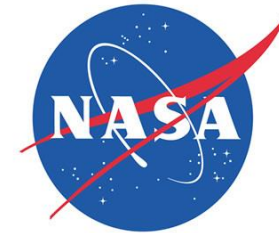# NASA Vision 2030 CFD Code
Final Technical Review

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Outline

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Acknowledgments

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  - Joerg Gablonsky, Mori Mani, Robert Narducci, Philippe Spalart, and Venkat Venkatakrishnan – *The Boeing Company*
  - Robert Bush – *Pratt & Whitney*

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  - Paul Durbin – *Iowa State University*
  - Sharath Girimaji – *Texas A&M University*
  - Brian Smith – *Lockheed Martin Corporation*

- **All who participated in the Vision 2030 CFD Survey**

Introductions

Overview of Study

- **"...Address(es) the long range planning required by NASA's Revolutionary Computational Aerosciences (RCA) sub-project, (which is managed under the Aeronautical Sciences Project) of the <u>Fundamental Aeronautics Program (FAP)</u>"**

  "…provide a knowledge-based forecast of the future computational capabilities required for <u>turbulent, transitional, and reacting flow simulations</u>…"

  "…and to <u>lay the foundation</u> for the development of a future framework/environment where physics-based, accurate predictions of complex turbulent flows, including flow separation, can be accomplished routinely and efficiently in cooperation with other physics-based simulations <u>to enable multi-physics analysis and design</u>."

Overview of Study

- **Create a comprehensive and enduring vision of CFD technology and capabilities:**
  - Define/develop CFD requirements
  - Identify shortcomings and impediments
  - Develop a long-term, actionable research plan
  - Develop a detailed technology development roadmap to
    - capture anticipated technology trends and future technological challenges,
    - guide investments for long-term research activities,

      "… the roadmap will <u>aid and support</u> NASA's long-range research planning of FAP program elements and exploit developments in physical modeling, numerical methods, software, and computer hardware to develop a system-level view of the technology required for a 2030 CFD code"

    - and provide focus to the broader CFD community for future research activities

Overview of Study

- **Develop and execute a comprehensive CFD community survey to refine the technical requirements, gaps, and impediments**

- **Based on the refined vision, hold a CFD workshop among subject matter experts within industry, government, and academia to:**
  - Get a definitive view on the relative priorities and importance of the impediments that need to be overcome
  - Develop realistic options for technical approaches and ideas for improving the CFD capability
  - Assemble suggested plans for maturing CFD technologies through the Technology Readiness Level (TRL) scale, including requirements for validation and computational resources
  - Develop a preliminary timeline for research

- **Develop and deliver a final report summarizing findings and recommendations**

Overview of Study

- **Key NASA Questions:**
  1. What hardware requirements and software attributes will characterize an advanced "Vision 2030" CFD code that is used to routinely compute complex turbulent flows, involving flow separation, at subsonic, supersonic, and hypersonic speeds, and exhibits greater robustness than current technology?

  2. How many orders of magnitude faster (time-to-solution), as compared with current capabilities, will 2030 CFD technology be?

  3. What will be the fundamental elements of 2030 turbulence models, and for what classes of problems will they be reliable?

  4. What are the principal impediments, both modeling and algorithmic, that must be overcome to achieve the 2030 CFD vision?

  5. What high-risk/high-yield obstacles remain as enduring and daunting challenges that should be the focus of long-range efforts by NASA?

Findings

1. **NASA investment** in basic research and technology development for simulation-based analysis and design **has declined significantly in the last decade and must be reinvigorated** if substantial advances in simulation capability are to be achieved.

   - Physics-based simulation is a cross-cutting technology that impacts all of NASA aeronautics missions and vehicle classes – *NAE Decadal Survey*

   - Advances in simulation capabilities are often driven by the requirement of short-term impact, or in response to simulation failure on a program → *results in incremental improvements to CFD software*

   - International government agencies (e.g., DLR, ONERA) routinely have base research and technology (R/T) elements as part of their long-term technology strategies

   - NASA's Revolutionary Computational Aerosciences (RCA) project is a step in the right direction *and should be maintained and expanded*

Findings CONTINUED

2. **HPC hardware is progressing rapidly** and technologies that will prevail are difficult to predict.

- Current advances in exascale hardware architecture involve scalar processors with 1000s of "streaming" processor cores, highly parallel memory interfaces, and advanced interconnects → *focus is on power consumption and failure recovery*

- Advanced software programming environments with higher levels of software abstraction will be required

- Current CFD tools and processes do not scale well on these systems → *improved software development, implementation, and testing is needed*

- Alternative computing architectures are under development:
  - **Quantum computers.** Much focused attention, but application to CFD is decades away.
  - **Superconducting logic.** Some initial demonstration. Low densities, high costs.
  - **Low-power memory.** Novel designs (e.g., cryogenics). Potentially higher latencies and densities.
  - **Massively parallel molecular computing.** Initial demonstrations (e.g., nanosecond biological simulation of cell synthesis). Promises speeds similar to quantum computers.

Findings

3. **The accuracy of CFD in the aerospace design process is severely limited by the inability to reliably predict turbulent flows with significant regions of separation**

    - No single "silver bullet"

    - RANS methods will continue to see broad application, and may possibly see improvement via RST methodologies

    - Hybrid RANS-LES methods show the most promise as a good compromise between accuracy and affordability → *better theoretical approaches for interface region are needed*

    - LES method development is an active area of research and is progressing → *significant investment still needed to enable the technology for broad engineering application in 2030*

    - Continued investment needed for the development of a validated, predictive, multi-scale combustion modeling capability (e.g., to optimize the design and operation of evolving fuels for advanced engines)
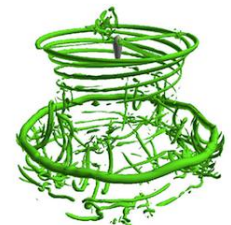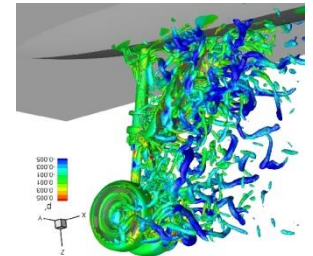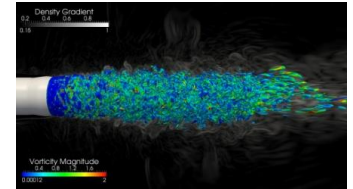
Case Study: LES Cost Estimates

- **Wall-modeled LES (WMLES) cost estimates**
  - Using explicit, 2nd order accurate finite volume/difference
  - Unit aspect ratio wing, Mach 0.2 flow

Re_c	N_{dof}	N_{iter}	FLOP	PFLOP/s
1e6	9.0e9	4.6e7	5.2e20	6
1e7	8.5e10	1.5e8	1.6e22	180
1e8	7.5e11	4.6e8	4.3e23	5,000

24 hour turn-around time

- **Comparison to current HPC #1 system: Tianhe-2**
  - 55 PFLOP/s theoretical peak; 34 PFLOP/s on Linpack benchmark
 - WMLES Re=1e6 feasible today on leadership class machines
- **2030 HPC system estimate**
  - 30 ExaFLOP/s theoretical peak
  - WMLES Re=1e8 feasible on 2030 HPC
- **Comments:**
  - These are capability computations (maxing out leadership HPC)
  - Simple geometry (unit aspect ratio; isolated, clean wing; etc)
  - Algorithmic advances critical for grand challenge problems

Findings

4. **Mesh generation and adaptivity** continue to be **significant bottlenecks** in the CFD workflow, and very little government investment has been targeted in these areas.

- Streamlined and robust geometry (e.g., CAD) access, interfaces, and integration into CFD processes is lacking

- Large-scale, automated, parallel mesh generation is needed as the size and complexity of CFD simulations increases → *goal is to make grid generation invisible to the CFD analysis process*

- Robust and optimal mesh adaptation methods need to become the norm

- Curved mesh element generation for higher-order discretizations is needed

- Consider newer strategies like cut cells, strand grids, "meshless"

Findings CONTINUED
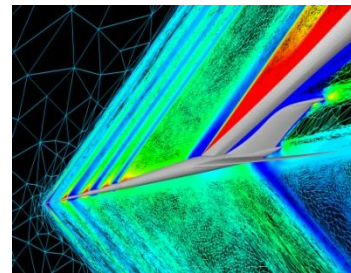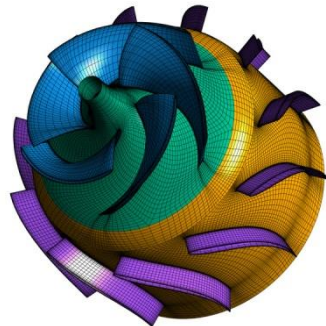
5. **Revolutionary algorithmic improvements will be required to enable future advances in simulation capability.**

- Robust convergence behavior for complex geometries and flowfields is lacking → *need automated, mesh-tolerant, monotone positivity-preserving and entropy-preserving schemes*

- Improved scalability of CFD algorithms on current and emerging HPC hardware is needed → *develop "optimal" solvers, improve discretizations (e.g., higher-order)*

- Robust uncertainty quantification methods are needed

  – Extension of output-based error techniques and grid adaptation is not robust for 3D viscous flows about complex geometries

  – Current output-based error estimates can be significantly inaccurate and/or produce unbounded errors

  – Error methods for parametric variability (e.g., boundary and initial conditions)

Case Study: Scalable Solvers

- **Basic research in optimal scalable solvers required to**
  - Advance numerical efficiency of CFD solvers (basic R&D)*
  - Capitalize on emerging HPC hardware (HPC access)*
- **Asymptotic properties of optimal solvers:**
  - Gains increase with problem size
  - Gains increase with increasing HPC parallelism
  - Orders of magnitude possible for large problems
- **Many agencies have focused scalable solver projects**
  - e.g. DoE ASCR program, CERFACS
- **Multigrid used as example**
  - Initially developed with NASA funding (Brandt & South, Jameson)
    - NASA codes utilize older NASA developed multigrid (limitations)
  - Considerable on-going development outside of NASA
    - LLNL AMG solvers demonstrated on 100,000 cores, 10^{12} DOFs
    - Not always directly transferrable to aero/CFD problems
- **Solver development should focus on techniques best suited for important NASA problems**
 - Hyperbolic, time-implicit, stiff source terms…
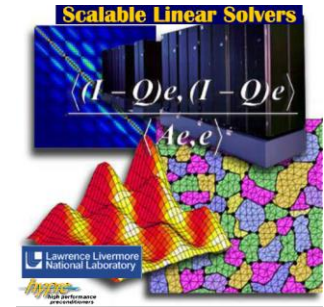
*Resources required

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Findings CONTINUED

6. **Managing the vast amounts of data generated by current and future large-scale simulations will continue to be problematic and will become increasingly complex due to changing HPC hardware.**

- Tools to effectively visualize, manage, and store single, very-large, high-fidelity simulations must improve → *development of innovative visualization and presentation techniques*

- Need for the processing (collection, synthesis, and interrogation) of thousands of CFD simulations in real-time → *ROM, "meta-models", etc.*

- Development of methods to merge CFD data with other aerodynamic source data (e.g., wind tunnel, flight data) and multi-disciplinary simulation data to create an integrated database (with confidence level) is critical

Findings

7. **In order to enable increasingly multidisciplinary simulations, for both analysis and design optimization purposes, several advances are required:**

- Individual component CFD solver robustness and automation will be required.

- Development of standards for coupling of CFD to high-fidelity simulations of other disciplines

- Emphasis on the Science of MDAO and the development of stable, accurate and conservatives techniques for information transfer

- Techniques for computing sensitivity information and propagating uncertainties in the context of high-fidelity MDAO problems
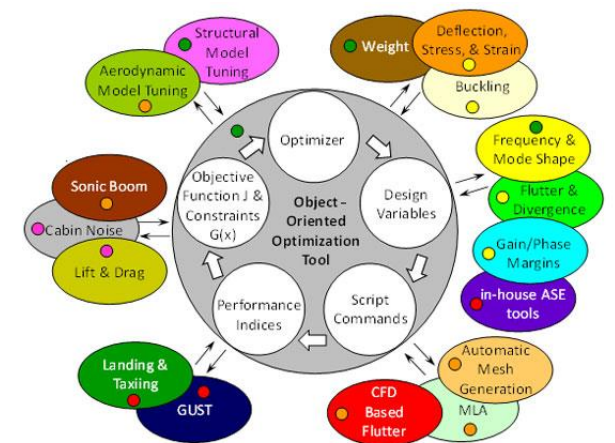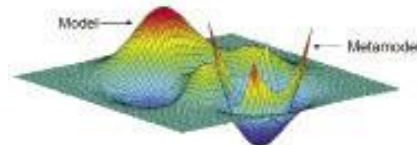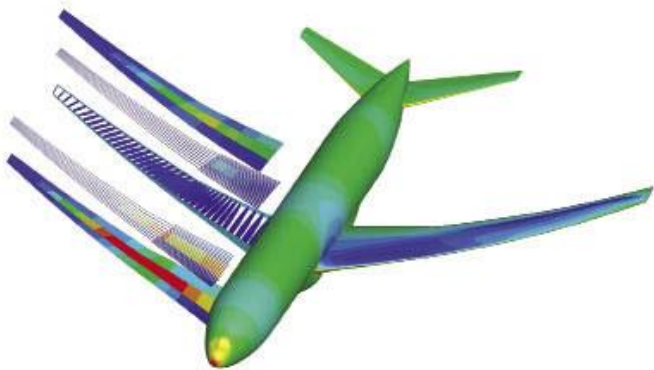
Vision of CFD in 2030

- **Emphasis on physics-based, predictive modeling**
  Transition, turbulence, separation, chemically-reacting flows, radiation, heat transfer, and constitutive models, among others.

- **Management of errors and uncertainties**
  From physical modeling, mesh and discretization inadequacies, natural variability (aleatory), lack of knowledge in the parameters of a particular fluid flow problem (epistemic), etc.

- **A much higher degree of automation in all steps of the analysis process** Geometry creation, mesh generation and adaptation, large databases of simulation results, extraction and understanding of the vast amounts of information generated with minimal user intervention.

- **Ability to effectively utilize massively parallel, heterogeneous, and fault-tolerant HPC architectures that will be available in the 2030 time frame** Multiple memory hierarchies, latencies, bandwidths, etc.

- **Flexible use of HPC systems**
  Capability- and capacity-computing tasks in both industrial and research environments.

- **Seamless integration with multi-disciplinary analyses**
  High fidelity CFD tools, interfaces, coupling approaches, etc.
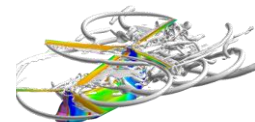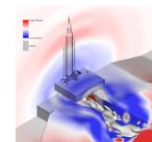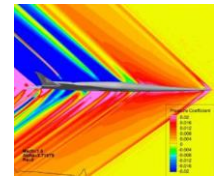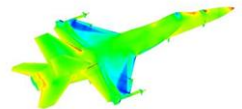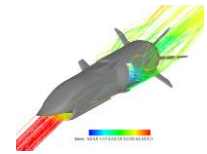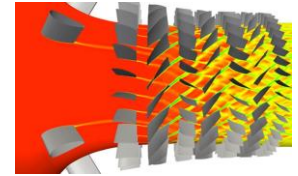
Grand Challenge Problems

- **Represent critical step changes in engineering design capability**

- **May not be routinely achievable by 2030**

- **Representative of key elements of major NASA missions**

1. Large Eddy Simulation (LES) of a powered aircraft configuration across the full flight envelope

2. Off-design turbofan engine transient simulation

3. Multi-Disciplinary Analysis and Optimization (MDAO) of a highly-flexible advanced aircraft configuration

4. Probabilistic analysis of a powered space access configuration
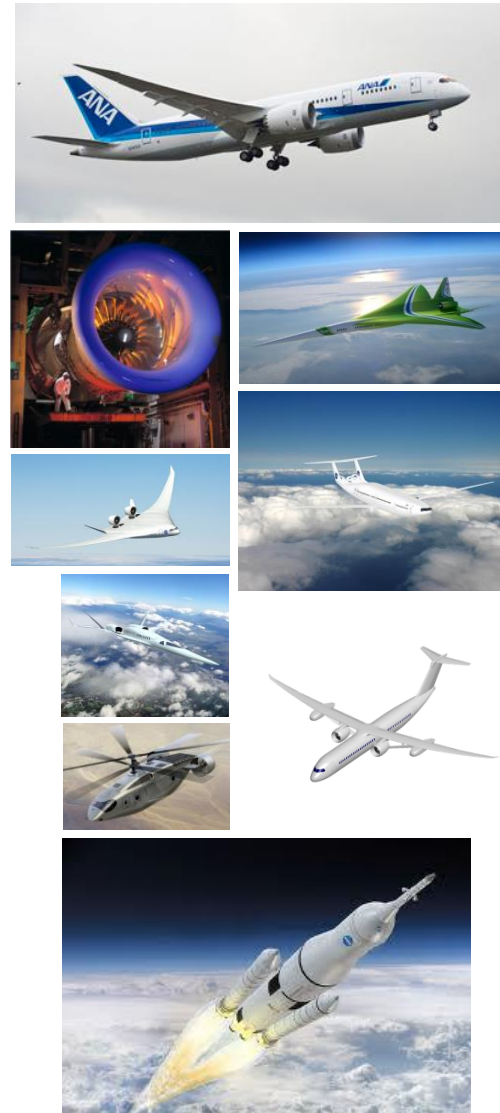
LES of a Powered Aircraft Configuration Across the Full Flight Envelope

- **Assess the ability to use CFD over the entire flight envelope, including dynamic maneuvers**

- **Assess the ability of CFD to accurately predict separated turbulent flows**
    - Monitor increasing LES region for hybrid RANS-LES simulations
    - Evaluate success of WMLES
    - Determine future feasibility of WRLES

- **Assess the ability to model or simulate transition effects**

- **Project future reductions in wind tunnel testing**
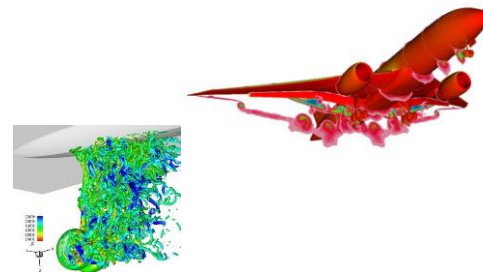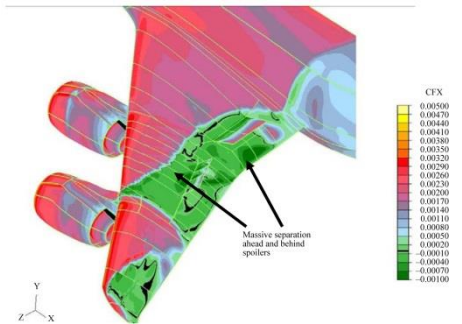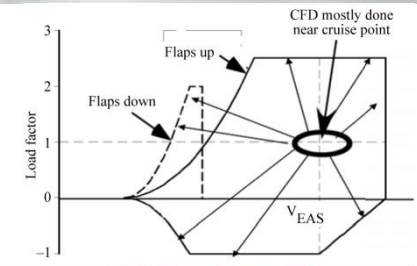
Off-Design Turbofan Engine Transient Simulation

- **Measure progress towards virtual engine testing and off-design characterization**

- **Assess the ability to accurately predict:**
    - Separated flows
    - Secondary flows
    - Conjugate heat transfer
    - Rotating components, periodic behavior

- **Potential to demonstrate industrial use of WRLES for lower Re regions**

- **Assess progress in combustion modeling and prediction abilities**
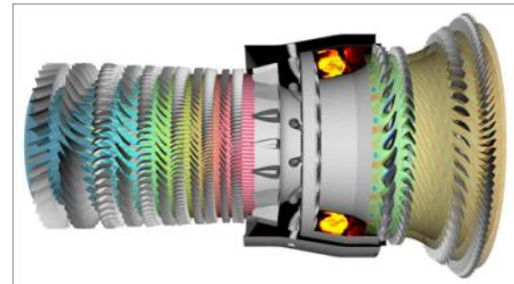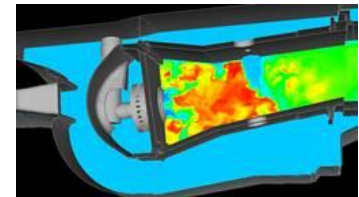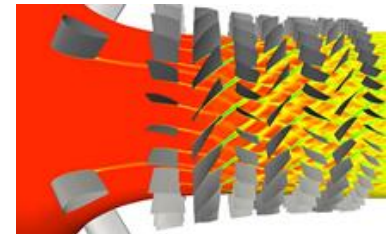
MDAO of a Highly-Flexible Advanced Aircraft Configuration

- **Ultimate utility of CFD for aerospace engineering is as component for MDAO**
- **Future vehicle configurations to be highly flexible**
- **Assess progress in analyzing the important multidisciplinary problems: Science of coupling**
  - Time dependent
  - Aero-structural
  - Aero-servo-elastic
  - Aerothermoelastic
- **Assess multidisciplinary optimization capabilities**
  - Availability of sensitivties
  - Performance of optimizations
  - Optimization under uncertainties

Probabilistic Analysis of a Space Access Vehicle

- **Opening up new frontiers in space vehicle design hinges on development of more capable high-fidelity simulations**

- **Assess specific relevant capabilities**
  - Separated turbulent flows
  - High-speed/hypersonic flows
  - Aero-plume interactions
  - Aerothermal predictions

- **Emphasis on reducing risk through uncertainty quantification techniques**
  - Unique configurations
  - Limited experience base
  - Difficult conditions for ground-based testing
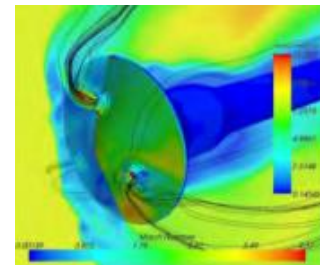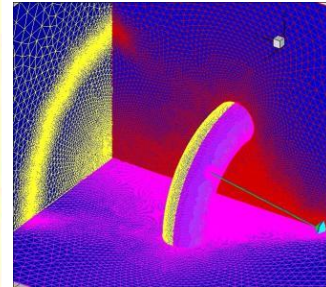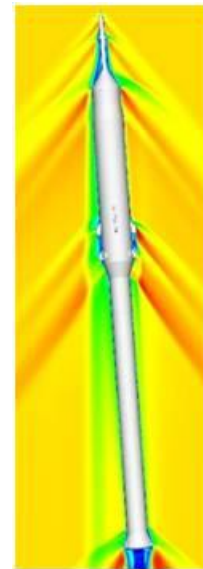
Technology Roadmap
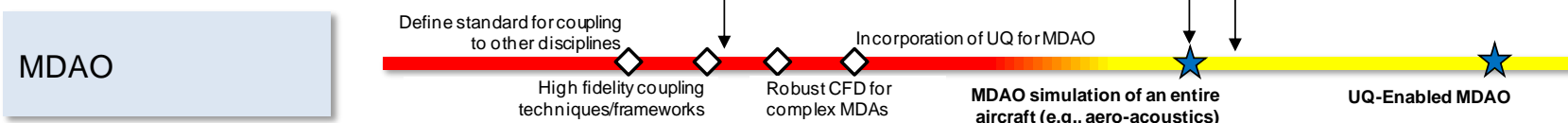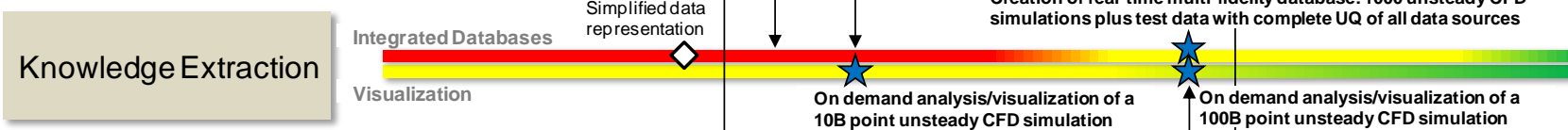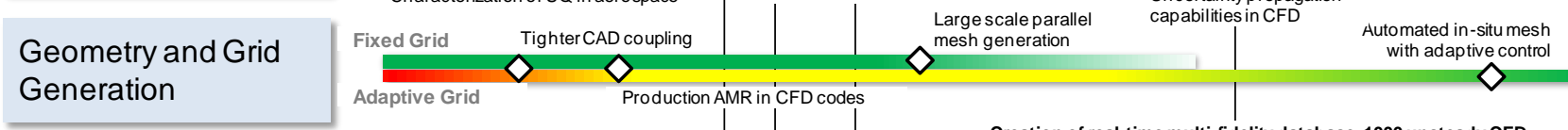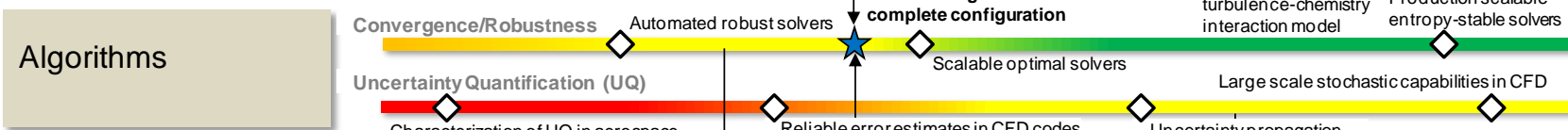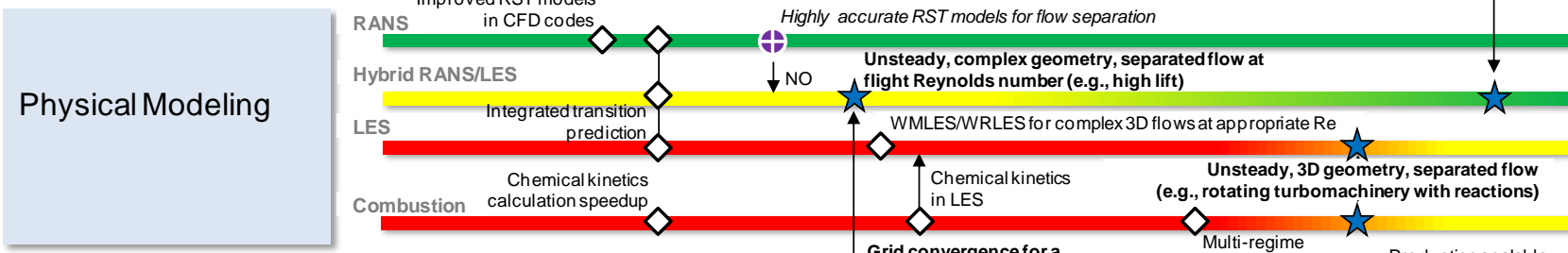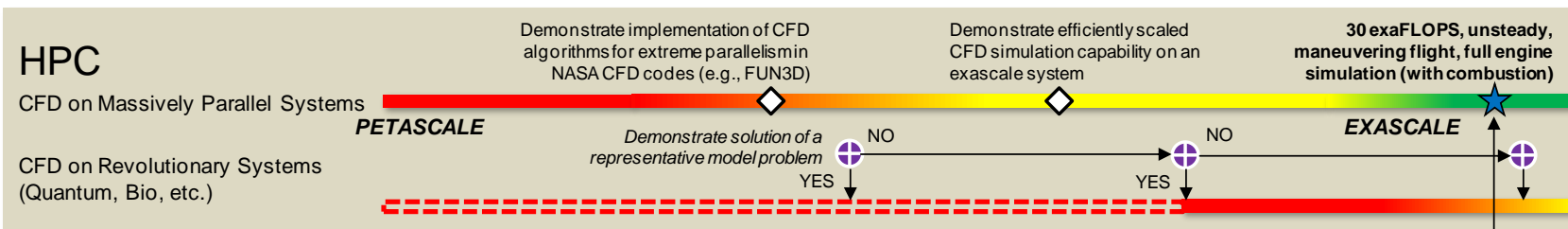
Recommendations

1. **NASA should develop, fund and sustain a base research and technology (R/T) development program for simulation-based analysis and design technologies.**

   - Required to fulfill technology development plan and address Grand Challenge problems

   - RCA program to coordinate ALL key CFD technologies, including combustion and MDAO→ *structured around six technology areas*

   - Success will require collaboration with experts in mathematics, computer science, computational geometry, and other aerospace disciplines

AERONAUTICS RESEARCH MISSION DIRECTORATE (ARMD)

FUNDAMENTAL AERONAUTICS PROGRAM

AERONAUTICAL SCIENCES PROJECT

STRUCTURES AND MATERIALS · CONTROLS · INNOVATIVE MEASUREMENTS · COMBUSTION · MDAO

SCIENCE MISSION DIRECTORATE (SMD)

HUMAN EXPLORATION AND OPERATIONS DIRECTORATE (HEO)

REVOLUTIONARY COMPUTATIONAL AEROSCIENCES (RCA)

- HPC
- Physical Modeling:
  - Turbulence
  - Transition
  - Combustion
- Numerical Algorithms
- Geometry/Grid
- Knowledge Management
- MDAO (Interfaces/coupling)

■ New thrust
↔ Shared investment and technology collaboration
---- Close coordination

Recommendations CONTINUED

HPC

1. Increasing access to leading-edge HPC hardware
2. Porting of current and future codes to leading-edge HPC
3. Radical emerging HPC technologies

GEOMETRY AND GRID GENERATION

1. CAD access and interfaces
2. Large scale parallel mesh generation
3. Adaptive mesh refinement

PHYSICAL MODELING

1. RANS turbulence model
2. Hybrid RANS-LES modeling
   a. Improved RANS component
   b. Seamless interface
3. LES (wall-modeled and wall-resolved)
4. Transition
5. Combustion

KNOWLEDGE EXTRACTION

1. Visualization
2. Data-base management
3. Variable fidelity models

MDAO

1. Interfaces and standards
2. Accurate and stable coupling techniques
3. UQ support and sensitivities (system-level)

NUMERICAL ALGORITHMS

1. Advances in current algorithms for HPC
2. Discretizations
   a. Higher-order methods
   b. Low dissipation/dispersion schemes
   c. Novel foundational approaches
3. Solvers
   a. Linear and non-linear scalable solvers
   b. Enhancements for MDAO and UQ
4. UQ
   a. Define aerospace uncertainties
   b. Leverage known techniques
   c. Improved error estimation techniques
   d. Statistical approaches

Recommendations CONTINUED

2. **NASA should develop and maintain an integrated simulation and software development infrastructure to enable rapid CFD technology maturation.**

- Maintain a world-class in-house simulation capability
  - Superior to capabilities within academia and industry
  - Cover all key vehicle classes (e.g., external aero, turbomachinery, science and space)
  - Critical for understanding principal technical issues, driving development of new techniques, and demonstrating capabilities
- Streamline and improve software development processes
  - Create formal software development, maintenance, and testing environment to build new and/or enhance existing NASA CFD tools and processes → *streamlines efforts, synergizes development teams, reduces costs*
- Emphasize CFD standards and interfaces
  - Emphasize common ways of exchanging data (e.g., geometry, grid, MDAO) → streamlines and optimizes development efforts
  - Must identify ALL key stakeholders, develop consensus, and advocate for standard approaches

Recommendations CONTINUED

3. **NASA should make available and utilize HPC systems for large-scale CFD development and testing.**

   - Provide access to large-scale computing for both throughput (capacity) to support on-going programs, but also development (capability) to directly support technology demonstrations and progress towards Grand Challenge problems.

     – Mitigates stagnating simulation capabilities

     – Drives progress by testing new algorithms at scale

     – Develops a more experienced and effective user base both within and outside NASA

   - Leverage existing internal, as well as other national HPC resources

   - Provide access to novel HPC platforms (e.g., D-Wave) to accelerate technology development

Recommendations

4. **NASA should lead efforts to develop and execute integrated experimental testing and computational validation campaigns.**

- High quality experimental test data for both fundamental, building-block and complex, realistic configurations, coupled with careful computational assessment and validation, is needed to advance CFD towards the Vision 2030 goals

- NASA is uniquely positioned to provide key efforts in this area due to the availability of experimental test facilities and experience, as well as key expertise to benchmark CFD capabilities
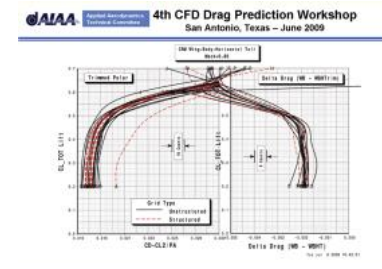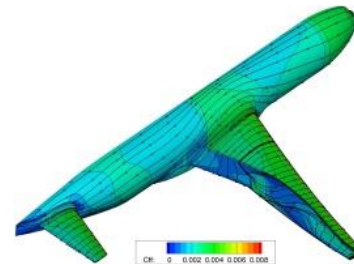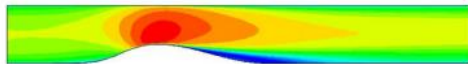
Recommendations

5. **NASA should develop, foster, and leverage improved collaborations with key research partners and industrial stakeholders across disciplines within the broader scientific and engineering communities.**

   - Leverage other government agencies and stakeholders (US and foreign) outside of the aerospace field → *collaborate with DoE, DoD, NSF, NIST, etc.*

   - Actively pursue collaborations with both academia AND industry → *Enables accelerated efforts for CFD advances in full flight envelope, reduction of physical testing, and certification by analysis*

   - Emphasize basic funding in applied math and computer science → *Advanced developments in CFD will require breakthroughs in numerical algorithms and efficient solution techniques for emerging HPC systems*

   - Embrace and establish sponsored research institutes → *acts as a centralized focal point for the development of cross-cutting disciplines, engages the broader scientific community, and executes a long-term research strategy*

Case Study: Sponsored Research Institutes

- **Research institutes provide an effective mechanism for:**
  - Engaging broader scientific community
  - Centralizing multidisciplinary & cross-cutting technology R&D
  - Enable long-term focus while aligning with agency missions

- **Self supporting institutes deemed unfeasible**
  - Compromises long term focus
  - Poorly aligned with NASA missions

- **Examples of aerospace computational science institutes**
  - CERFACS
    - Multidiscplinary: aero, climate, computer science
    - Includes public and private funding (6 shareholders)
  - $C^2A^2S^2E$
    - Highly focused on external aeronautics
    - Includes public and private funding
  - ICASE
    - Highly successful
    - Long term focus required core funding and independent agenda

- **Institute structure and strategy more important than funding levels**
  - Must be considered carefully
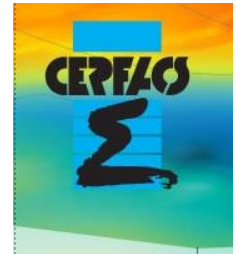
Recommendations

6. **NASA should attract world-class engineers and scientists.**

- Success in achieving the Vision 2030 CFD capabilities is highly dependent on obtaining, training, and nurturing a highly educated and effective workforce → *need for researchers, developers, and practitioners from diverse backgrounds*

- How?

  - Expand fellowship programs in key computational areas

  - Encourage and fund long-term visiting research programs

  - Provide visiting students with meaningful opportunities to make progress towards the solution of Grand Challenge problems

Answers to the Key NASA Questions

1. **What hardware requirements and software attributes will characterize an advanced "Vision 2030" CFD code that is used to routinely compute complex turbulent flows, involving flow separation, at subsonic, supersonic, and hypersonic speeds, and exhibits greater robustness than current technology?**

   - HPC systems that provide a dramatic increase in computational power, are fault tolerant, and are available and affordable for the routine, production design and analysis of aerospace vehicles and systems
   - CFD flow solvers that:
     - run efficiently on future exascale systems,
     - predict vehicle/system performance with certifiable accuracy and full quantification of errors,
     - utilize optimal solution schemes and intuitive, parameter-free interfaces,
     - fully incorporate mesh generation and adaptation as part of the solution,
     - employ advanced turbulence and transition models that predict all types of flow separation,
     - are seamlessly integrated into visualization and data mining techniques, and
     - are effectively coupled with other disciplines in computational mechanics

Answers to the Key NASA Questions

2. **How many orders of magnitude faster (time-to-solution), as compared with current capabilities, will 2030 CFD technology be?**

- Expect 1000-10000x increase in computational power which will enable:
  - 10^{11} grid point or equivalent high-order resolution full-configuration steady-state RANS simulations in *minutes* on commodity hardware, or 10^{12} grid point simulation in *seconds* on leadership hardware
  - Equivalent highly resolved steady-RANS based optimization in *minutes* to *hours*
  - Highly resolved time-dependent production RANS simulations (e.g., full rotorcraft simulations at high spatial and temporal resolution ($1/10^{th}$ degree time step, hundred revs) in *hours* on commodity hardware)
  - Increased emphasis on including more complex physics into the simulations
  - Generation of a complete, CFD-based aerodynamic database (~10,000 data points) in *under one day* using steady RANS (for all flight regimes)
  - Tightly coupled multidisciplinary simulations (e.g. aeroelastic, aerothermoelastic, aeroservoelastic, maneuvering aircraft/digital flight) and optimizations at varying levels of fidelity *overnight* on commodity hardware and in *hours* on leadership hardware

Answers to the Key NASA Questions CONTINUED

3. **What will be the fundamental elements of 2030 turbulence models, and for what classes of problems will they be reliable?**

- Hybrid RANS-LES methods will continue to improve
  - RANS will cover the area where the boundary layer (BL) is too thin for LES (and the area will shrink as computing power rises)
  - Simulations at low Reynolds numbers may be treated with LES only
  - All high Reynolds number LES will be Wall-Modeled LES

- RANS models will remain very empirical
  - Reynolds-Stress Transport models will improve…
  - …but may or may not retire "few-equation" models, especially non-linear versions

- Transition prediction will become much more routine
  - e^n methods and those based on empirical transport equations will co-exist
  - The primary challenge is integration of e^n methods with flow solvers

- The accuracy of aerodynamics CFD will be competitive with wind tunnels
  - Fair or better prediction of BL transition and separation (RANS + LES)
  - Fair or better predictions after massive separation (LES)
  - Affordable for attached flows; expensive for wide range of scales (e.g., AFC)
  - Full Reynolds number and Mach number with access to flow field data leading to better understanding of flow physics through advanced visualization

- CFD combustion predictions will be less competitive (than aero)
  - Turbulent combustion models will remain challenged by modeling at the subgrid scale

Answers to the Key NASA Questions CONTINUED

4. **What are the principal impediments, both modeling and algorithmic, that must be overcome to achieve the 2030 CFD vision?**

- Effective utilization of HPC
  - Need for scalable solver/algorithm/pre-post-processing development
  - Software issues/programming paradigm
  - Lack of access to HPC for scalable software development and testing

- Physical modeling
  - Turbulent separated flow:
    - RANS models stagnant and inadequate
    - Hybrid RANS-LES rely on RANS and require better RANS-LES interface
    - Sheer cost of LES with current discretizations/solvers
  - Transition modeling
  - Combustion

Answers to the Key NASA Questions

4. **What are the principal impediments, both modeling and algorithmic, that must be overcome to achieve the 2030 CFD vision?**

- Autonomous and reliable CFD
  - Cumbersome CAD/mesh/adaptivity processes
  - Lack of optimal and scalable solvers (impediment grows with problem size)
  - Unreliable error estimates
  - Uncertainty quantification implemented as after-thought or not at all

- Knowledge extraction and visualization
  - Effective analysis of large simulation (e.g. parallel co-visualization)
  - Real time processing of entire simulation databases
  - Merging of variable fidelity simulation data and experimental data

- Multi-disciplinary/multi-physics simulations and frameworks
  - Robustness and automation of CFD within MDAO
  - Science of multidisciplinary coupling at high fidelity
  - Fully coupled sensitivities
  - Frameworks/standards

Answers to the Key NASA Questions

5. **What high-risk/high-yield obstacles remain as enduring and daunting challenges that should be the focus of long-range efforts by NASA?**

    - Daunting challenge:
      - Develop reliable physics-based high-fidelity MDAO tools for aerospace vehicle analysis, design, and reduce risk through quantifiable uncertainties
        - For aeronautics and space vehicles

    - High-Risk/High-Yield:
      - Our listed obstacles show that this will not be achieved by investment in one or two specific technologies (e.g. current LES approaches remain out of reach due to cost considerations)
      - Requires investment in broad range of synergistic technologies to bring step changes in simulation capability to fruition
        - Foundational (applied math, computer science, physical modeling)
        - Combine algorithmic advances with HPC advances

    - Organizational, cultural, and collaborative challenges are just as important as technical challenges and must be addressed

Backup

Thoughts on Revolutionary Approaches

- **Advances in CFD between now and 2030 will likely include both *evolutionary* improvements to current tools, methods, and processes, and *revolutionary*, "paradigm-shifting" advances in technology.**

- **Although revolutionary breakthroughs cannot be predicted, emerging technologies that promise significant advances in capability, such as quantum or bio-computing, must be properly followed and nurtured.**

- **Evolutionary improvements in CFD technology (e.g., upwind shock capturing algorithms) do lead to revolutionary advances in simulation capability (e.g., routine prediction of cruise drag).**

Unstructured mesh technology development:

- First demonstration of full aircraft CFD using unstructured mesh (full potential) : Dassault Aviation **1982**

- First demonstration of full aircraft CFD using unstructured mesh (Euler equations): Jameson **1985**

- NASA unstructured mesh development: initiated in **1990's** (FUN3D)

- Unstructured mesh RANS solvers dominant approach (e.g. DPW series by late **2000s**)

4   © Copyright 2011 D-Wave Systems Inc.
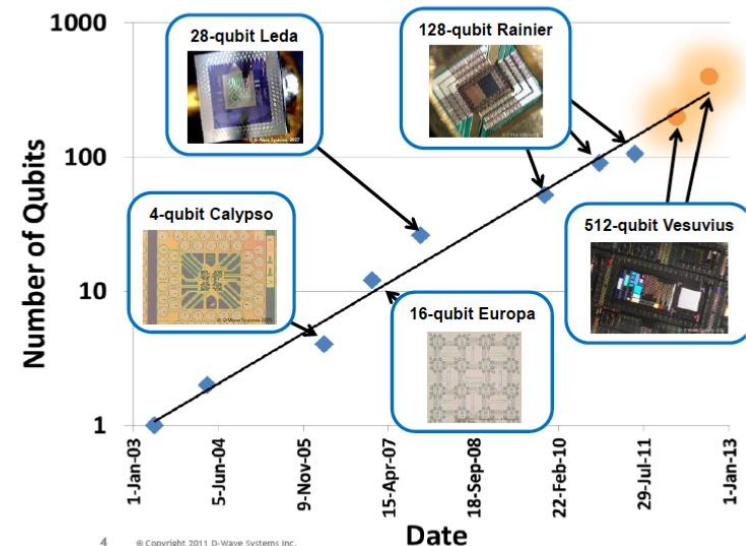
CFD Survey

- **Objectives**
  - Collect critical feedback from the engineering and scientific communities on key topics related to CFD
  - Develop definitive views on CFD requirements, shortcomings, and impediments
  - Identify key discussion topics for CFD workshop
- **Conducted during February 2013**
  - Hosted by SurveyMonkey
  - 175 total participants
  - 22 total questions (14 technical)
  - Excellent feedback (especially the written responses)

CFD Survey – What We Learned

1. CFD requirements captured well by Vision 2030 CFD team

2. 68% would use increases in HPC for **MDA/O and multi-physics analysis**

3. Most important enhancement to CFD: Increased accuracy of **flow physics modeling**

4. Critical impediments: Lack of validation datasets, academia/govt/industry coordination, CFD best practices

5. Primary focus of turbulence model development: **Enhancement to hybrid RANS/LES models**

6. User aspects: More automation, faster visualization, need for hard error estimates, more feedback (solver, trouble areas)

7. MDA/O: Most critical discipline to couple – **Structures**

8. MDA/O: Key issue – **Integration**

CFD Survey – What We Learned

9. **Revolutionary capabilities**: Certification, maneuvering flight, full flight envelope + aeroelastics + complete engine effects

10. CFD software development: Better **interaction between math/CS/engineering**, better **software engineering practices**

11. HPC: Speed-up likely through **parallelism**, Quantum computing unlikely to be ready by 2030

12. Long term development plan: Improvements to physical modeling and numerical algorithms (44%), streamlining and error-proofing of CFD processes (25%), enhancements to parallel computing efficiency (19%)

13. Use and impact: CFD will be easier for non-experts, CFD will be used earlier in the design process, CFD will reduce/replace physical testing

14. Development and validation of **large-scale CFD simulations**

CFD Workshop

- **Develop consensus view of key requirements and impediments**

- **Held 1-2 May 2013 at NIA in Hampton, VA**

- **50+ attendees (16% academia, 46% government, 32% industry, 6% CFD software vendors)**

- **7 sessions each covering a specific discussion topic:**
  - Revolutionary Thoughts
  - HPC Trends, Software Development
  - Turbulence Modeling, Separated Flows, etc.
  - Numerics, Error Quantification, Solution Quality
  - Geometry, Grid, CFD Process
  - Complex Flow Physics
  - MDA/O, Multi-Physics

CFD Workshop – Key Issues

- **Unsteady, turbulence/transition/separated flows**
  - Numerical efficiency and accuracy
- **Autonomous and reliable CFD**
  - ★ Geometry
  - Grid generation, adaptation, convergence
  - UQ: Modeling, Numerical, Natural Variability
- **Knowledge extraction**
  - Data mining, data fusion (merging CFD/test, etc.), "Big Data"
- **HPC challenges**
- **Interface/frameworks for MDA/O, multi-physics**
- **CFD Validation**
- ★ **Coordination/Collaboration**
- ★ **Education of the CFD Workforce**

★ "Surprise"

Team Structure

Boeing Research & Technology
Greg Hyslop, President

Technical Advisory Team
Mark Anderson, Leader

Boeing Business Team
Kurt Bratten

Flight Sciences Technology
Mark Anderson, Director

Program Manager
Abdi Khodadoust

NASA COTR
William Kleb

Airframe
Boeing
Jeffrey Slotnick
Principal Investigator

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- K. Bowcutt, Boeing
- M. Mani, Boeing
- R. Narducci, Boeing
- P. Spalart, Boeing
- J. Vassberg, Boeing
- V. Venkatakrishnan, Boeing

Propulsion
Pratt & Whitney
Elizabeth Lurie
Focal

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- J. Croxford, Boeing
- M. Lamoureux, P&W
- W. Lord, P&W
- R. Shaw, Boeing
- N. Somanath, P&W

HPC
NCSA
William Gropp
Focal

- D. Dominik, Boeing
- P. Fussell, Boeing
- J. Gablonski, Boeing

Academia
Research Team
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Focal

- J. Alonso, Stanford
- D. Mavriplis, Wyoming

NASA and Government Lab Researchers

- Sandia
- AFRL
- …

Statement of Work
3.2 Initial Vision of 2030 CFD Code

- **3.2.1 Initial Vision Development**
  - Collect and establish requirements **(Deliverable 2)**
  - Identify shortcomings and gaps in current CFD technology
  - Consider interplay of 2030 CFD Code with multi-physics analysis capabilities, quantification of computational uncertainty, and emerging High Performance Computing (HPC) infrastructure
  - Identify impediments to achieving the 2030 Vision CFD Code

- **3.2.2 Survey of CFD Community**
  - Develop and conduct comprehensive technical survey to pulse CFD and scientific communities on CFD requirements, gaps, limitations, and impediments
    - NASA Centers
    - Government Labs
    - Aerospace Industry
    - Academic Institutions
    - HPC Community
    - CFD Vendors
  - Develop list of CFD limitations, gaps, and impediments **(Deliverable 3)**

Statement of Work
3.3 Refined Vision of 2030 CFD Code

- **3.3.1 Collect Survey Feedback (Deliverable 4)**
  - Create a comprehensive summary of CFD community survey results
  - Obtain feedback from CFD community on survey results

- **3.3.2 Vision 2030 CFD Code Workshop**

  - Plan and host a 2-3 day joint workshop between Boeing team members, NASA FAP and CFD leaders, and the broader CFD community
    - Establish a definitive view on requirements, priorities, roadblocks, and impediments
    - Develop realistic technical approaches and generate new ideas in improving CFD capability
    - Assemble consensus and actionable plans for maturing CFD technologies (using the TRL scale), including identifying validation activities and computational resources
    - Develop initial timeline for required research

Statement of Work
3.4 Mid-Term Review

- Present a finalized vision of the 2030 CFD Code

- Present an outline of the initial research plan and technology development roadmap

- Develop and deliver mid-term review presentation package **(Deliverable 5)**

Statement of Work
3.5 Vision 2030 CFD Code Integrated Plan and Roadmap

- **3.5.1 Develop Detailed Research Plan and Roadmap**
  - Technology trends
  - Anticipated technology challenges
  - Success metrics and appropriate exit criteria
  - Estimated 2030 code performance

- **3.5.2 Develop System-Level View of Architecture**
  - Numerical algorithms and solution technology
  - Software design
  - Acknowledge and consider likely interconnectivity with future multi-disciplinary design/optimization and analysis systems

- **3.5.3 Answers to the Key NASA Questions**

Statement of Work
3.6 Final Review

- Present a complete summary of the Vision 2030 CFD Code including comprehensive research plans and technology roadmap

- Develop and deliver final review presentation package **(Deliverable 6)**

Statement of Work
3.7 Final Report

- Provide a written report for the complete summary of the Vision 2030 CFD Code including comprehensive research plans and technology roadmap **(Deliverable 7)**

Deliverables

#	DELIVERABLE	TASK REF	FORMAT	DATE
1	Kickoff meeting presentation package	3.1	Presentation MS Powerpoint	26 October 2012
2	Initial 2030 CFD Code Requirements	3.2.1	Informal Report MS Word	28 November 2012
3	CFD limitations, gaps, and impediments	3.2.2	Informal Report MS Word	21 December 2012
4	Survey Input Summary	3.3.1	Informal Report MS Word	28 February 2013
5	Mid-term Technical Review Presentation Package	3.4	Presentation MS Powerpoint	27 March 2013
6	Final Technical Review Presentation Package	3.6	Presentation MS Powerpoint	28 August 2013
7(a)	Final written report (draft)	3.7	NASA Contractor Report Format	28 August 2013
7(b)	Final written report			27 September 2012
8	Monthly Project Telecon minutes	5.2	Informal Report MS Word	5 working days after meeting
9	Monthly Progress Reports	5.3	Informal Report MS Word	15th calendar day of following month

PROPOSED

Meeting & Teleconference Schedule

REF	MEETING	DATE	DURATION	LOCATION
3.1	Kick-Off Meeting	31 October 2012	1 Day	NASA Langley
4.1	Monthly Project Meeting Telecons	3rd Thursday of each month (8am-9am PST)	1 hr	Telephone WEBEX
3.3.2	2030 Vision CFD Code Workshop	5-7 March 2013	3 Days	TBD
3.4	Mid-Term Technical Review	27-28 March 2013	2 Days	NASA Langley
3.6	Final Technical Review Meeting	24-25 September 2013	2 Days	NASA Langley

Technical Approach

2030

NASA
Requirements developed for N+2/N+3 systems, including noise, emissions, fuel consumption targets, etc.

Academics
Gov't Labs
Industry Labs

Identify current CFD technology **gaps** and **shortcomings**

Industry
Define anticipated aerodynamic and performance **requirements** for competitive aerospace vehicle and systems

Determine **impediments** and **roadblocks**

HPC
Establish expected **computing performance** and **likely outlook for CFD technology application**

DoD

Detailed Research Plan and Technology Roadmap

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