Advancing CFD Vision 2030
Progress and Future Plans within the Aerospace Community

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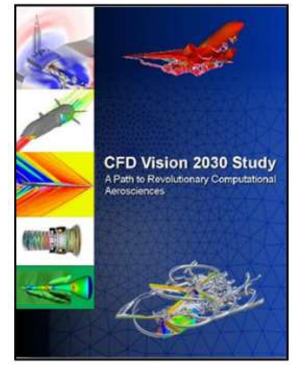
53rd Fluid Dynamic Conference / 39th Aerospace Numerical Simulation Symposium
30 June 2021

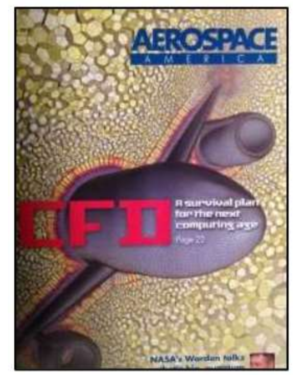
Outline

- CFD Vision 2030
- Current Landscape
- AIAA CFD2030 Integration Committee
- Activities
  - Progress Towards CFD Vision 2030
  - CFD Grand Challenges
- Community Collaboration Opportunities
  - High Lift Common Research Model (CRM-HL) Ecosystem
  - High Lift Prediction Workshop
  - Certification by Analysis (CbA)
- Summary

CFD Vision 2030

- **Emphasis on physics-based, predictive modeling**
  Transition, turbulence, separation, unsteady/time-accurate, chemically-reacting flows, radiation, heat transfer, acoustics and constitutive models
- **Management of errors and uncertainties**
  Quantification of errors and uncertainties arising from physical models, mesh and discretization, and natural variability
- **Automation in all steps of the analysis process**
  Geometry creation, meshing, large databases of simulation results, extraction and understanding of the vast amounts of information
- **Harness exascale HPC architectures**
  Multiple memory hierarchies, latencies, bandwidths, programming paradigms and runtime environments, etc.
- **Seamless integration with multi-disciplinary analyses and optimizations**
  High fidelity CFD tools, interfaces, coupling approaches, the science of integration, etc.

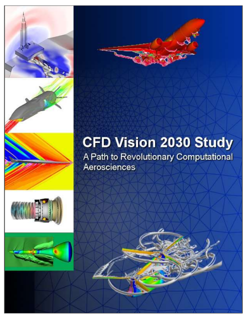




Slotnick, et al., "CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences," NASA/CR-2014-218178, 2014

Landscape

2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2025 | 2030



F360 Panel **CFD Vision 2030**

AEROSPACE AMERICA

POINTWISE

Workshop **Flight Prediction**

Workshop **Future CFD Technologies**

AIAA

AIAA CFD2030
Integration Committee

F360 Panel **HPC**

F360 Panel **Grand Challenges**

F360 Panel **Physical Modeling**

F360 Panel …

F360 Panel …

Special Session **CFD Vision 2030 Progress**

Special Session **Grand Challenges**

Special Session **CFD Prediction Workshops**

Special Session …

CFD Vision **Technology Update**

Working Groups **Grand Challenges**

CFD Vision **Technology Update**

CFD Validation Experiments

- High Speed Common Research Model (CRM-HS)
- High Lift (CRM-HL) Ecosystem)
- Aeroelastic (CRM-AE)
- Aero Propulsion CRMs
- Turbulent Heat Flux (THX)
- Juncture Flow
- Canonical Flow Separation Bump Configurations

CFD Prediction Workshops

DPW-5, HLPW-2, BANC-3, AEPW-1, PAW-2

DPW-6, AEPW-2, PAW-3, BANC-4

HLPW-3, GMGW-1

PAW-4, BANC-5

GMGW-2

SCPW-1, Icing-1, PAW-5, BANC-6

HLPW-4, GMGW-3, LES-1, HIFI-1

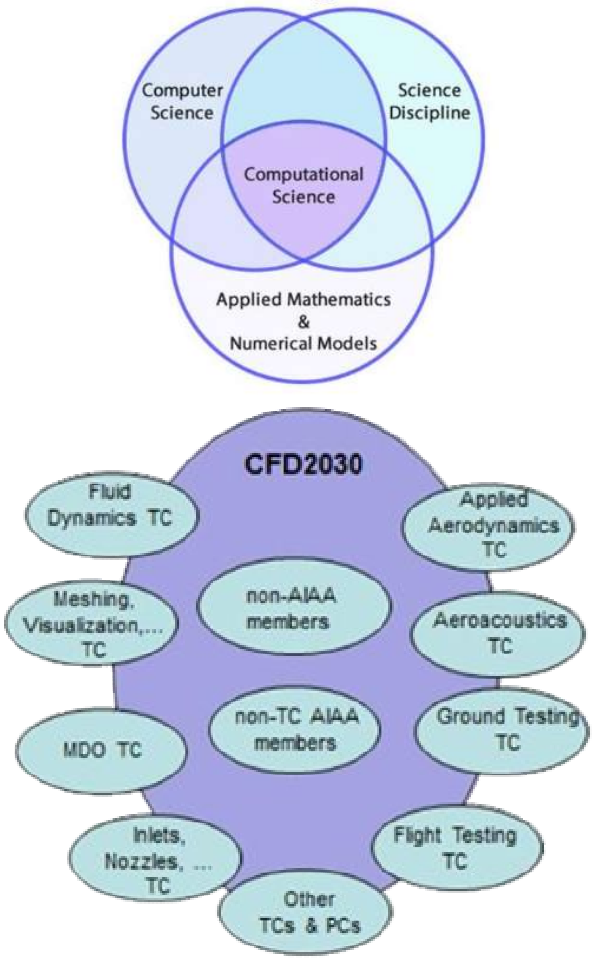
DPW-7, AEPW-3, Icing-2, PAW-6, MFM-6

HLPW-5

CFD2030 Integration Committee (IC)

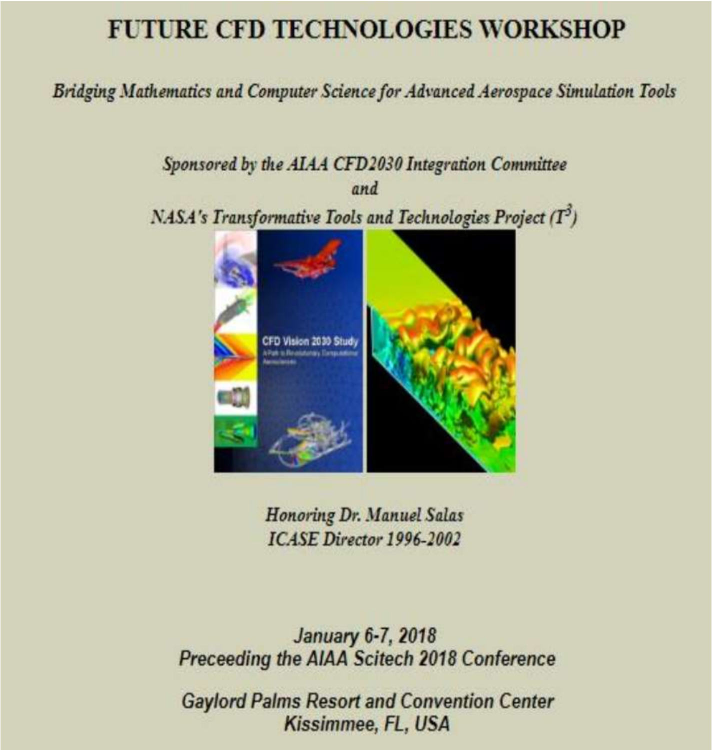
- Established in 2017
- Hosted by AIAA
- Paid membership in AIAA is not required for participating as a member of IC
- Objective: *Promote a **community of practice** engaged in developing methods, models, physical experiments, software, and hardware for revolutionary advances in **computational simulation technologies** for analysis, design, certification, and qualification of aerospace systems*
- http://www.cfd2030.com/index.html
- Chair: Dimitri Mavriplis, Univ. of Wyoming
- 44 current members (48% government, 36% industry, 16% academia)
  - All US-based, but the IC is open to international participation

Computational Science Venn Diagram



Future CFD Technologies Workshop

- January 6-7, 2018 – Proceeded AIAA SciTech conference
  - **First event hosted by CFD2030**
- Objectives:
  - Bridging **fundamental disciplines** for advanced aerospace simulation tools:
    - – Applied Mathematics/Computer Science/Physical Modeling
  - **Coordination/collaboration/interaction** with government agencies/professional societies/technical communities
  - Raise awareness of importance of intersecting disciplines in Aerospace community
- Multiple sessions held over 2 days:
  - Basic research
  - Application drivers
  - Math/algorithmic drivers
  - Technology drivers
  - HPC
  - Emerging Technologies



Progress Towards CFD Vision 2030

Special Session: Progress Towards CFD Vision 2030

2019 (Aviation)

John Cavolowsky (NASA-TAC Program)
Jeffrey Slotnick (Boeing)
Gorazd Medic (UTRC)
Eric Nielsen (NASA-LaRC)
Scott Morton (CREATE-AV Program)
Dimitri Mavriplis (Univ of Wyoming)
John Chawner (Pointwise) / Nigel Taylor (MBDA)
Philippe Spalart (Boeing) / Michael Strelets (NTS)

Discussion Topics

- Role of NASA Aeronautics
- Industry (airplane/propulsion) perspectives
- Importance of HPC
- Geometry and Mesh Generation
- Turbulence prediction

Roadmap Update

Forum 360: HPC

2020 (SciTech)

Jeffrey Slotnick (Boeing, Moderator)
Roy Campbell (DoD-HPCMP)
Doug Kothe (DoE-ECP Program)
Eric Nielsen (NASA-LaRC)
Scott Morton (CREATE-AV Program)

Discussion Focus

- Drivers: Virtual testing, streamlined product acquisition
- Hardware: Shift to exascale, GPUs, load/system balancing, capability vs capacity
- Software: Toolkits→ stacks→ apps, strategic/long-term code refactoring,
- Algorithms: Asynchronous communication, concurrency, strong scaling, mixed-precision

Forum 360: Physical Modeling

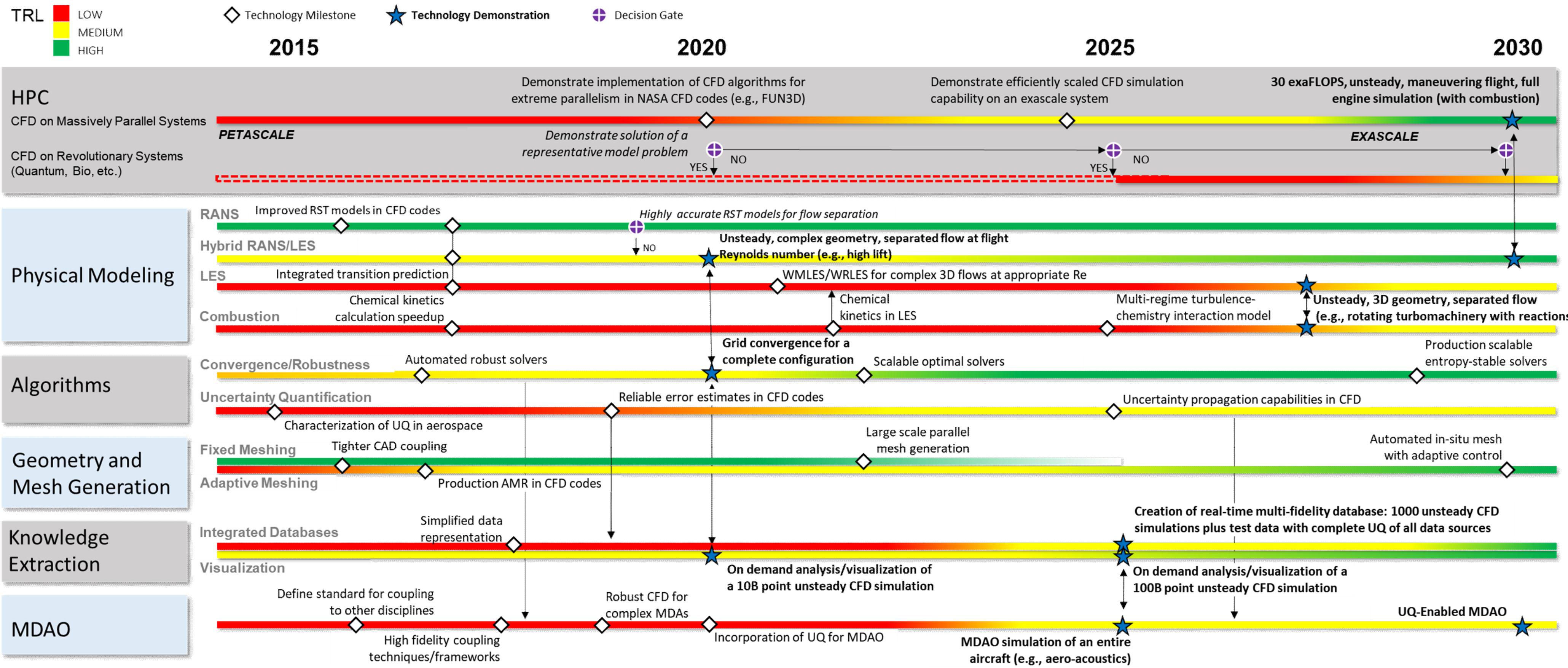
2021 (Aviation) – *Planned*

Brian Smith (Lockheed Martin, Moderator)
Florian Menter (Ansys)
Oriol Lehmkuhl (BSC)
Meelan Choudari (NASA)
Venkat Raman (Univ of Michigan)

Discussion Focus

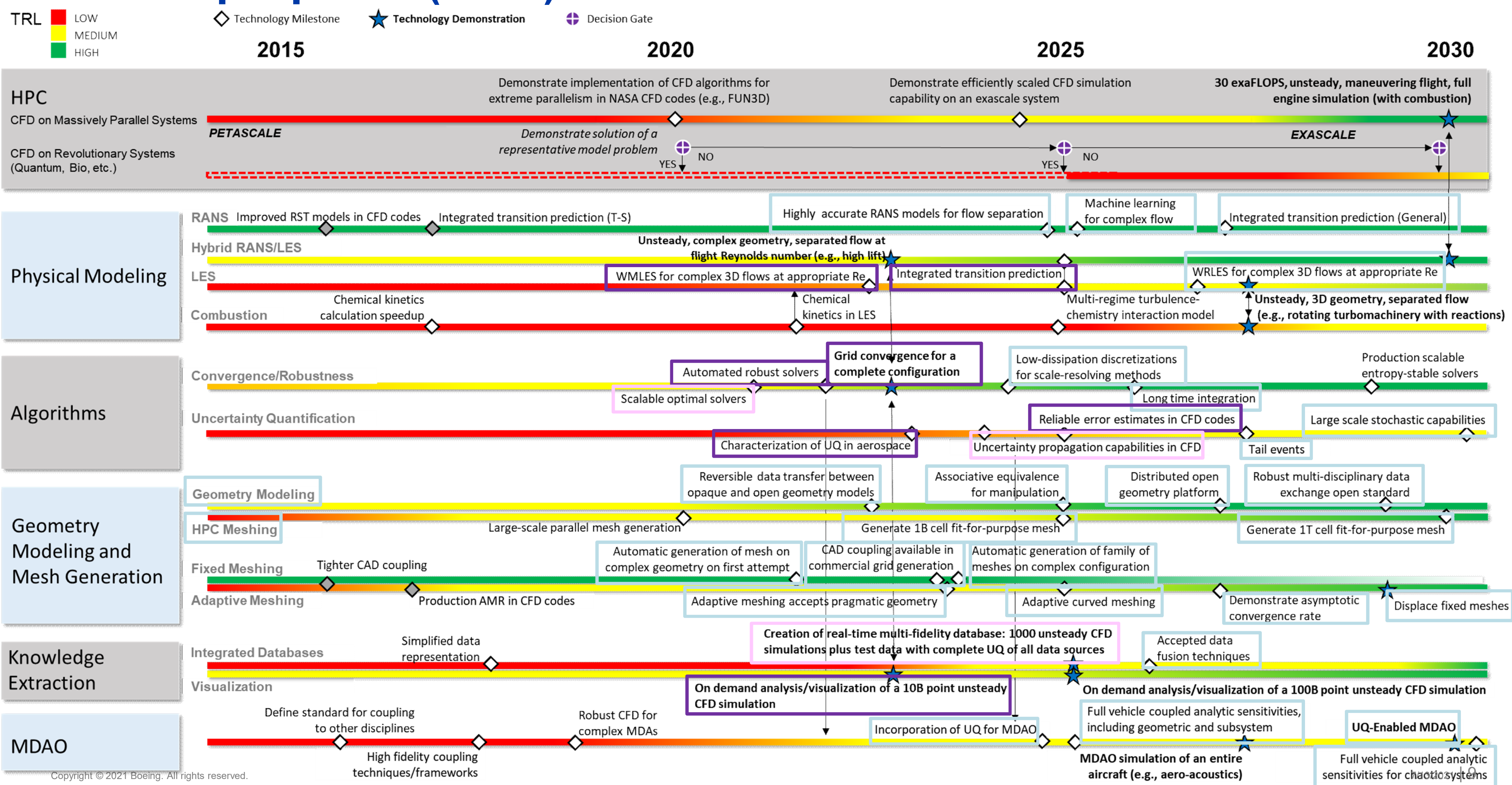
- Scale-resolving simulations and high-fidelity modeling of combustion and flow transition
- Error control and UQ
- Use of AI/ML and data fusion with limited test data
- CFD validation requirements

Original CFD Vision 2030 Roadmap (2014)



Roadmap Update (2021)

Milestone achieved | Accelerated
Deferred/reformulated | New



CFD Grand Challenges

F360: Aerospace Grand Challenge Problems for Revolutionary CFD Capabilities

2020 (Aviation)

Juan Alonso (Stanford, Moderator)
John Cavolowsky (NASA-TAC Program)
Ray Gomez (NASA-JSC)
Micah Howard (Sandia)
Om Sharma (UTRC)
Steve Wells (Boeing)

Discussion Focus

- Need and value of Grand Challenge (GC) problems to drive technology innovation
- Overview of 4 GCs described: high-lift, full engine simulation, space access, and hypersonics
- Highlights key technical obstacles and the quantified benefit to industrial product development in overcoming those obstacles.

Special Session: CFD 2030 Grand Challenge Problems for Numerical Simulation in Aerospace Engineering

2021 (SciTech)

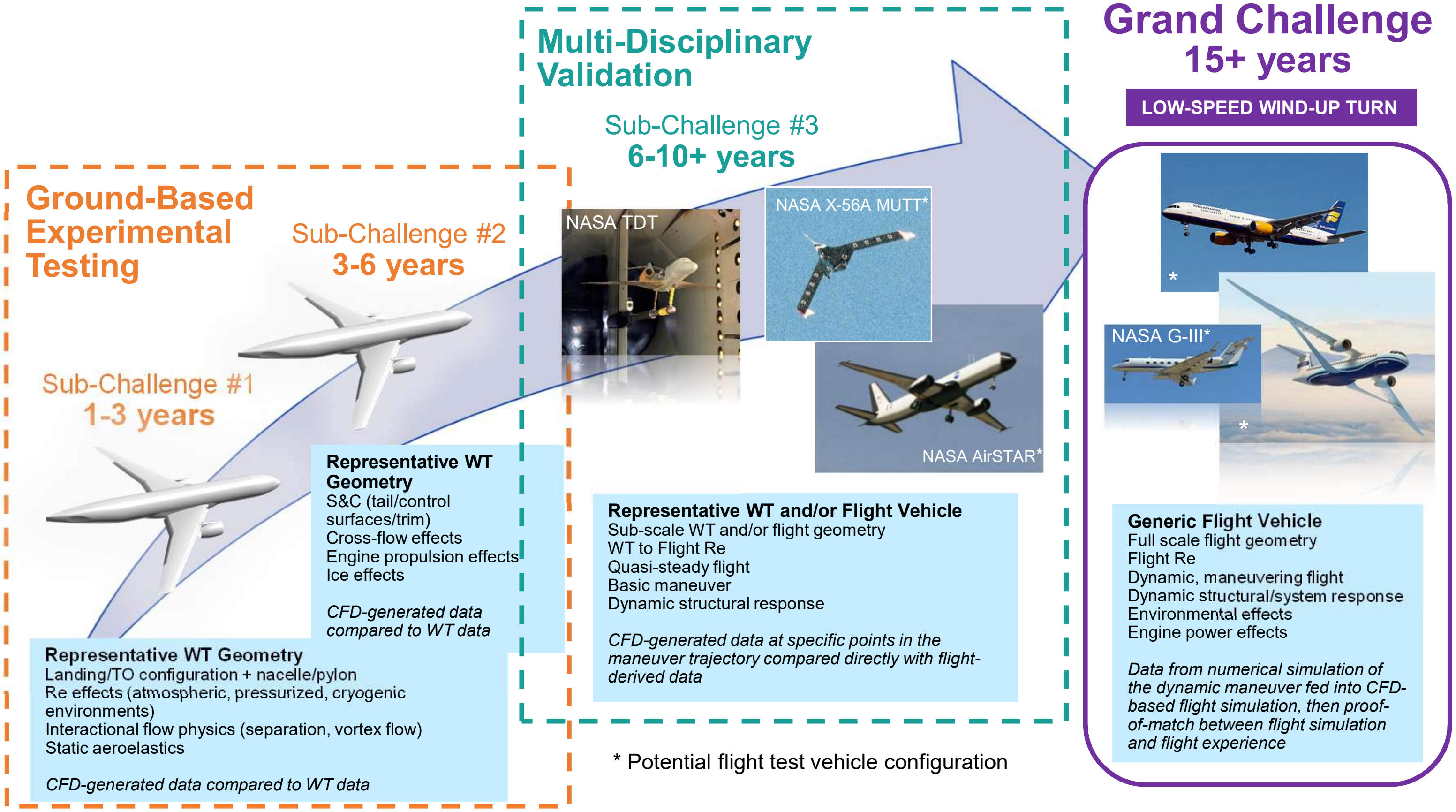
Jeffrey Slotnick (Boeing)
David Schuster (NASA-LaRC)
M. S. Anand (Rolls Royce)
Michelle Munk (NASA-LaRC)
Robert Meakin (CREATE-AV Program)
Doug Kothe (DoE-ECP Program)

Discussion Topics

- Described details of 3 GCs: high-lift, full engine simulation, and space access
- Highlighted key technical obstacles, and the quantified benefit to industrial product development in overcoming those obstacles.
- Experience with GCs within research and government labs

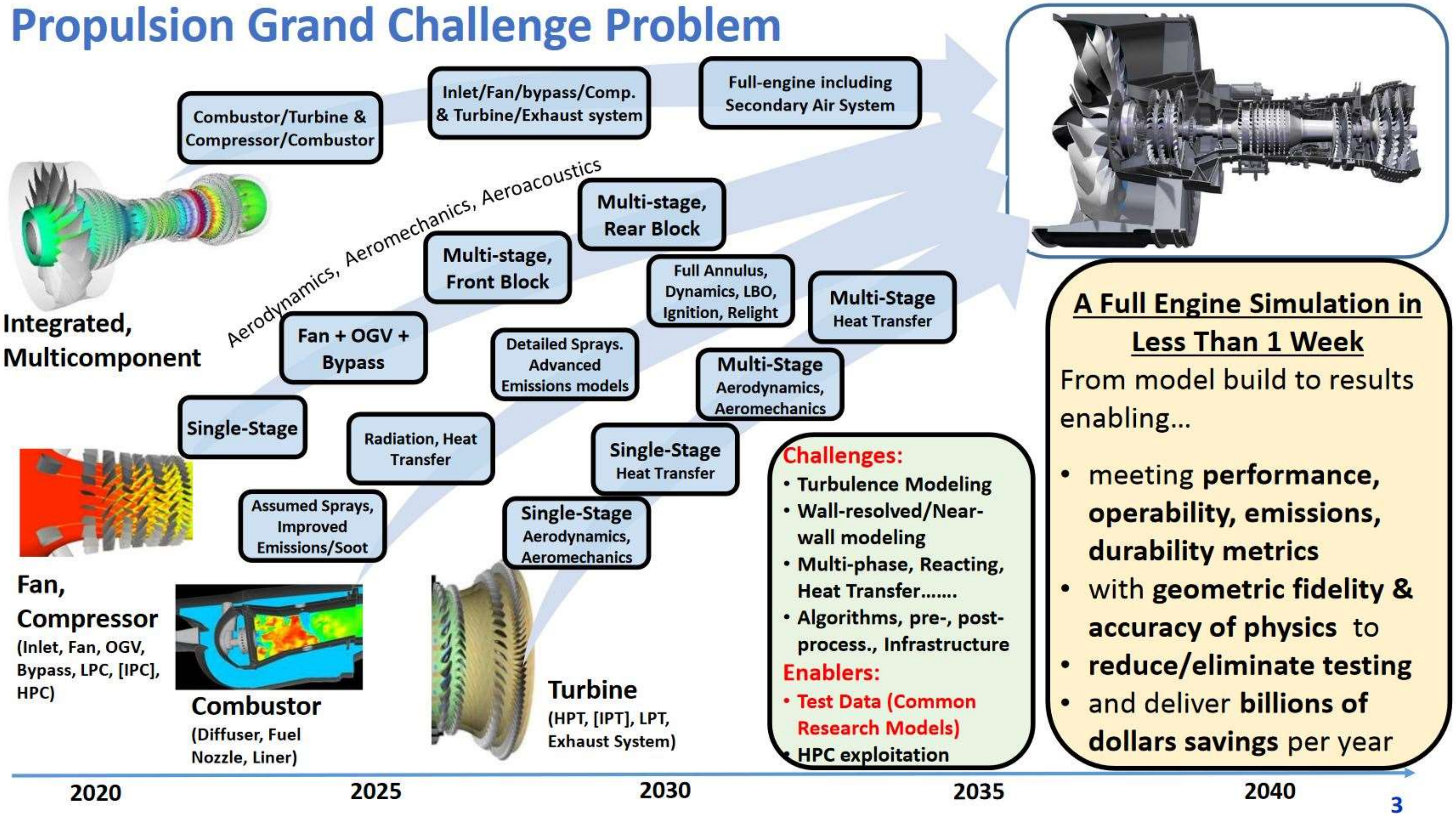
Working Groups
Grand Challenges

Advancing High Lift Aerodynamic Prediction
Series of Technical Challenges



Slotnick, J., and Mavriplis, D. “A Grand Challenge for the Advancement of Numerical Prediction of High Lift Aerodynamics”, AIAA 2021-0955, https://doi.org/10.2514/6.2021-0955

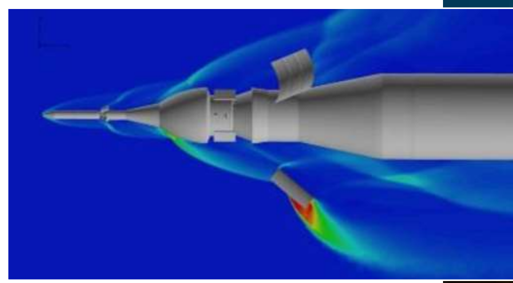
Propulsion Grand Challenge Problem

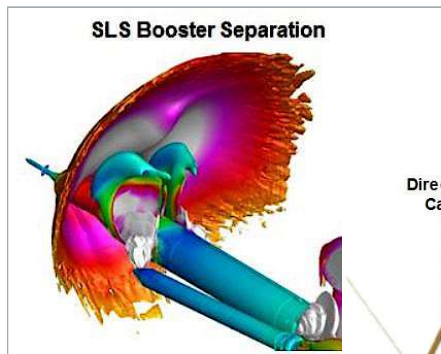


Anand, M. S., et al.,. "Vision 2030 Aircraft Propulsion Grand Challenge Problem: Full-engine CFD Simulations with High Geometric Fidelity and Physics Accuracy", AIAA 2021-0956, https://doi.org/10.2514/6.2021-0956

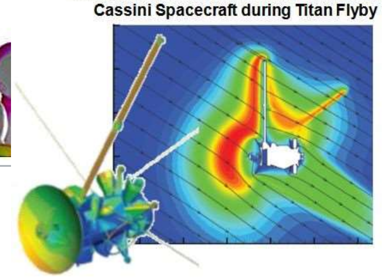
CFD-in-the-Loop Monte Carlo Flight Simulation for Space Vehicle Design

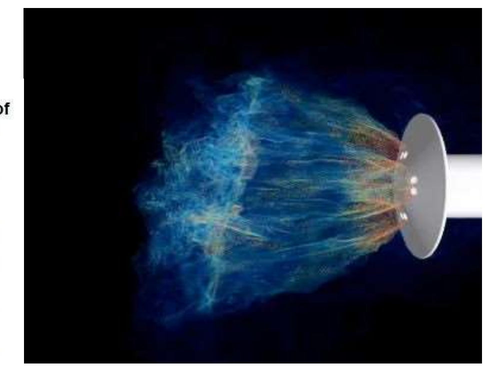
- Detailed analysis is required in two primary flight phases for space vehicles: **Ascent/Abort** and **Entry Descent and Landing (EDL)**.
  - Vehicles not optimized for aerodynamics.
  - Prediction of unsteady flows, plume/surface/aerodynamic interaction, shock effects, heating, and vehicle flight stability are prime requirements.
- Designers regularly deal with unsteady flow –
  - Steady CFD is prone to large variations.
  - Community increasingly turning to DES and LES-based methods for select cases.
- **CFD-in-the-loop MC simulation** has potential to significantly reduce design development time and lessen the cost and schedule impact of vehicle design changes and/or block upgrades
- Challenges to realizing this capability are significant and well-aligned with the goals proposed in the CFD Vision 2030 Study.
- The grand challenge is partially scalable and could be initially **demonstrated on only a segment of a flight simulation**.
  - EDL may be a good choice for demonstrating capability; several initial efforts in free-flight CFD EDL analysis are underway.
- **ROM** and **Machine Learning** techniques may be required for near-term implementation of CFD tools capable of simulating space vehicle flows of interest.





Direct Simulation Monte Carlo Analysis of Cassini Spacecraft during Titan Flyby





Schuster, D. "CFD 2030 Grand Challenge: CFD-in-the-Loop Monte Carlo Flight Simulation for Space Vehicle Design", AIAA 2021-0957, https://doi.org/10.2514/6.2021-0957

Community Collaboration Opportunities

Success requires **coordinated collaboration** within **engineering and simulation communities**

Courtesy NASA

Courtesy DLR

CFD Validation Partnerships

- Encourages pooling of critical resources (people, time, $) to develop appropriate configurations and/or platforms (e.g. CRM-HL)
- Drives community consensus on data requirements (type, location, etc.)
- Enables joint sharing of data and lessons learned
- Establishes steering of future CFD validation activities

CFD Prediction Workshops

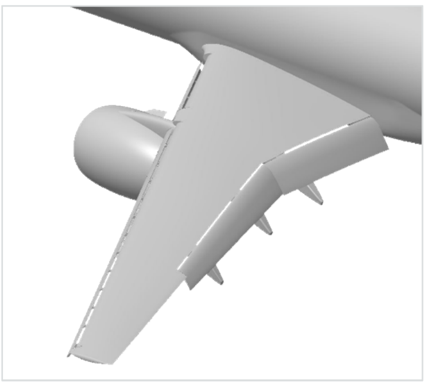
- Growing number within aerospace community – several (e.g. HLPW) directly address issues associated with Grand Challenges (e.g. high lift GC)
- Focuses attention on specific problems of interest
- Encourages newcomers to get involved
- Increasingly tied to the development and testing of common research models (e.g. CRM-HL)

Future Activities

- Increasing emphasis on engine/propulsion simulation technologies → CRMs, workshops
- Integration of simulation and test data to enhance/accelerate product development
- "Digital Flight" workshops focusing on multi-disciplinary coupling strategies using building block approaches
- Formation of Grand Challenge Working Groups

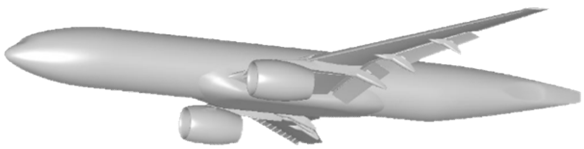
High Lift Common Research Model (CRM-HL) Ecosystem

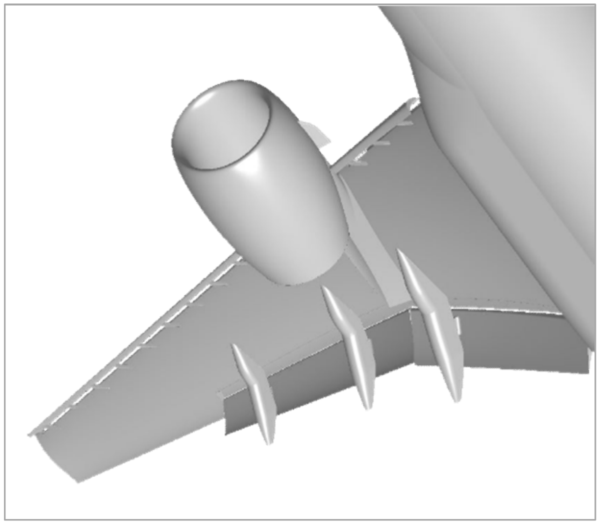
- **Community-sourced** collaboration of international partners established in 2018
- **Partners fund activities** within the ecosystem (e.g. building/testing wind tunnel models, providing flow measurement technology, etc.) and **share the results** (e.g. test data, CFD results, etc.)
- Partners decide if/when to make any of the **data publically available** (e.g. for community workshops)
- **~12 organizations** from industry, government, and academia, representing 5 countries (US, UK, France, Germany, Japan)
- Serves as an **effective example** for future community collaboration efforts



Lacy, D. and Sclafani, A, "Development of the High Lift Common Research Model: A Representative High Lift Configuration for Transonic Transports" AIAA-2016-0308, https://doi.org/10.2514/6.2016-0308.

High Lift Common Research Model Ecosystem – Benefits





- Provides **industry-relevant** configuration(s) and consistent models.
- Enables **direct assessment and comparison** between CFD flow solvers and modelling approaches.
- Provides a **common standard** to assess the predictive capabilities of emerging computational tools.
- With proper controls, enables the design and fabrication of nearly **identical models in multiple facilities** (for data repeatability).
- Provides a challenging open-source configuration(s) to demonstrate **advanced measurement and sensing techniques**
- Provides a **freely-sharable geometry**, which enables new, and strengthens existing, partnerships to accelerate technology development.
- Provides a geometrically-relevant testing platform to jointly develop, assess, and share **pre-competitive aerodynamic technology** (e.g. Active Flow Control, noise, etc.) with external partners (e.g. NASA, etc.)
- Drives development of enabling technologies which provide indirect benefits, like improved **test facility capability/utilization** and **workforce development** (e.g. industry/university collaboration).

High Lift Common Research Model Ecosystem – Test Plan

June 2021

NASA 10% SS (14x22/Q, 1atm / 3atm)
- Confirm CRM-HL design features
- Data for reference configurations
- NASA research (AFC, noise)
- Tie in to NTF-derived Re # trend data

NASA 5.2% SS cryo (NTF/ETW/others)
- Primary model for Re # trends
- SS/FS model issues deemed Re # dependent
- Wall effects
- NASA research (Flow measurements, AM, others)

NASA 2.7% SS/FS cryo (NTF/ETW/others)
- SS/FS model issues deemed Re # dependent
- NASA research (Flow measurements, AM, others)

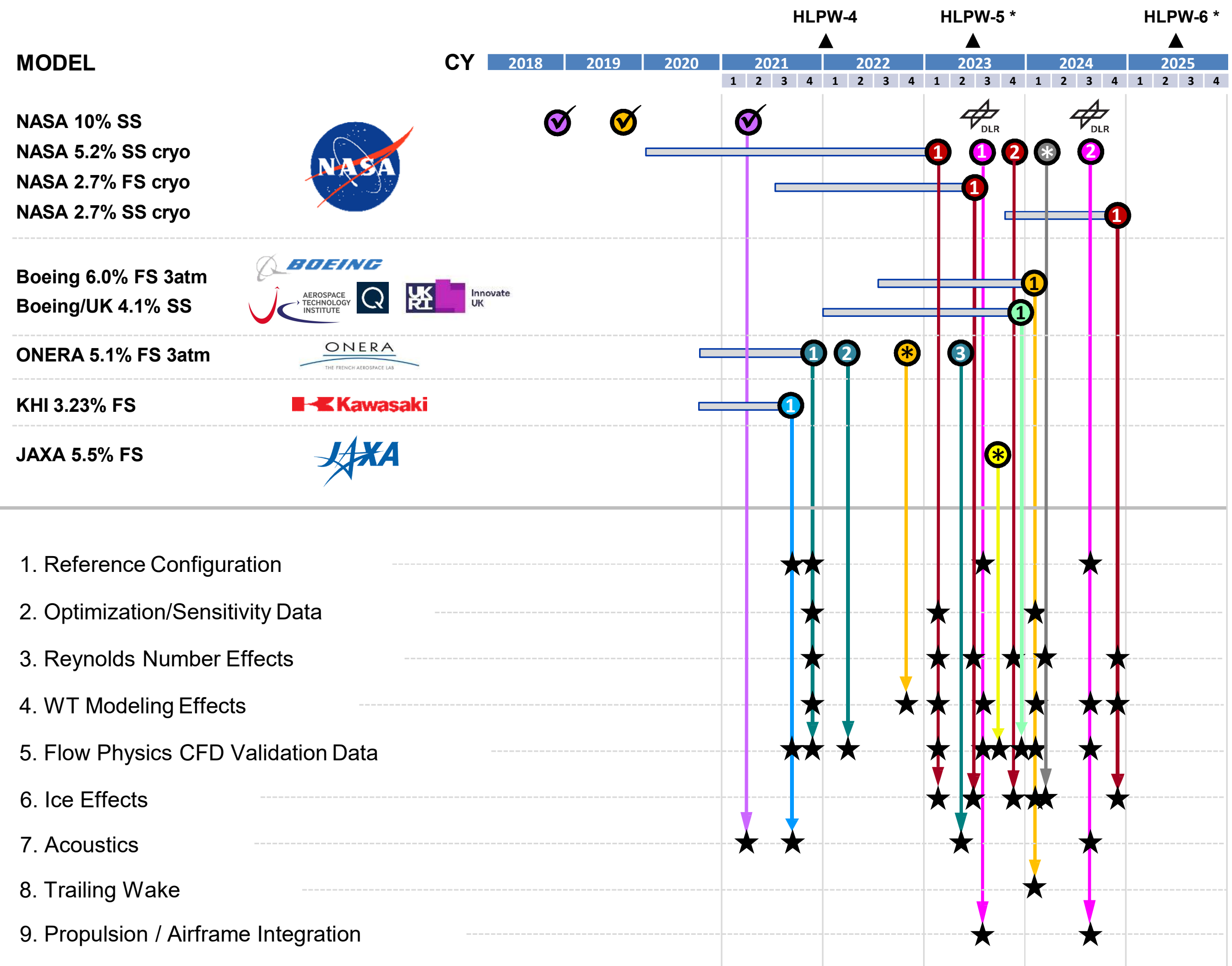
Boeing 6.0% SS/FS 3atm (Q/F1/others)
- Configuration variation data
- SS/FS model issues
- Tie in to NTF-derived Re # trend data
- Mounting system effects (T&I)
- Wall effects (collaboration with ONERA)
- Configuration-level PIV data

Boeing/UK 4.1% SS (Academic)
- Flow measurement technology development
- Platform for UK aerodynamic research

ONERA 5.1% FS 3.85atm (F1/Q)
- Wall effects (collaboration with QinetiQ)
- Exploit unique data collection opportunities
- Tunnel Standard Model

KHI 3.23% FS
- Aerodynamic and noise research
- Tunnel Standard Model

JAXA 5.5% FS
- CFD validation
- Aerodynamic research
- Tunnel Standard Model



CRM = Common Research Model

HL = High Lift

SS = Semi-Span
FS = Full Span

atm = Atmosphere

- NASA NTF
- ETW
- Q5m
- NASA 14x22
- NASA TDT
- ONERA F1
- DNW-NWB
- Imperial College
- KHI 3.3m
- JAXA 6.5x5.5

Design/Fab

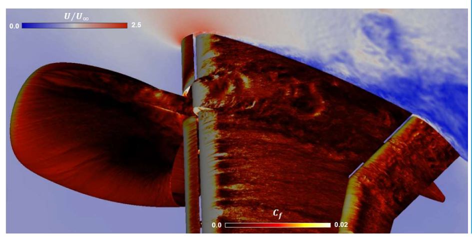
★ Test Objective

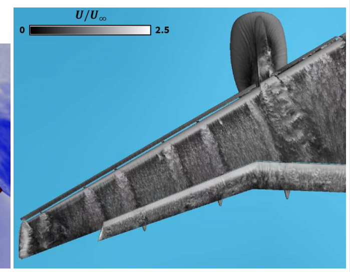
* Proposed

✓ Completed

4th High Lift Prediction Workshop (HLPW-4)

- Closely aligned with geometry/mesh generation community (GMGW)
- First in series to utilize CRM-HL configuration data **directly from ecosystem testing**
  - NASA 10% semi-span model tested in QinetiQ in 2019
  - Test cases focus on flap effectiveness, CLmax
- New approach – accelerate learning through collaborative **Technology Focus Groups (TFGs)**
  - Geometry
  - Fixed Grid RANS
  - Adaptive Meshing RANS
  - Higher-order CFD
  - Hybrid RANS-LES
  - WMLES
- Emphasis on in-tunnel simulations using “more complete” WT facility CAD definitions and run procedures





AIAA
SHAPING THE FUTURE OF AEROSPACE

4th AIAA CFD High-Lift Prediction Workshop
Sponsored by the Applied Aerodynamics Technical Committee

Co-located with the
3rd Geometry and Mesh Generation Workshop

January 2022
at the AIAA SciTech Forum and Exposition
San Diego, CA

HLPW Objectives:

- Assess the numerical prediction capability (meshing, numerics, turbulence modeling, high-performance computing requirements, etc.) of current- and next-generation CFD technology/codes for swept, medium-to-high-aspect ratio wings for landing/take-off (high-lift) configurations.
- Develop practical modeling guidelines for CFD prediction of high-lift flow fields.
- Determine the elements of high-lift flow physics that are critical for modeling to enable the development of more accurate prediction methods and tools.
- Enhance CFD prediction capability for practical high-lift aerodynamic design and optimization.

General Information:

- Participation in the high-lift prediction studies is not required to attend the workshop; everyone is welcome.
- Open, unbiased forums are included in the workshop to discuss the results and promote cross-pollination of best practices.
- Slightly modified format aimed at boosting the collaborative nature of the workshop, based on community feedback.
- The HLPW-4 test cases will utilize the High Lift Common Research Model (CRM-HL) landing configuration, and will focus on CFD prediction for flap deflection effectiveness and maximum lift ($C_{L,max}$). Data obtained from testing of the NASA 10% semi-span model in the QinetiQ 5-metre wind tunnel will be used for comparison.

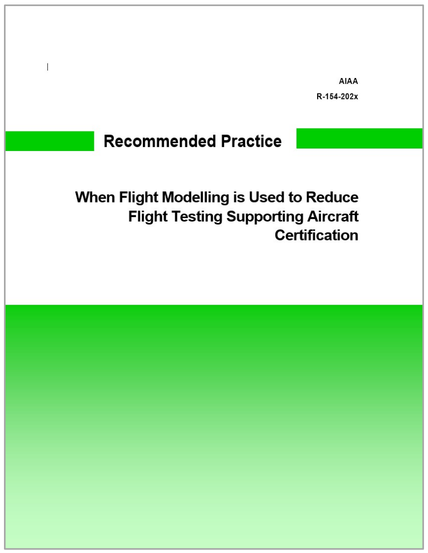
For more information, visit the HLPW website: http://hiliftpw.larc.nasa.gov or send email to: hiliftpw@gmail.com

HLPW-4
Organizing Committee Organizations:

Amazon Web Services
The Boeing Company
DLR – German Aerospace Center
Gulfstream Aerospace Corporation
JAXA – Japan Aerospace Exploration Agency
MBDA UK Ltd.
NASA – National Aeronautics and Space Administration
National Aerospace Solutions
Cadence Design Systems, Inc.
The Spaceship Company
Textron Aviation
University of Tennessee, Knoxville
University of Wyoming

https://hiliftpw.larc.nasa.gov

Certification by Analysis – Recent Community Efforts



AIAA-hosted Community of Interest (CoI)

- Started in 2018
- Report published in 2021
- International participation between industry, government research labs, academia, and regulatory agencies (50+ contributors)
- 6 recommended practices identified

American Institute of Aeronautics and Astronautics, "**When Flight Modelling Is Used to Reduce Flight Testing Supporting Aircraft Certification**," Reston, VA, R-154-2021.

NASA Research Announcement (NRA) – "CbA2040"

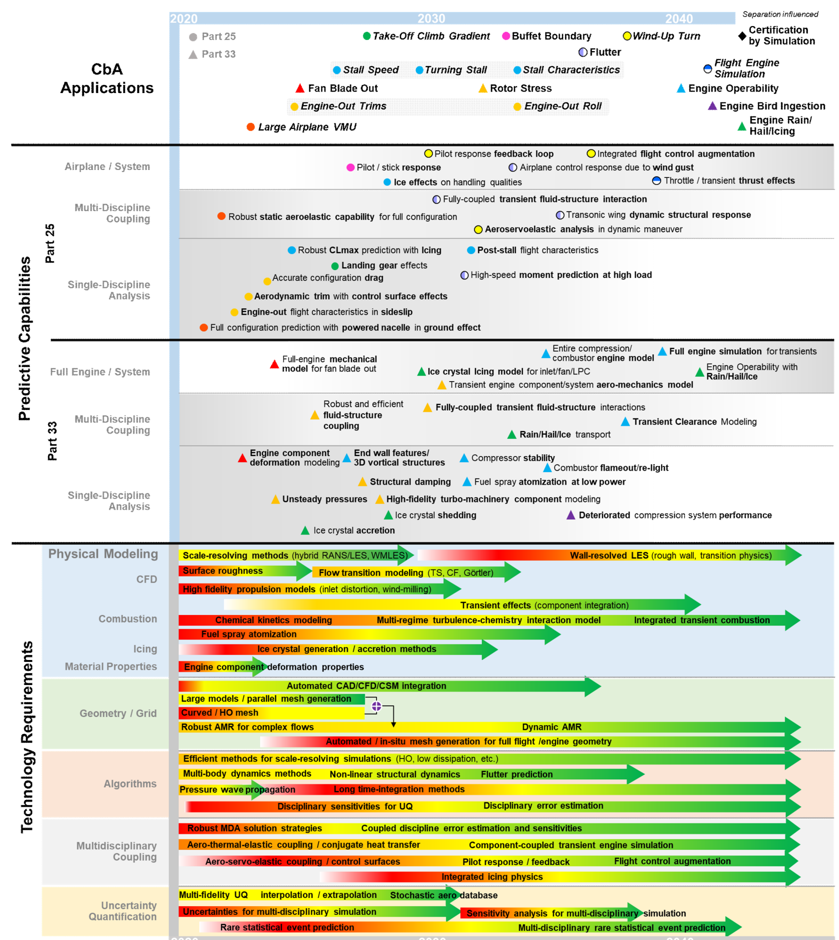
- Awarded to Boeing in 2018
- Report published in 2021
- Coordination between industry, government research labs, academia, and regulatory agencies through online survey and technical workshop
- Technology roadmap developed
- 9 technical / logistical / programmatic recommendations

https://ntrs.nasa.gov/citations/20210015404

CbA Vision 2040

- The ability to numerically simulate the **integrated system performance and response of full-scale airplane and engine configurations** in the flight and/or ground-test environment in an accurate, robust, and computationally efficient manner.
- The development and implementation of quantified **flight and engine modeling uncertainties** to establish appropriate confidence in the use of numerical analysis for certification.
- The rigorous **validation of flight and engine modeling capabilities** against full-scale data from critical airplane and engine testing.
- The use of flight and engine modeling to enable **Certification by Simulation**.

Certification by Analysis – Integrated Roadmap



Summary

- An **AIAA Integration Committee (CFD2030)** has been established to promote and advance the findings and recommendations from the CFD Vision 2030 report.
- CFD2030 actively **engages the aerospace community** through **AIAA-sponsored panel discussions and special sessions** on topics directly related to CFD Vision 2030 goals.
- The CFD Vision 2030 roadmap has been **updated to reflect progress to date**.
- Several **Grand Challenges (GCs)** in key focus areas have been developed and published. Working groups to drive progress towards the GCs will be forming in the near future.
- **CFD validation** collaborations, in combination with **CFD prediction workshops** and focused **technology roadmap development (CbA)**, are being established to accelerate learnings and progress.

- The CFD2030 IC steering committee **strongly encourages international participation** to help shape and drive efforts to advance CFD simulation technology
  - Desire to leverage **specialized expertise and knowledge**
  - Desire to promote **cross-fertilization of ideas**
  - Desire to assist with **national activities (e.g. Japan CFD Vision 2040)**