SIEMENS

Demonstration of Enabling Spar-Shell Cooling Technology in Gas Turbines

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Outline

Programmatics – History – Engr'g. Devl. – Des./Manu. – Engine Test

- Programmatics
- History/background & advantages of the technology
- Engineering development - Component-level testing
- Design and manufacture of demonstration hardware
- Engine test and results

Programmatics

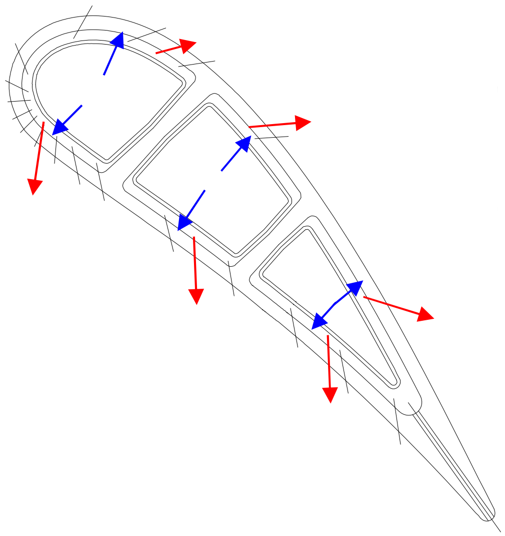
- Initial design concept studied under DOE Phase I SBIR (DE-SC0002713) "Development of Innovative Cooling Approaches for Robust Design"
- Follow-on commercialization program (DE-FE0006696) supported "Demonstration of Enabling Spar-Shell Cooling Technology in Gas Turbines"
  - FTT providing matching funds (23.2% cost share)
  - Contract objective was to demonstrate the concept in an engine
  - Siemens provided a full-scale IGT test vehicle – testing completed in Germany, 2014.

Background/Motivation

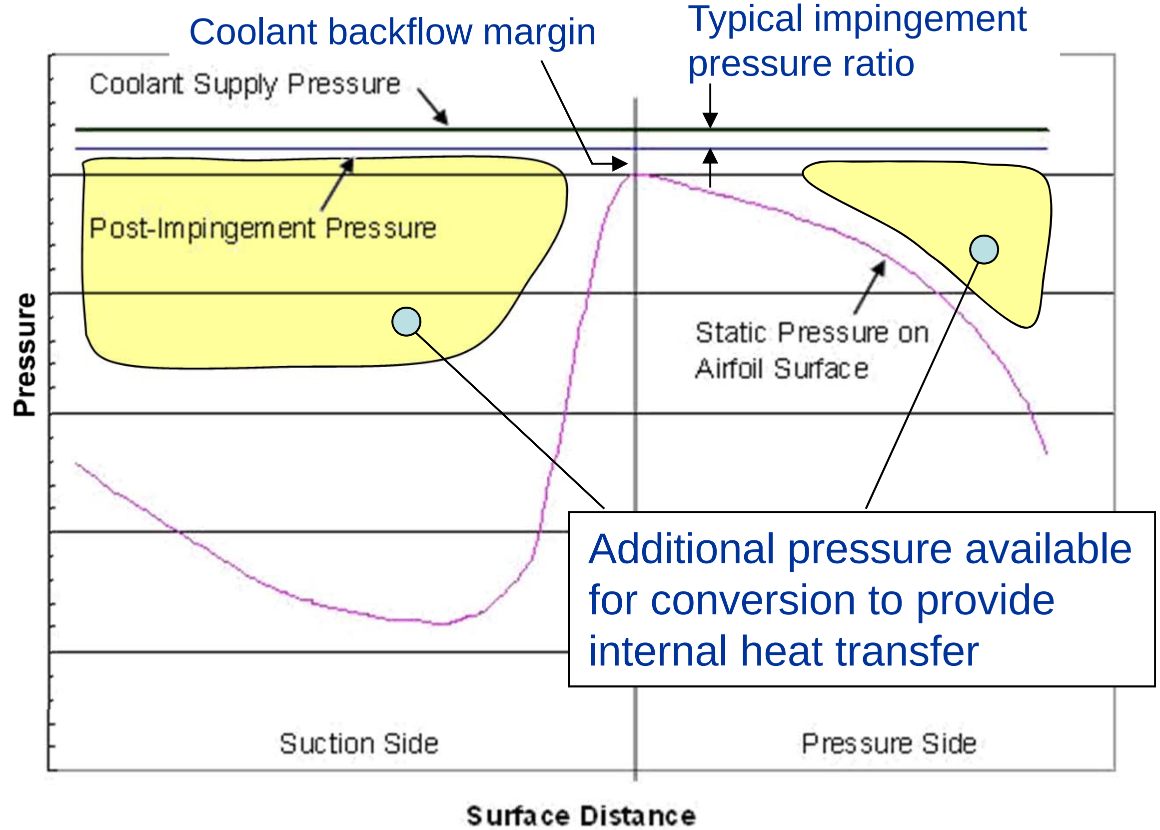
Programmatics – History – Engr'g. Devl. – Des./Manu. – Engine Test

Current design philosophy/practice limits cooling potential

- Impingement pressure ratio typically near constant around airfoil
- Post-impingement pressure set high enough for coolant outflow … Required to prevent hot gas ingestion



Vane Pressures

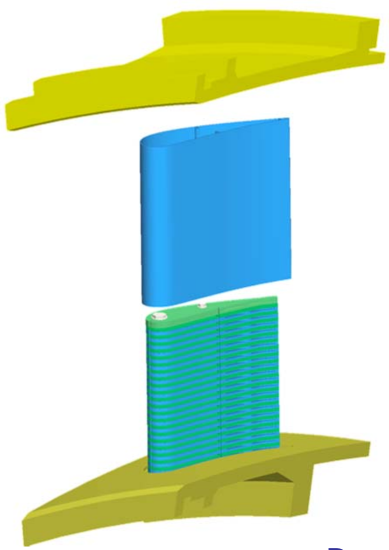


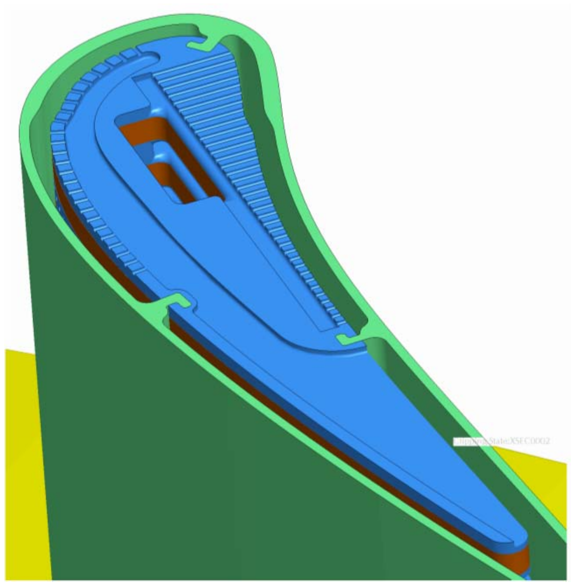
How do we utilize the additional pressure?

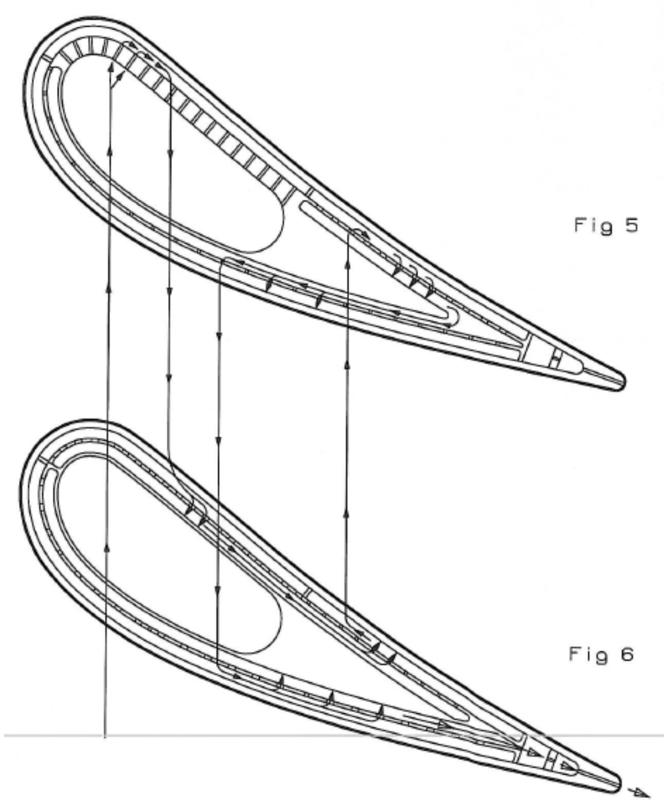
Spar-Shell: What Is It?

Programmatics – History – Engr'g. Devl. – Des./Manu. – Engine Test

- Alternative to existing state-of-the-art
  - FTT sequential-impingement cooling scheme based on new insert design improves cooling
  - Provides path for implementation of next generation materials
  - Optimized thermal/structural arrangement allows increased firing temperatures and improved efficiency







Ref: U.S. Patent #8096766 "Air Cooled Turbine Airfoil with Sequential Cooling".,J. P. Downs, 2012

Initial design concept envisioned to solve problem

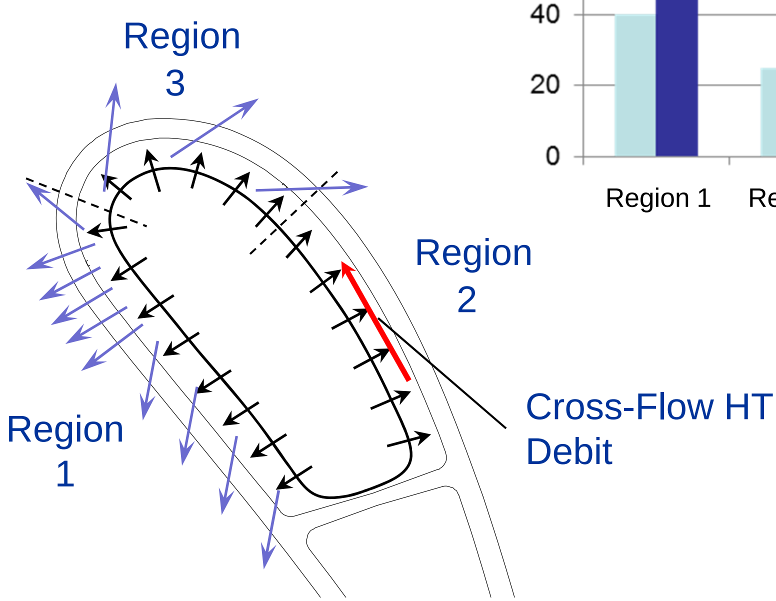
How Does it Work?

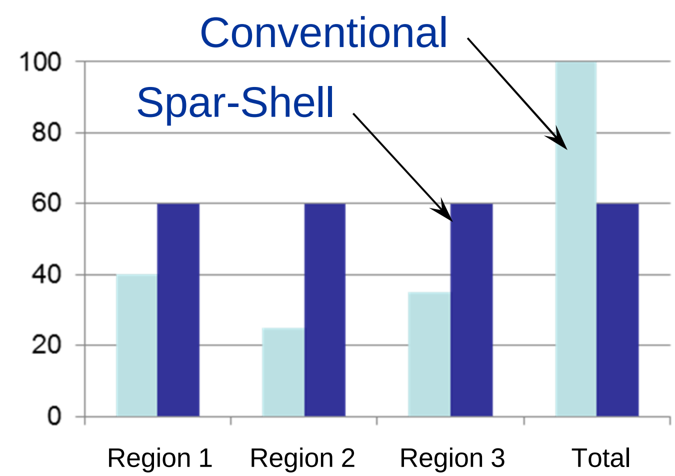
Programmatics – **History** – Engr'g. Devl. – Des./Manu. – Engine Test

Sequential (series) impingement leverages cooling air usage

Conventional Cooling

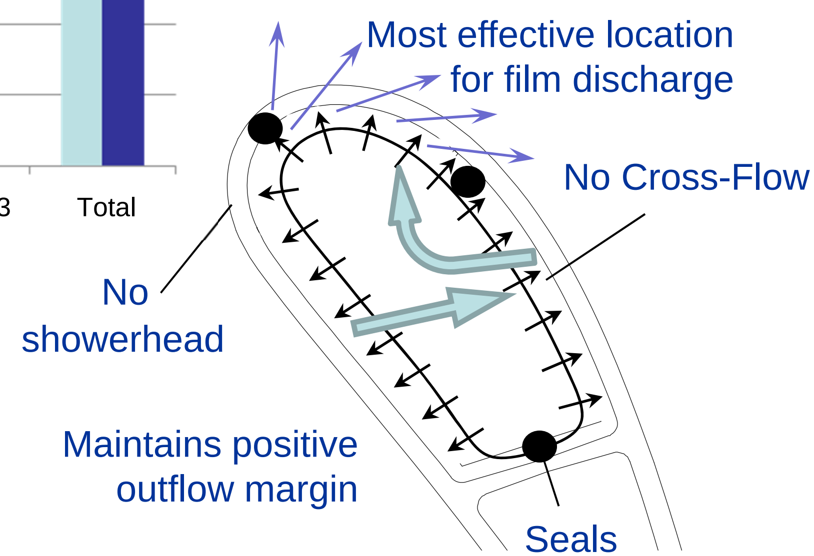
- Single impingement
- Film cooling





Spar-Shell Cooling Technology

- Sequential impingement (x3)
  - Increases effective cooling flow



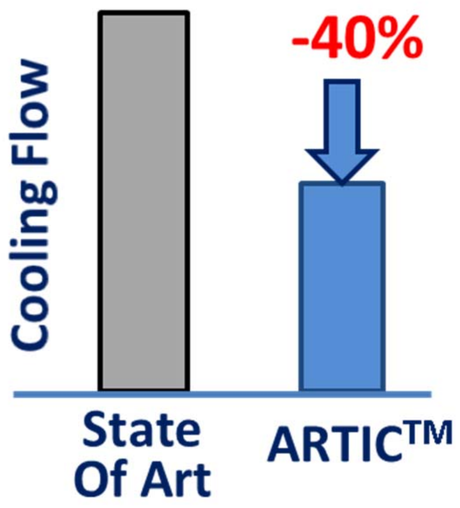
Results in higher thermal efficiency

Benefits of the Technology

Programmatics – History – Engr'g. Devl. – Des./Manu. – Engine Test

- Spar-Shell vane offers substantial cooling flow savings

Same Metal Temperature with Less Cooling Flow



- Estimated performance benefits for implementation in 1st vane:
  - +0.25% combined cycle efficiency
  - +2.0% gas turbine power

- ARTIC*™ trademarked for sequential impingement cooling arrangement of Spar-Shell technology

* Advanced Recirculating Total Impingement Cooling

Benefits contribute to DOE NETL turbine program goals

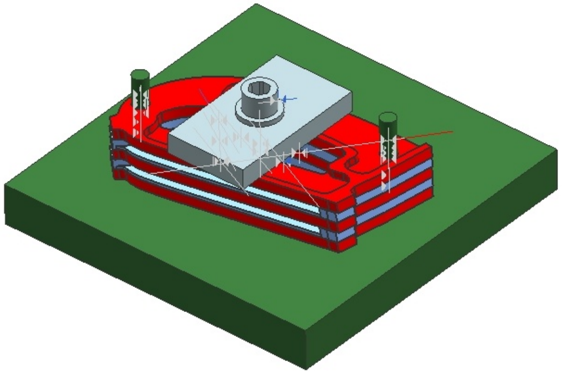
Initial Foundation for Design

Component technologies - Important to the success of ARTIC^{TM}

Impingement Heat Transfer Testing
(Unique, high efficiency design)

Seal Testing
(Design depends on good sealing)

Manufacturing Development
(New methods required)



Component testing contributes to technical risk reduction

Impingement Heat Transfer

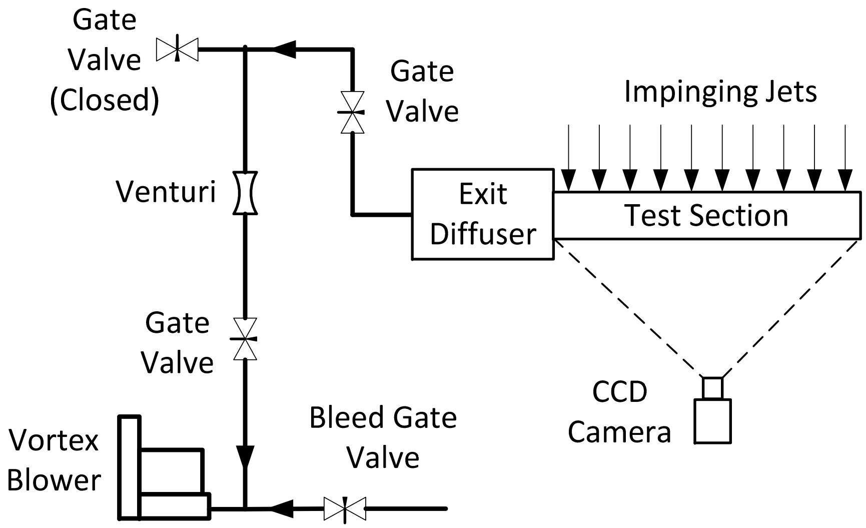
Programmatics – History – **Engr'g. Devl.** – Des./Manu. – Engine Test

- Accurate prediction of structure temperatures is critical to the life of the part in the operating environment
- The ability to predict temperatures accurately depends on whether a corresponding standard exists and how close the design is to the standard
- Testing to validate/strengthen the coefficients used in the standards helps improve accuracy

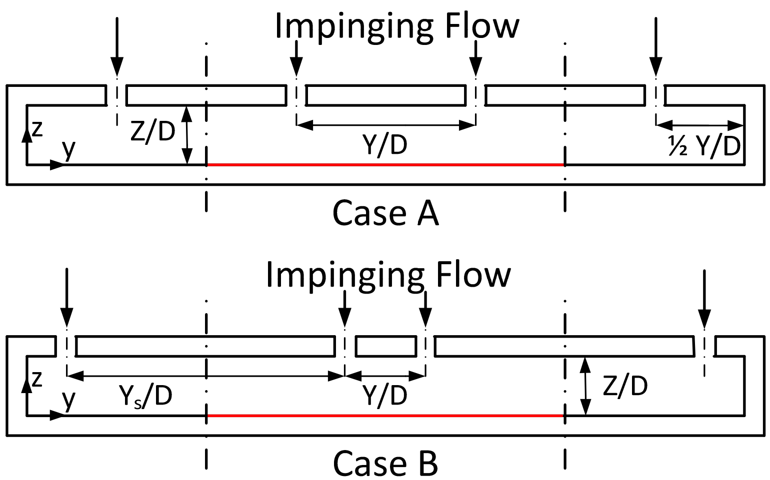
Impingement Testing Performed at UCF*

Programmatics – History – **Engr'g. Devl.** – Des./Manu. – Engine Test

Experimental Setup



Impingement Arrangements



Test Matrix

Case	X/D	Y/D	Z/D	Y_s/D	Re_{javg} x 10^3
A	3	8	3	-	10, 13, 16
B	3	3	3	13	

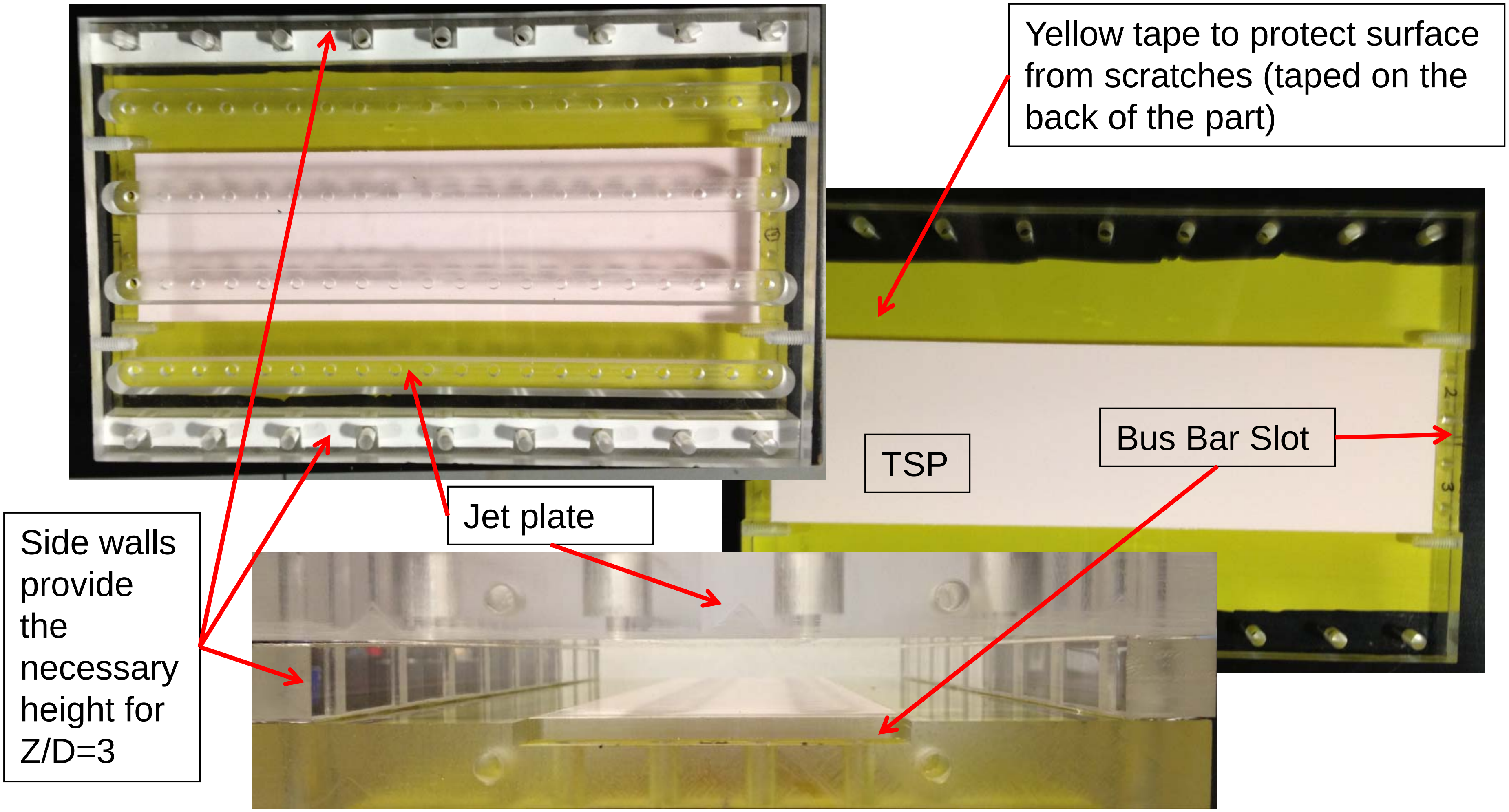
* University of Central Florida

Ref: GT2013-94469, "Heat Transfer Characteristics of Jet Array Impingement at Low Streamwise Spacing", Roberto Claretti, Jahed Hossain, S. B. Verma, J. S. Kapat, James P. Downs & Gloria E. Goebel

Objective: Validate heat transfer characteristics of unique sequential impingement geometry

Assembled, Instrumented Test Article

Programmatics – History – Engr’g. Devl. – Des./Manu. – Engine Test

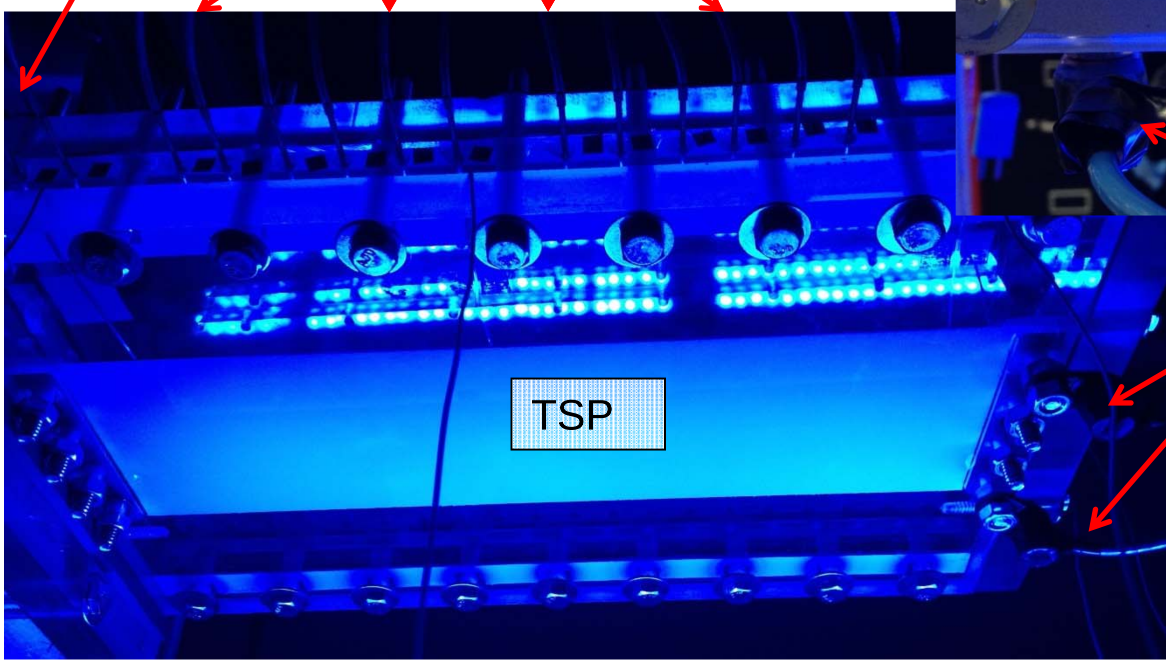


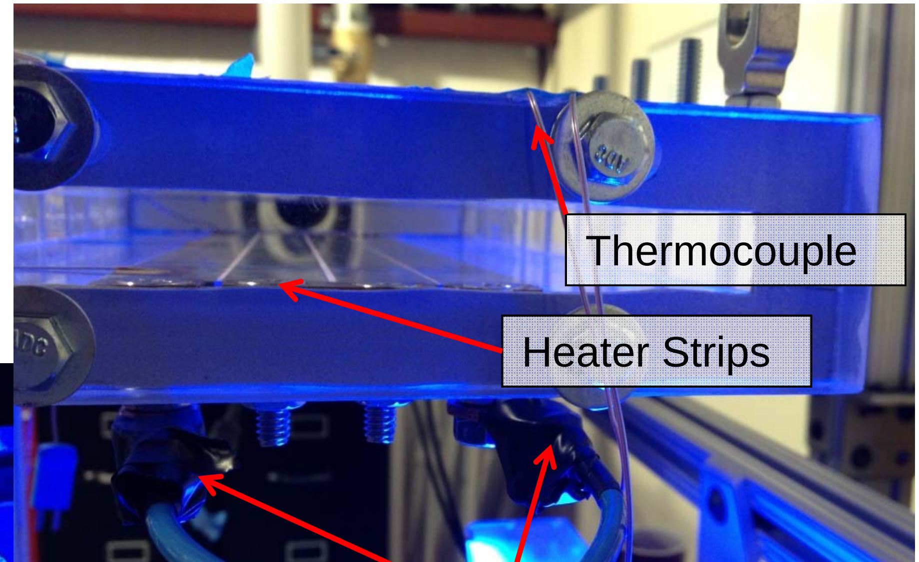
Model design/build/test by UTSR Fellow Roberto Claretti under direction of Prof. Jay Kapat

Iluminated Impingement Test Article

Programmatics – History – Engr'g. Devl. – Des./Manu. – Engine Test

Test technique: Constant heat flux, temperature sensitive paint

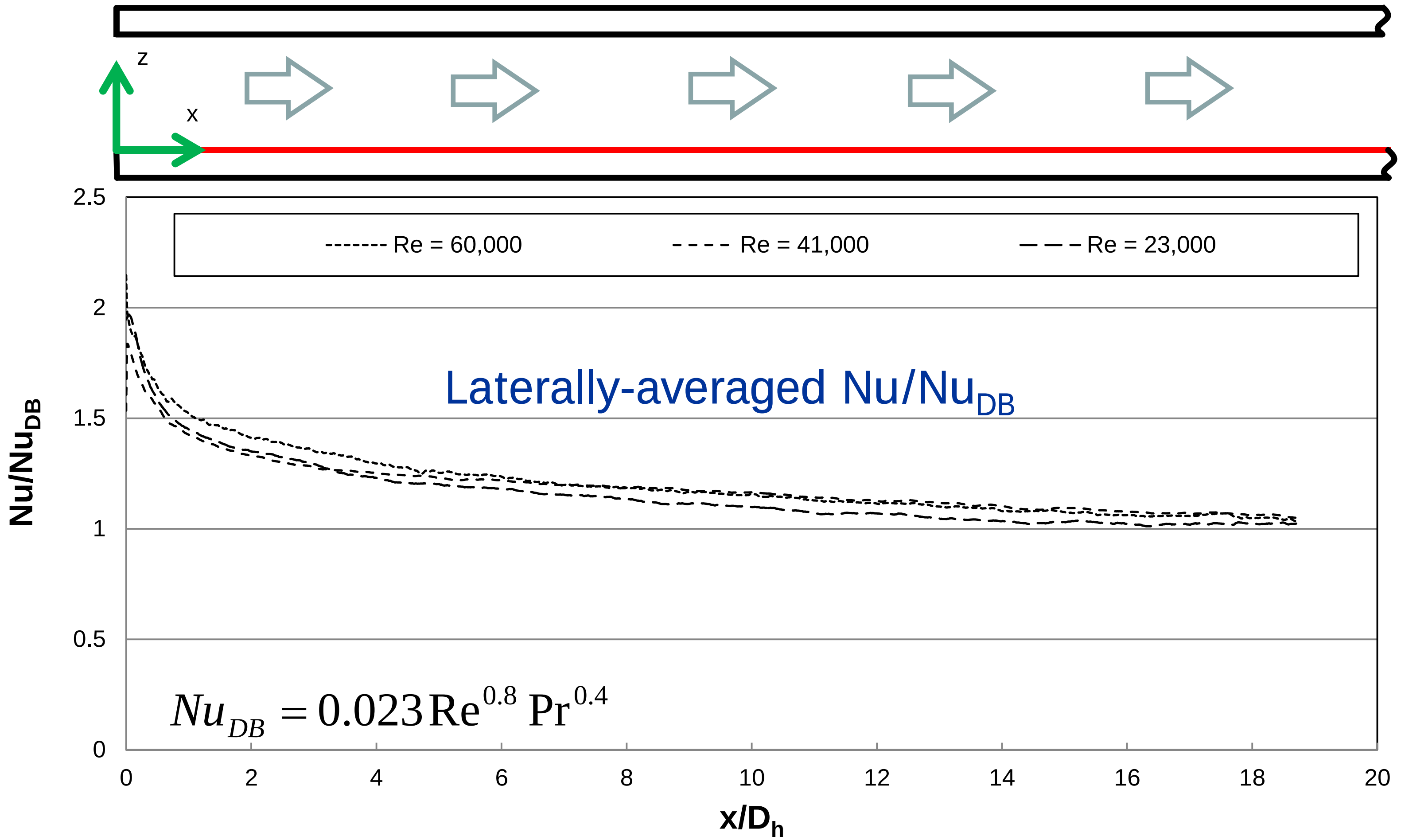




- Proven experiment methodology
- Accurate results

Smooth Channel Checkout Case

Programmatics – History – Engr'g. Devl. – Des./Manu. – Engine Test



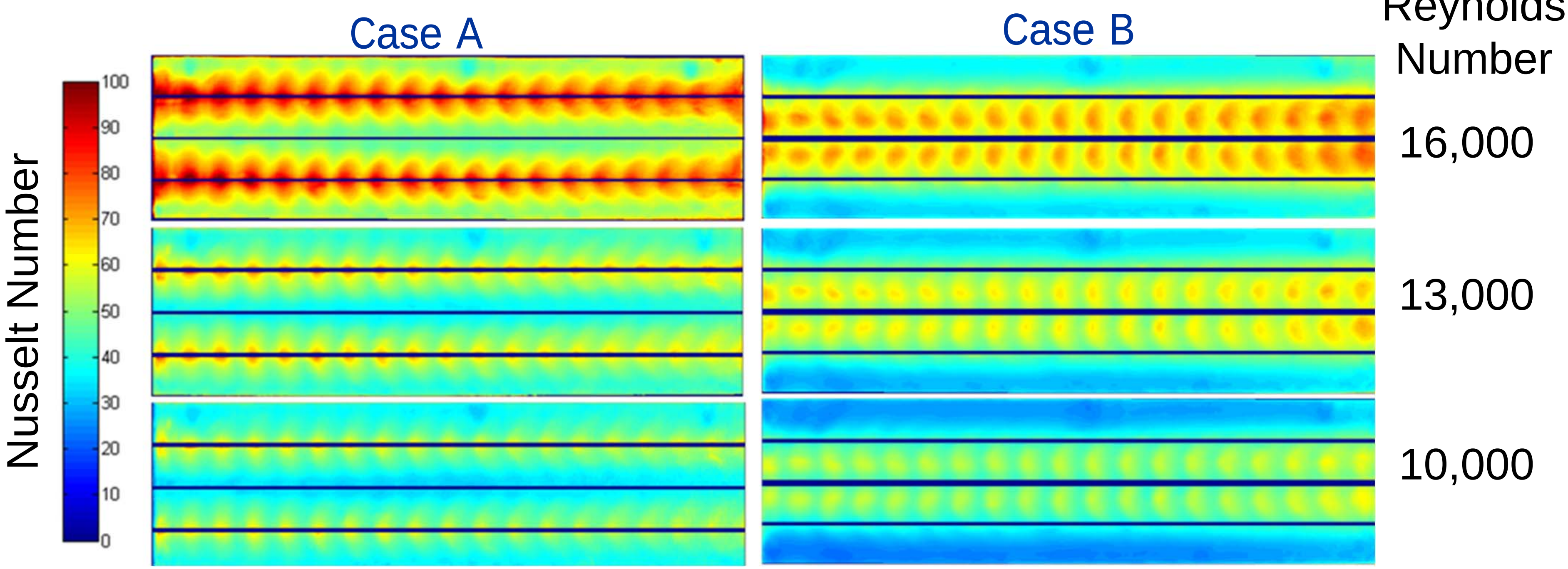
$$Nu_{DB} = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}$$

Baseline results consistent with expectations

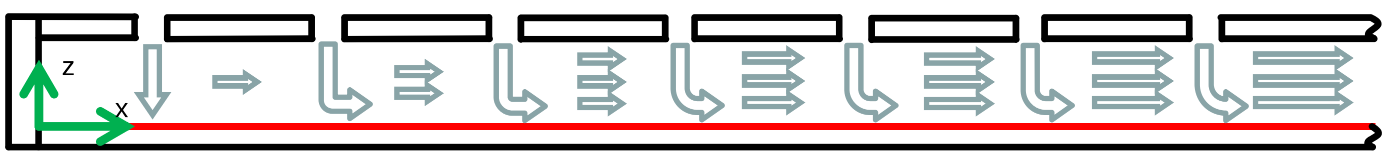
Sample Impingement HT Results

Programmatics – History – **Engr'g. Devl.** – Des./Manu. – Engine Test

Results with cross-flow



Cross-flow direction



Average results are comparable (within ~10%)

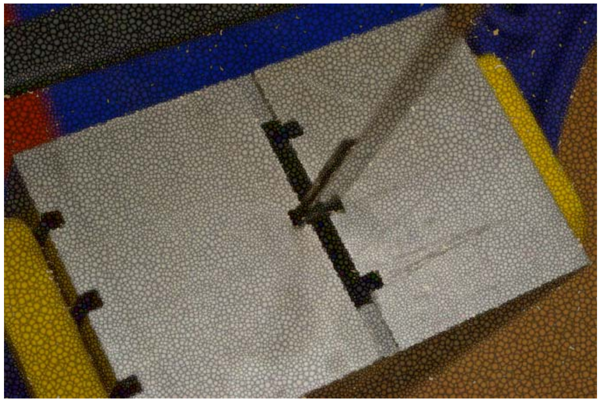
Sequential Impingement Requires Sealing

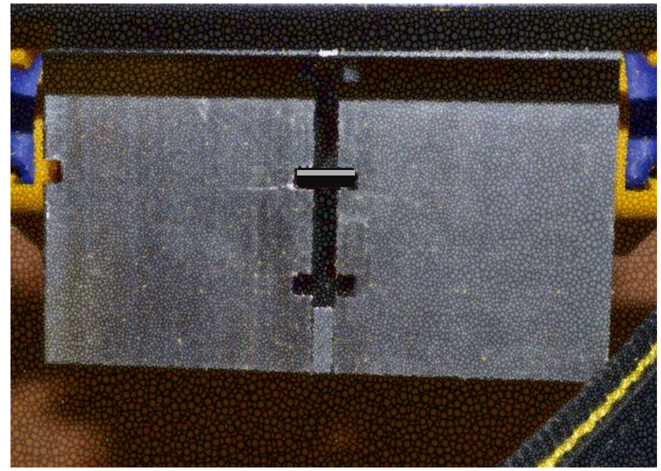
Programmatics – History – Engr'g. Devl. – Des./Manu. – Engine Test

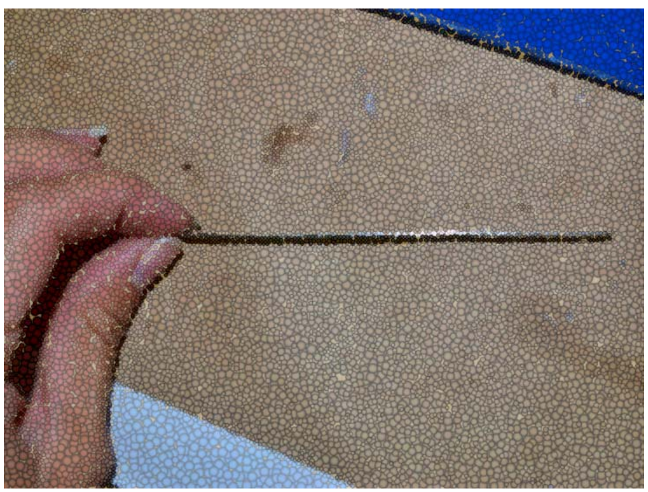
- Sequential flow of cooling air from high pressure region to successively lower pressure regions
- Imperative to segregate the impingement regions and prevent contamination from adjacent regions
- Due to this, must maintain effective sealing between the regions throughout the range of operating conditions of the part
- Testing used to evaluate competitive design approaches and to arrive at the best approach for this application

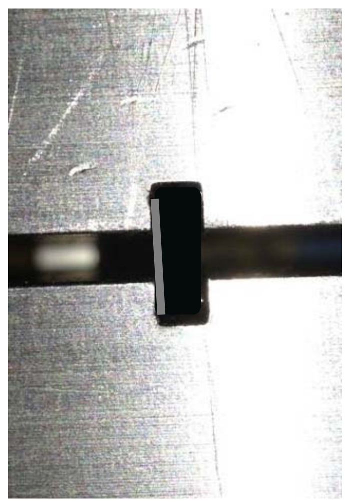
Seal Rig Constructed to Test Leakage

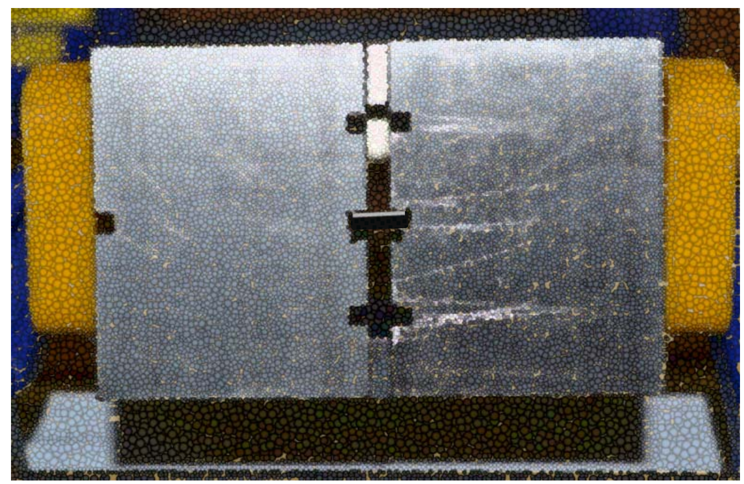
Programmatics – History – **Engr'g. Devl.** – Des./Manu. – Engine Test









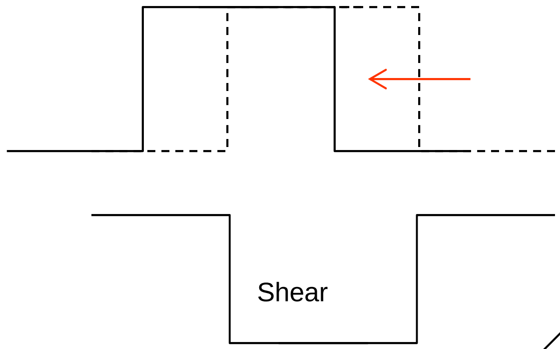


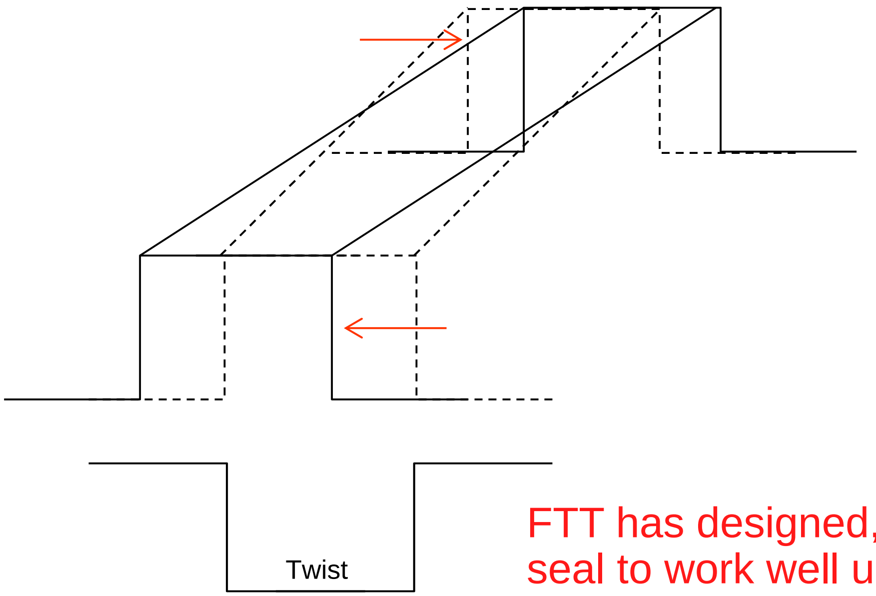
Rig design/build/test performed in FTT's aerothermal research lab

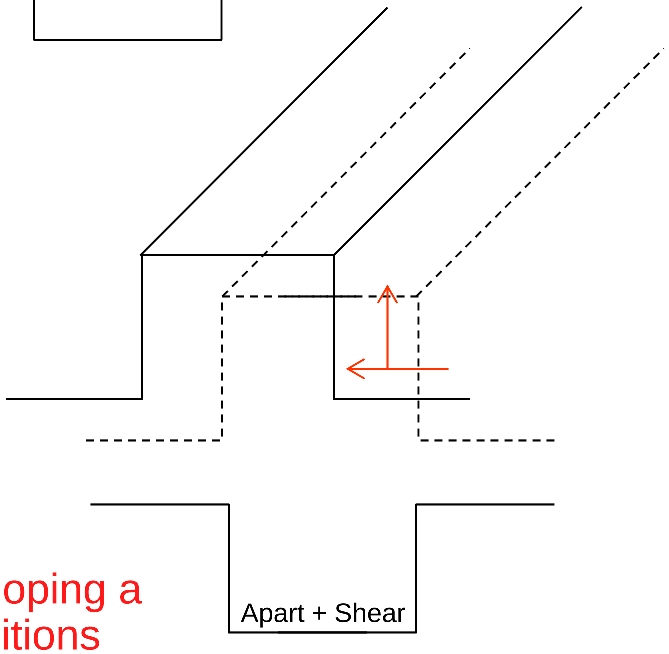
Seal Misalignments Evaluated in Test

Programmatics – History – Engr'g. Devl. – Des./Manu. – Engine Test

- Conventional (feather) seals can be expected to operate well under ideal conditions
- Mateface misalignment causes seal leakage to increase



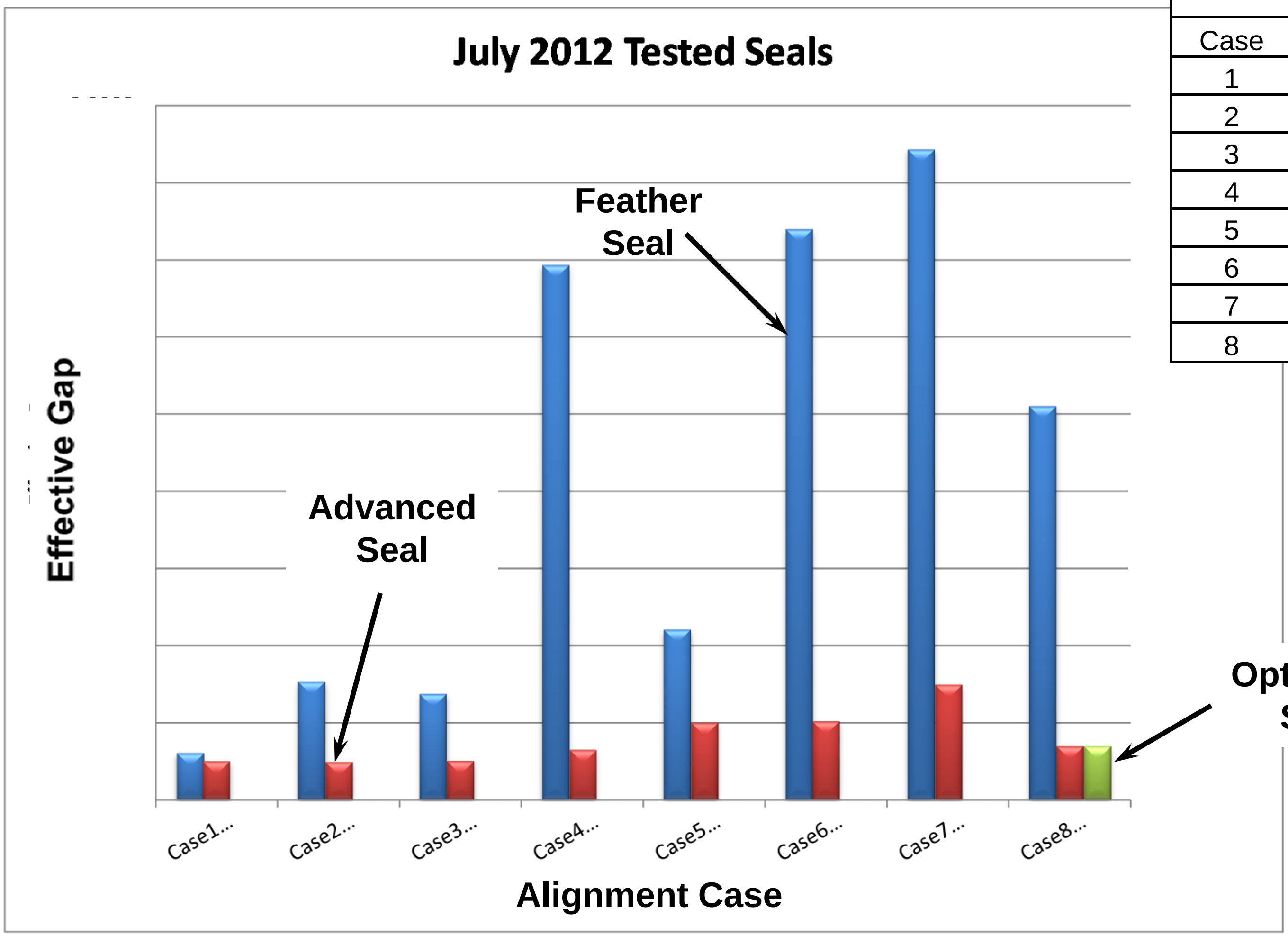




FTT has designed, and is developing a seal to work well under all conditions

Results: Large Leakage Reduction Potential

Programmatics – History – **Engr'g. Devl.** – Des./Manu. – Engine Test



Test Matrix			
Case	Offset	Shear	Bow
1	3mm	0mm	0mm
2	3mm	0.25mm	0mm
3	3mm	0.5mm	0mm
4	3.25mm	0.25mm	0mm
5	3.25mm	0.5mm	0mm
6	3.5mm	0.25mm	0mm
7	3.5mm	0.5mm	0mm
8	3mm	0mm	0.125mm

Large leakage reduction potential

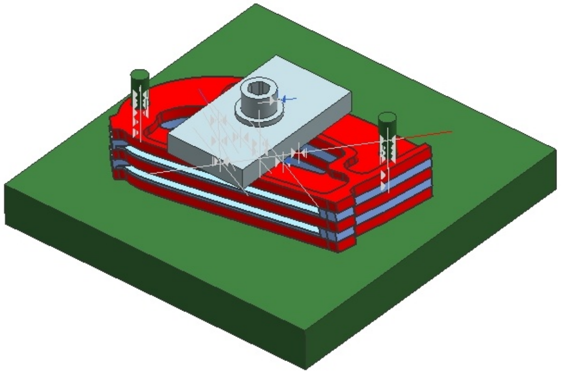
Manufacturing Challenges Addressed Early

Programmatics – History – Engr'g. Devl. – Des./Manu. – Engine Test

- Manufacturing and cost considered during the design process
- Existing manufacturing techniques utilized where possible
- New manufacturing technologies demonstrated and prototyped

Spar Manufacturing Trials Successful

Programmatics – History – Engr'g. Devl. – Des./Manu. – Engine Test



- Bond trial used a dead weight load
- Essentially 100% complete bonding
- External faying surfaces have concave faces
- Lesson learned:
  - Base material grain boundaries next to bond surface exhibited solid boride precipitation
  - Process improvement measures identified

Demonstration hardware produced using rapid prototyping technology

The Transition from Concept to Design

- Accuracy/confidence of heat transfer predictions validated/improved
- A viable sealing concept was selected
- A spar fabrication approach was selected

→ Ready to move forward to the detailed design phase

Approach to Demonstrate in Gas Turbine

Programmatics – History – Engr'g. Devl. – Des./Manu. – Engine Test

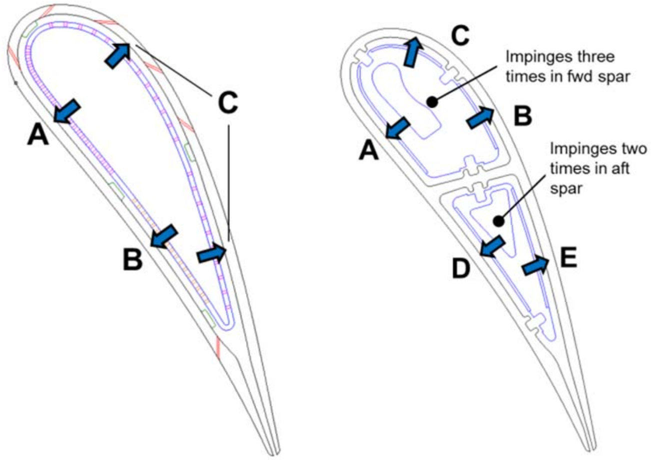
- Implement within 1st stage turbine vane application
- Detailed design of hardware performed by FTT
- Sequential-impingement cooling provided by FTT spar insert
- Airfoil shell manufacture and fabrication completed by FTT with Siemens support
- Instrumentation installed by FTT

Detailed Design Considerations

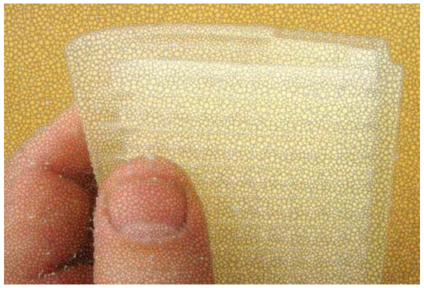
Programmatics – History – Engr’g. Devl. – Des./Manu. – Engine Test

Design changes based on Integrated Product Team approach

- Overall configuration modified from one insert to two
  - Permitted existing casting (with modifications) to be used



- Spar manufacture changed from bonded assembly to rapid prototype method

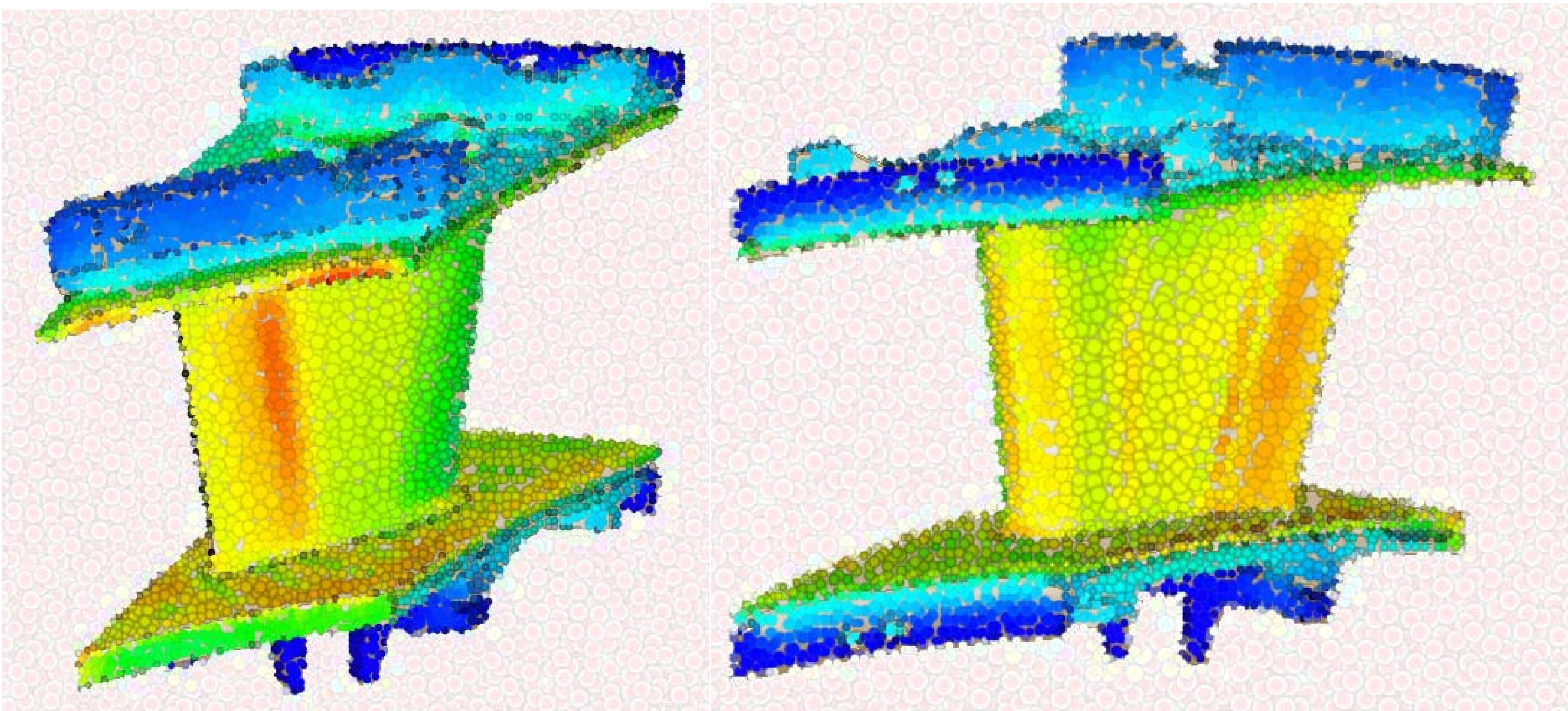


SLA of Prototype Spar

Changes addressed cost, schedule and technical risk factors

3D Thermal Analysis Results

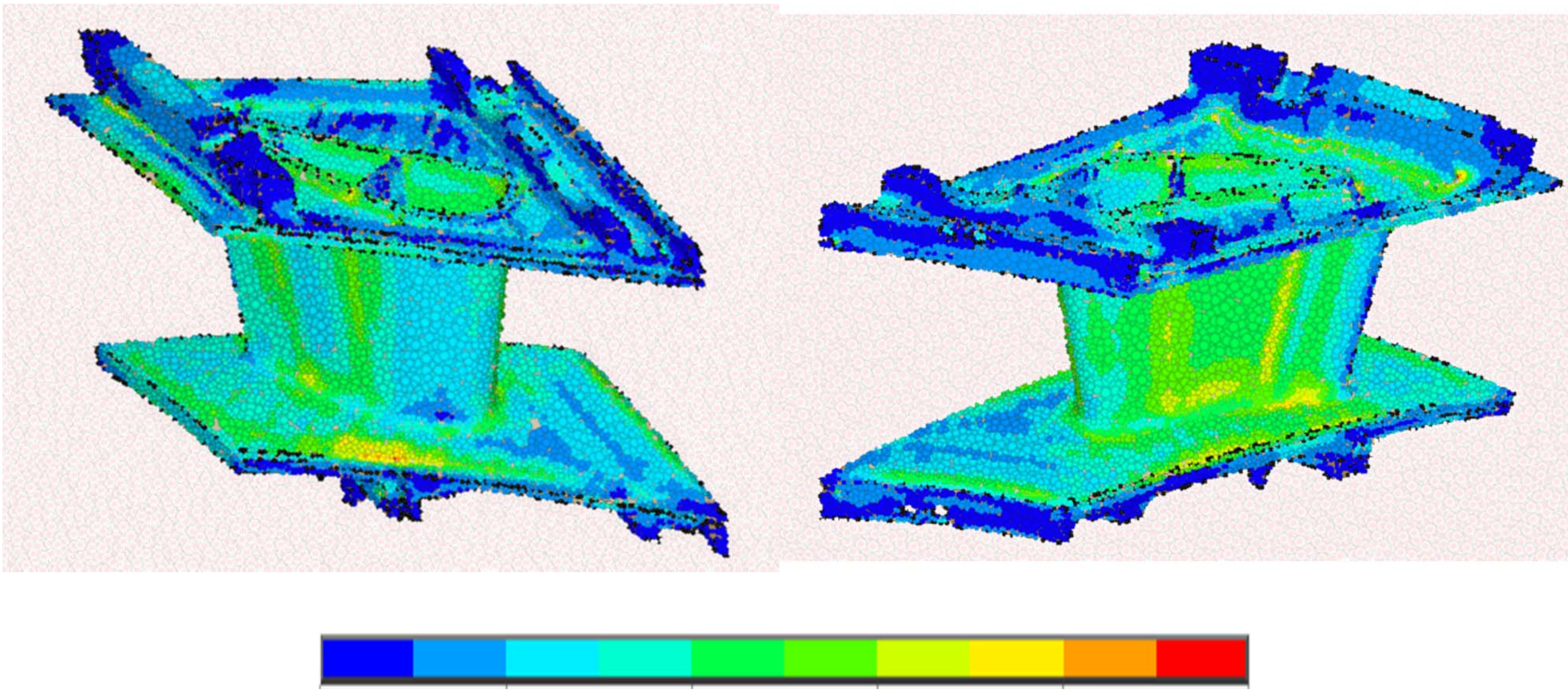
Programmatics – History – Engr'g. Devl. – Des./Manu. – Engine Test



Average surface temperature increased less than 10°C while cooling flow was reduced 35% (Relative to current hardware)

3D Structural Analysis Results

Programmatics – History – Engr’g. Devl. – Des./Manu. – Engine Test

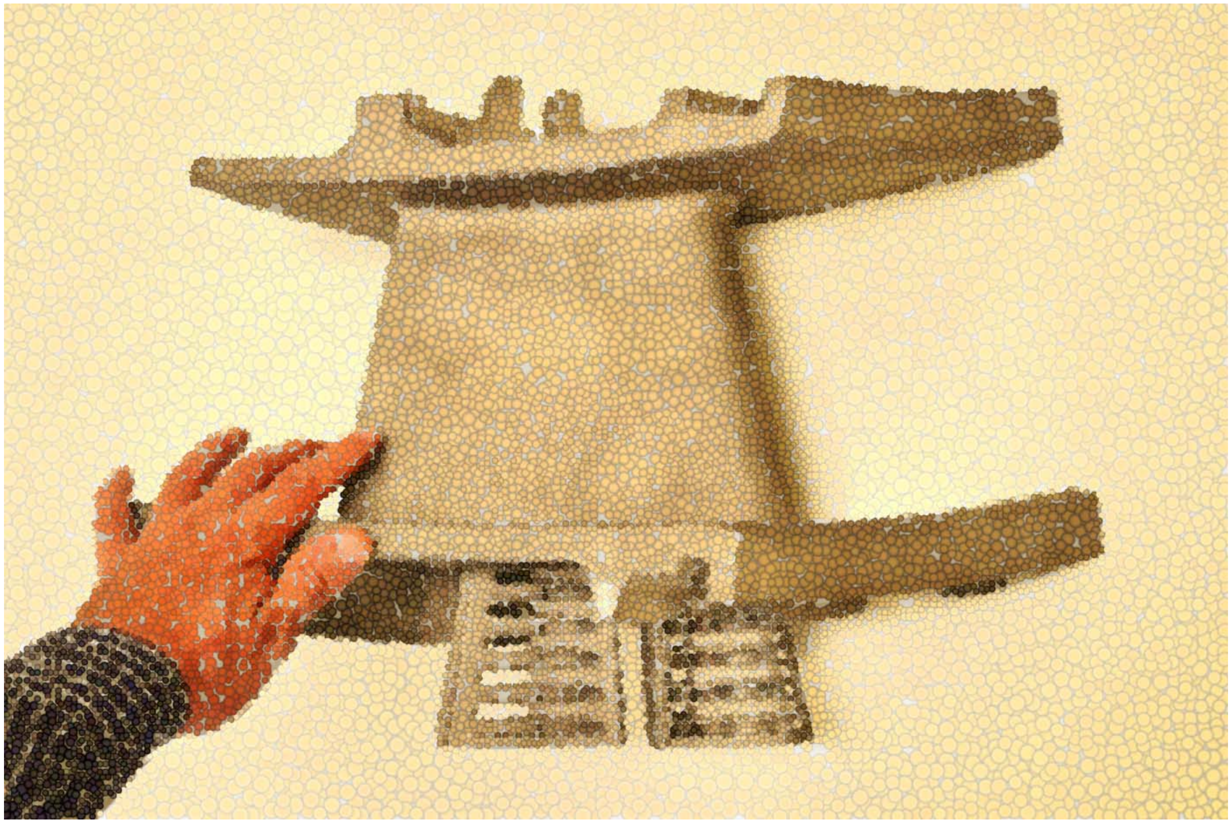


Von Mises Stress

Stresses and predicted cyclic capabilities are consistent with baseline design

Hardware Successfully Produced for Test

Programmatics – History – Engr'g. Devl. – Des./Manu. – Engine Test



Demonstration hardware produced using rapid prototyping technologies

Manufacture of Hardware

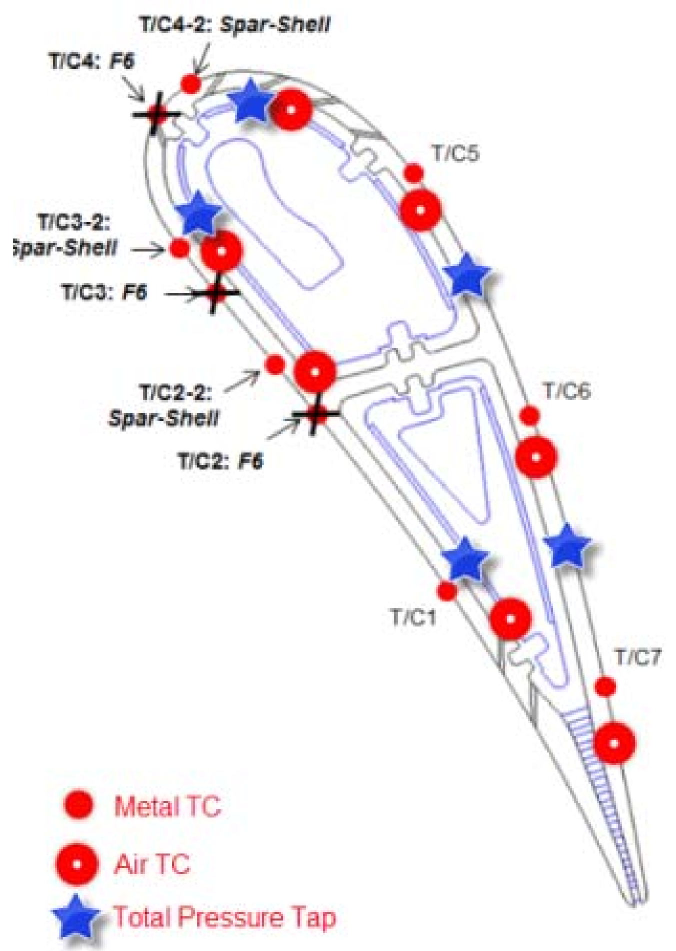
TBC eliminated for engine test

- Engine test schedule/hardware delivery constraints precluded application of TBC to Spar-Shell hardware
- Thermal and structural analysis used to indicate magnitude of expected increased structural temperatures and stresses
- Uncoated condition actually gives more confidence in metal temperature measurements (eliminates TBC thickness and conductivity uncertainties)
- FTT and Siemens agreed the risk of minor distress in a short-term test was acceptable

Instrumentation

Programmatics – History – Engr'g. Devl. – Des./Manu. – Engine Test

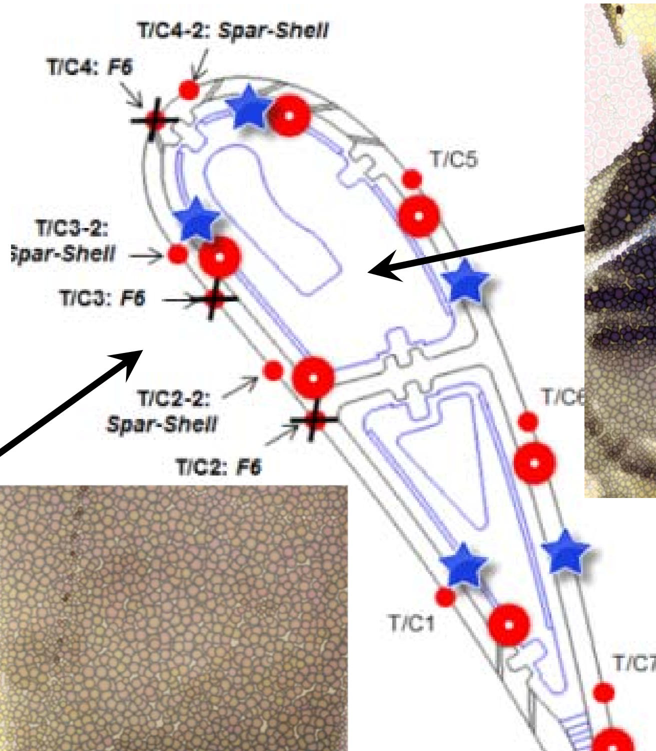
- Metal thermocouples at airfoil mid-span
  - 7 TM (metal) per vane
  - Installed into EDM slots
- Internal cavity TC's approximately opposite metal TC's
  - 7 TE (air) per vane
- Internal static pressure taps located just inboard of the end cap
  - 5 PS per vane
- On each vane, external of the end cap, supply air TCs and pressure taps
  - 1 TE per vane
  - 1 PS per vane

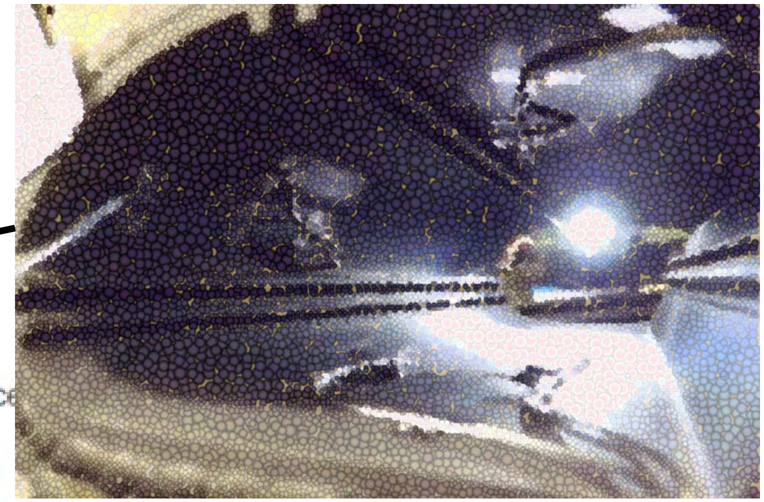


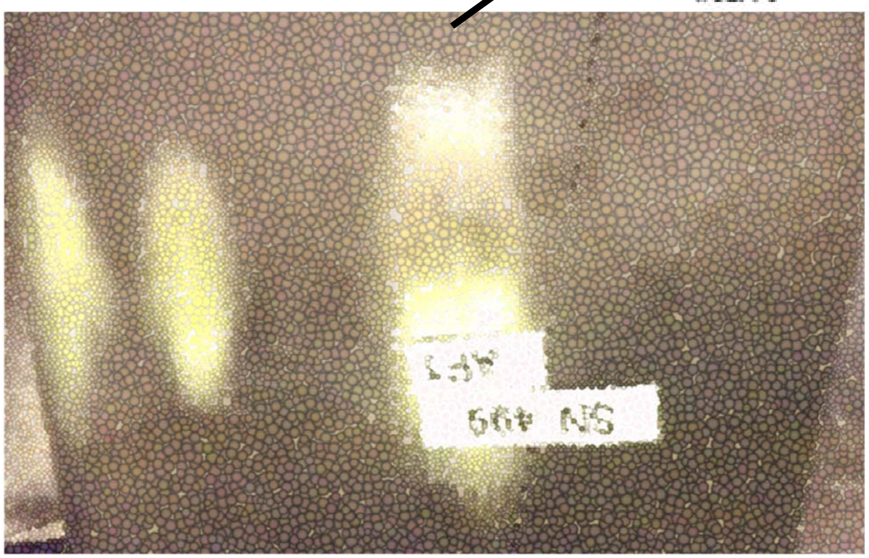
Extensive instrumentation installed on test articles

Instrumentation

Programmatics – History – Engr'g. Devl. – Des./Manu. – Engine Test







All sensors installed in FTT's instrumentation lab

Validation of the Concept by Engine Test

Programmatics – History – Engr'g. Devl. – Des./Manu. – **Engine Test**

- Large-scale IGT engine test provided by Siemens
  - 3 parts placed individually in hot locations adjacent to bill-of-material parts
  - Health of hardware monitored during engine test to assure product integrity (Data monitoring and visual (borescope) inspections)

Testing completed successfully with all test/data points achieved

Test Campaign

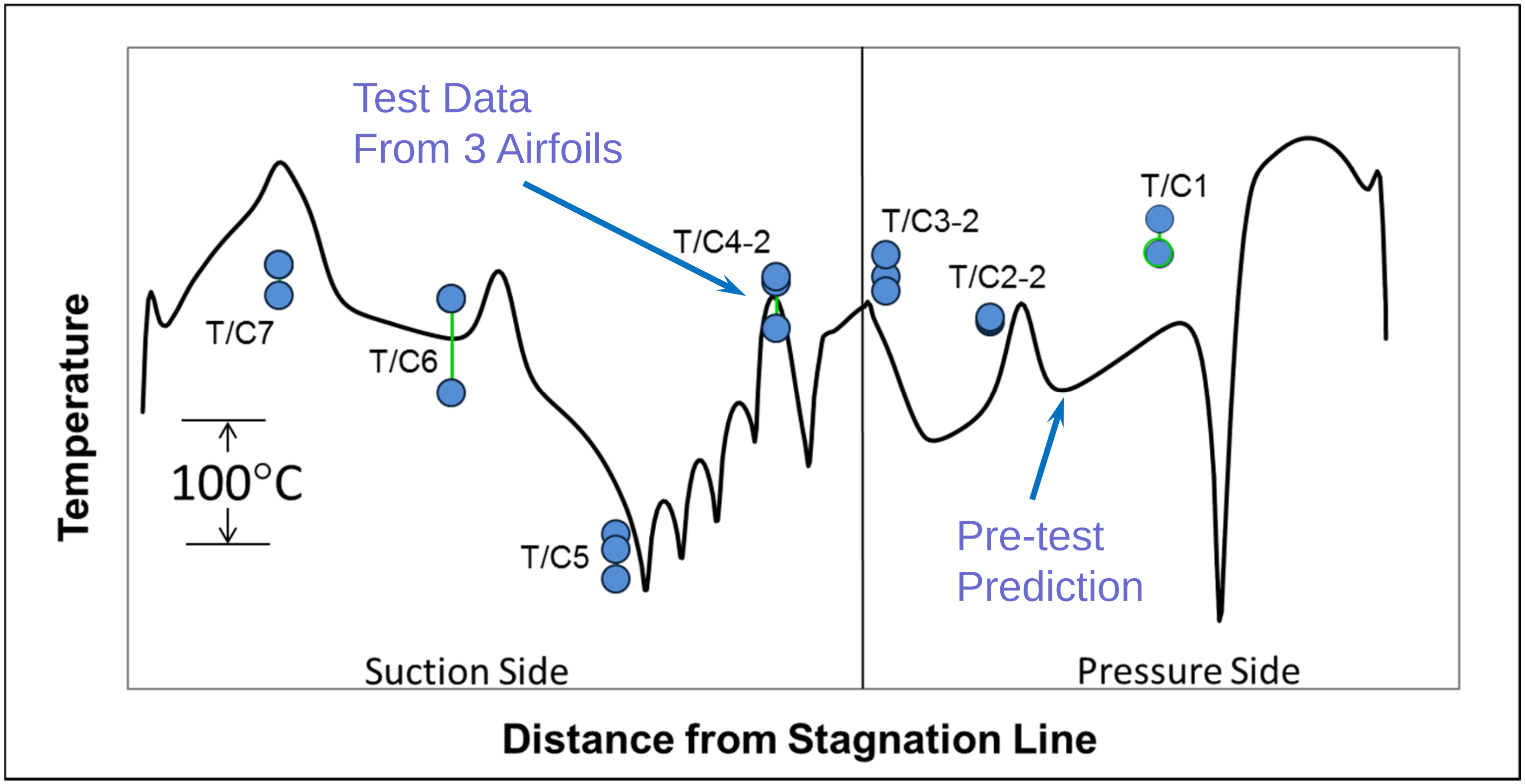
Performed in Siemens' Berlin Test Bed

- Engine ran from March to April, 2014 with Spar-Shell parts installed
- Total estimated run time ~ 115 hours
  - ~25 hours at maximum power temperature rating
- Total estimated number of cycles ~ 50
- All objectives of planned test campaign were completed

Data Quality was Good!

Programmatics – History – Engr'g. Devl. – Des./Manu. – Engine Test

Measured temperatures in good agreement with predictions

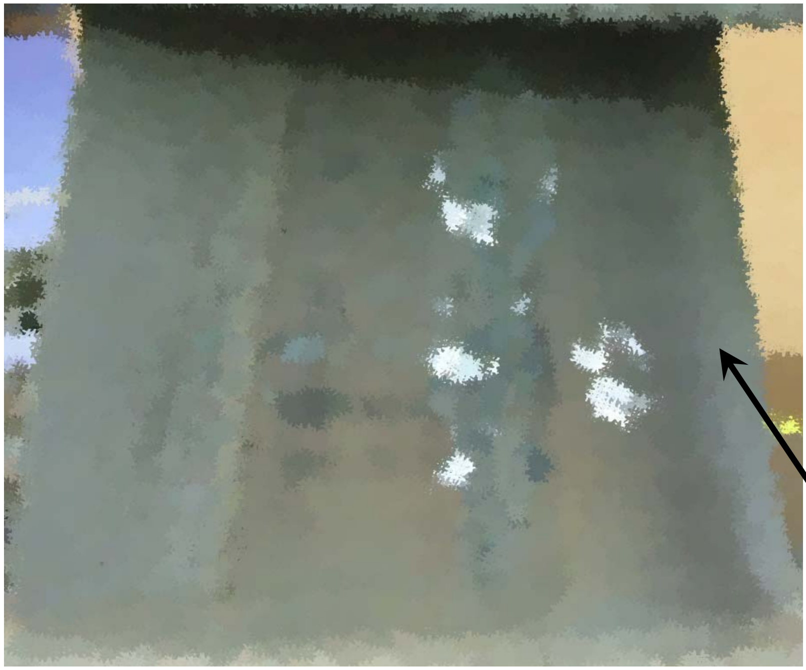


- Excellent instrumentation survivability
- Measurements in general agreement with expectations
- Pressure side was warmer than expected

Typical Hardware Condition

Programmatics – History – Engr'g. Devl. – Des./Manu. – Engine Test

Pressure Side



Leading Edge

Suction Side

Note: No showerhead cooling

- All parts exhibited thermal-stress indications on pressure side
- All parts contained an oxide scale

Summary

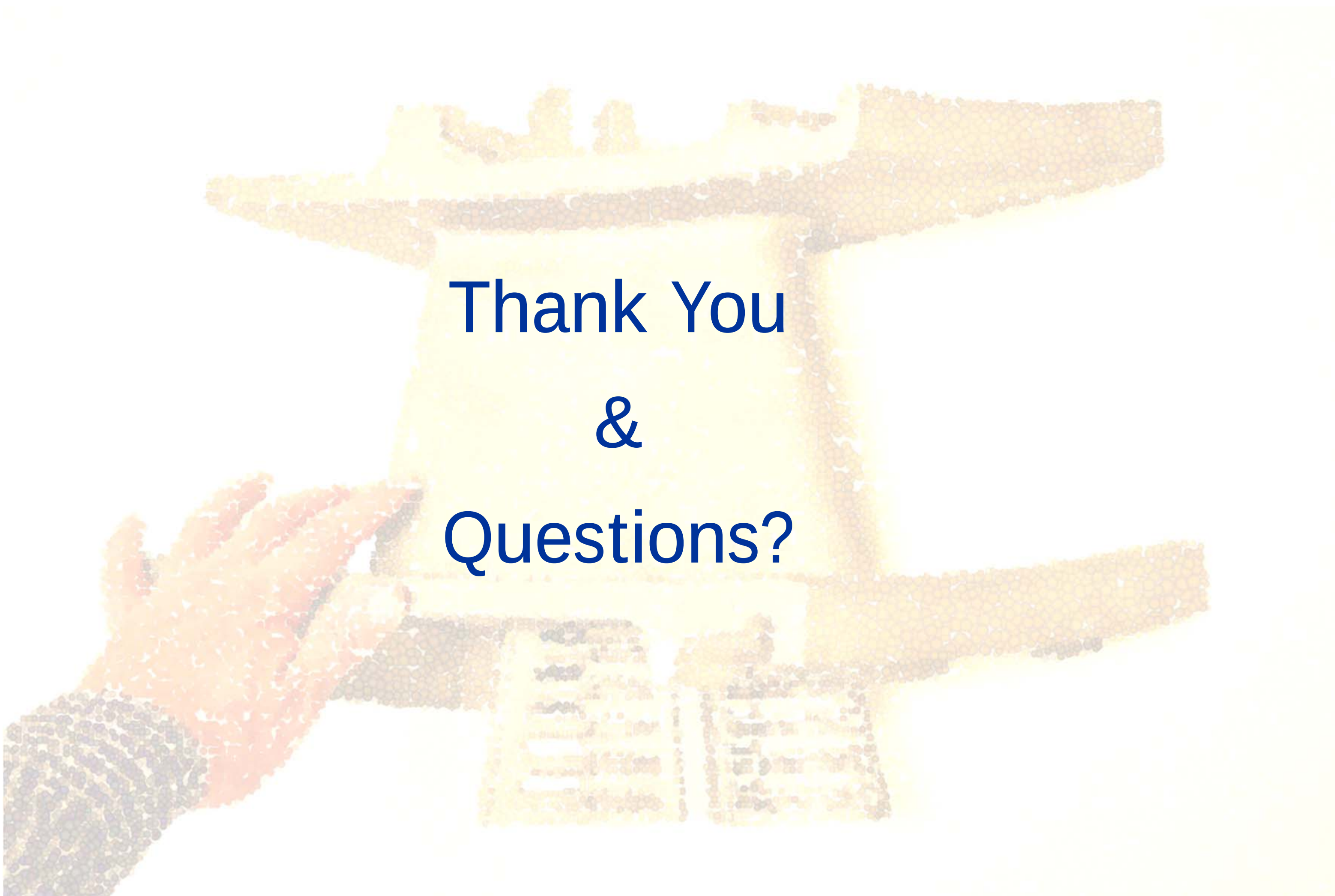
- Successful advanced technology development collaboration comprised of FTT, DOE NETL and Siemens
- Accelerated schedule – leapfrog from Phase I SBIR to pre-production prototype demonstration program
- Spar-shell cooling technology based on sequential impingement successfully demonstrated in full-scale IGT engine test
- Potential commercialization of the technology in an IGT is pending post-test engineering review
- A spin-off of the technology for use in an aircraft engine is being developed under an Air Force Phase I (FA8650-13-M-2413) and Phase II SBIR programs

Acknowledgements

Department of Energy

National Energy Technology Laboratory

Siemens Energy



Thank You

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Questions?