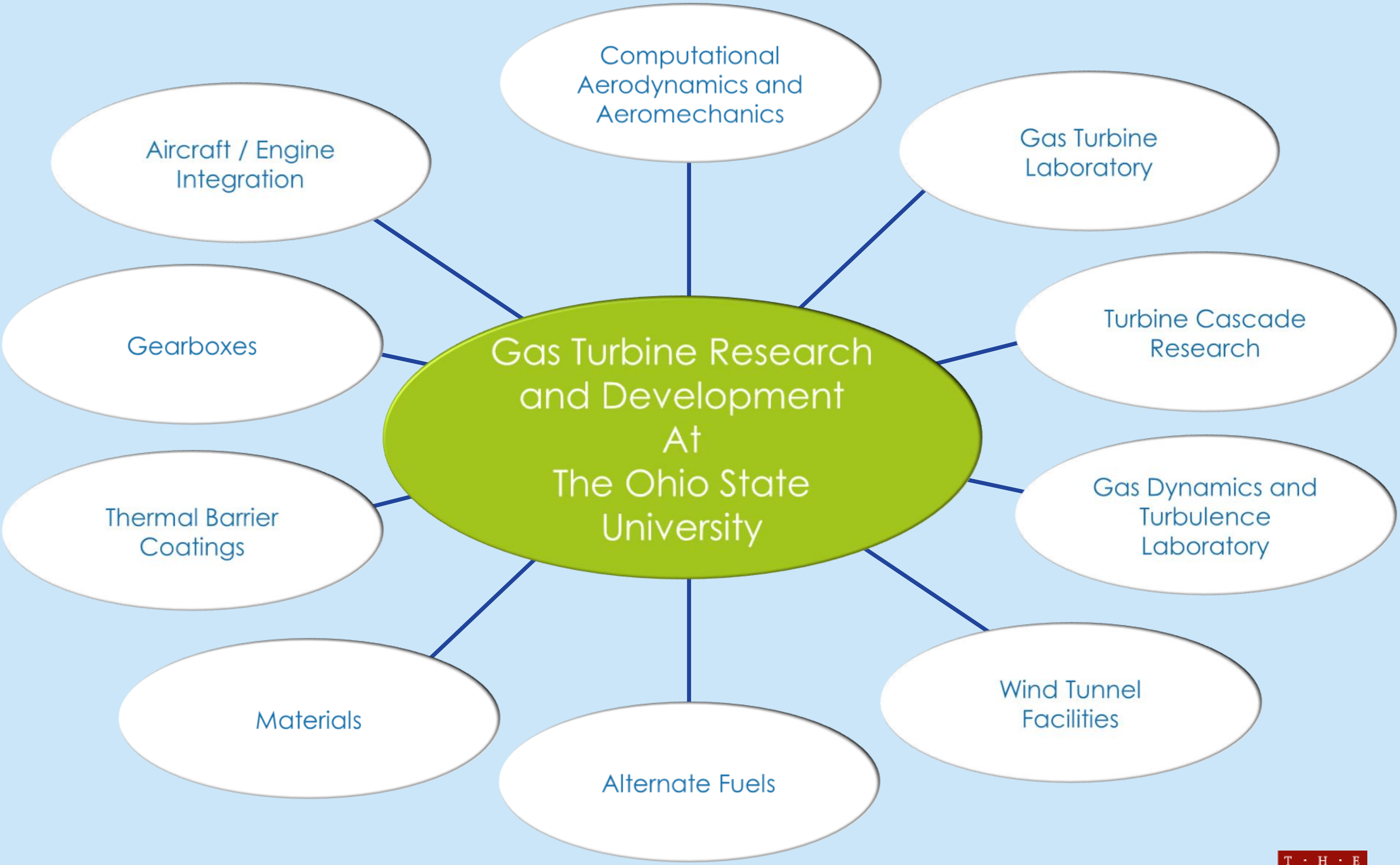
Gas Turbine Research and Development at The Ohio State University

October 25th 2011

THE OHIO STATE UNIVERSITY


Gas Turbine Research and Development At The Ohio State University
Computational Aerodynamics and Aeromechanics
Gas Turbine Laboratory
Turbine Cascade Research
Gas Dynamics and Turbulence Laboratory
Wind Tunnel Facilities
Alternate Fuels
Materials
Thermal Barrier Coatings
Gearboxes
Aircraft / Engine Integration

Aircraft Engine Integration

Aircraft Engine Integration

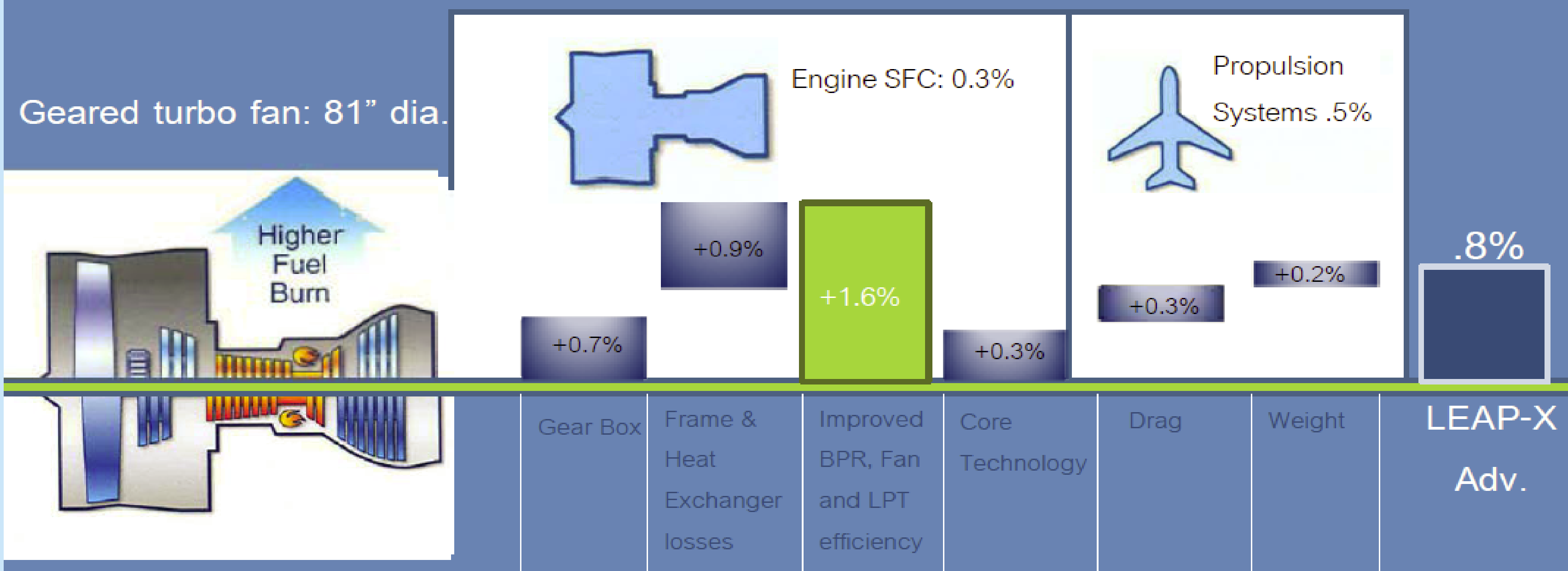
- System Optimization Capabilities have been put in place to provide optimization studies of commercial and military engines
- Focus is being applied to intelligent engines direct drives and geared fans as well as variable engines

Design and Analysis Tools

- Cycle Design & Analysis: **NPSS** (Numerical Propulsion System Simulation)
    - System performance, operability, modeling integration, map generation
    - Engine Architecture: **WATE** (Weight Analysis of Turbine Engines)
        - Dimensions weight, geometric/ structural feasibility
- Turbo machinery meanline Design**: CDE, TDE**, (Compressor & Turbine Design Envelopes)
    - Aerodynamic feasibility, component performance
- Mission Analysis: **FLOPS** (Flight Optimization System)
    - Mission Feasibility fuel savings

PW Geared V.S. LEAPx Fuel Burn Evaluation

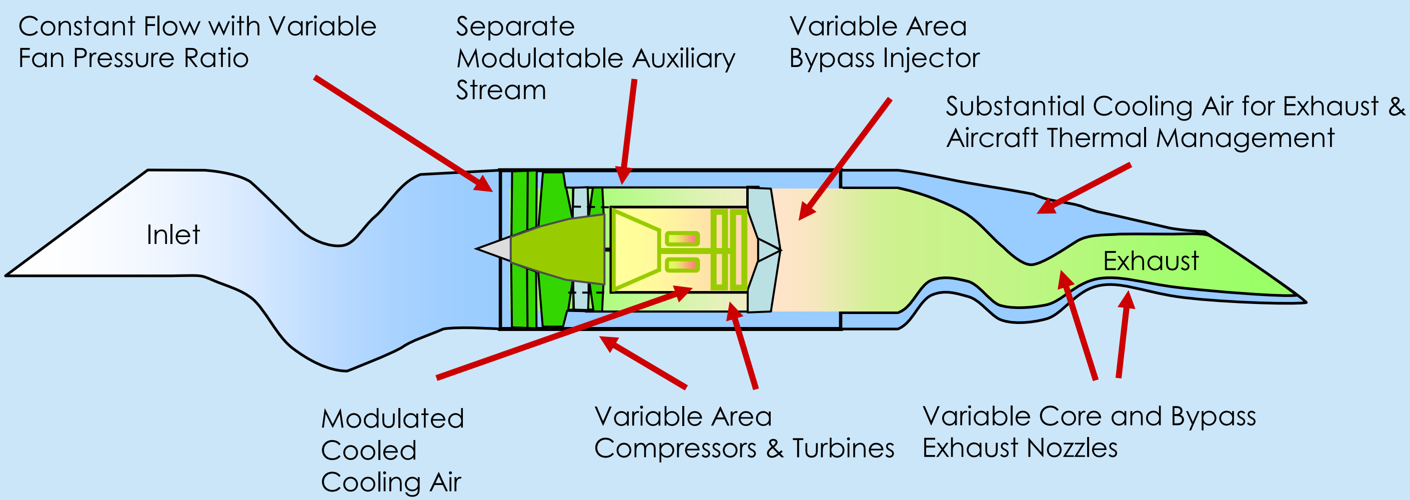
Geared turbo fan: 81” dia.

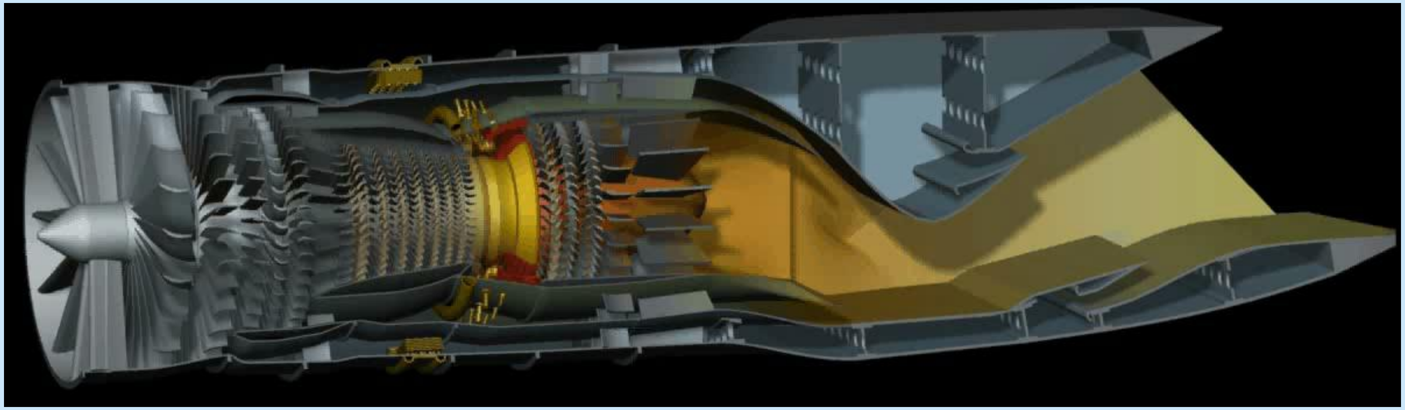


Direct-drive turbofan: 78” dia.

Architectures Within 1% Fuel Burn

Adaptive/Variable Cycle Engines





Two spool, three stream adaptive cycle engine offers great opportunities

Study Engines

- A 2000 State Of the Art (SOA) & an advanced turbofan (with the same thermo properties as the VCE) were created to assess VCE performance
- Engines were sized to produce takeoff thrust required by each mission
- Fan PR was varied until each had the same overall mass flow
- High specific thrust design points resulted in low bypass configurations
- Following parameters were common across all vision mission studies

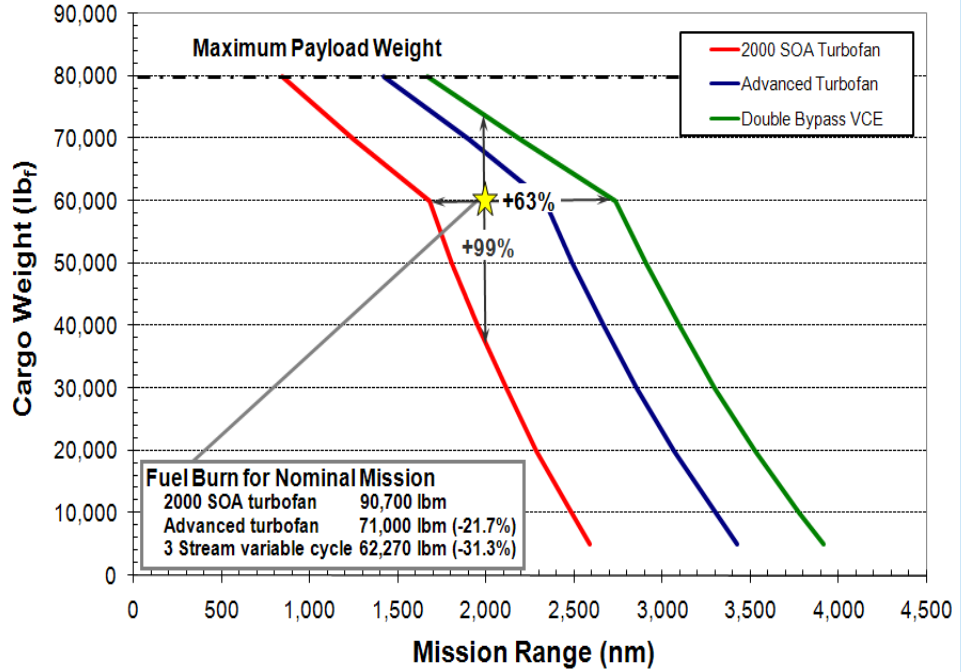
	2000 SOA Turbofan	*Advanced Turbofan*	*Double Bypass VCE*
% Adiabatic efficiency (Fan/LPC/HPC/HPT/LPT)	85 / na / 85 / 87 / 88	88.5 / na / 86 / 89 / 90	88.5 / 88.5 / 86 / 89 / 90
Cooling %W_{25}[a] (HPTN/HPTB/LPTN/LPTB)	10 / 5 / 5 / 2	15 / 10 / 4 / 2	15 / 10 / 4 / 2 Modulated[b] 15 / 5 / 2 / 1
Primary Nozzle CFG	0.95	0.97	0.97
Pri. Nozzle Cooling CFG[c]	0.92	0.92	n/a
Fan Nozzle CFG	n/a	n/a	0.96
Inlet Flow Control (%W_{23})	0	2.5	2.5
Ram Recovery	0.95	0.97	0.97
$T3_{max}$ (^{0}F)	1200	1400	1400
$T41_{max}$ (^{0}F)	2940	3400	3400
VABI	No	Yes	Yes

[a] Both the advanced turbofan and variable cycle utilize cooled cooling air
[b] Variable cycle modulates cooling at cruise power
[c] 2000 SOA and advanced turbofans use film cooling of the primary nozzle

Performance Analysis

- All three study engines were evaluated in the same notional airframe; engine weights vary with technology level & addition of variable features
- VCE accomplishes stated mission with 31% less fuel than yr 2000 cycle
  - Or it can carry 99% more cargo over the same range
  - Or it can carry the stated cargo 63% further
- These translate into operational benefits including reductions in air refueling, sorties generated, deployed aircraft/crew & increase standoff

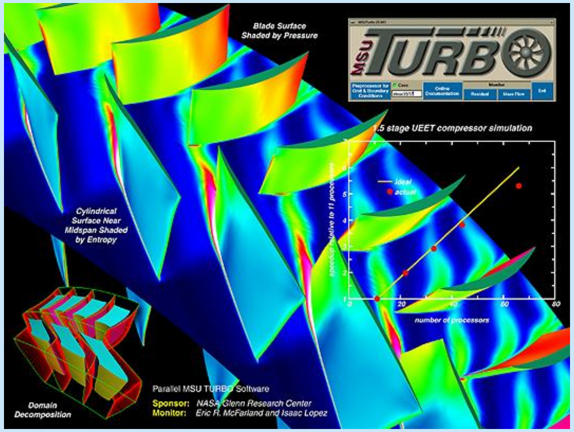
	2000 SOA Turbofan	Advanced Turbofan	Double Bypass VCE
Structural weight	115,000	115,000	115,000
Engine weight	20,000	18,000	19,800
Max gross weight	275,000	275,000	275,000
Max fuel Weight	80,000	80,000	80,000
Max payload Weight	80,000	80,000	80,000



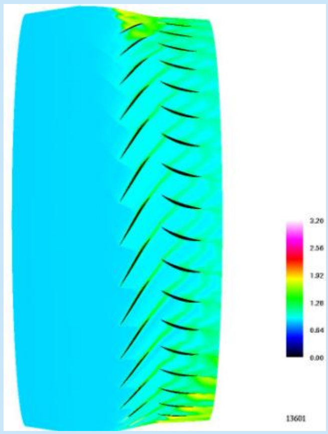
Computational Aerodynamics and Aeromechanics

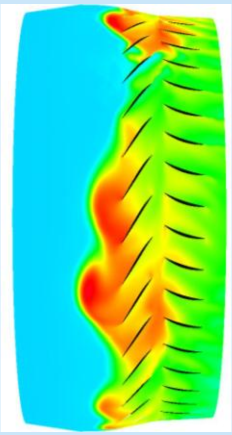
Computational Aerodynamics and Aeromechanics

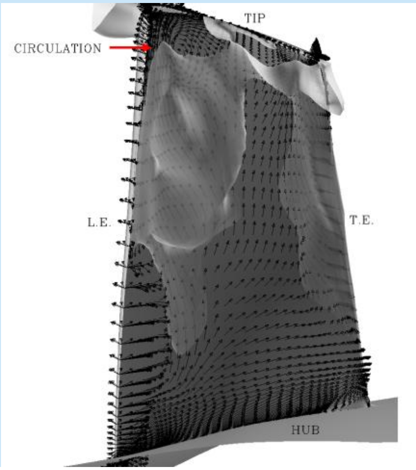
- **In-house turbomachinery code**
  - **Unsteady RANS CFD solver**
- **HPC resources**
  - **Ohio Supercomputer Center**
  - **Glenn IBM 1350 Cluster (10000+ processors)**
  - **Parallel efficiency of 93%-95%**

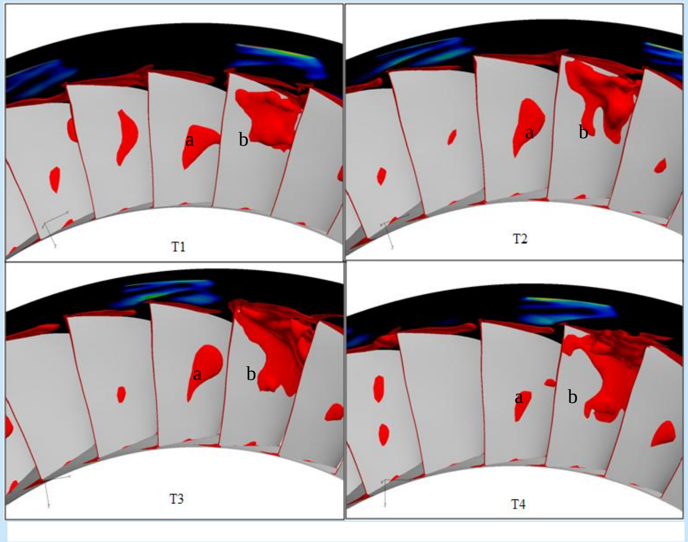


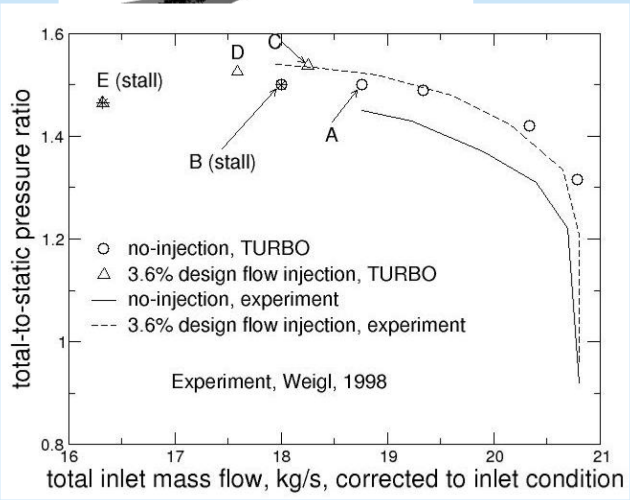
Tip-Injection Compressor Stall Control



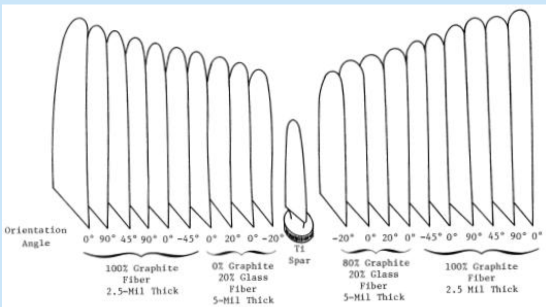


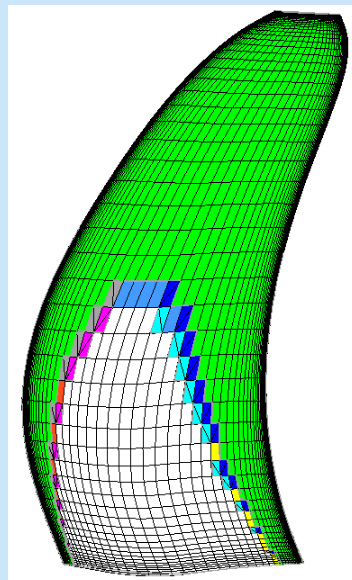


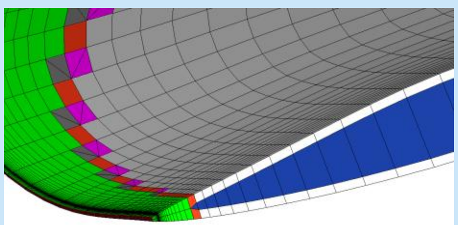


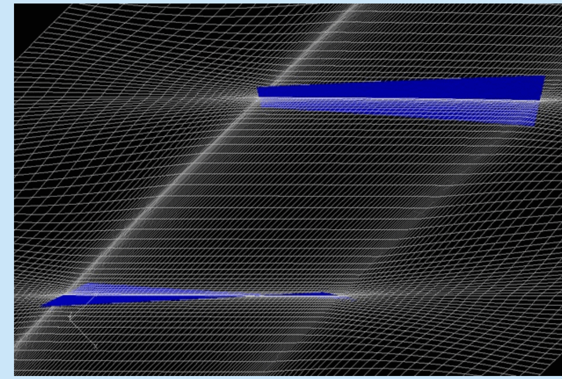


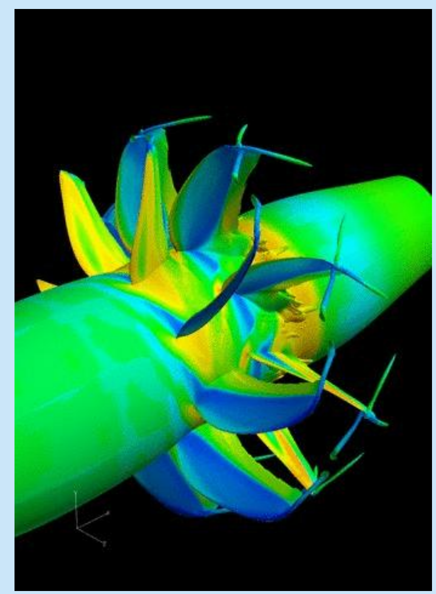
Open Rotor Fluid/Structure Coupling











- Structural Pre-Processor
  - Input: Blade geometry, composite ply material properties, thickness and orientation
  - Output (NASTRAN input deck format)
- Parallel grid deformation scheme using the exponential decay method with transfinite interpolation

Potential Applications

- Improved off-design prediction
- Inlet/ fan coupling, unsteady aero
- Open rotors, fluid-structure interaction, noise source
- Multi-stage compressors & turbines
- Compressor/ turbine flow control

Gas Turbine Laboratory

Gas Turbine Laboratory

- **Full Scale Rotating Turbines , Fans & Compressors**
  - Engine hardware at design corrected conditions
  - Heat transfer: both internal & external
  - Aerodynamics: time-averaged & time-resolved
  - Aeromechanics: structural response & damping
- **Concentrate on experimental, with 3 major facilities**
  - Large blow down turbine facility (up to 33-inch diameter turbine)
    - Have run cooled turbine stage (3 different machines, two fully cooled) as well as many, many, un-cooled turbine stages back to 1975
  - Compressor in-ground spin pit facility (engine speed)
  - Fan in-ground spin pit facility (engine speed)
- **Also have ongoing CFD effort using following codes**
  - UNSFLO-2D (on loan from Rolls-Royce)
  - STAR-CD (commercially available)
  - MSU-TURBO (NASA funded code that Dr. Chen runs)
  - Fine TURBO (Numeca)

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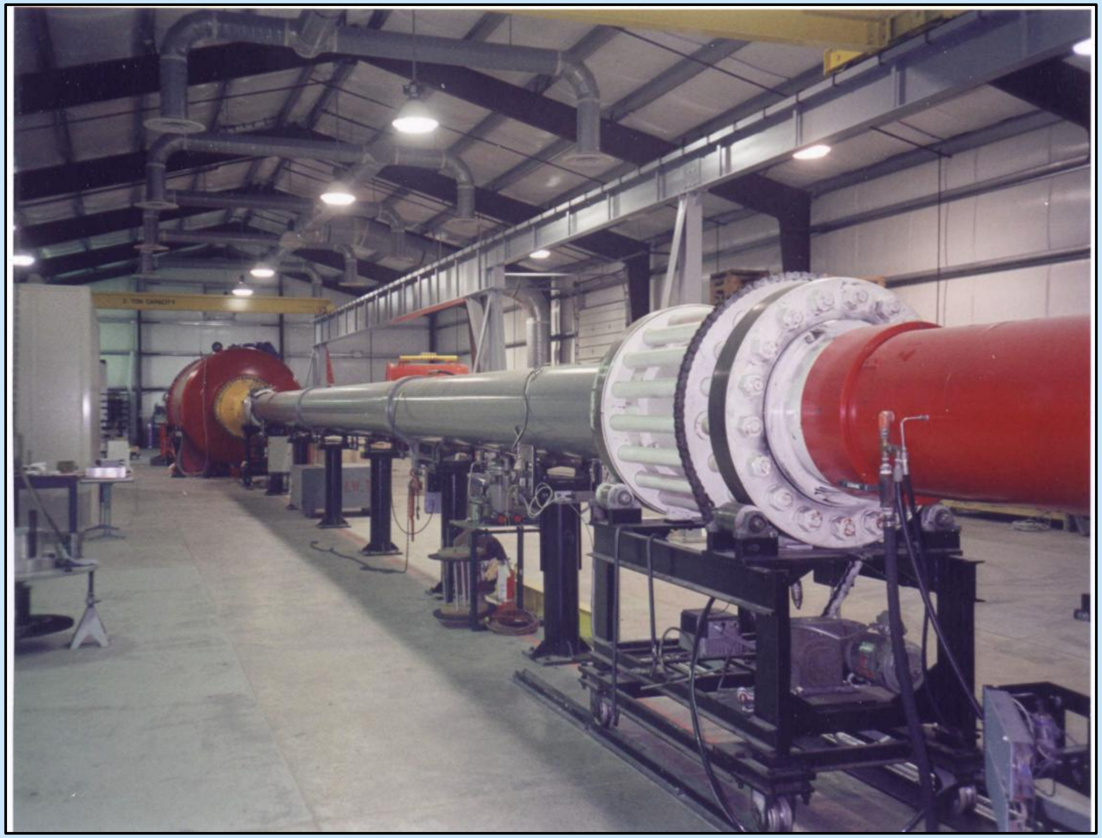
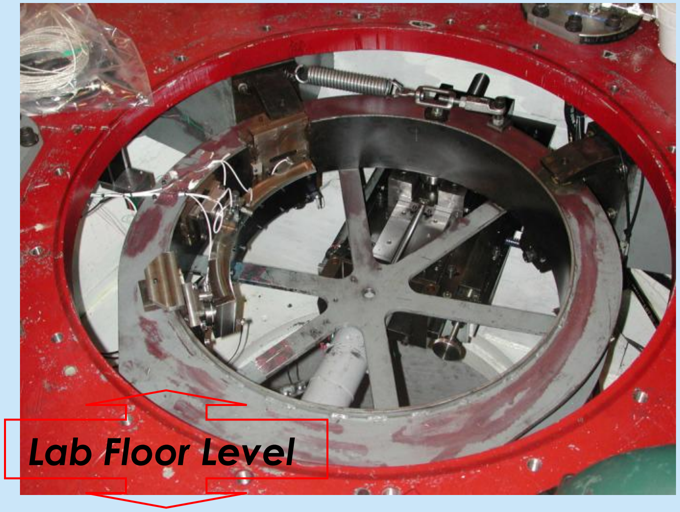
OSU Gas Turbine Laboratory Facility

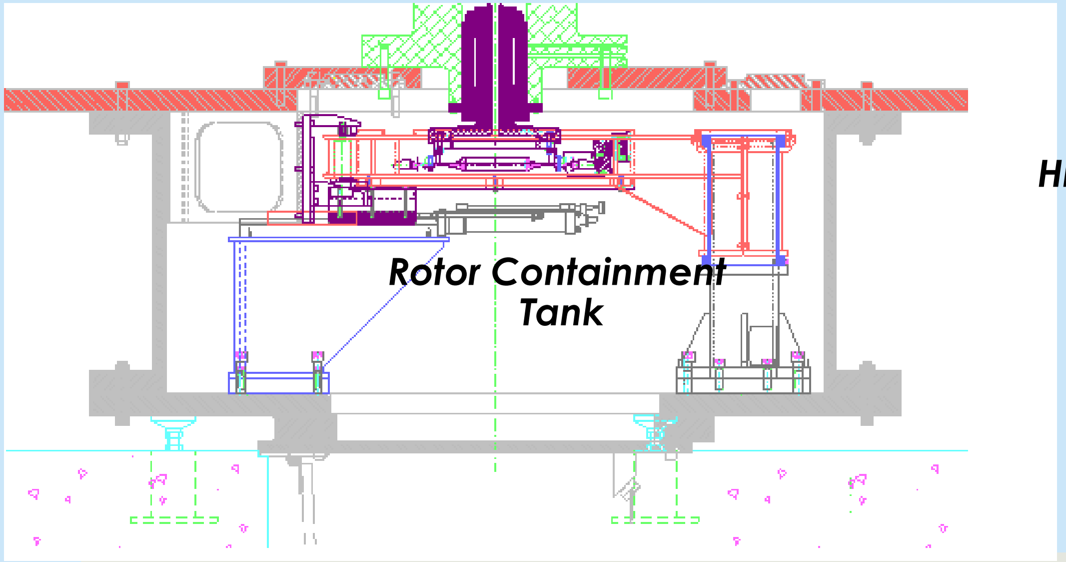
- **Facility can operate in either shock tube or blowdown mode**
  - Purchased this facility from Calspan & built building with loan $'s
- **Turbine stage located in yellow nozzle**
  - Design Reynolds number
  - Design flow function, corrected speed, & stage pressure ratio
- **Digital data acquisition system in beige building**

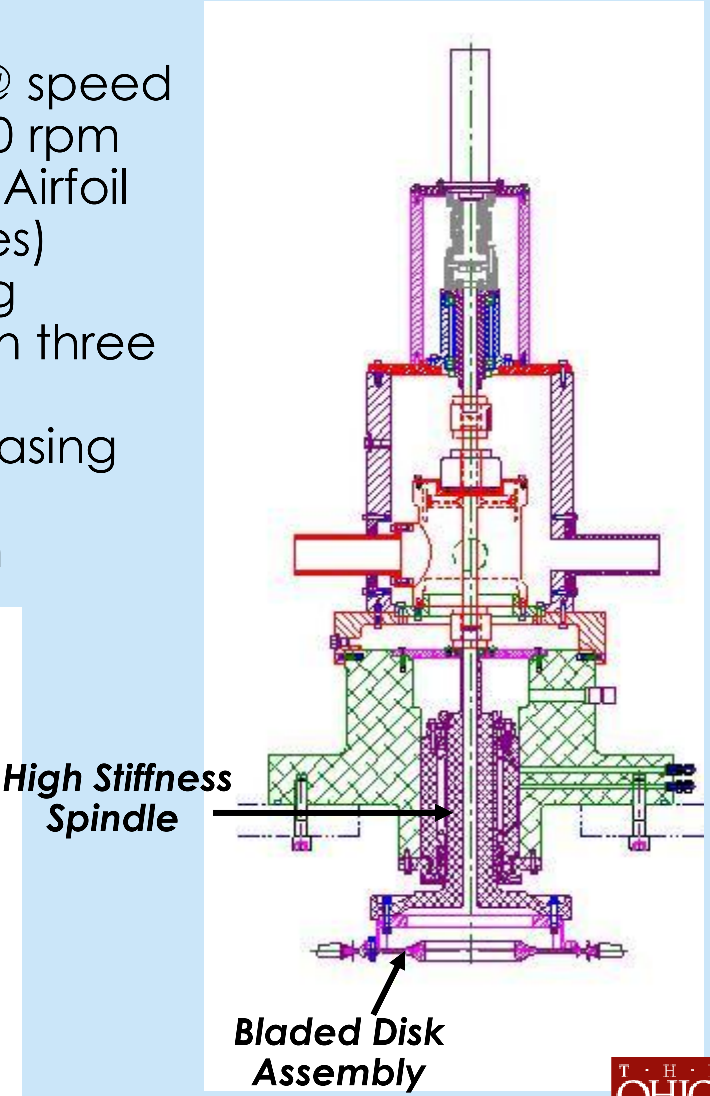


Compressor Spin Pit Facility

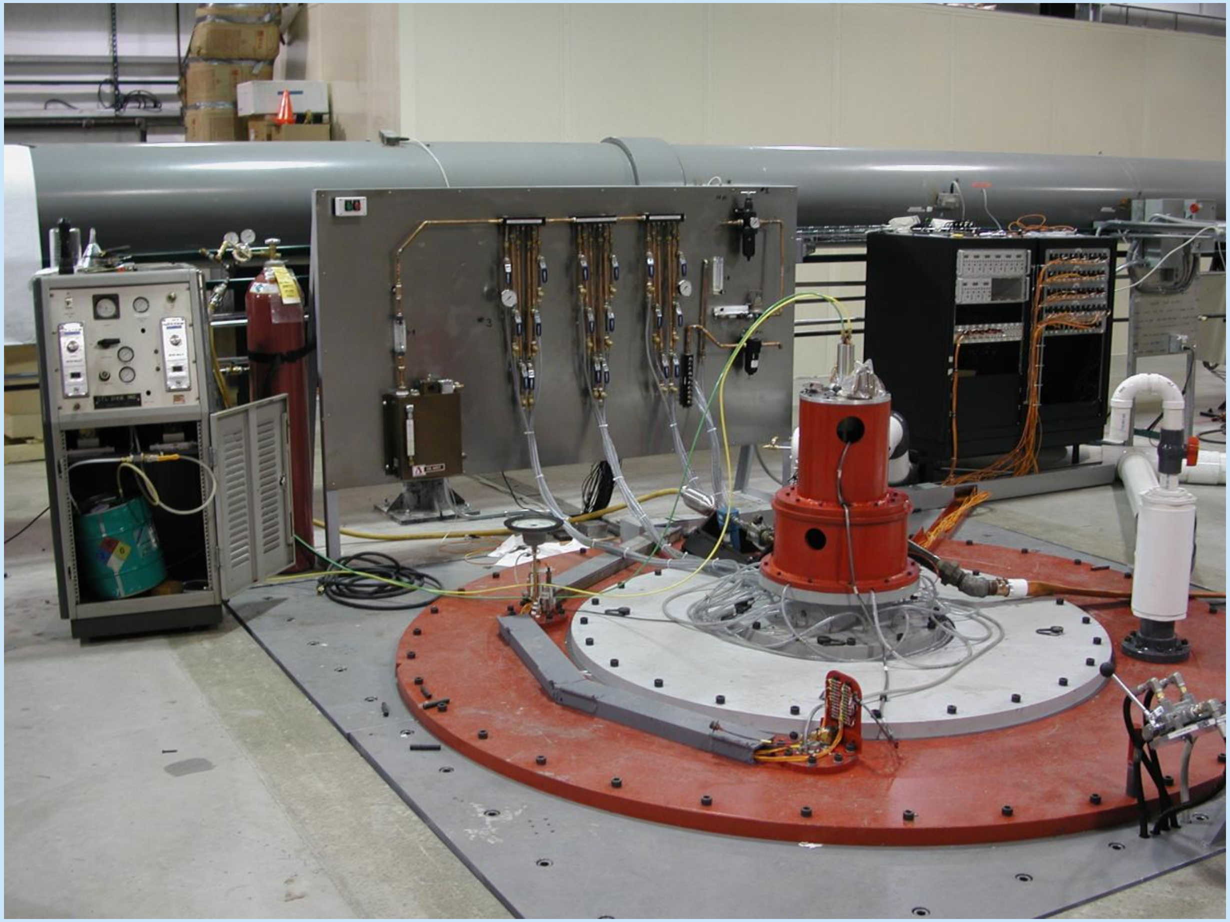


- Spindle runs @ speed up to 20,000 rpm
- Instrumented Airfoil (strain gages)
- Engine Casing mounted on three Load Cells
- Fast-acting Casing Incursion Mechanism





Fan Spin Pit Facility - Top



• Operates @ speeds
up to 6,000 rpm
• Can run fan with tip dia ≈ 70-inches
• Has 200-channel slip ring for rotating Measurements
• Machine tool incursion mechanism
with variable rate & depth

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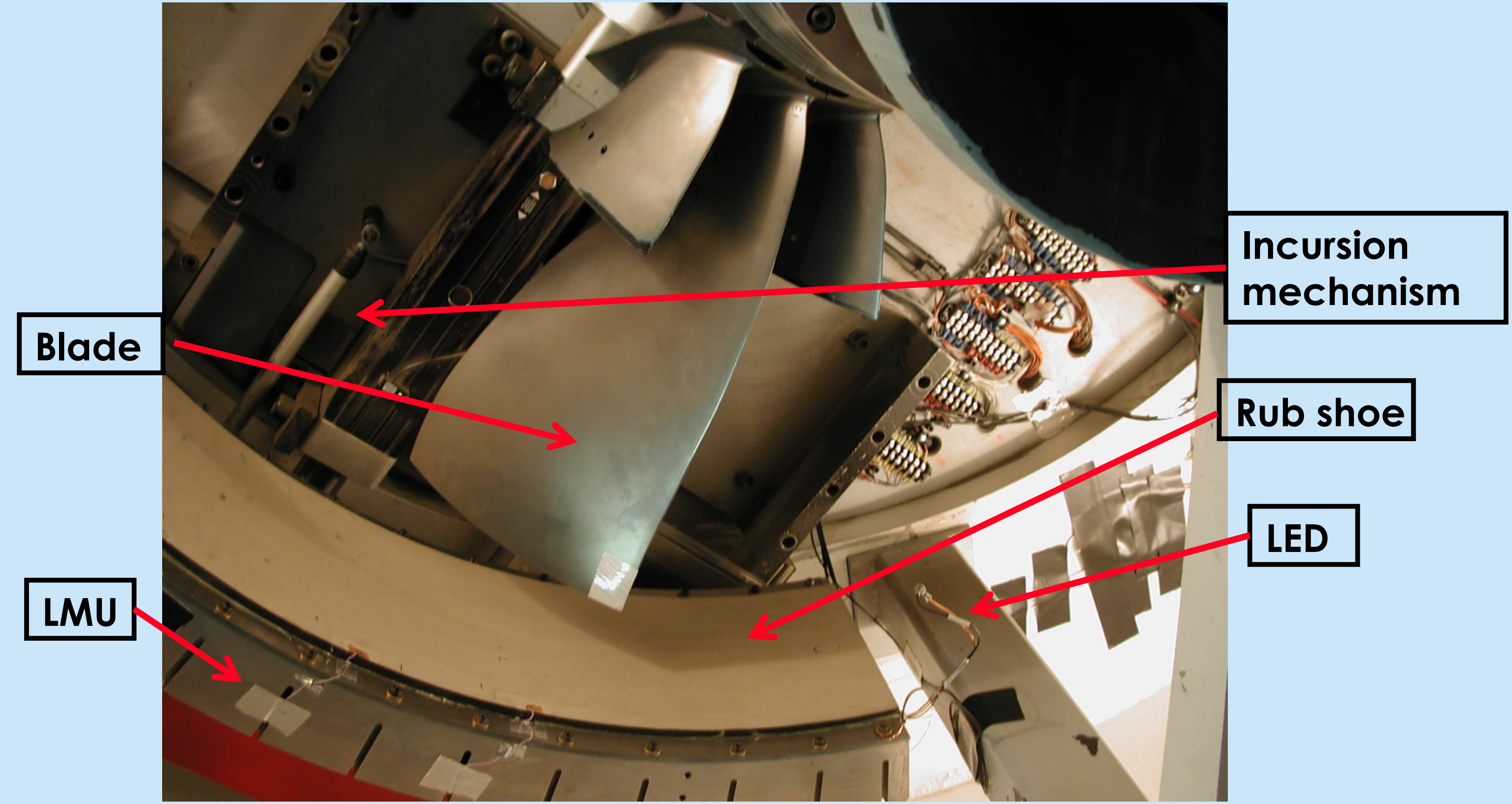
Inside the Fan Facility



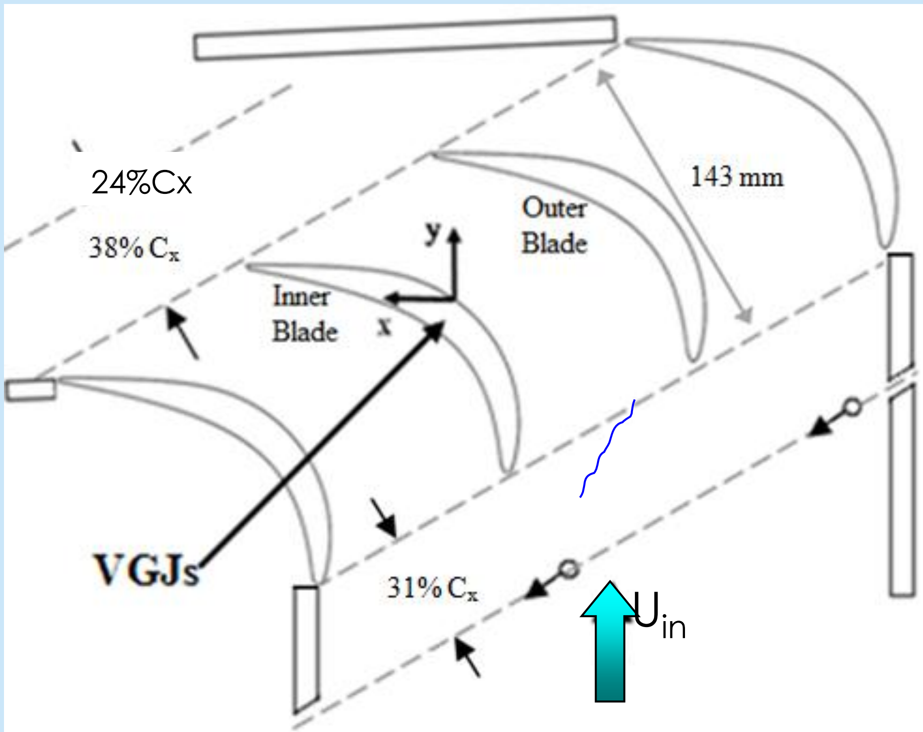
Data Acquisition System

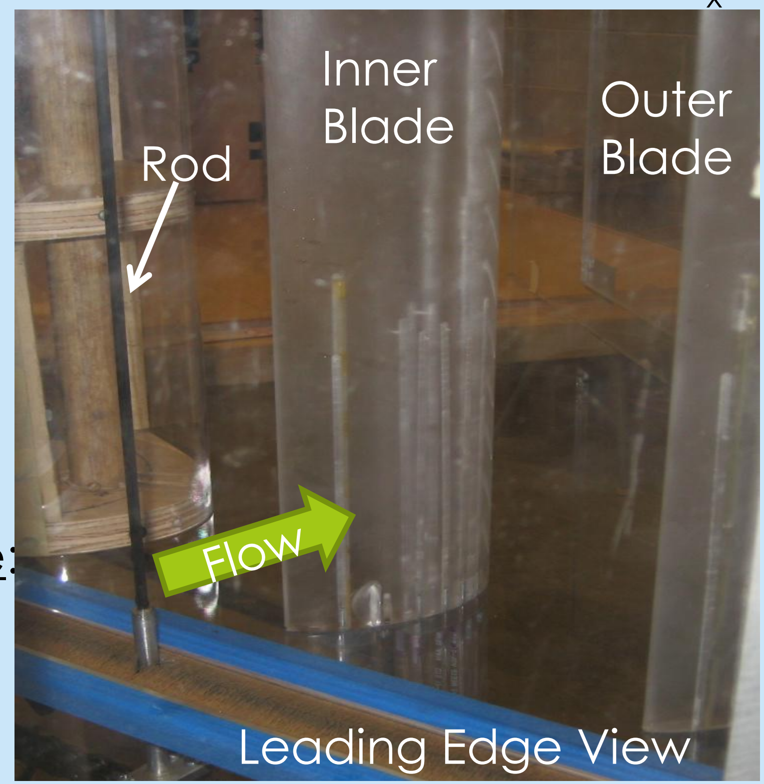
- Measurement programs require many channels of very high sampling frequency digital data acquisition capability:
- 256-channels, 12-bit, 100kHz per channel system
- 388-channels, 16-bit, 500kHz per channel system
- Numerous Natl. Inst. slow speed channels

Turbine Cascade Research

Turbine Cascade Research and LPT Linear Cascade Facility

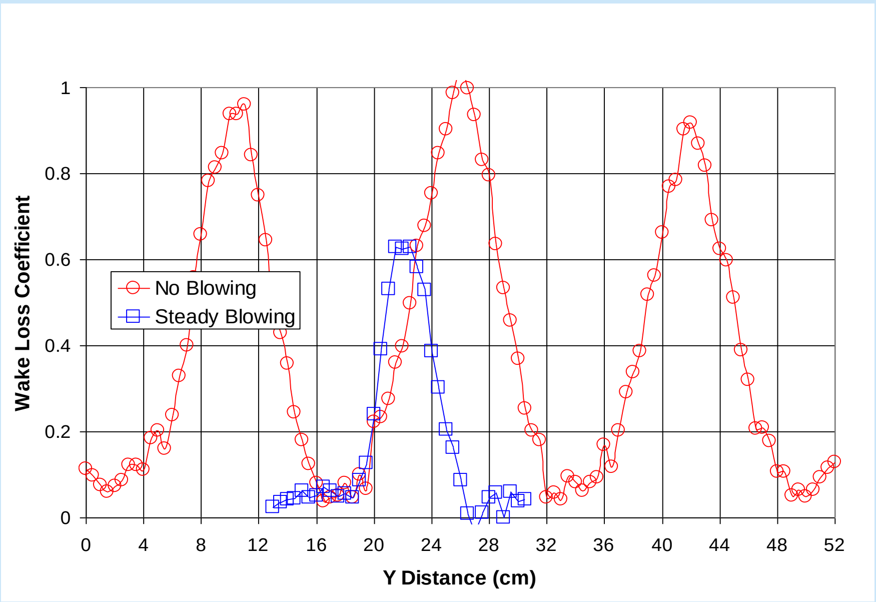
<u>VGJ Configuration</u>:
- 30 degree pitch
- 90 degree skew
- 10d spacing
- located at 59% and 72% C_x

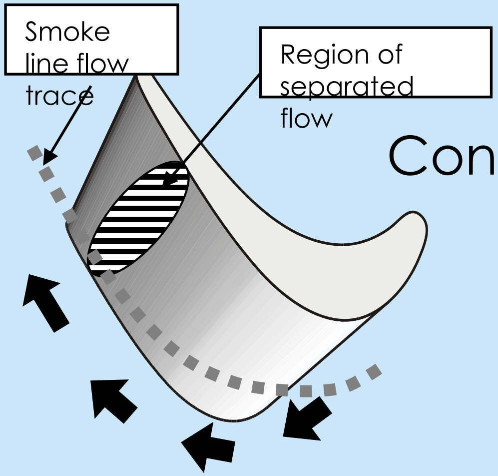




<u>4-blade (3 passage) low speed cascade</u>:
- 3% inlet freestream turbulence
- static pressure taps → c_p
- $Re_{cx} = U_{in}*c_x/\nu = 20{,}000$
- $Re_c = U_{ex}*c/\nu = 34{,}000$
- $Re_{ssl} = U_{ex}*SSL/\nu = 50{,}000$

Active Control of LPT Separation

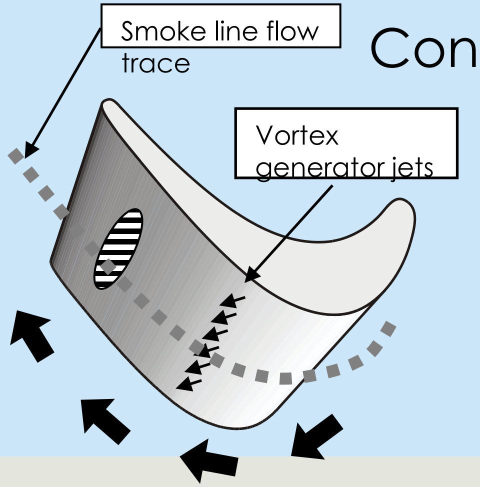




Control OFF

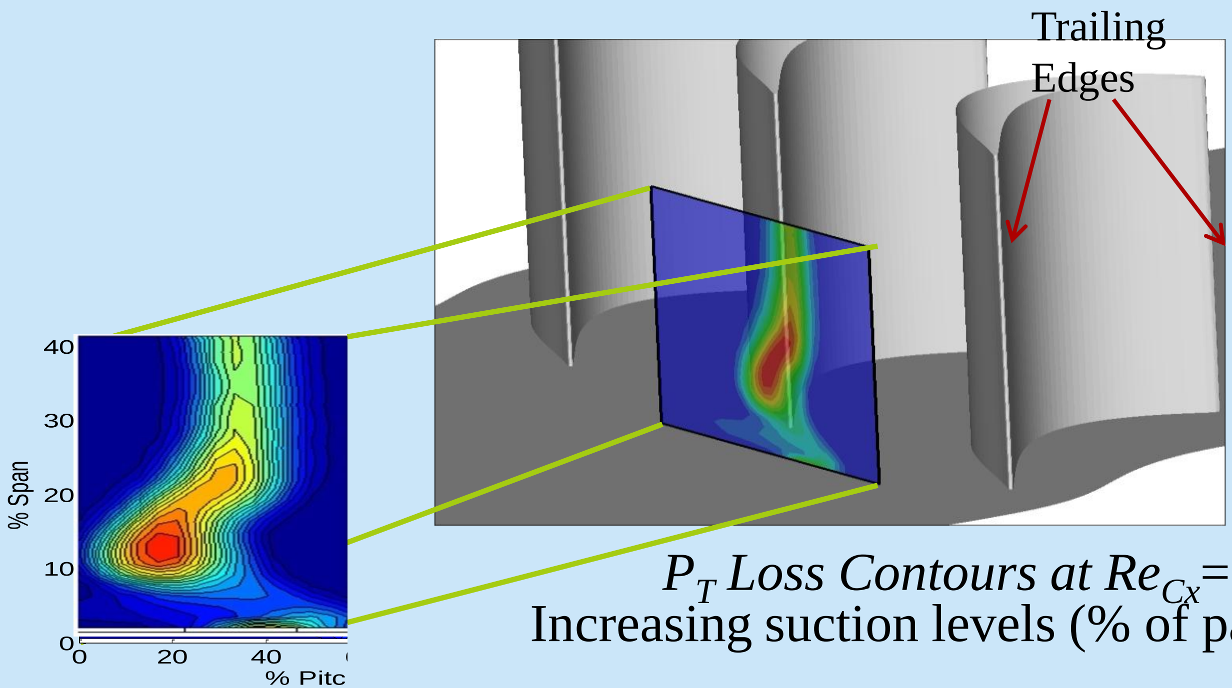
Control OFF

Control ON

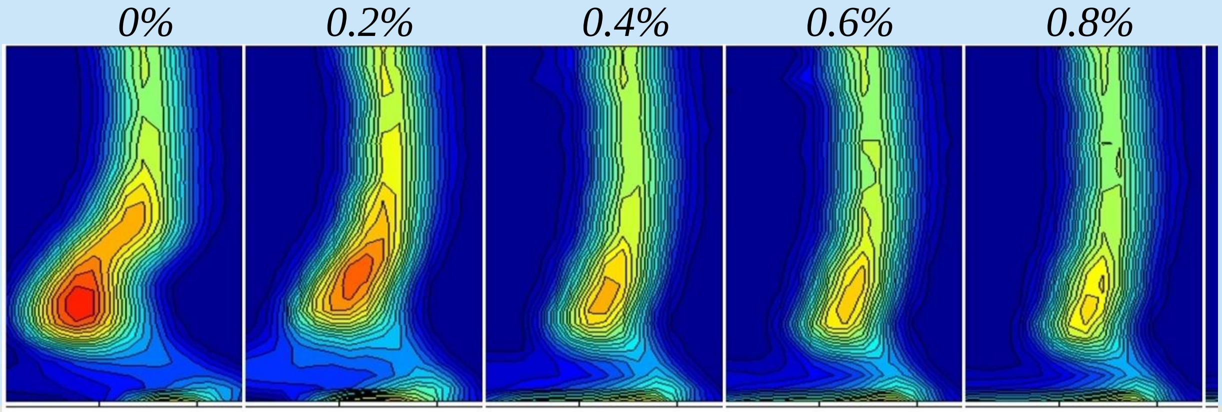


Control ON

Endwall Loss Reduction with Suction

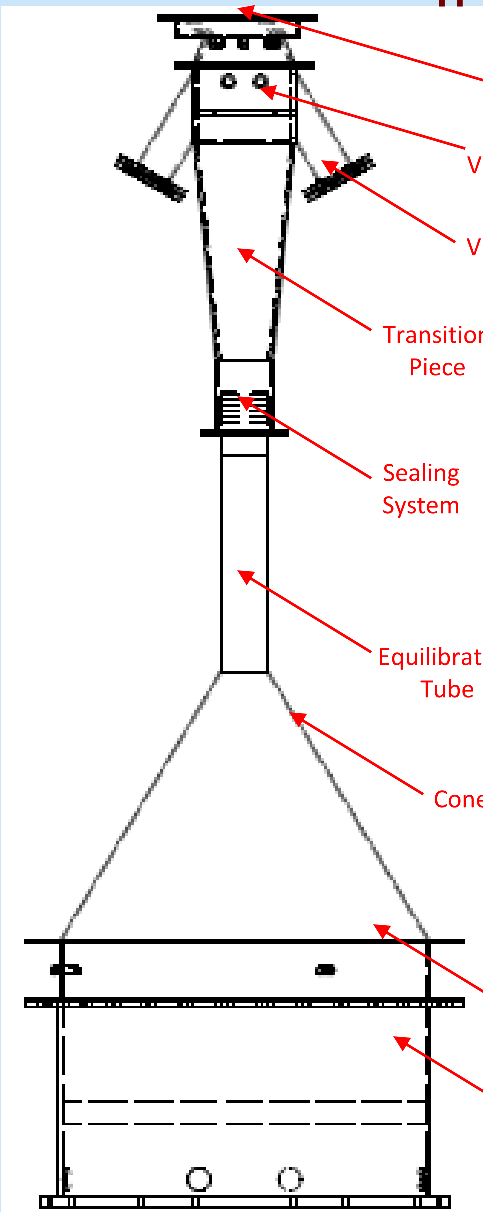


P_T Loss Contours at Re_{Cx}=50000
Increasing suction levels (% of passage flow)

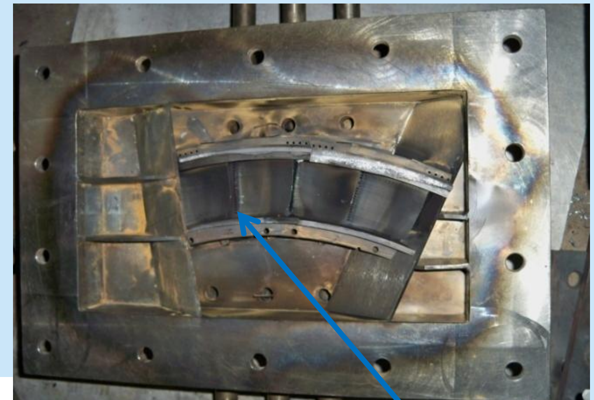


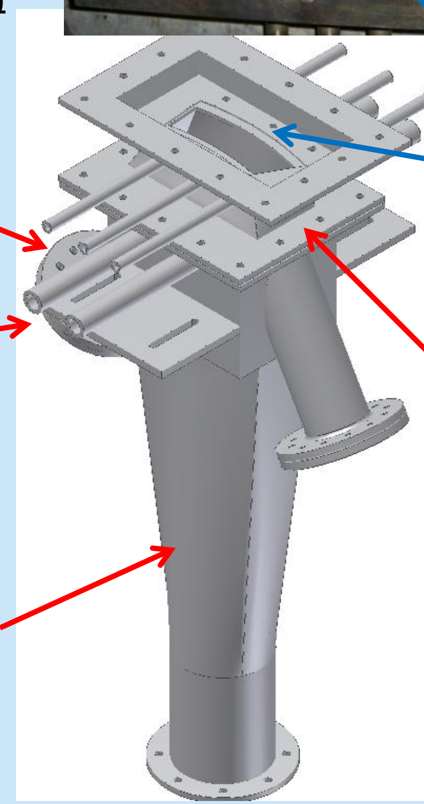
(Use fluid removed from endwall to supply midspan VGJs!)

DOE-Sponsored Synfuel Deposition in Hot Cascade

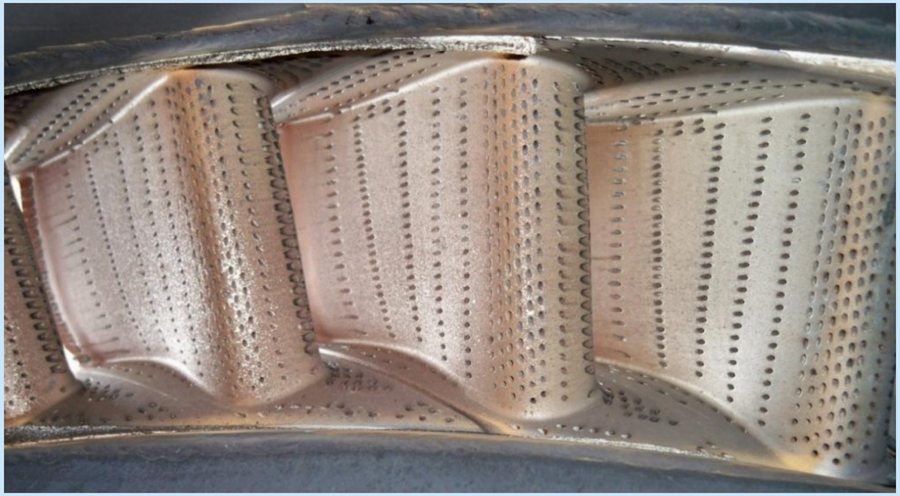


Cascade Facility Replicates Flow at HP Turbine Inlet – Suitable for Deposition Studies with Film Cooling and Hot Streaks

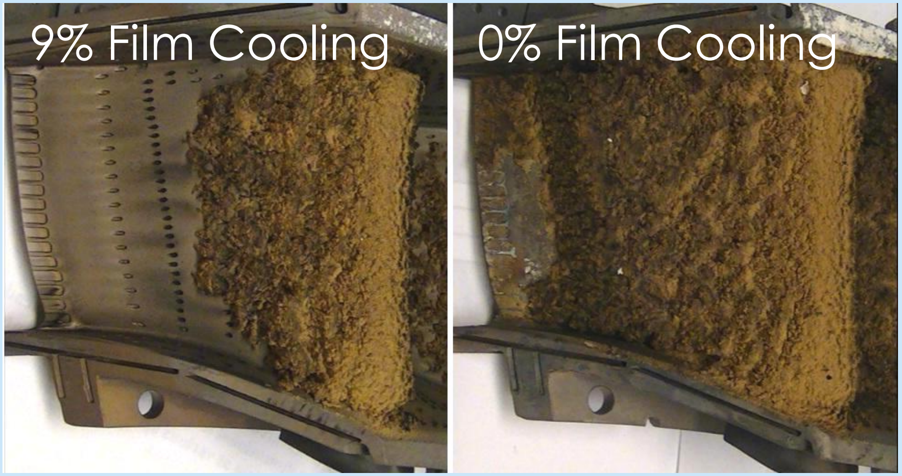




Turbine Deposition

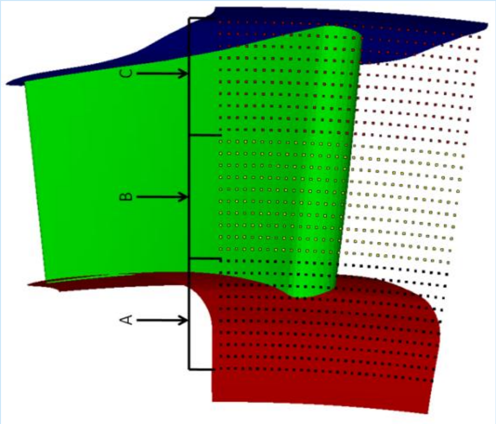


Turbine vane after 1hr of deposit testing at 1850F

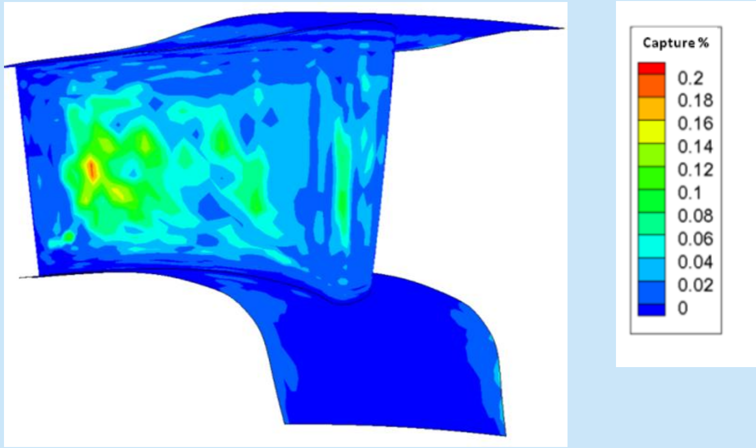


Turbine vane after 30min of deposit testing at 1950F

Particle Deposition Modeling

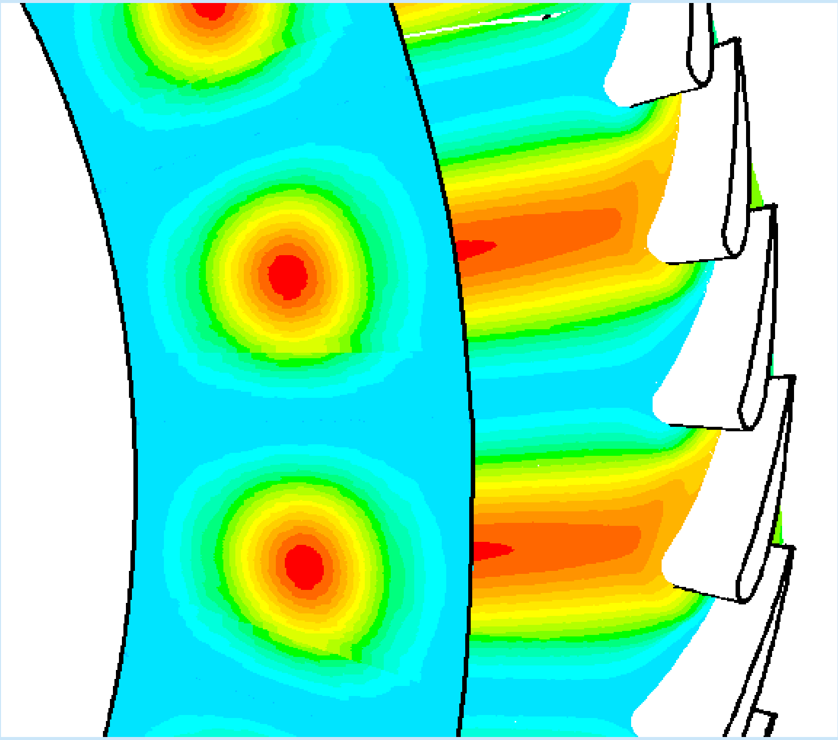


Predicted Deposition Pattern for E^3 Turbine Vane (3D)

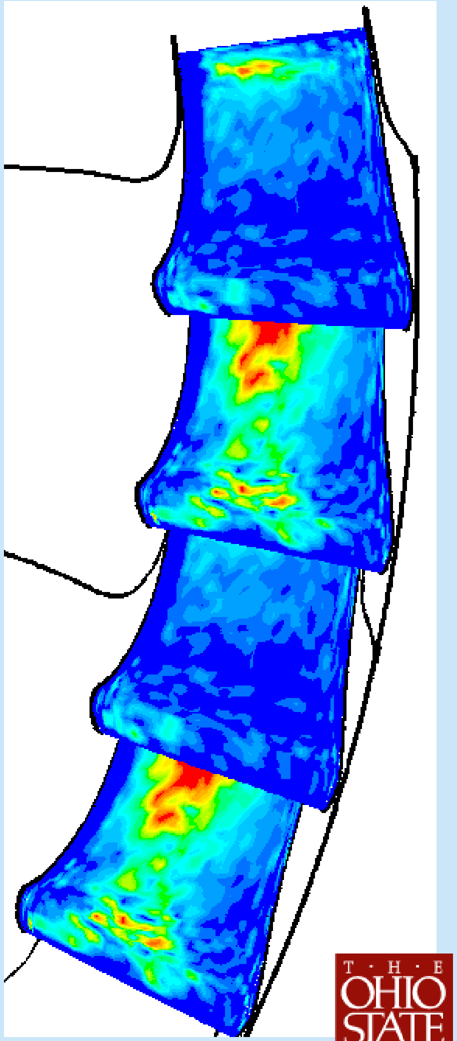


Modeling Hot Streaks AND Deposition

Hot streaks modeled as 1500K Gaussian peak in 1340K mean background temperature. Two vanes per fuel nozzle.



Model predicts 3X increase in deposition on HOT vane vs. COLD vane.



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Gas Dynamics and Turbulence Laboratory

Gas Dynamics and Turbulence Laboratory

Gas Dynamics and Turbulence Laboratory (GDTL)

- The work at GDTL is focused on flow and acoustic diagnostics and control to improve performance and mitigate environmental impact of Aerospace vehicles
- The work is often interdisciplinary in nature and brings together researchers from OSU as well as NASA, Air Force Research Laboratory, and industry to develop and implement
  - Realistic flow and acoustic models,
  - Advanced actuators and sensors,
  - Control technology, and
  - Laser-based diagnostics
- The work is supported by NASA, Air Force, Navy, National Sciences Foundation, and industry
- There are four experimental facilities detailed on the next slide and an array of advanced laser-based diagnostic systems
- GDTL share air supply with Gas Turbine Lab and the Aeronautics and Astronautics lab (three Norwalk model TDR-S5T 5-stage reciprocating compressors; 220 horsepower each, 1700 SCFM, 3000 psig

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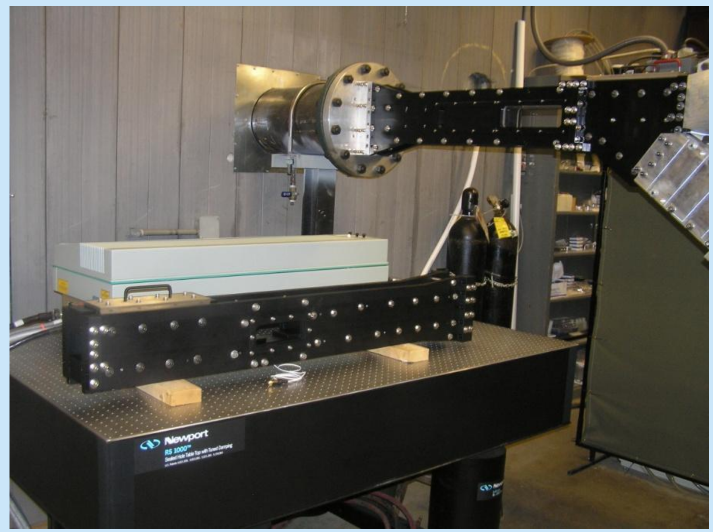
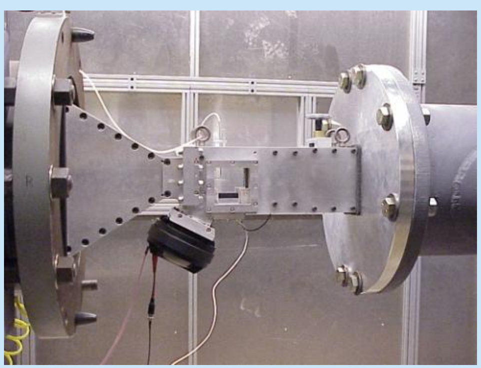
Gas Dynamics and Turbulence Laboratory (GDTL)

Heated jet facility for noise mitigation research in commercial and military aircraft using patented plasma actuators

Supersonic tunnel
(for inlet flow control and Mauro-optics)





High Reynolds number flow facility currently used for cavity flow control for military aircraft weapon bay application

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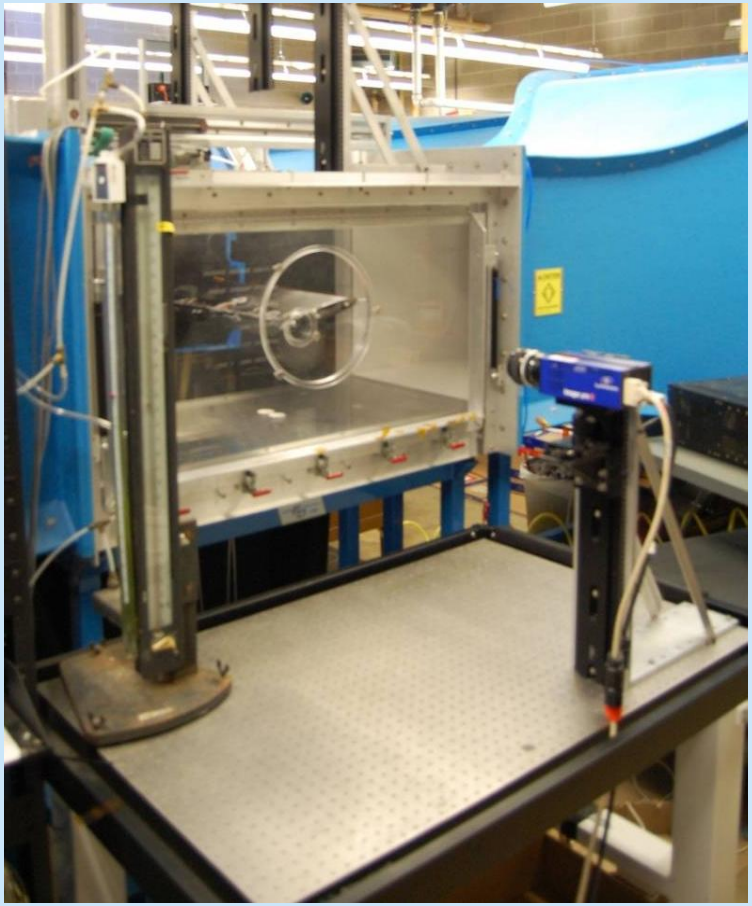
Gas Dynamics and Turbulence Laboratory (GDTL)



Large-scale subsonic tunnel currently used for airfoil flow control research in military and commercial aircraft using Nano-Second pulse driven Dielectric Barrier Discharge (NS-DBD) plasma actuators

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Acoustics

- Passive control using chevrons
  - Reduces jet noise by 2 to 3 dB, needed only for 10 minutes during takeoff and landing, but affects the thrust in the entire flight
- Active control using flow instabilities
  - Jets are known to behave like an amplifiers, significantly amplifying perturbations over a range of frequencies and modes – these amplified perturbations rollup into large-scale turbulence structures dynamics of which are responsible for peak far-field noise.
  - It is also known that dynamics of certain structures are less efficient noise generator/radiator
  - We have designed and built high amplitude and wide bandwidth plasma actuators for tailoring flow structures and noise field and have shown that they work both experimentally and computationally
  - Have tested the technology with both commercial and tactical typenozzle in our lab - preparing for scale-up experiments at NASA and GE

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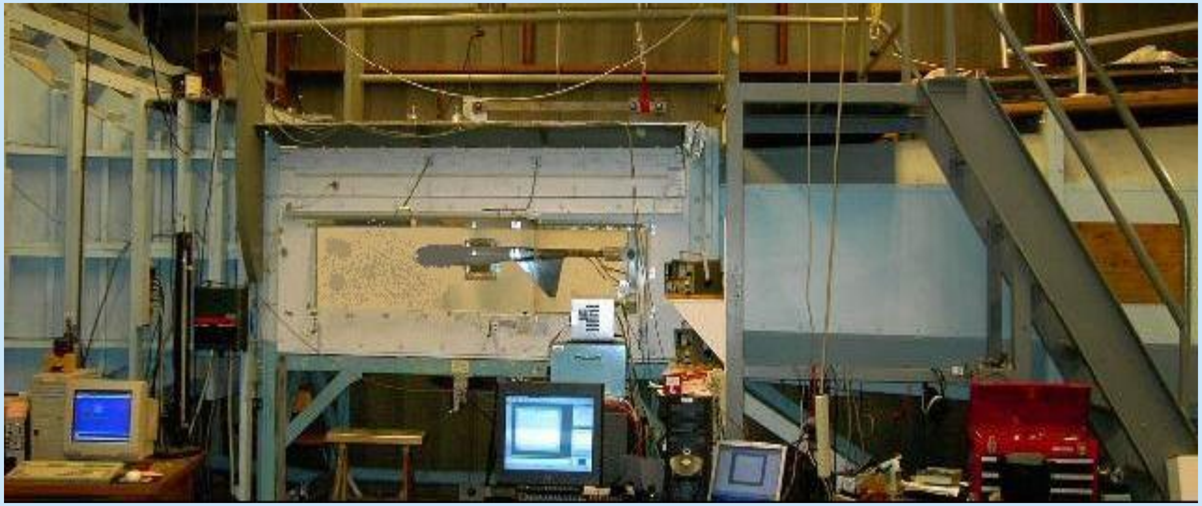
Wind Tunnel Facilities

Wind Tunnel Facilities

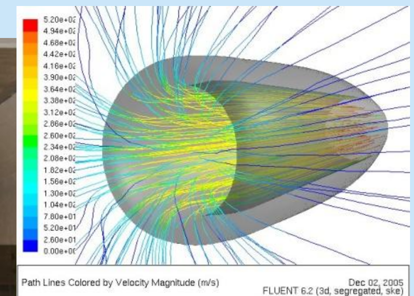
Subsonic: 3’ x 5’ Open Circuit Low Turbulence Wind Tunnel top speed 150 ft/sec

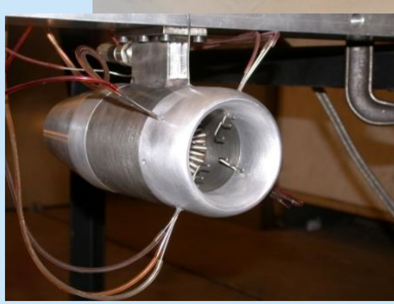


- Steady and Unsteady Test Equipment
- Pressure, Force and Moment Measurements used for many airfoil, wind energy aircraft studies

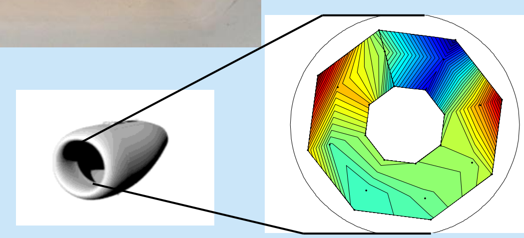
Propeller/Jet Interaction Study in Subsonic Wind Tunnel

CFD Solution



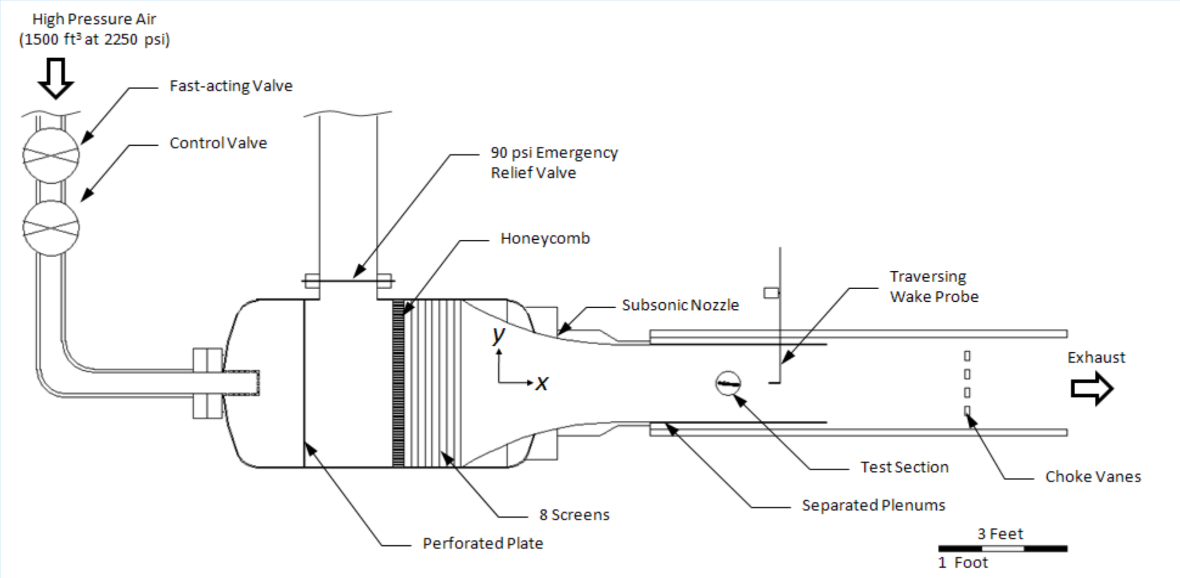


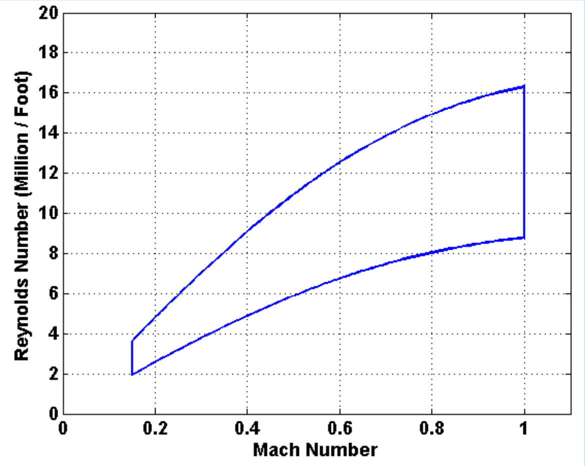
Jet Engine Simulator



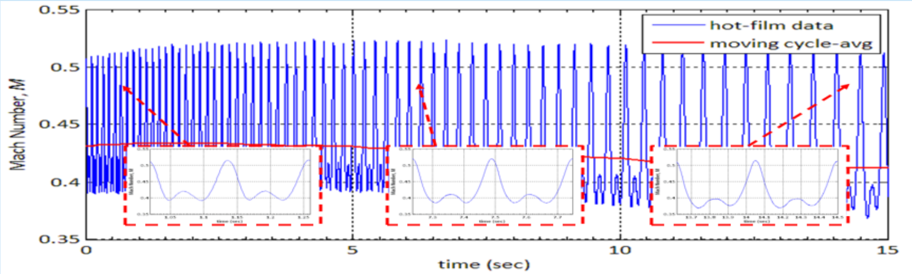
Pressure Distribution at Compressor Face

6x22 Transonic Tunnel



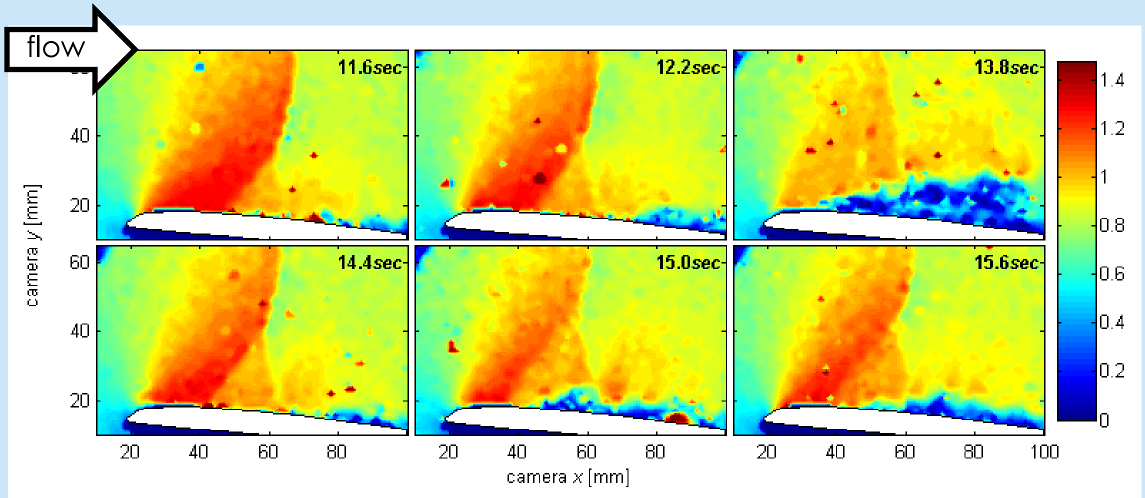


- Blowdown short-duration tunnel
- 6" span airfoil sections
- Mach number uniquely set by downstream choke area
- Reynolds number set by upstream stagnation pressure
- Rotating elliptical choke bars add <u>unsteady</u> Mach capability



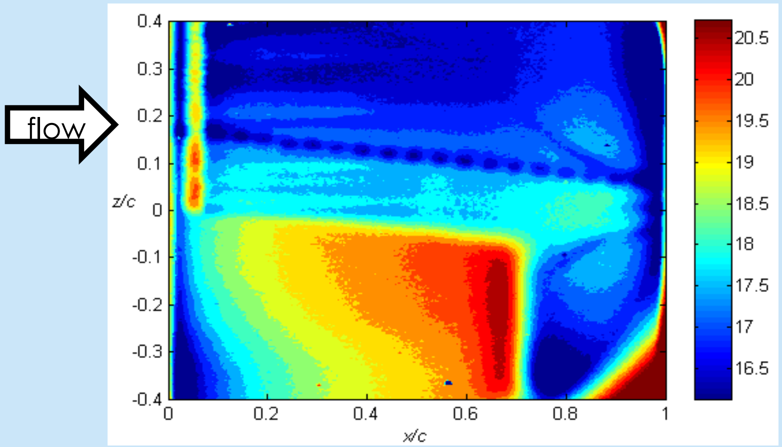
6x22 Tunnel Advanced Instrumentation

Unsteady PIV shows oscillating shock during tunnel Mach oscillation



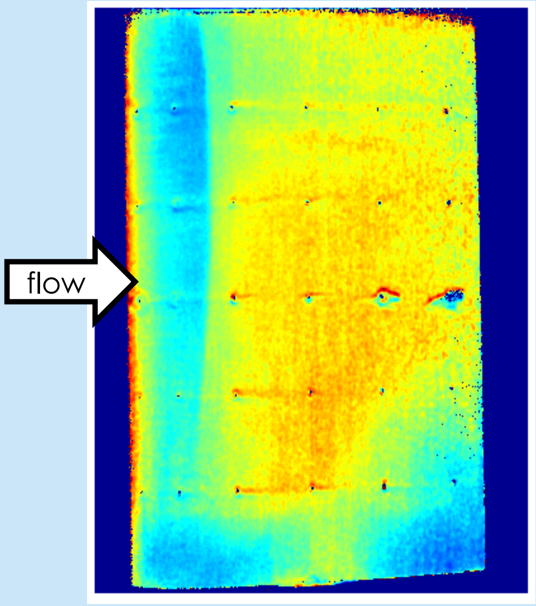
(Contours of Mach number for thin airfoil at mean M_∞ = 0.75, Re_c = 5 × 10^6, and α = 8°.)

Infrared imaging detects boundary layer transition



Representative thermogram of thin airfoil at M_∞ = 0.3, Re = 2 × 10^6, α = -6°; contours of temperature (°C).
Top half: ZigZag tape at x/c = 5%, Bottom half: no passive trip (natural transition).

Fast response Pressure Sensitive Paints (PSP) yield full-field surface pressures in unsteady transonic flow



NACA 0012 in pitch oscillation at 0.5Hz.Mean Mach number 0.6.

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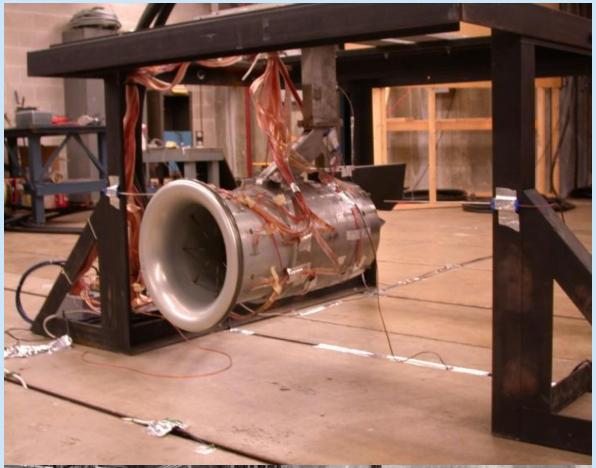
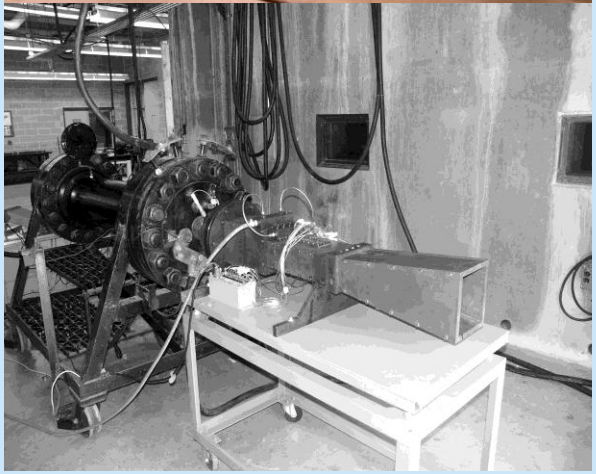
Special Test Facilities

- **<u>Jet Engine Simulators</u>**:
  - Array of 1/12 Scale GE Engine Simulators for use in Jet Engine Test Cell Developments
    - Provides Scaled Correct Mass Flow and Thrust
- **<u>6” x 6” Heated Blowdown Tunnel</u>**:
  - M = 0.6 – 0.8
    - Used for Heat Transfer Measurements on Turbine Blades
- **<u>Hypersonic</u>**:
  - Mach 6
    - 6” Diameter Blowdown Wind Tunnel (Now in Assembly)
    - P_0 = 600 psia T_0 = 1000^{0}F
    - To be used in NANOTECH Studies





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Propulsion Material Research

Propulsion Material Research

Center for Accelerated Maturation of Materials

Structural Materials Research


- Katharine Flores (Materials Science Engineering)
  - Bulk Metallic Glasses, Mechanical Behavior
- **Hamish L. Fraser** (Materials Science Engineering)
  - Titanium Alloys, Characterization, Alloy Synthesis


- Michael Mills (Materials Science Engineering)
  - Superalloys, Characterization, Mechanical Behavior
- Yunzhi Wang (Materials Science Engineering)
  - Phase Field Modeling


- John Wilkins (Physics)
  - Atomistic Potentials and Calculations
- James Williams (Materials Science Engineering)
  - High performance metallic materials


- Wolfgang Windl (Materials Science Engineering)
  - Electronic Structure Calculations
- J. Cheng Zhao (Materials Science Engineering)
  - Combinatorial Synthesis and Property Measurement

CAMM

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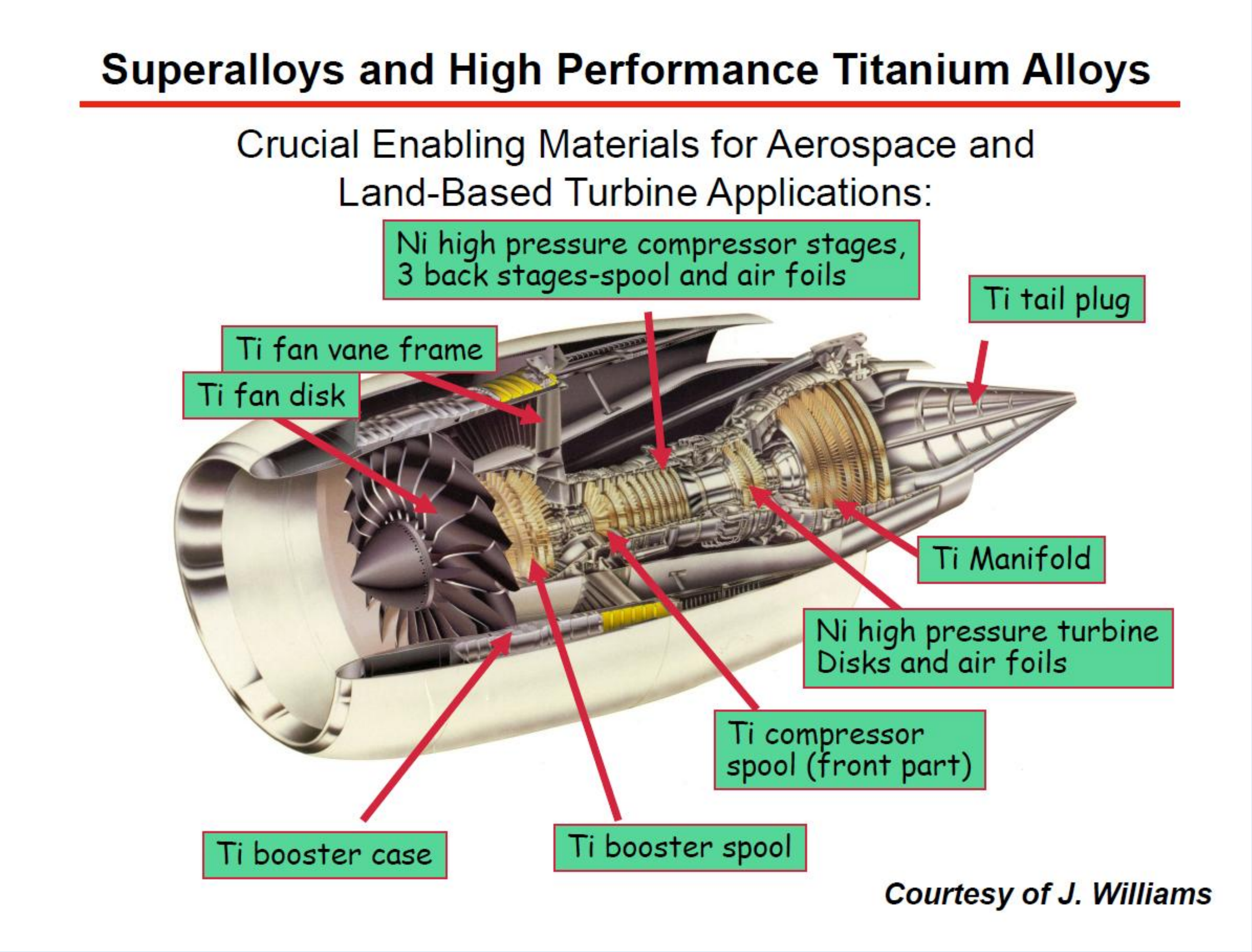
Propulsion Material Research

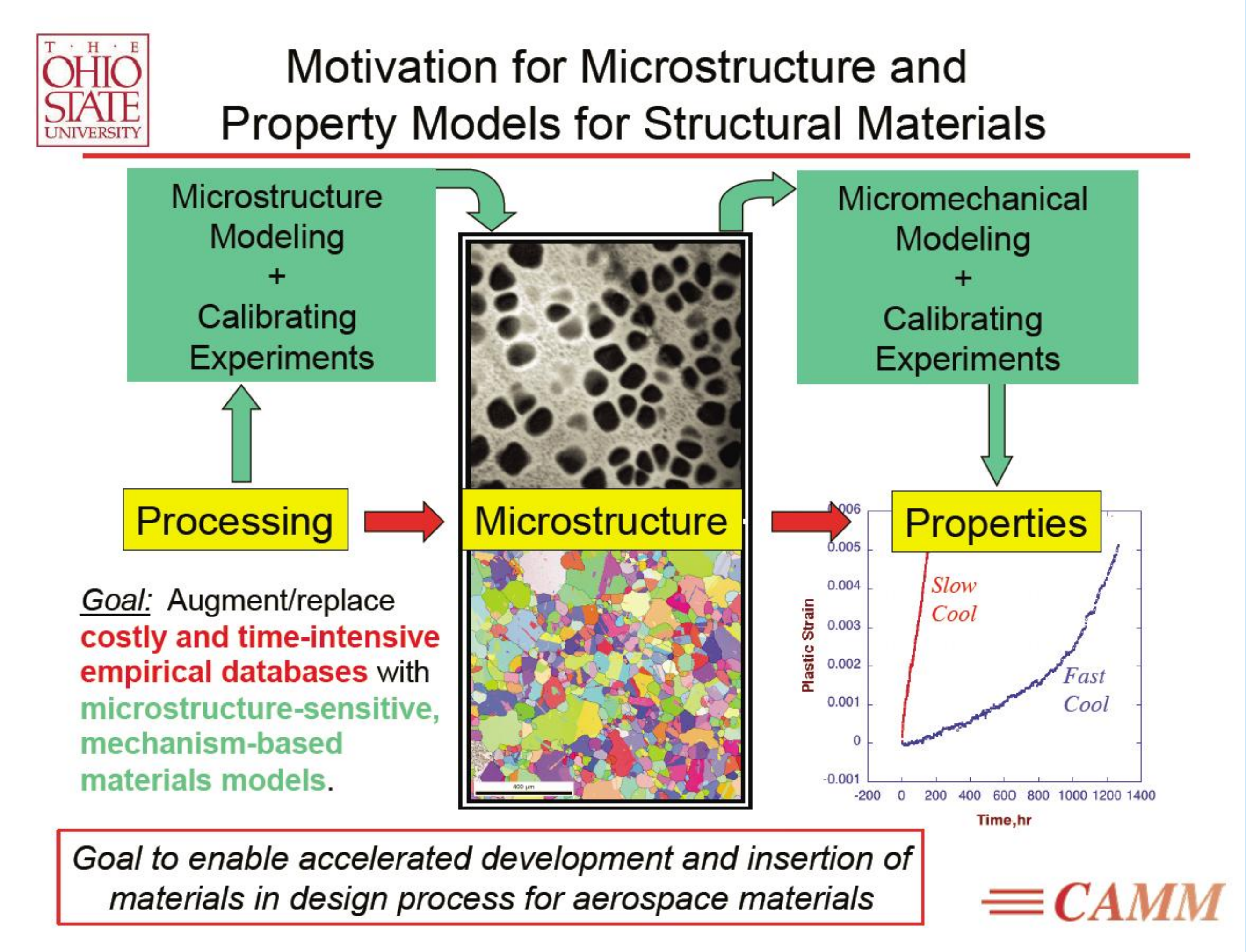
Examples of Funded Programs in Structural Materials

- *DARPA D-3D: Digital Microstructures and Properties in Titanium Alloys*
- *AFRL MAI:* Durable Ni Disk Program
- *AFOSR STW-21 Initiative: Multi-Materials with Adaptive Microstructures*
- *AFRL MAI: Microstructure and Strength Modeling in IN718*
- *AFOSR MEANS:* Ni disk & air foil alloy creep and fatigue
- *NASA URETI:* Nb-Si alloy studies, TBC failure modes, CMC combustor liners
- *FAA*: Dwell fatigue of Ti-6-2-4-2
- *GE USA Materials:* Experiment/modeling of grain growth/fatigue in Ni Superalloys
- *NASA:* High Temperature Shape Memory Alloys
- *DOE/ORNL:* Nanocluster Strengthened Ferritic Steels
- *Bettis:* Creep modeling of Zirconium alloys
- *Lincoln Electric:* Microstructure Analysis in Arc Welded Steels

Propulsion Material Research



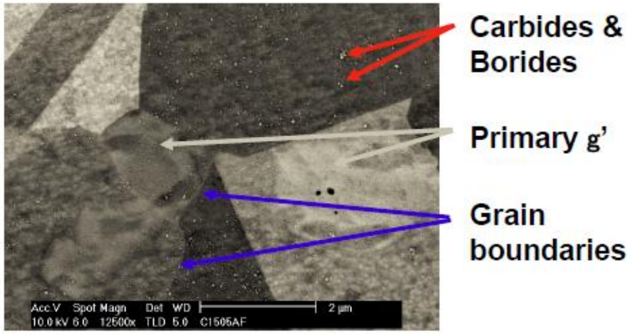
Propulsion Material Research



Advanced Materials Characterization at OSU

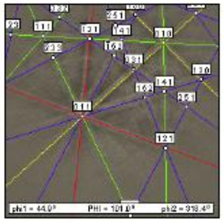
FEI Sirion SEM

- *Ultra high resolution imaging and computer-based image processing allow measurements of the gamma prime and carbide distributions*
- *Light-element EDS allows micro-scale study of microstructure chemistry*

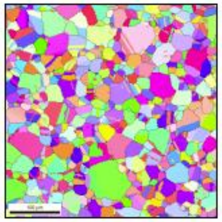


FEI XL-30 ESEM SEM

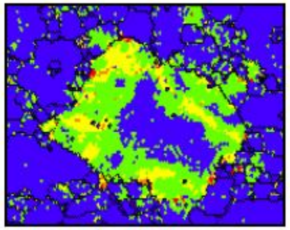
- *Orientation Imaging Microscopy (OIM) provides a precise measure of the grain size distribution, measurement of fraction of special boundaries such as twins, and crystal orientation data that compliments TEM analyses*



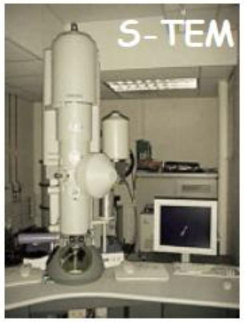
Backscatter Electron Diffraction Pattern Indexed by Software



Grain-scale image from thousands of indexed points

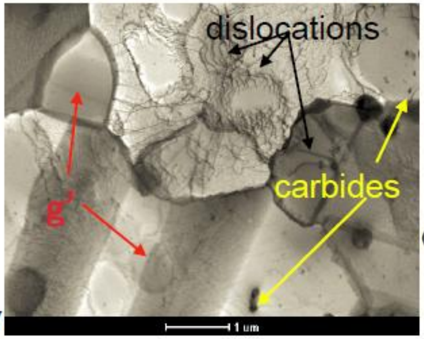


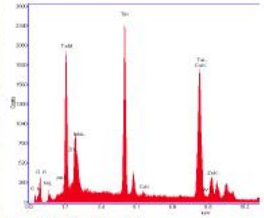
Misorientations within grains indicating stored energy from forging



FEI Tecnai TF20 S-TEM

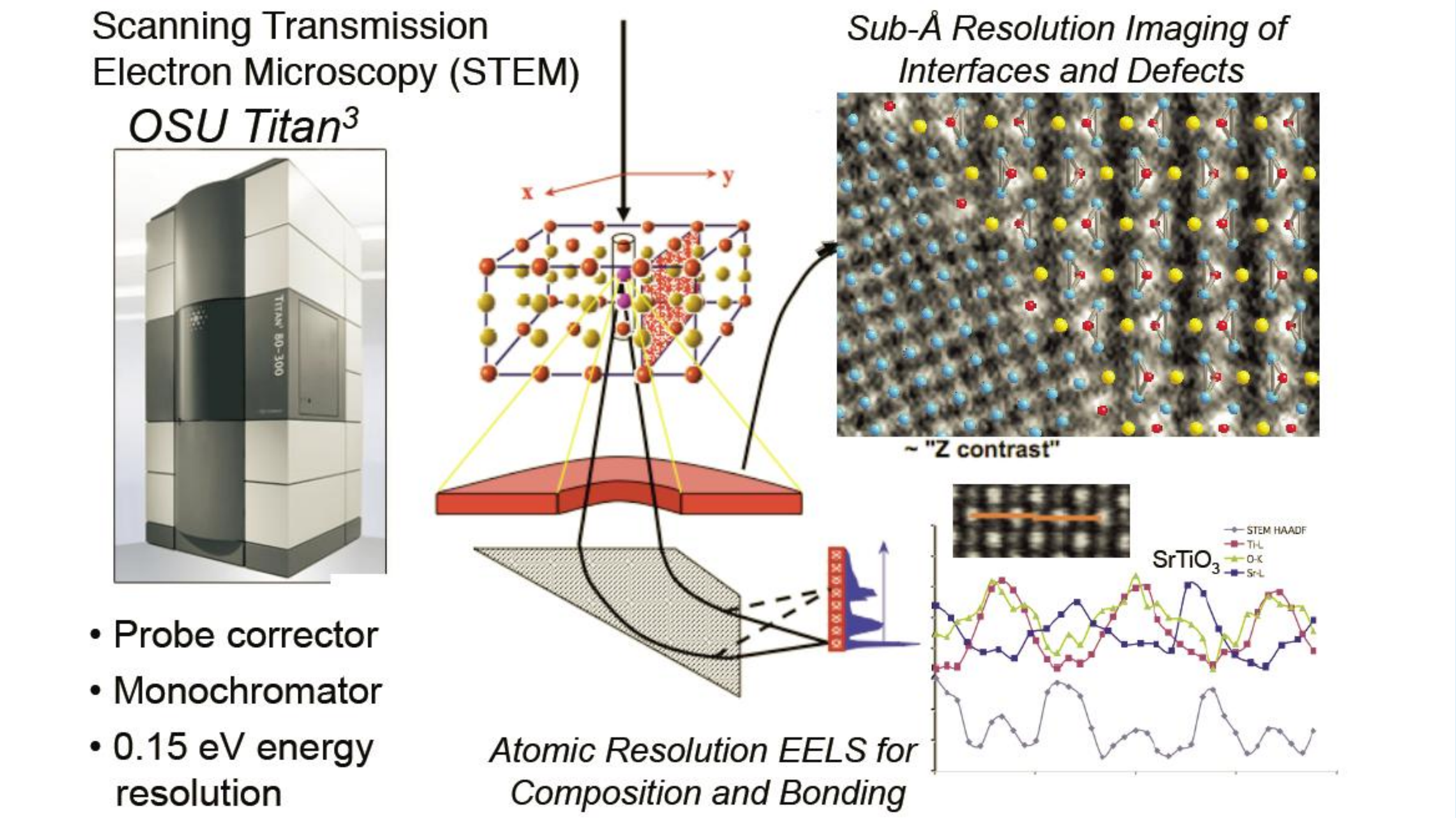
- *Bright-field scanning TEM allows imaging of crystal defects in many grains simultaneously.*
- *Advanced chemical analysis capabilities allow for nano-scale study of microstructure chemistry*





Carbide EDS spectrum

Advanced Characterization at OSU

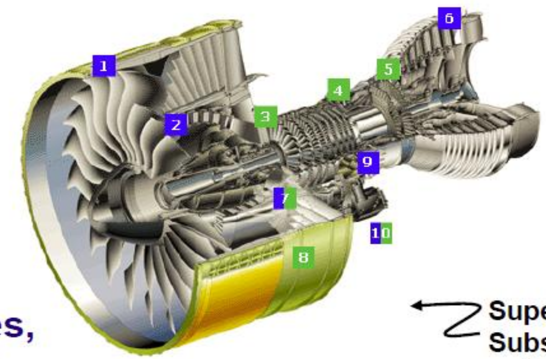


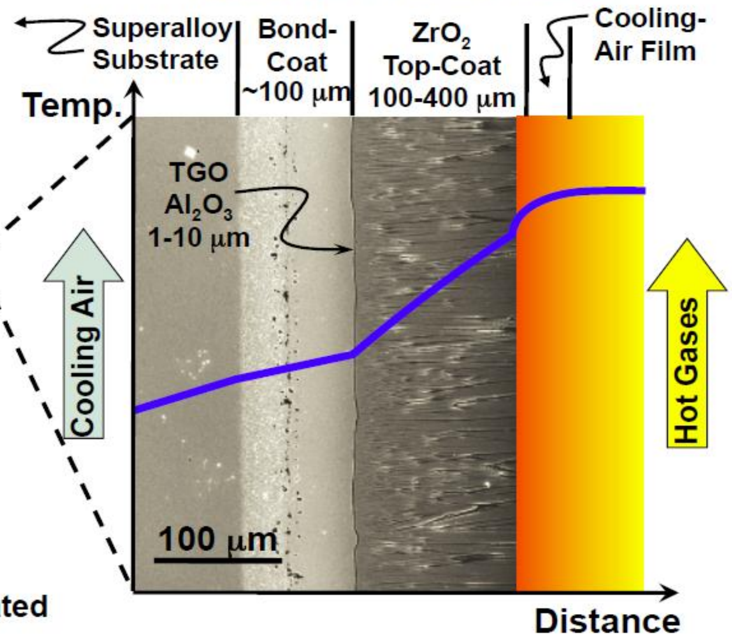
Characterization underpins model development

Thermal Barrier Coatings

Thermal Barrier Coatings

* Engines
  - Aero
  - Power
* Blades/Vanes, Combustors, Shrouds
* Strain-Tolerant, Low Th. Cond.
* Up to 300 ˚C Temp. Reduction
* Improved
  - Performance
  - Efficiency
  - Durability

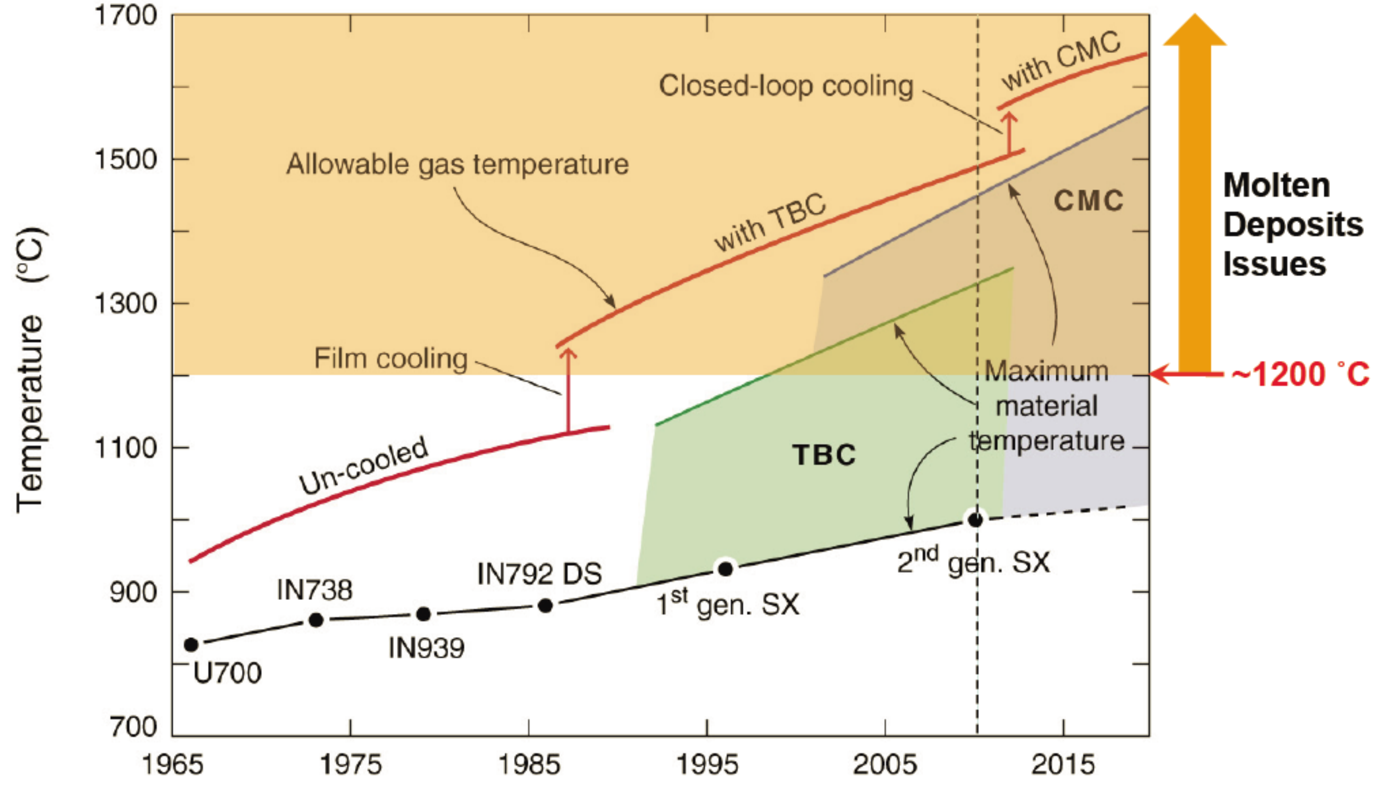




Thermal-Barrier-Coated Turbine Blade

Padture *et al.*, *Science*, 2002

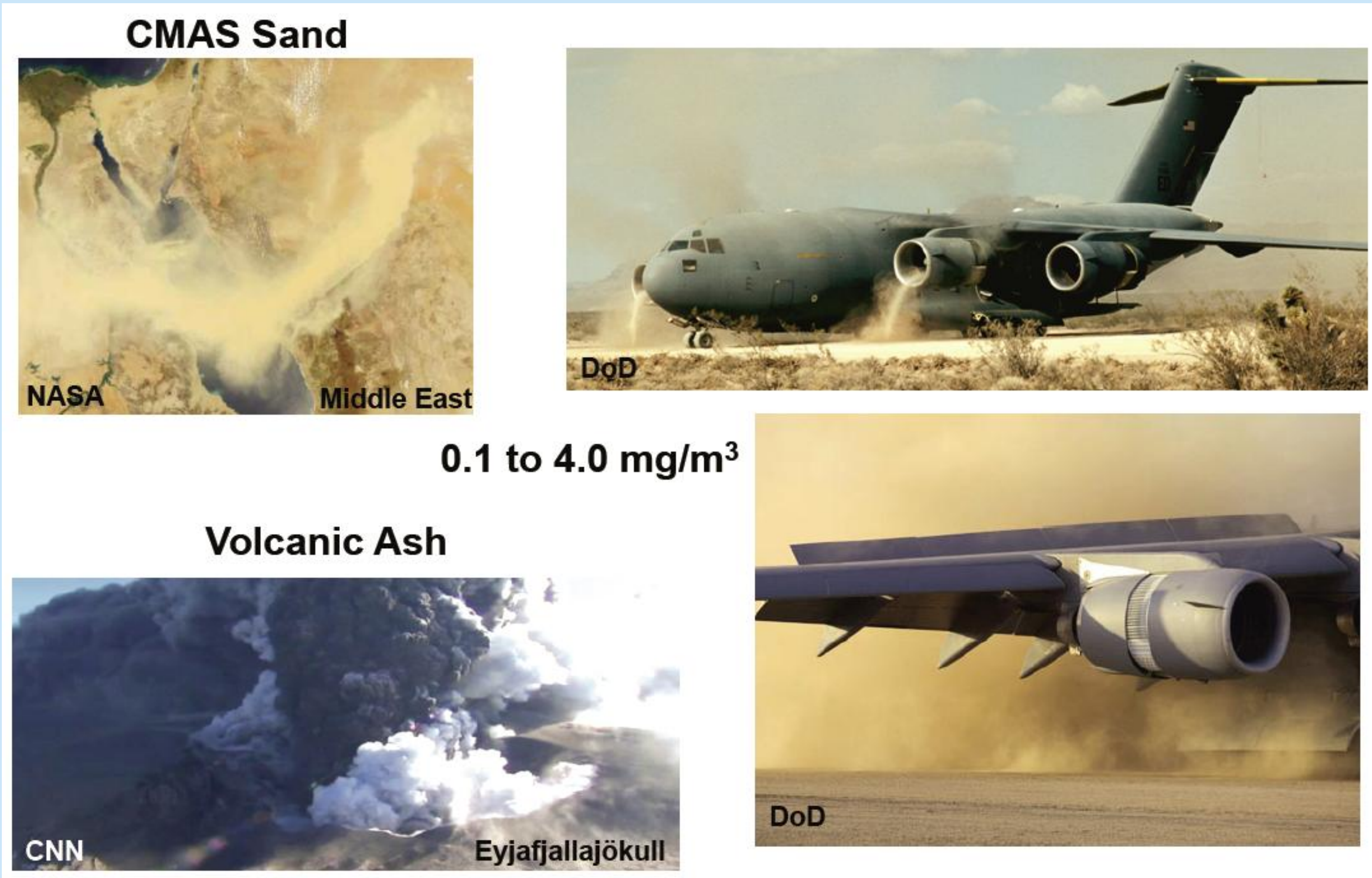
Molten Deposits



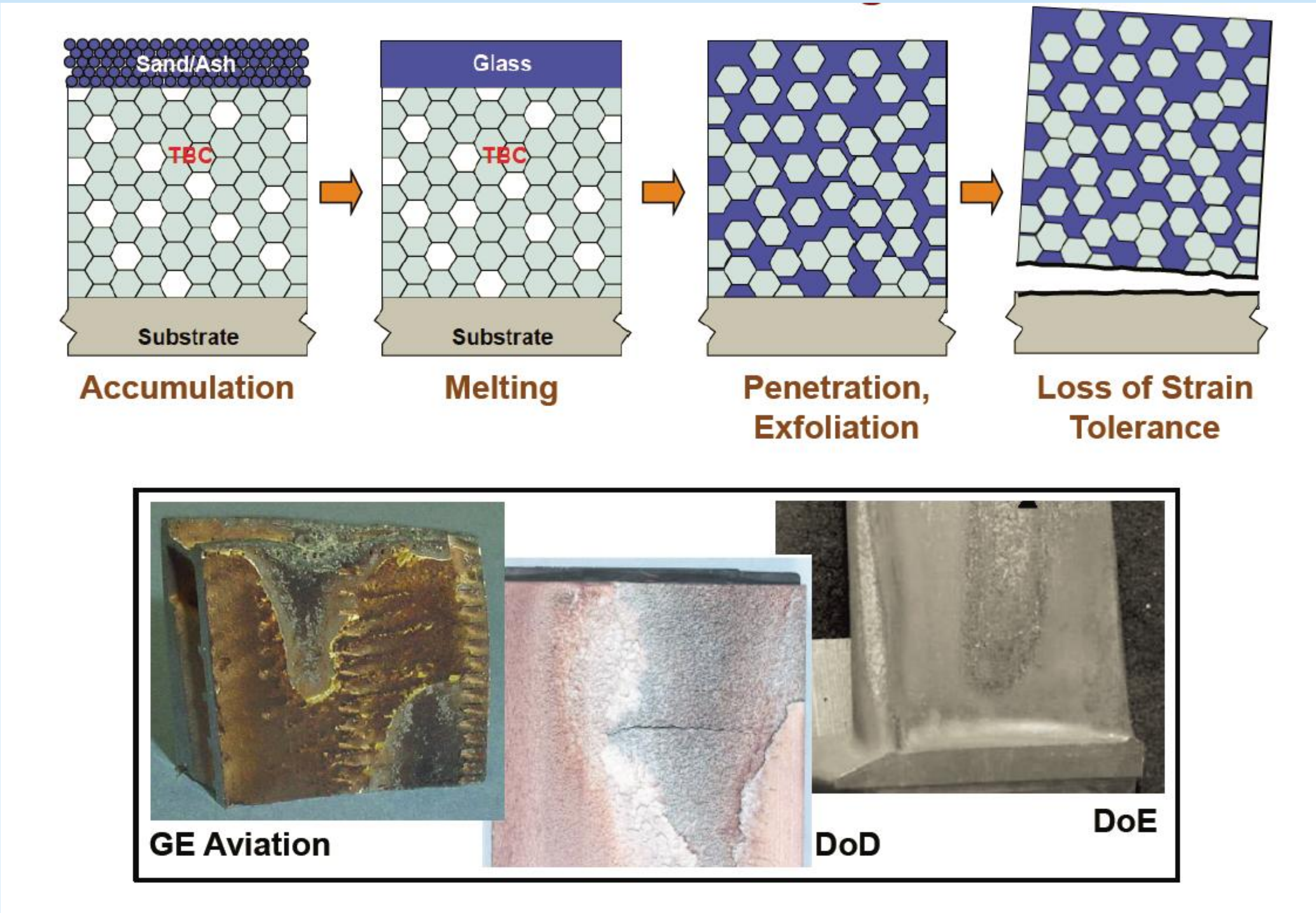
Evans *et al.*, 2009

Push for Higher Temperatures Engendering New Materials Issues

Sources of Silicate Deposits in Aero Engines



Thermo-Chemo-Mechanical Damage of TBCs



Alternate Fuels

Alternative Fuels

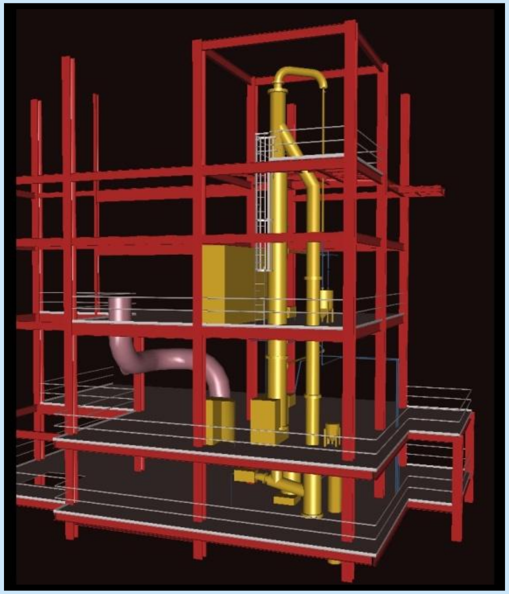
Coal-Direct Chemical Looping

Cold Flow Model

Sub-Pilot Scale Unit

Syngas Chemical Looping

Sub-Pilot Scale Unit



250kW$_{th}$ Pilot Unit (Wilsonville, Alabama)

Project I: Pilot Scale Testing of the Carbon Negative, Product-flexible Syngas Chemical Looping Process

- **Novelty and Readiness of the Proposed Technology**
  - 10 – 20% improvement for power generation, hydrogen production, and liquid fuel synthesis with nearly 100% CO_2 capture
  - Successful bench and sub-pilot scale demonstrations
- **Project Objectives**
  - Pilot unit design and construction at NCCC
  - Long term continuous operation
  - Validate the techno-economic attractiveness of SCL
- **Potential Impacts**
  - GHG Emission Reduction
  - Energy Efficiency Enhancement
  - Energy Security Improvement
- **Budget**
  - \$5 million from DOE ARPA-E
  - \$4.9355 million cost share

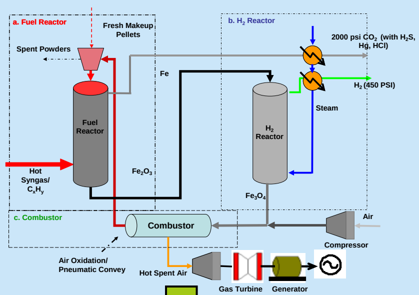
Project II: Coal Direct Chemical Looping Retrofit to Pulverized Coal Power Plants for In-Situ CO_2 Capture

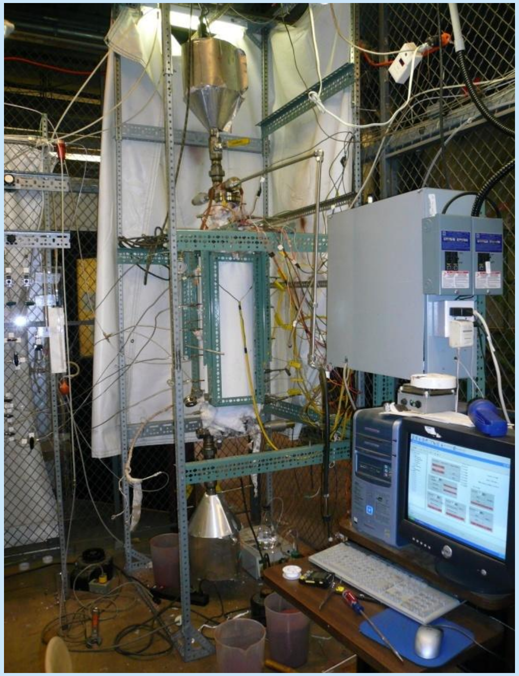
- Period of Performance: 2009-2012
- Total Funding ($3.98 million):
  - U.S. Department of Energy, National Energy Technology Laboratory ($2.86 million)
  - Ohio Coal Development Office ($300,000)
  - The Ohio State University ($487,000)
  - Industrial Partners ($639,000)
- Major Tasks:
  - Phase I: Selection of iron-based oxygen carrier particle
  - Phase II: Demonstration of fuel reactor (coal char and volatile conversion) at 2.5 kW_t scale and cold flow model study
  - Phase III: Demonstration of integrated CDCL system at 25 kW_t scale and techno-economic analysis of CDCL process

CRI CATALYST · NETL · B&W · AIR PRODUCTS · CONSOL ENERGY · The Ohio Air Quality Development Authority · THE OHIO STATE UNIVERSITY

Project III: Process/Equipment Co-simulation on Syngas Chemical Looping Process

SCL





Process Demonstration

NETL's Advanced Process Engineering Co-Simulator*

*http://www.netl.doe.gov/onsite_research/Facilities/apecs.html

Techno-Economic Evaluation

	IGCC Process	SCL Process Electricity	CDCL Process Electricity	Conventional to Hydrogen Process	SCL Process Hydrogen	CDCL Process Hydrogen
Coal Feed (ton/hr)	132.9	132.9	132.9	132.9	132.9	132.9
Carbon Capture (%)	90	100	100	90	100	100
Hydrogen (ton/hr)	0	0	0	14.4	15.6	20.0
Net Power (MW)	321	365	435	2.1	26	3
Efficiency (%HHV)	32.1	36.5	43.5	57.8	64.1	79.0

Process unit performance conditions and Assumptions used are similar to those adopted by the DOE baseline studies given in "Cost and Performance Baseline for Fossil Energy Plants", DOE/NETL-2007/1281.

- Improvement in Efficiency over conventional processes
- Lowest cost of electricity under a CO_2 regulated scenario
- SCL can pave the way to CDCL demonstrations in the future
- H_2 Production: SCL is 7 – 10% More Efficient Than Conventional Process (Analyzed by SAIC)
- Electricity Generation: SCL is 4.5 – 7% More Efficient Than IGCC with 100% CO_2 Capture (Analyzed by Noblis)
- When Integrated CTL, SCL can Increase the Liquid Fuel Yield by 10% with 19% Reduction in CO_2 Emission (Analyzed by Noblis)

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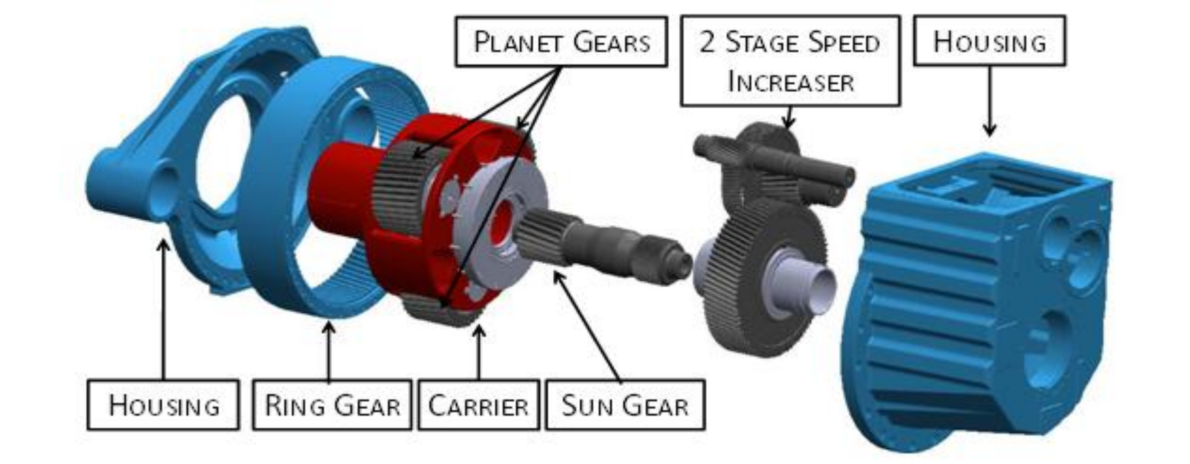
Gearboxes

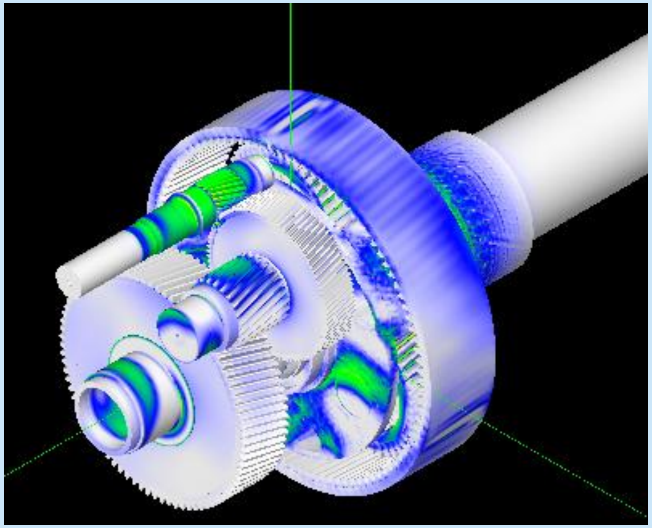
Propulsion and Power Center

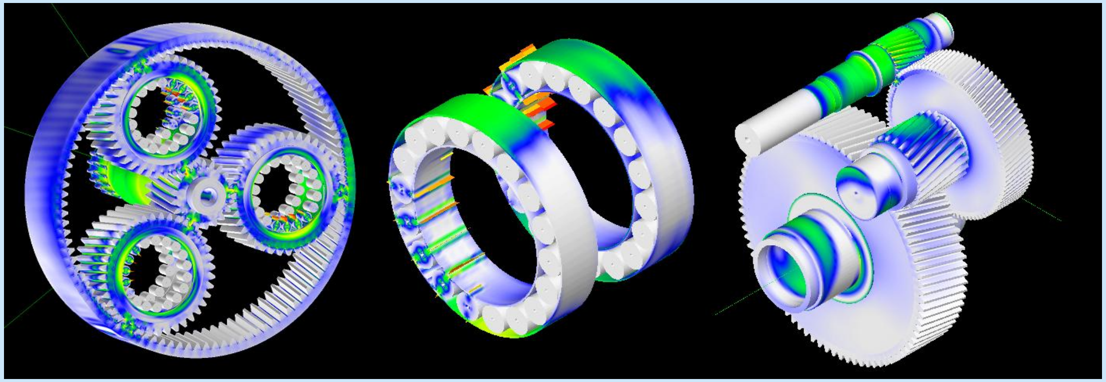
Wind Turbine Gearbox Research of OSU GearLab



Modeling of Actual Wind Turbine Gearboxes

NREL Test Gearbox:

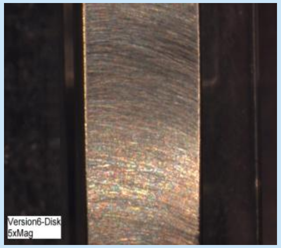


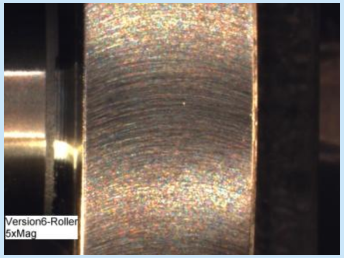


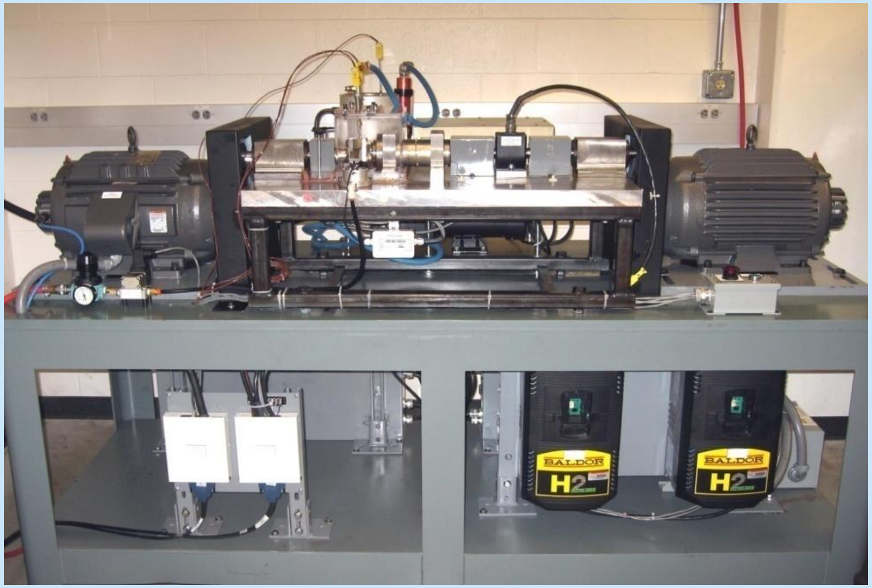
Propulsion and Power Center

Gearbox Research of OSU GearLab

- Simulated roller contact test methodology
- Both gear and bearing contacts
- Accelerated tests including the effect of run-in conditions







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Ohio State Gear Turbine Research and Development Activities Summary

Ohio State has a vibrant multifaceted academic activity in Gas Turbine Research

We are hosting a world class program in education and research with the involvement of forty plus faculty and over 100 graduate students working to grow as we move forward with a strong cooperation with industry and the government.