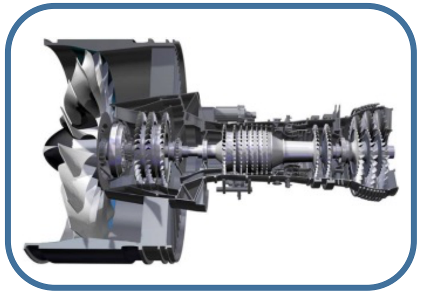

# Vision 2030 Aircraft Propulsion Grand Challenge Problem: Full-engine CFD Simulations with High Geometric Fidelity and Physics Accuracy

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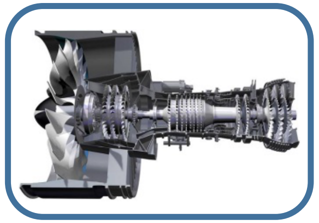
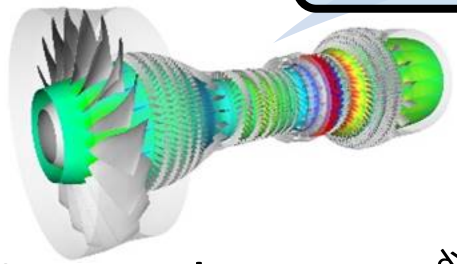


# Propulsion GC: Full-Engine Simulation

- Objective: Perform a full-engine simulation from model build to results within a week to a level of accuracy to reduce or eliminate component/engine testing
- Benefits:
  - Billions of dollars savings per year - OEM's and aircraft operators
  - Enabler for Advanced Propulsion/Airframe concepts – Fuel consumption, emissions, noise benefits
- Considerations:
  - Level of accuracy to replace testing – previously full-engine/part-engine simulations have been demonstrated, but not to the level of geometrical fidelity and physical accuracy, including transient simulations targeted here
  - Tests (Common Research Models) and validation data for model development included – component level
  - Includes algorithm/physical model development, infrastructure (pre- and post-processing)
  - Exploiting high-performance computing (exascale) will be a key enabler

# Propulsion Grand Challenge Problem



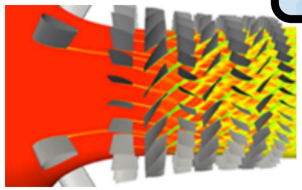
**Integrated, Multicomponent**

Aerodynamics, Aeromechanics, Aeroacoustics

Combustor/Turbine & Compressor/Combustor

Inlet/Fan/bypass/Comp. & Turbine/Exhaust system

Full-engine including Secondary Air System



**Fan, Compressor**

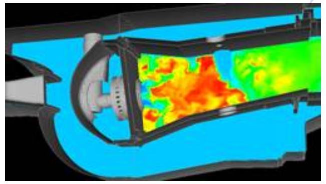
(Inlet, Fan, OGV, Bypass, LPC, [IPC], HPC)

Single-Stage

Fan + OGV + Bypass

Multi-stage, Front Block

Multi-stage, Rear Block



**Combustor**

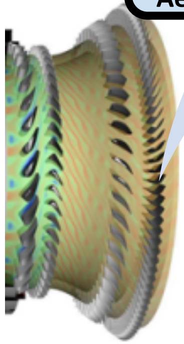
(Diffuser, Fuel Nozzle, Liner)

Assumed Sprays, Improved Emissions/Soot

Radiation, Heat Transfer

Detailed Sprays. Advanced Emissions models

Full Annulus, Dynamics, LBO, Ignition, Relight



**Turbine**

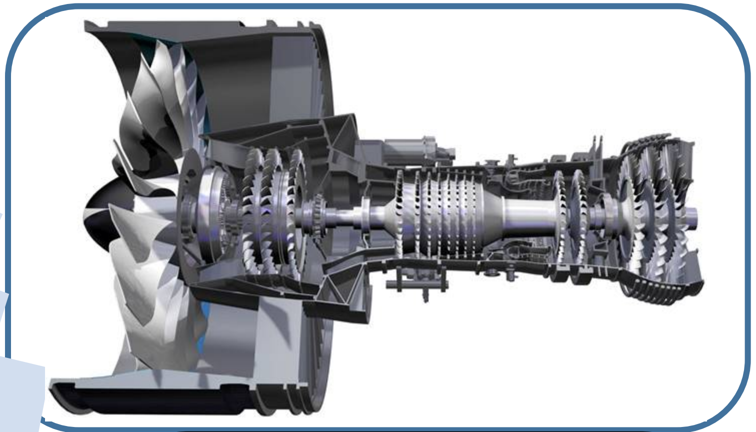
(HPT, [IPT], LPT, Exhaust System)

Single-Stage Aerodynamics, Aeromechanics

Single-Stage Heat Transfer

Multi-Stage Aerodynamics, Aeromechanics

Multi-Stage Heat Transfer



**Challenges:**

- Turbulence Modeling
- Wall-resolved/Near-wall modeling
- Multi-phase, Reacting, Heat Transfer…….
- Algorithms, pre-, post-process., Infrastructure

**Enablers:**

- Test Data (Common Research Models)
- HPC exploitation

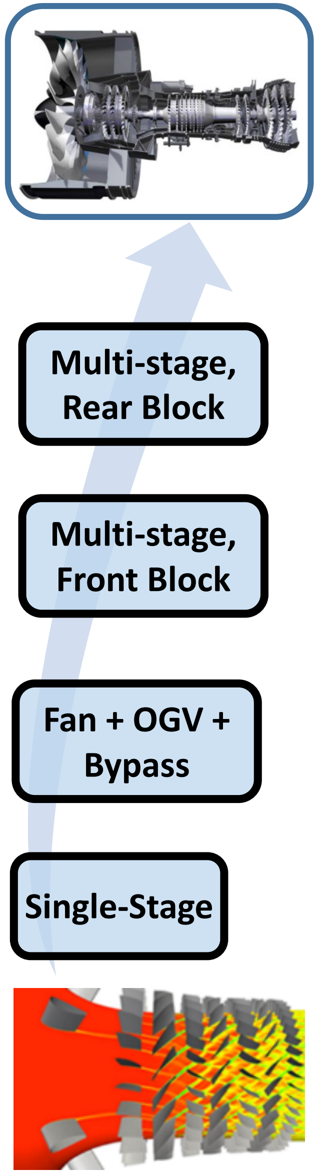
## A Full Engine Simulation in Less Than 1 Week

From model build to results enabling…

- meeting **performance, operability, emissions, durability metrics**
- with **geometric fidelity & accuracy of physics** to
- **reduce/eliminate testing**
- and deliver **billions of dollars savings** per year

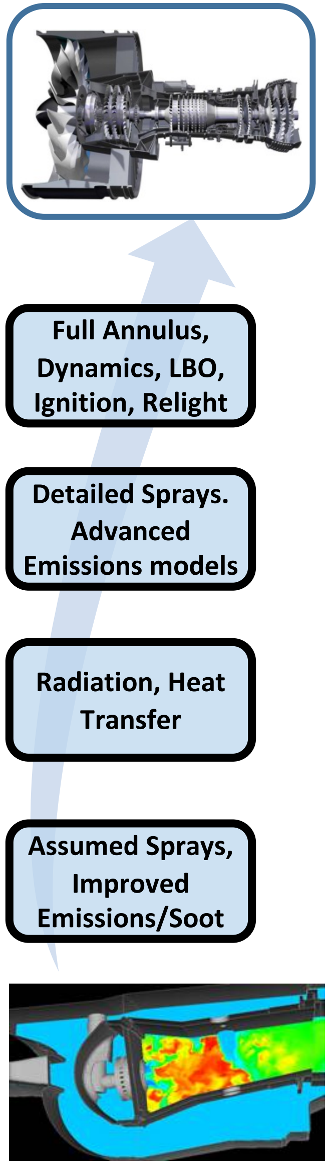
2020 2025 2030 2035 2040

# Fan, Compressor (Inlet, Fan, OGV, Bypass, LPC, HPC)



- Current status
  - Typically axisymetric inlet boundary conditions  RANS with mixing plane used in design cycle
  - Final design may utilize URANS with simplified blade counts for sector calculations
  - Good predictions of performance at design point, off-design performance and stall margin prediction reasonable for designs within experience base having measured performance maps
- Opportunities
  - Reduced testing of multiple builds
  - Higher fidelity modeling of 3D non-axisymetric geometry with fillets, leakages, etc
  - Reduce variable geometry, bleeds, and casing treatments by better prediction of performance and operability at off-design conditions over the speed range.
  - Ability to predict aeromechanic fluid structural interactions over the operating range
- Gaps and Challenges
  - Full wheel RANS/URANS for blade row interactions, shock/ vortex interactions, inlet distortions effects with propagation through multiple rotating and stationary blade rows
  - LES, wall resolved LES, or hybrid URANS/LES to predict BL transition, separation and reattachment and in a flowfield dominated by secondary flows
  - Rewrite all solvers to take advantage of GPU's and other High Performance Computing advancements

# Combustor (Diffuser, Fuel Nozzle, Liner, Cooling, Leaks)



Full Annulus, Dynamics, LBO, Ignition, Relight

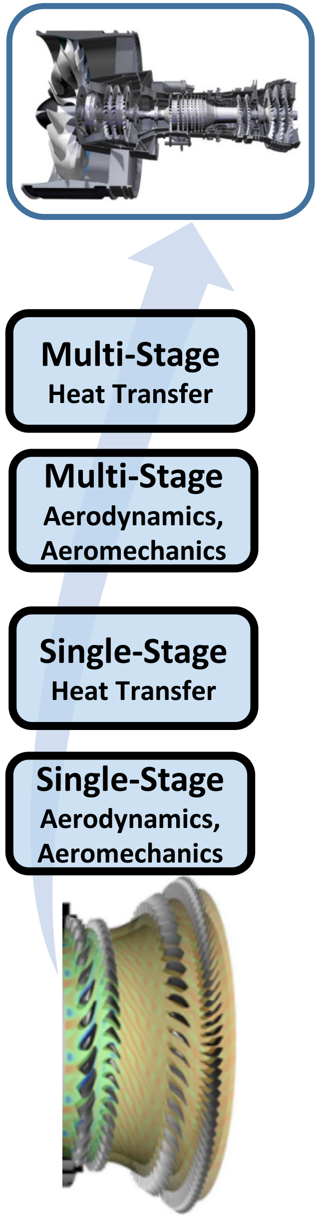
Detailed Sprays. Advanced Emissions models

Radiation, Heat Transfer

Assumed Sprays, Improved Emissions/Soot

- **Current status**
  - Wide range of physical processes, time and length scales
  - More routinely RANS and URANS in design cycle, but LES also used
  - Specified spray BCs, simplified combination of chemistry/turbulence-chemistry
  - Good predictions of exit temperature traverse and trends of NOx, CO emissions
- **Opportunities**
  - Significant opportunity to further reduce rig testing
  - Optimized designs to meet stringent emissions regulations without sacrificing efficiency and operability
- **Gaps and Challenges**
  - More use of LES (unsteady simulations); higher geometric fidelities
  - Detailed, spray, combustion, turbulence-chemistry, soot, heat transfer models
  - Acoustics (instabilities), Lean Blow Out, Relight simulations (full annulus models)

# Turbine (HPT, [IPT], LPT, Exhaust System)



**Multi-Stage** Heat Transfer

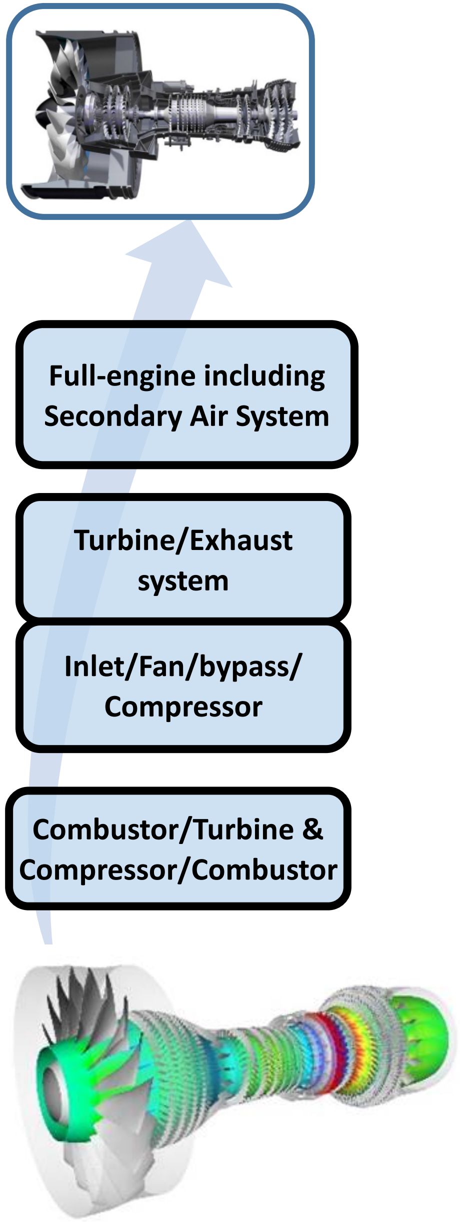
**Multi-Stage** Aerodynamics, Aeromechanics

**Single-Stage** Heat Transfer

**Single-Stage** Aerodynamics, Aeromechanics

- ## Current status
  - Design space consisting of 1000s of design parameters → SRANS for early design
  - Transient URANS later in the design, LES for simpler canonical problems due to computational cost
  - HPT dominated by high temperature flows, hot streaks, SBLI & secondary flows, LPT more sensitive to variations in Reynolds number, flow transition & separation
- ## Opportunities
  - Faster and more accurate solutions to evaluate aero-thermal performance trade studies sooner in the design process
  - Efficiency targets need to be identified and simulation workflows need to be sufficiently validated over a broad design space to help displace physical testing
- ## Gaps and Challenges
  - Frame change between stator and rotor; multi-stage physics for compressors and turbines
  - Boundary condition accuracy & uncertainty: combustor exit gas temperature profile, inter blade-row
  - Surface roughness and coatings are 1st order effects
  - Complex geometric features of wide range of length scale (blade tip gap, 1000s of film cooling holes, 1000s of impingement cooling holes, small scale leakage flows
  - Complex physics including wake & thermal mixing, SBLI, turbulence transition, geometry variation over time

# Integrated Systems and Full-engine



Full-engine including Secondary Air System

Turbine/Exhaust system

Inlet/Fan/bypass/ Compressor

Combustor/Turbine & Compressor/Combustor

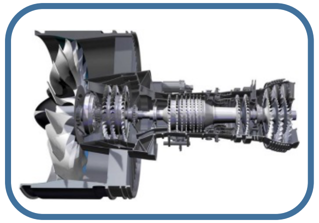
## STATUS

- Pioneering full-engine simulations (ASCII - Medic et al 2007, Turner 2010)
    - Limited component interactions, geometric details, grid resolution
- More recent works on improving component coupling

## PROPOSED GC:

- Hi-fidelity geometry, methods and models
- Multi-component interactions, unsteady and transients
- Secondary flows, bleeds, leaks, accurately represented or secondary systems included explicitly
- Some simulations may need full-wheel/full-annulus
- Estimates of number of control volumes and computational time given in the paper
- Need to leverage advanced methods and exascale computing
- Ultimate goal is to have sufficient accuracy to be able to certify engines with limited or no engine testing

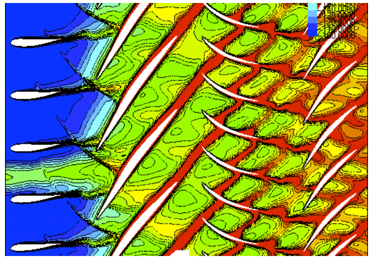
# Validation Data – Common Research Models (CRMs)

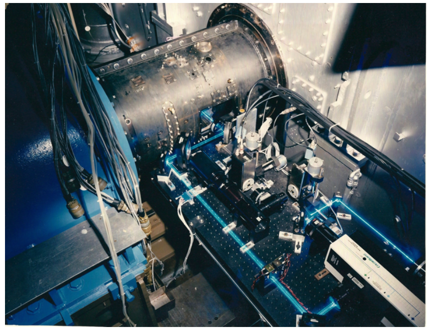


- Component level as well as component interactions
- Reliance on OEMs for full-engine data and validation
- Advanced diagnostics – detailed data for model development
- CRM must represent relevant design parameters/geometries/ operating conditions
- Critical for OEMs, Govt. Labs and Academia to work together
- Funding by government agencies is vital

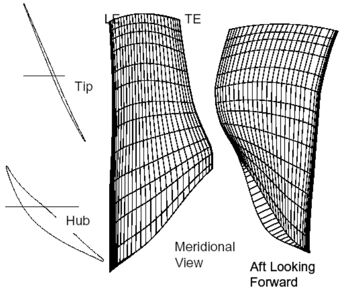
# CRM Validation Data: Fan/Compressors example

- **Leverage existing Benchmark datasets**
  - NASA Rotor 67 (single LDV channel)
  - NASA Stage 67 – LDV: Rotor/Stator interactions
  - NASA Rotor 37 – 2 channel LDV w/ Simultaneous $V_{axial}$, $V_{tan}$
  - NASA Stage 35 : Stall Management, Blade row interactions





- **CRM: must have relevant design parameters/ geometries**
  - Blade loading, Pressure Ratio, No. of Stages, Reaction, Specific Flow, Thrust/Weight, Stall Margin, etc
  - Flowpath, Shrouded vs Cantilevered Stators, Variable Geometry, Bleeds, Casing Treatments, etc



a) Advanced technology forward swept

- **CRM: Advanced Instrumentation & Validated Geometries**
  - TU characterization, inlet / exit conditions
  - Sensors: type, location, & resolution in space and time/frequency

**CHALLENGES: To reach OEM consensus on the above for a Relevant Design Geometry for CRM, and securing funding**

# Common Research Models & Workshops

**EXTERNAL AERODYNAMICS HIGH LIFT PREDICTION WORKSHOPS**

- 4th AIAA CFD High Lift Prediction Workshop (June 2021)

**EXTERNAL AERODYNAMICS DRAG PREDICTION WORKSHOPS**

- 6th AIAA CFD Drag Prediction Workshop (June 2016)

**PROPULSION AERODYNAMICS WORKSHOPS**

- 4TH AIAA Propulsion Aerodynamics Workshop (June 2021)

**AEROACOUSTICS WORKSHOPS**

- 5th Workshop on Benchmark Problems for Airframe Noise Computations (BANC-V, June 2016)

**NJFCP - National Jet Fuels Combustion Program (FAA-led, Multi-agency funded)**

- Multiple, OEMs, Govt. Labs, Universities.  CRM employed at realistic conditions

**VISION:  PROPULSION CORE PREDICTION WORKSHOPS**

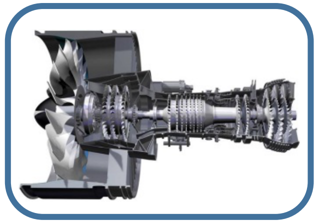
- *1st CFD Compressor Aerodynamics Prediction Workshop (June 2024)*
- *1st CFD Turbine Aerodynamics Prediction Workshop (June 2024)*
- *1st CFD Combustor Aerothermal Prediction Workshop (June 2024)*

***There are other past and ongoing examples of collaboration at component levels, but the emphasis here is on realistic geometries at relevant pressure and temperature conditions, as well as component interactions***

Source: https://hiliftpw.larc.nasa.gov/index-workshop3.html

Source: Liou and Yao, GT2014-25474

# Conclusions



- **Developments in modeling, algorithms and HPC hardware has the potential of enabling full engine simulation turnaround in less than a week, with required geometric fidelity and accuracy**
  - Enabler for Advanced Propulsion/Airframe concepts – noise, emissions, operability benefits
  - Better optimized engines and integration with airframes
  - Significantly reduce or eliminate component/engine testing
  - Billions of dollars savings for airlines/DoD/operators per year
- **Sustained investment from funding agencies needed to harness the potential**
  - Collaboration between government, industry and academia is necessary to make progress in the computational technology development and validation experiments