FTT Aerothermal Research in Support of DOE Initiatives/Goals

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Outline

- Oxy-fuel turbomachinery development (with Clean Energy Systems & Siemens)
- Demonstration of enabling Spar-Shell cooling technology in gas turbines
- Sealing and leakage control technology

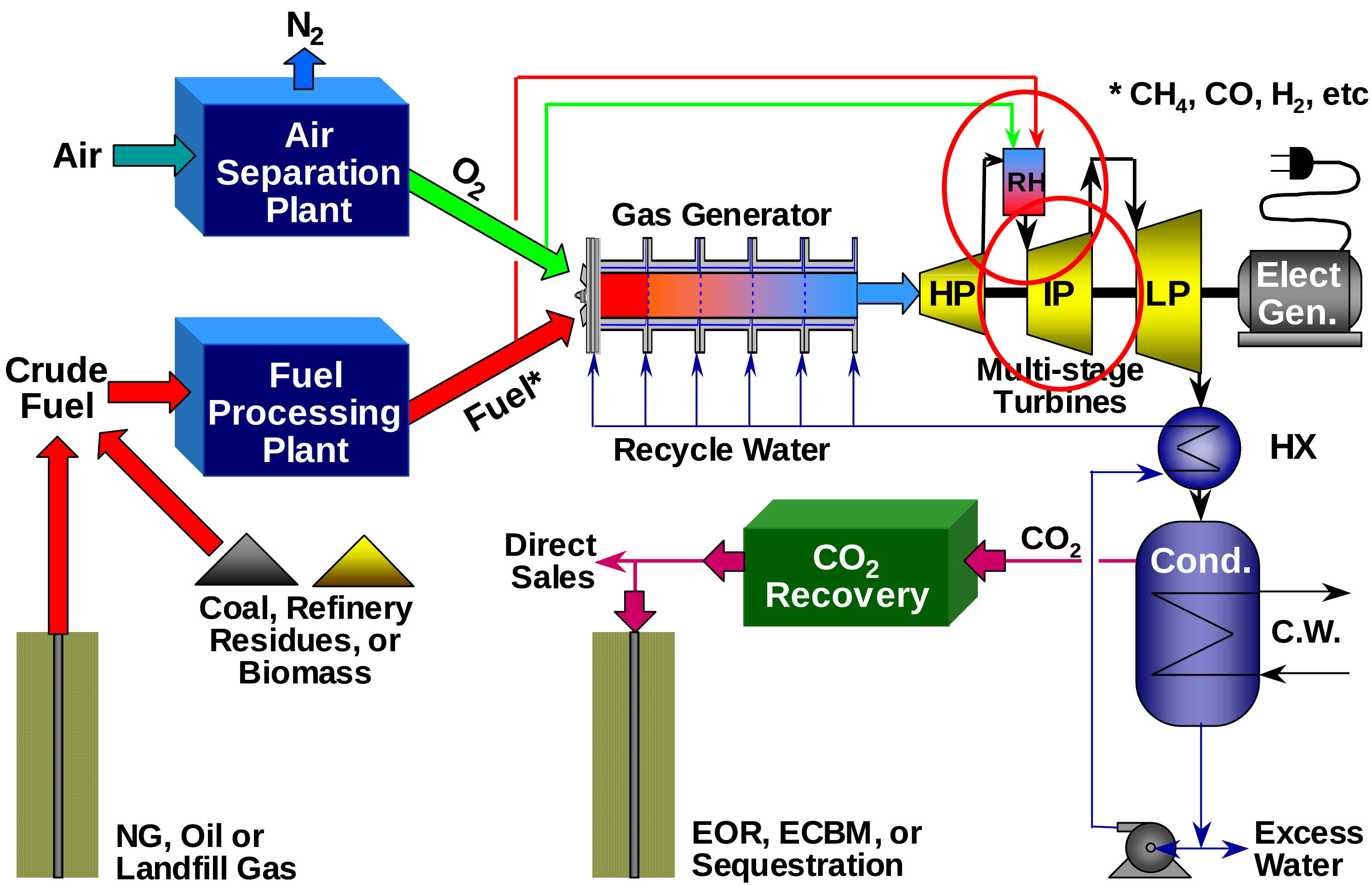
Oxy-Fuel Turbomachinery Development

Program goals and objectives

- Objective: Design, manufacture & test a commercial-scale oxy-fuel turbine (OFT) for use in industrial O-F plants that:
  - Capture and sequester 99% of produced CO_2
  - Operate at competitive cycle efficiencies
  - Utilize diverse fuels
- Schedule: 48 months
  - FY2011 thru FY2014
- Development partners
  - Clean Energy Systems, Siemens Energy, Inc., Florida Turbine Technologies, Inc. and Integrated Engineers and Contractors Co.

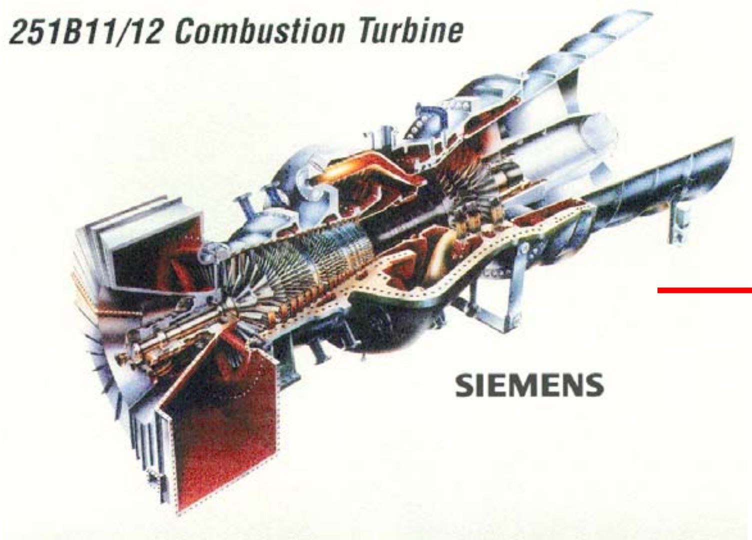
Oxy-Fuel Turbomachinery Development

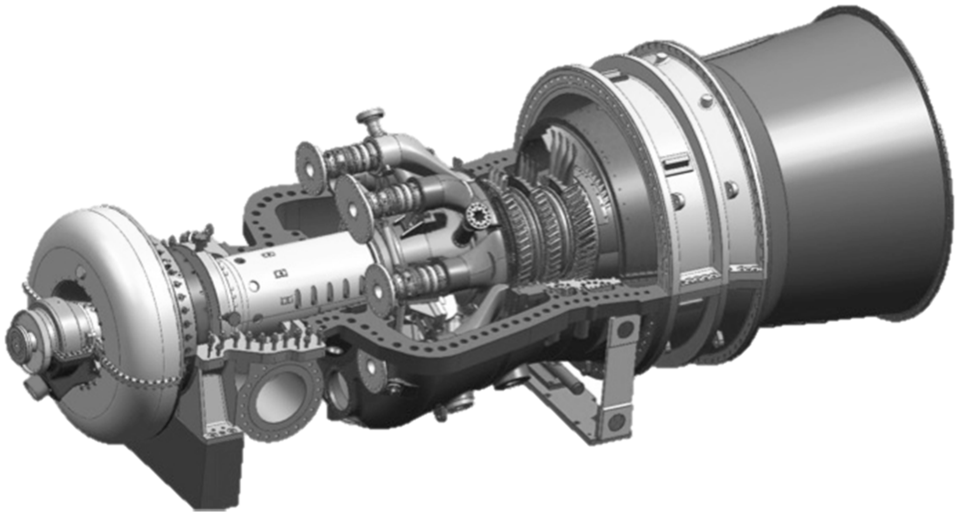
Oxy-fuel cycle – Zero emission power plant



Oxy-Fuel Turbomachinery Development

Adaptation of existing turbomachinery for IPT



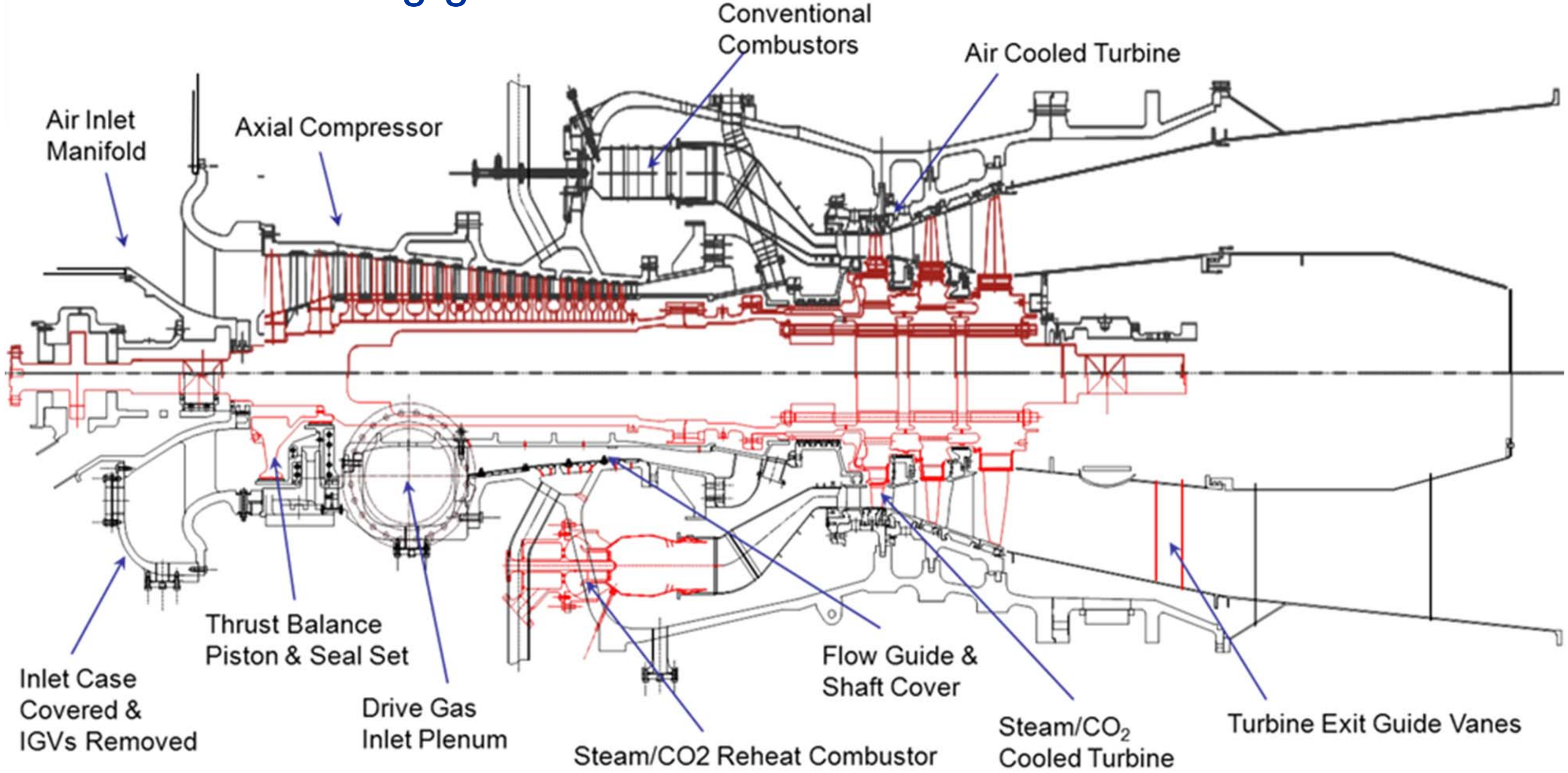


- Originally a W251 (SGT-900) gas turbine
- Remove compressor, convert combustors to O-F reheaters
- Converted to a **150 MW** oxy-turbine
- CO_2 by-product is a revenue stream

Oxy-Fuel Turbomachinery Development

Transformation of SGT-900 to OFT-900/SXT-150

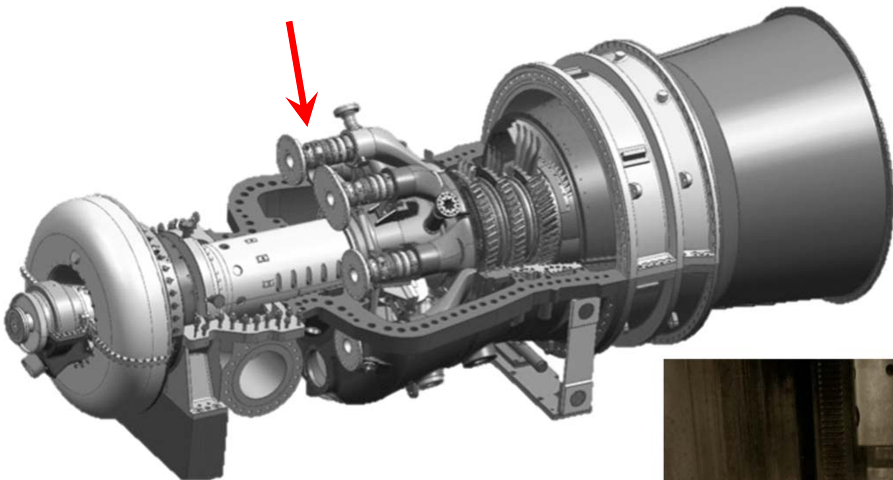
SGT-900 air-breathing gas turbine

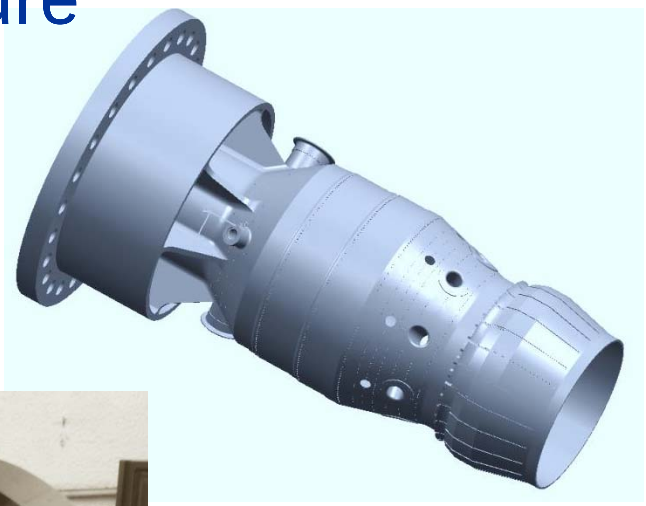


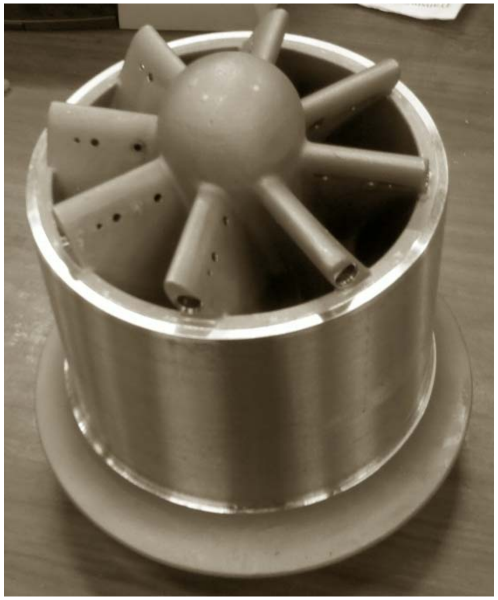
OFT-900/SXT-150 oxy-fuel intermediate pressure turbine

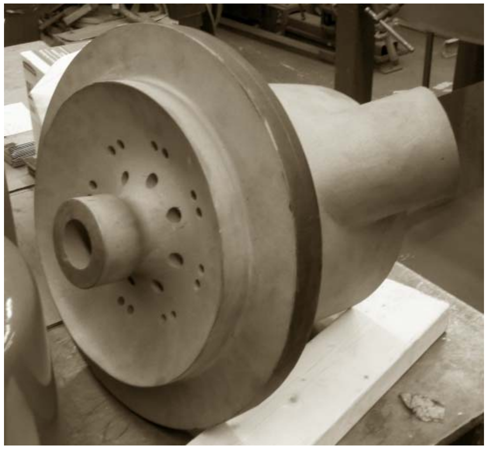
Oxy-Fuel Turbomachinery Development

FTT reheat combustor manufacture



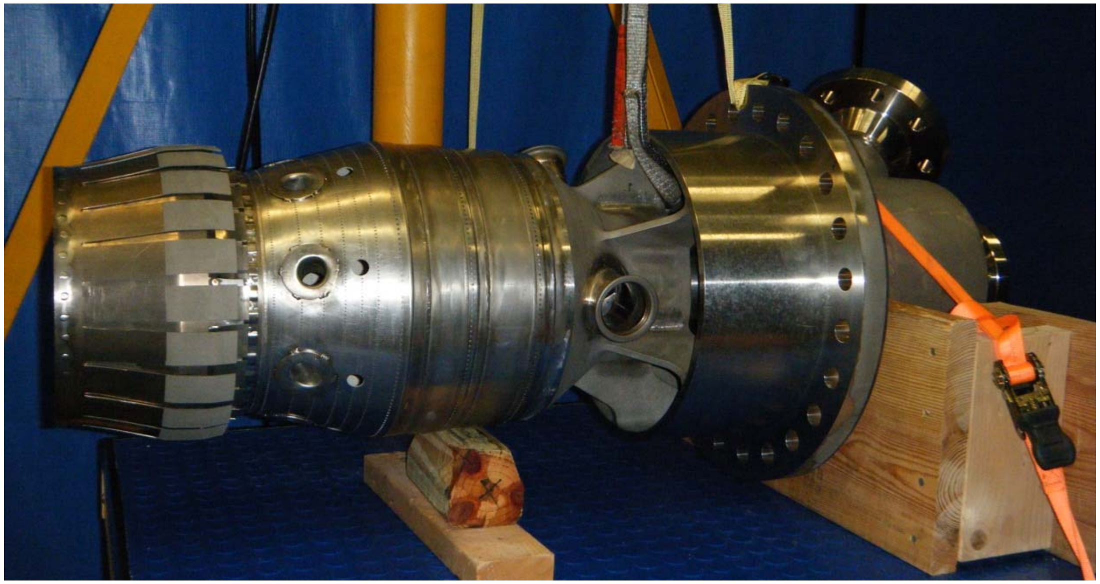






Oxy-Fuel Turbomachinery Development

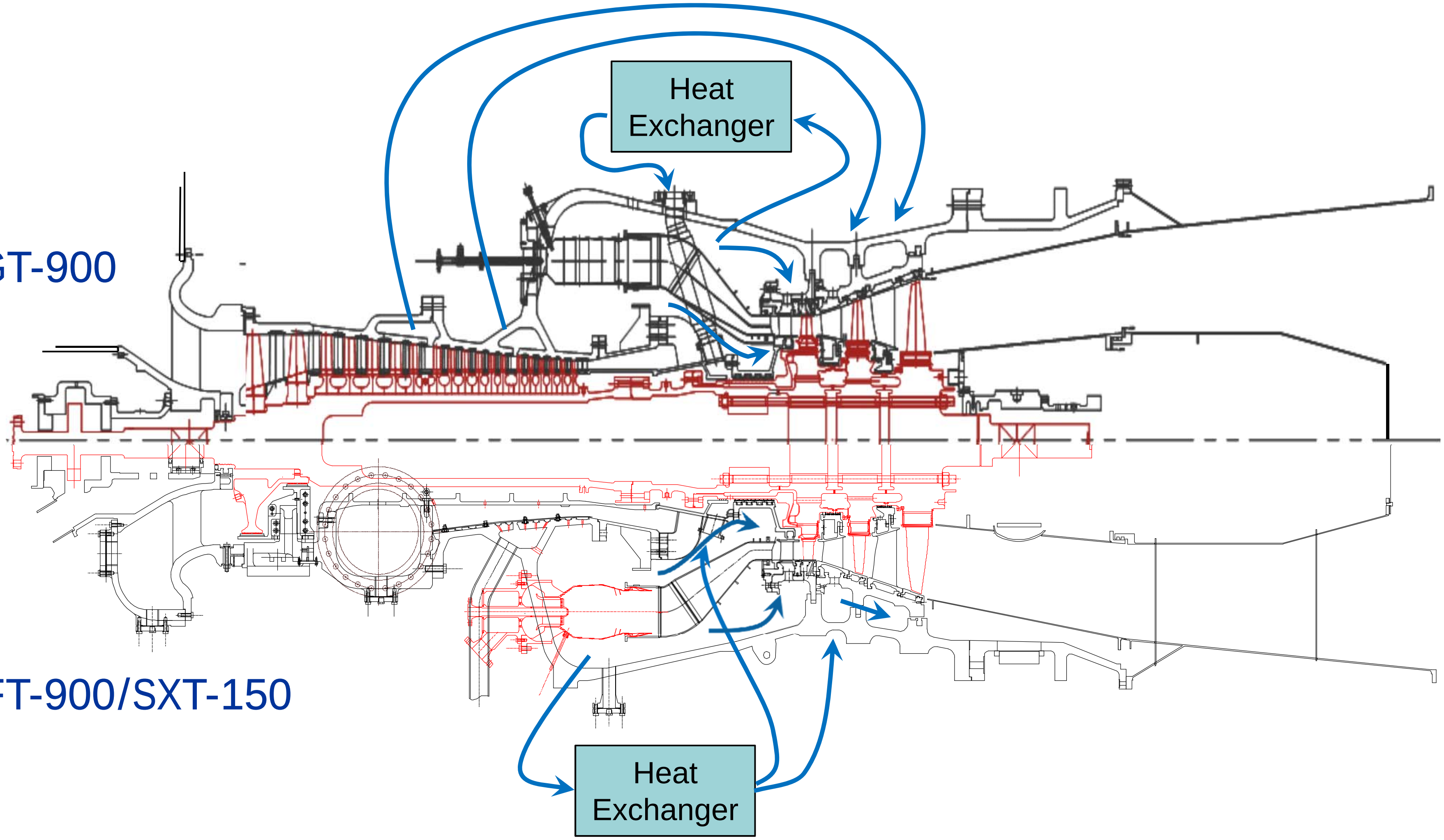
Assembled reheat combustor received from FTT



Oxy-Fuel Turbomachinery Development

Secondary flow system routing/modeling

SGT-900

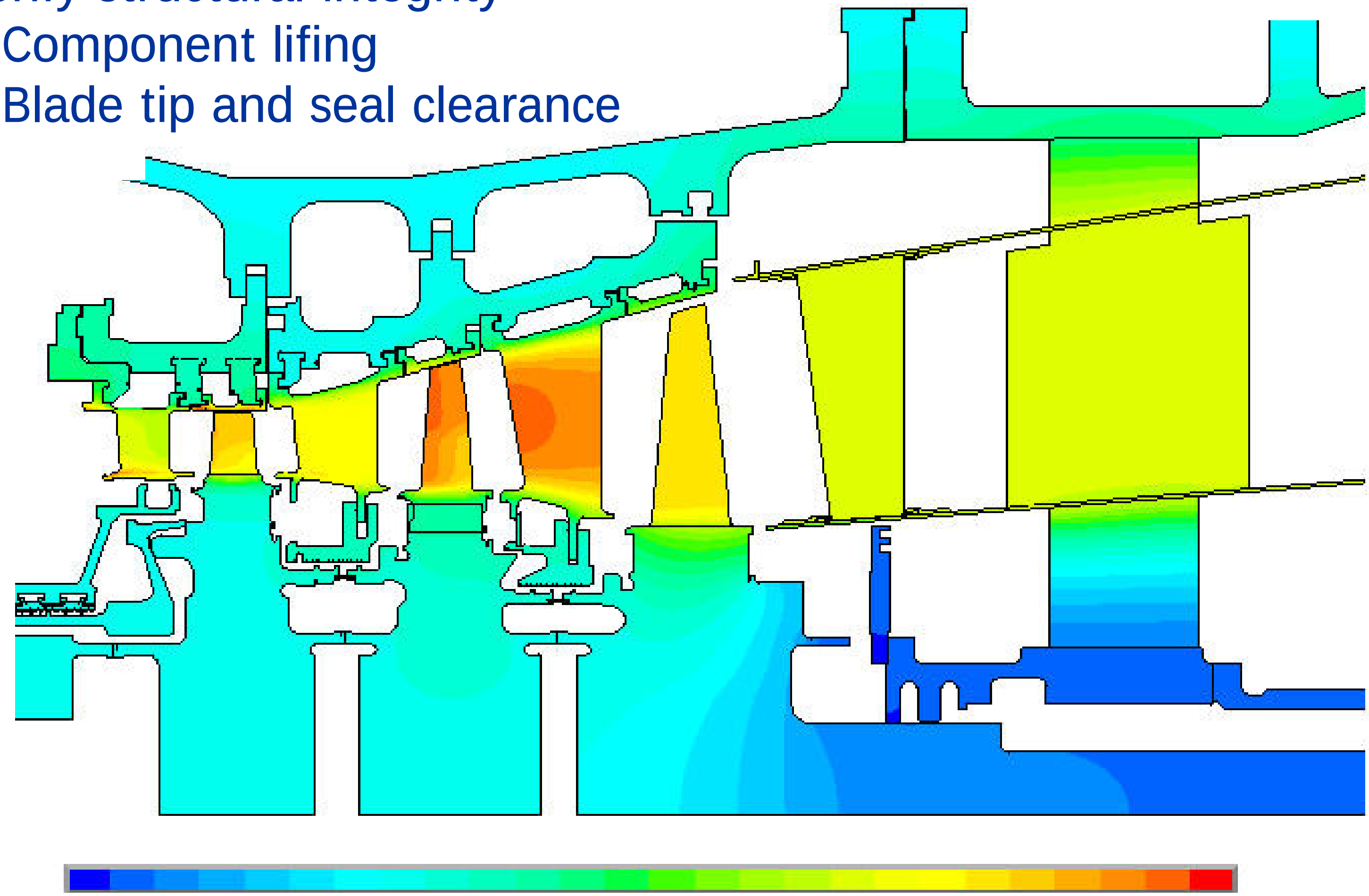


OFT-900/SXT-150

Oxy-Fuel Turbomachinery Development

Whole engine thermal/structural modeling

Verify structural integrity
- Component lifing
- Blade tip and seal clearance



Oxy-Fuel Turbomachinery Development

Status

The program:

- CES has partnered with Siemens Oil & Gas and FTT to retrofit an SGT-900 to a highly efficient OFT under the DOE-CES program.
- Will demonstrate a full-scale OFT at reduced loads, off the grid
- Is currently one year ahead of its 4-year development schedule

Once successful:

- The OFT can be deployed in several applications - all offering clean, reliable power without pollution

Oxy-Fuel Turbomachinery Development

Equipment arrival in Bakersfield, CA August 27, 2012

Oxy-Fuel Turbomachinery Development

Transport to Kimberlina via heavy hauler 8/27/12

Oxy-Fuel Turbomachinery Development

OFT installed on foundation at KPP September 13th

Outline

- Oxy-fuel turbomachinery development (with Clean Energy Systems & Siemens)
- Demonstration of enabling Spar-Shell cooling technology in gas turbines
- Sealing and leakage control technology

Enabling Spar-Shell Cooling Tech.

Program goals and objectives

- Develop and test – commercial prototype:
  - First-stage turbine airfoils requiring significantly less cooling flow than the current state-of-the-art (SOTA)
- Proposed cooling approach addresses durability concerns associated with turbine inlet pressure and temperature increases desired for future gas turbines
- Open door to commercialization of this new technology in both F-frame and other highly cooled turbine airfoil applications

Enabling technology for future gas turbine-based power systems

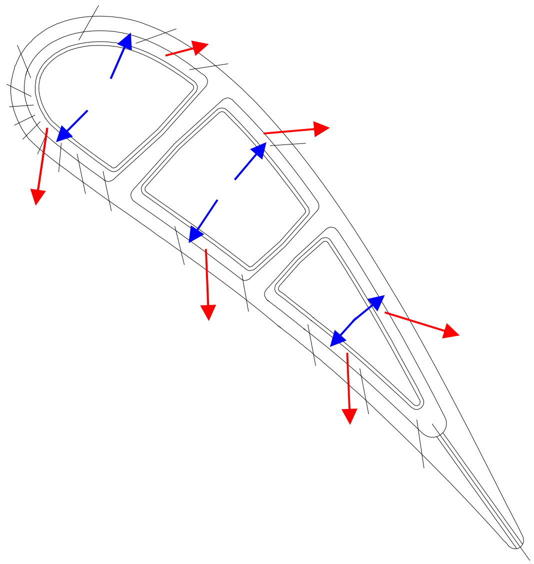
- DOE Office of Fossil Energy-sponsored hydrogen and oxy-fueled turbomachinery programs

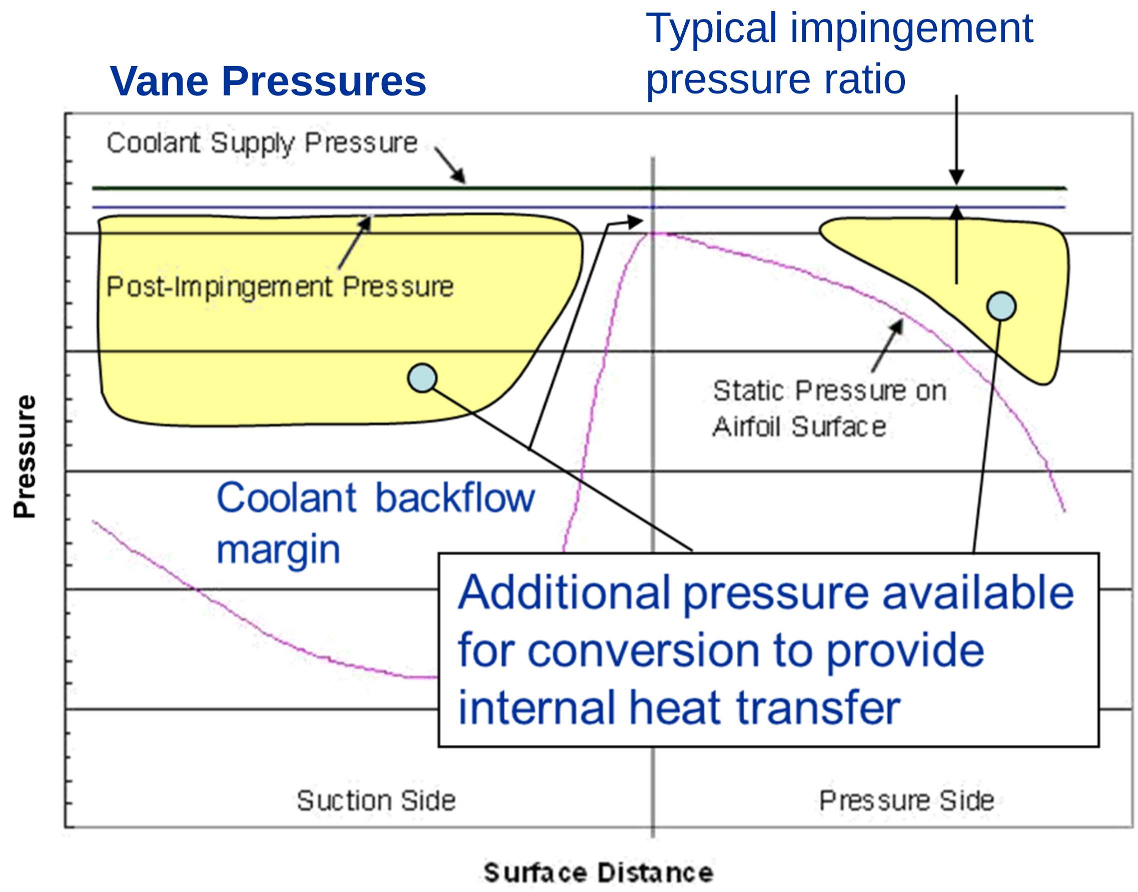
Enabling Spar-Shell Cooling Tech.

Conventional cooling design

→ Philosophy/practice limits cooling potential

- Impingement pressure ratio typically near constant around airfoil
- Post-impingement pressure set high enough for coolant outflow to leading edge

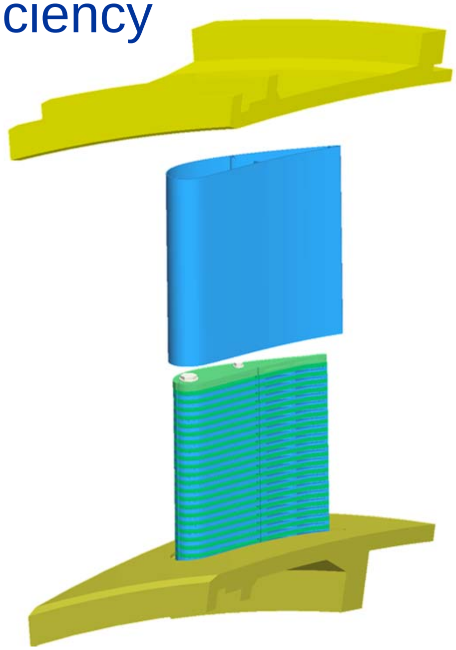


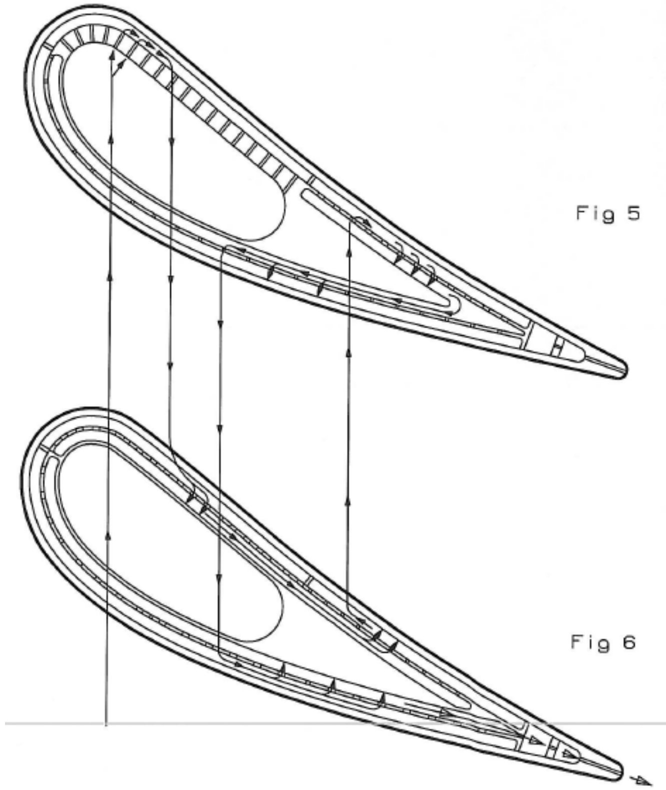


Enabling Spar-Shell Cooling Tech.

What is it? - Alternative to existing state-of-the-art

- FTT sequential-impingement cooling scheme based on new insert design improves cooling (reduces cooling flow 40%)
- Provides path for implementation of next generation materials
- Optimized thermal/structural arrangement allows increased firing temperatures and improved efficiency



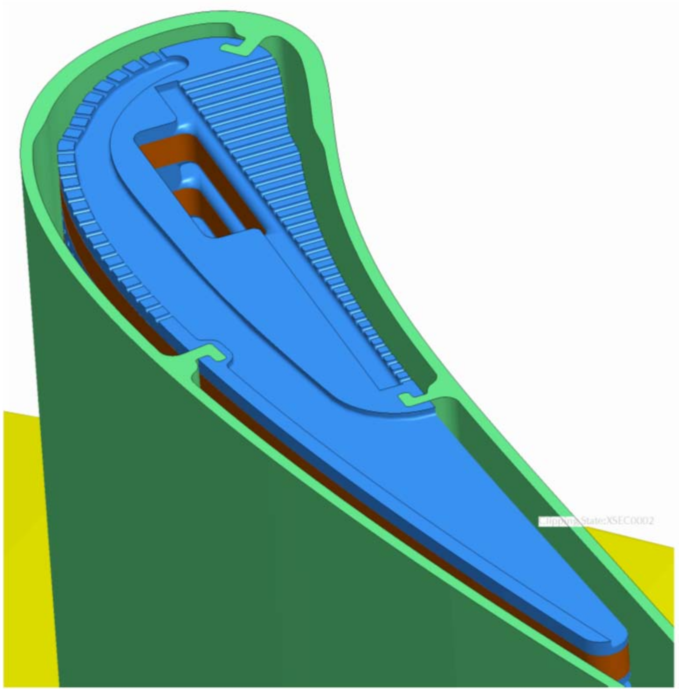


Ref: U.S. Patent #7080971, "Cooled Turbine Spar Shell Blade Construction, J. W. Wilson and W. Brown, July 25, 2006.

Enabling Spar-Shell Cooling Tech.

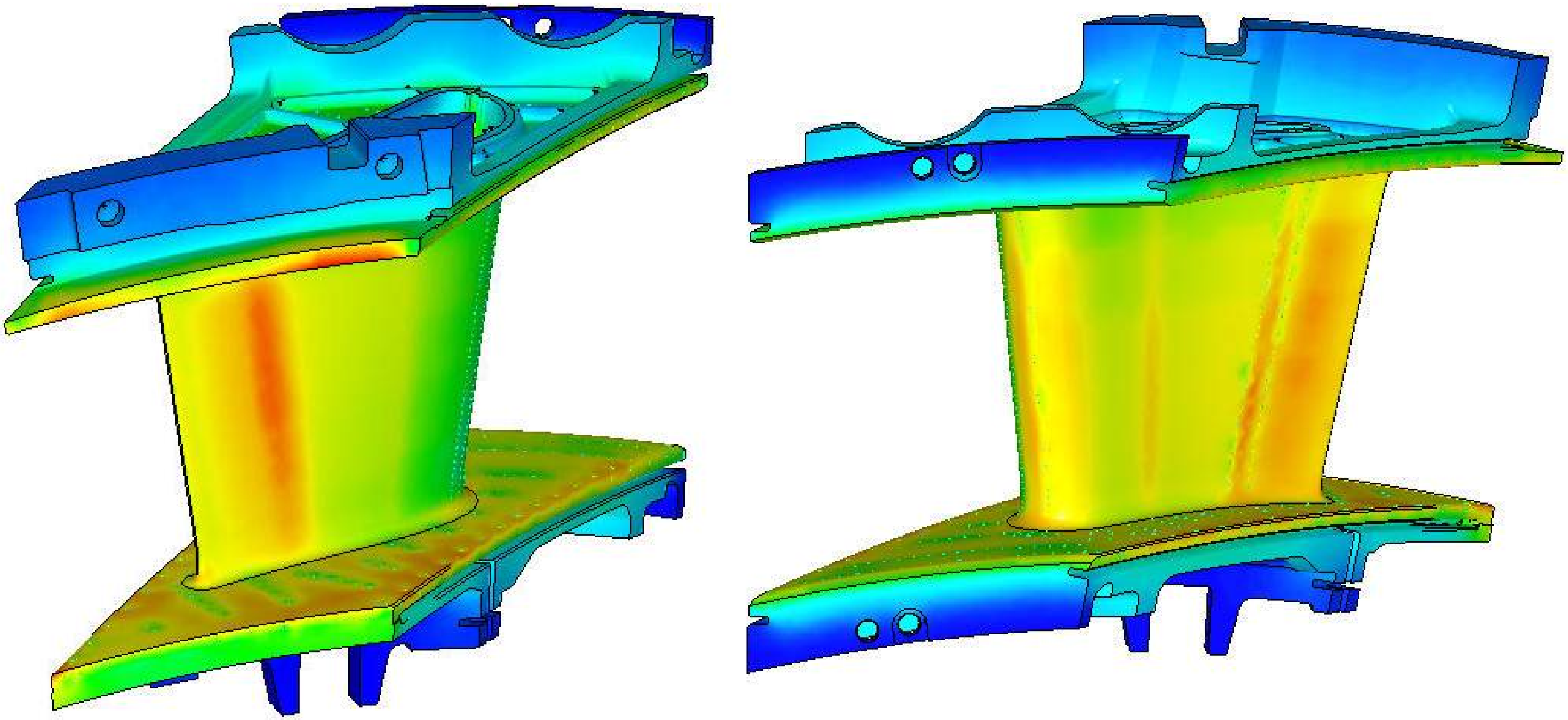
Commercialization program: DOE, FTT & Siemens

- Use existing (proven) 1st stage turbine vane casting as the shell
  - No rotating mass concerns
- Sequential-impingement cooling provided by FTT spar insert
- Demonstration will install 6-8 parts in a rainbow arrangement with bill-of-material parts



Enabling Spar-Shell Cooling Tech.

3D thermal analysis results

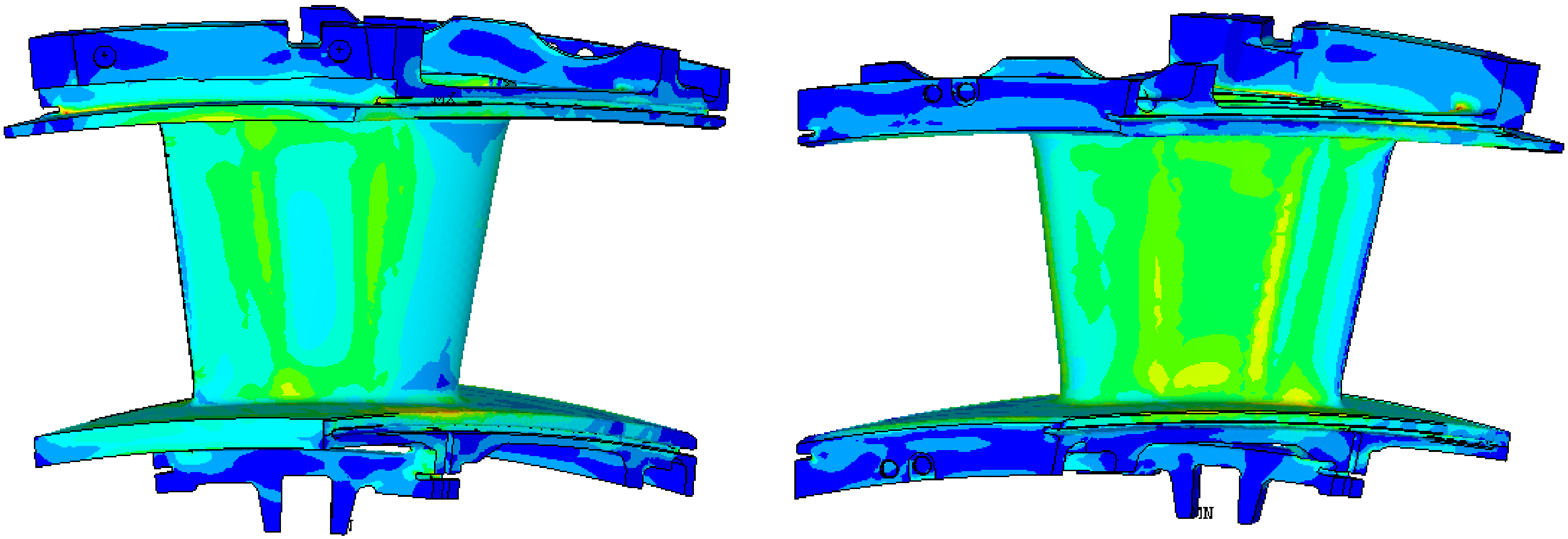


Average surface temperature increased less than 10°C while cooling flow was reduced 35% (Relative to current hardware)

Temperature

Enabling Spar-Shell Cooling Tech.

3D structural analysis results




Von Mises Stress

Stresses and predicted cyclic capabilities are consistent with baseline design

Enabling Spar-Shell Cooling Tech.

Design validation and verification activities

Basic cooling flow and heat transfer performance evaluation via experimental test prior to engine installation

- Impingement heat transfer test (FTT/UCF)
- Cold flow and pressure drop testing of actual engine hardware
- Seal leakage test (FTT)

Management of manufacturing/fabrication risk

- Production of engineering mockups and models
- Manufacturing, fabrication and assembly trials

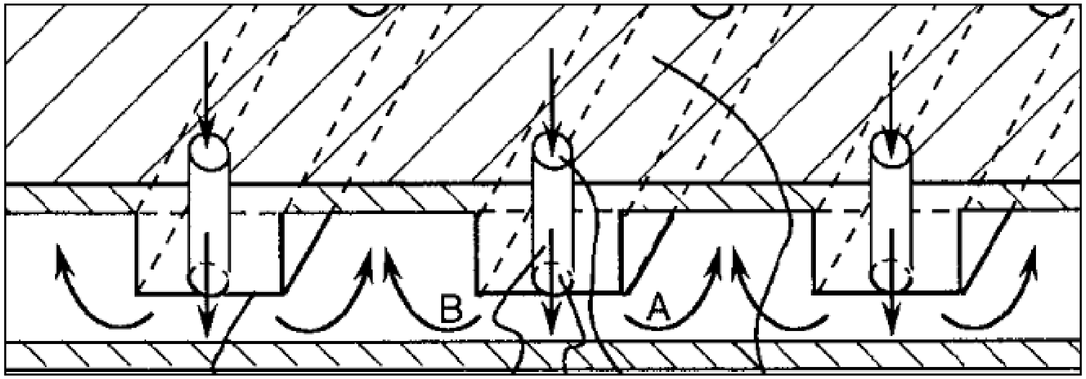
Health can be monitored during engine test to assure product integrity

- Temperature and pressure sensors
- Frequent borescope (visual) inspection

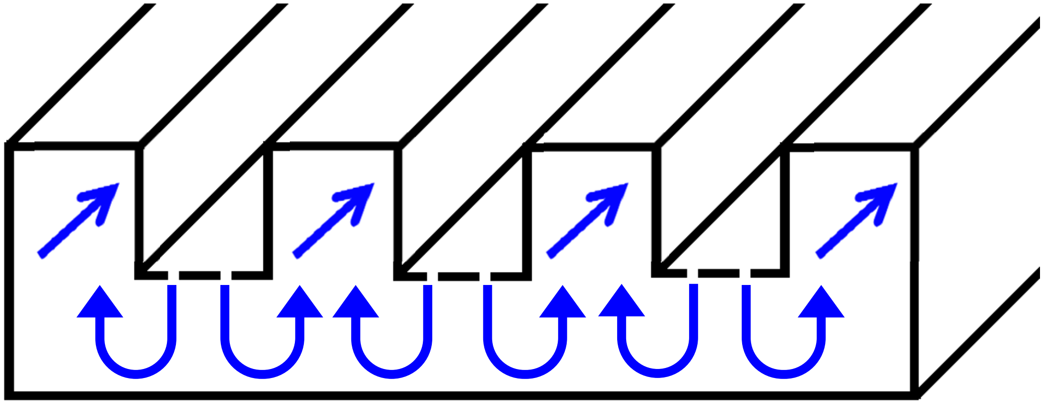
Enabling Spar-Shell Cooling Tech.

Purpose of heat transfer testing

- Downstream rows of large scale jet impingement arrays suffer from crossflow
- This negative effect can be mitigated by increasing the crossflow area



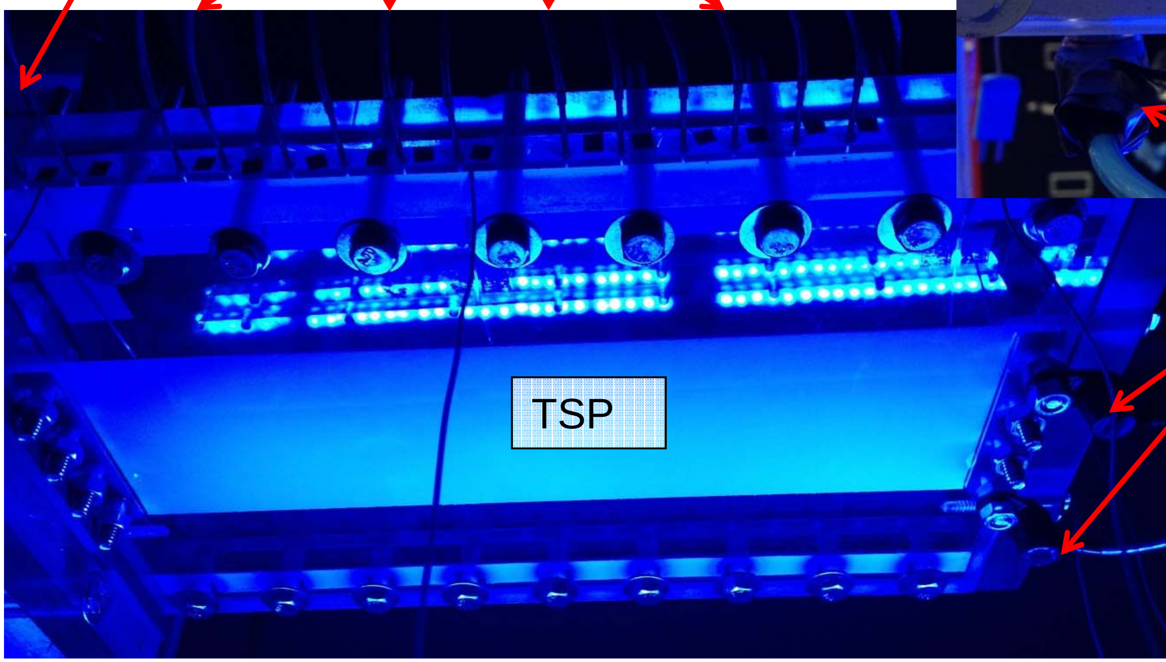
Bunker. US Patent No. 6,000,908

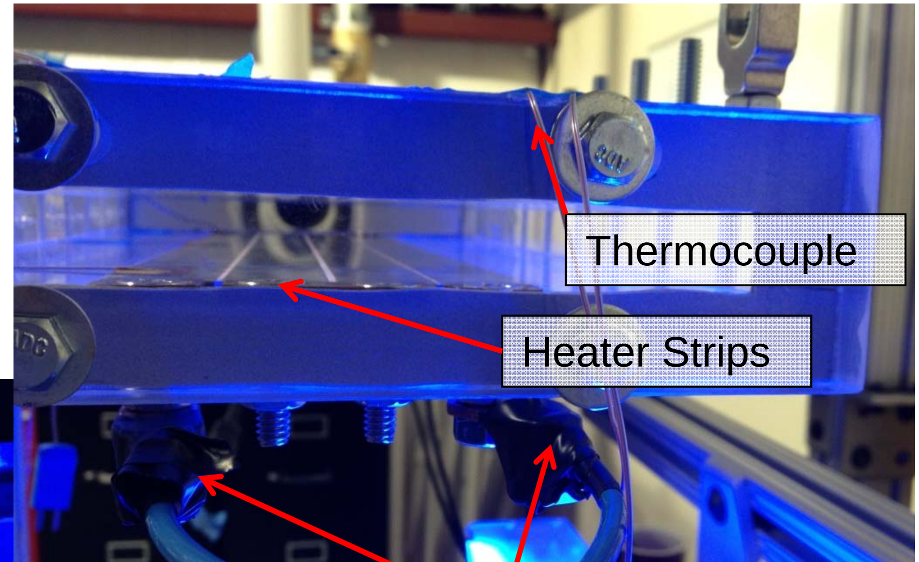


Enabling Spar-Shell Cooling Tech.

Impingement heat transfer testing performed at UCF*

Test technique: Constant heat flux, temperature sensitive paint



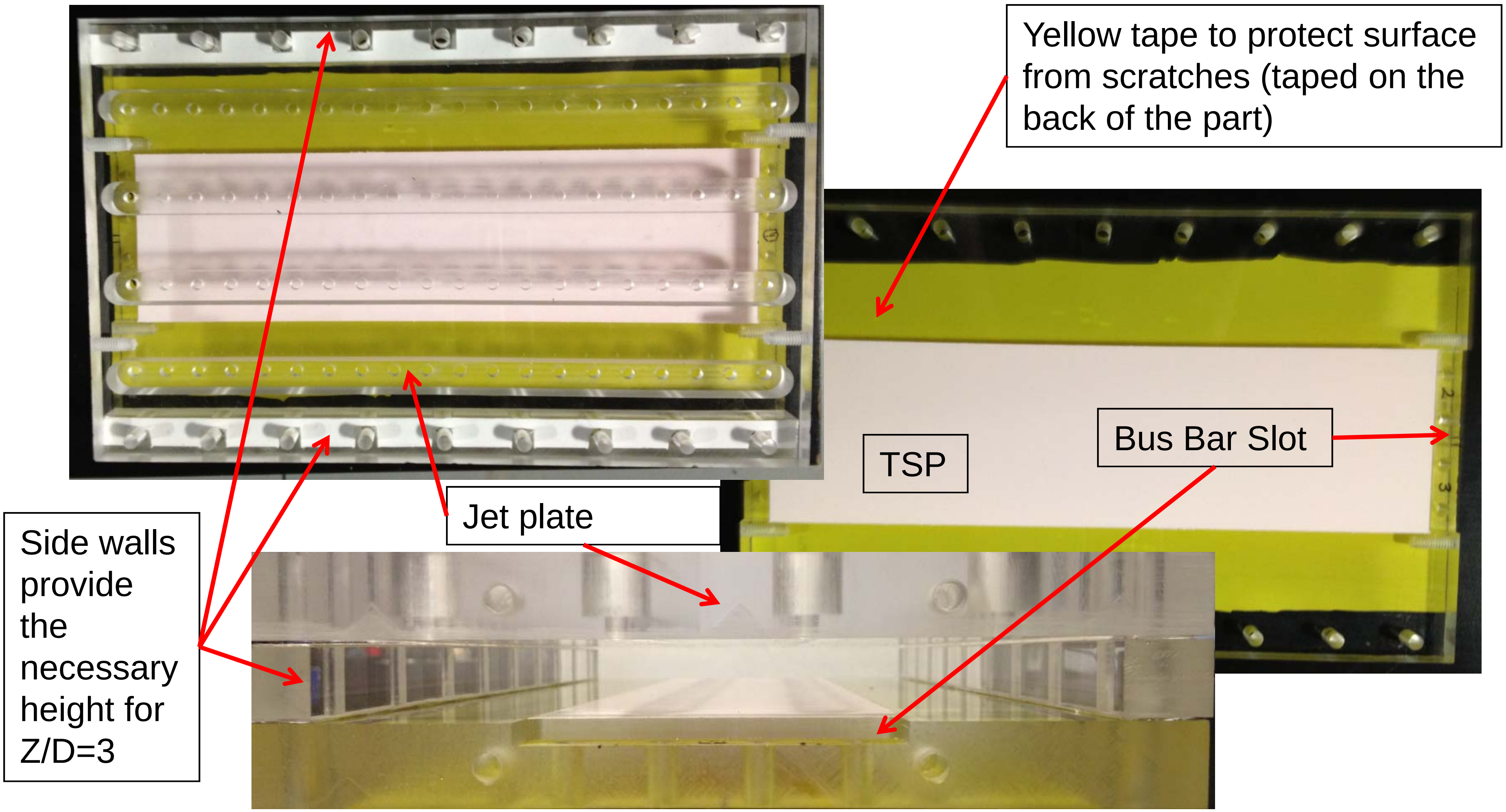


- Proven methodology
- Accurate results

* University of Central Florida – UTSR Fellow Roberto Claretti under direction of Prof. Jay Kapat

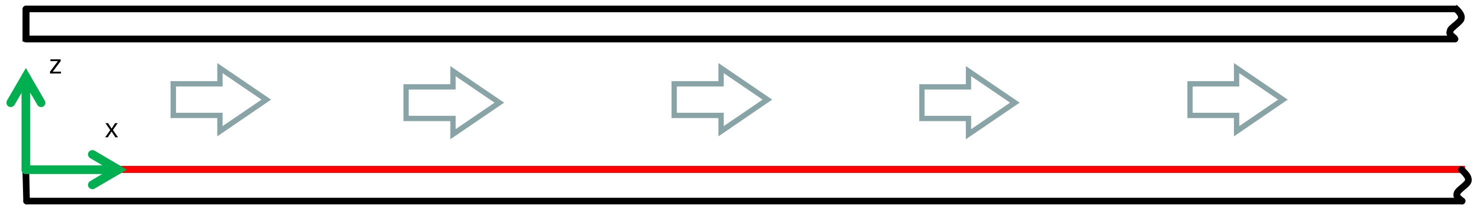
Enabling Spar-Shell Cooling Tech.

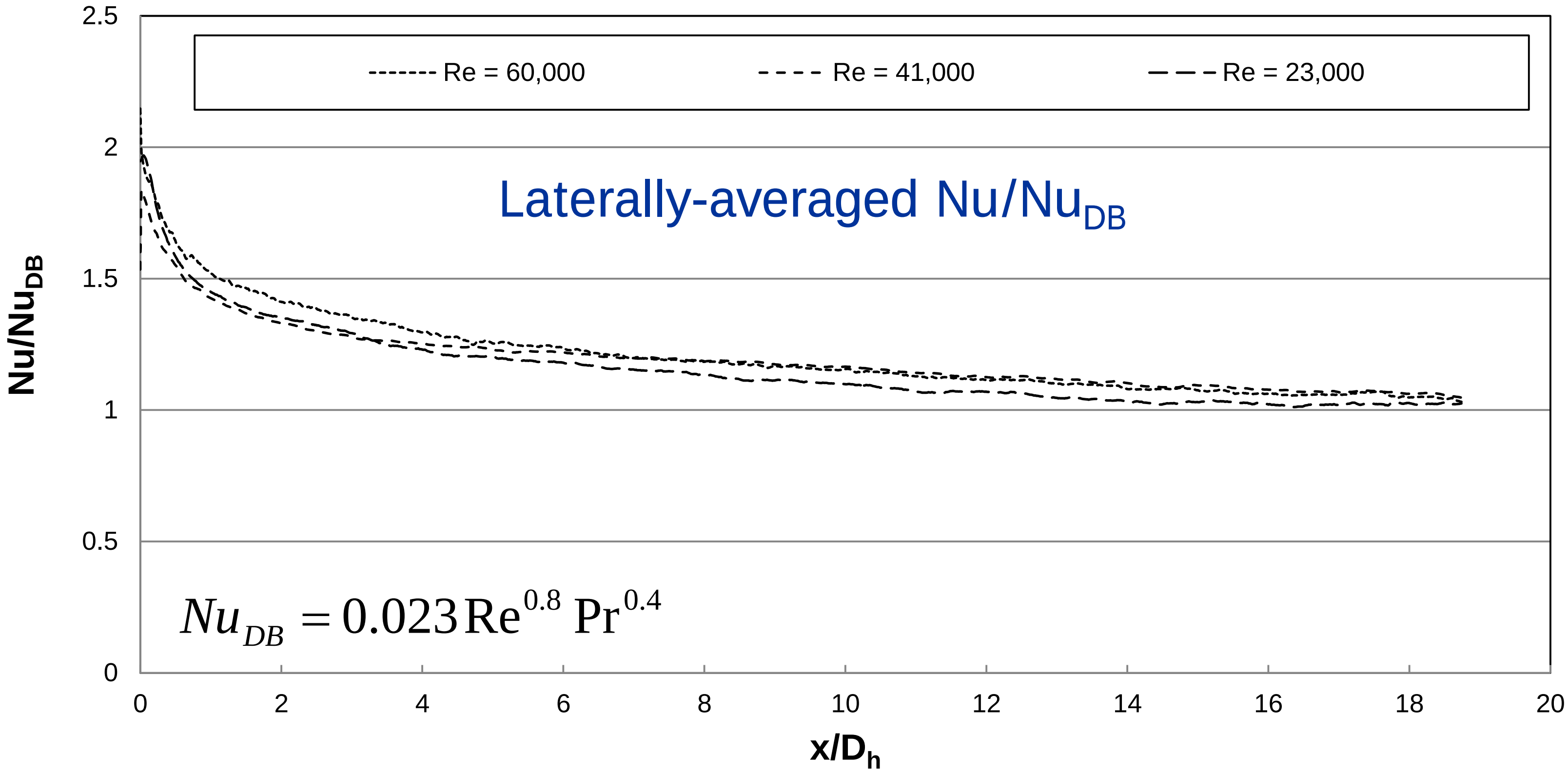
Assembled, instrumented test article



Enabling Spar-Shell Cooling Tech.

Smooth channel checkout case

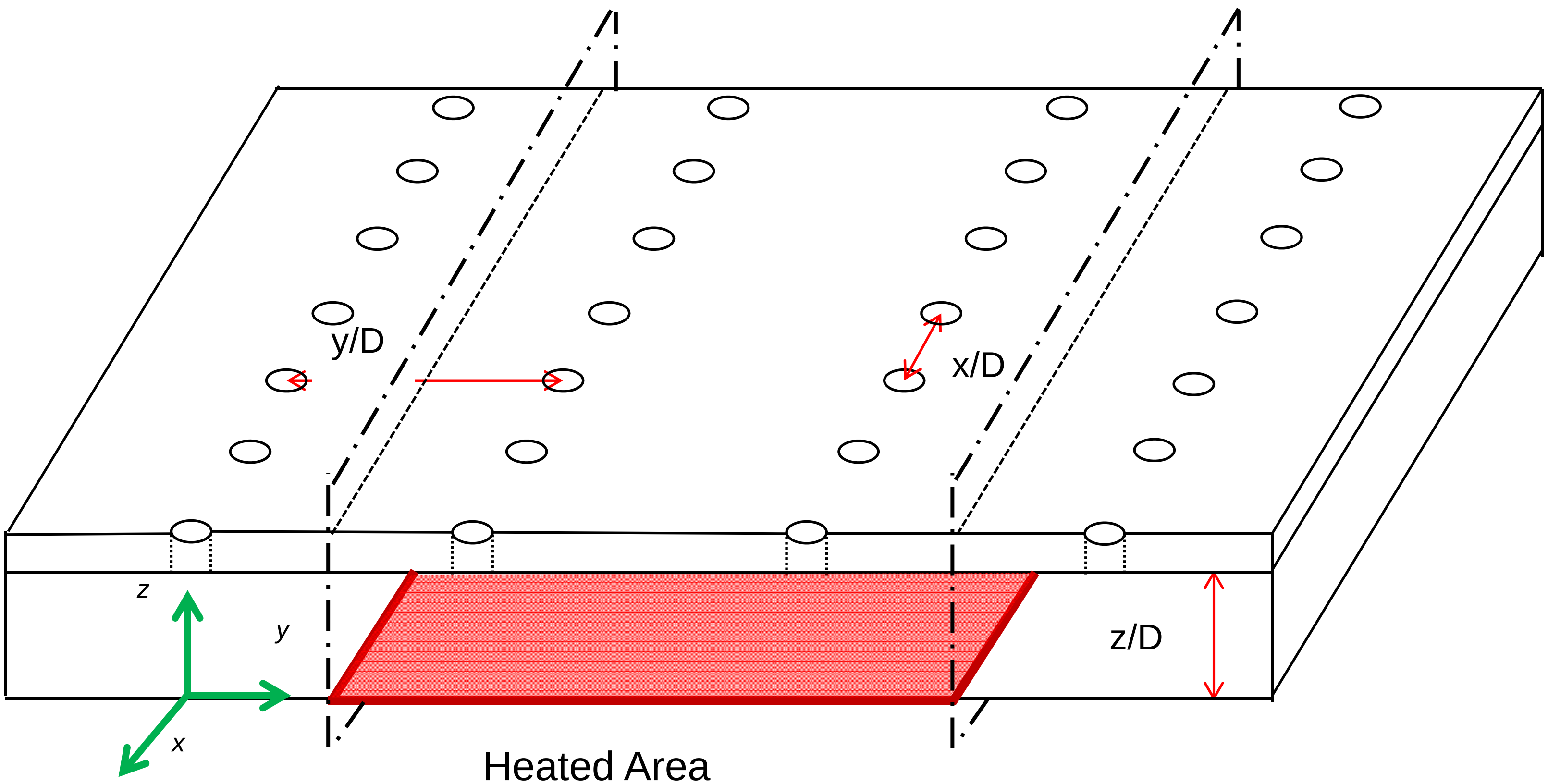




Enabling Spar-Shell Cooling Tech.

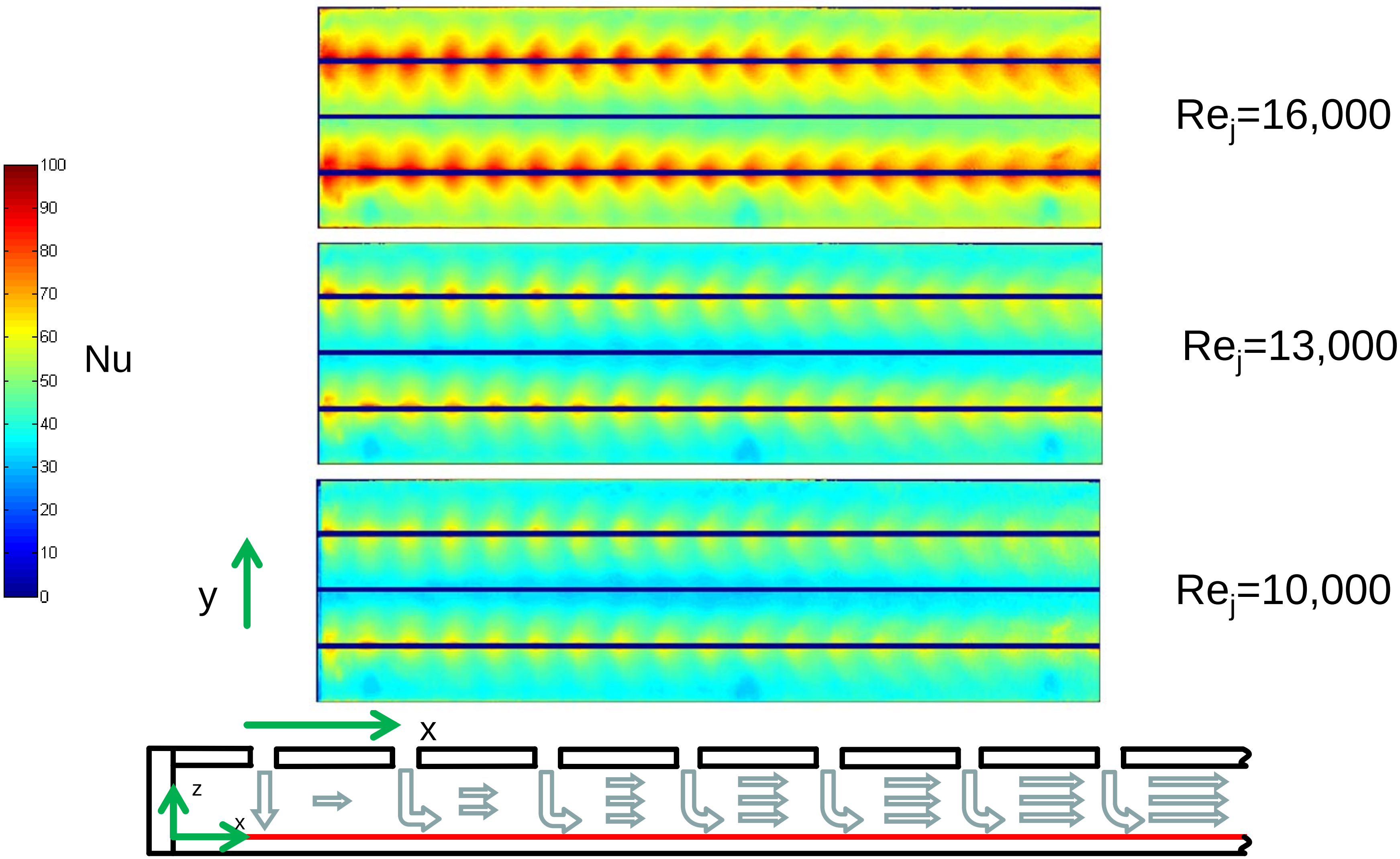
Impingement geometry

Case	z/D	x/D	x_c/D	N_x	y/D	y_c/D	N_y
Validation	3	3	63	20	8	32	4



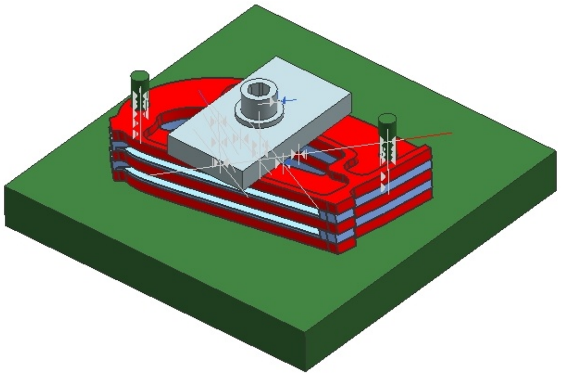
Enabling Spar-Shell Cooling Tech.

Impingement validation test results



Enabling Spar-Shell Cooling Tech.

Spar fabrication/bonding trials were successful



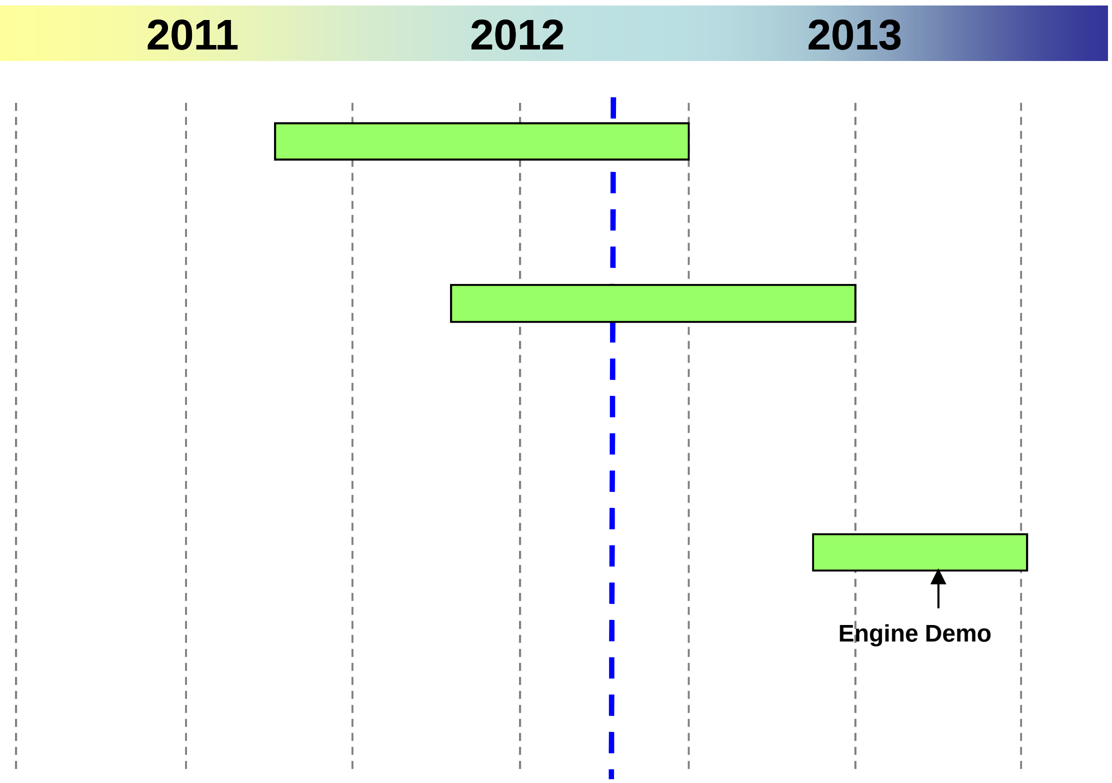
- Bond trial used a dead weight load
- Essentially 100% complete bonding
- External faying surfaces have concave faces
- Lesson learned:
  - Base material grain boundaries next to bond surface exhibited solid boride precipitation
  - Process improvement measures identified

Enabling Spar-Shell Cooling Tech.

Commercialization program schedule

DOE – Supported Program Designs, Develops, Manufactures, Instruments and Delivers Demonstration Hardware for Engine Test

- **Design/Development of Spar-Shell Cooling Technology into an Existing Production Engine**
- **Procurement of Partial Engine Set (10 Parts Total. 6 Parts Delivered to Engine) of Modified Production Engine Turbine Vanes with Enhanced Spar-Shell Enabling Cooling Technology**
- **Instrumentation, Assembly and Initial Engine Test/validation of Modified Production Engine Turbine Vane with Enhanced Spar-Shell Enabling Cooling Technology**



Enabling Spar-Shell Cooling Tech.

Program on track to test Spar-Shell late next year

- Test vehicle and window of opportunity for Spar-Shell insertion identified
- Design is nearly complete
- Long-lead hardware (castings) have been released to production
- Bench-level testing and dimensional inspections are validating the hardware prior to full-scale engine test
- Hardware will be instrumented with thermocouples and pressure taps

Outline

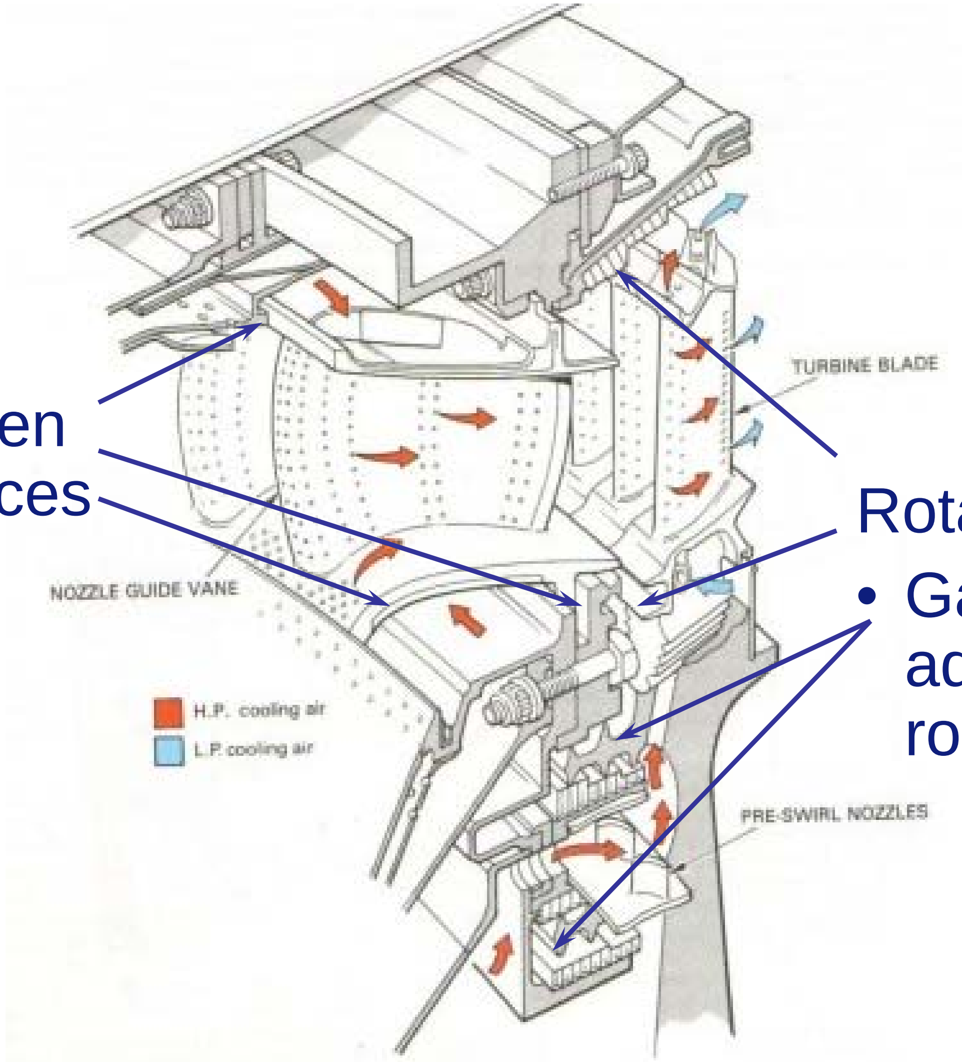
- Oxy-fuel turbomachinery development (with Clean Energy Systems & Siemens)
- Demonstration of enabling Spar-Shell cooling technology in gas turbines
- Sealing and leakage control technology

Sealing & Leakage Control Technology

R & D needs

Static seals

- Joints between mating surfaces



Rotating seals

- Gaps between adjoining static and rotating hardware

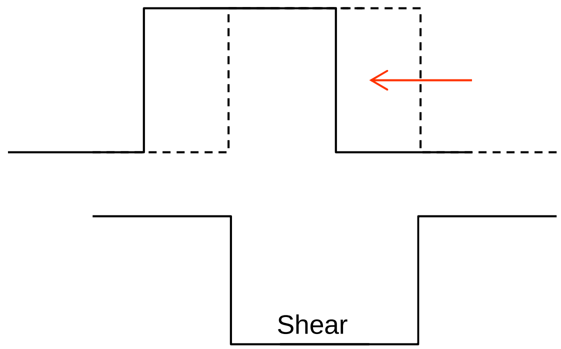
→ Control leakage while permitting relative movement between parts

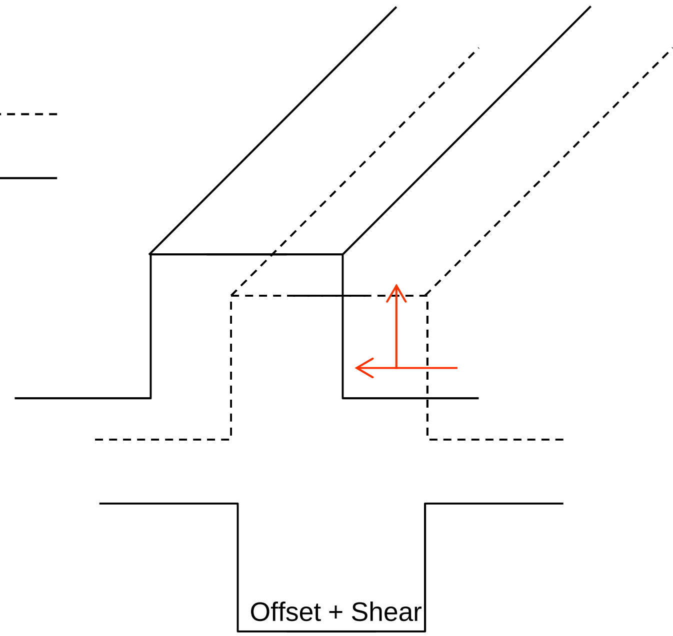
Sealing & Leakage Control Technology

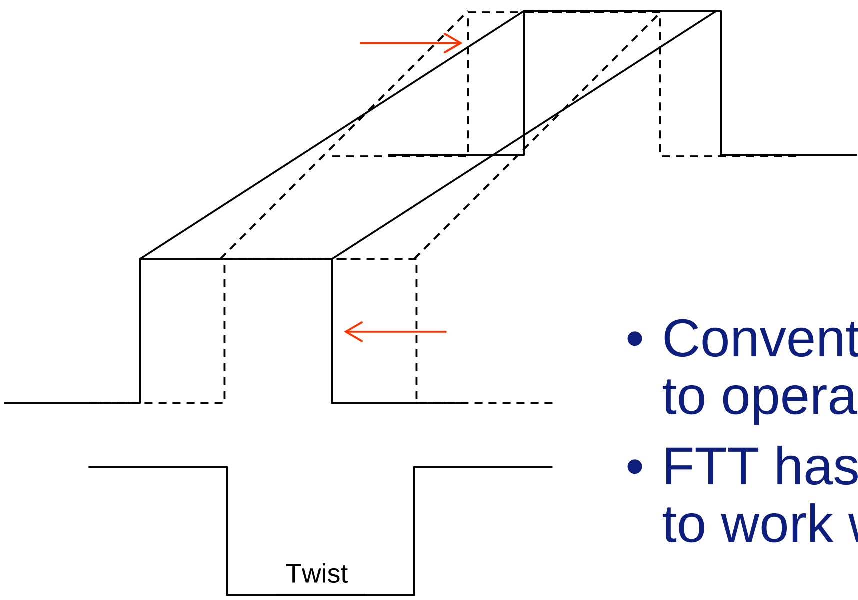
R&D Needs:

- Leakage accounts for ~25% of parasitic losses in gas turbine engines
- Turbo machines are inherently leaky
  - Comprised of many parts having joints, gaps and clearances
  - Static-to-static interfaces
  - Static-to-rotating interfaces
- Pressure difference maintained across these orifices to control environment

Anticipated seal misalignments considered in test plan



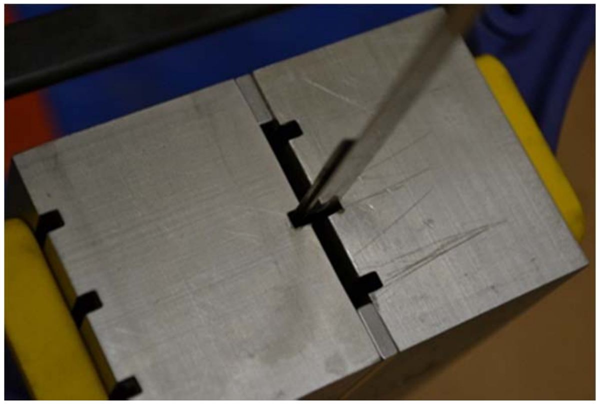


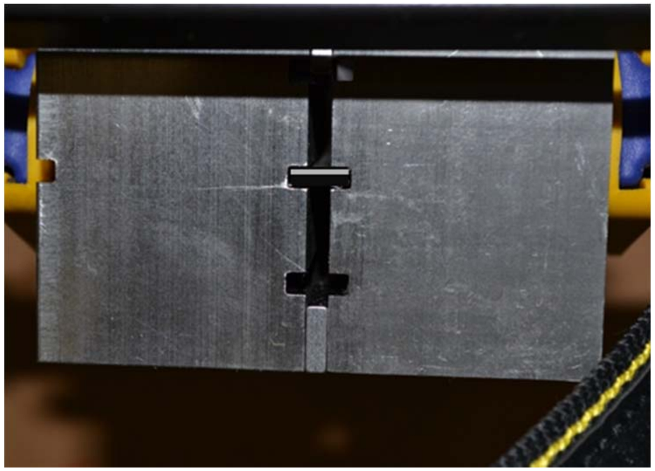


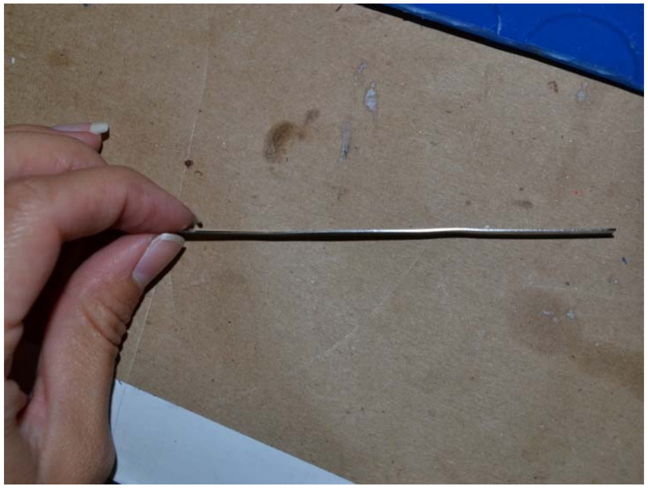
- Conventional (feather) seals can be expected to operate well under ideal conditions
- FTT has designed, and is developing a seal to work well under all conditions

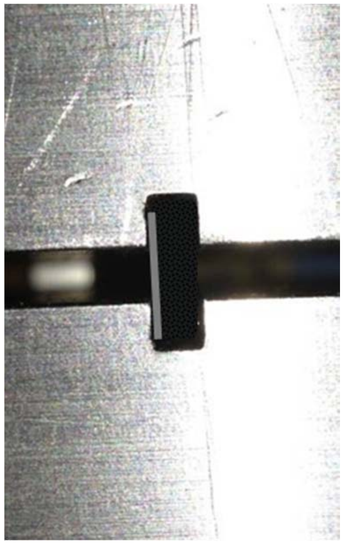
Sealing & Leakage Control Technology

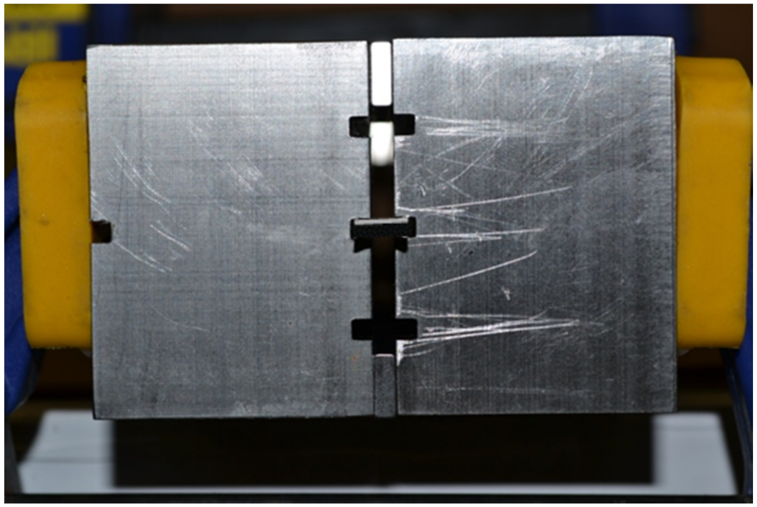
Static seal rig constructed to test leakage flows





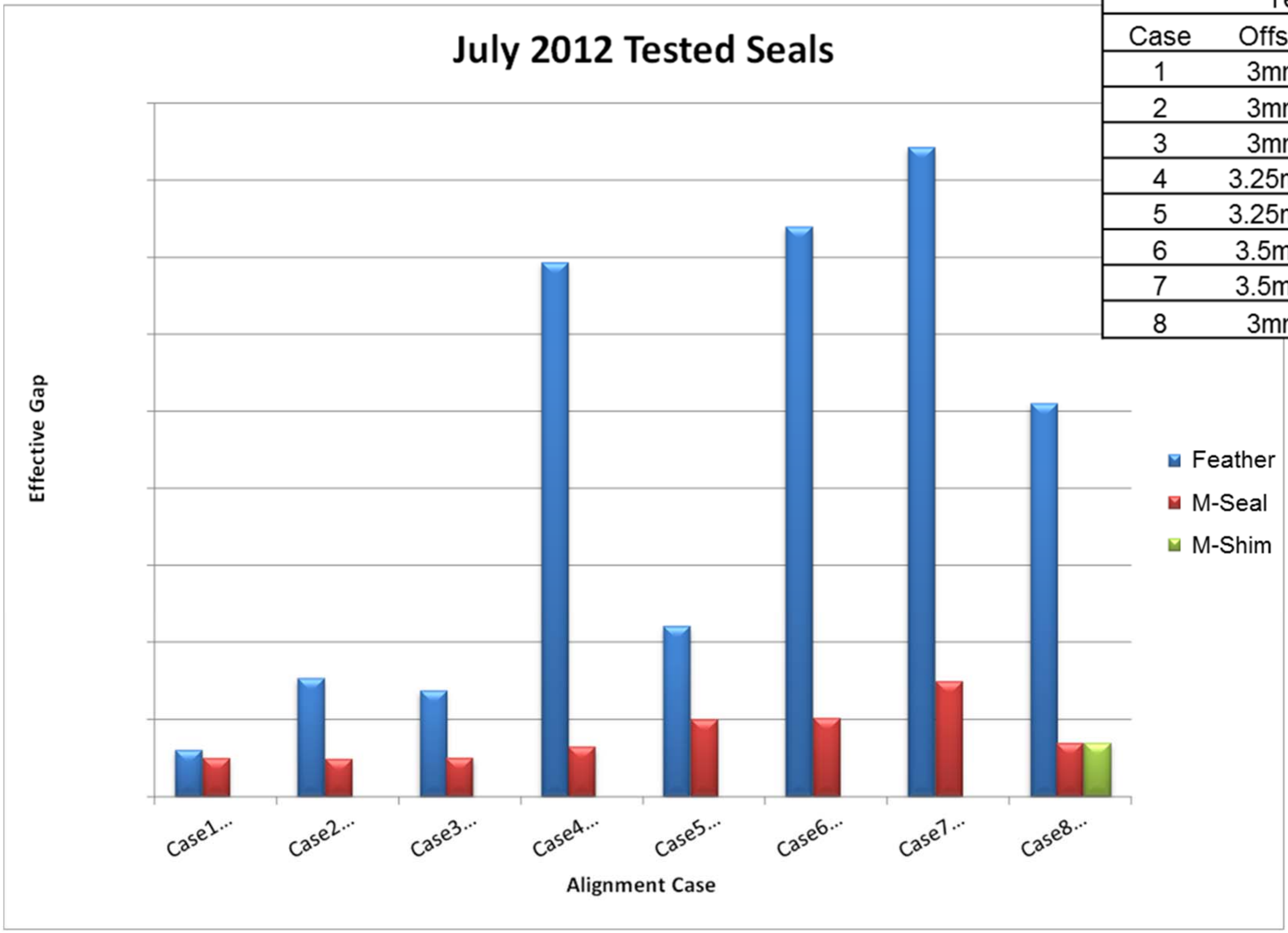






Sealing & Leakage Control Technology

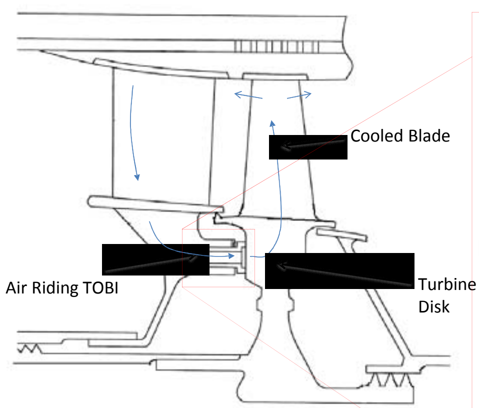
Initial results = Very encouraging

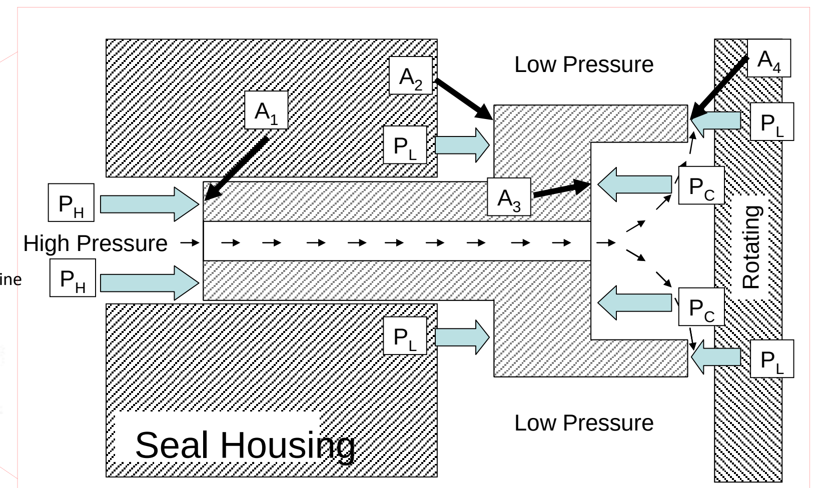


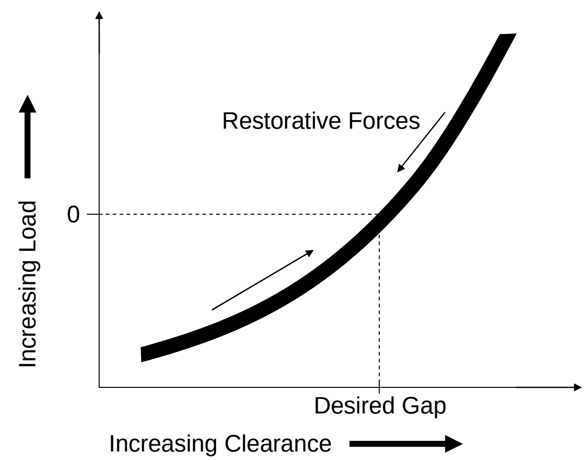
Test Matrix			
Case	Offset	Shear	Bow
1	3mm	0mm	0mm
2	3mm	0.25mm	0mm
3	3mm	0.5mm	0mm
4	3.25mm	0.25mm	0mm
5	3.25mm	0.5mm	0mm
6	3.5mm	0.25mm	0mm
7	3.5mm	0.5mm	0mm
8	3mm	0mm	0.125mm

Sealing & Leakage Control Technology

Air-riding seal technology for advanced gas turbines







At Equilibrium: $P_H(A_1) + P_L(A_2) = P_C(A_3) + P_L(A_4)$ Net Force = 0

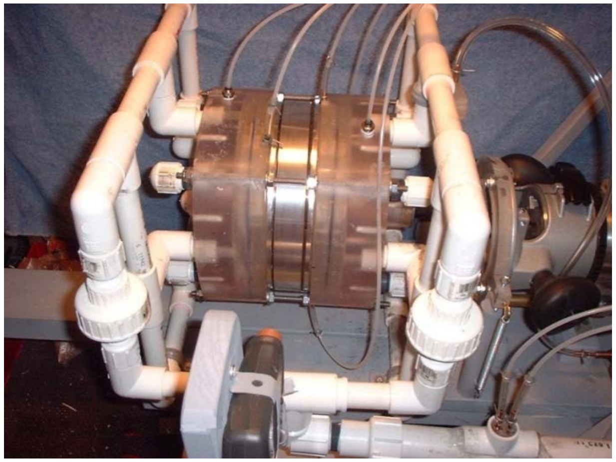
Reduced Clearance: $P_H(A_1) + P_L(A_2) < P_C(A_3) + P_L(A_4)$ Net Force = ⇦

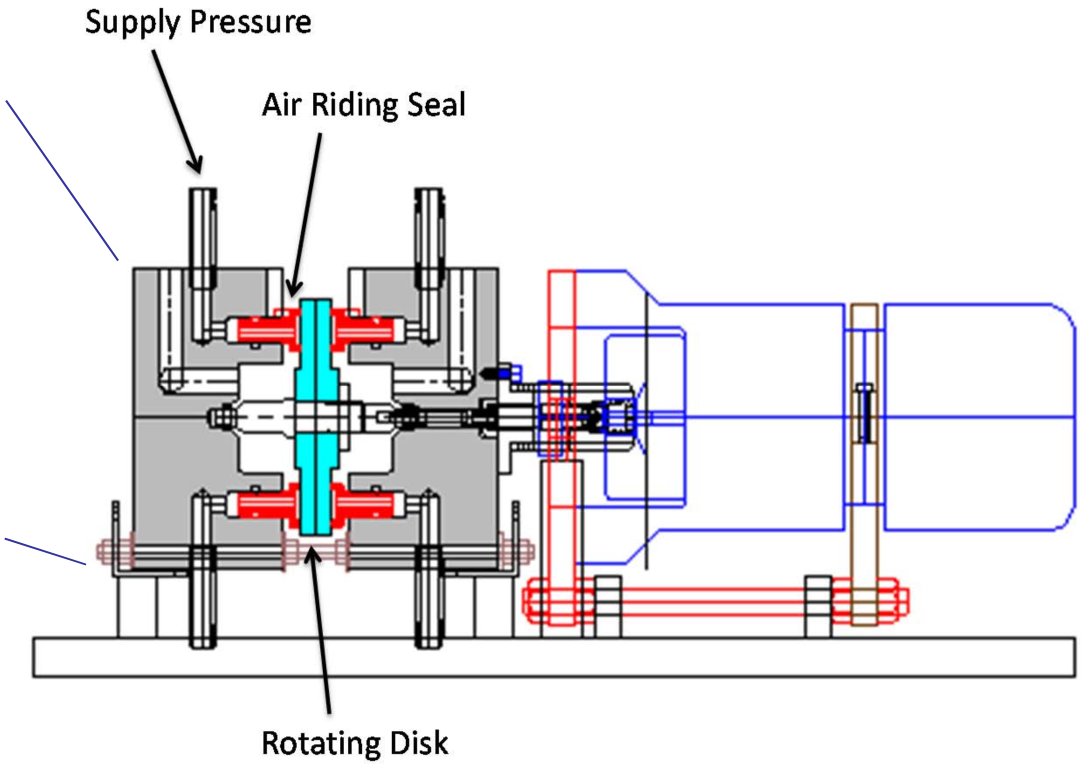
Increased Clearance: $P_H(A_1) + P_L(A_2) > P_C(A_3) + P_L(A_4)$ Net Force = ⇨

Sealing & Leakage Control Technology

Existing test rig achieved surface speeds up to 620 ft/sec

- Proof-of-concept demonstration
- Measured leakage to date represents very small (~0.002”) effective gap at various pressure ratios
- Additional testing to extend and expand database





Summary

- FTT is working closely with CES and Siemens to develop oxy-fuel turbomachinery.
- Spar-Shell turbine components incorporating sequential-impingement cooling are on target for first test late next year.
- FTT has taken a proactive role in the development of advanced sealing technologies.

Acknowledgements

Department of Energy

National Energy Technology Laboratory

Siemens Energy

Clean Energy Systems, Inc.

Power Without Pollution

Thank You & Questions?