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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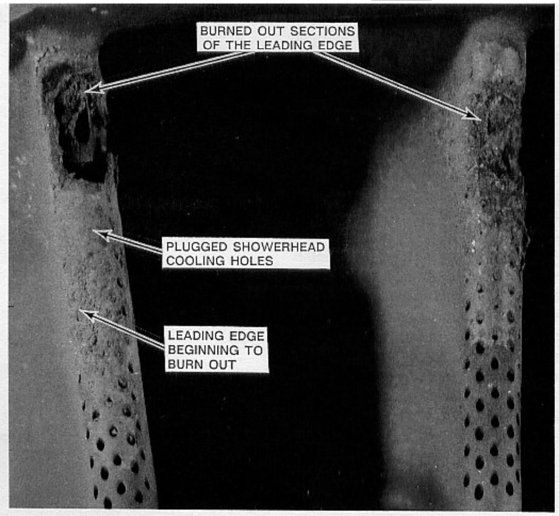
Motivation

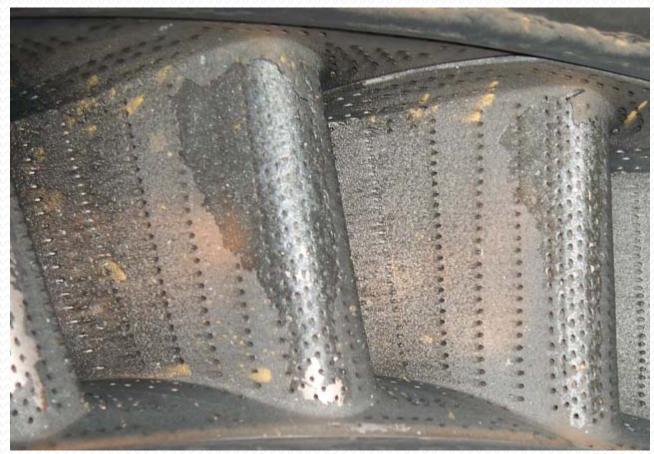
Turbine design considerations:

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

Better tools for turbine vane LE heat load, cooling requirements, and potential for deposition???



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)

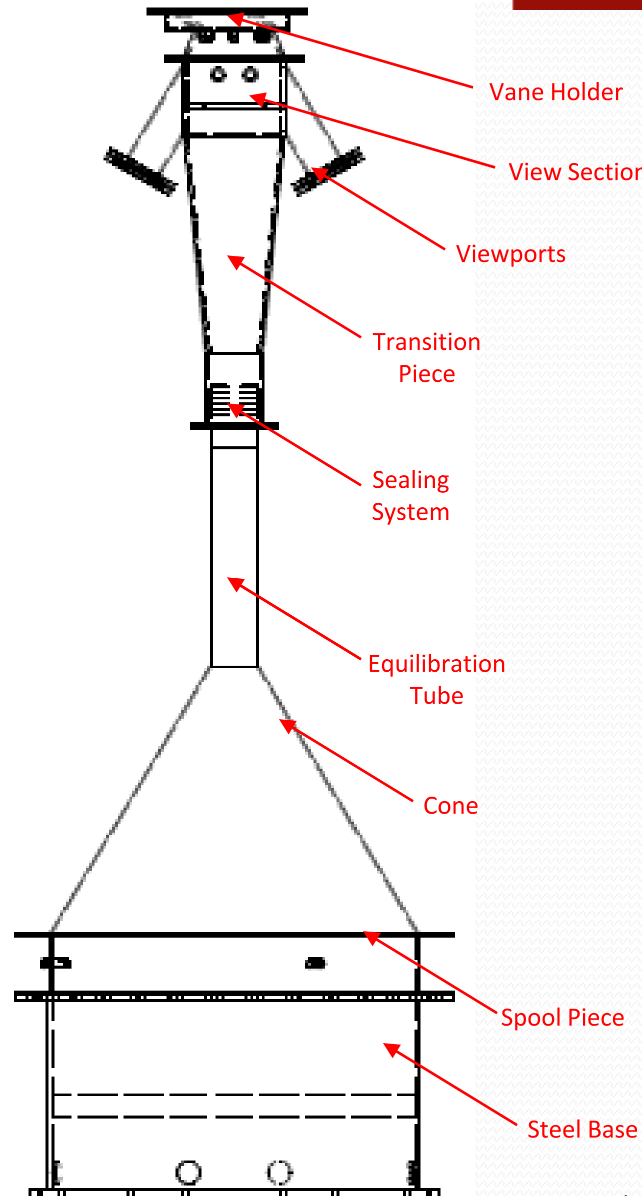
Critical Unanswered Questions

- 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!

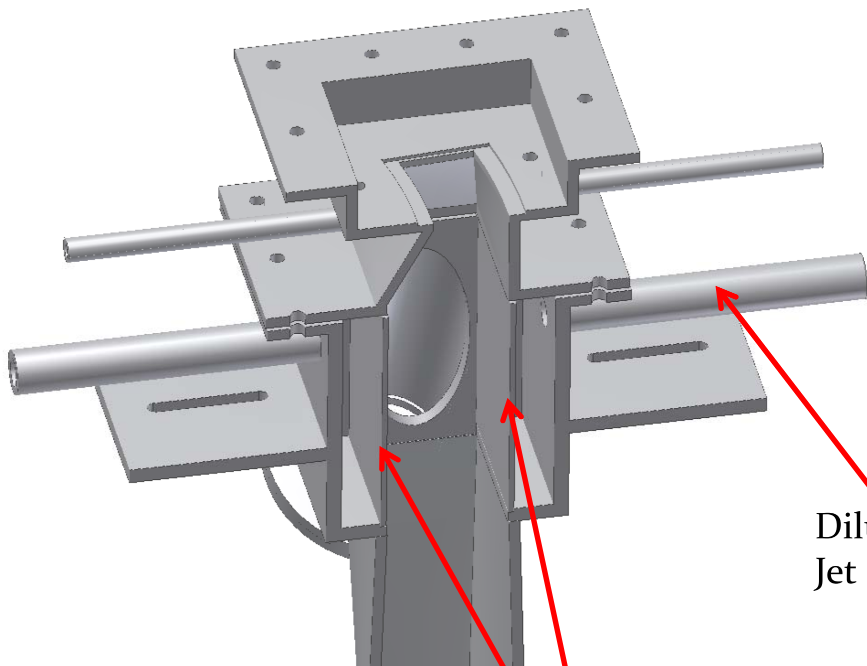
OSU's Turbine Reacting Flow Rig (TuRFR)

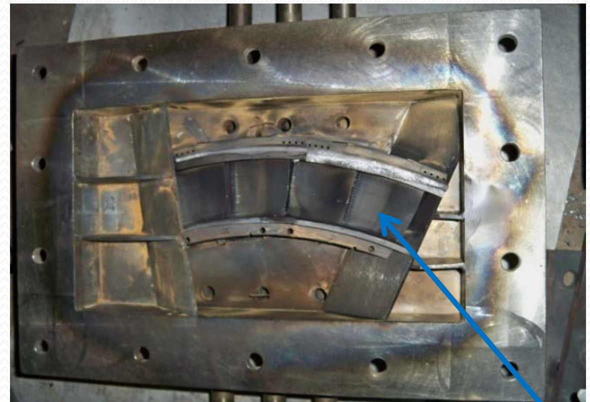
- Natural gas burning combustor rig
- Combustor exit flow accelerated in cone nozzle
- Transition from circular to annular sector
- Real vane hardware (industry supplied) installed in annular cascade sector
- Tt4 up to 1120°C (2050°F)
- Inlet Mach number ~ 0.1
- $300{,}000 < Re_{cex} < 1{,}000{,}000$
- 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)

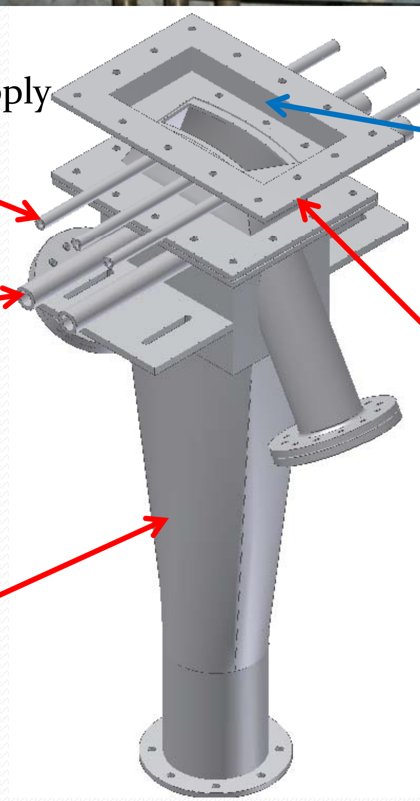


OSU's Turbine Reacting Flow Facility (TuRFR)

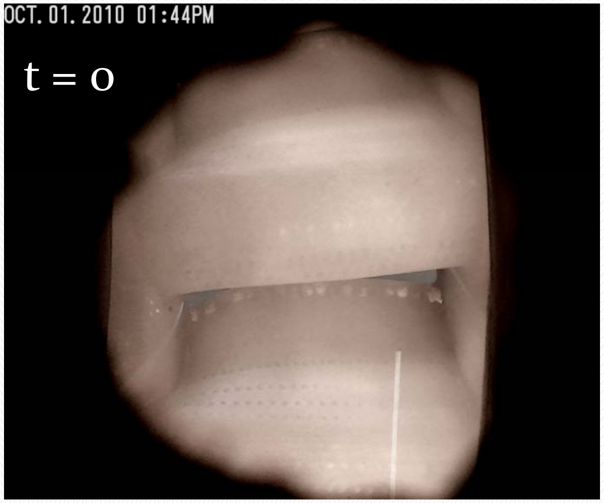
Vane Holder and Upstream Conditioning

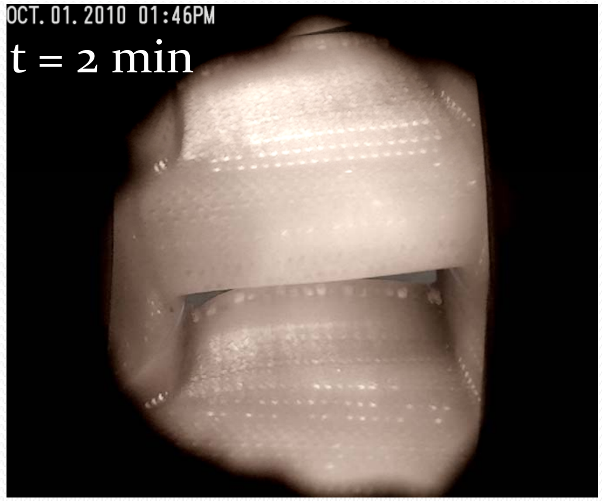


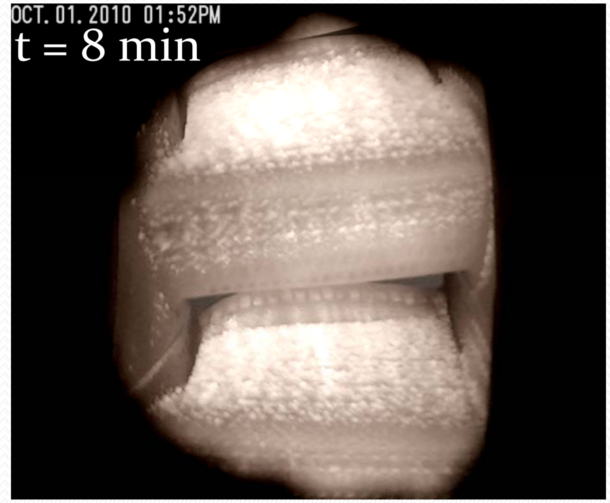


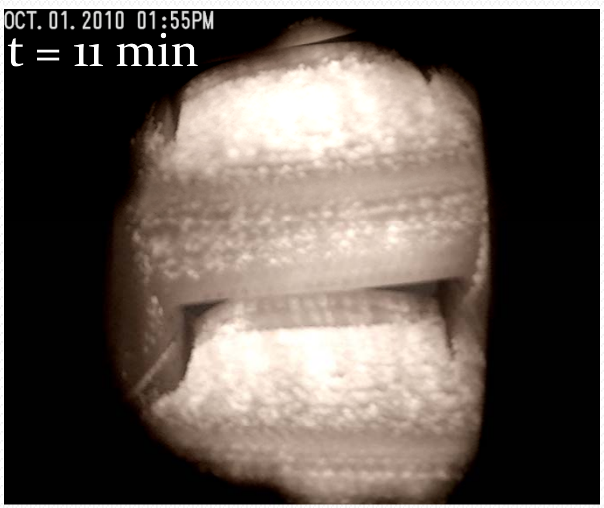


Typical TuRFR Test Sequence

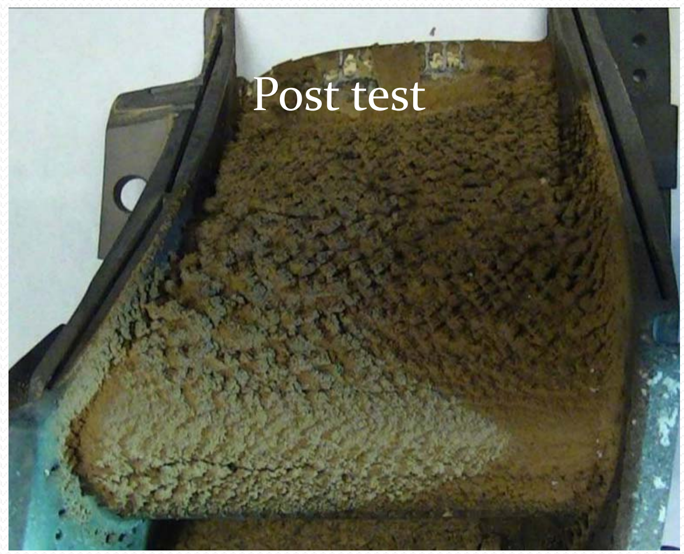




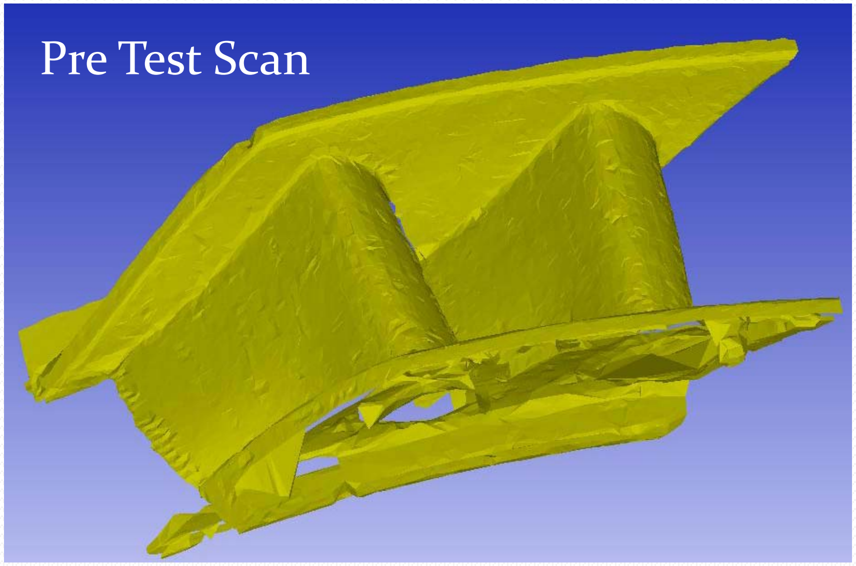


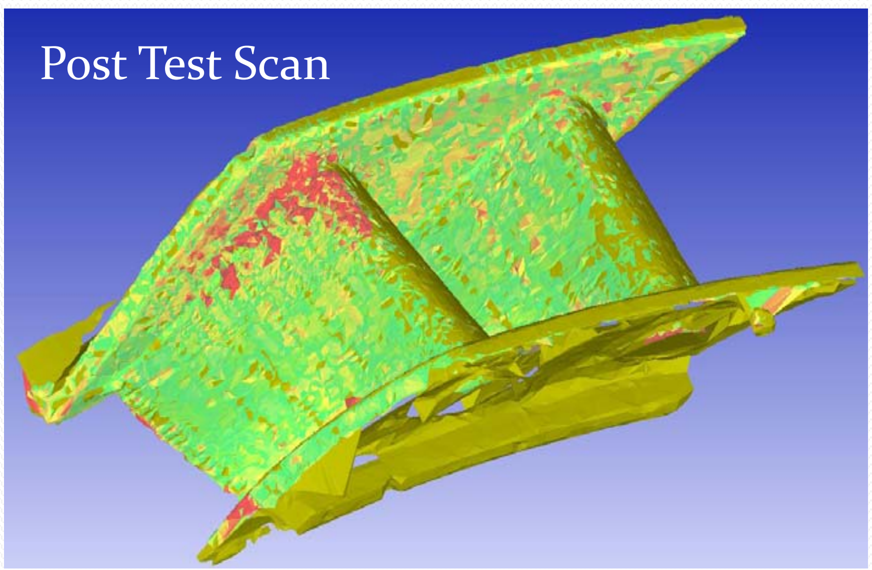


Time Lapse Images
Wyoming
Sub-Bituminous Ash
Test Conditions:
T_{t4}~1900F
M_{in}=0.90

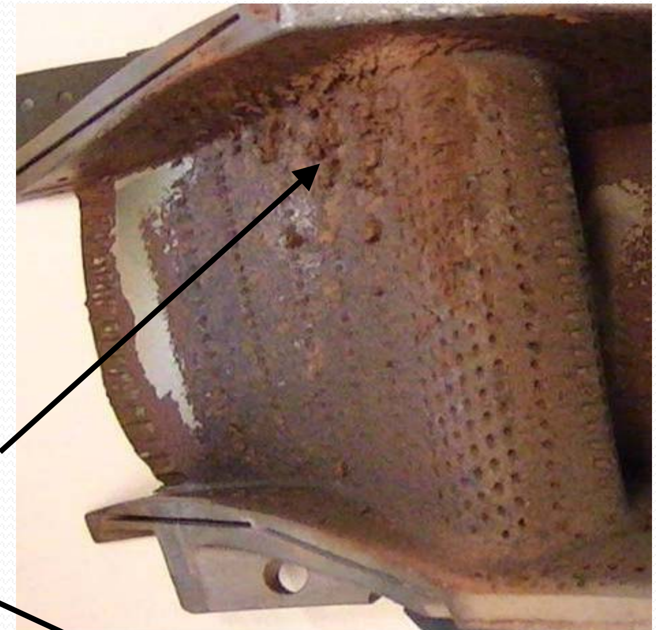


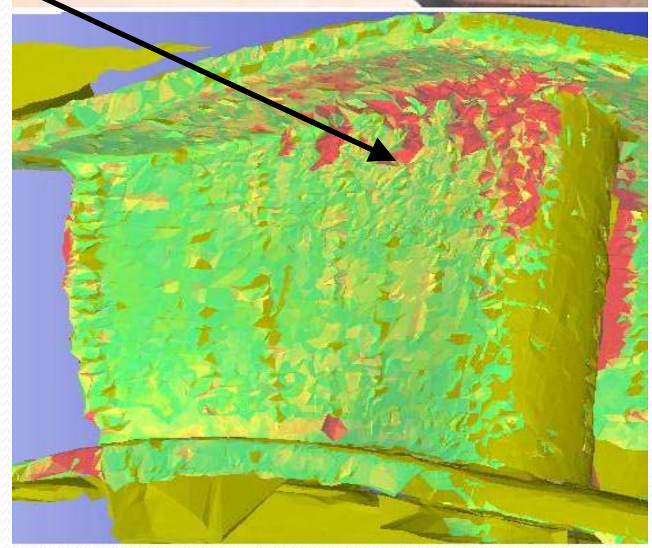
Post Test Diagnostics - Metrology





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



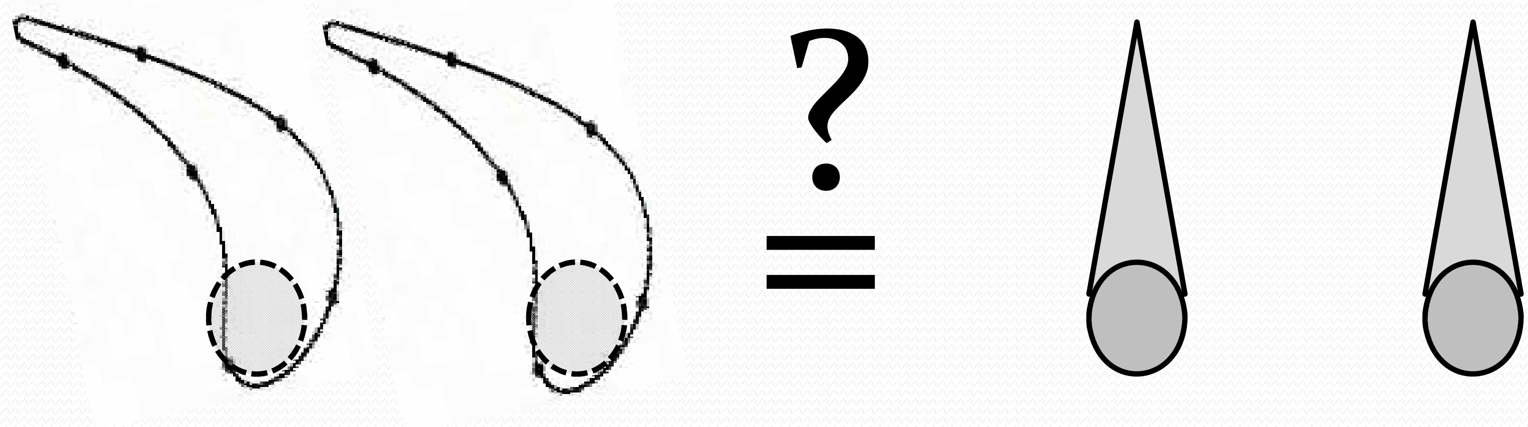


OSU Focus for New Grant

- 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



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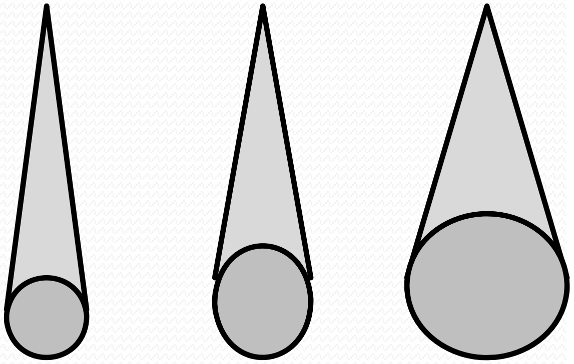
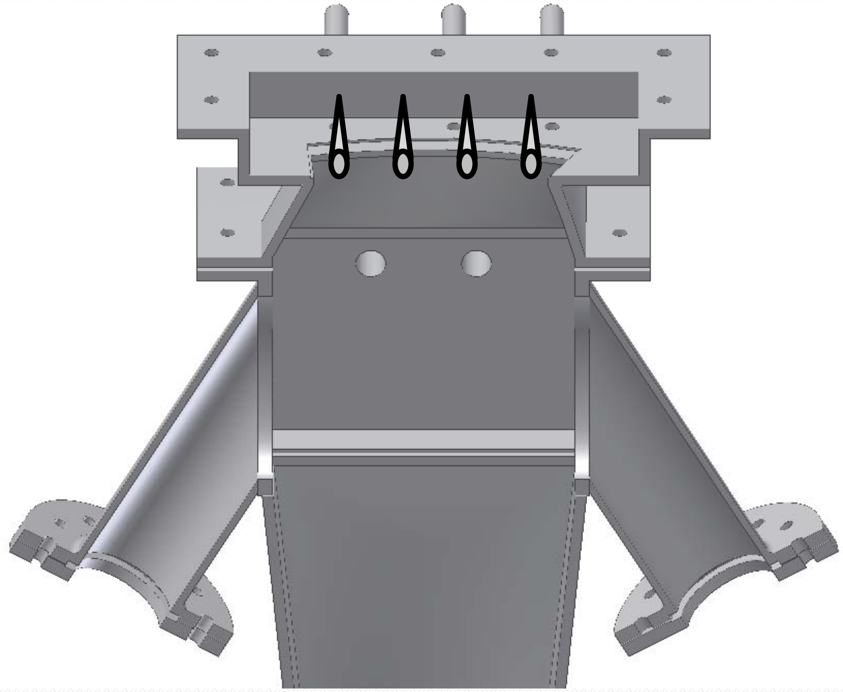
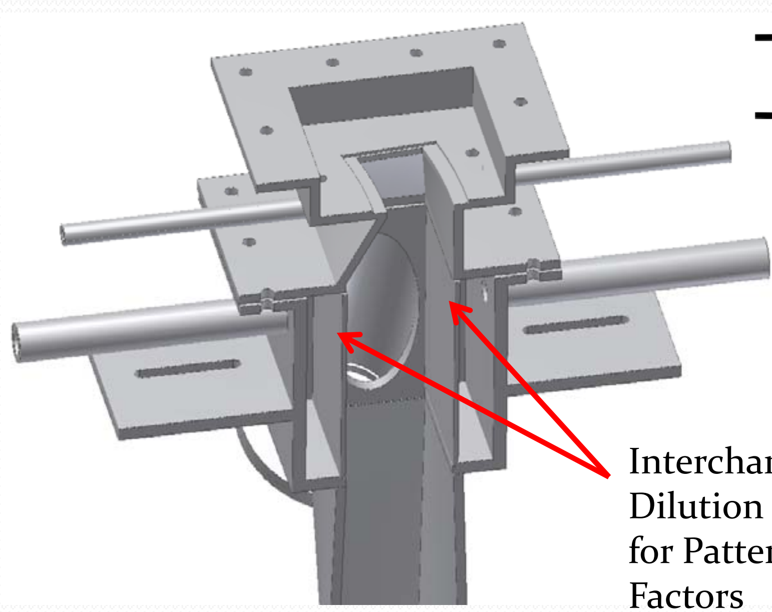


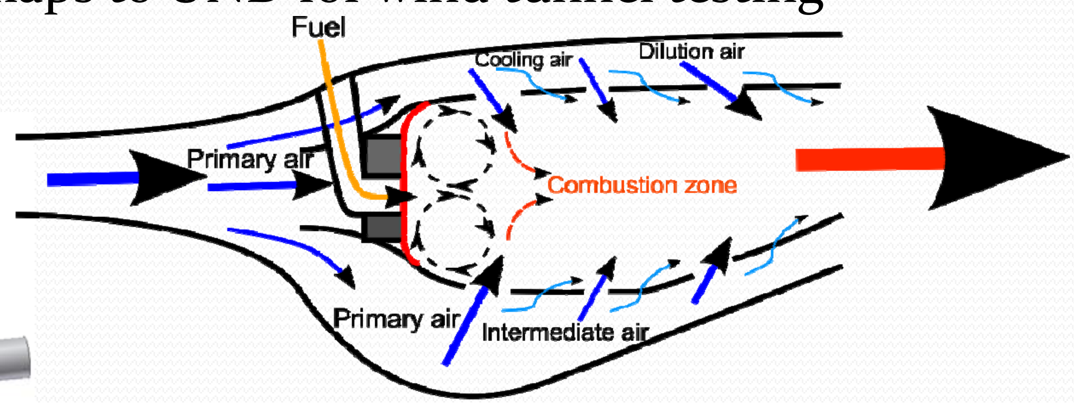


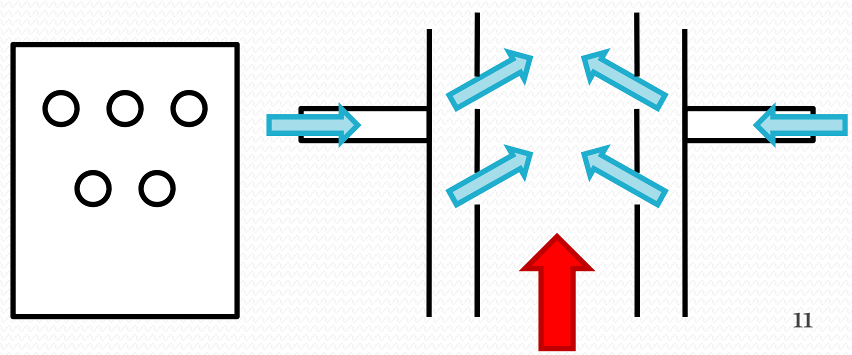
Phase 2: Deposition and Vane Inlet Turbulence

- 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 Pattern Factors





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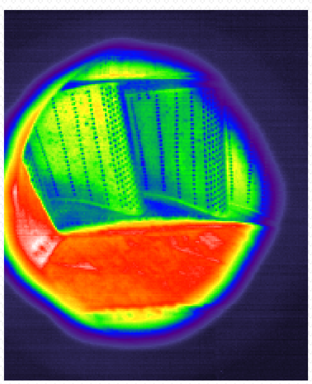
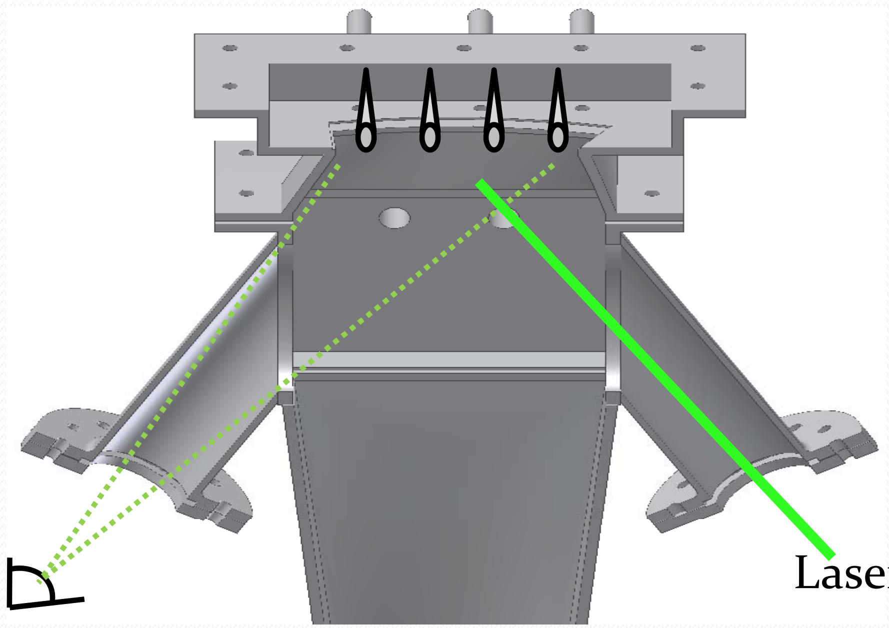
IR Camera Image



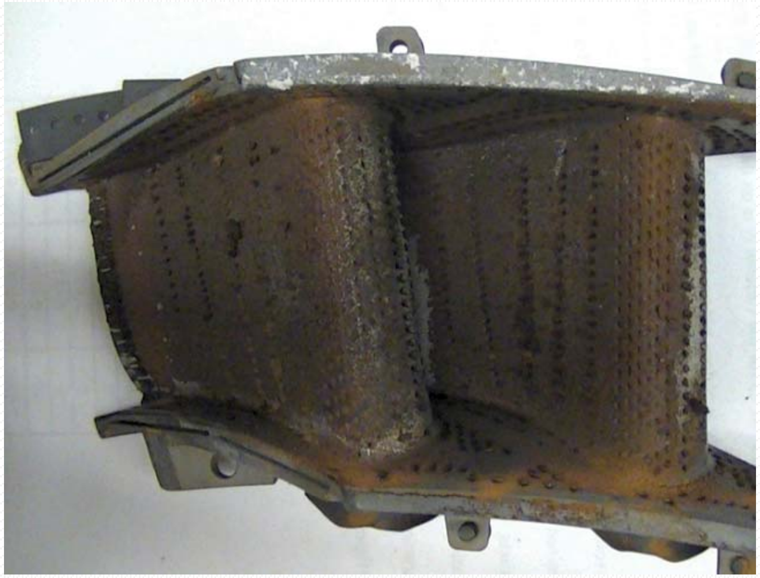


In-Situ Measurement
Rangefinder + IR camera + surface thermocouples = deposit thickness and conductivity
(Ref: Baxter et al., Sandia)

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

Critical Unanswered Questions

- What is the impact of increasing leading edge diameter with aggressive combustor turbulence on heat transfer?
- What is the combined influence of realistic roughness, larger leading edges and turbulence on heat transfer?
- How quickly does realistic roughness and turbulence dissipate downstream film cooling? What is the resulting effect on downstream heat transfer?
- Can we manage the heat load on the leading edge of vanes using internal cooling with larger leading edge diameter and TBC coatings?

Enabling Experimental Methodologies

- Generation of a wide range of relevant turbulence conditions.
- Isolating the influence of leading edge diameter on HT.
- Generation of realistically rough heat transfer surfaces.
- Acquisition of turbulent spectra and boundary layer measurements.
- Acquisition of local and full surface heat transfer and film cooling measurements.
- Acquisition of internal cooling and pressure drop data

Inlet Turbulence Conditions

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

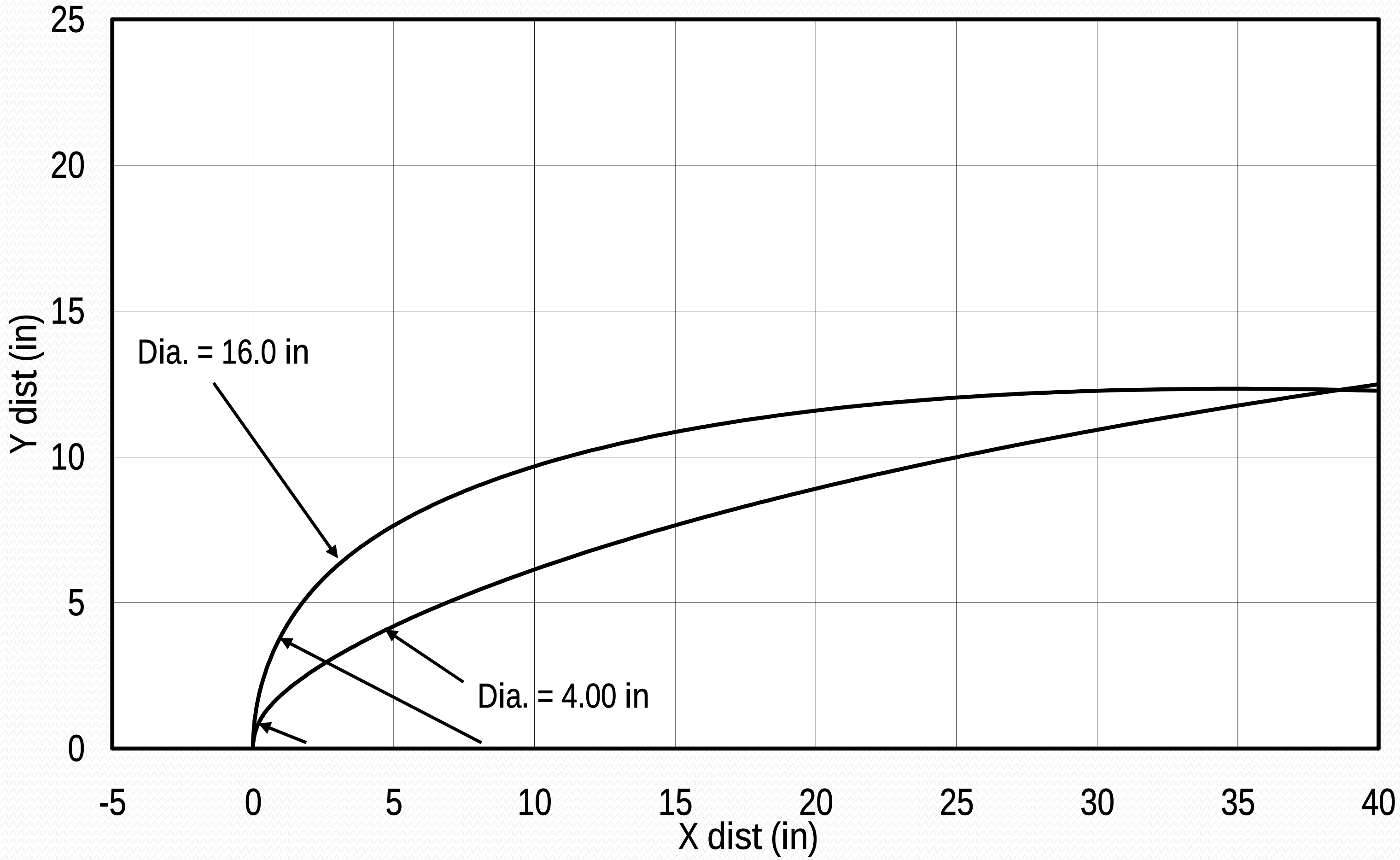
Grid turbulence will be generated with a small and a large grid. Both grids will be positioned 10 mesh lengths upstream from the cylinder leading edge. The small grid will also be positioned about 30 mesh lengths upstream to produce a lower level turbulence.

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

Turbulence Generator	Tu	Lu (cm)	Uinf (m/s)	Uinf (m/s)	Uinf (m/s)	Uinf (m/s)
AeroCombustor (no contraction)	***0.28***	***3.7***	***15***	***10***	***5***	***2.5***
AeroCombustor (2:1 area ratio contr.)	0.14	7.25	20	10	5	2.5
AeroCombustor (with decay spool)	0.09	9	20	10	5	2.5
Grid (bar=1.27cm, mesh = 6.35 cm)	0.08	3.5	20	10	5	2.5
Grid (bar=.635 cm, mesh = 3.175 cm)	***0.08***	***1.75***	***20***	***10***	***5***	***2.5***
Grid (bar=.635 cm, mesh = 3.175 cm)	***0.05***	***2***	***20***	***10***	***5***	***2.5***
Low Turbulence	0.007	5	20	10	5	2.5

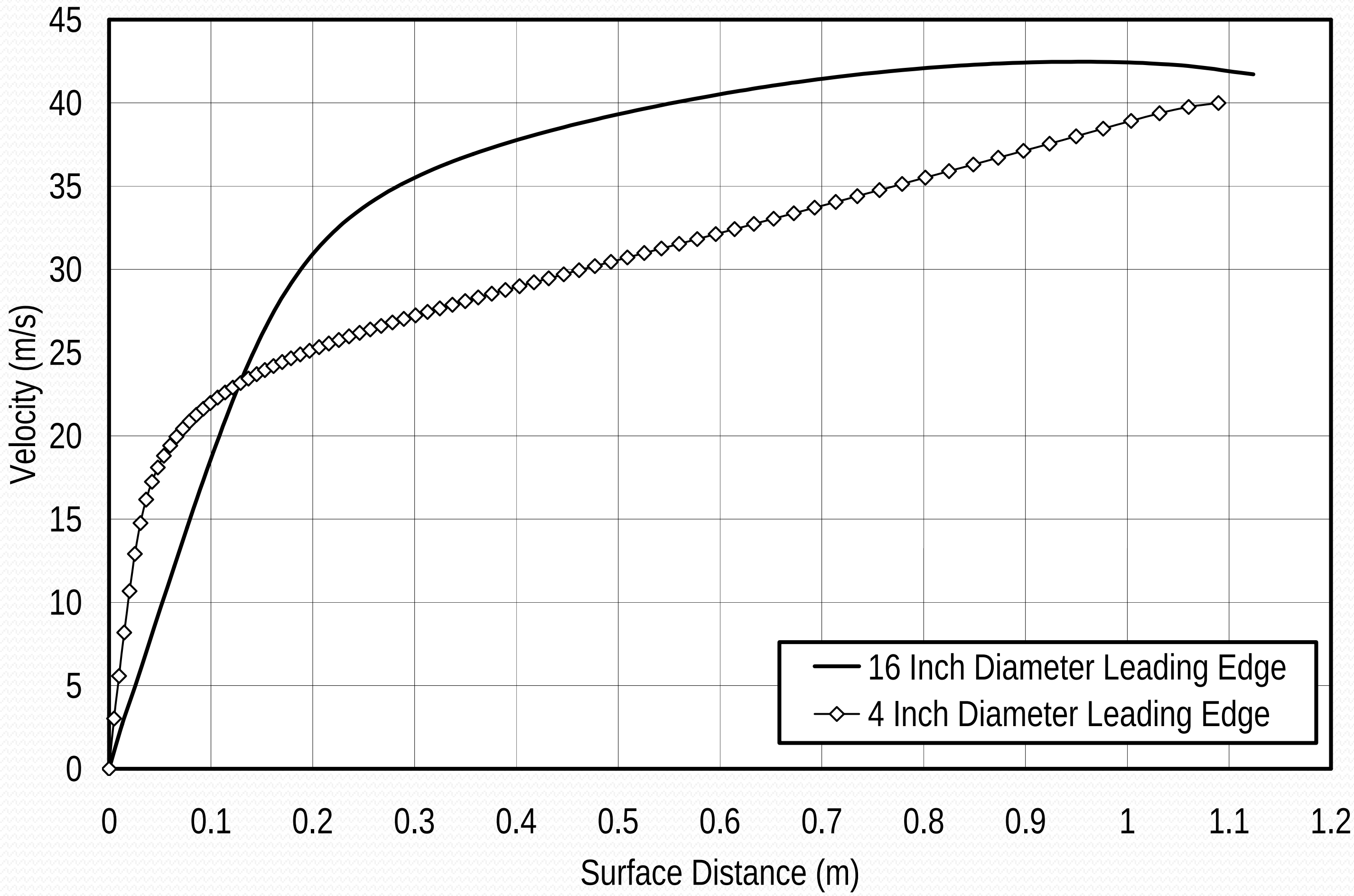
Leading Edge Cylinders

The two leading edge cylinders have 10.16 cm and 40.64 cm diameter leading edge regions over +/- 30°. The downstream afterbodies are designed to keep the flow accelerating over the entire heat transfer surface.



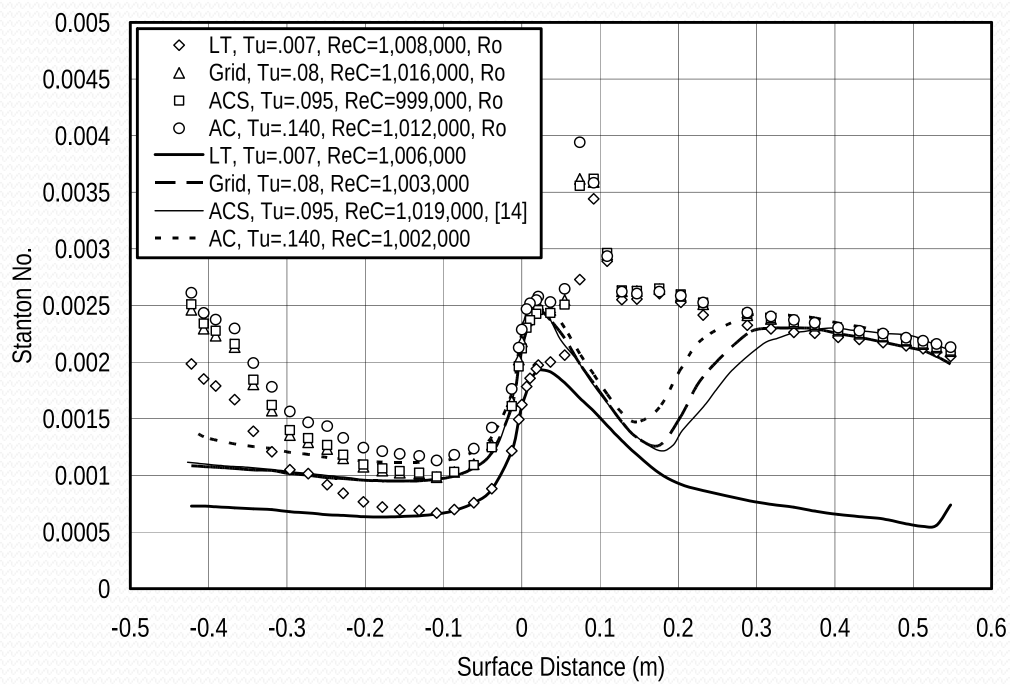
Leading Edge Cylinders

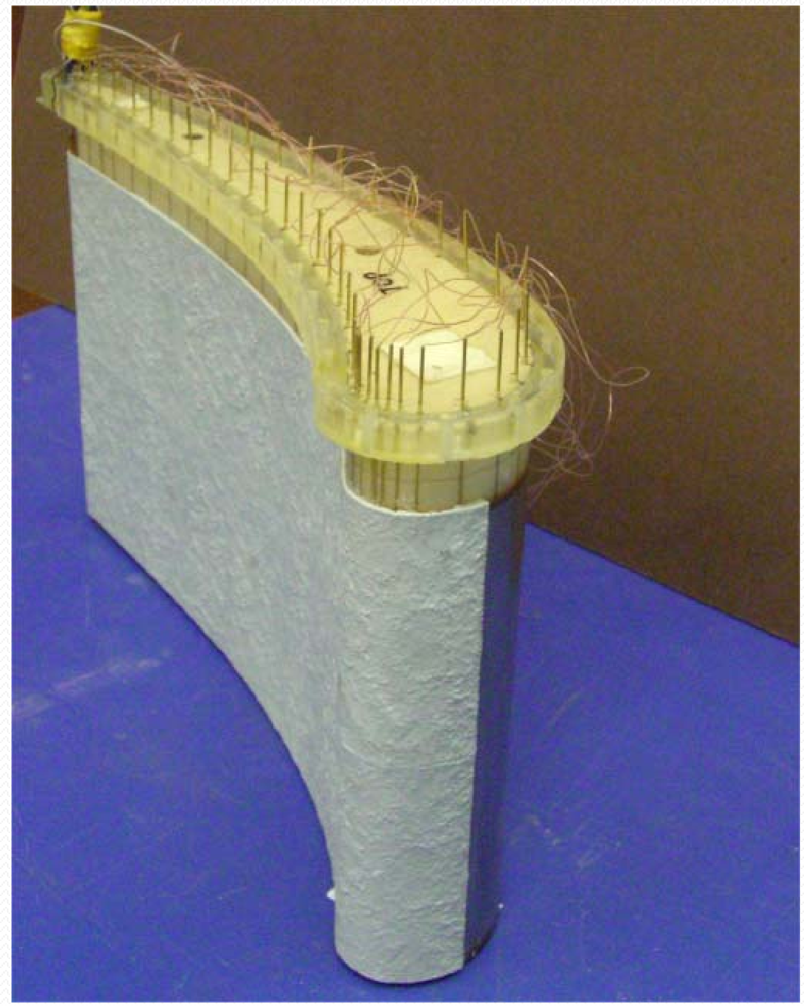
The stagnation region of two leading edge cylinders exhibit a strong linear acceleration. Locations for full coverage film cooling, downstream of the stagnation region, will chosen based on industry recommendations.



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.

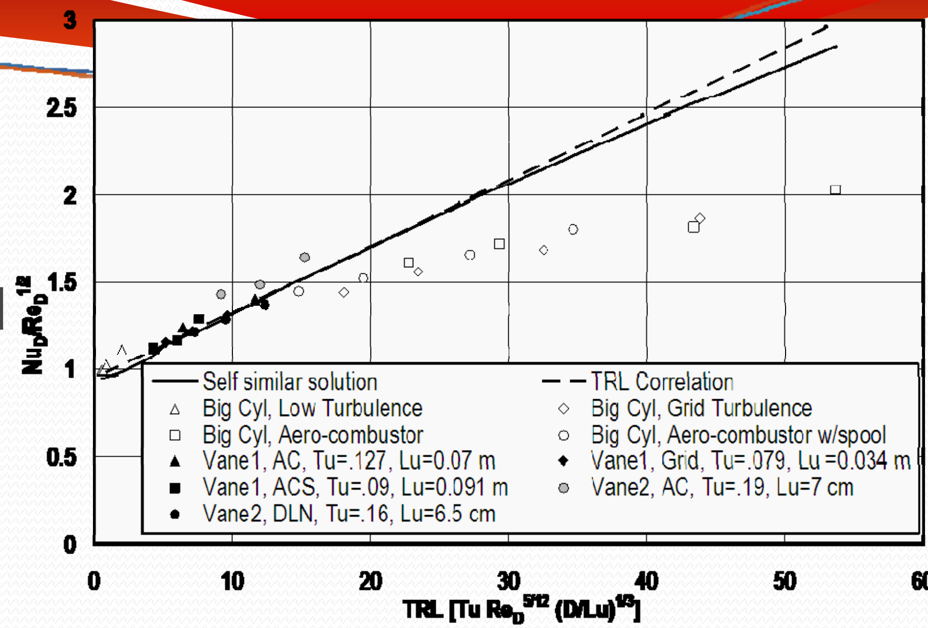
Vane surface Stanton number data show that roughness causes early transition but in this case has no impact before transition. Literature data (Bunker) show direct augmentation on leading edge at high Reynolds numbers.

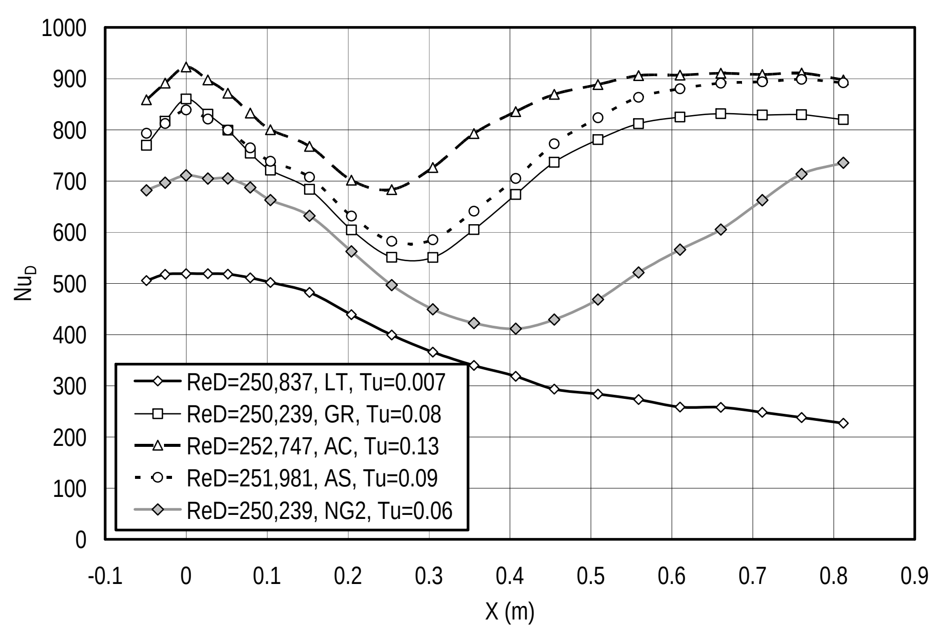




Initial stagnation region heat transfer data from UND's Large Cylinder Rig show new trends compared with conventional studies. UND's Large Cylinder Rig, with largest diameter cylinder is pictured below attached to UND's wind tunnel

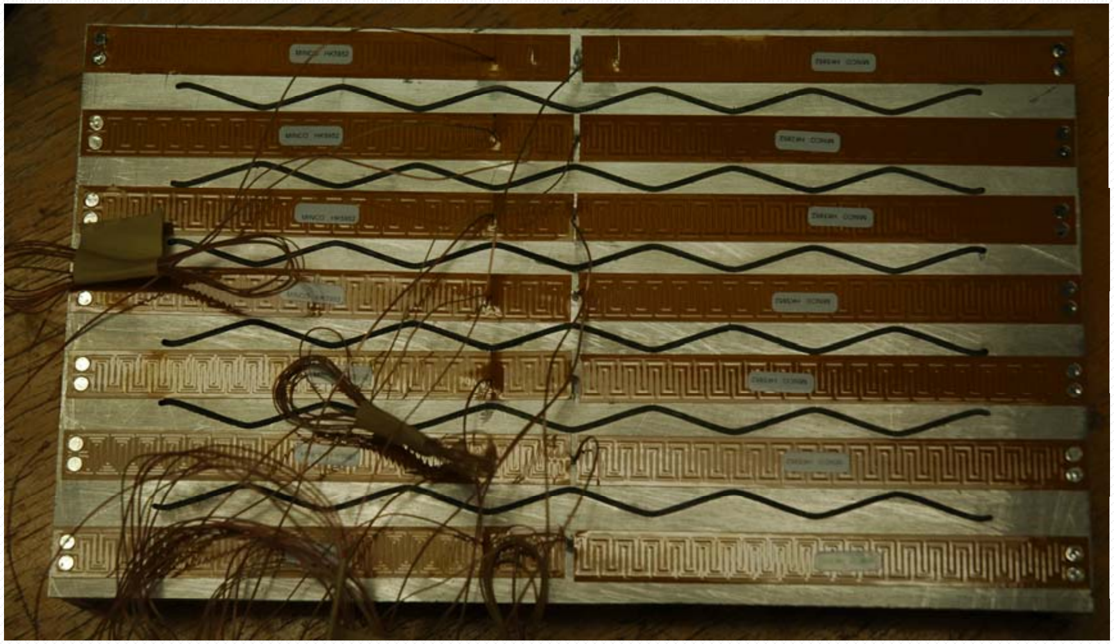
Initial streamwise data for UND's Big cylinder rig show high heat transfer augmentation as well as transition effects.





Internal Cooling Methods

Double wall cooling arrangements offer more surface area for internal cooling. However, solidity of pedestals needs to be high enough to mitigate stresses and transfer thermal energy between inner and outer walls. For longer arrays both pressure drop and local coolant to wall temperatures will need to be managed.



Questions?