Firebolt - A High Fidelity Airframe/Propulsion Integration Tool

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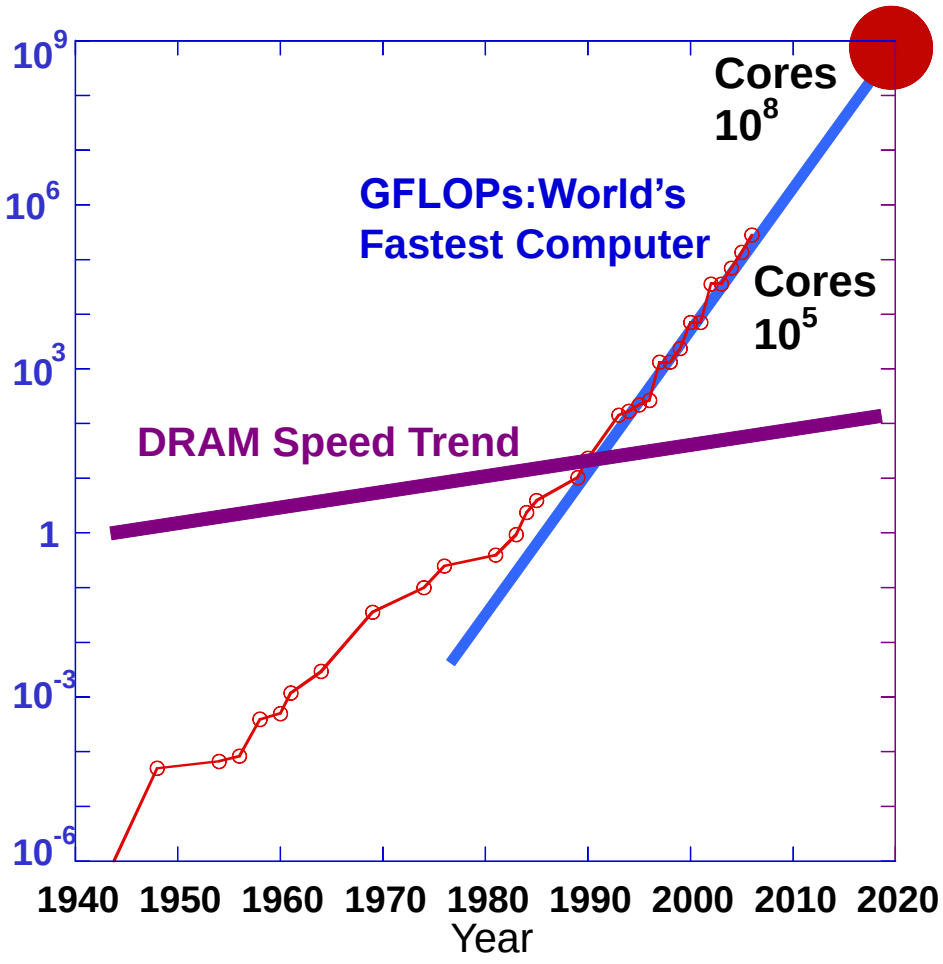
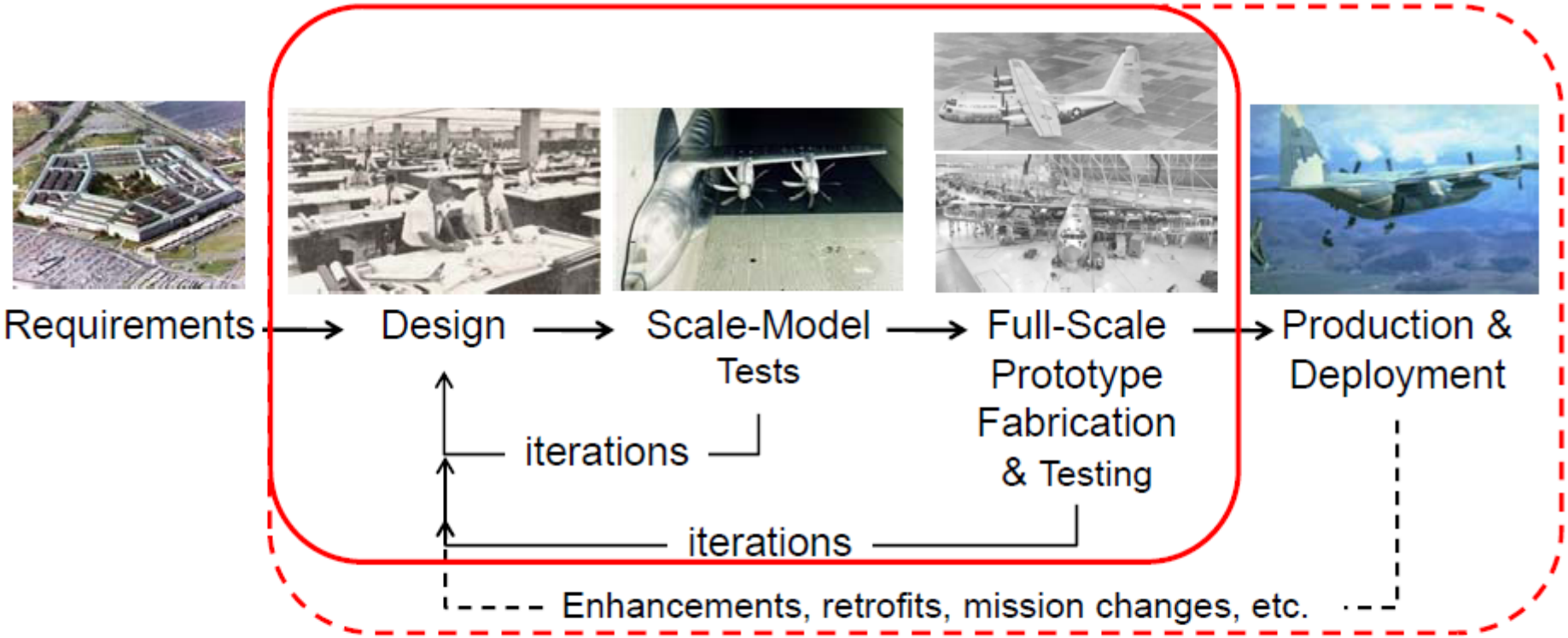
DOD HPC MODERNIZATION PROGRAM

CREATE Program Overview

Computational Performance Trends



Traditional "Design-Test-Build-Fix" Acquisition



- Requires many lengthy and expensive design/build/test/fix iterations
- Process converges slowly, if at all
- Design flaws discovered late in process (Long time to market)

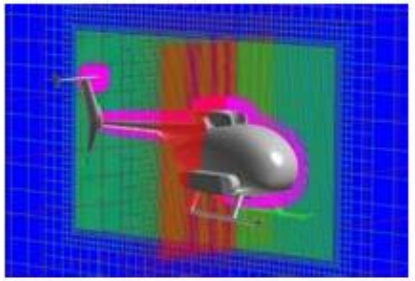
This is not a sustainable paradigm in today's global economic and political environment

CREATE Project Genesis

CREATE-AV

CREATE-SH

CREATE-RF

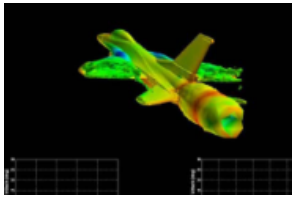


CREATE-MG

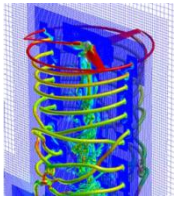
- In 2007, DoD HPCMO proposed an initiative to develop and deploy Computationally Based Engineering (CBE) tools that exploit next generation HPC computer resources to improve DoD acquisition processes for aircraft, ships, and RF antennas.
- CREATE is a sustained 12 year development program to develop production quality design and analysis software that is adaptable and maintainable.

CREATE-AV Software Products

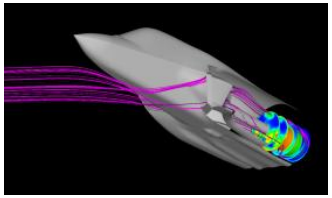
- Fixed Wing A/C (Kestrel)
  - Hosted at Eglin AFB



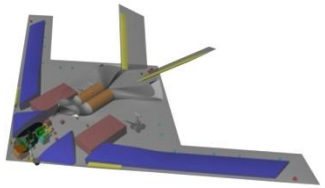
- Rotary Wing (Helios)
  - Hosted at ARMDEC (AMES)



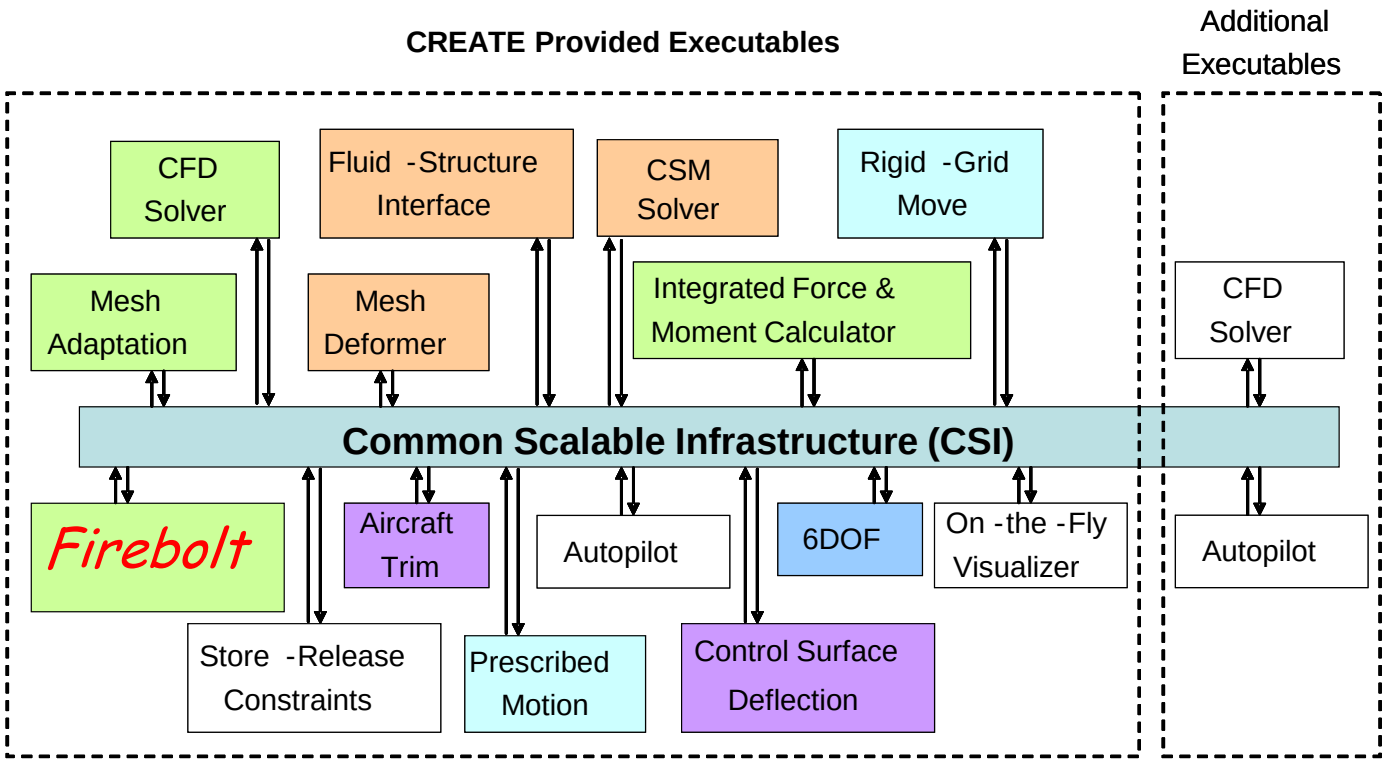
- Airframe/Propulsion Integration (*Firebolt*)
  - Hosted at AEDC



- Conceptual Design (DaVinci)
  - Hosted at WPAFB

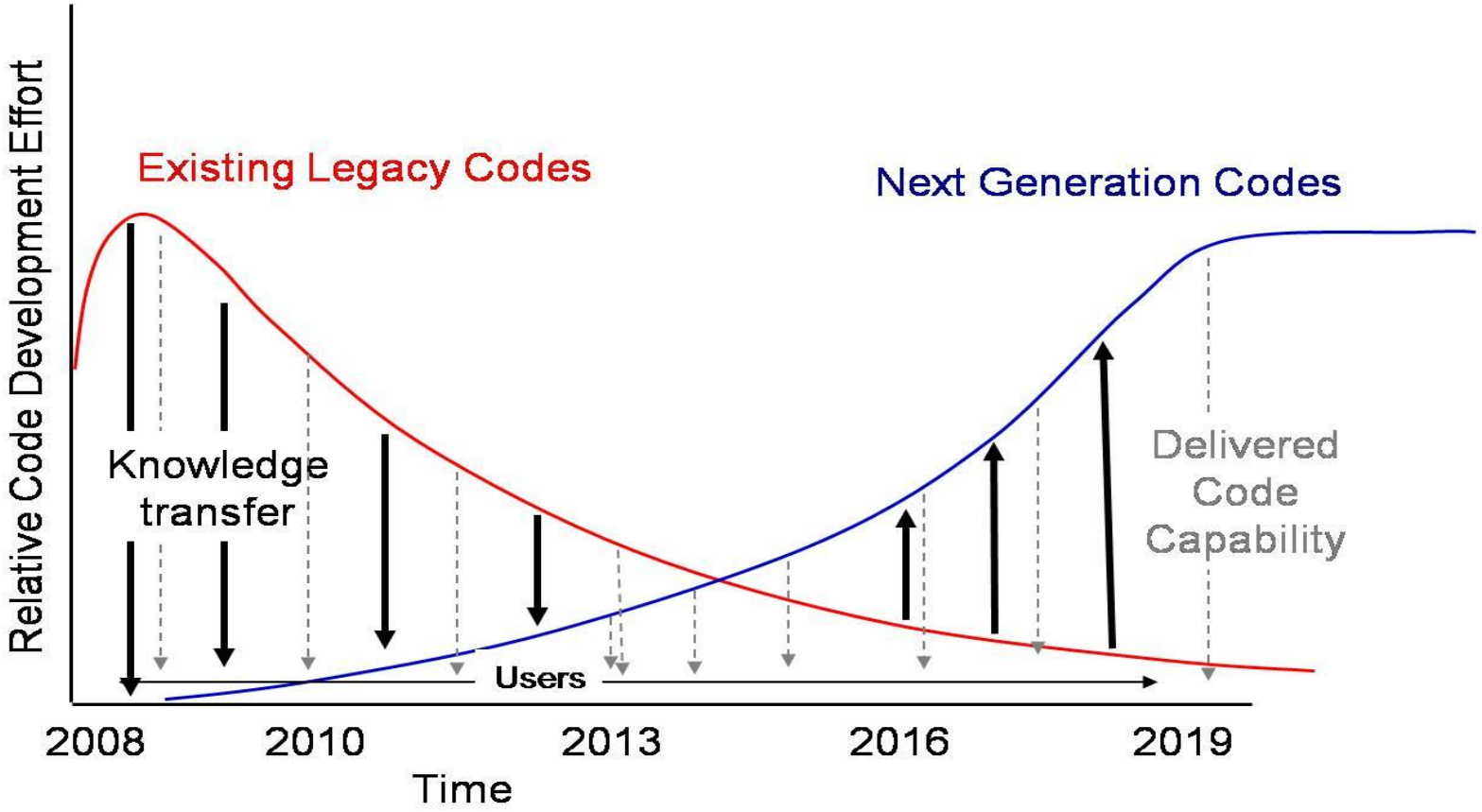


Kestrel Fixed Wing Virtual Aircraft Description



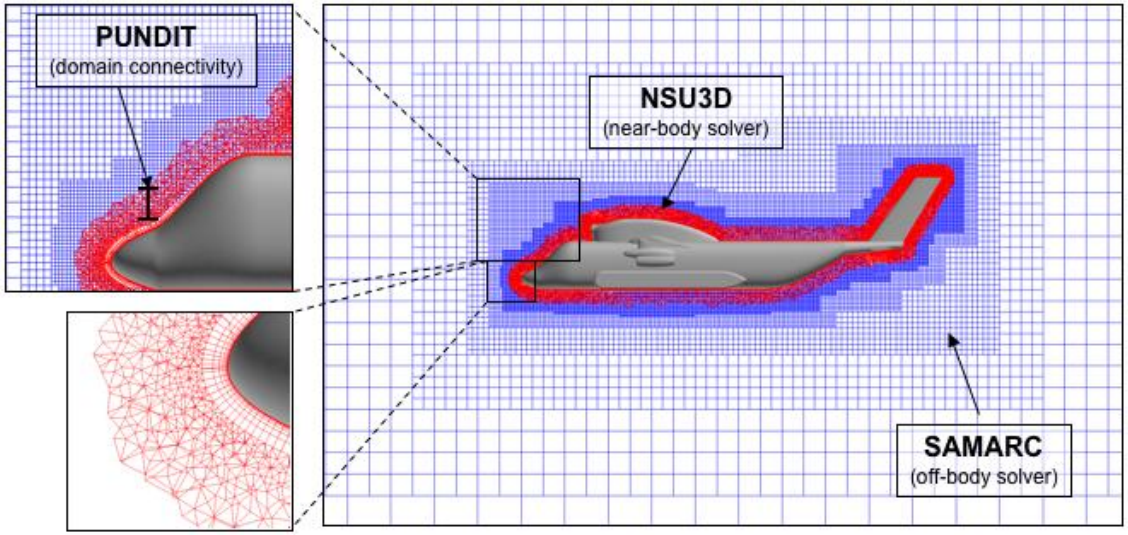
- Cross-over between aerodynamics, stability and control, structures, propulsion, store separation
- Improved performance on parallel architectures with from 10^4 to 10^6 cores (giga-flop to peta-flop)
- Event driven architecture
- CSI Infrastructure and Executive in Python, KUI Graphical User Interface in wxPython
- Components programmed in F90/95/03 and C
- All APIs and data structures for components consistent across CREATE-AV products

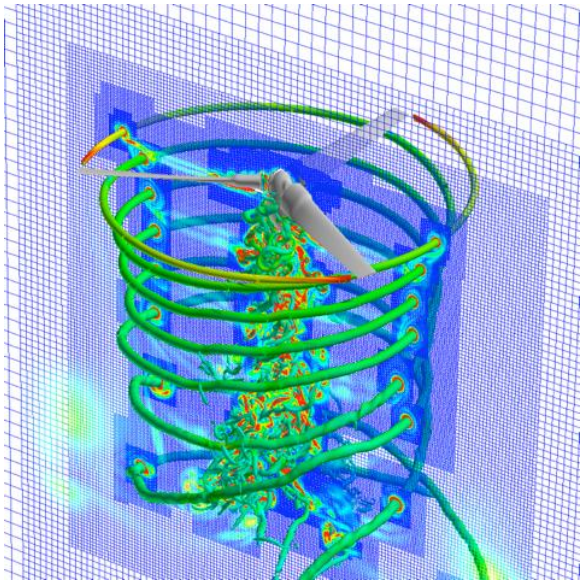
Provide CBE Tools for Both the Near-Term and the Long-Term



CREATE-AV CFD Code Philosophy

- **Control and couple solvers with an agile infrastructure**
  - Overset communication
  - Common heavy data (pass pointers)
- **Use the best solver or solvers for the problem**
  - Near body solvers (structured, unstructured, strand)
  - Off body solvers (cartesian)
- **Use common modules**
  - Gas properties
  - Chemical source terms
  - Grid deformation
  - AMR
- **Use common procedures**
  - Turbulence models
  - Low Mach number preconditioning





DOD HPC MODERNIZATION PROGRAM

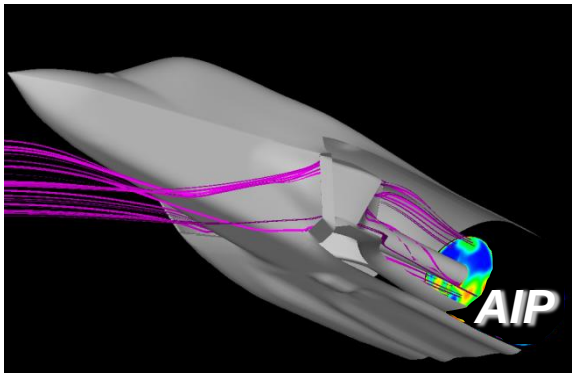
Firebolt Module

Firebolt Requirements

- Software product must be able to integrate high fidelity transient/dynamic representations of the aircraft forebody-inlet-compression systems
- Turbomachinery component must be able to compute full annulus solutions for multiple blade row fan and compression systems for complex inlet flow fields
- Software product should be multiphysics including combustion chemistry and CSM capability
- Software product must be configured for multiple processors beyond the current parallelization techniques to be able to compute solutions in hours or days (current turbomachinery CFD calculation take weeks to months)
- Software product must be validated with experimental results
- Software product must be easy to use with examples that provide guidance to an inexperienced user for use in other specific applications

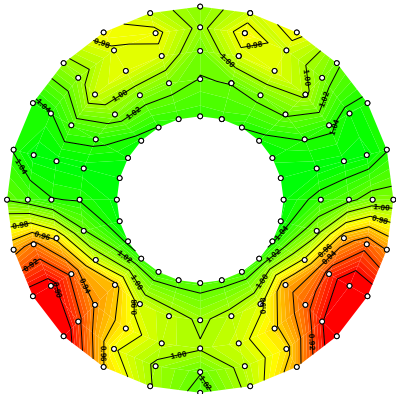
Current Airframe-Propulsion Integration Process

Inlet Design Using CFD and Subscale Duct Tests



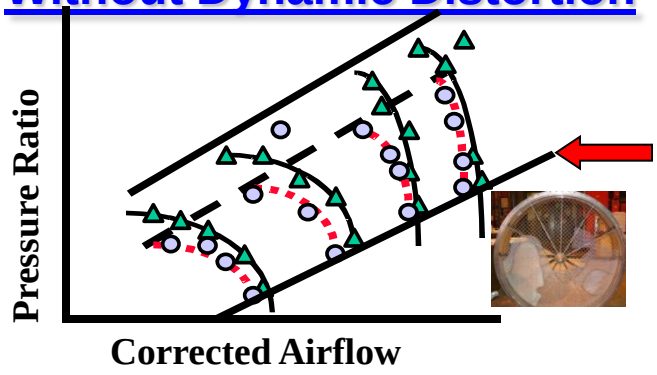
Aircraft Subscale Wind Tunnel Tests

AIP Distortion Patterns



Full Scale Distortion Screen Engine Tests

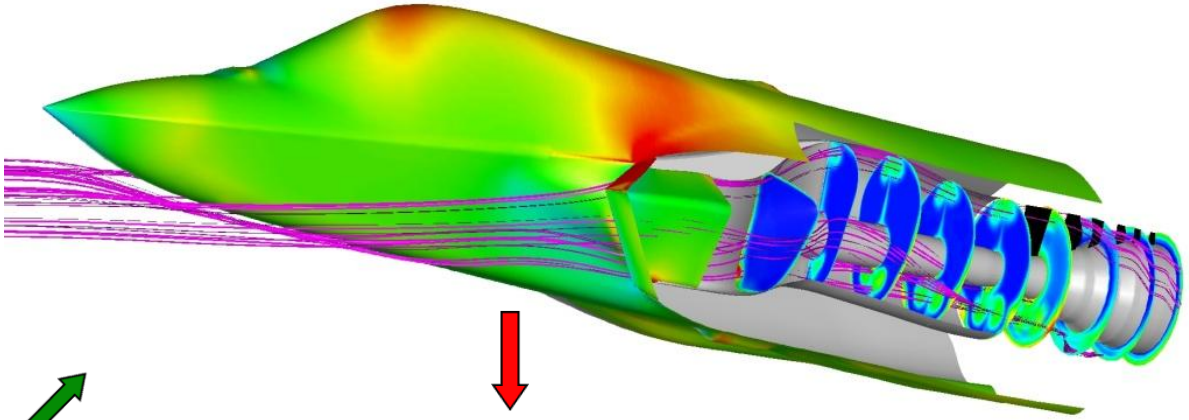
Performance and Operability Analysis Without Dynamic Distortion



Flight Test Verification

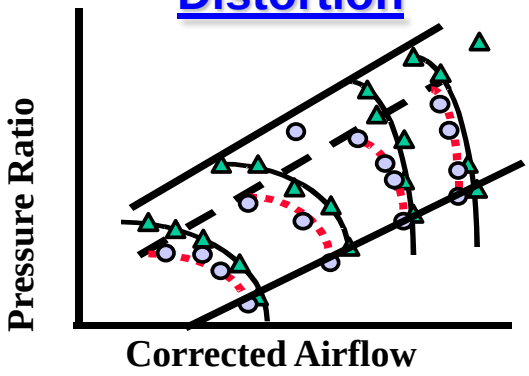
Augmented Airframe-Propulsion Integration Process

Full Scale Aircraft/Fan CFD/CSM Validated With Wind Tunnel and Engine Test Data

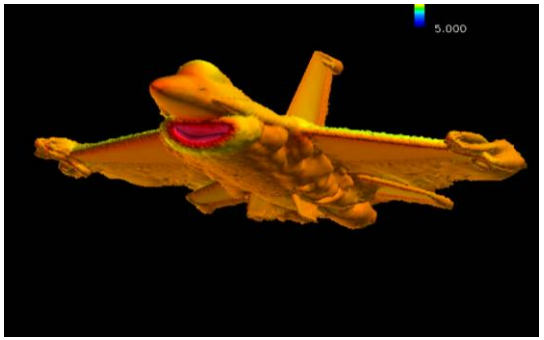


Flight Test Verification

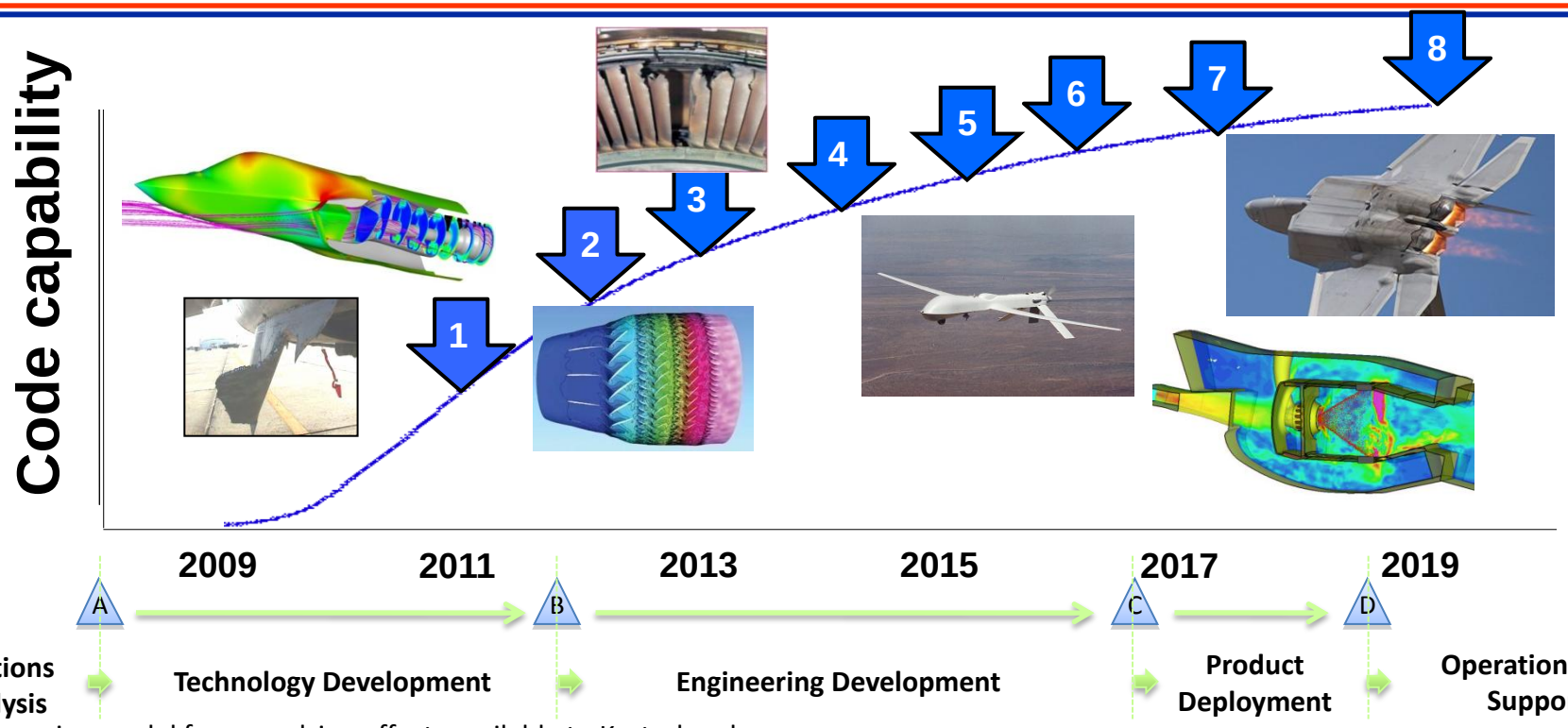
Performance and Operability Analysis With Dynamic Distortion



Transient API Analysis



Firebolt Annual Release Schedule



1) Engineering model for propulsion effects available to Kestrel and Helios.
2) Full vehicle engine inlet and compression system performance prediction structured grid capability.
3) Full vehicle engine inlet and compression system performance prediction unstructured grid capability.
4) Engine compression system (aero-elastic) blade life assessment capability.
5) Enhanced vehicle aerodynamic performance through accurate representation of nozzle geometry shape changes.
6) - High altitude UAV engine cooling and performance analysis capability.
   - Engine-bay cooling analysis capability.
7) Significantly improved physical accuracy of engine combustion prediction.
8) Propulsion module for Kestrel and Helios – Rotating machinery simulation (single passage, full annulus, FSI, Inlet/forebody coupling, maneuvering aircraft); Nozzle simulation (variable area capability, multispecies); Engineering model of combustion w/ architecture for future gas-phase chemistry modeling)

DOD HPC MODERNIZATION PROGRAM

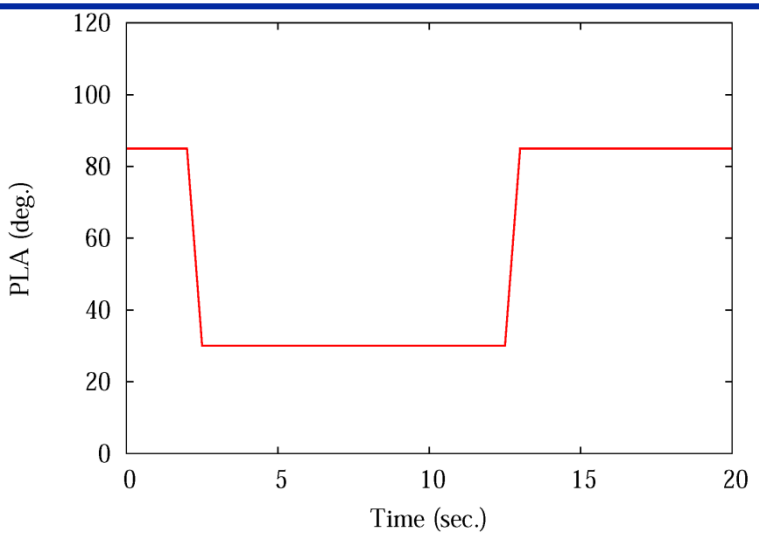
Firebolt v1

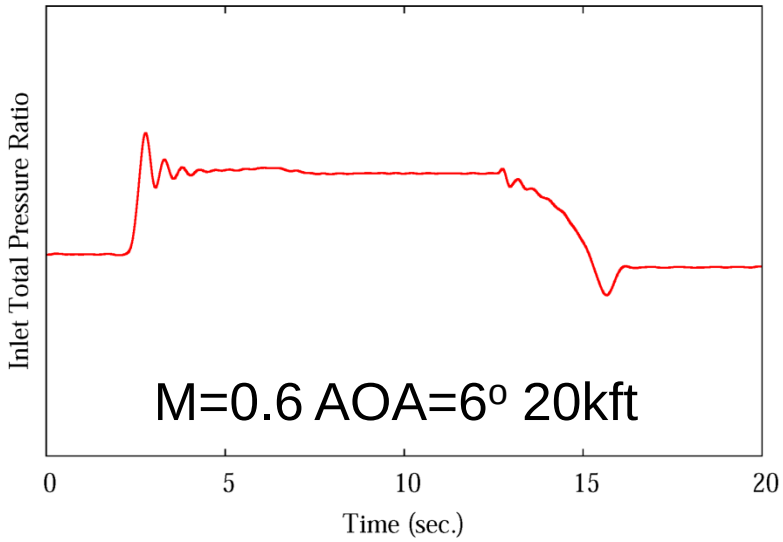
0D Engine Model Coupling

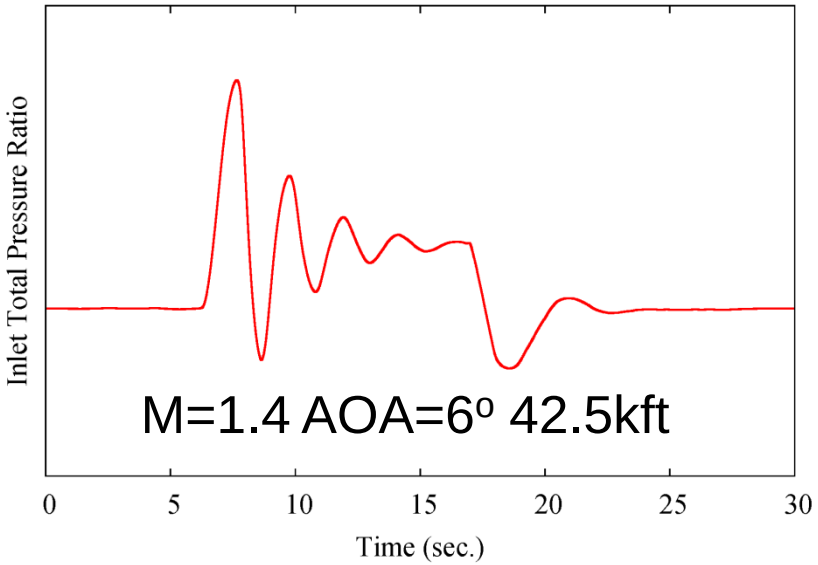
- Developed a common methodology for creating engine modules from existing 0D engine models
  - ATEST (AEDC Developed)
  - NPSS (NASA Developed)
  - OEM customer decks
  - Flat Engine (General tabular engine input for steady state or transient)
- Created coupling interface for CREATE-AV CFD codes
  - Engine transient time step advancement controlled by the infrastructure
  - CFD code (kAVUS) coupling through inflow and outflow boundary conditions
  - 0D interface data clipping and filtering
- User interface through KUI and HUI
  - Setup engine model inputs
  - Preflight engine models
  - Post process engine model output

Kestrel/*Firebolt* Throttle Transient

- F-16 Unstructured Grid (17M elements)
- F110-100 Transient ATEST Engine Model
- M=0.6 AOA=6º 20kft
- Throttle Decel/Accel

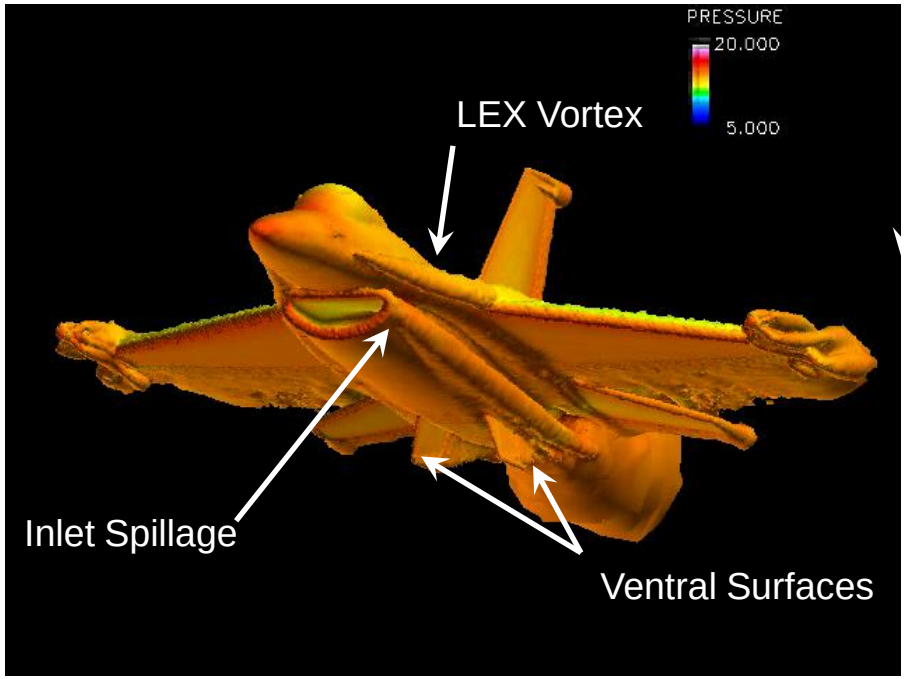






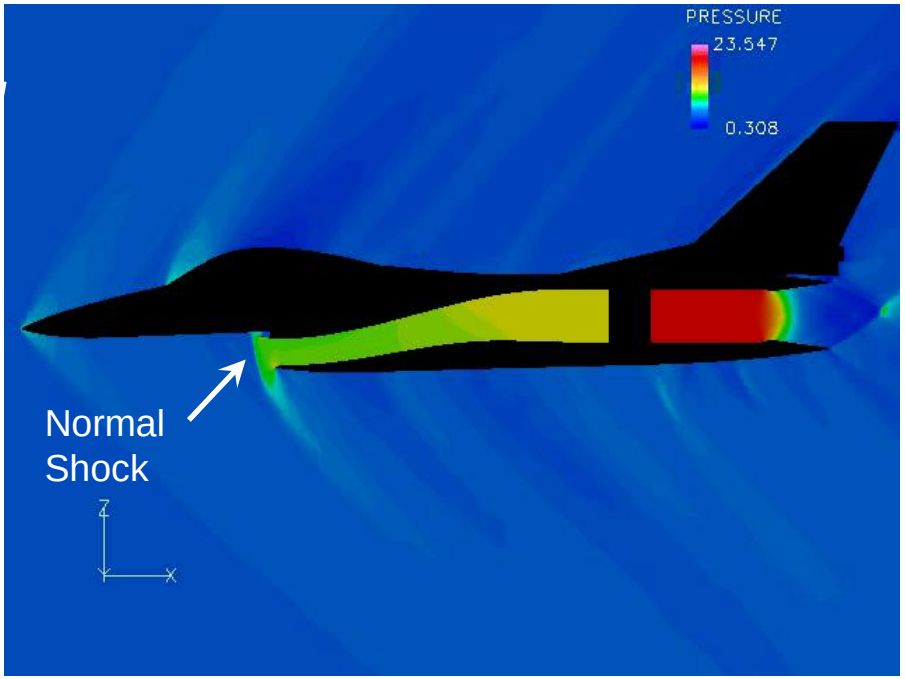
Kestrel/*Firebolt* Throttle Transient

M=0.6 AOA=6º 20kft



Vorticity Isosurface Colored by Mach

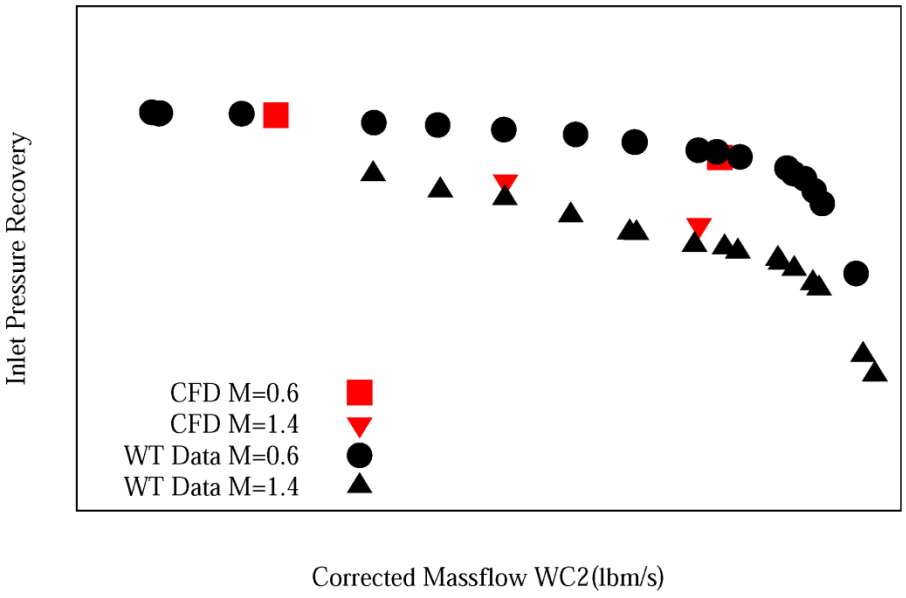
M=1.4 AOA=6º 42.5kft

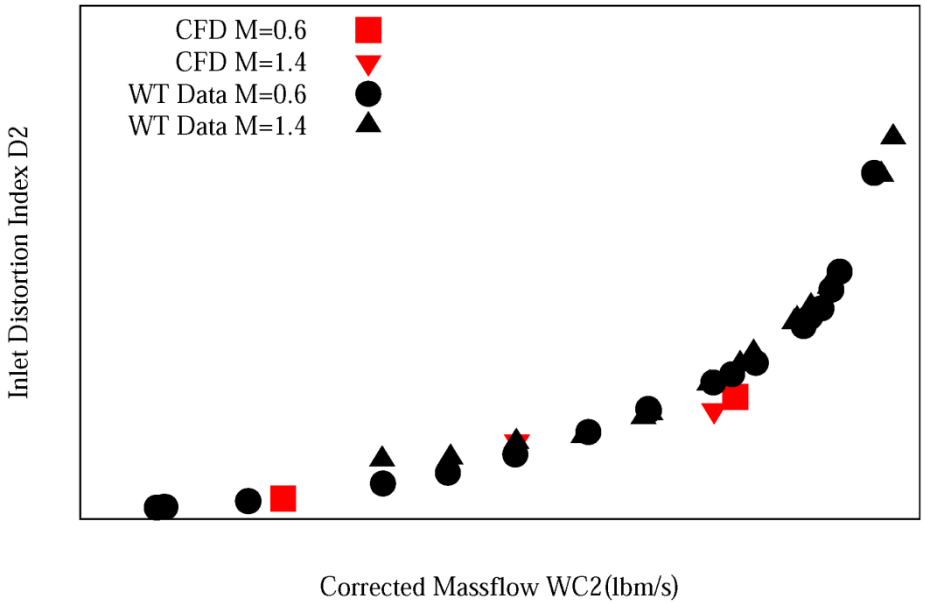


Centerline Pressure Distribution

F-16/F110-100 PLA Decel/Accel

Kestrel/*Firebolt* Throttle Transient





DOD HPC MODERNIZATION PROGRAM

Firebolt v2

Turbomachinery CFD Challenges

- Large computational grids
  - $2x10^6$ points/blade, 20 – 100 blades/row, ~$1x10^9$ points
- Multiple time scales
  - Time for throttle transient (10 sec.)
  - Time for pressure wave to traverse the inlet ($1x10^{-2}$ sec.)
  - Blade revolution time ($1x10^{-3}$ sec.)
  - Blade structural response time ($1x10^{-6}$ sec.)
- Complex flow physics
- Difficult to start solution process
- Stringent accuracy requirements
  - Mass flow, total pressure, and total temperature to within 0.5%
- Multiphysics (CFD/CSM)

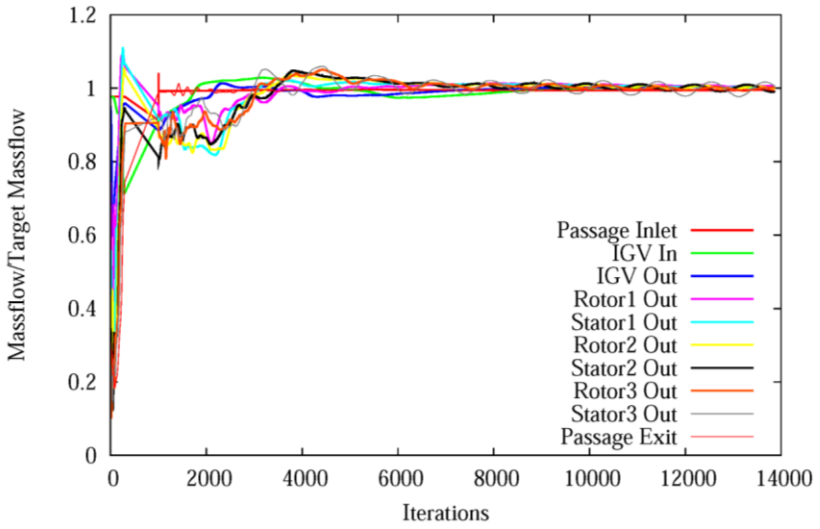
Structured Grid Solver

- Built around modules from OVERFLOW 2.2
- Why OVERFLOW 2.2 ?
  - NASA maintained code with large user and contributor base
  - Contains SOA flux algorithms, implicit solvers, and turbulence models
  - Overset grid capability
  - Moving body capability
  - Perfect gas and multispecies capability
  - Dual parallel capability using MPI and OPENMP
  - Run time grid decomposition for parallel load balancing
- Modifications for rotating machinery
  - Added additional bc's for single passage simulations
  - Added general rotating reference plane capability
  - Developed methodology for starting multistage simulations
  - Developed mixing plane multistage capability
  - Developed utility codes for assembling full annulus composite grid

CFD Starting Problems

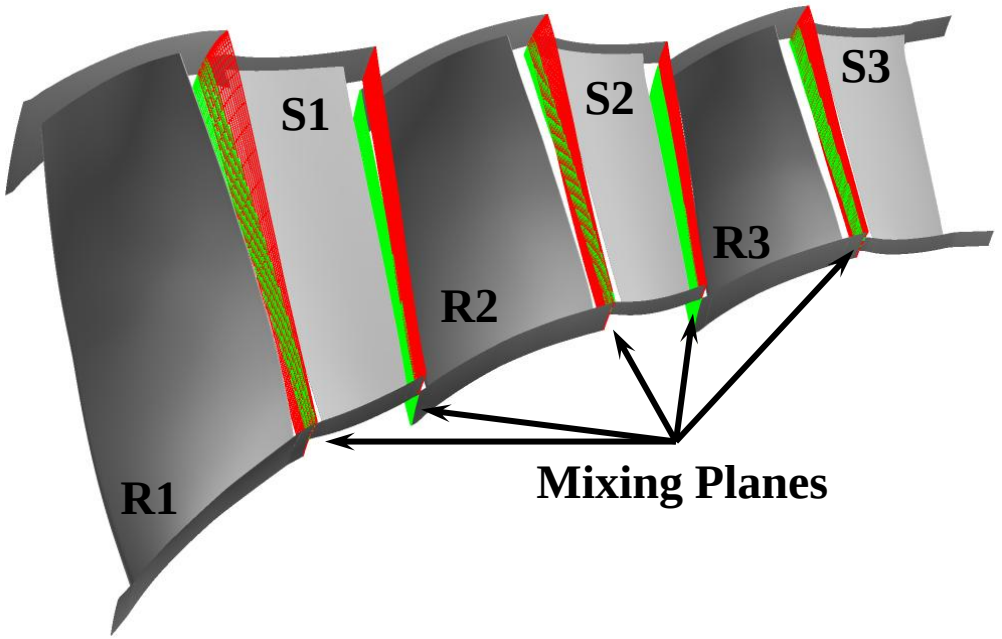
- Difficult to start a multi-stage full annulus solution
  - Need pressure rise through machine to get required mass flow in back stages
  - High specified outflow pressure can cause reverse flow on boundary
  - Must keep solution between stall and choke
- Developed a starting process from uniform flow conditions
  - Ramp up rotational velocity of rotor
  - Use grid sequencing during initial solution transients
  - Ramp up rotational velocity of rotor on coarse grid level
  - Created Mach number limited specified pressure outflow BC
- Can now easily start multi-stage solutions using this procedure

3 Stage Military Fan with an IGV



Mixing Plane Capability

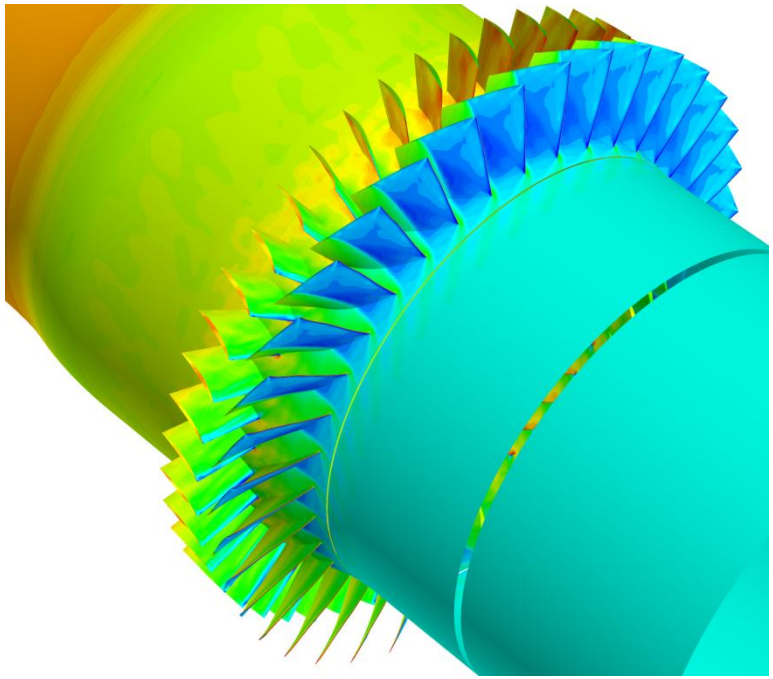
- Mixing plane simulations use a single passage representation
  - Use inflow and outflow boundary conditions for each passage
  - Circumferentially average to remove blade wakes
- Quantities conserved on mixing plane
  - Mass flow
  - Total pressure
  - Total temperature
  - Flow angles



Single Stage V&V Example

NASA Stage 35

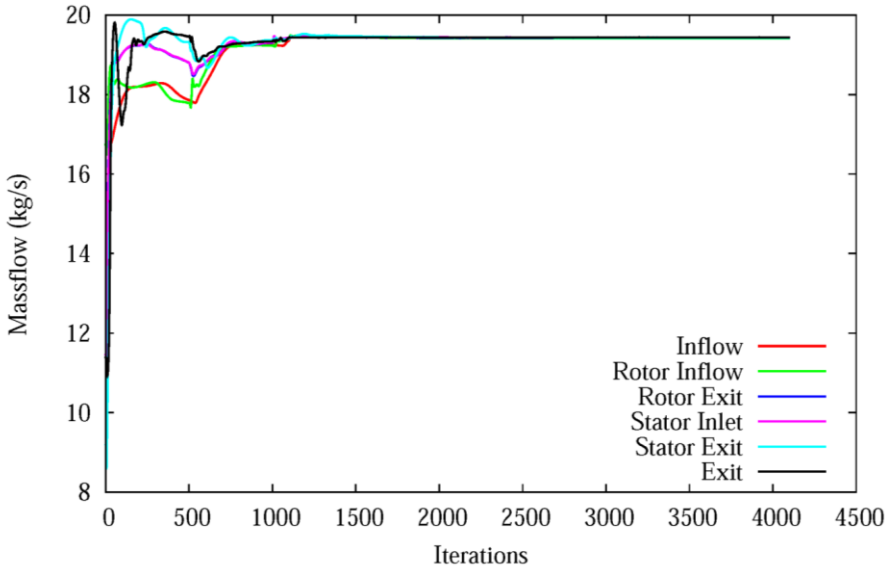
- 36 high aspect ratio fan blades
- 46 stator blades
- 70%, 80%, 90%, and 100% speed lines
- 1.8M points/passage
- Gridded 0.37 mm tip gap (0.65% tip chord)
- Full annulus and mixing plane simulations



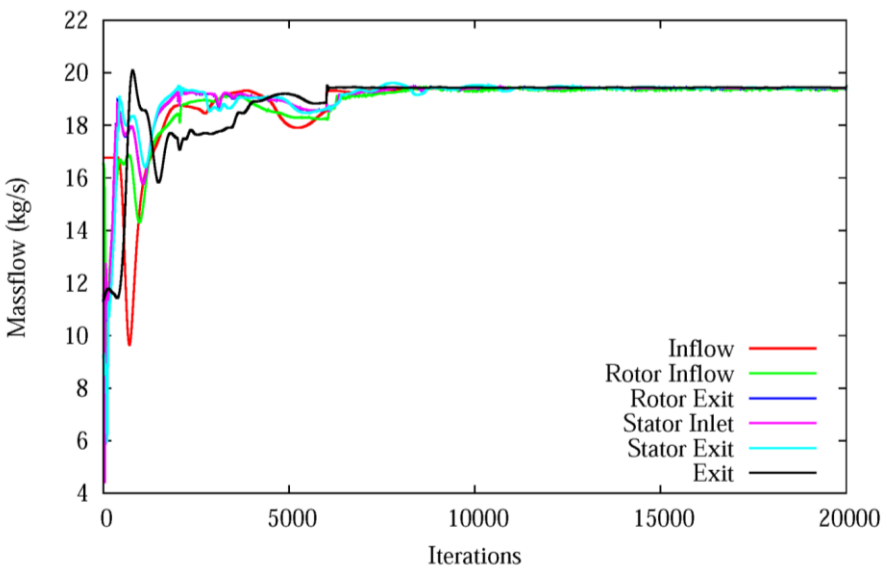
- Reid, L. and Moore, R., “Design and Overall Performance of Four Highly Loaded, High Speed Inlet Stages for an Advanced High-Pressure-Ratio Core Compressor,” NASA-TP-1337, 1978.

Stage 35 Massflow Convergence

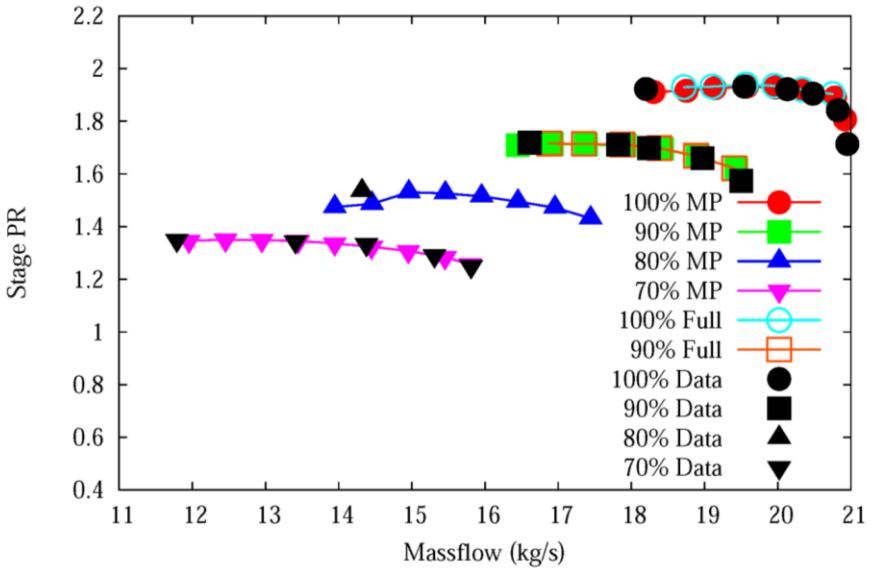
Mixing Plane

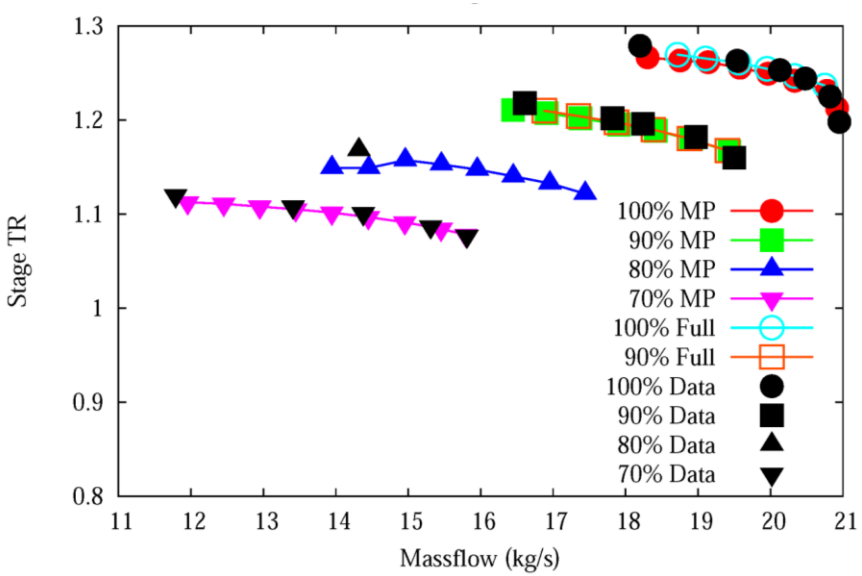


Full Annulus



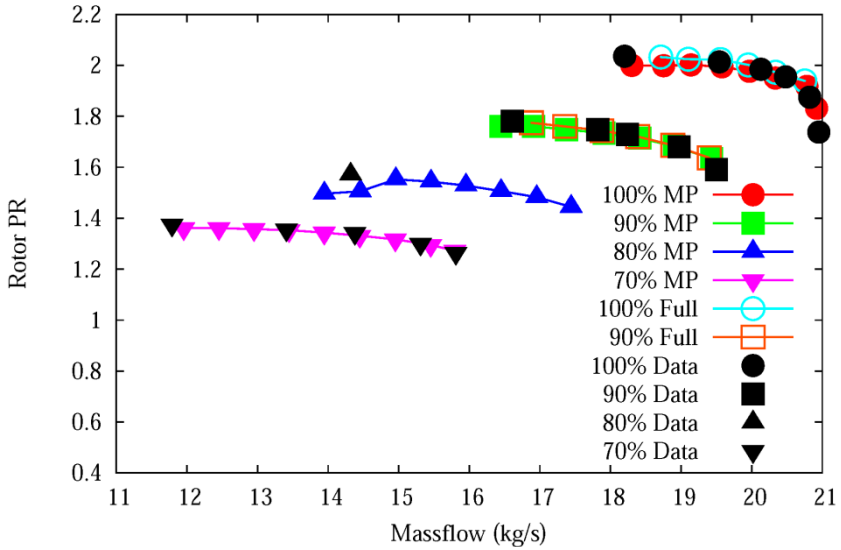
Stage 35 Overall Performance

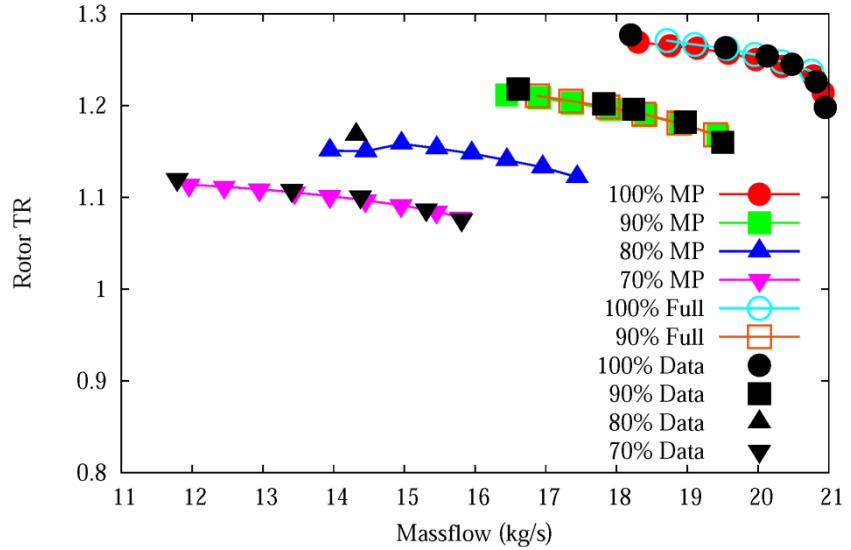


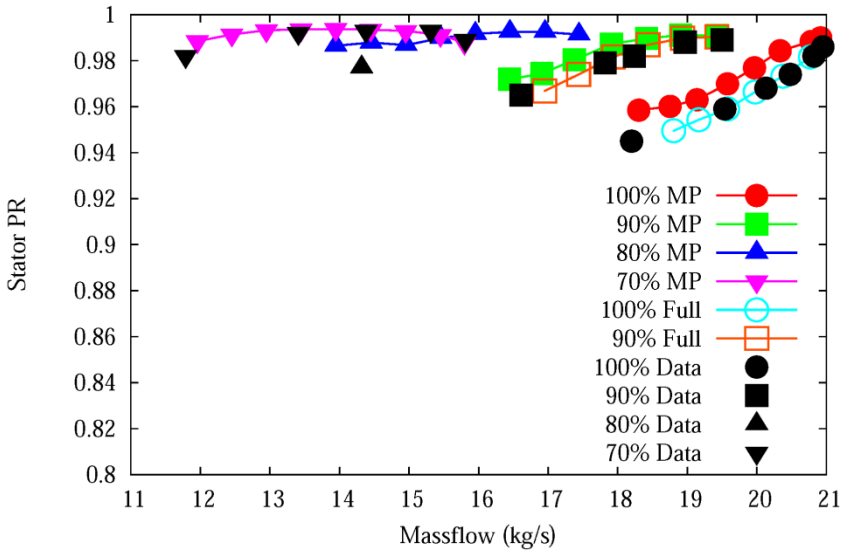


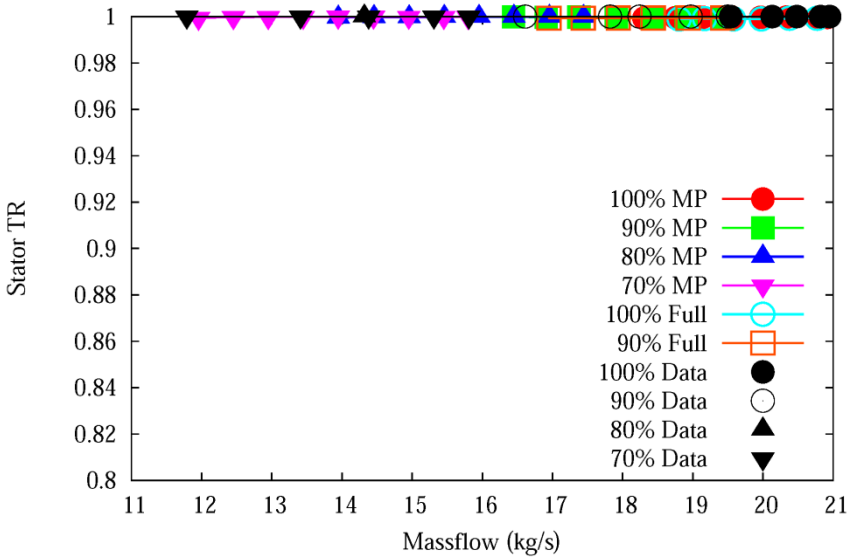
MP = Mixing Plane CFD
Full = Full Annulus CFD

Stage 35 Component Performance

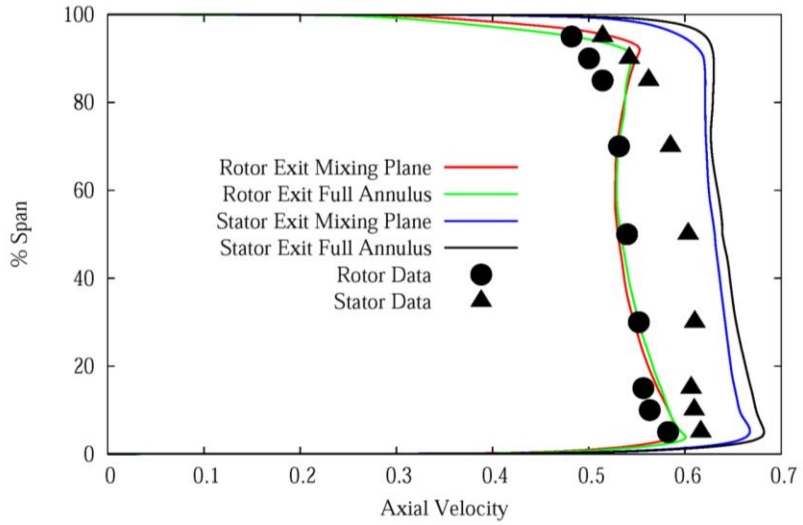


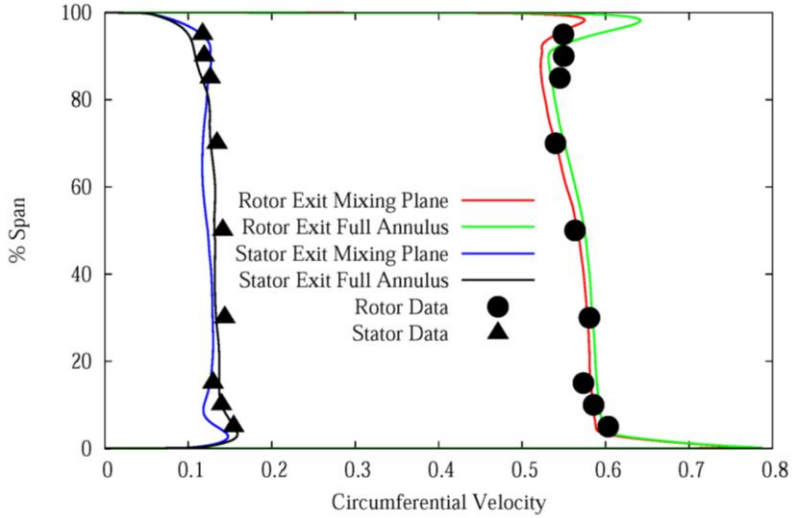


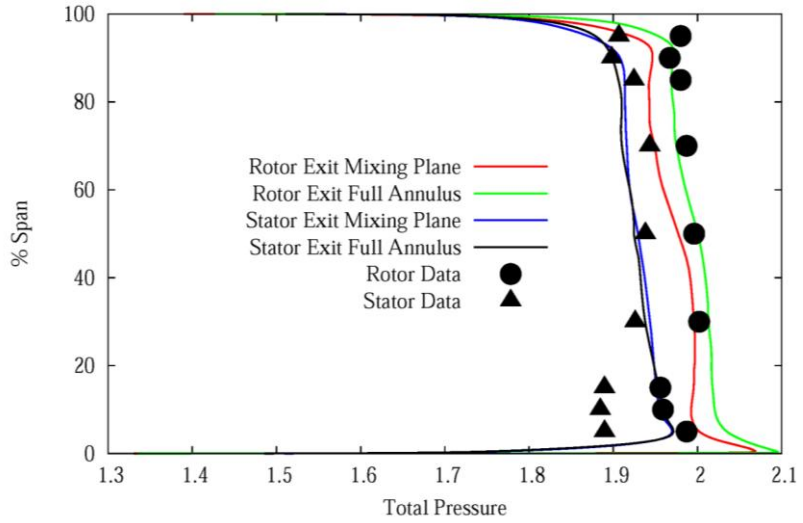


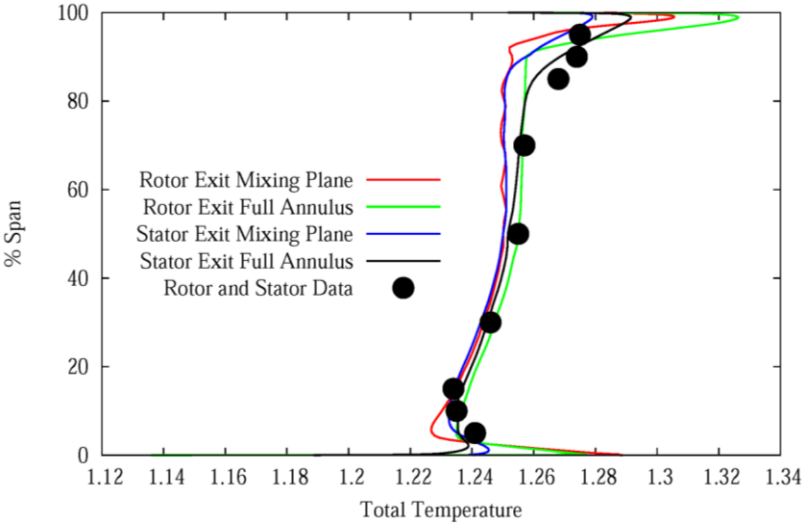


Stage 35 Circumferential Averages
100% Speed 20.0 kg/s

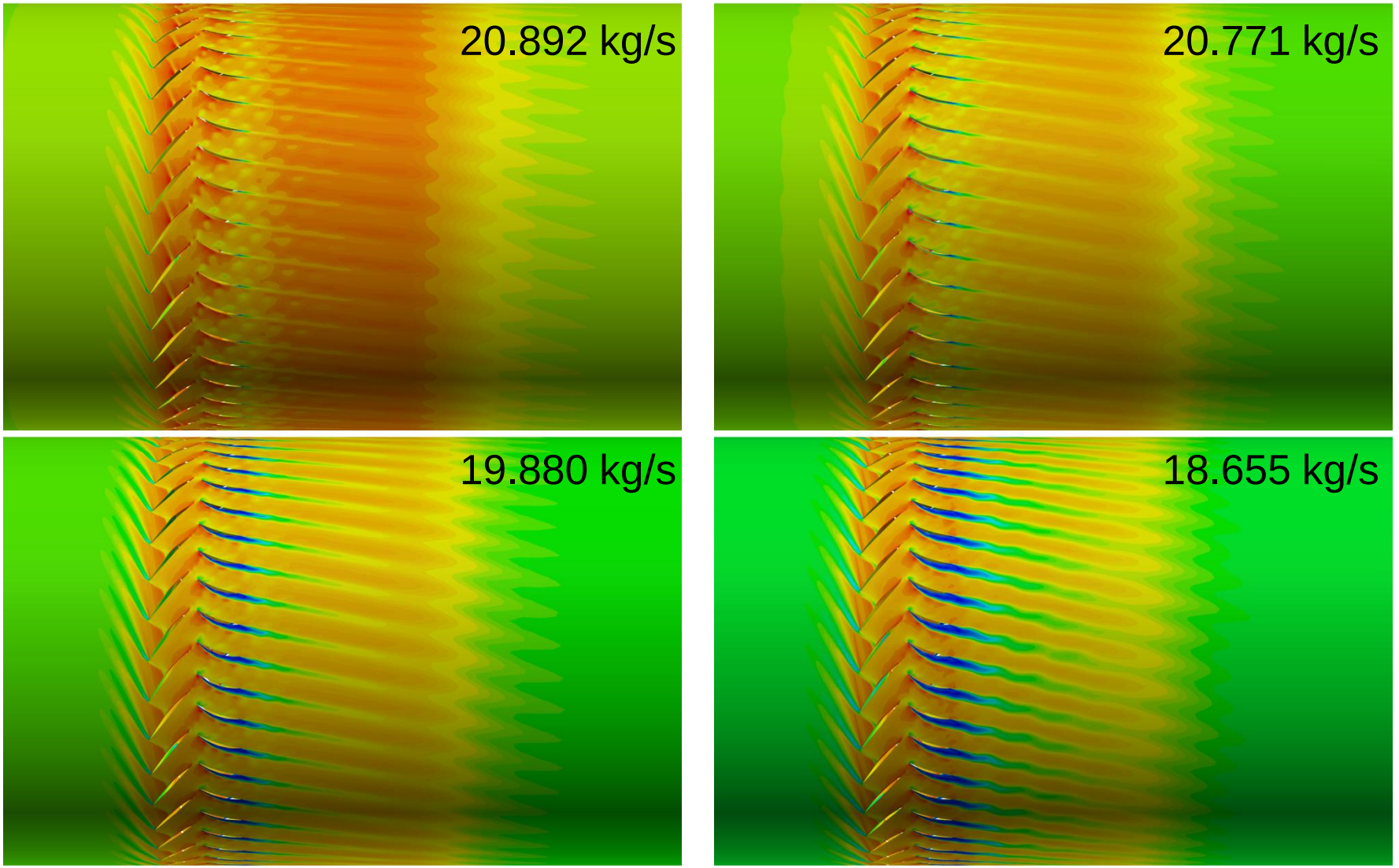








Stage 35 100% Speed Mach No.



Summary

- ***Firebolt*** **v1 designed to couple 0D engine models with high fidelity Navier-Stokes codes within a light weight Python infrastructure**
  - Kestrel spring 2012
  - Helios spring 2013
- ***Firebolt*** **v2 designed for structured grid Navier-Stokes simulations of aircraft and engine rotating machinery**
  - Kestrel spring 2013
  - Helios spring 2013
- **Software product includes training, user and developer documentation, and user support**
- **GUI will be provided to set up inputs and post process results**

References

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