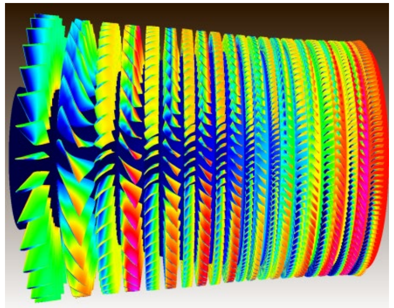
Overview of Numerical & Experimental Activities

Mark L Celestina, Chief
NASA Glenn Research Center

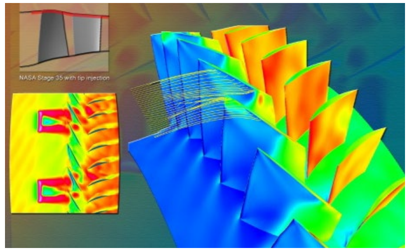
Gulfstream Workshop
6/20/2023

LTE Overview

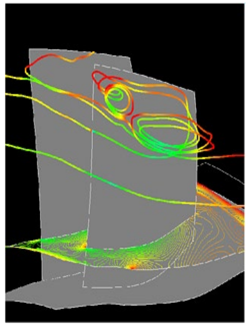
Numerical Methods:

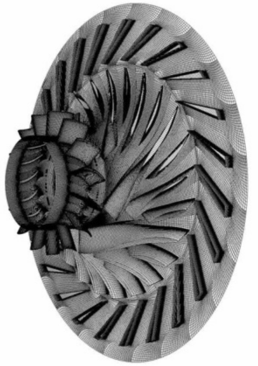


- Multistage Flow Physics

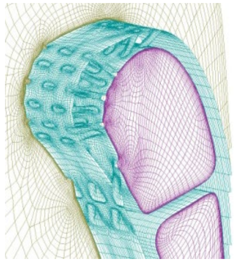


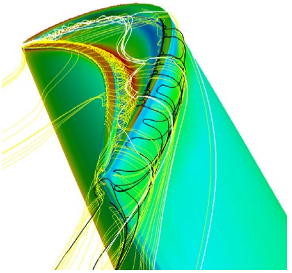
- Advanced Concept Simulation

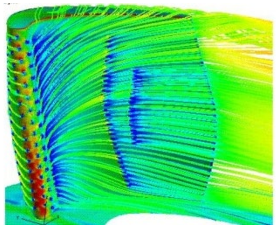




- Axial & Centrifugal Configurations







Turbine Aero / Conjugate Heat Transfer / Film Cooling

Turbomachinery Aerodynamics Codes

- Analysis and Design of Turbomachinery:
  Compressor, Fan, Turbine, and Pump
- Enabling Technologies Being Developed:
  Reynolds Averaged Navier-Stokes Solver
  Large Eddy Simulation, Parallel Process
  Pre- and Post-Processors
  Flow Transition; Modeling, Blade Losses
  Film Cooling; Turbine Coolant Passages

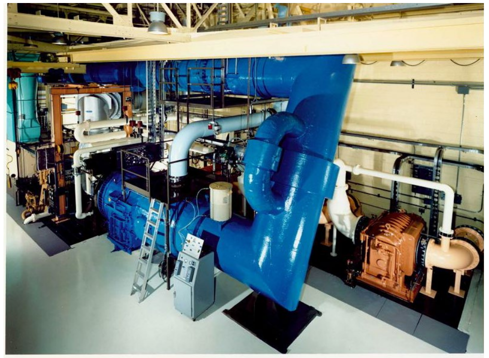
Advanced Design Concepts:

- Efficiency Improvement; Reduced Losses
- Compressor Operability; Stall Margin
- Improved Turbine Cooling

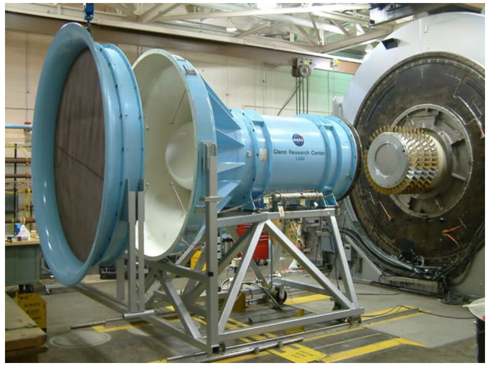
Turbomachinery Testing and Experiments

- Multistage Compressor - W7; 15,000 HP
- Centrif Compressor - CE18; 6,000 HP
- Turbine Test Facility – W6 12,4000 HP
- Single Stage Compressor - W8; 7,000 HP

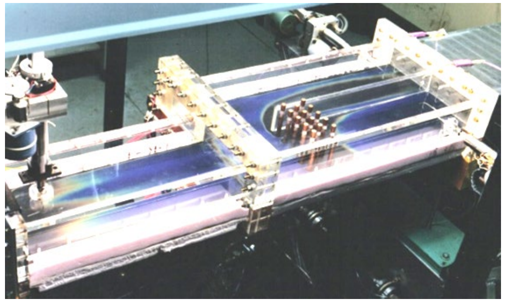
Validation Testing



HP Compressor and Turbine Tests



Low Pressure Compressor



Laboratory Experiments

LTE Tools, Techniques and Facilities

- **Computational Tools**
  - 0D (NPSS), 1D (ComDes), 2D design tools for aero design of turbomachinery
  - 3D CFD: Hah3d, APNASA, Glenn-HT, TURBO, Fun3D
  - Compressor Ice Accretion Modeling (ComDes-MELT)
- **Experimental Methods**
  - LDV, LDA, PIV for turbomachinery applications
  - Flow Control, synthetic jets
  - Flow Visualization – PSP, TSP, IR, Trace gas sampling
  - Unsteady measurements – Kulites, hotwires, tip clearances, …
- Facilities
  - ✓ Engine testing (PSL) for Hybrid electric / turbine power extraction, Engine Icing
  - ✓ Turbine: W-6 Warm turbine rotating rig, CW-22 cascade facility, SW-2 & SW-6 low speed cascade
  - ✓ Axial Compressor: W-7 multistage compressor, W-8 transonic single stage, W1 Large Low speed Axial Compressor,
  - ✓ Radial Compressor: CE-18 high speed, smaller size centrifugal or axial compressor facility
  - ✓ CW-7 low speed wind tunnel, (being repurposed…)

AATT: eTC Boundary Layer Ingesting Tailcone System (BLITS)

Objective:

- FY20: Assess vehicle efficiency and fuel burn benefits of tail cone thruster propulsion systems ingesting viscous boundary layers and distorted flow.
- FY21-23: Validated Integrated Simulation Capability to make system-level predictions for BLI Configurations.

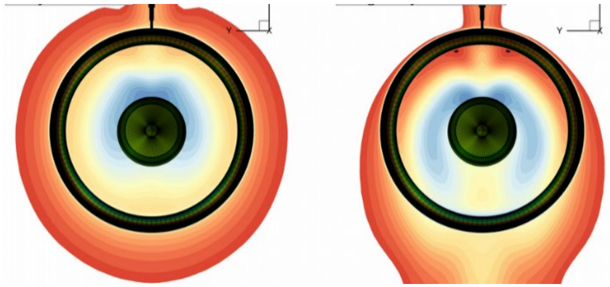
Approach:

- Conduct propulsion-airframe testing to: (1) evaluate propulsion airframe integration interactions to assess the conditions a tail cone thruster will ingest, (2) to validate computational predictions, and (3) design an in-house distortion tolerant fan.
- Integrate airframe and turbomachinery computational tools (LAVA and TURBO) using test data in order to make system level predictions to evaluate effects from the fan on the airframe, and airframe on the fan.
- Utilize NASA TTBW design and distortion tolerant fan design tools in combination with a validated coupled simulation capability to assess performance of a TTBW BLITS.

Key Elements:

- Propulsion Airframe Integration (PAI)
- Concept Analysis/Prediction
- Distortion Tolerant Fan (DTF)

Conceptual Aircraft Design with BLI TCT



Undistorted versus distorted air flow into fan

AATT: eTC Small Core Advanced Thermal Management

Objective

Develop advanced thermal management technologies pertaining to the gas turbine for hybrid electric propulsion. (TRL 4, FY25)

Approach/Challenges

Cooling Effectiveness and Aerodynamic Penalties for CMC Turbine Blades

- Assess the aerodynamic and heat transfer changes when using CMC material for turbine blades. CMC blades have different surface characteristics which will alter both the cooling effectiveness and aerodynamics.

Advanced Heat Exchanger Design and Testing

- Develop design tools enabling topology optimization of heat exchanger fins (thermal, aero, structural)
- Assess other high performing, novel topologies
- Enables higher performance heat exchangers at a lower weight

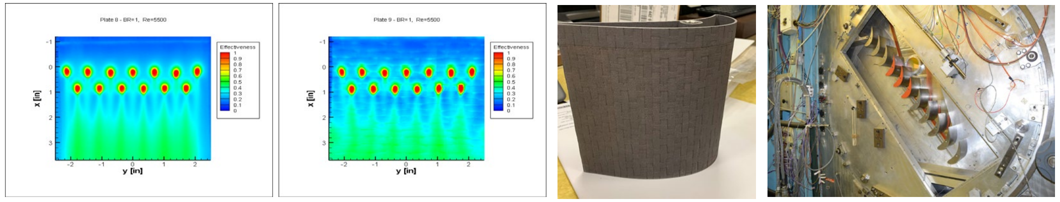
Multifunctional Acoustic and Thermal Radiation Liner

- Develop an acoustic liner with novel materials that can radiatively participate with the incoming hot air.
- Allows the liner to harvest more energy from the engine exhaust, which can be used to drive an auxiliary cycle

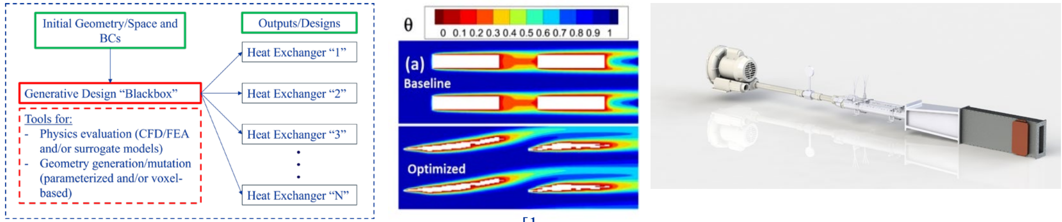
Benefit/Pay-off

- Enables more efficient cycles and opens the door for more advanced engine architectures

Cooling effectiveness and Aerodynamic Penalties for CMC Turbine Blades

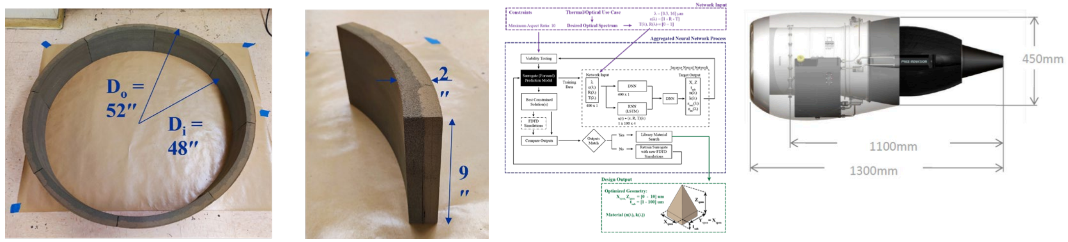


Advanced Heat Exchanger Design and Testing



[1]

Multifunctional Acoustic and Thermal Radiation Liner

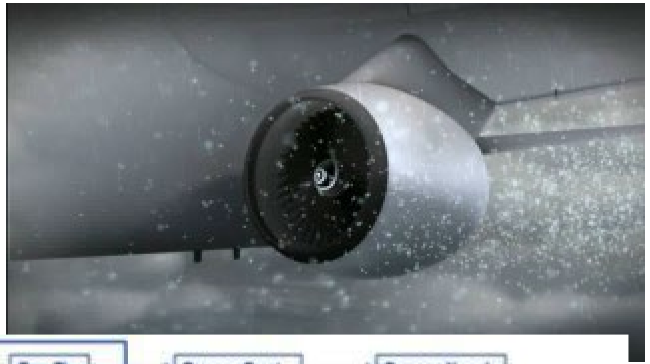


[1] Bashir S. Mekki, Joshua Langer, Stephen Lynch, "Genetic algorithm based topology optimization of heat exchanger fins used in aerospace applications", International Journal of Heat and Mass Transfer, Volume 170, 2021, 121002, ISSN 0017-9310, https://doi.org/10.1016/j.ijheatmasstransfer.2021.121002.

AATT: Compressor Icing Modeling and Altitude Testing

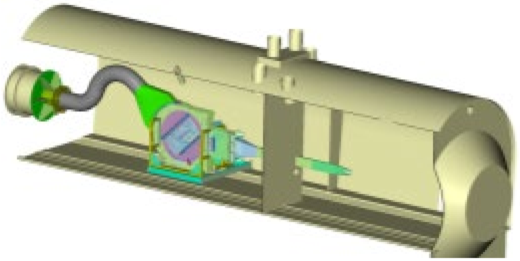
Objective:

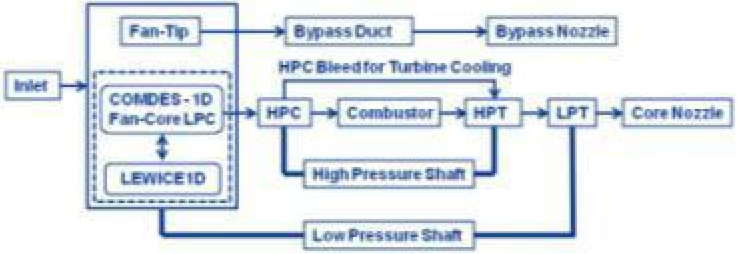
To develop key technologies needed to address the problem of aircraft engine icing due to high altitude ice-crystal ingestion. These key technologies include knowledge bases, both computational and experimental, analysis methods, and simulation tools.



Approach:

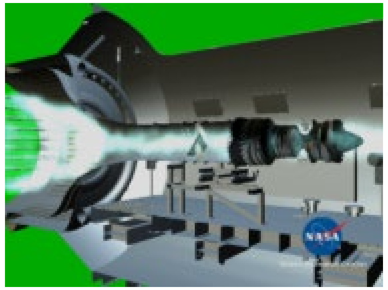
- Laboratory testing: of compressor vane under iced conditions (Collaboration with National Research Council of Canada)

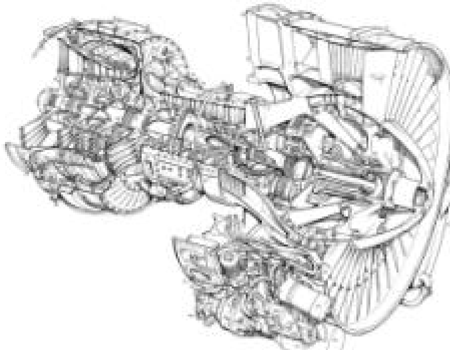


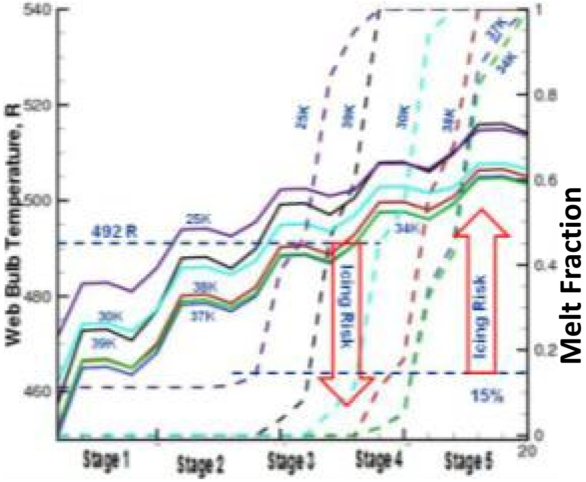


- Computational Research: Application of modern numerical simulation codes to the investigation, understanding, and ultimately, the solutions to avoid engine icing.

- Engine Testing: Propulsion System Laboratory (PSL) Direct connect full scale gas turbine engine ice ingestion tests at altitude conditions, with water spray bars to create ice crystals.







TTT: High Efficiency Centrifugal Compressor (HECC)

PROBLEM

Advancing the state-of-the-art of turboshaft engines requires highly loaded aft compressor stages (low exit corrected flows/small size). Maintaining efficiency and stability margins can be achieved with well designed centrifugal compressor stages, but limited open geometry and data sets exist to benchmark design and analysis tools against.

OBJECTIVES

Design, fabricate, test, and analyze an advanced open-geometry, highly loaded and efficient centrifugal compressor rig under NRA. Acquire benchmark data & document key aerodynamic challenges identified during testing

ACCOMPLISHMENTS

Final report and briefing documenting the design approach, geometry, test results, pre and post test analysis, and CFD-based RCA of HECC performance shortfall delivered and published.

Benchmark datasets obtained using probe based steady state instrumentation for all stations throughout the machine will be used to provide insight into the identification and resolution of aerodynamic challenges causing the performance shortfalls.

Documented advancement of UTRC and NASA CFD tools

Acquired stall inception data & initiated HECC stability analysis

SIGNIFICANCE

The high resolution steady & unsteady data support assessment
of 3-D design approach & constitute a rotorcraft-engine-relevant dataset for advanced centrifugal compressors

Advanced UTRC/industry design/analysis tools capability

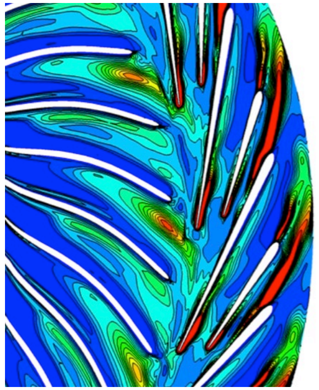
Future Plans

Conduct a vaneless diffuser test to assist in determining impeller performance, and redesign and test a second diffuser vane pack to recover original design intent efficiencies and stability margins

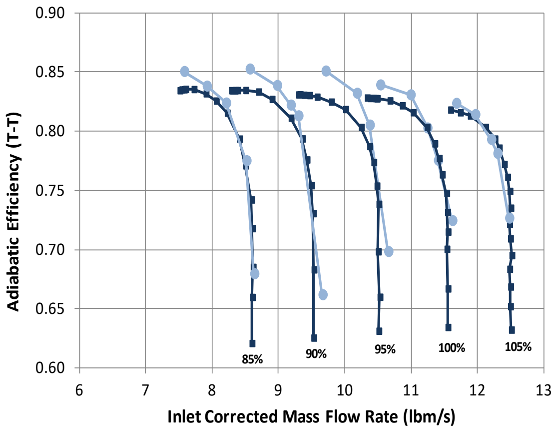
Begin groundwork for an Axial-Centrifugal design and test effort that incorporates highly loaded compact centrifugal compressors and addresses issues with matching axial and centrifugal stages

Partners

UTRC cost-share NRA partner (2/3 NASA, 1/3 UTRC)
VAATE community (ARL, AATD, NAVAIR, AFRL) supported design reviews & AFRL supported impeller vibrometry



Contours of computed TKE from URANS simulation, highlighting impeller/diffuser mismatch



Comparison of adiabatic efficiency from experiment and post-test URANS CFD

Multi-Fidelity Multi-Disciplinary Optimization of Turbomachinery

NASA is extending their in-house turbomachinery design capabilities using advanced computational tools integrated with the python based OpenMDAO optimization framework

Multi-objective Constraint-capable Optimization Drivers

- SimpleGADriver (Gradient free)
- SLSQP - Sequential Least SQuares Programming (Gradient based)

Meanline Codes

- TC_Des, TT_des, Py-c-Des
- NASA OTAC (NPSS foundation)

Axisymmetric Codes

- T-Axi

Turbomachinery Blade Generator

- T-Blade3
- ESP

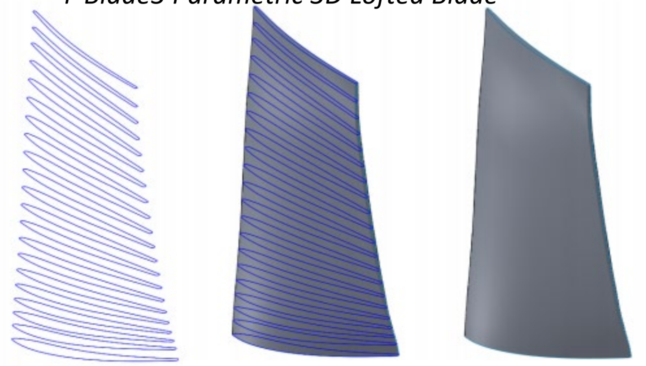
CFD Solvers

- MISES
- APNASA (Deploying parallel compute capabilities)
- FUN3D (Planned development for turbomachinery in FY23)
- FINE/Turbo by Cadence

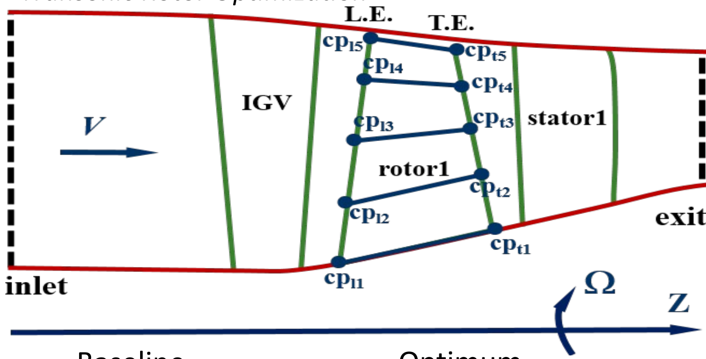
Structural Solvers

- Ansys
- NASTRAN
- TACS - Toolkit for the Analysis of Composite Structures

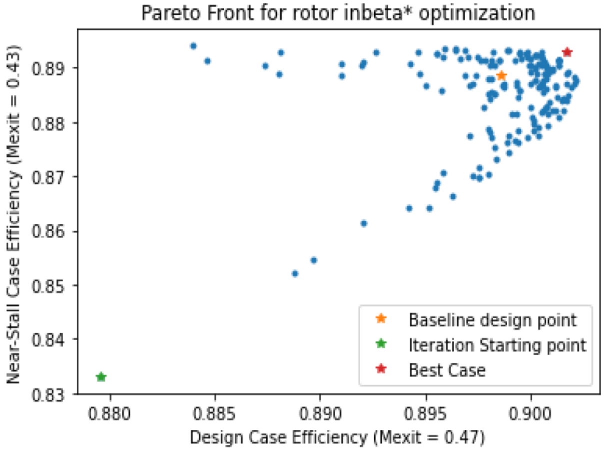
T-Blade3 Parametric 3D Lofted Blade

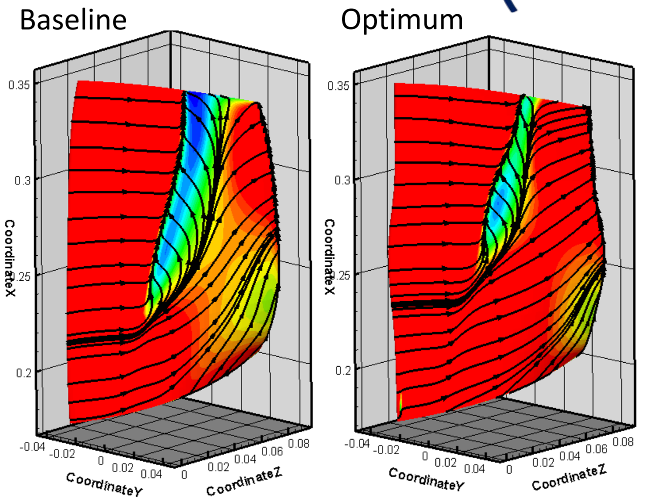


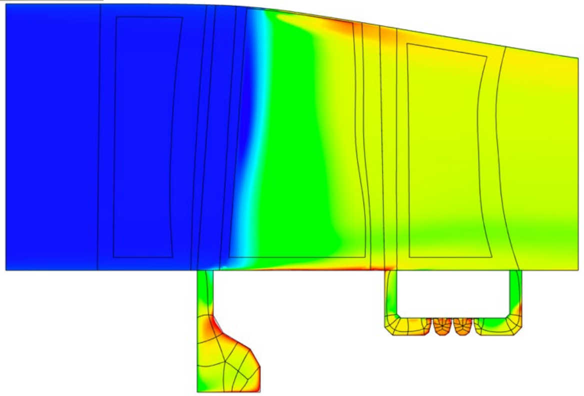
Transonic Rotor Optimization

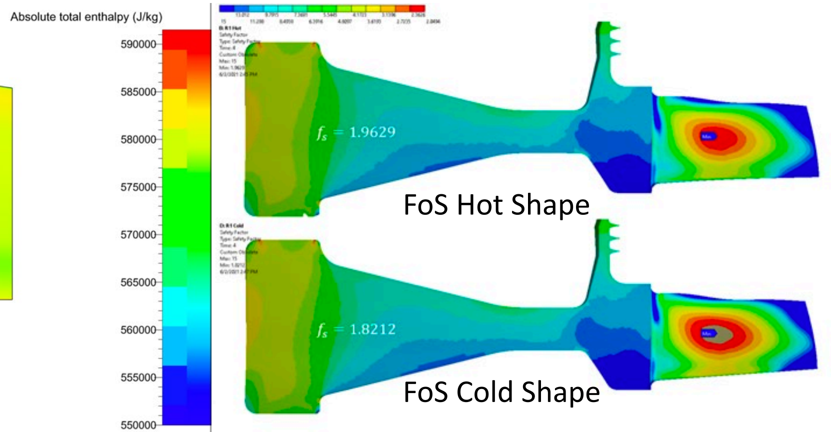


Machined Stator 1 for Axial SCO2 Compressor







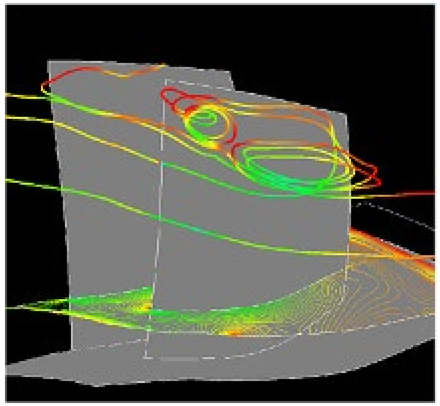


Turbomachinery Codes - APNASA

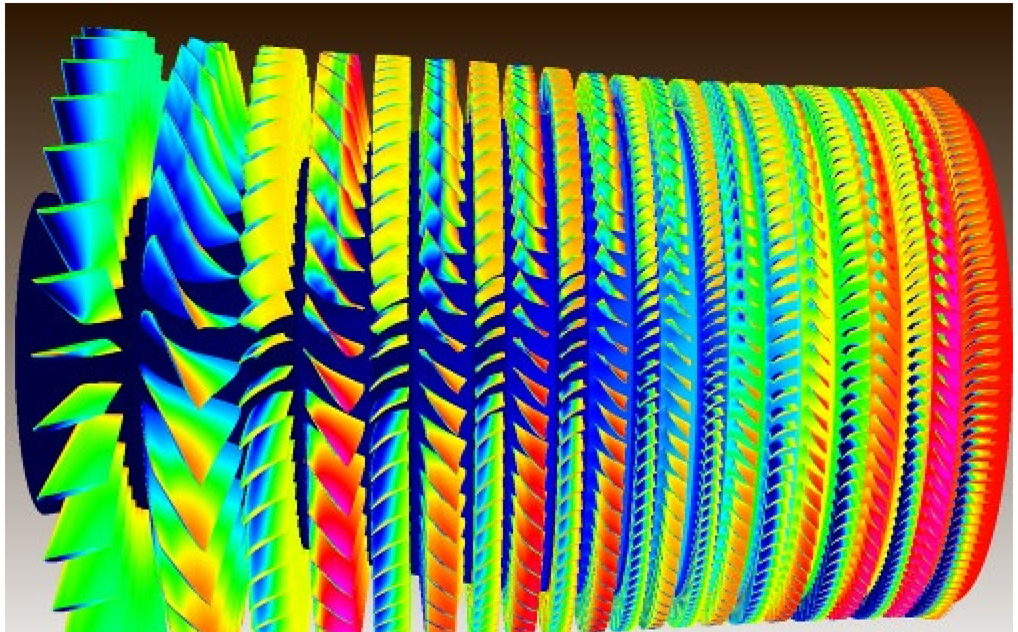
Multi-stage compressor CFD code. Tip clearance and circumferential groove casing treatments can be modeled.

Features:

- 4 Stage Runge-Kutta Explicit Navier-Stokes Solver
- Local Time Steps
- Implicit Residual Smoothing
- Implicit k-ε Turbulence Model
- Models Multi-Stage Effects by Calculating Deterministic Stresses with Generalized Closure
- Domain Decomposition in Axial Direction
- Cooling and Leakages handled by Source Terms and Endwall Model
- Real Gas (Linear Gamma) Model in 3D
- Uses MPI Message Passing Interface
- Two levels of parallelism
- Radial and Tangential Multiblock with I-Grid



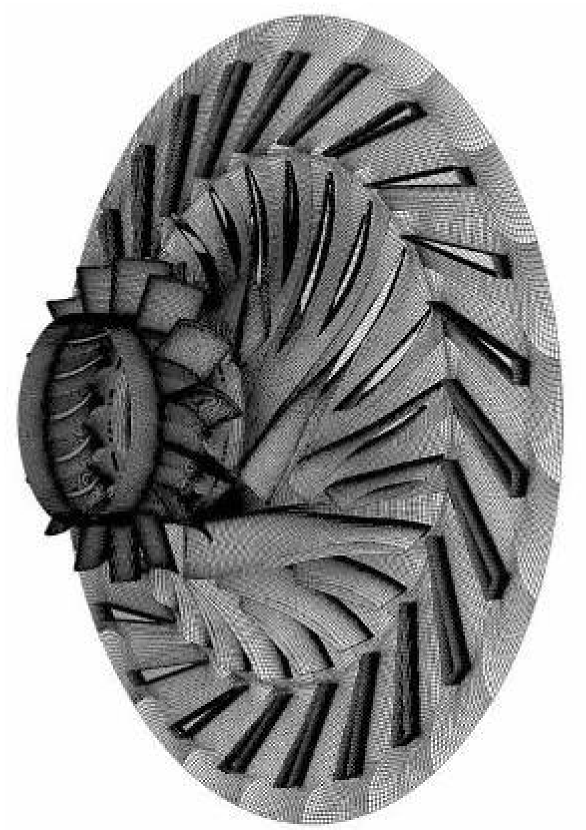
Flow Separation



21 Blade Row HPC

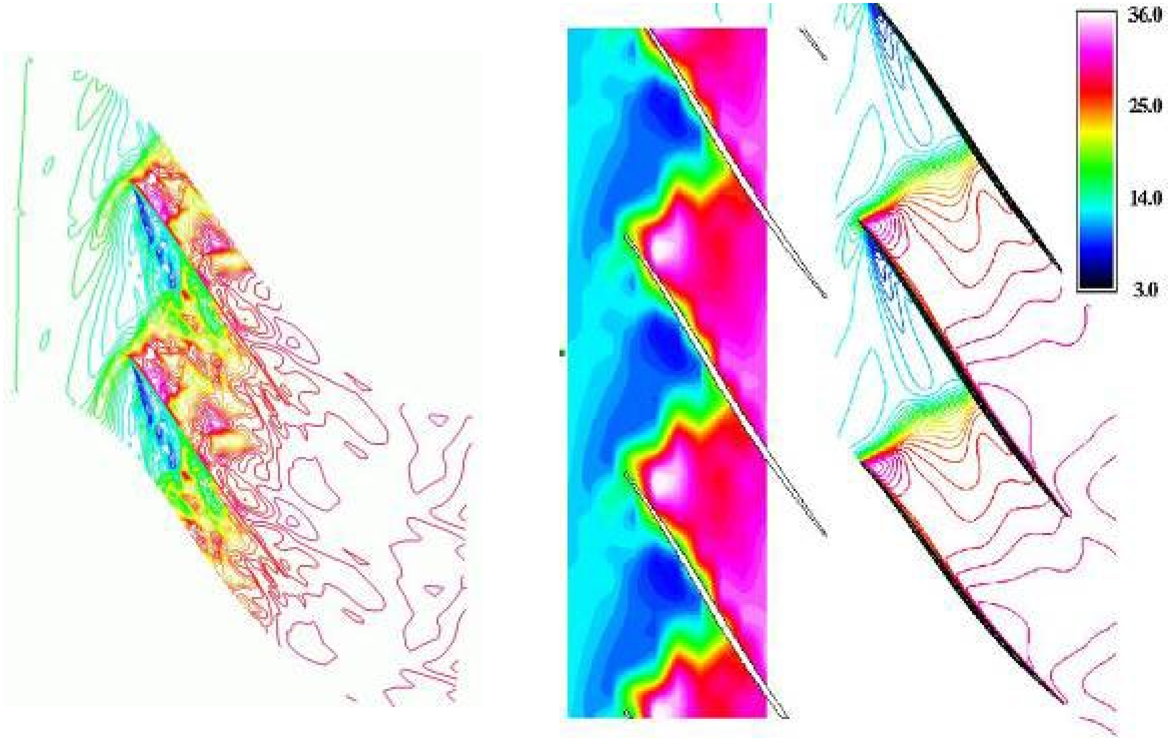
Turbomachinery Codes – H3D

Pressure-based Navier-Stokes analysis code for all types of turbomachinery. Pressure based solver. Two-equation k-epsilon turbulence model RANS, Unsteady Reynolds Averaged Navier-Stokes (RANS) , and Large Eddy Simulation (LES) modes.



Centrifugal Pump with Wedge Diffuser

Axial Compressor



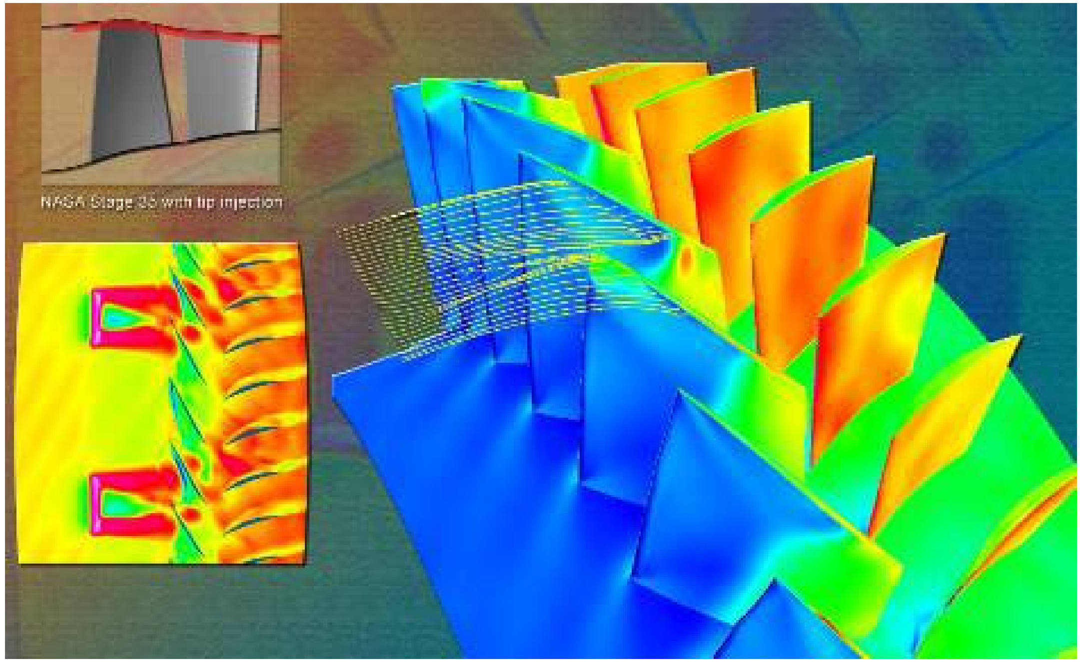
LES

Test Data

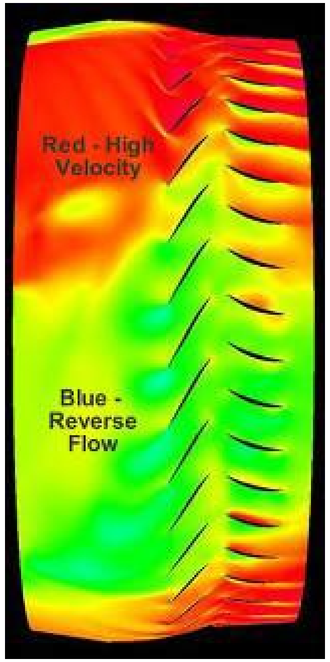
RANS

Turbomachinery Codes - Turbo

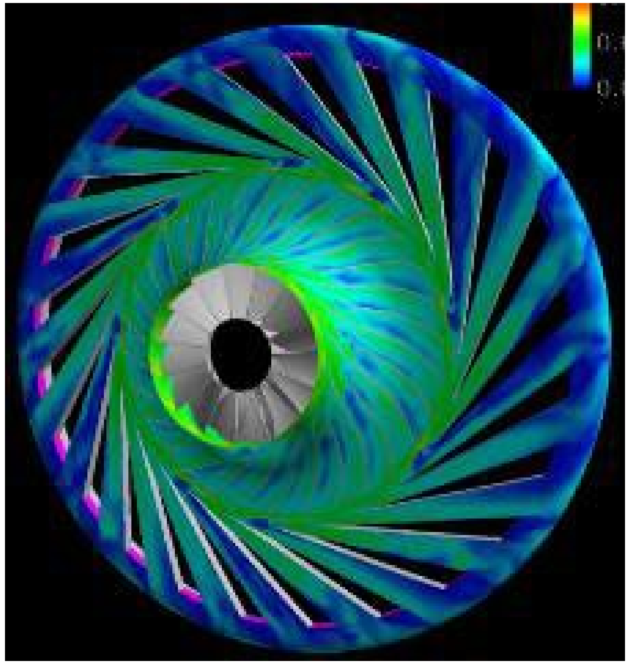
Unsteady Navier-Stokes flow code for multi-stage axial and centrifugal turbomachinery.



Axial Compressor with discrete flow injection to mitigate rotating stall



Full Annulus Simulation Of Axial Compressor with Rotating Stall Cell

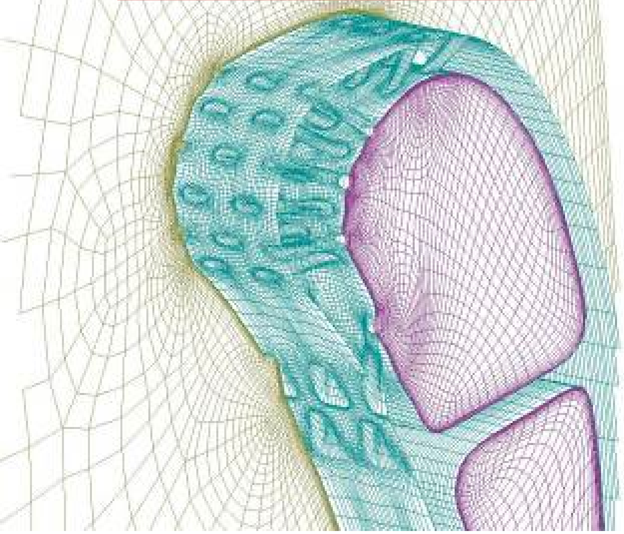


Full Annulus Simulation of Centrifugal Compressor & Wedge Diffuser

Turbomachinery Codes - GlennHT

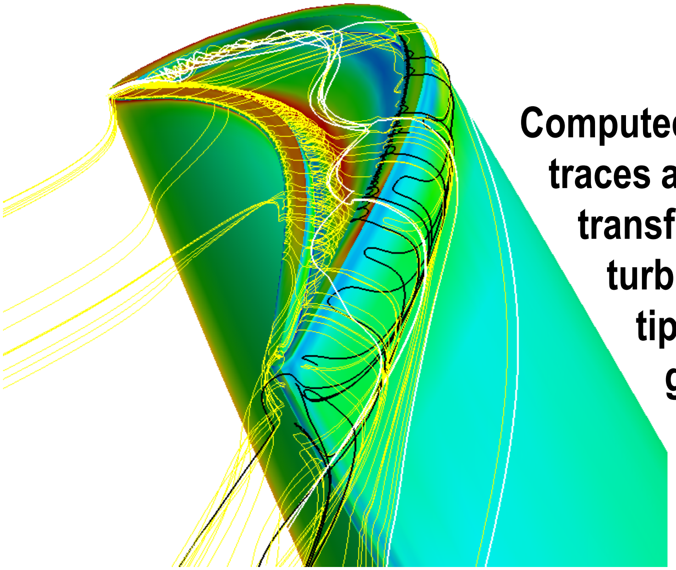
Examples showing detailed predictions of internal and external flow and heat transfer

Details of 3-D Grid



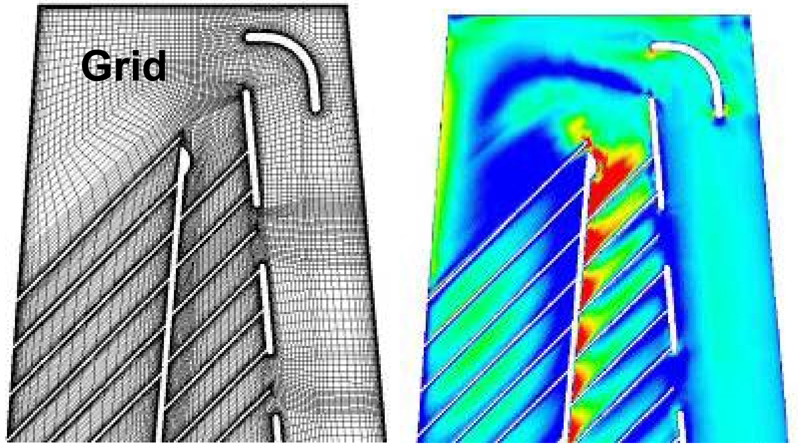
Detailed grid for conjugate film cooling

Tip Gap Modeling



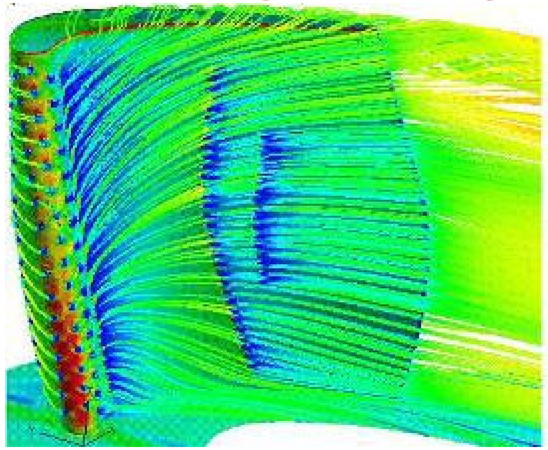
Computed flow traces and heat transfer in a turbine rotor tip clearance gap

Internal Coolant Passage Modeling



Glenn-HT computed heat transfer in internal passages

Film Cooling Modeling



Whole blade film cooling analysis

Turbomachinery Codes – Fun3D

- Developed by NASA Langley and still being actively improved
- Fully unstructured node-based finite volume implementation
  - Second-order in time and space
- Range of turbulence models from SA to full Reynolds Stress models
- Overset and dynamic grids supported
  - Rigid motion
  - 6 DOF
  - Aeroelastic coupling
- Two overset assemblers
  - Yoga – LaRC developed
  - Suggar++ - 3rd party developed but license available
- Adjoint optimization
- Additional boundary conditions and coding being developed for turbomachinery-specific flows [POC: Mike Borghi]