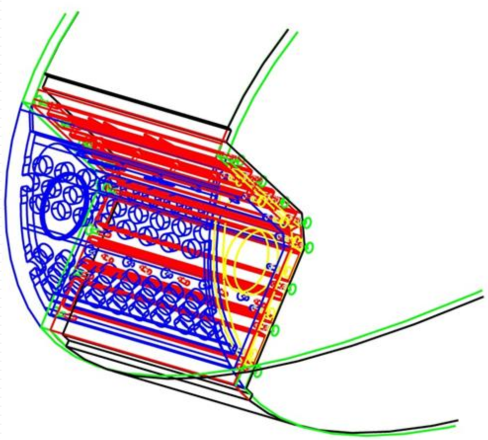


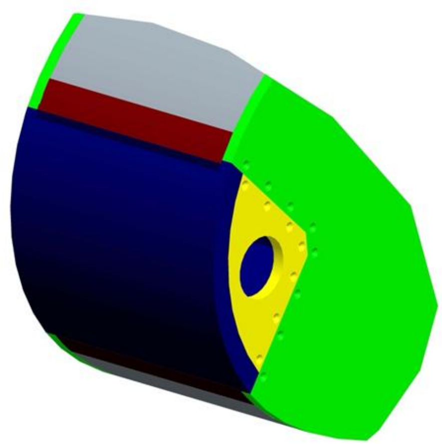



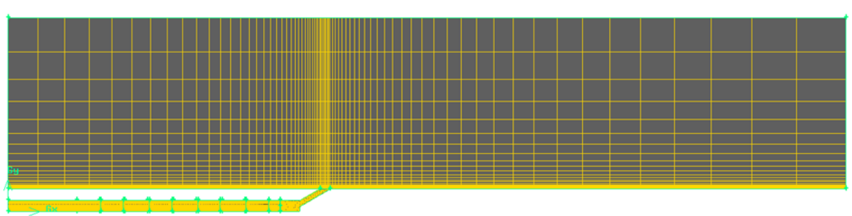
UND plans to use the leading edge cylinders to study the influence of turbulence and later turbulence and roughness on adiabatic effectiveness and downstream heat transfer for full coverage film cooling.
If film cooling is discharged from internal cooling features with rows of high solidity pin fins we need to include this as a boundary condition to insure the proper turbulence levels and flow nonuniformities discharging.
We have addressed this issue computationally and we have also looked at the issue of secondary flows.
We have fabricated a replaceable film cooling plenum to allow updating the discharge geometry.

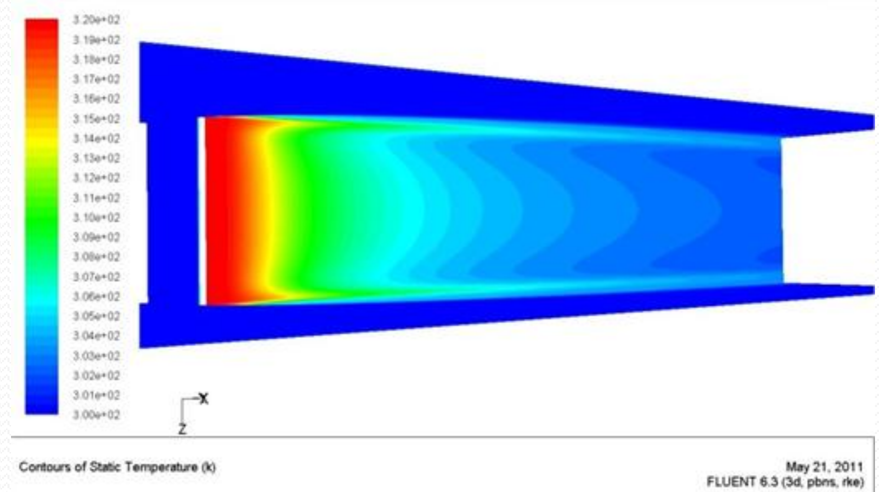




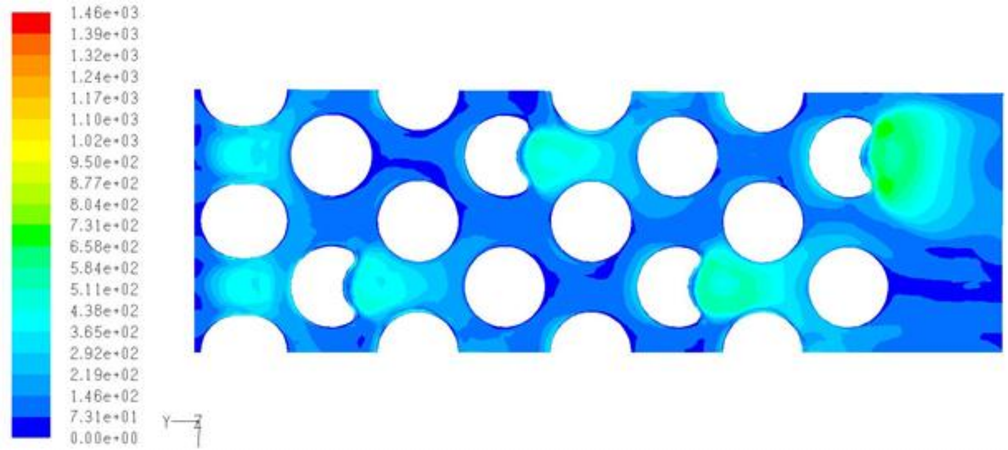




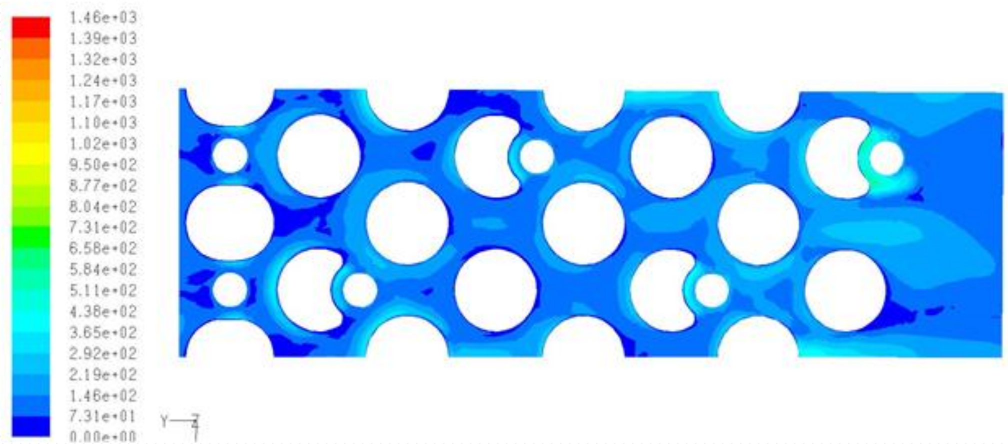


# High solidity cooling array design and CFD

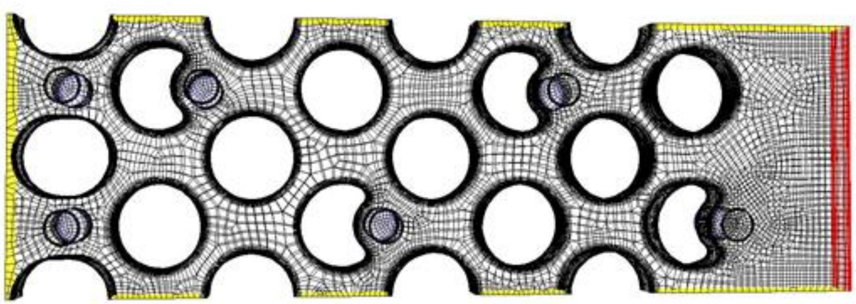
**Developing internal cooling geometries for stagnation regions with larger diameters requires the ability to cool significant surface areas before coolant discharge. Double wall cooling systems offer increased surface areas but require high solidity pedestals to transmit heat and stress. To counter heat pickup incremental cooling injection will also be required.**




Internal heat transfer distribution for outer surface of high solidity cooling array.



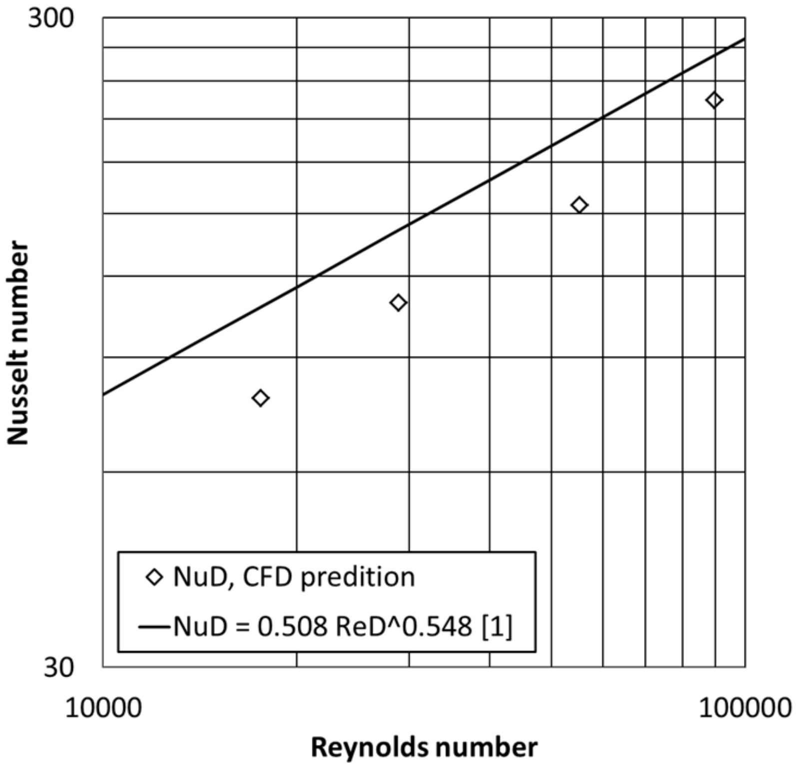

Internal heat transfer distribution for inner surface of high solidity cooling array.

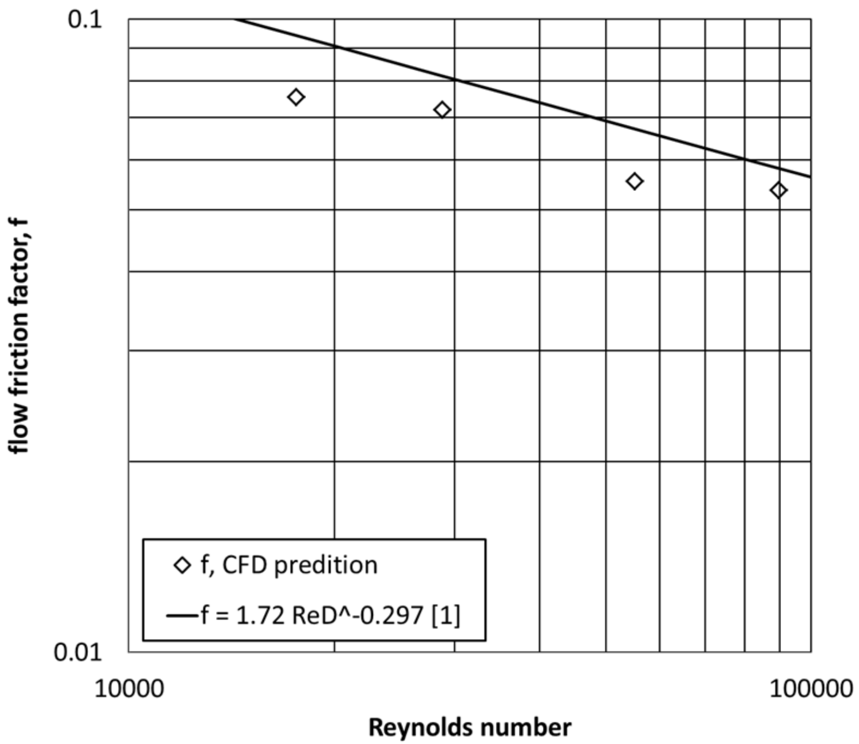


CFD Mesh for Internal Cooling Geometry

# Comparison between prediction for new cooling feature with distributed cooling injection and standard high solidity pin fin array

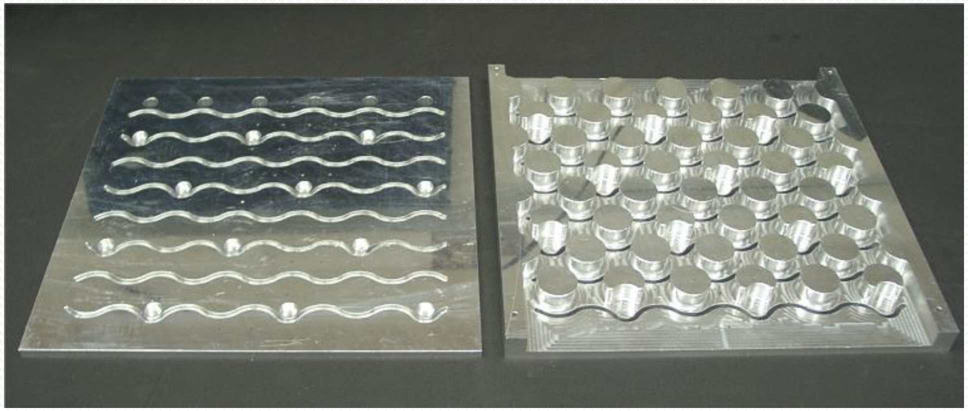
These figures show a comparison of CFD results for the new leading edge cooling feature and a high solidity (45%) pin fin array. The figures compare Nusselt number and flow friction factor versus Reynolds number in log coordinates. The Reynolds number for the new internal cooling array is based on a average velocity the total flow would generate through the minimum area. Although the calculations show a lower Nusselt number distribution, calculations often predict lower heat transfer levels than actual data. Also, due to the distributed cooling air injection overall heat transfer levels are more uniform for the new array.



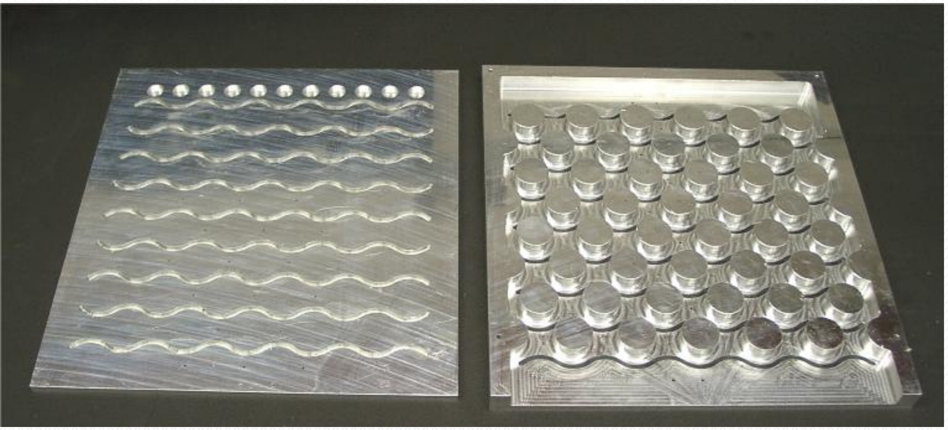



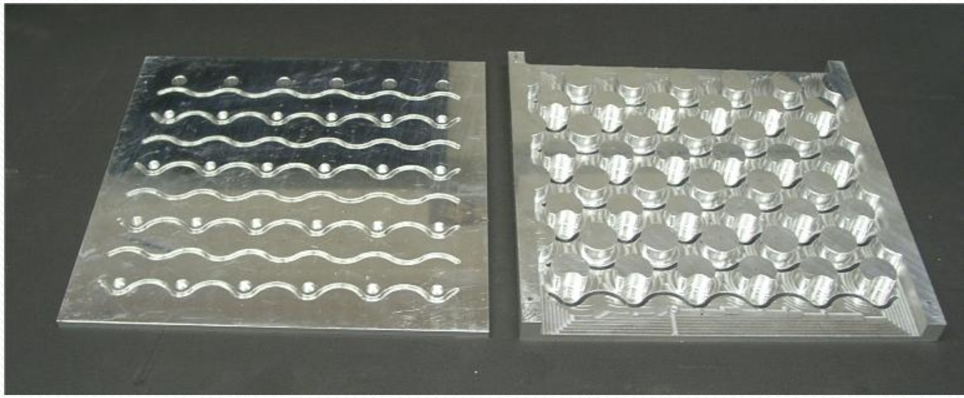
# High solidity cooling array fabrication

**Three geometries were developed for testing our internal cooling approach. A simple high solidity pin fin array was developed as a baseline array and to investigate the influence of the initial impingment hole injection and downstream heat transfer. Later two arrays with both inlet and distributed cooling injection were designed and fabricated**



In new arrays a balance between inlet injection of distributed injection is developed.





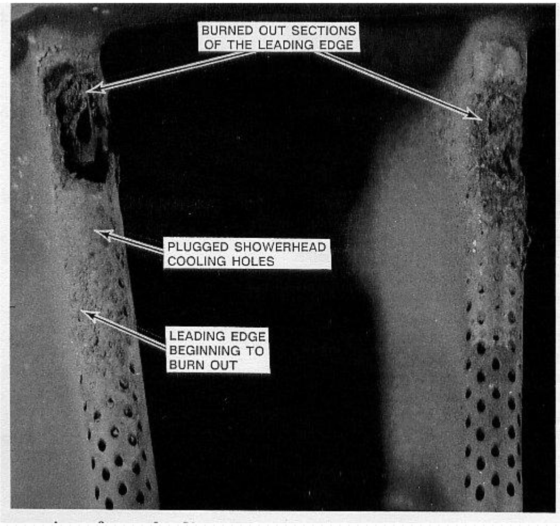
Baseline configuration shows inlet impingement holes and grooves to develop row by row thermal barrier.

Independent row by row heating with thermo-couple and pressure instrumentation allows for row by row assessment of HT and $\Delta$P.

# Motivation

Turbine design considerations:

- Higher $T_{T4}$
- LE Clogging Potential
- Combustors:
  - High turbulence levels
  - Non-uniformities
- Film cooling
- Larger leading edge diam.
- Better TBC coatings




Ash Deposition on F-100 Vane Leading Edge (Ref: Kim et al., 1993)

Ash Deposition on CFM56-5B Vane Leading Edge (Ref: Smith et al., 2010)

Need better tools for predicting turbine vane LE heat load, cooling requirements, and potential for deposition???

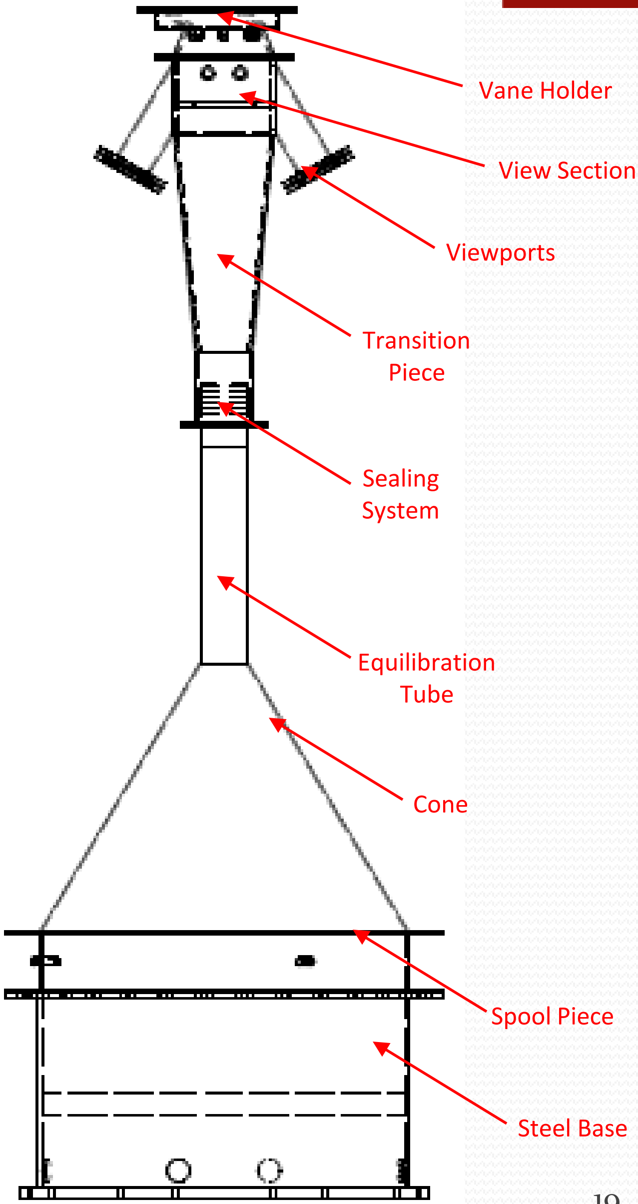
# Critical Unanswered Questions

- What is the effect of increased LE radius on deposition?
- What is the effect of increased inlet turbulence on deposition?
- What is the effect of roughness on film cooling?
- What is the effect of film cooling on deposition?

….requires unique test facilities!

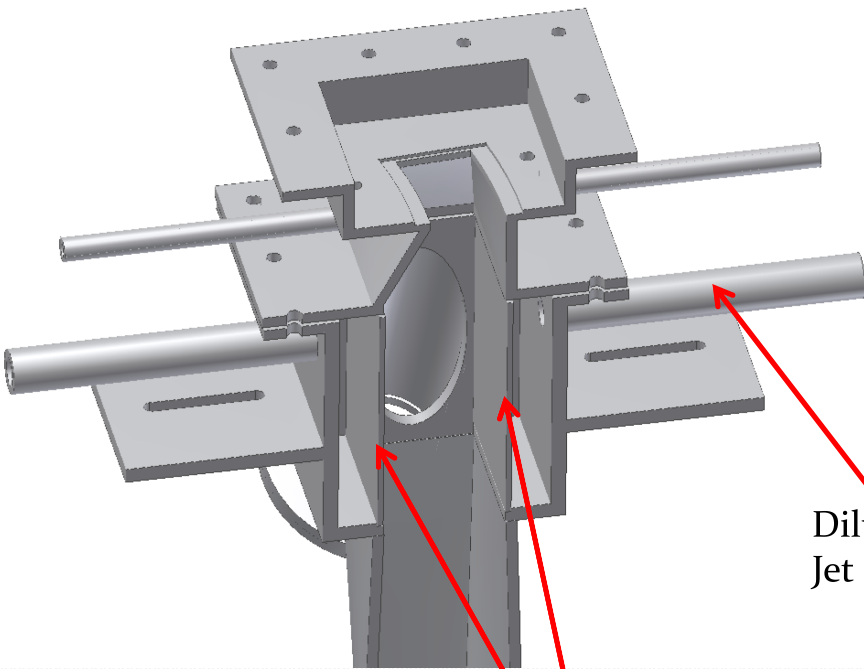
# OSU's Turbine Reacting Flow Rig (TuRFR)

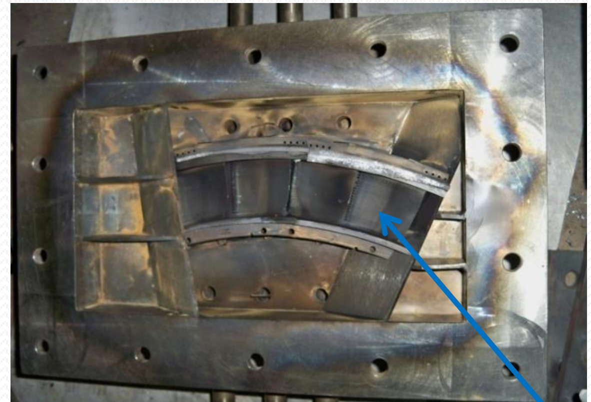
- Natural gas burning combustor rig
- Combustor exit flow accelerated in cone nozzle
- Transition from circular to annular sector
- Real vane hardware (industry supplied) installed in annular cascade sector
- Tt4 up to 1120°C (2050°F)
- Inlet Mach number ~ 0.1
- $300{,}000 < Re_{cex} < 1{,}000{,}000$
- Adjustable inlet temperature profiles
- Adjustable inlet turbulence profiles (through dilution jets)
- Film cooling from vane casing and hub (density ratio 1.6-2.0)
- Ash particulate feed in combustion chamber (10 µm MMD)

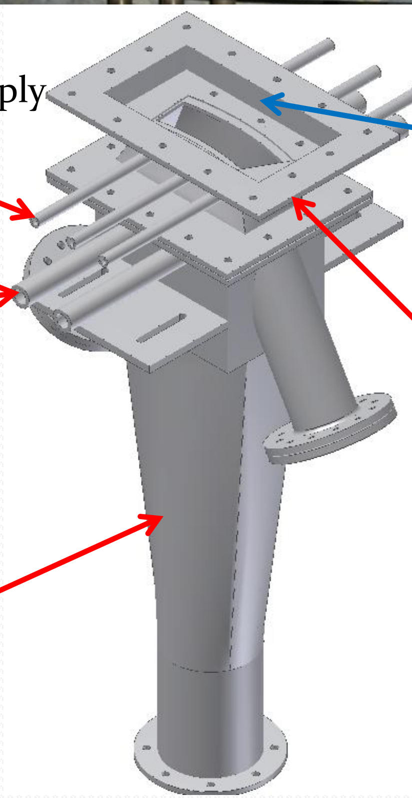


# OSU's Turbine Reacting Flow Facility (TuRFR)

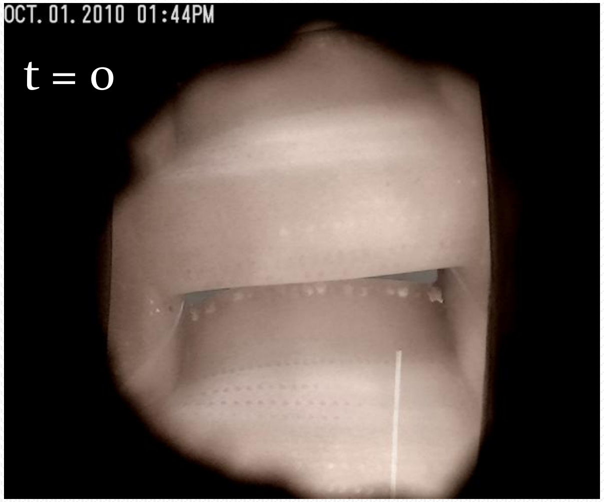
## Vane Holder and Upstream Conditioning

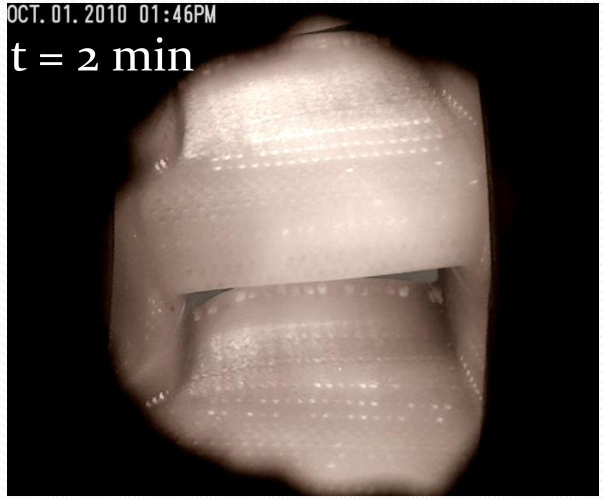


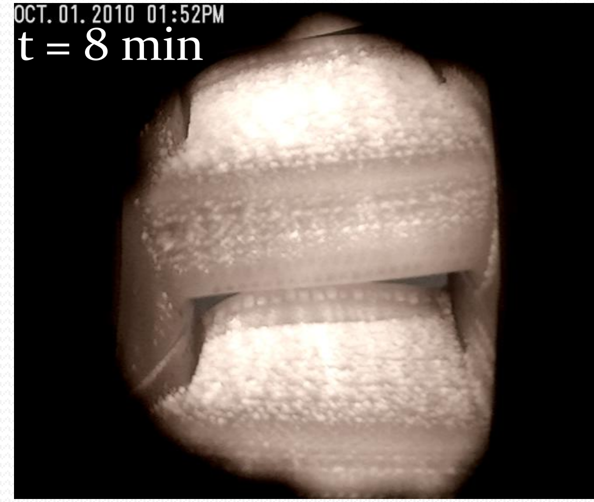


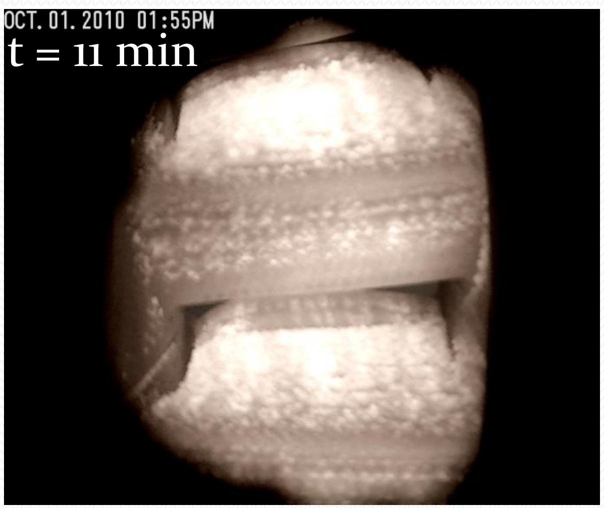


# Typical TuRFR Test Sequence

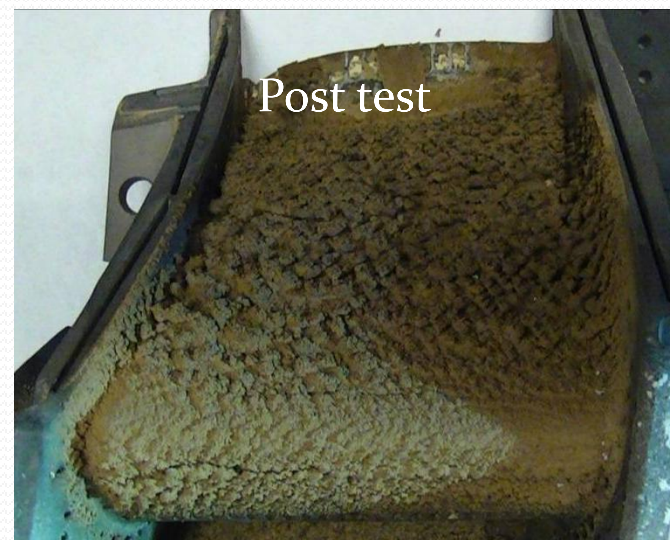


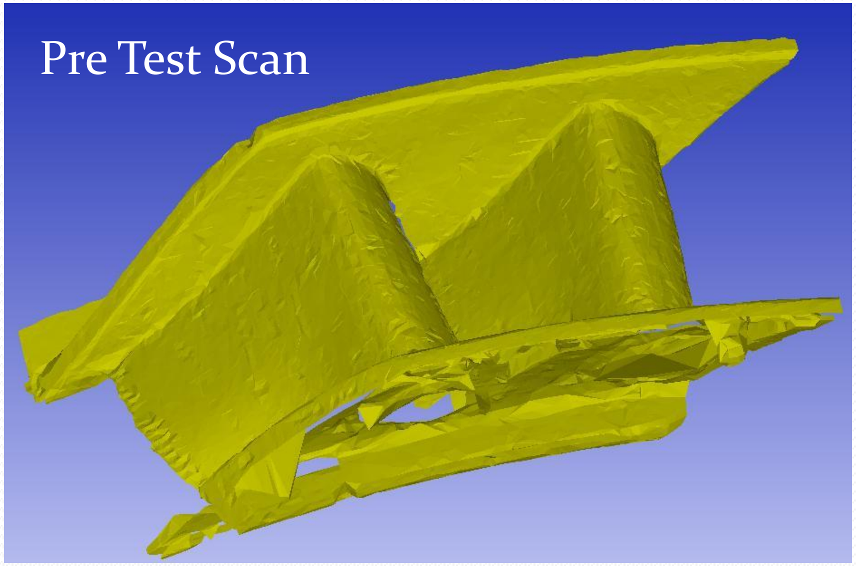



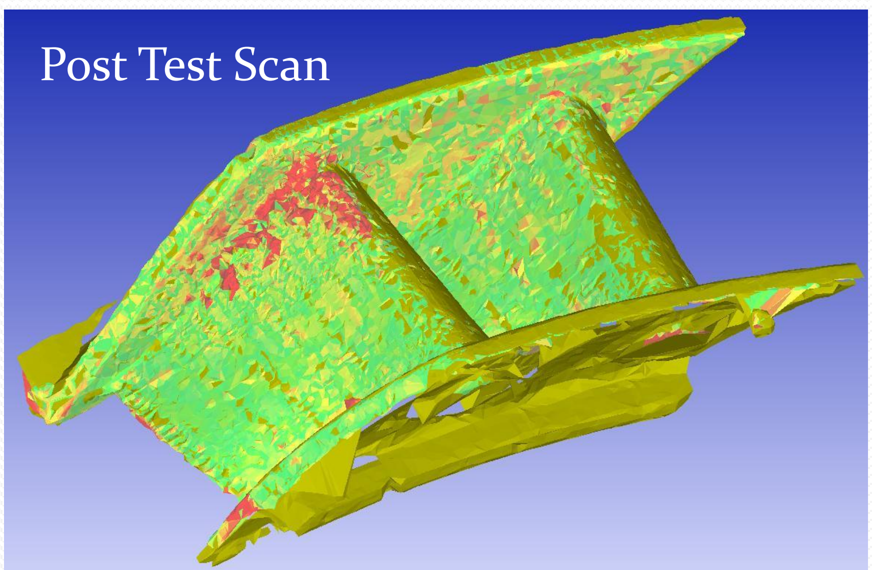



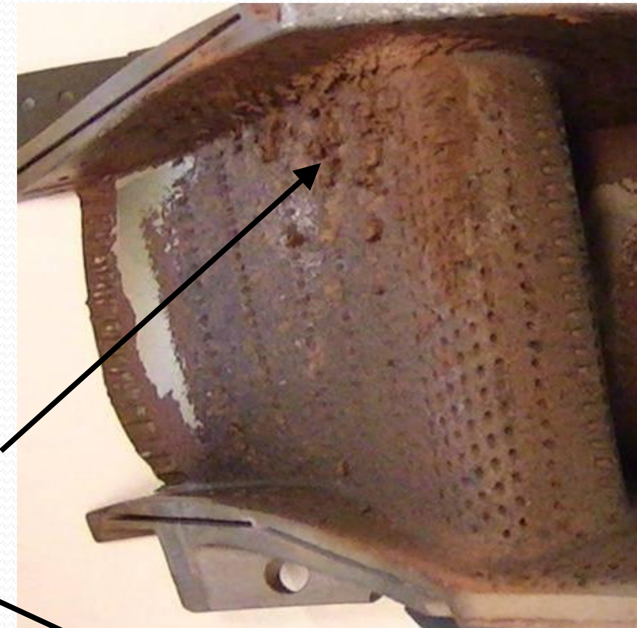

Time Lapse Images
Wyoming
Sub-Bituminous Ash
Test Conditions:
$T_{t4}$~1900F
$M_{in}$=0.90



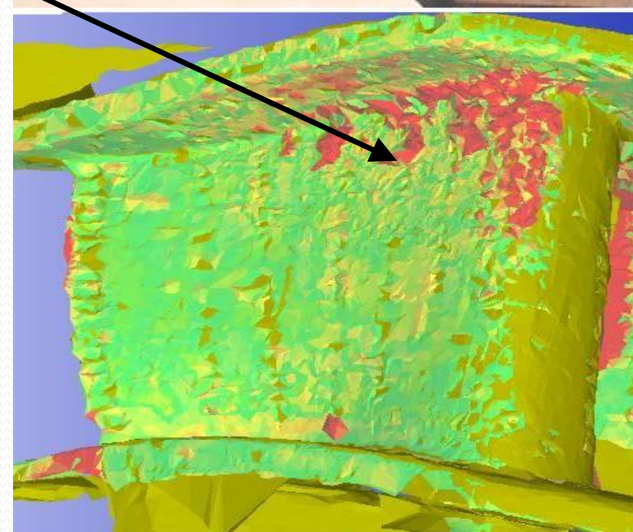
# Post Test Diagnostics - Metrology



Deposit height indicated in contour map relative to Pre-Test Datum

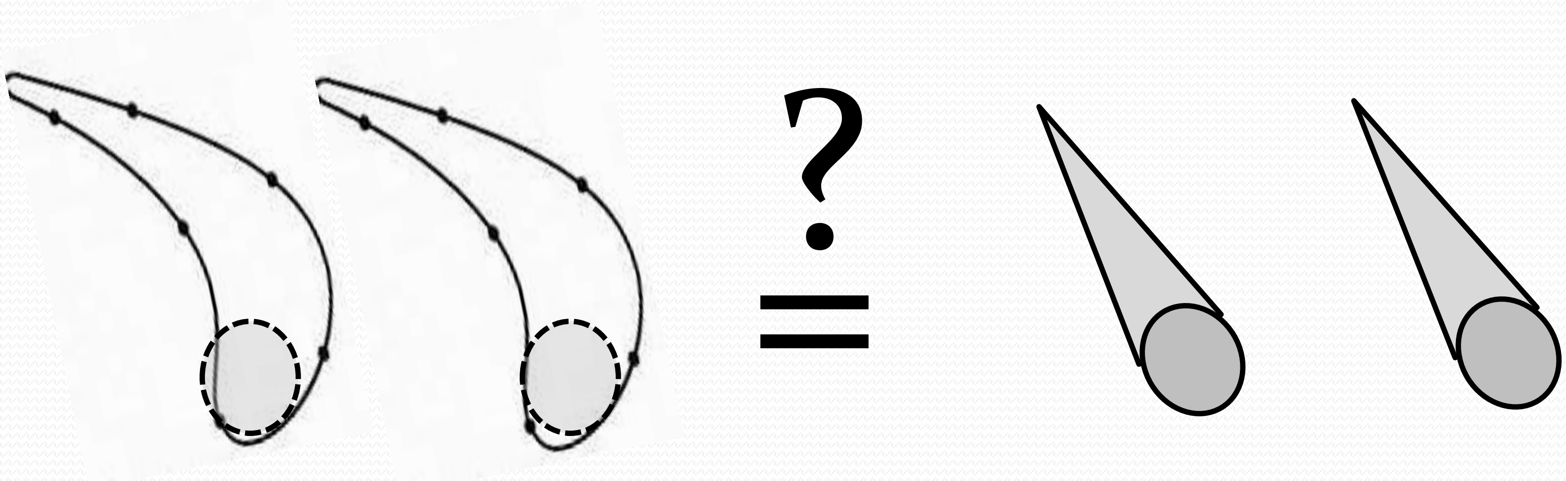


# OSU Focus for New Grant

- Phase 1: Influence of Leading Edge Radius on Deposition Rates
- Phase 2: Influence of Vane Inlet Turbulence on Deposition Rates
- Phase 3: The Mitigating Effect of Film Cooling on Deposition

# Phase 1: Deposition and Leading Edge Radius

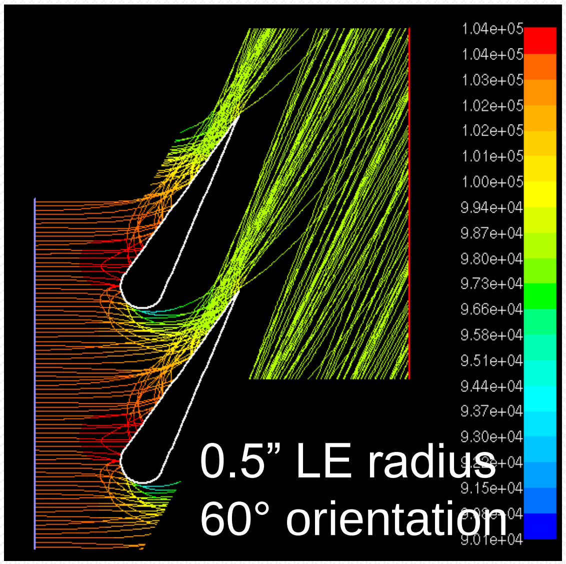
- Validate use of faired cylinder to model vane LE deposition
- Study deposition as a function of LE radius
- Provide deposition surface maps to UND for wind tunnel testing



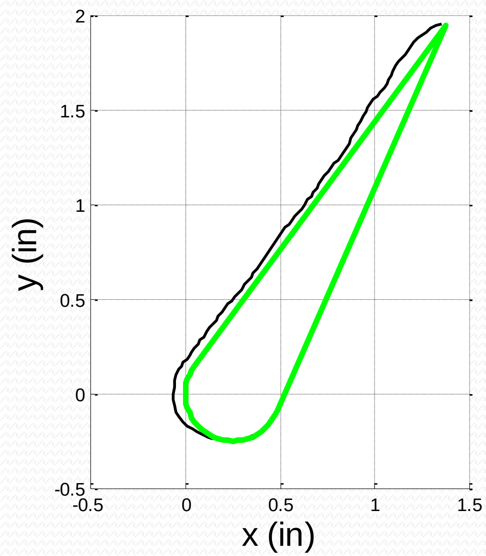

- WHY faired cylinders? Ability to quickly and economically study effect of LE radius on deposition!

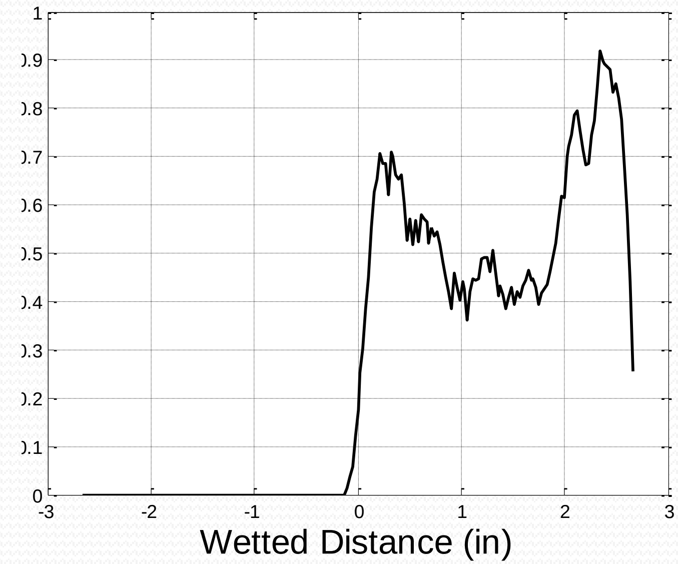
# Phase 1: Deposition and Leading Edge Radius

## Fluent Model of Particle Trajectories



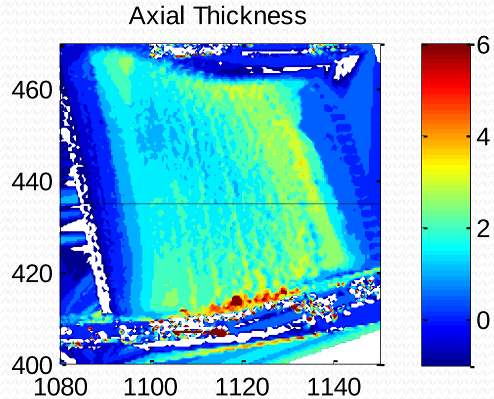

## Prediction Deposition Pattern

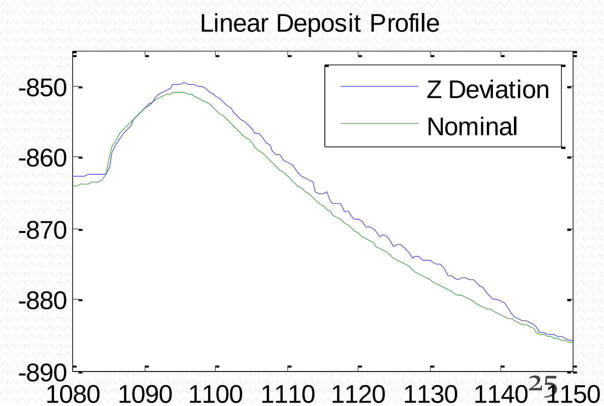



## TuRFR Deposition Test with Uncooled Vane

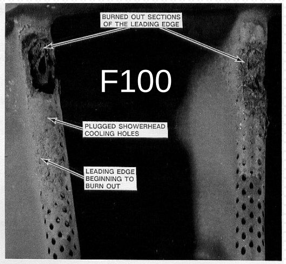
Optical Surface Scan yields similar Deposition Pattern



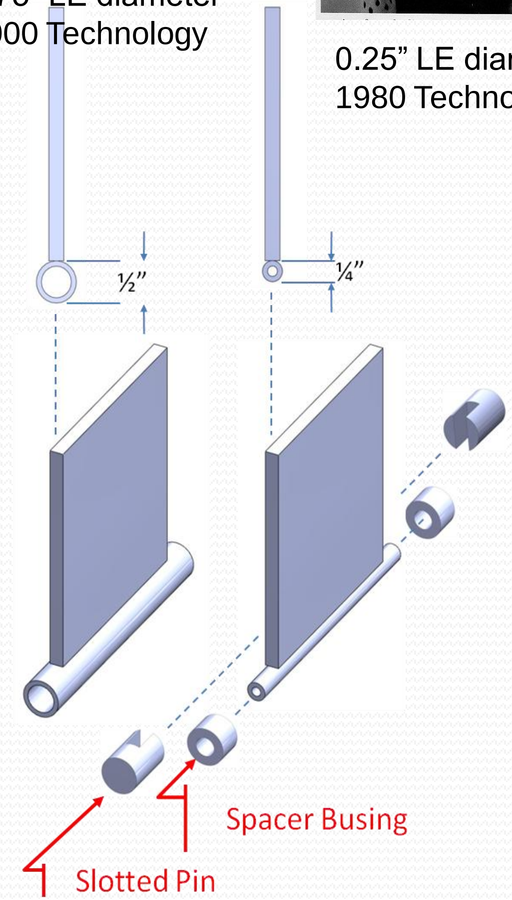



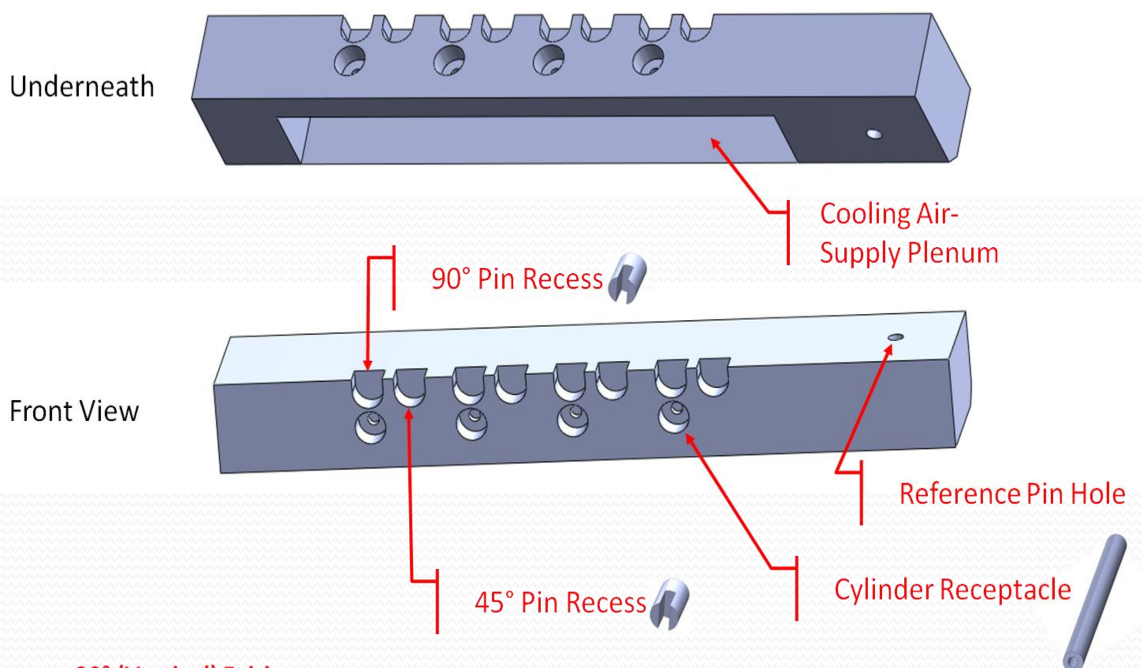
# Phase 1: Faired Cylinder Design


0.75” LE diameter
2000 Technology

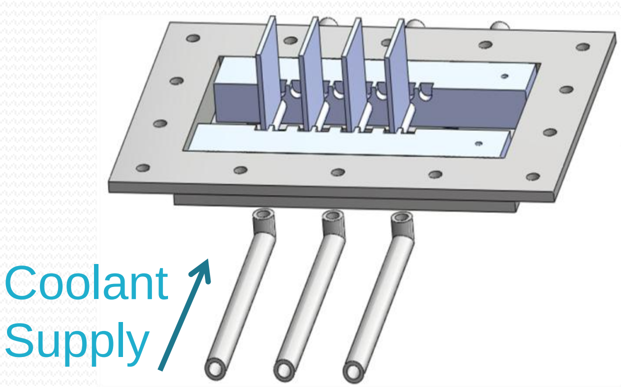



0.25” LE diameter
1980 Technology

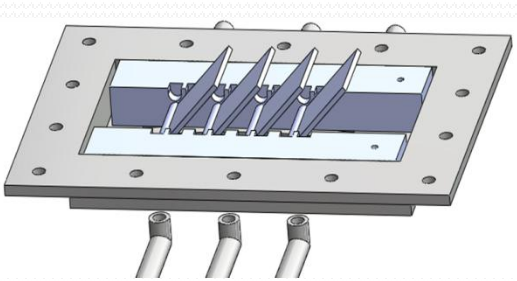



90° (Vertical) Fairing




45° (Canted) Fairing

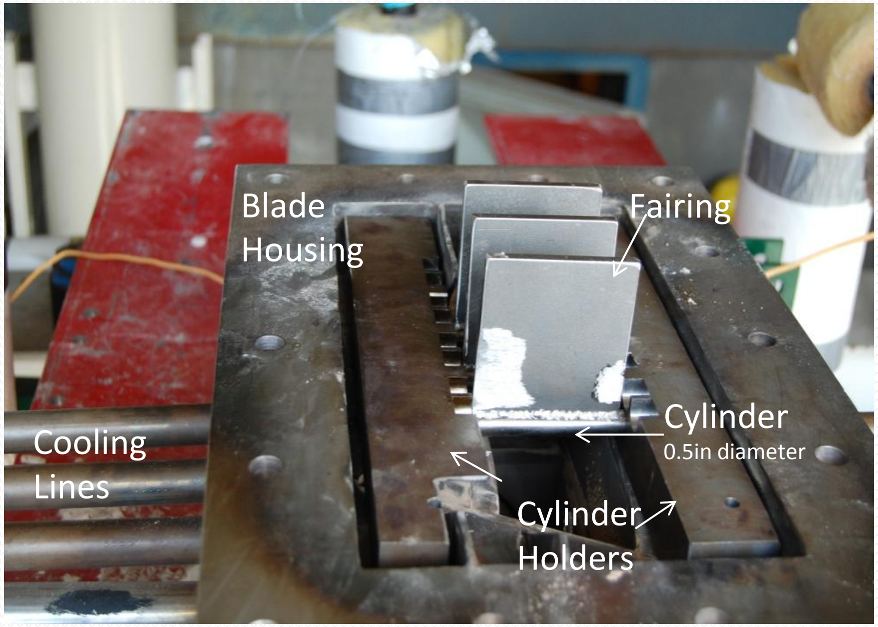


# Phase 1: Faired Cylinder Test Section

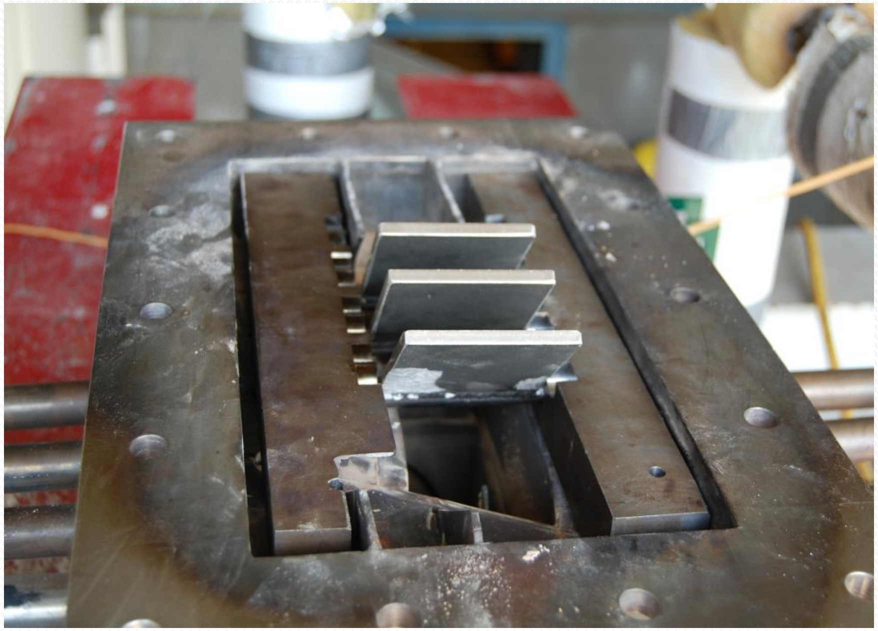
- High temperature materials (INCO 601)
- Diameters currently available: 0.25, 0.375, 0.5
- Fairing to reduce unsteady wake shedding
- Internal cooling possible
- Film cooling, with modification, possible

Faired Cylinders

Left to right: 0.5, 0.375, and 0.25 inch diameter




Vertical Position



Canted Position, 40º

# Phase 1: Faired Cylinder Results

Test setup and conditions changed to mitigate flake off

- Different diameters, ash type, fairing position, injection rate, and cooling
- Coolant reduced thermal expansion of the cylinders which prevented cracking of deposits during facility cool down.
- A lower ash injection rate also proved beneficial in creating robust deposits.

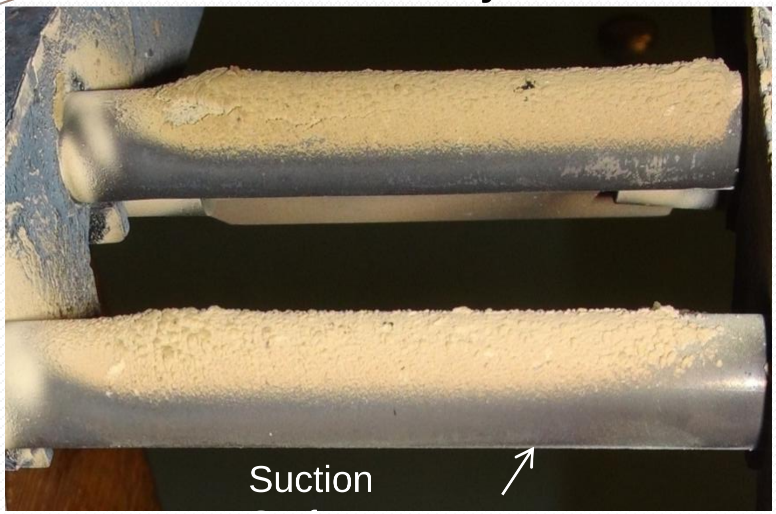
| Test | Cyl. Diameter (in) | Fairing Position | Temperature (°F) | Ash Type | Injection Rate | Cooling |
|---|---|---|---|---|---|---|
| 1 | 0.5, 0.5, 0.5 | Vertical | 1960 | JBPS | Normal | No |
| 2 | 0.5, 0.375, 0.25 | Vertical | 1960 | JBPS | Normal | No |
| 3 | 0.5, 0.375, 0.25 | Vertical | 2000 | Lignite | Normal | No |
| 4 | 0.5, 0.375, 0.25, 0.5 | Canted | 2000 | Lignite | Normal | No |
| 5 | 0.5 , 0.5, 0.5, 0.5 | Canted | 2000 | Lignite | Reduced | Yes |
| 6 | 0.25, 0.25, 0.5, 0.375 | Canted | 2000 | Lignite | Reduced | Yes |

Severe flake off during initial testing (Test 1)

With coolant and reduced ash injection rate (Test 5)

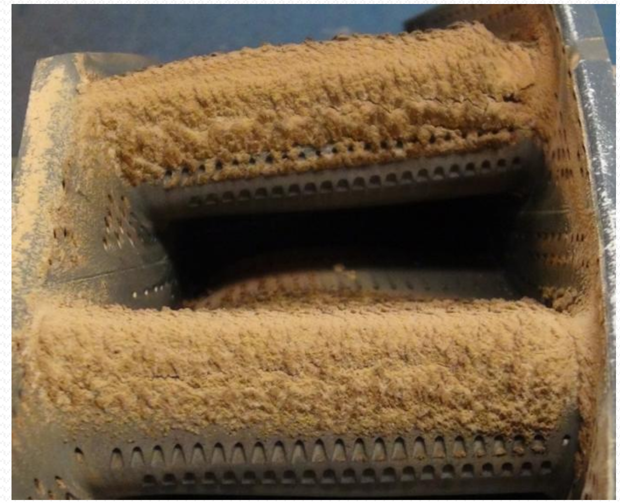
# Phase 1: Cylinder vs. Vane Results

**Test 5 – Canted Cylinders**




**vs.**

**CFM56 Vanes**

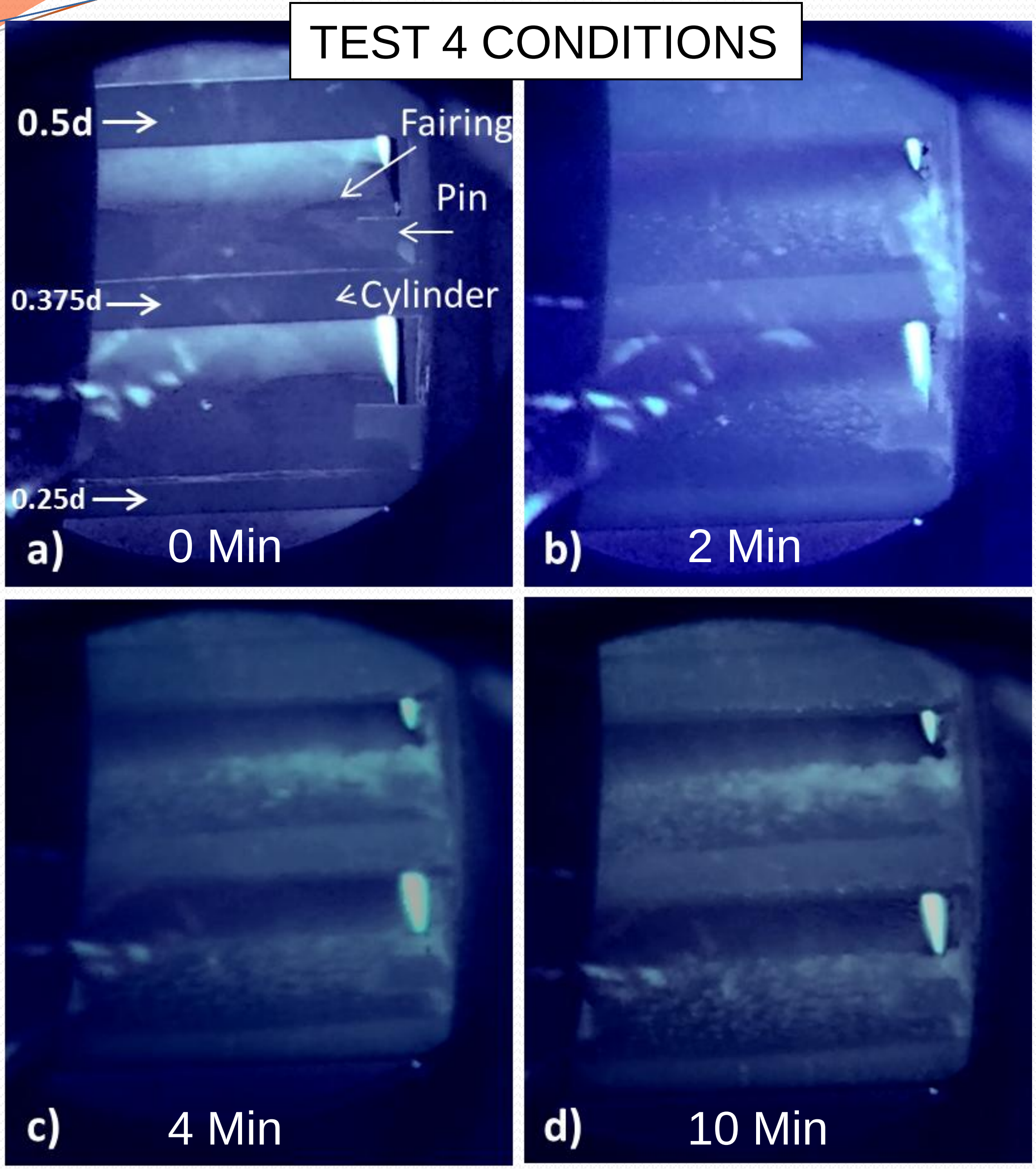


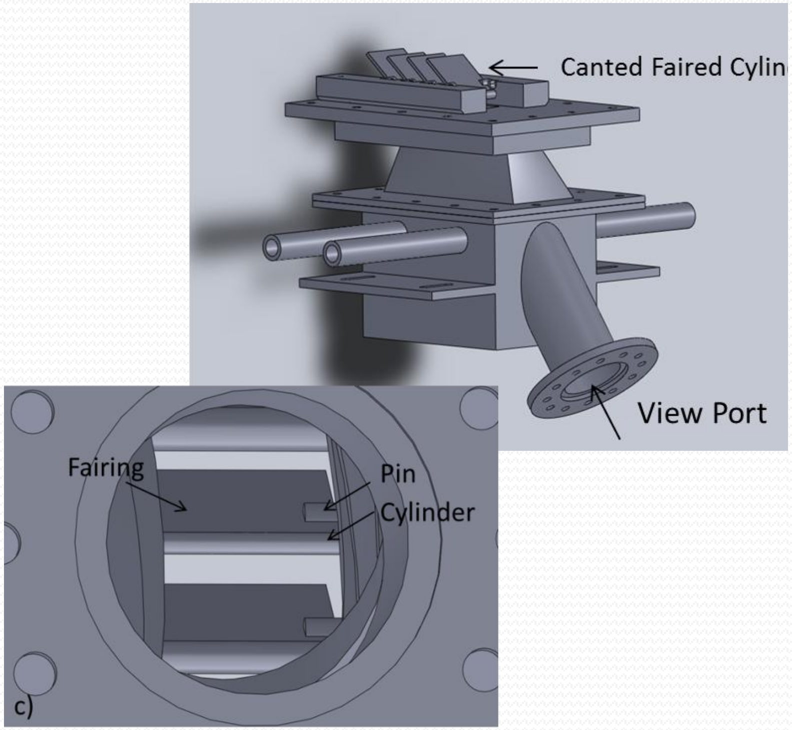
| | |
|---|---|
| **LE Dia. (in)** | 0.5 |
| **Internal Cooling** | Yes |
| **Film Cooling** | No |
| **Flow Temp (°F)** | 2000 |
| **Mass flow (lb/s)** | 0.8 |
| **Ash Type** | Lignite |
| **Stokes** | Large |
| **Loading (g)** | 124.7 |

| | |
|---|---|
| **LE Dia. (in)** | 0.75 |
| **Internal Cooling** | No |
| **Film Cooling** | No |
| **Flow Temp (°F)** | 1975 |
| **Mass flow (lb/s)** | 0.8 |
| **Ash Type** | JBPS |
| **Stokes** | Small |
| **Loading (g)** | 101 |

- Stagnation region shows thickest deposits ✓
- Thickness decreases to zero towards the suction surface ✓
- Surface of deposits display lower roughness on faired cylinder. ?
- Possible explanation for differences:
  - Film cooling holes, ash type, LE diameter, geometry

# Phase 1: Cylinder vs. Vane Results



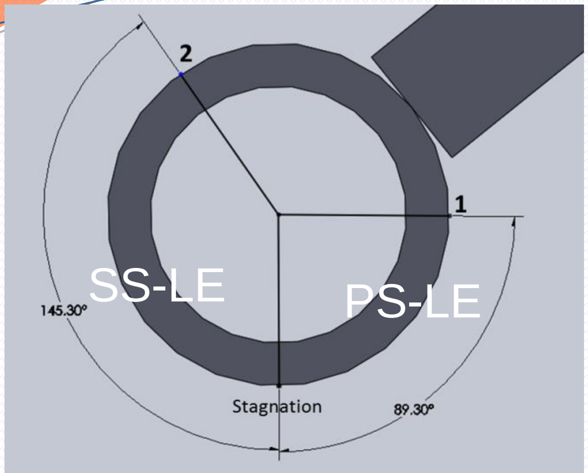

OBSERVATIONS

•Deposits form first on fairing (similar to vane)

• Larger size cylinder shows more apparent deposits

• Post test assessment difficult due to flaking during cooldown (non cooled)

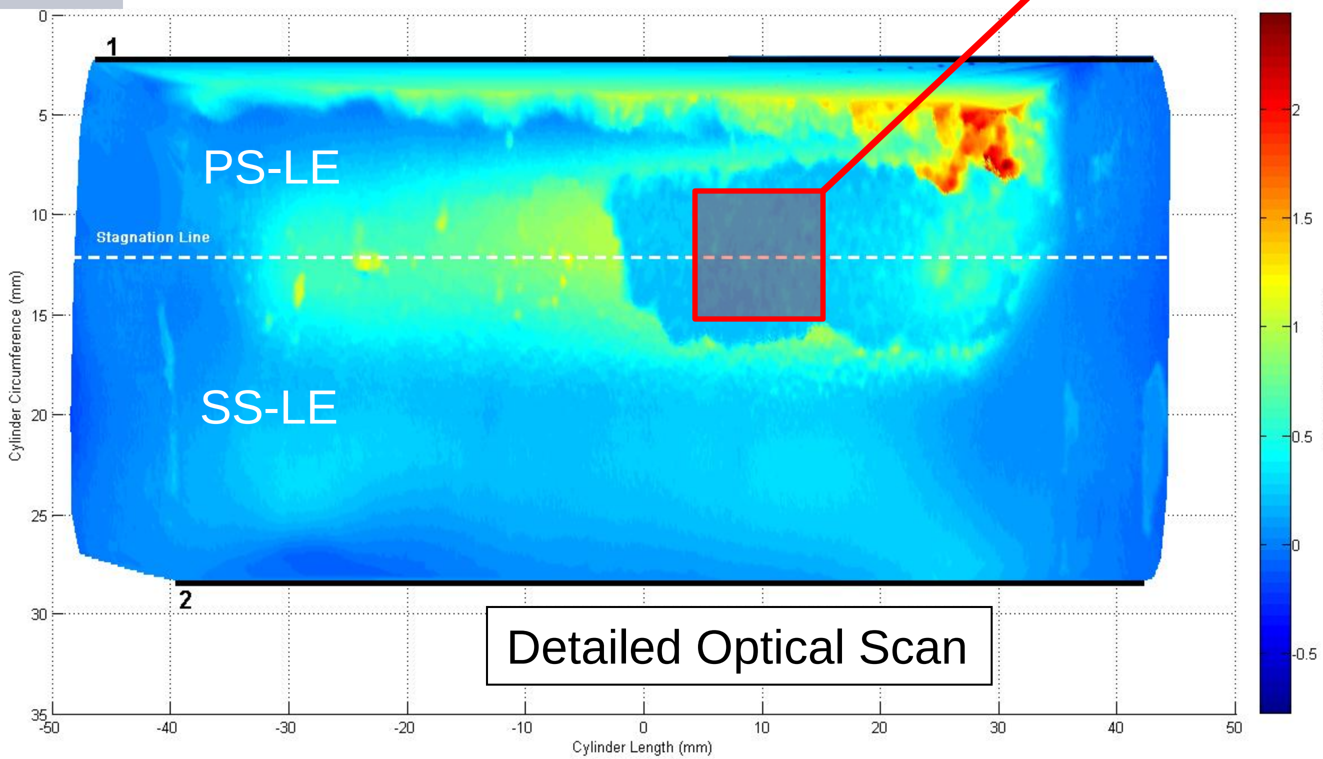
# Phase 1: Surfaces for UND




TEST 4 CONDITIONS
0.5” Diameter Canted Cylinder

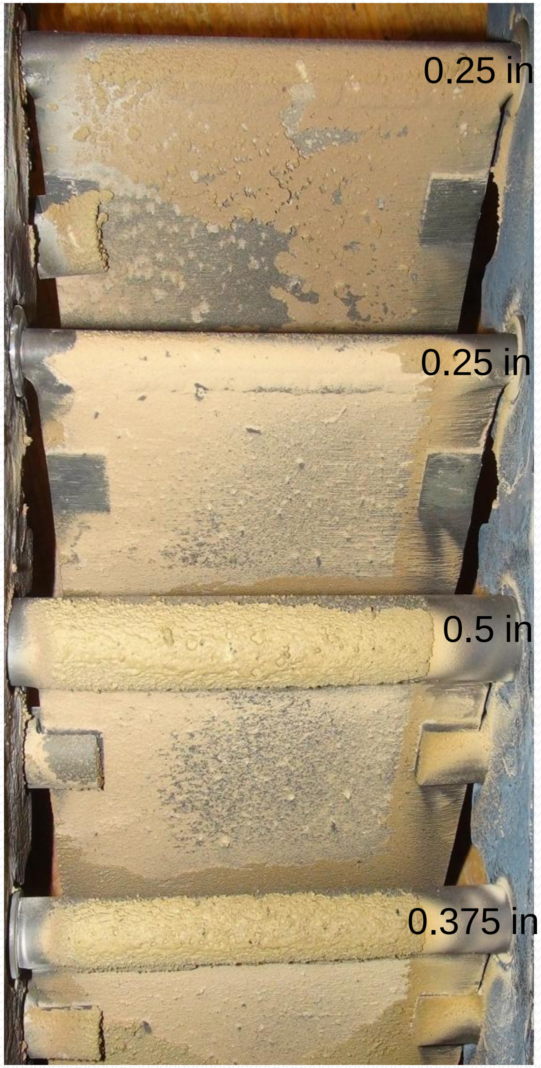
Surface data extracted for UND

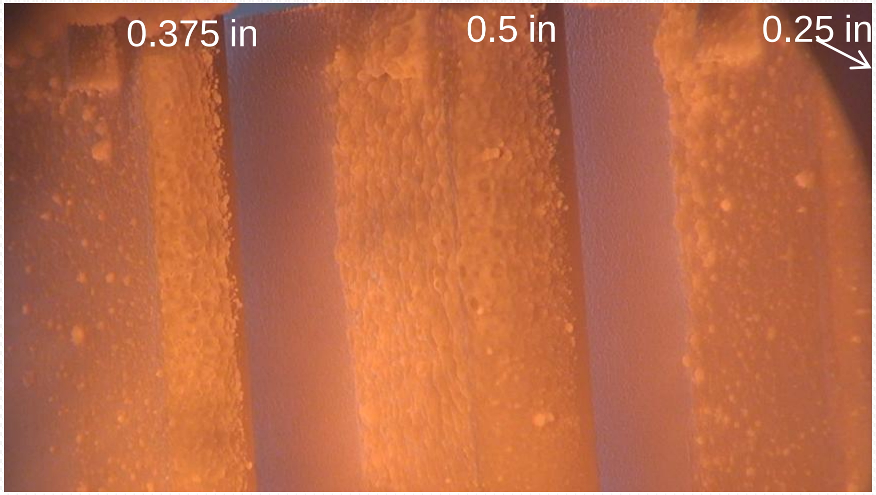
FLOW



# Phase 1: Effect of Different Cylinder LE Diameter

TEST 6 CONDITIONS
Cooled Canted Cylinders



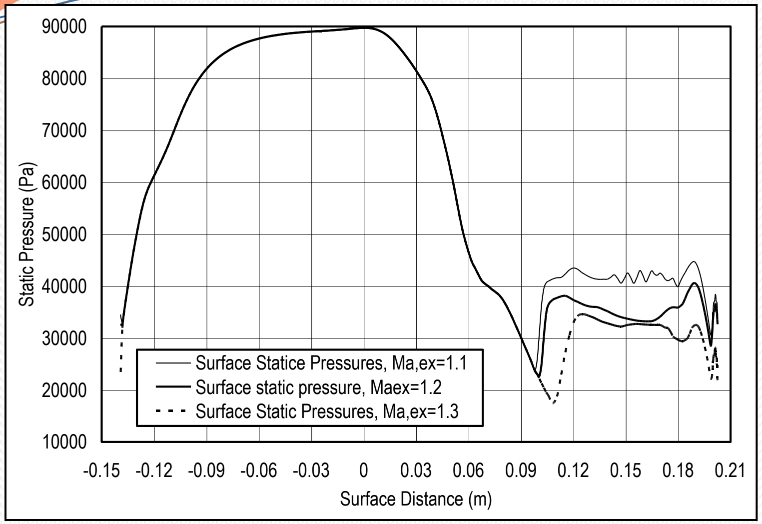

OBSERVATIONS

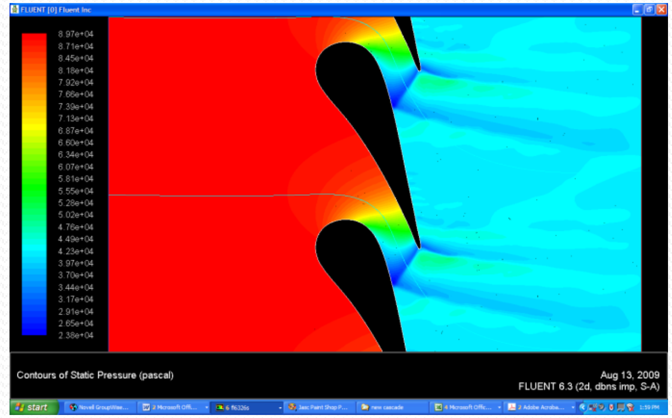
- Larger size cylinder shows more apparent deposits on leading edge AND fairing
- With internal cooling, flaking is primarily observed on smallest diameter cylinder (deposits are more curved – less stable during thermal contraction)

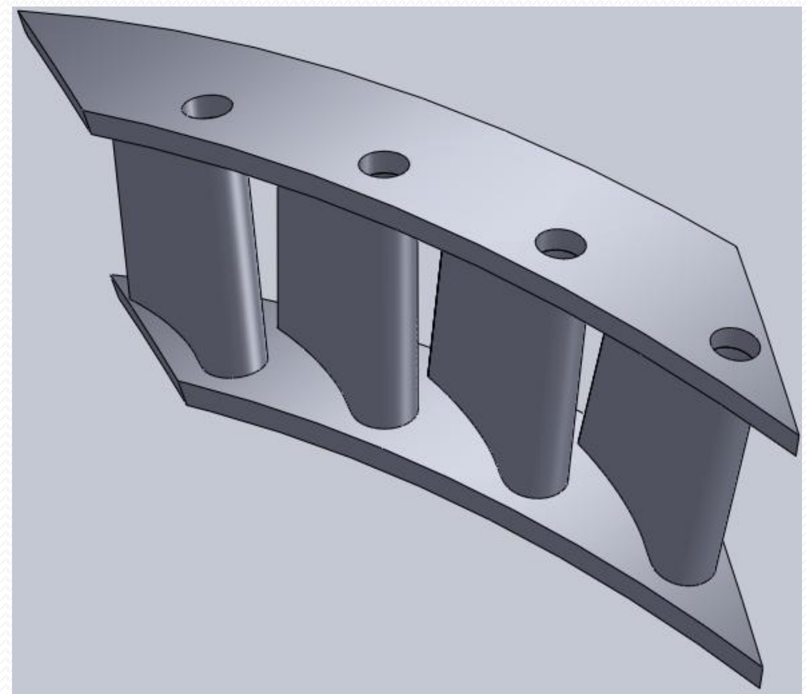
# Phase 1: Unresolved Questions

- Is the faired cylinder a suitable replacement for a vane?
  - What effect do film cooling holes have?
  - Do they act as an anchor for deposits on vane?
- What is the effect of larger leading edge diameters on deposition?
  - Larger accumulation per unit area
  - Larger structures (higher roughness)

# Phase 1: New Test Section



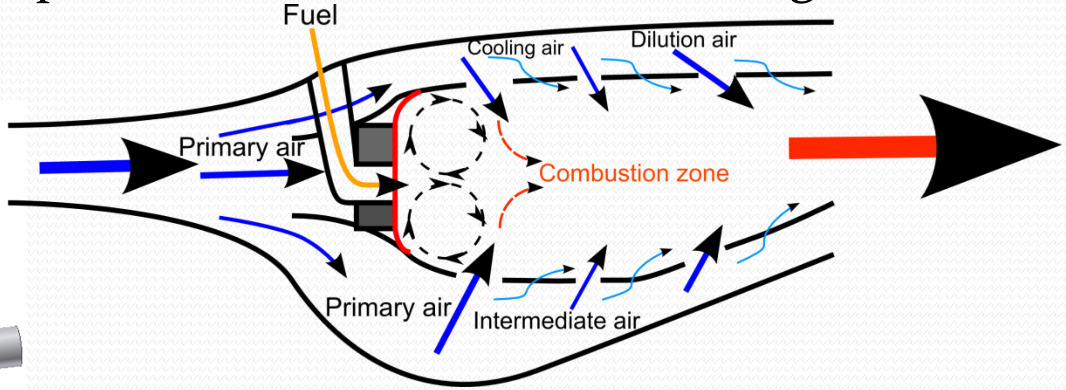



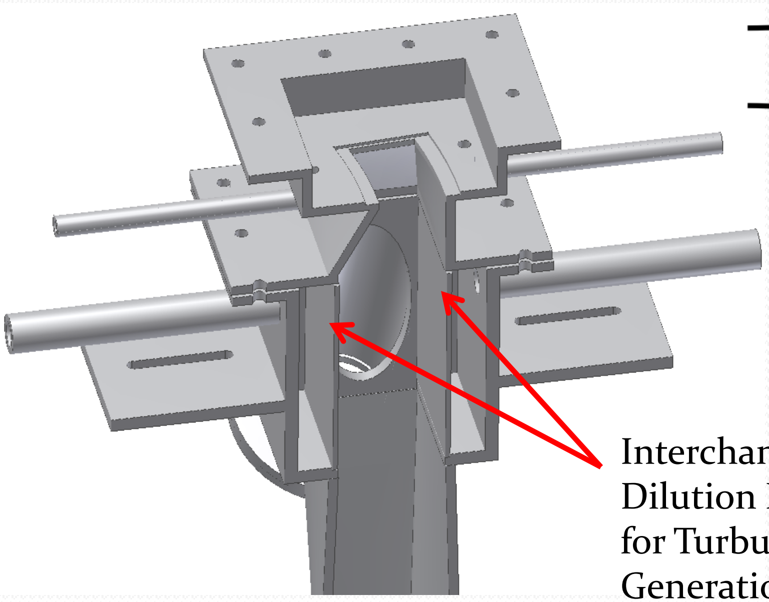



- 2D NGV profile donated from Rolls-Royce
- No cooling holes
  - Better comparison between cylinders and vanes
  - Provides validation for CFD code
- Leading edge cooling to prevent deposit flaking
- 0.65” leading edge diameter

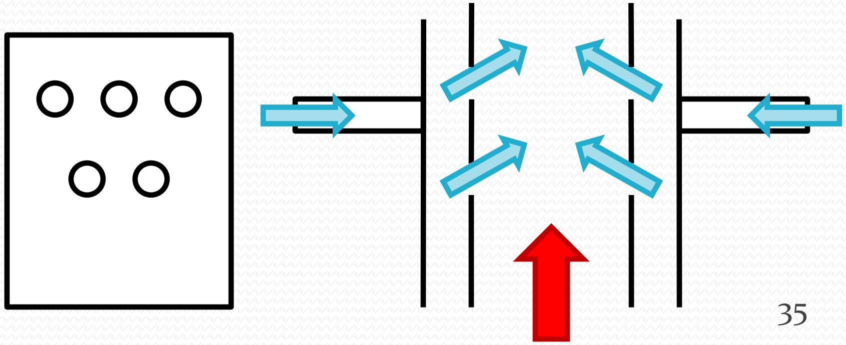
# Phase 2: Deposition and Vane Inlet Turbulence

- Generate elevated inlet turbulence & temperature non-uniformities with dilution jets in TuRFR
- Study deposition for various turbulence levels and LE geometries
- Develop in-situ deposit thickness and surface temperature measurement capability
- Provide deposition surface maps to UND for wind tunnel testing



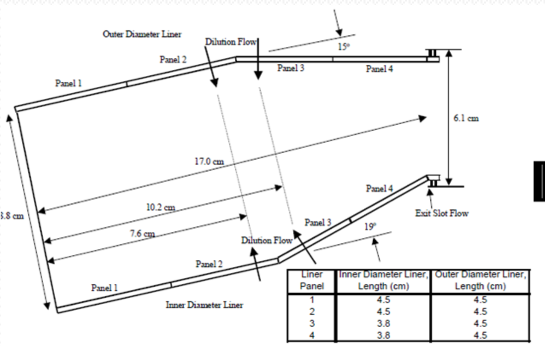



Interchangeable Dilution Plates for Turbulence Generation



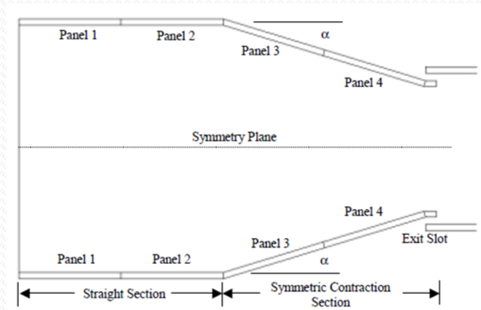
# Phase 2: Turbulence Generator Design

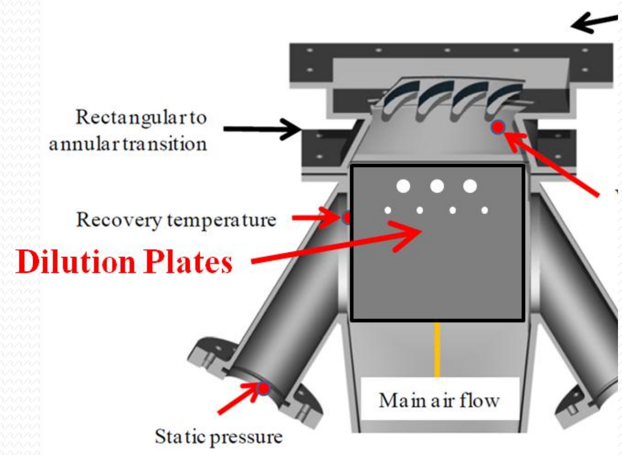
Cross-section of Pratt & Whitney Annular Combustor Geometry

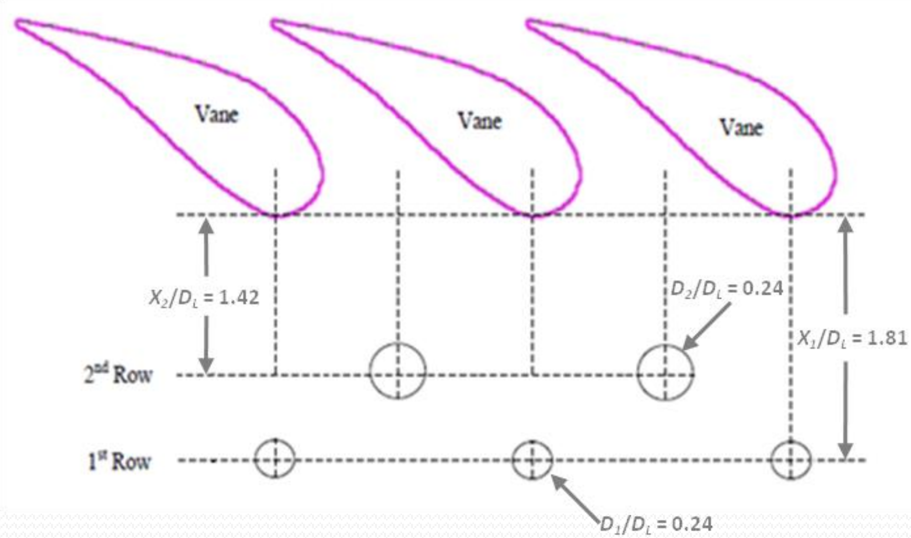



| Liner Panel | Inner Diameter Liner, Length (cm) | Outer Diameter Liner, Length (cm) |
|---|---|---|
| 1 | 4.5 | 4.5 |
| 2 | 4.5 | 4.5 |
| 3 | 3.8 | 4.5 |
| 4 | 3.8 | 4.5 |

Cross-section of Combustor Simulator at Penn State University

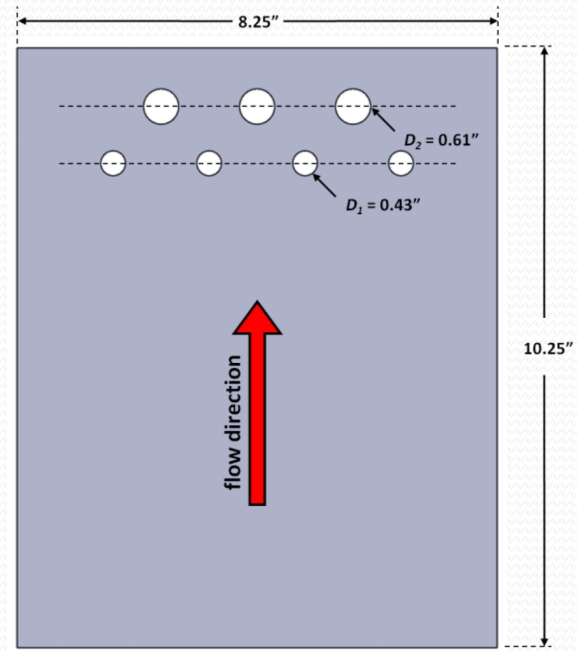



Final design matches:

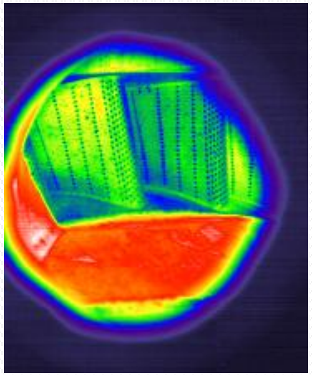
- hole pattern
- hole/LE diameter ratio
- upstream distance/LE diameter ratio
- $D_1/D_2$ ratio

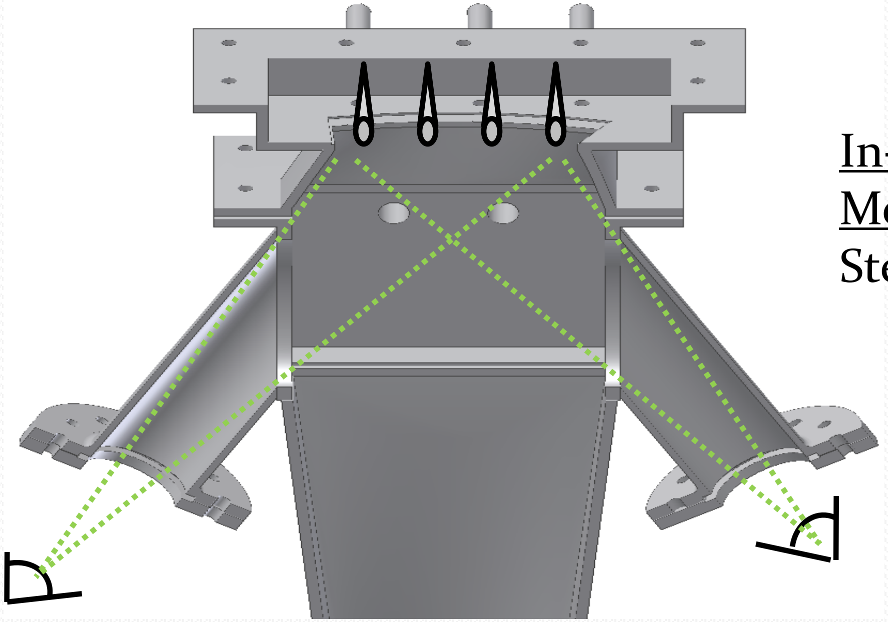


# Phase 2: Deposition and Vane Inlet Turbulence

- Generate elevated inlet turbulence & temperature non-uniformities with dilution jets in TuRFR
- Study deposition for various turbulence levels and LE geometries
- Develop in-situ deposit thickness and surface temperature measurement capability
- Provide deposition surface maps to UND for wind tunnel testing

Real time surface temperature:
IR Camera Image



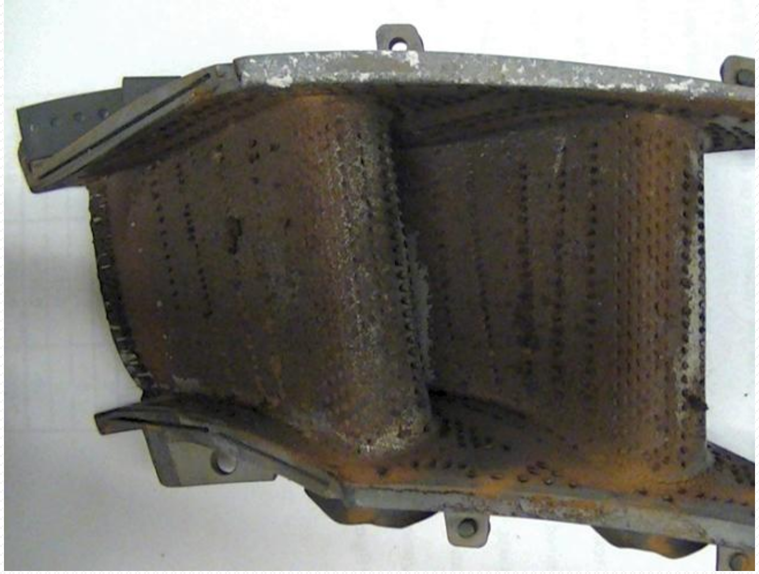


In-Situ Deposit Thickness Measurement
Stereo photo-grammetry

# Phase 3: Deposition and Film Cooling

- Study film cooling effects on LE deposition with faired cylinders
- Study film cooling effects on pressure surface deposition with vane hardware
- Provide deposition surface maps to UND for wind tunnel testing

Bituminous Coal Ash at 1900F



No Film Cooling

Film Cooling

# Questions?