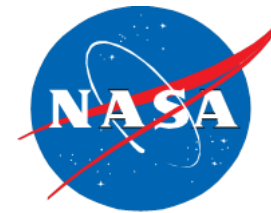


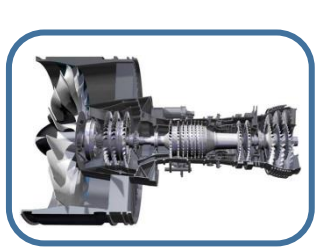
# Vision 2030 Aircraft Propulsion Grand Challenge Problem: Full-engine CFD Simulations with High Geometric Fidelity and Physics Accuracy

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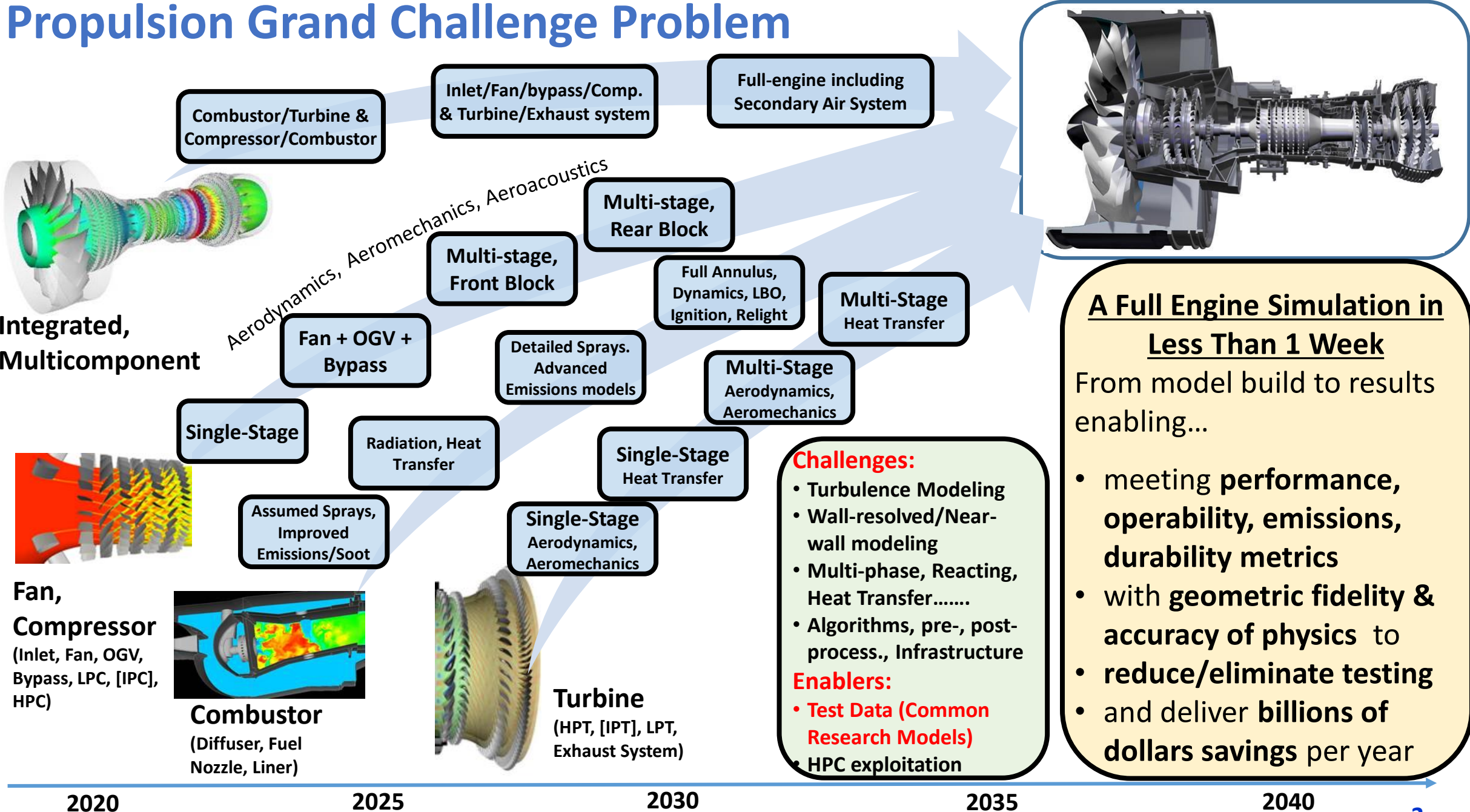




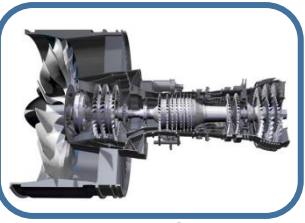
# Propulsion GC: Full-Engine Simulation

- **Objective:** Perform a full-engine simulation from model build to results within a week with sufficient accuracy to reduce or eliminate component/engine testing
- **Benefits:**
  - Billions of dollars savings per year for OEM's and aircraft operators – Fuel consumption, emissions, noise benefits
  - Enabler for Advanced Propulsion/Airframe concepts
- **Considerations:**
  - **Level of accuracy to reduce/eliminate 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)
  - **Exploitation of high-performance computing** (exascale) will be a key enabler

# Propulsion Grand Challenge Problem



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



- **Current status**

- Steady RANS with mixing plane and axisymmetric inlet BC's, used in design cycle
- Final design may utilize URANS with simplified blade counts
- Good predictions of performance and stall margin (for known designs) at design point

- **Opportunities**

- Higher fidelity modeling of 3D non-axisymmetric geometry w/ gaps, fillets, leakages
- Better design of variable geometry, bleeds, casing treatments to reduce cost
- Pre-test prediction of aeromechanic fluid structural interactions
- Reduced testing / reduced number of builds

- **Gaps and Challenges**

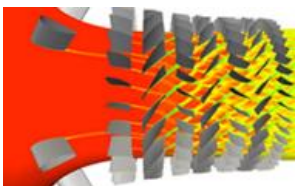
- Full wheel RANS/URANS simulations for inlet distortion, blade row interactions, shock/vortex interactions, and secondary flow impacts
- LES methodologies to predict BL transition, separation and reattachment
- Need validation data, and new hardware/solvers for faster computing times

Multi-stage,  
Rear Block

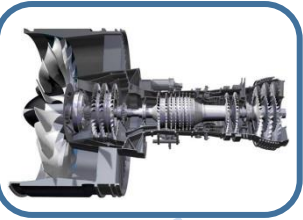
Multi-stage,  
Front Block

Fan + OGV +  
Bypass

Single-Stage



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



## • 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 NO<sub>x</sub>, 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

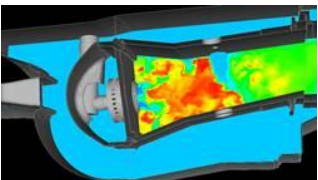
- More use of LES (unsteady simulations); higher geometric fidelities
- Detailed, spray, combustion, turbulence-chemistry, soot, heat transfer models
- Acoustics (instabilities), Lean Blow Out, Relight simulations (full annulus models)

Full Annulus,  
Dynamics, LBO,  
Ignition, Relight

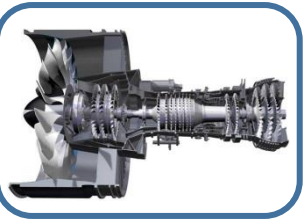
Detailed Sprays.  
Advanced  
Emissions models

Radiation, Heat  
Transfer

Assumed Sprays,  
Improved  
Emissions/Soot



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



- **Current status**

- Design space has 1000s of parameters → RANS for early design
- URANS later in the design, LES for simpler 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 for aero-thermal trade studies earlier in design
- 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**

- BC accuracy & uncertainty: combustor exit gas temperature profile, inter blade-row
- Complex geometry with wide range of length scales (1000s of film and impingement cooling holes)
- Complex physics – wake/thermal mixing, SBLI, transition, geometry variation over time, frame change between stator and rotor

Multi-Stage  
Heat Transfer

Multi-Stage  
Aerodynamics,  
Aeromechanics

Single-Stage  
Heat Transfer

Single-Stage  
Aerodynamics,  
Aeromechanics





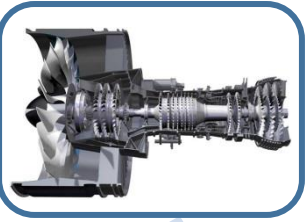
# Integrated Systems and Full-engine

## 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

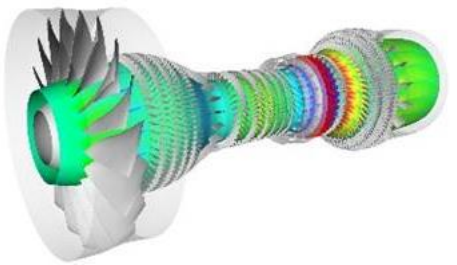


Full-engine including  
Secondary Air System

Turbine/Exhaust  
system

Inlet/Fan/bypass/  
Compressor

Combustor/Turbine &  
Compressor/Combustor



# Full-engine Simulations: Computational Resource Estimates

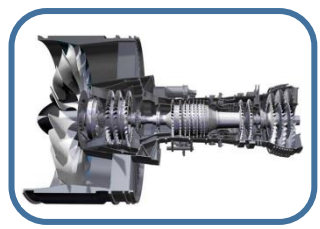
Table 1. Full engine simulations cost estimates			
Type of full engine simulation	Grid Size #Control Volumes	Integration Time	Computational time Total core-hours*
Main gas path (sector)	$O(10^9)$	$O(100 \text{ ms})$	$O(10^6)$
Main gas path (full annulus)	$O(10^{10})$	$O(100 \text{ ms})$	$O(10^7)$
Main gas path + bypass stream	$O(10^{10}-10^{11})$	$O(100 \text{ ms})$	$O(10^7-10^8)$
Including secondary flow path	$O(10^{11}-10^{12})$	$O(100 \text{ ms})$	$O(10^8-10^9)$
Long time integration for transients	$O(10^{11}-10^{12})$	$O(10 \text{ s})$	$O(10^{10}-10^{11})$

\*Based on current high-performance computers

- Ultimate goal is to have sufficient accuracy and computational efficiency to be able to certify engines with limited or no engine testing
- Need to leverage advanced methods and latest compute hardware



# Validation Data – Common Research Models (CRMs)

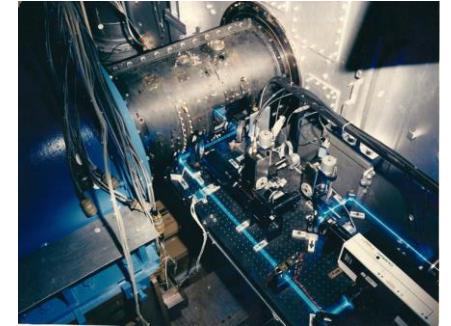
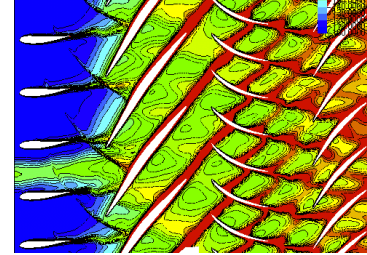


- **Component level as well as component interactions**
- **Reliance on OEMs for full-engine data and validation**
- **Advanced diagnostics – detailed data for model development**
- **CRM must be non-proprietary and represent relevant design parameters/geometries/ operating conditions**
- **Critical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

# CRM Validation Data: Fan/Compressors example

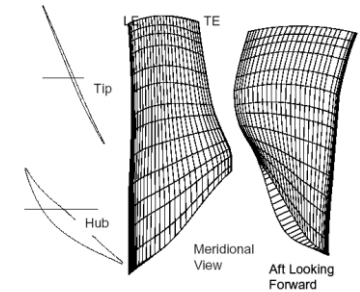
- **Leverage existing Benchmark datasets**

- 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



- **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

- 4<sup>th</sup> AIAA CFD High Lift Prediction Workshop (June 2021)

## EXTERNAL AERODYNAMICS DRAG PREDICTION WORKSHOPS

- 6<sup>th</sup> AIAA CFD Drag Prediction Workshop (June 2016)

## PROPULSION AERODYNAMICS WORKSHOPS

- 4<sup>TH</sup> AIAA Propulsion Aerodynamics Workshop (June 2021)

## AEROACOUSTICS WORKSHOPS

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

## NJFCP - National Jet Fuels Combustion Program (FAA-led, Multi-agency funded) (2014-2019)

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

## VISION: PROPULSION CORE PREDICTION WORKSHOPS

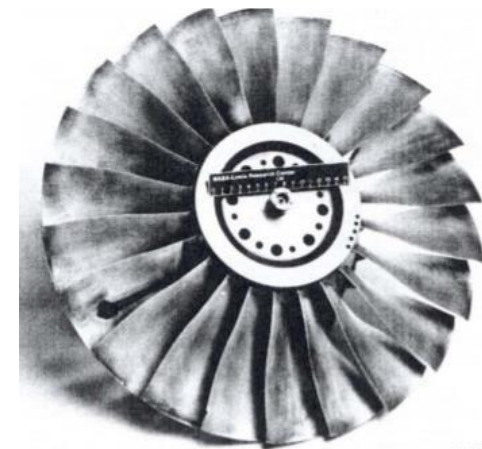
- 1<sup>st</sup> CFD Compressor Aerodynamics Prediction Workshop (2023?)
- 1<sup>st</sup> CFD Combustor Aerothermal Prediction Workshop (2024?)
- 1<sup>st</sup> CFD Turbine Aerodynamics Prediction Workshop (2025?)

*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:

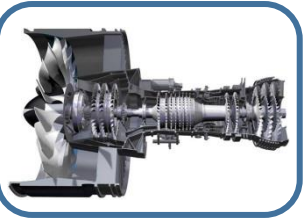
<https://hiliftpw.larc.nasa.gov/index-workshop3.html>



Source:

[Liou and Yao, GT2014-25474](#)

# Conclusions



- **Developments in modeling, algorithms and HPC hardware have the potential of enabling full engine simulations with turnaround time of less than a week, with required geometric fidelity and accuracy**
  - Enabler for Advanced Propulsion/Airframe concepts
  - Better optimized engines and integration with airframes
  - Significantly reduce or eliminate component/engine testing
  - Billions of dollars savings for airlines/DoD/operators per year – noise, emissions, operability benefits
- **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