Development of Cooled Vanes for the HIT Research Turbine

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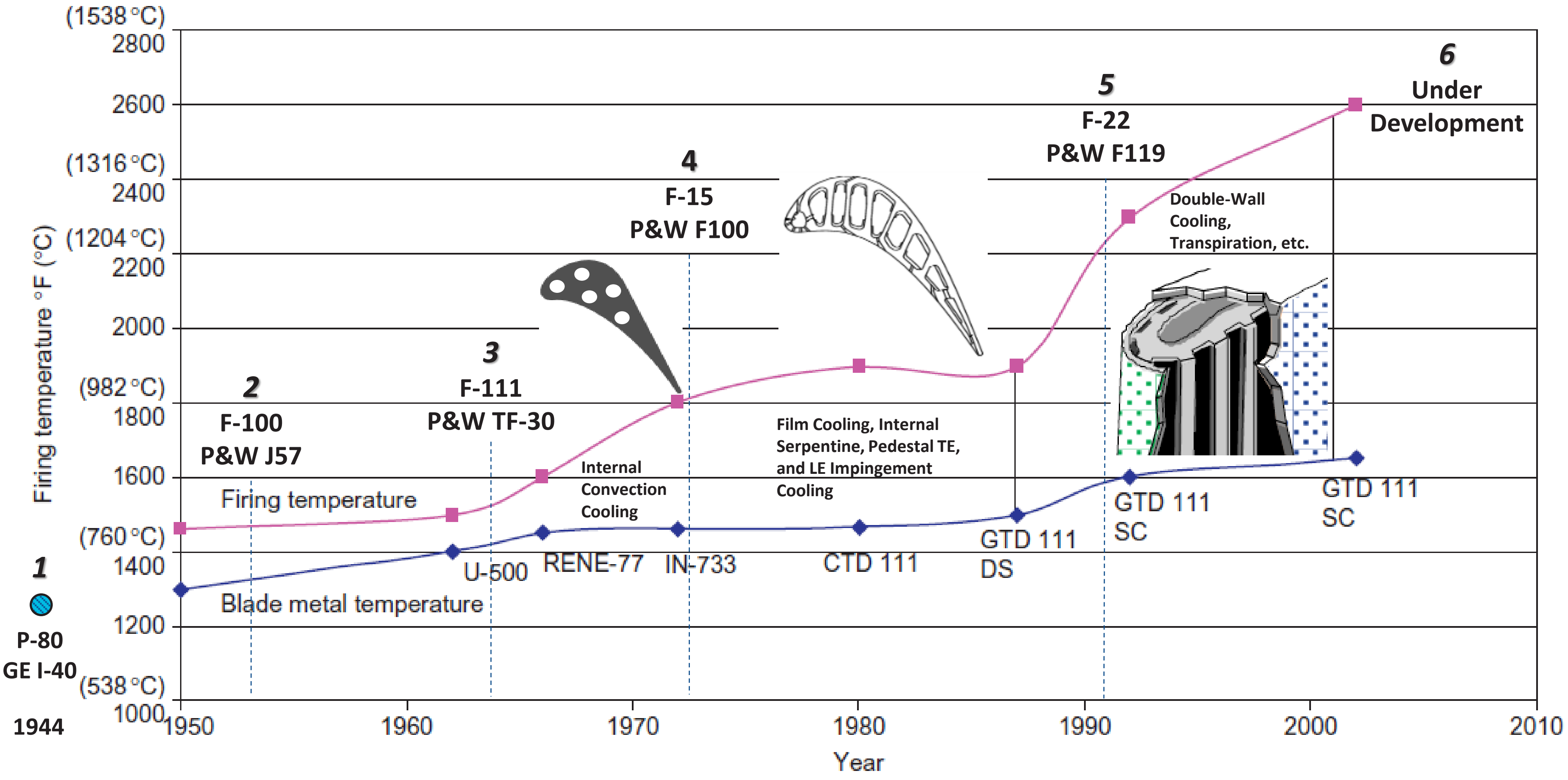
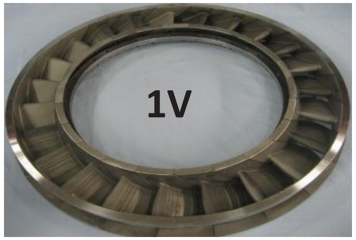
Turbine Development Relative to Fighter-Aircraft Generations

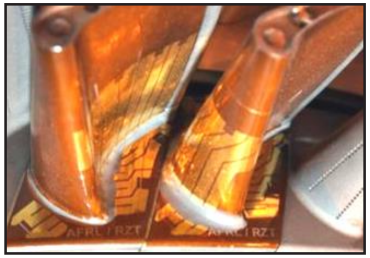


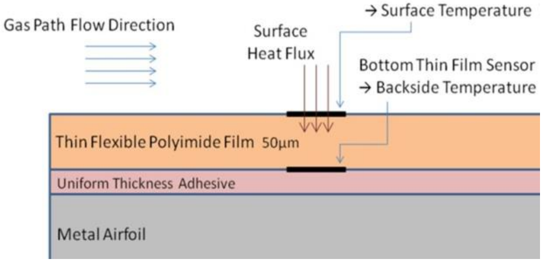
Adapted from : Boyce, M. P., 2006, *Gas Turbine Engineering Handbook*, 3rd Edition,
Sullivan, M. P., 2008, *Dependable Engines*,
Lakshminarayana, B., 1996, *Fluid Dynamics and Heat Transfer of Turbomachinery*,
and Bunker, R. S., 2013, GT2013-94174

Rotating Turbine Experiments are Conducted in the AFRL Turbine Research Facility (TRF)

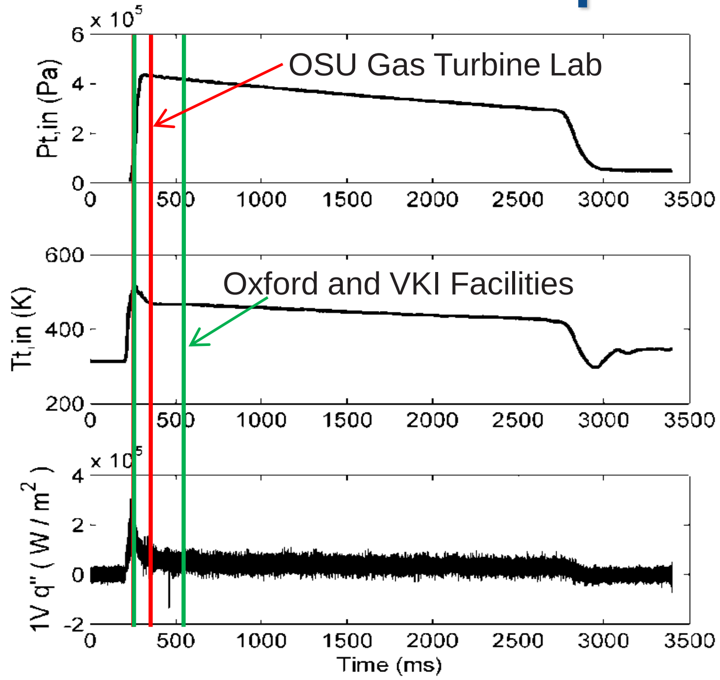
- Short-duration turbine blowdown rig capable of testing full scale turbine hardware
- Cost-effective study of complex 3D unsteady rotating turbine flowfields with heat transfer
- Provides detailed rotating HPT measurement options at much lower cost than engine testing

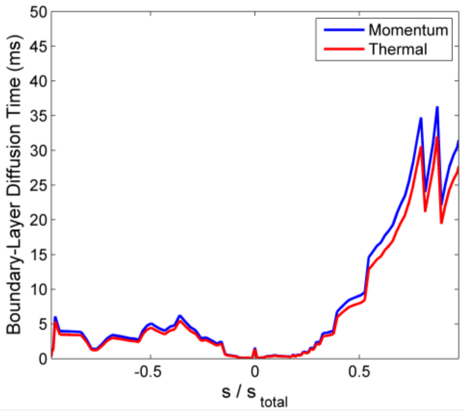






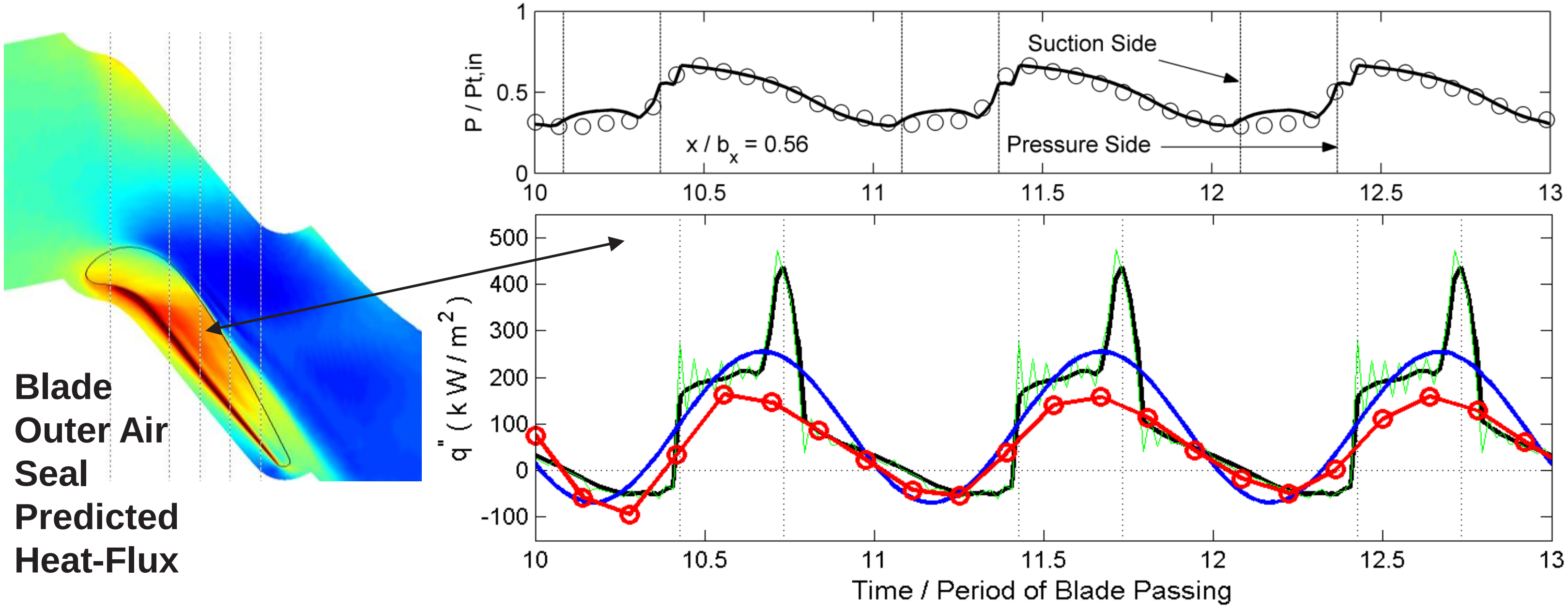
AFRL TRF has a Significantly Longer Run Time Than Comparable Short-Duration Facilities





- Time-scale of compression-wave on startup ≈250ms
- Time-scale of boundary-layer establishment on surfaces ≈ 50ms
- Time-scale to set airfoil pressure field ≈ 5ms
- So, useful run-time is ≈ 2000ms

Early Validation Efforts in TRF Focused on OEM Geometries, e.g. BOAS Heat-Flux Validation

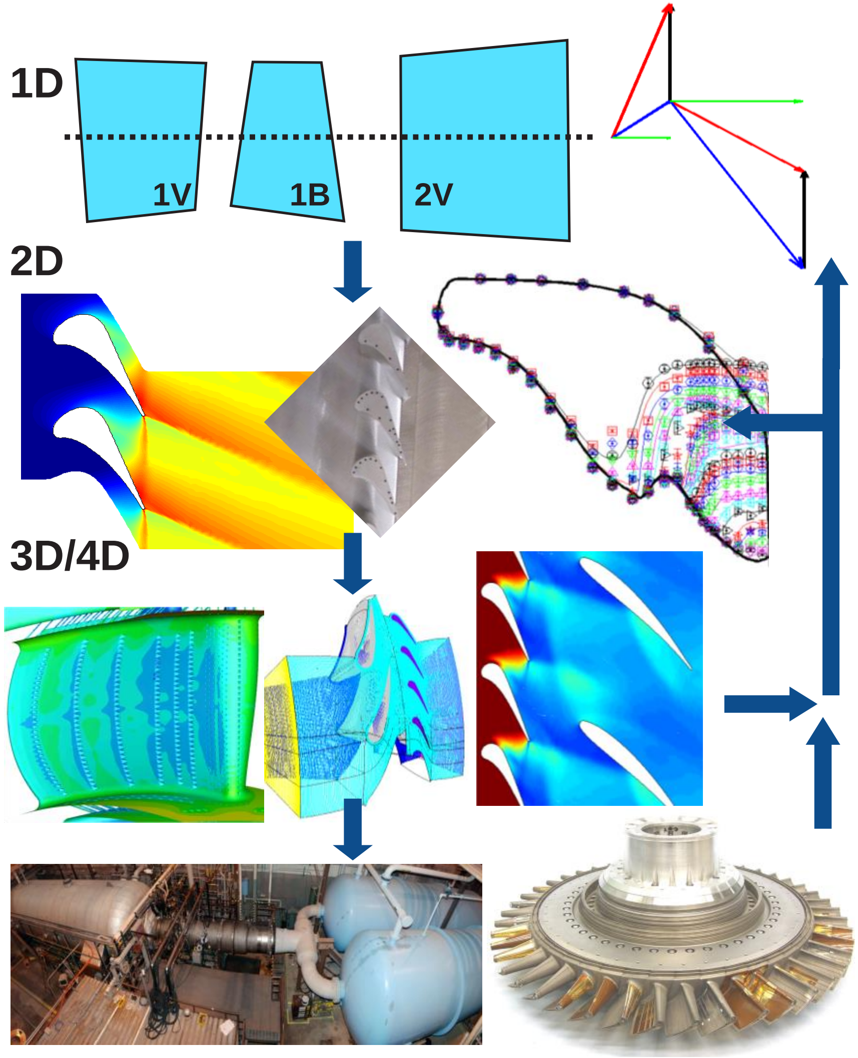


Blade Outer Air Seal Predicted Heat-Flux

- Ability to predict unsteady loadings and local heat-flux benchmarked directly
- Time-mean inlet flowfield measurements from a TRF run were used to set CFD boundary conditions

SAB 2002: Benchmarking Efforts at AFRL Must be of Use Throughout US Gas Turbine Industry

Turbine Research at AFRL Involves Well Integrated Numerical and Physical Experiments

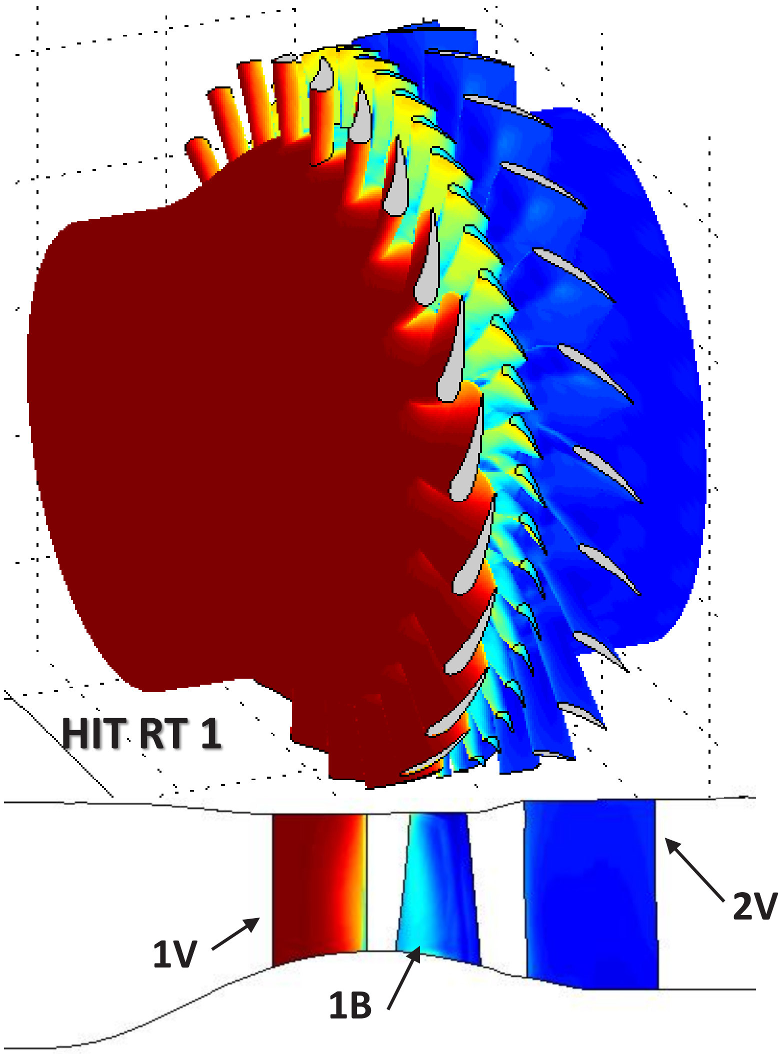


- Development of turbine components consistent with advanced engines
  - Geometries and data are freely available to US industry

- Physical experiments in a number of facilities to enhance understanding
  - Flat plate experiments to assess cooling behavior
  - Transonic cascade experiments to gauge predictions of nominally steady aerodynamics
  - Heavily instrumented rotating experiments

- Numerical experiments to enhance understanding and to improve physics-based design methods
  - Benchmarked CHT analysis
  - Evaluated means to mitigate shock interactions
  - Optimized airfoils for improved cooling effectiveness

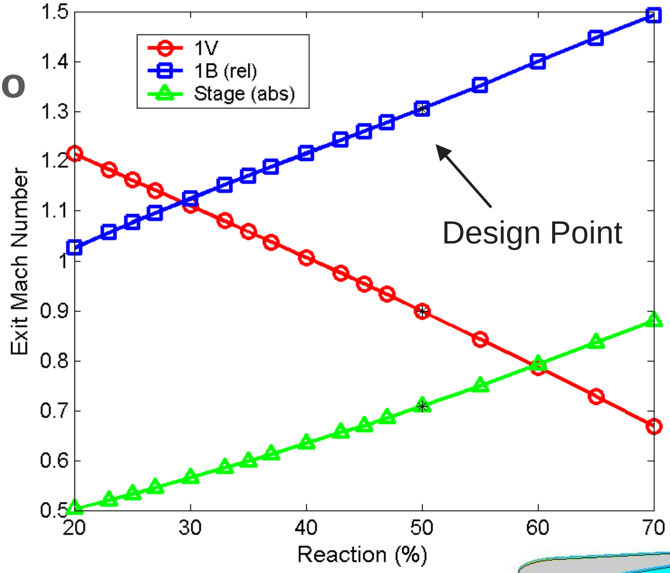
AFRL HIT Research Turbine: A Platform for Investigating Unsteady Aero and Heat Transfer



T3 (K)	**222**			
T4 (K)	**444**			
Inlet Flow Parameter [(kg/s) $K^{1/2}$ / kPa]	**1.13**			
	1V	1B	2V	2B
Work Coefficient [(g J Δh) / U_{mean}^2]	----	2.08	----	2.01
Flow Coefficieny ($C_{x,exit}$ / U_{mean})	----	0.71	----	1.2
Efficiency (%)	----	87.3	----	95.8
Pressure Ratio (Total-Total)	**----**	**3.75**	**----**	**1.85**
Reaction (%)	----	49.5	----	55.0
N / $Tt,in^{1/2}$ (RPM / $K^{1/2}$)	----	361	----	279
AN^2 x10^{-6} (m RPM)^2 [Engine / Rig]	----	37 / 8.4	----	21 / 4.8
Exit Mach Number	0.88	1.30 (rel)	0.89	0.94 (rel)
Turning (degrees)	77	115	11	80
Percent Cooling	**7**	**4**	**5**	**2**
Airfoil Count	23	46	23	69
Zweifel Coefficient	0.85	1.13	0.4	1.25

HIT RT: Development of the NGV

1D Aero

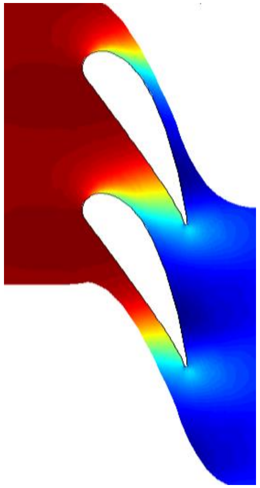


Instrumentation

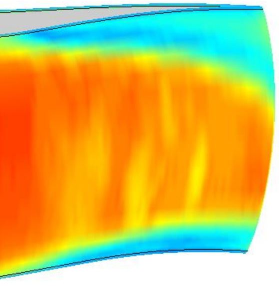
Finish Machining

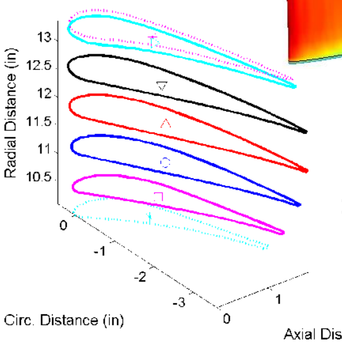
Casting

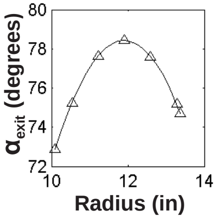
2D Aero



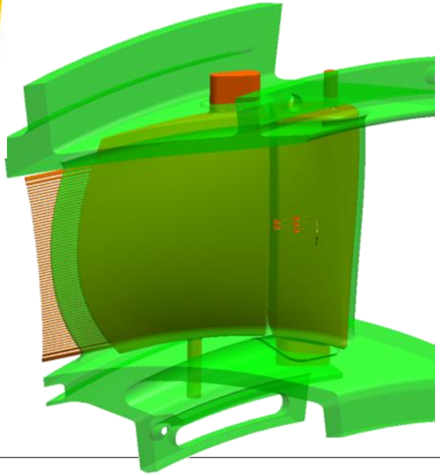
3D/4D Aero/Heat Transfer

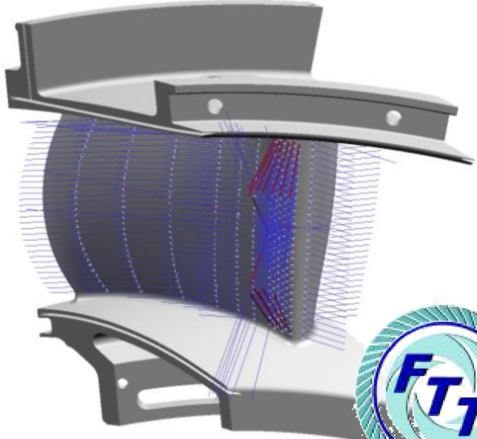




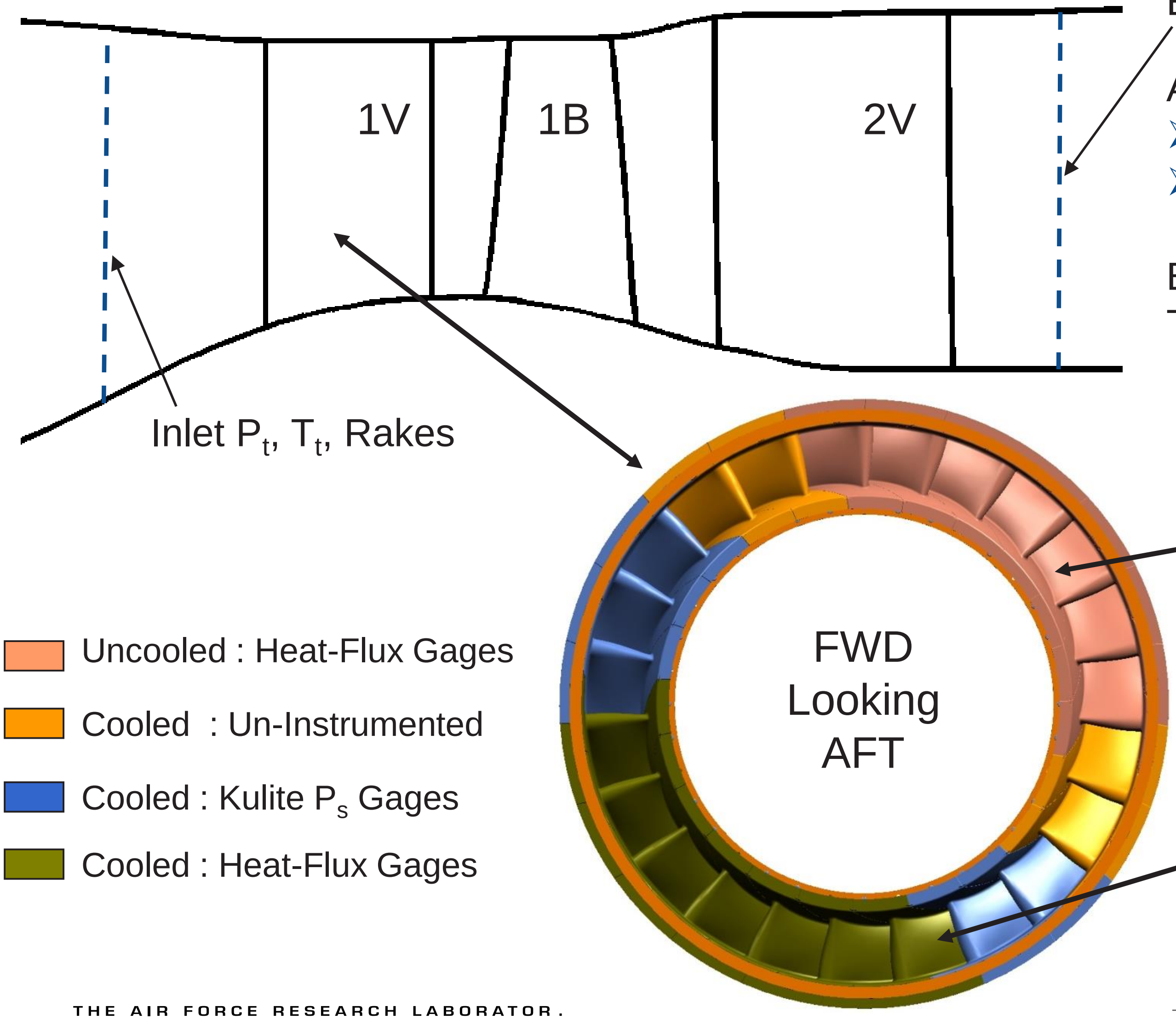


Mechanical and Cooling Design





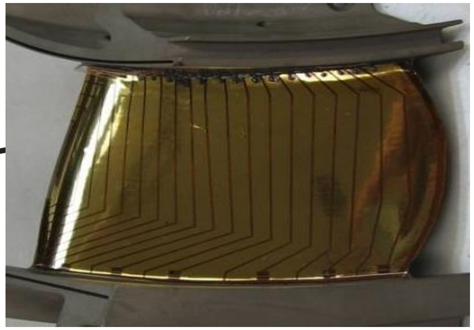
HIT RT Instrumentation Summary

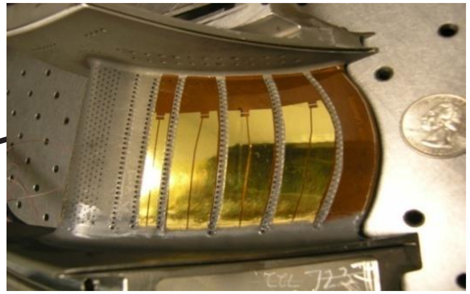


Exit P_t and T_t Rakes

Airfoils and Endwalls:
- 289 Kulite P_s Gages
- 347 Heat-Flux Gages

Broach Slot: Heat-flux, Temperature, and P_s Gages





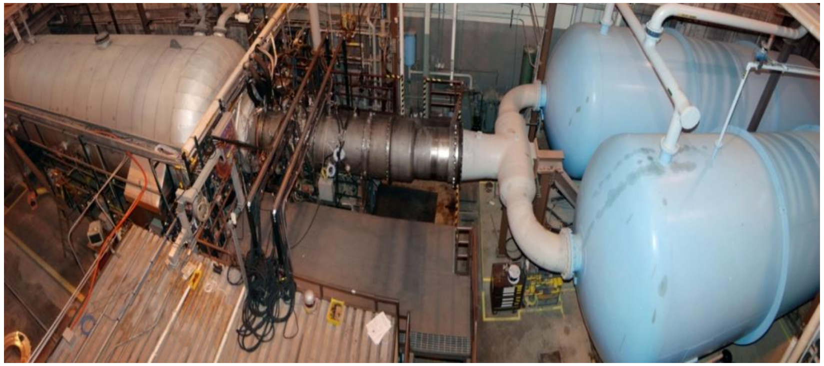
🟥 Uncooled : Heat-Flux Gages

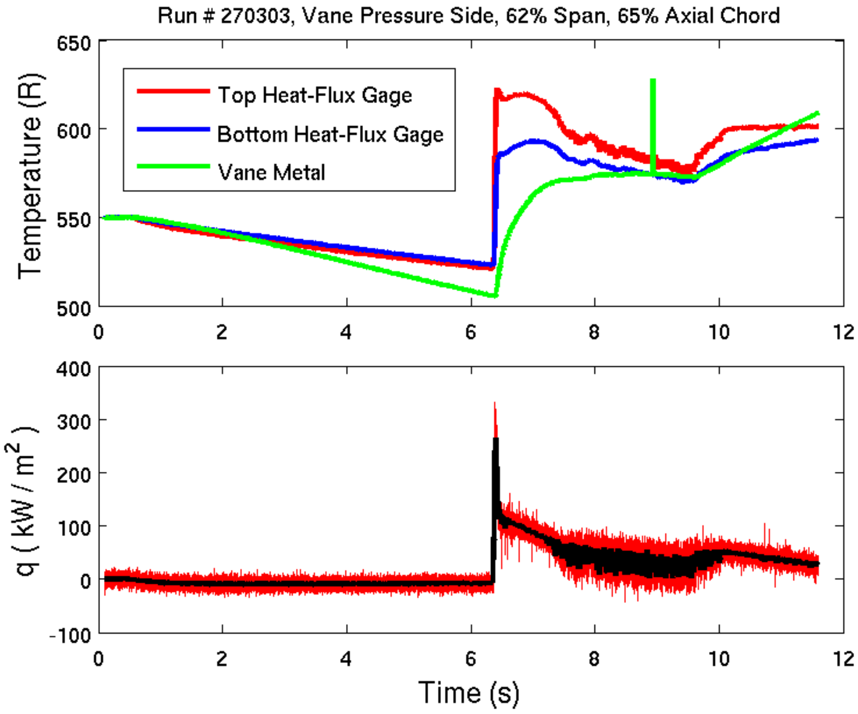
🟧 Cooled : Un-Instrumented

🟦 Cooled : Kulite P_s Gages

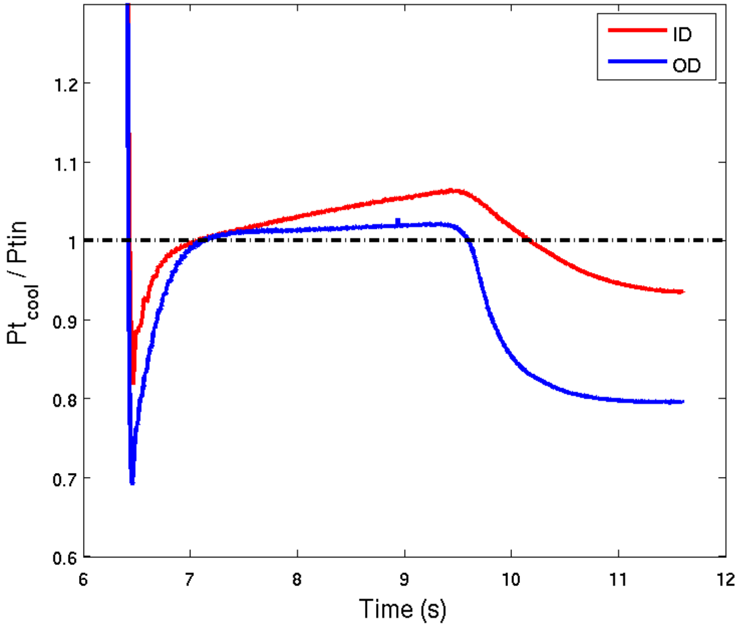
🟩 Cooled : Heat-Flux Gages

TRF Time Scales for Annular Cascade Experiments

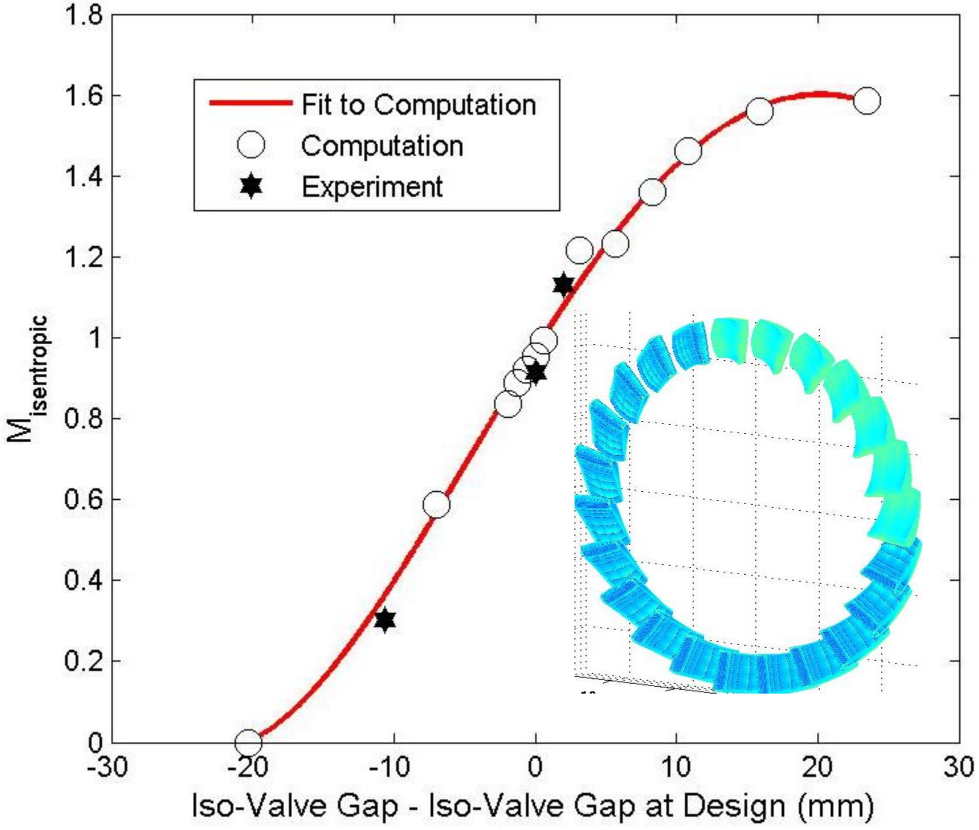


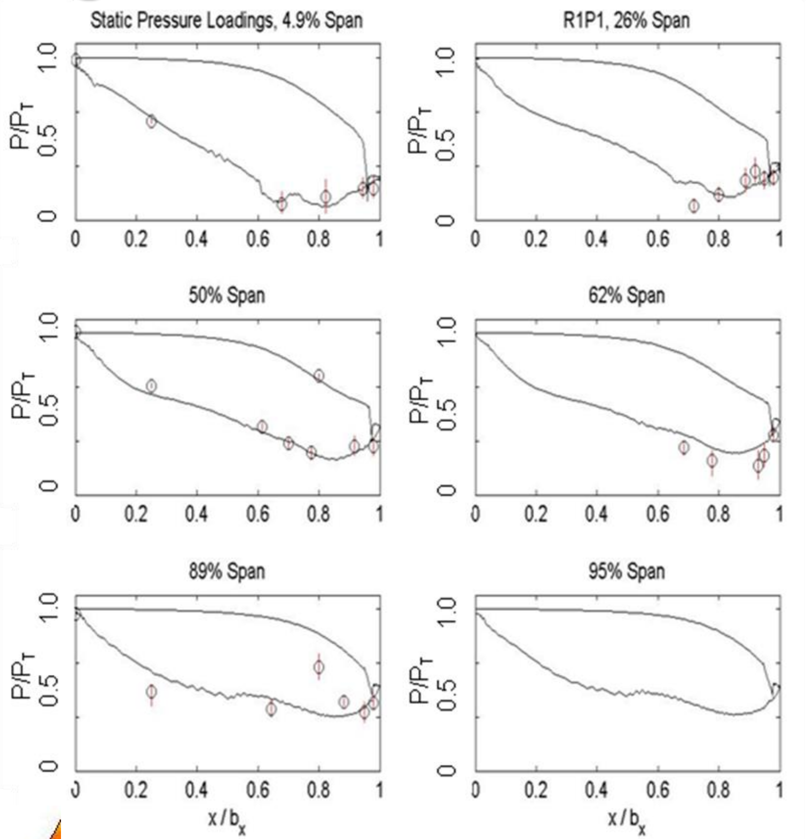


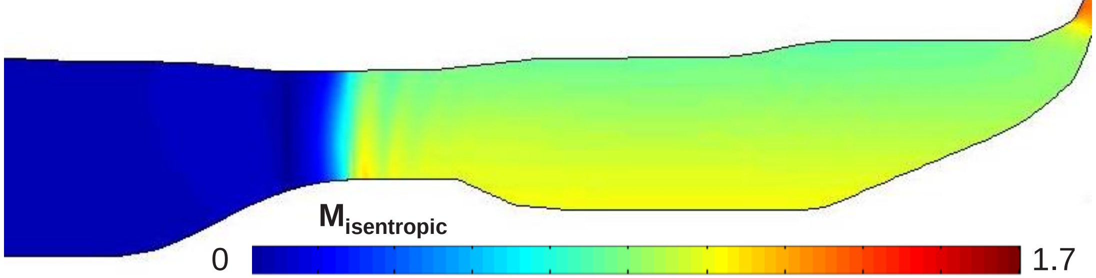
- Startup compression-wave ≈250ms
- Boundary-layer establishment ≈ 50ms
- Airfoil pressure field ≈ 5ms
- **Cooling-flow transients ≈1200ms**
- Useful run time ≈ 2000ms



Pre-Test Simulations are Used to Guide Experimental Programs

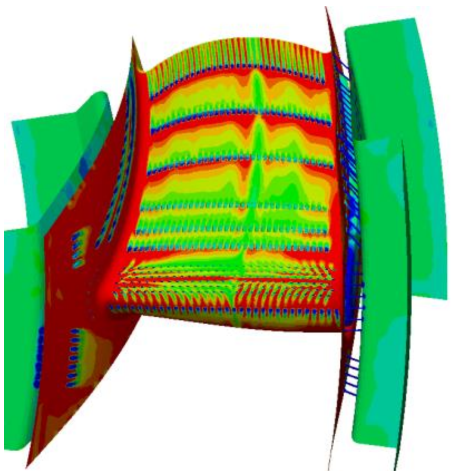


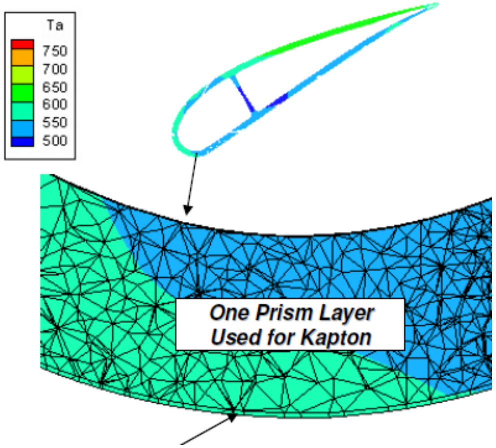




Isolation-valve position required to achieve design exit Mach number was set via 3D RANS analysis

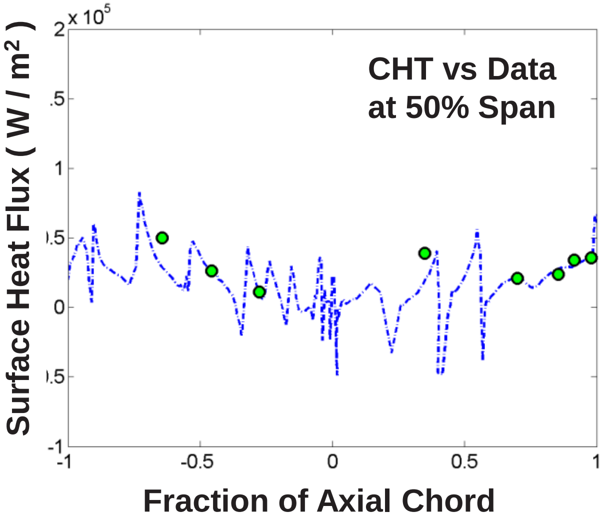
HIT RT 1V Annular Cascade Data was Used to Benchmark CHT Analysis



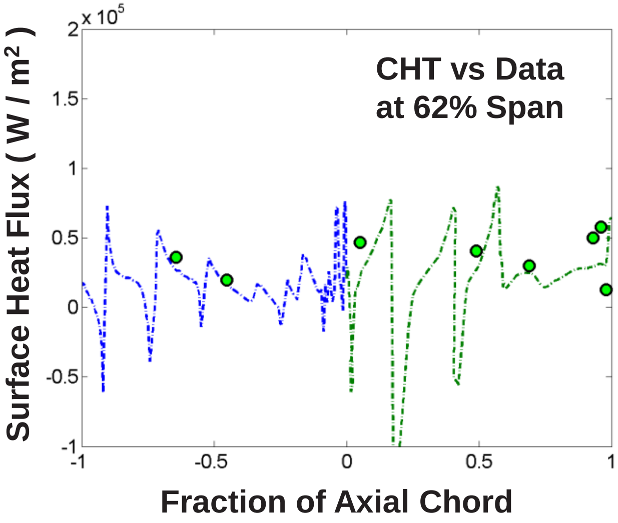


Kapton acts as a TBC Layer

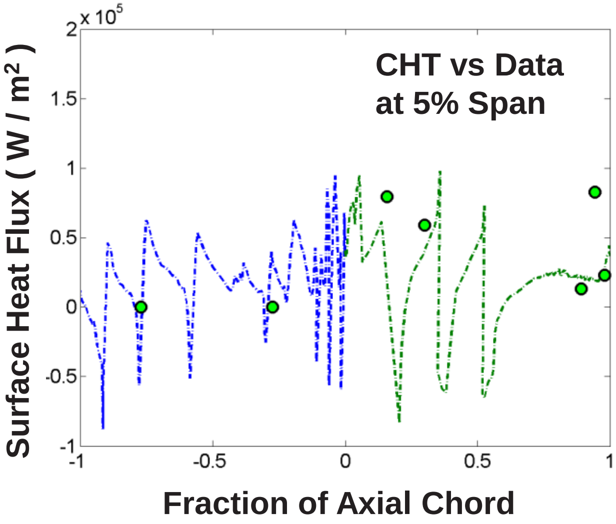
Instrumented Vanes



CHT vs Data at 50% Span



CHT vs Data at 62% Span



CHT vs Data at 5% Span

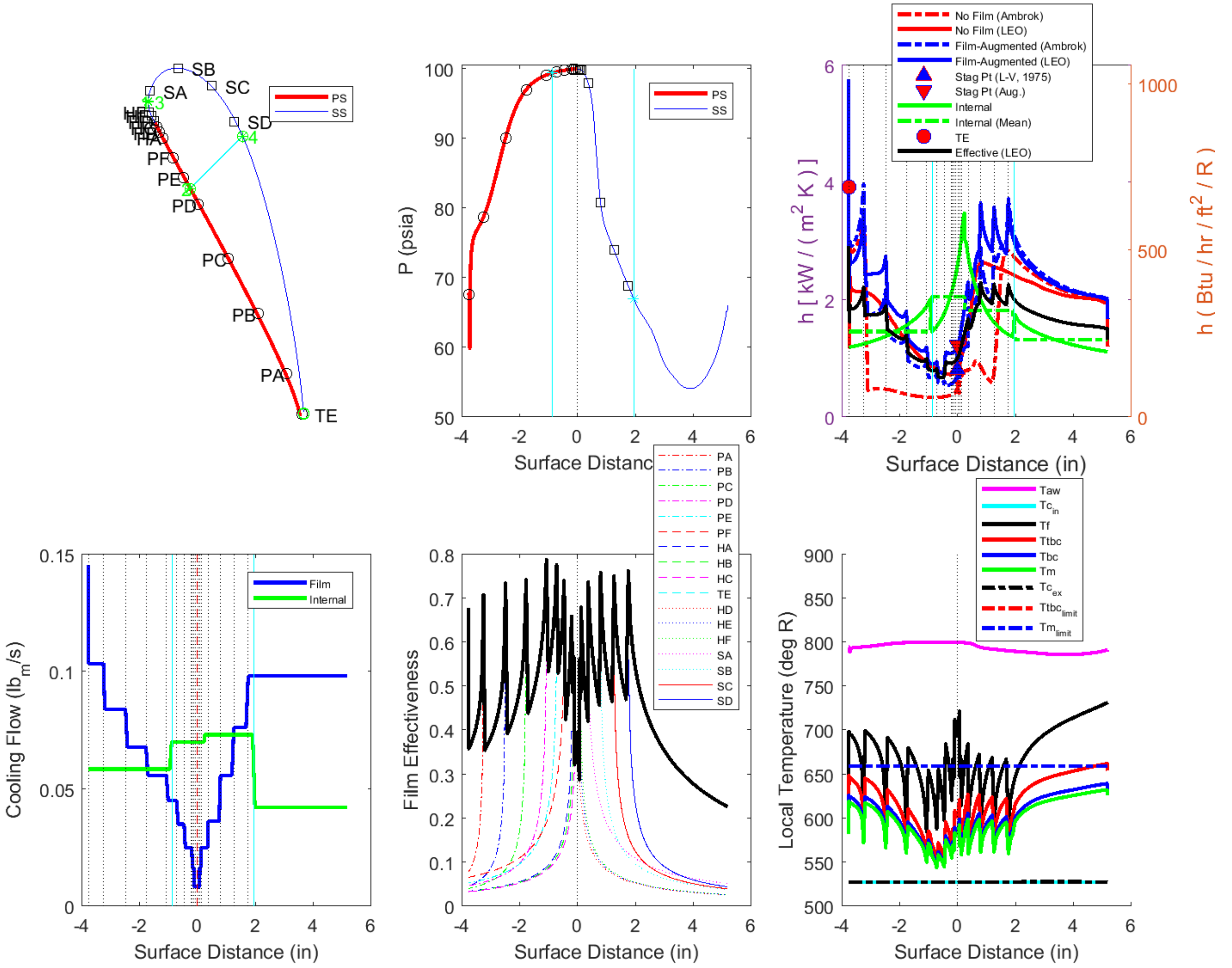
Most Durability Design is Based on Simplified Analysis and Correlations

See, e.g.

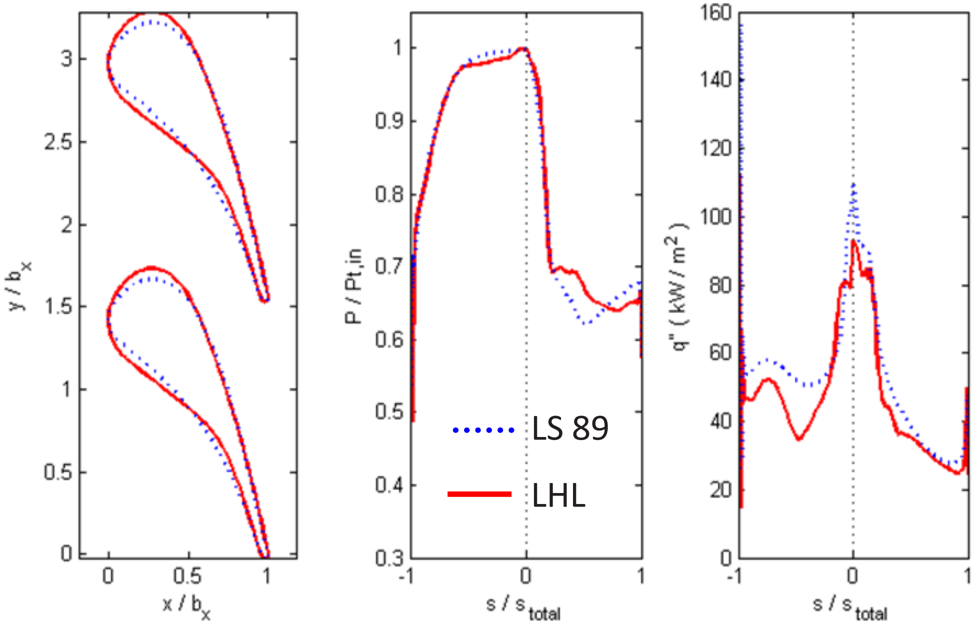
- Han et al., 2013, *Gas Turbine Heat Transfer and Cooling Technology*
- Downs and Landis, GT2009-59991

Strategies to Improve Durability :

1. Design for Reduced Heat Load Concurrently with Aero Design
2. Tailor Cooling Distribution to 3D Aerodynamics



1. Design for Reduced Heat Load Concurrently with Aero Design

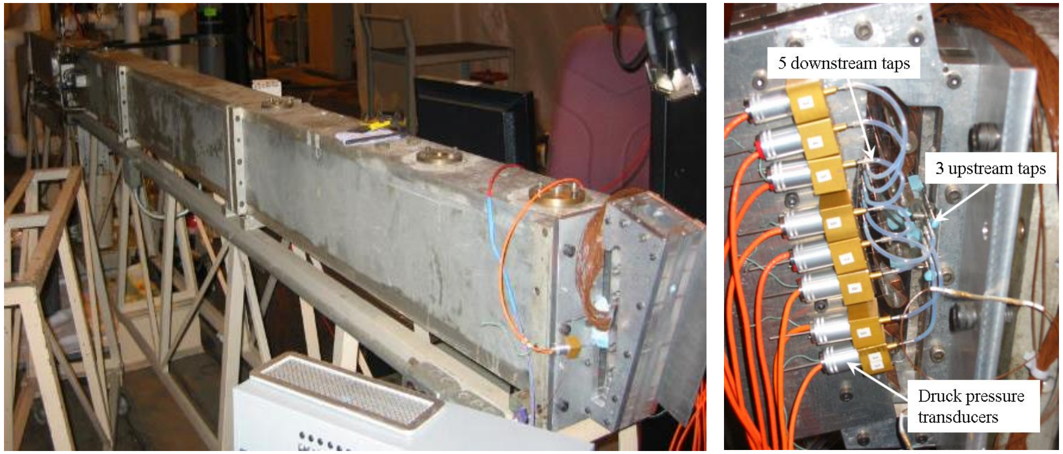


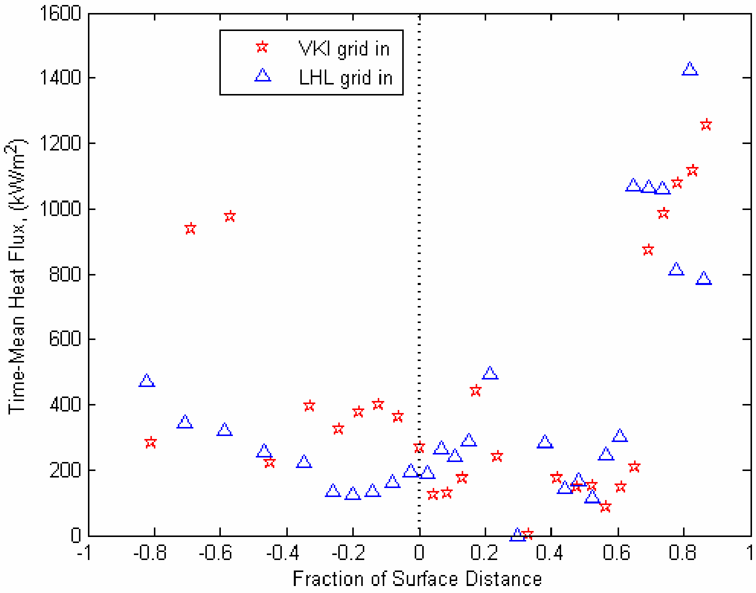
- RANS-based aero-thermal analysis was used to develop a Low Heat Load (LHL) vane
- The well documented LS 89 vane from VKI (Arts, 1990) was used as the baseline design
- Both design optimization techniques and user-directed design iterations were used to obtain the geometry
- Compared to the baseline, a 28% reduction of heat flux was achieved in the showerhead region
- Delay of transition onset was predicted on both the pressure and suction sides

1. Design Validation was Conducted in a Reflected-Shock Tunnel

Heat-Flux Measured with Thin-Film Gages

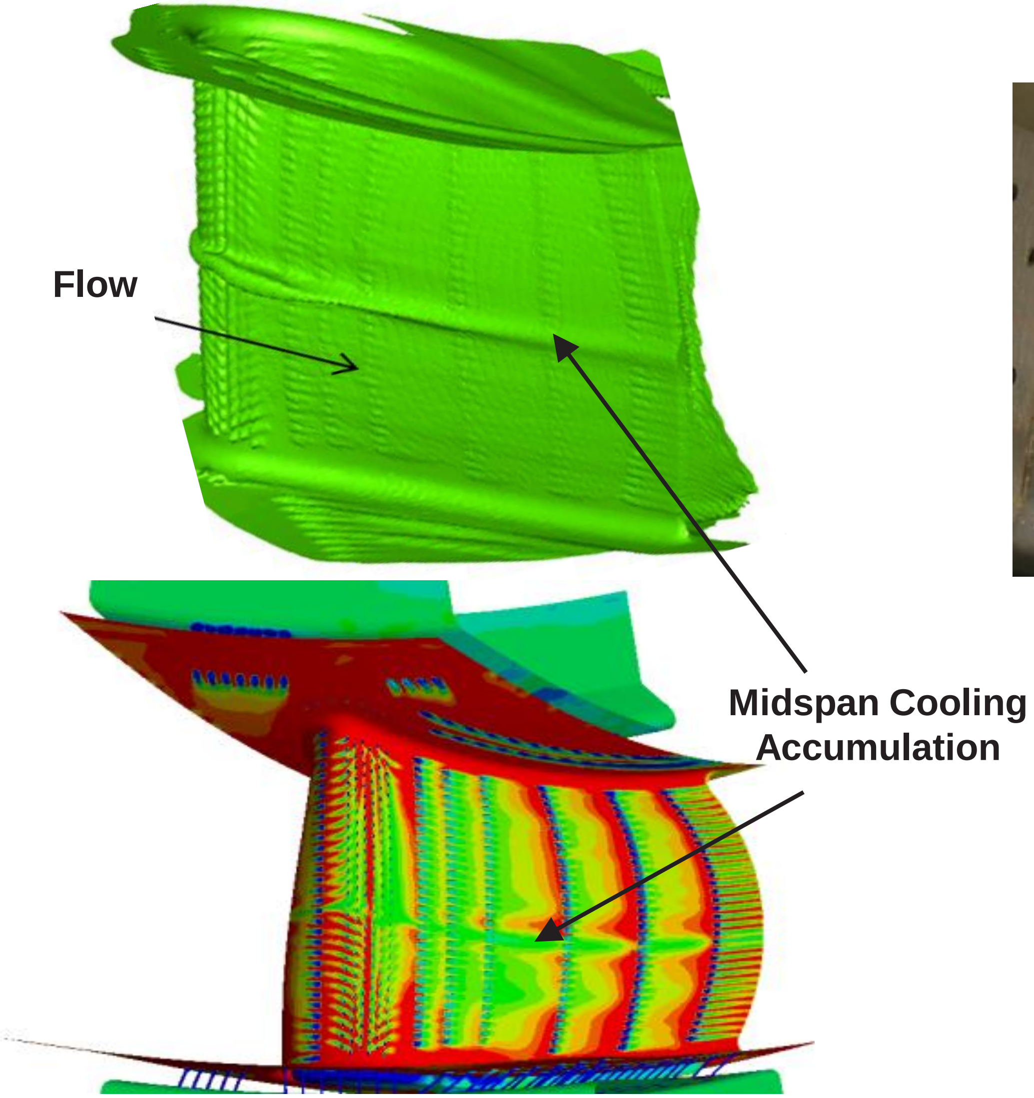
Vane Cascade Positioned at the End of Driven Section





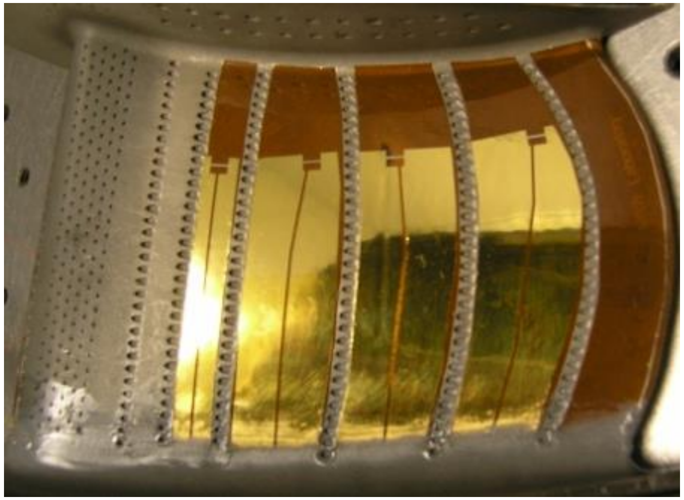
- The exceptionally short run-time (<10 ms) resulted in very high measured heat flux levels
- The heat flux was reduced in the shower-head region
- Boundary-layer transition was delayed on the vane pressure side

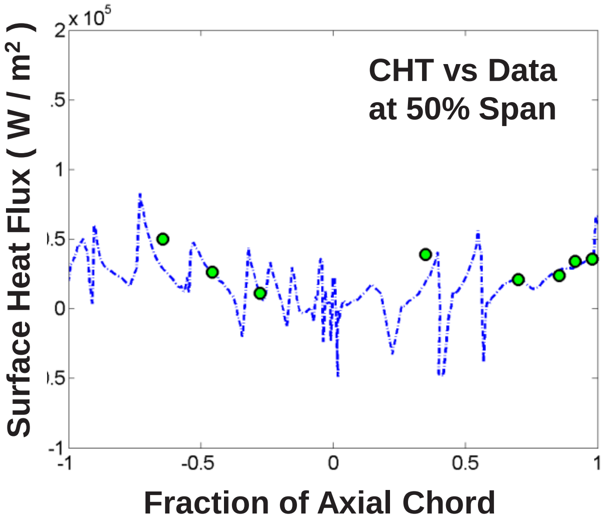
2. Tailor Cooling Distribution to 3D Aerodynamics



Flow

Midspan Cooling Accumulation

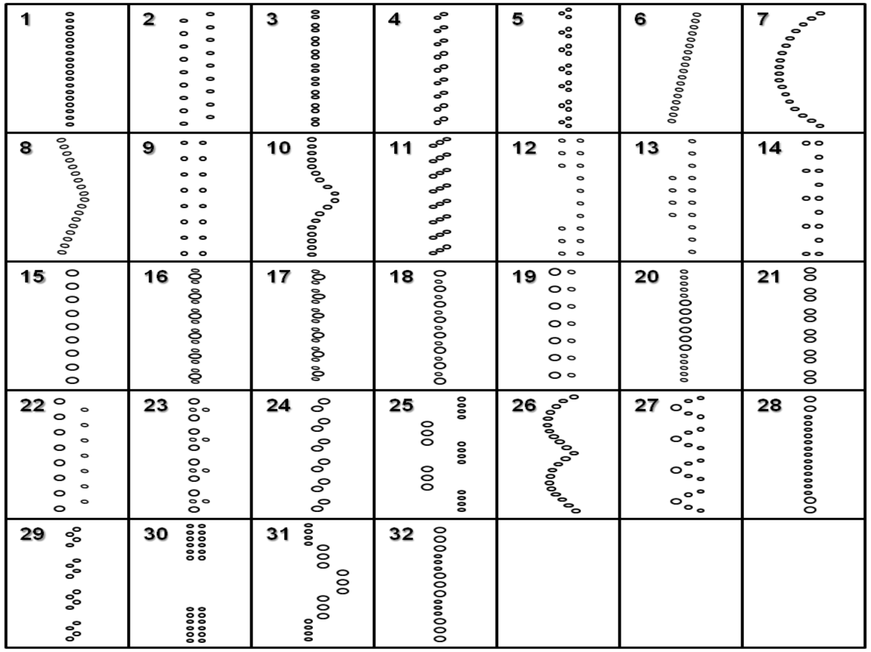




CHT vs Data at 50% Span

2. Use Optimization Techniques and 3D RANS to Re-Distribute Available Cooling Flow

Possible Row Patterns



Constraints :

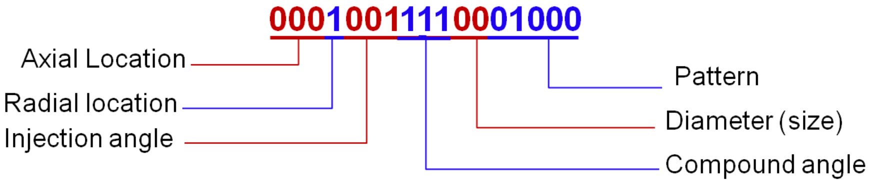
- 3D vane geometry
- Aerodynamic boundary conditions
- Overall cooling flow and flow per row

Variables :

- Hole location, diameter, injection angle, compound angle, and row pattern

Design target :

- Lower surface temperature
- Reduce hot spots and thermal gradients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Axial Location

Radial location

Injection angle

Pattern

Diameter (size)

Compound angle

$$fitness_1 = \phi_{aavg}$$

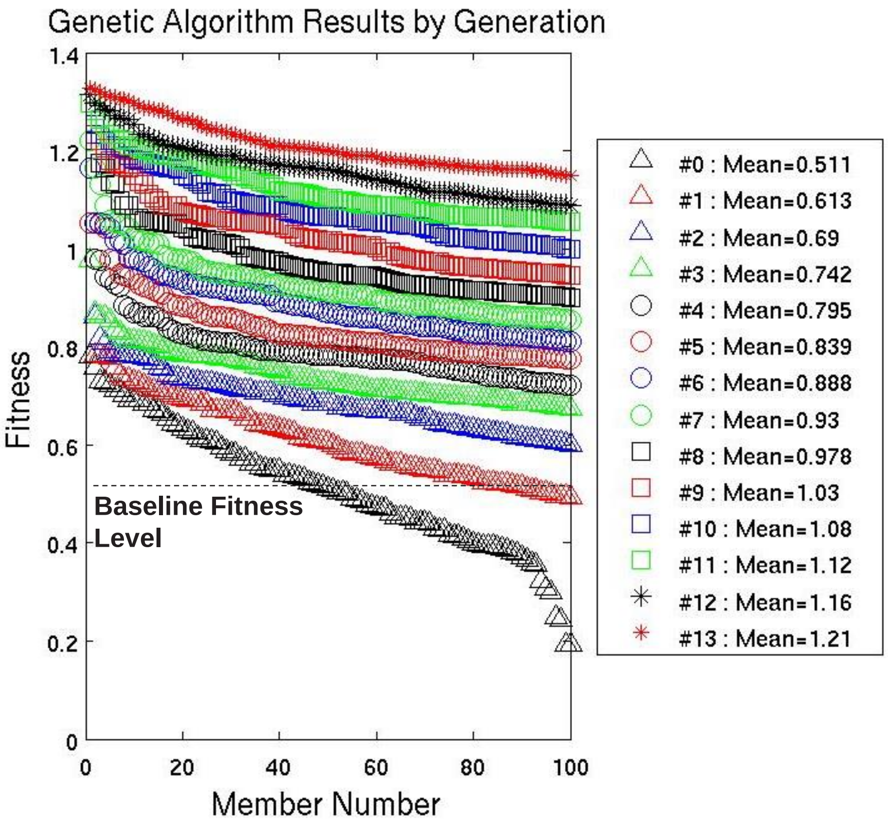
$$fitness_2 = 1 - (T_{\infty,nw,max} - T_{\infty,nw,min})/(T_{\infty} - T_c)$$

$$fitness_3 = 1 - (T_{\infty,nw,aavg} - T_{\infty,nw,min})/(T_{\infty,nw,max} - T_{\infty,nw,min})$$

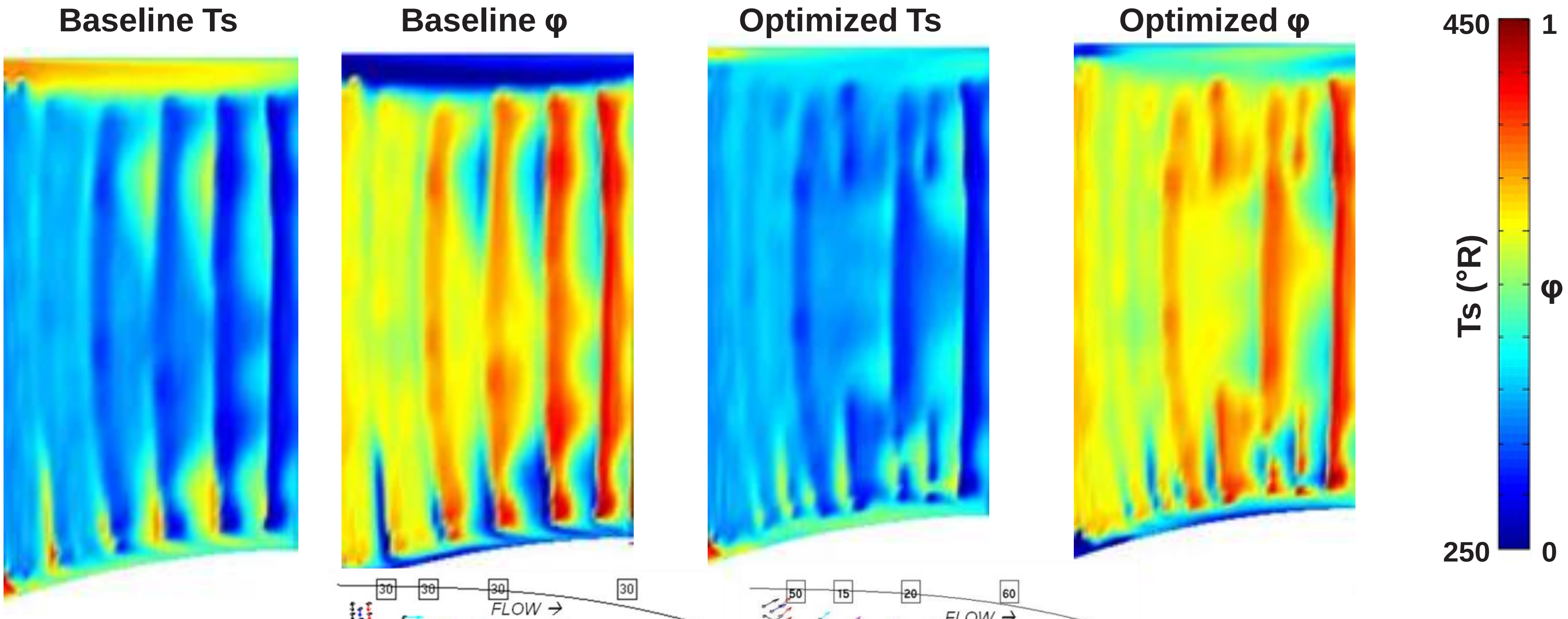
$$overall\ fitness = (fitness_1 + 2 * fitness_2 + \ fitness_3)/4$$

2. Optimization Results

- Latin Hypersquare Sampling was used to create an initial population of 100 airfoils
- Genetic algorithm techniques were used to evaluate the fitness of each airfoil and define new members of the population
- 100 new airfoils were evaluated per generation
- Variation between genomes decreased with generation
- Average fitness increased 237% over 13 generations
- Fitness increased 257% between the baseline and optimized designs



2. Optimization Results

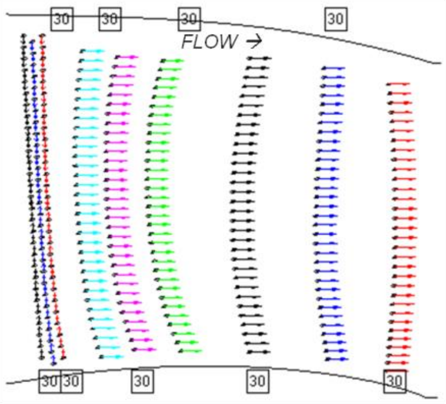


Baseline Ts

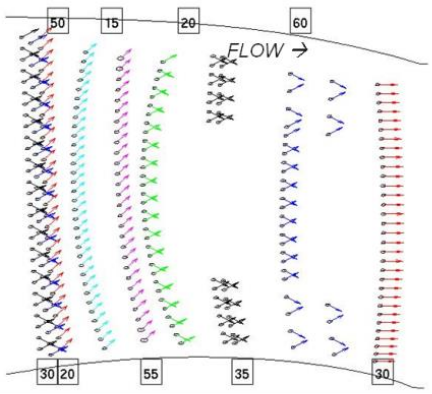
Baseline φ

Optimized Ts

Optimized φ



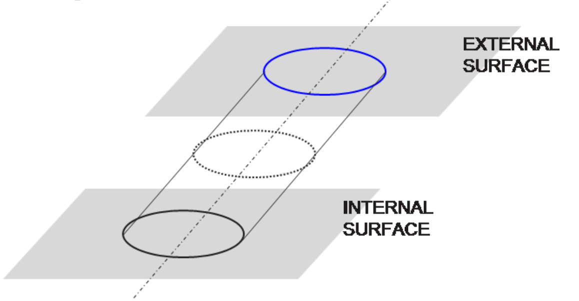
Baseline



Optimized

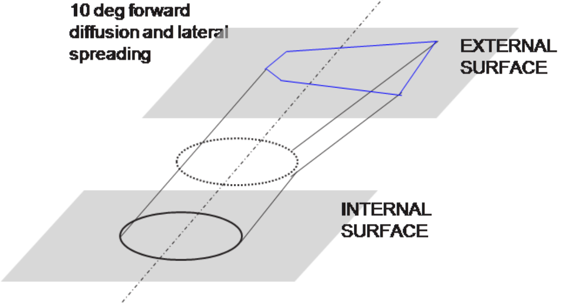
2. Results from Optimized Cooling-Hole Analysis Were Supplemented with Flat-Plate Experiments

Cylindrical



Shaped

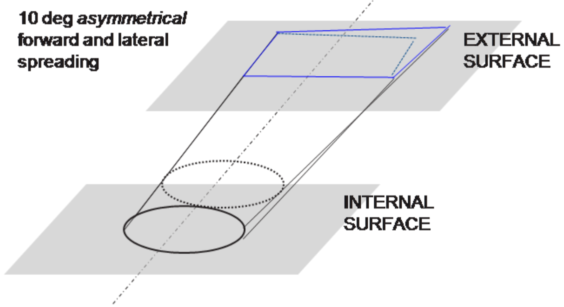
10 deg forward diffusion and lateral spreading



FLOW →

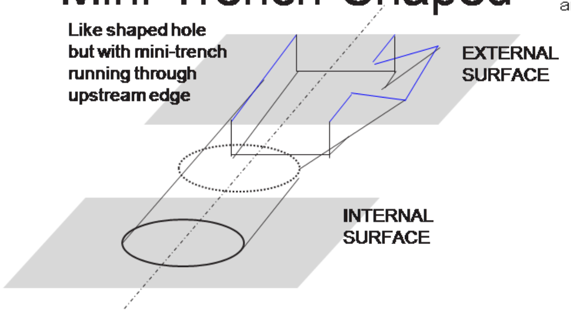
Vehr (U.S. Patent 4,653,983)

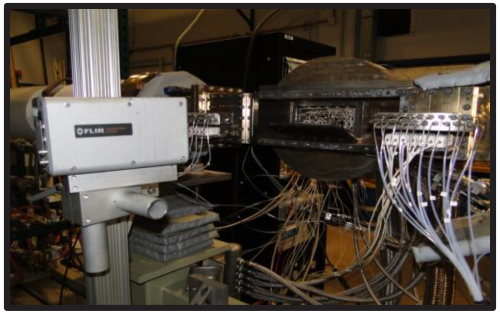
10 deg *asymmetrical* forward and lateral spreading

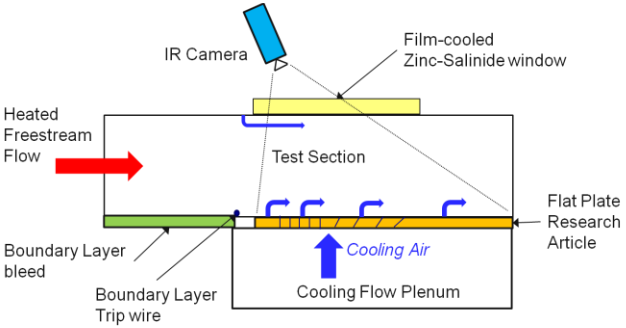


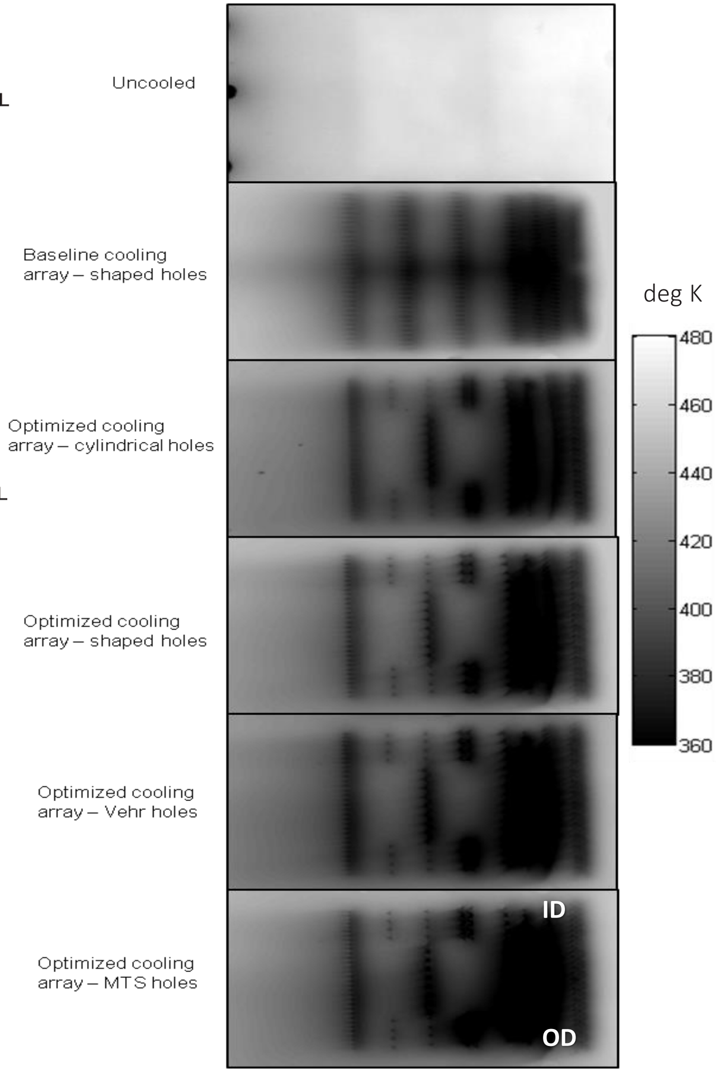
Mini-Trench Shaped

Like shaped hole but with mini-trench running through upstream edge

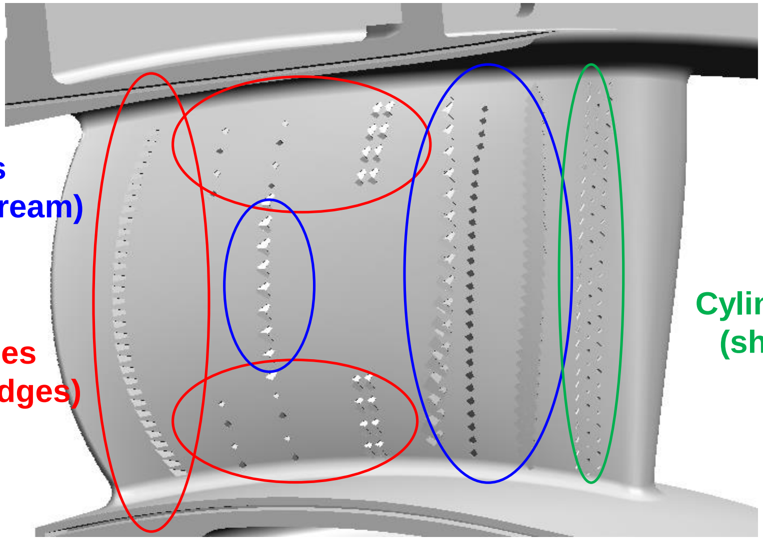








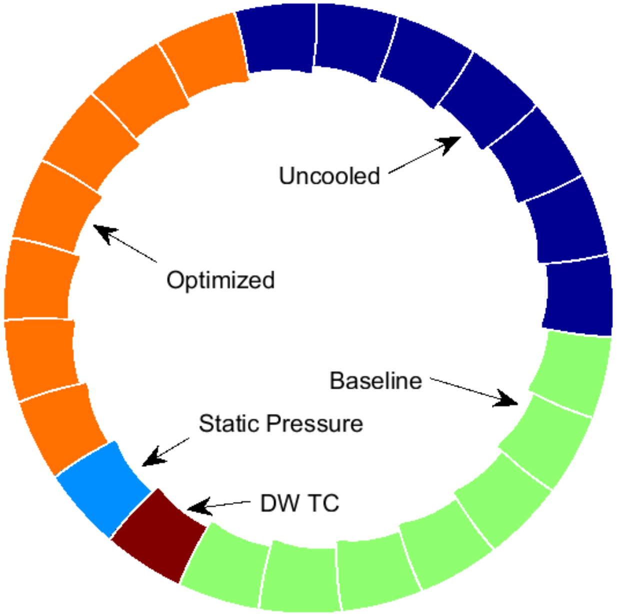
2. Optimized Distribution with Best Embodiment of Holes was Validated in the TRF Annular Cascade



MTS holes (midspan, upstream)

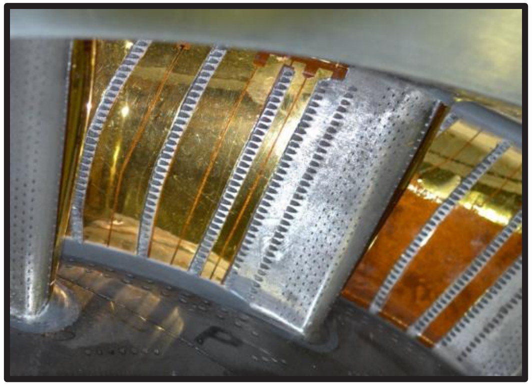
Vehr holes (last row, edges)

Cylindrical holes (showerhead)

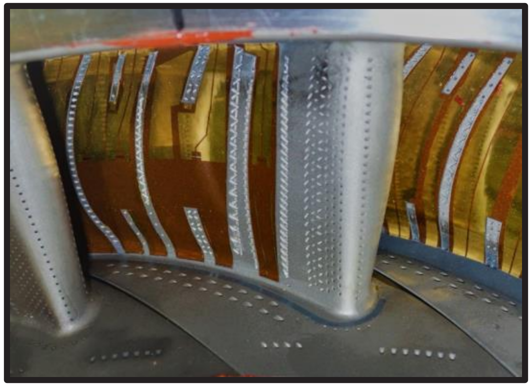


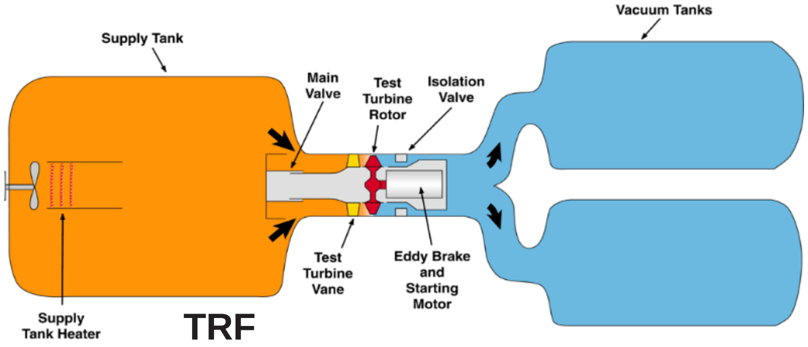
Rainbow Cooling Configuration

Baseline

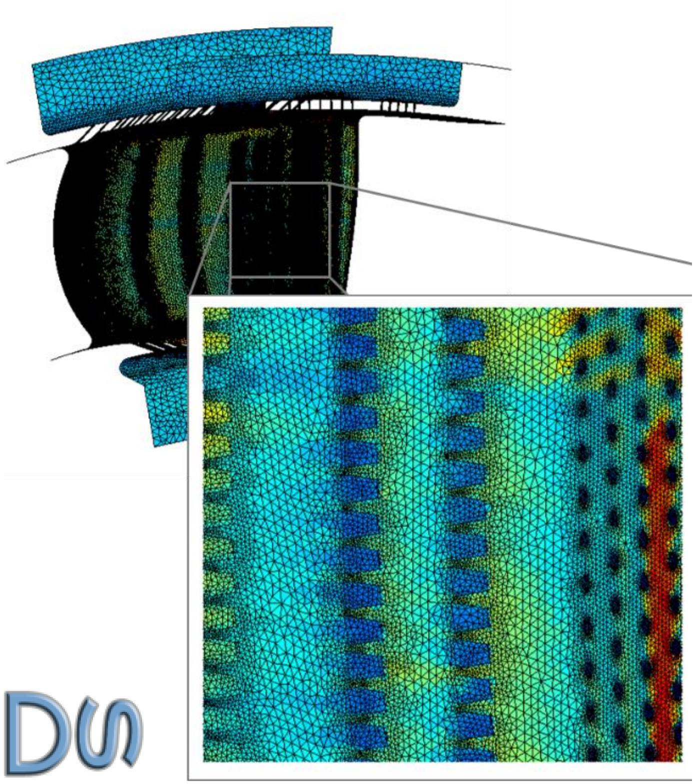


Optimized



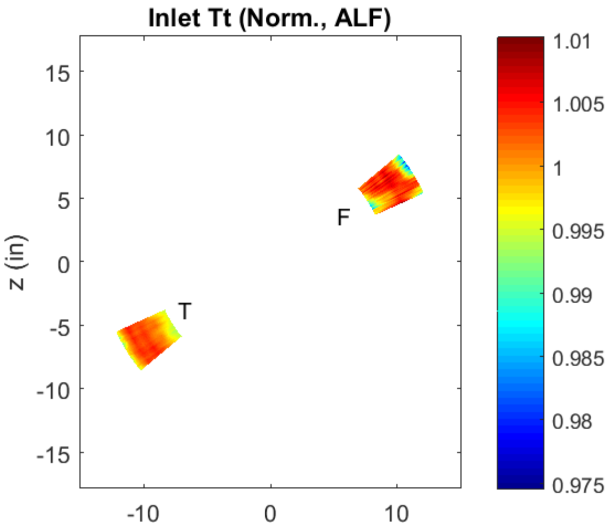


2. Baseline and Optimized Vanes were Also Compared via Conjugate Heat Transfer Analysis at Exp. Conditions

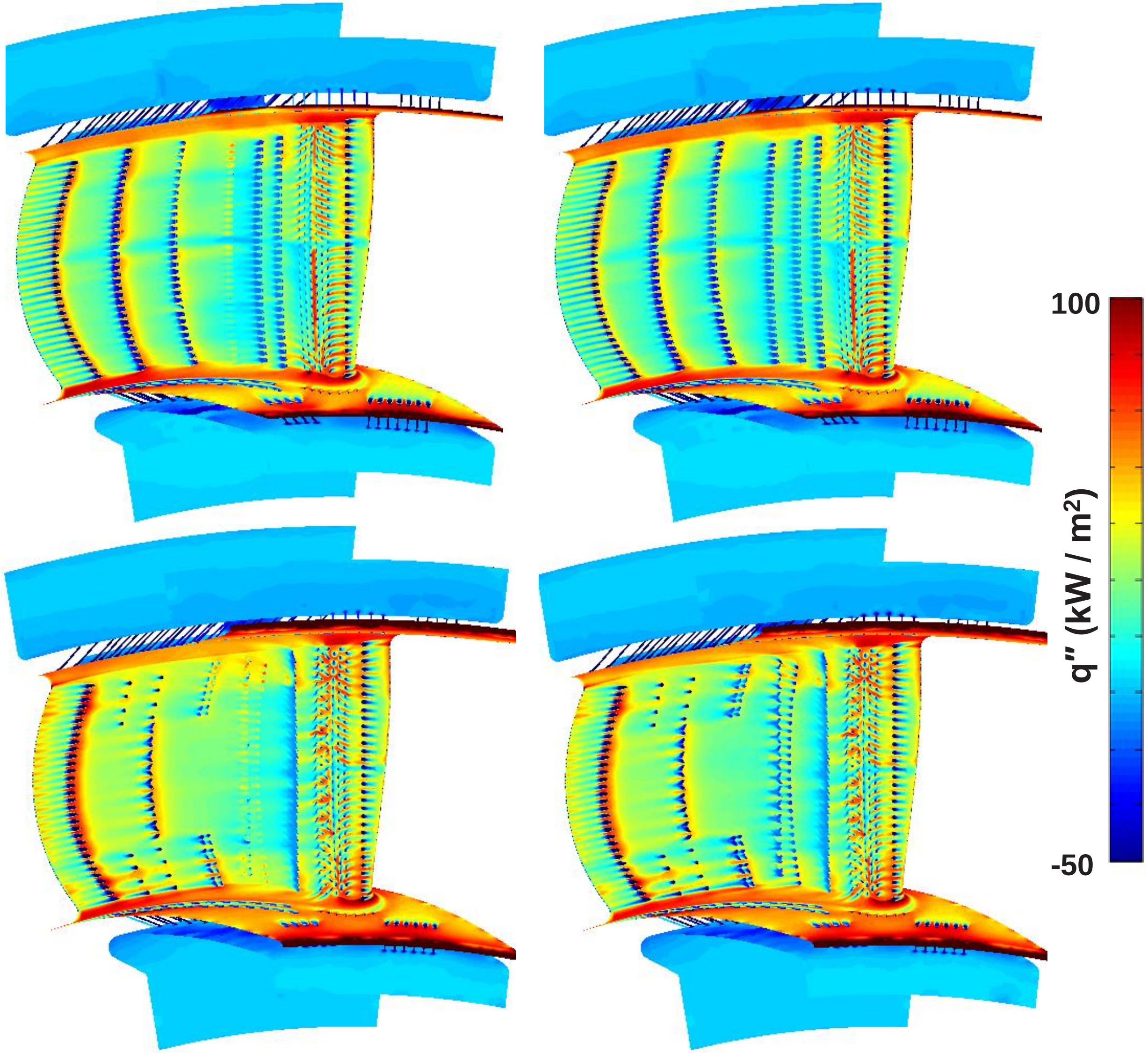


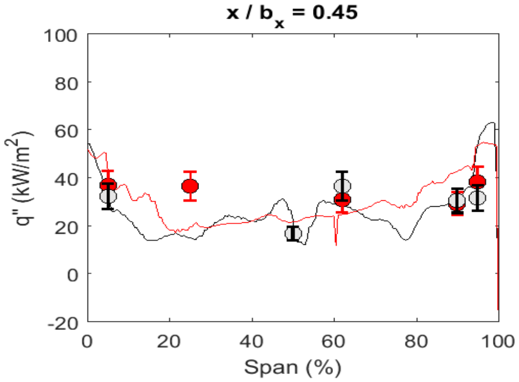
Profile-averaged main flow $T_{t,in}$	451 K
Profile-averaged main flow $P_{t,in}$	4.21 atm
Profile-averaged main flow $P_{s,ex}$	2.26 atm
Main flow M_{in}	0.11
ID cooling flow $T_{t,in}$	321 K
ID cooling flow $P_{t,in}$	4.31 atm
OD cooling flow $T_{t,in}$	299 K
OD cooling flow $P_{t,in}$	4.21 atm
Wall temperature (initial condition)	306 K
Kapton layer thickness	50 µm

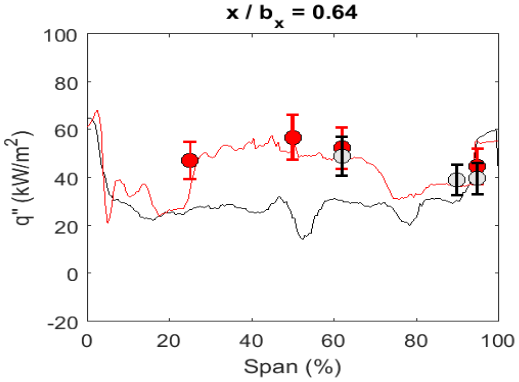
Name	Number of cores/gpus	Iterations/hr	Time – 6000 its	Speedup
Serial	1	121	50 h	1X
16 pieces	16	900	6 h 40m	7.43X
ACC (VOLTA) + MPS	16 / 8	21480	16 m	187X

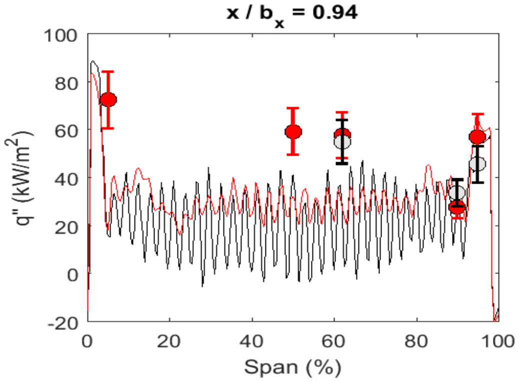


2. Final Experimental Verification is Inconclusive

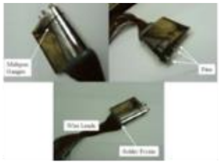






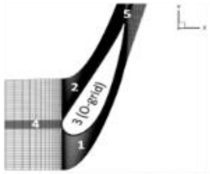


Summary of Component Development Process



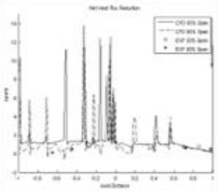
TRL 1-5

Determine viability of GAs by creating optimized Low Heat Load (LHL) 2D VKI vane profile.



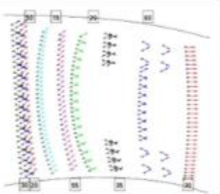
TRL 2

Use RANS CFD to model complete TRF experimental flow path.



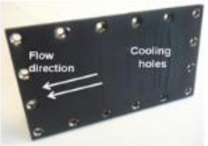
TRL 3

Validate external-flow-only RANS CFD with added source term for cooling against TRF heat flux data.



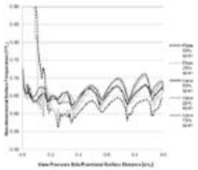
TRL 3

Use same CFD and GAs to optimize full-map vane PS cooling array for best overall effectiveness.



TRL 3

Test optimized cooling design using IRT flat plate experiments and determine best 3-D hole shapes.



TRL 4

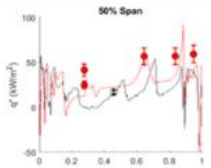
Validate use of repeatable flat plate experiments by comparing CHT CFD heat flux of plate to 3D vane.

TRL 4

Verify advantages of MTS cooling hole shape in reducing heat transfer.

TRL 5

Build/test optimized 3D full scale vane cooling array with selected hole shapes in TRF using thin films.



TRL 5

Simulate same vane experiments using CHT CFD and compare optimized and baseline cooling.

Summary and Conclusions

- The development of aero-thermal research components at AFRL was described with reference to the HIT Research Turbine vane
- Advances in component durability require a decreased reliance on empiricism in the overall design process
- Improved durability designs were attempted both by reducing the convective heat load to a vane and by more effective distribution of available cooling flow
- Experimental verification of advanced designs proved difficult with available methods
- The availability of rapid turnaround conjugate heat transfer analysis is critical to achieving more efficient future designs

Acknowledgements and Collaborations

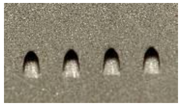
Design and Analysis NASA FTT ADS

Tooling Laszeray

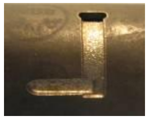
Cores DAI CERAMICS, INC. Innovative Ceramic Solutions

Castings PCC

Finish Machining FAA FLORIDA AERO PRECISION



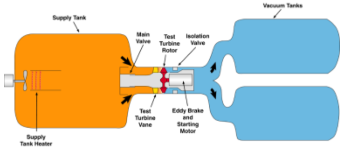
Instrument Mods ATLANTIC PRECISION INC API



Instrumentation KS kulite®

Assembly FTT

Test



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