Integrated (Physical and Digital) Collaborative Experimentation: Advancing Dialog and Leveraging by Aerospace Researchers and Developers

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This paper 1) documents findings and observations from the American Institute of Aeronautics and Astronautics (AIAA) Ground Test Technical Committee (GTTC) Future of Ground Test Working Group and the Applied Aeronautics Technical Committee (APATC) Collaborative Experiments & Computation Discussion Group, and 2) develops a more focused approach for sharing and advancing integrated development and use of physical experimental and computational capabilities for aerospace research and development. The GTTC and APATC are engaging with the larger AIAA technical community by creating a Focus Group on this topical area that will support working together on common interests in the public domain. This paper summarizes the knowledge capture from the last ten+ years and proposes a structure and scope going forward for the new, combined Focus Group.

I. Introduction

In the early 2000's, the American Institute of Aeronautics and Astronautics (AIAA) Ground Test Technical Committee (GTTC) was tasked to produce some form of report or opinion paper to predict the future of ground testing. This has long been the challenge for those responsible for ensuring readiness. To paraphrase Gen. Hap Arnold, "research and development ground test capabilities must be developed and fielded in advance of need; if we wait and start when needed, we've missed it" [1]. This requires having some decent vision of the future and using that to justify and gain buy-in to develop and field capabilities in advance of need.

Since (actually, preceding) the early days of flight, physical aeronautical ground testing was used in conjunction with mathematical theory development to understand and verify the physics of flight. Early basic wind tunnels and propulsion stands were used for research and development (R&D) but were challenged to keep up with technology advancements – so, often unsafe flight testing was used to try new things and expand flight envelopes. Through World War II, ground testing was critical for foundational and applied research, concept development, and interactive verification with flight testing – while constantly improving data products to be sufficiently predictive for as yet unproduced geometries/systems, with 'reasonable' uncertainties between verification points.

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As the United States (US) Army Air Corps began to mature in the mid-1930's under the leadership of Gen. Arnold, he drew on relationships he had fostered with key university researchers to focus research and development on growing military needs. Later, after experiencing the rapid advancement of German aviation and rocketry, Gen Arnold appointed Dr. Theodore Von Karman in 1944 to chair the inaugural US Army Air Forces Scientific Advisory Group with the task to "think ahead twenty years … I wanted them to think about supersonic-speed airplanes, airplanes that would move and operate without crew, improvements in bombs … defenses against modern and future aircraft … communication systems … television … weather, medical research, atomic energy, and any other phase of aviation which might affect the development of the airpower to come. [2]."

Dr. Von Karman's team produced "Toward New Horizons" in 1945 [3], with the Introduction/Summary volume "Science, the Key to Air Supremacy" being a major selling logic toward Congress and President Truman passing the "Unitary Wind Tunnel Plan Act" of 1949 [4]. This 'Unitary Plan' created a new United States Air Force (USAF) Air Engineering Development Center in Tennessee, new National Advisory Committee for Aeronautics (NACA) transonic and supersonic wind tunnels and other infrastructure and capabilities, and new, advanced capabilities for industry and universities. The US was achieving Gen. Arnold's vision of 'getting out in front of need.'

The next decades were full of advancements in US research, development, test, and evaluation (RDT&E) capabilities, with a skilled workforce providing services and accomplishing R&D that resulted in a wide array of military and commercial products and mission types. Also in these decades, R&D for computer capabilities was advancing, leading to early computational modeling and simulation in the 1960s and computational fluid dynamics (CFD) codes in the 1970s and 80s.

By the mid to late 1980s with improving CFD capabilities and into the early 1990s with the end of the Col War, predictions were rife that physical ground testing would no longer be needed in 'XX years.' This combination of changing political priorities and new technologies led to massive industry consolidation (with its large military underpinning) and a perceived lessoning of military needs, resulting in a significant decline in aerospace RDT&E ground testing through the 90s and into the 2000s. Many ground test capabilities were closed or mothballed due to lack of work and the skilled workforce moved on to other industries – an uncoordinated retreat from Gen. Arnold's vision.

Advance to the year 2013, when the "Future of Ground Testing" (FoGT) working group was formed by the GTTC to develop a document on the future of ground testing and the APATC created the "Validation of Numerical Models" Discussion Group (DG). CFD efficacy for predicting flow solutions had advanced greatly, a result of significant investment from government labs and industry while 'riding the wave' of broadly advancing use cases for computing hardware and software capabilities and applications. While not replacing physical ground testing, which is also used to validate codes, CFD had shown strengths in some areas of ground test weaknesses and the future was clearly going to be some complementary form of physical ground testing and computational modeling and simulation (M&S). Mapping the future of aeronautical ground testing would have to be integrated with the future of CFD targeted to produce research and technologies to be used in the development of some yet to be defined future air vehicles.

Now, ten years later, the purpose of this paper is to transition from the work of the GTTC working group and the APATC DG to provide a public domain forum to join with many other topical physical experimental and CFD forms of information and predictions. This paper provides a summary in the form of a knowledge capture of the FoGT working group and the APATC DG. This will inform and guide an initial draft of needs and requirements for a new AIAA integrated ground test and CFD Focus Group to use for advancing Gen. Arnold's vision via cross-organizational dialog and sharing and making associated recommendations for capability sustainment and investment based on projected needs.

II. Recent Related Work Products and Findings

The government budget reductions for aerospace R&D in the 1990s and into the 2000s [5] resulted in the closure and/or mothball of many government and industry experimental ground test facilities, resulting in the loss of both capabilities and capacities as well as creating gaps in the highly skilled workforce that both provided and used test services. Despite many efforts at coordination, shutdown decisions were largely based on particular organizational priorities and budgets, resulting in a patchwork of remaining capabilities and generally declining readiness due to lean staffs, maintenance backlogs, and reduced investment in new test techniques and capabilities.

By the early to mid-2000s, funding for experimental ground test capabilities was trending up, not at a pace to make up the losses, but enough to provide some stability for remaining capabilities and a start toward reinvesting in the workforce. An experienced observation by the authors is that organizational-based interests became more entrenched, since with limited capabilities and throughput, organizational (not national) needs had higher priority. Additionally, the organizational owners developed various cost charging algorithms for use of ground test capabilities in order to recover the cost of ownership and of use – typically with lower rates for partner organizations and higher rates for others. This tended to limit access to those who could pay, forcing others to use some combination of lesser experimental capabilities and available computational tools – possibly resulting in lower quality data and information and accordingly impacting R&D products.

Membership within the AIAA technical community recognized that more active engagement and advocacy was necessary to provide decision-makers with more and better information, based on needs and in terms of larger aerospace and defense system level technical and business cases. The GTTC, with extensive support and teaming with/from other technical committees, member home organizations, the AIAA Public Policy Committee, and the National Partnership for Aeronautical Testing (NPAT), reviewed, contributed to, and authored contemporary assessment reports and papers and chaired technical conference sessions on the state of national aerospace ground testing. GTTC personnel additionally contributed via interviews to two in-depth and influential technical reports from the Rand Corporation. A review of the work products (not exhaustive) listed below illustrates that many of the issues being worked coming out of the post-Cold War "dive" are still alive today.

- Rand Corporation Technical Report, 2004, "Wind Tunnel and Propulsion Test Facilities, Supporting Analyses to an Assessment of NASA's Capabilities to Serve National Needs." [6]
- AIAA (sponsored by the GTTC) U.S. Industry Aeronautics Test Facilities Working Group, 2007, "Perspectives on Implementation of Executive Order 13419—National Aeronautics Research and Development Policy." [7]
- Rand Corporation Technical Report, 2008, "An Update of the Nation's Long-Term Strategic Needs for NASA's Aeronautics Test Facilities." [8]
- U.S. Air Force T&E Days, 2009, Hypersonic Test Capabilities Overview, AIAA 2009-1702. [9]
- NPAT report, 2009 (limited distribution), "Assessment of National Supersonic Wind Tunnel Capabilities", AEDC-TR-09-F-3 [10]
- ITEA Journal, 2009, Shaping an Evolving Test and Evaluation Enterprise for the Operation and Sustainment of Government Aerospace Test Facilities. [11]
- AIAA Aerospace Sciences Meeting, 2010, "Industry Expectations for Aerodynamic Test Facility Capabilities to Support Future Development Programs – A User Perspective", AIAA-2010-0145. [12]
- AIAA Aerodynamic Measurement Technology and Ground Testing Conference, 2010
    - Session, "Ground Facilities Capability Sustainment I" [13]
        - "Embracing Safe Ground Test Facility Operations and Maintenance", AIAA-2010-4529. [13a]
        - "Structured Transition of Wind Tunnel Operations Skills from Government- to Contractor-Managed", AIAA-2010-4531. [13b]
        - "Using Facility Condition Assessments to Identify Actions Related to Infrastructure," AIAA-2010-4532. [13c]
        - "The Mothball, Sustainment, and Proposed Reactivation of the Hypersonic Tunnel Facility (HTF) at NASA Glenn Research Center Plum Brook Station", AIAA-2010-4533. [13d]
        - "Investing American Recovery and Reinvestment Act Funds to Advance Capability, Reliability, and Performance in NASA Wind Tunnels", AIAA-2010-4534. [13e]
        - "An Overview of the NASA Aeronautics Test Program Strategic Plan", AIAA-2010-4666. [13f]
    - Session, "Ground Facilities Capability Sustainment II" [14]
        - Oral Presentation, "Tactical Pressures on National Ground Test Infrastructure Will Lead to Strategic Changes in Capability and Capacity." [14a]
        - Oral Presentation, "National Ground Test Infrastructure Panel: Capabilities and Sustainment." [14b]
- NPAT report, 2013 (limited distribution), "Assessment of National Hypersonic Wind Tunnel Capabilities," AEDC-TR-13-F-7. [15]

When the GTTC FoGT WG was forming in 2013, a parallel NASA-funded effort was also working to produce a report that would lay out a road map for the future of computational methods. This culminated in the publication of a forward-looking paper in 2014, "CFD Vision 2030" [16]. In addition to defining a development roadmap to achieve several key challenges (updated in 2020 [17]), findings and recommendations were produced, noted verbatim in Appendix 1.

From its founding in 2013, the GTTC FoGT explored and advocated for a funded effort similar to the NASA CFD Vision 2030 report to develop an integrated computational and experimental sustainment and investment roadmap. In the interim, a "small" volunteer effort was started to collect and produce information collected from computational and experimental subject matter experts (SMEs) in two moderated panel sessions:

- AIAA CASE conference, "Direction and Integration of Experimental Ground Test Capabilities and Computational Methods, Part I", August 2013. [18]
- AIAA Aerospace Sciences Meeting, CASE session, "The Direction and Integration of Experimental Ground Test Capabilities and Computational Methods, Part II", January 2014. [19]

Comments from these sessions were collected and curated to produce a conference paper in 2016, "Direction and Integration of Experimental Ground Test Capabilities and Computational Methods" [20]. The take-aways were organized from near to longer term and are shown in Appendix 2.

By 2017, the GTTC/FoGT team had been unable to put together a funded project to develop an in-depth, national study and report on the future of aerospace experimental ground testing. A volunteer effort was begun to produce a form of such a report using existing publications and reports, with a meta-analysis published in 2018, "GTTC Future of Ground Testing Meta-Analysis of 20 Documents" [21]. In consultation with the AIAA technical community, the most important/best/comprehensive/credible documents were collected and these were distilled by the writing team down to the twenty that were deemed "seminal." Each document was mined for content related to the health and needs of experimental ground testing and then organized into information sections and sub-groups within each section. From this, a set of "system" observations and recommendations/needs were developed. These are shown in Appendix 3.

Additional related work products were produced and supported by the GTTC FoGT working group from 2018 to the present, noted below.

- Aerospace RDT&E workforce
  - AIAA conference paper: "Aerospace Human Resources for the 21st Century: Workforce Challenges Facing Research and Development", AIAA-2018-3413, June 2018. [22]
  - International Astronautical Conference paper: "Workforce for the Future Development of Space Access Vehicles", IAC-19, E1, 5.1, June 2019. [23]
  - Five AIAA conference invited panel sessions
    - Aviation 2018, Session GT-06, RDT&E Capabilities: Defining RDT&E Experimental/Computational Capability and Workforce Challenges. [24]
    - SciTech 2019, Session GT-03: RDT&E Capabilities: Defining RDT&E Experimental/Computational Capability and Workforce Challenges. [25]
    - Aviation 2019, GT-06: Special Session: Future Aerosciences R&D Workforce. [26]
    - SciTech 2020, CASE-04/GT-04: Future Workforce Development in Complex Aerospace Systems. [27]
    - Aviation 2020, GT-04/CASE-02, Ensuring the Future Workforce for Complex Aerospace Systems. [28]
- Aerospace R&D risk management, two AIAA invited CASE sessions
  - Aviation 2020, session GT-02/CASE-01 (Invited), Risk Management Sufficiency for Complex Aerospace Systems, two oral presentation and a panel with info capture (paper pending). [29]
  - SciTech 2021, Session CASE-02, Aerosciences RDT&E Risk Management Sufficiency Initiative, (paper pending) [30]
- Aerospace RDT&E Capabilities:
  - AIAA conference paper: "A Value-Based Justification Process for Aerospace RDT&E Capability Investments, AIAA-2018-0388, January 2018. [31]

In 2011, six members of the APATC initiated a "Validation of Numerical Models" Discussion Group (VDG) out of the recognition that while much progress had been achieved in numerical methods (e.g., CFD, turbulence models), ground test techniques (e.g., non-intrusive on-body and off-body flow diagnostics), and in-flight test techniques (e.g., flight test telemetry miniaturization), when results disagree, each community "blames" another. Most of the emphasis within each community focused on methods as opposed to correlating disparate results, with little cooperation and collaboration. Therefore, the VDG set out to, "*Foster cooperation and collaboration between numerical, ground test, and flight test communities to determine causes for differences in results, with an intention to improve 'best practices' within each community*." The stakeholders of this endeavor included not only the discipline subject matter experts, but also the senior and business leadership within the various industry, government, and academic organizations. The

VDG identified several potential products including special/invited conference sessions and documentation of sources of numerical/physical differences, and resources for solutions.

With semi-annual VDG meetings corresponding to the SciTech and AVIATION forums, the group exchanged experiences of collaborative experiment/numerical simulations. It was noted that numerical simulation are very dependent on the researcher and codes used and final papers presented at conferences do not usually discuss problems and errors that occurred during the work. It was decided that the VDG would organize a special session of invited speakers/panel at the 2014 Aerospace Sciences Meeting with the intent that this session would lead to an annual event. The 2014 invited session of six speakers met with very good success with session attendance ranging from 65 to 110, and this success was in spite of the unfortunate planning, which resulted in the invited session being scheduled at the same time as the CFD Standards Committee meeting. Additional invited sessions were sponsored at SciTech 2015, 2016 (joint session with the Non-Deterministics Approaches (NDA) TC), 2017, and 2018 (joint sessions with Ground Test and Flight Test TCs).

In 2017, the VDG rebranded itself as the "Collaborative Experiments & Computations" DG (CECDG) in order to reinforce the informal goal to, "… learn from each other's limitations, successes and failures." Throughout the CECDG DG has augmented the invited/special sessions with guest presentations at its CECDG meetings. Notably, Chris Rumsey from NASA Langley discussed the Fluid Dynamics TC Turbulence Model Benchmark Working group and its website. The website contains detailed descriptions about multiple one- and two-equation turbulence models and a rating system that assesses the readiness and maturity of the models. The website also provides multiple verification and validation test cases with meshes that can be downloaded to facilitate users in assessing their own codes. More information about the website can be found in AIAA paper 2010-4742 [32] and at the website that is hosted at http://turbmodels.larc.nasa.gov/tmbwg.html. In another guest presentation, Philip Morgan presented an overview of the AIAA Journal paper "Experimental Methodology for Computational Fluid Dynamics Code Validation," by Daniel Aeschliman & William Oberkampf [33]. The review consisted of an overview of CFD code hierarchy of code confidence levels, the future of CFD/experimental collaboration, philosophical guidelines for CFD validation, and recommended CFD code validation procedures.

Several other activities have been pursued with varying success. During the CECDG's 2013 SciTech meeting the APA TC chair requested the CECDG to consider updating the AIAA G-077-1998 "Guide for the Verification and Validation of Computational Fluid Dynamics Simulations." However, the CECDG decided that since the Computational Fluid Dynamics Committee on Standards had authored the original guide that they should be responsible for updating it. This recommendation corresponded with the AIAA authorizing the standards committee to update the guide as well as generate "AIAA Code Verification Project-Test cases for CFD Code Verification" [34].

As a step towards developing best practices, the CECDG made the following recommendations for CFD code validation procedures in 2015:

- Obtain detailed, accurate freestream flow calibration data at spatial resolution consistent with code requirements.
- Precisely characterize the model geometry and wall boundary conditions, as tested.
- Varying model size in the same facility at the same nominal test conditions.
- Conduct the same experiment in different facilities.
- Apply redundant measurement techniques for critical experimental variables.
- Develop an uncertainty analysis technique, that can identify and quantify the significant random and bias errors.
- Obtain and plot data for positive and negative angle of attack with the model rolled 180 degrees.
- Take and keep notes that are as careful, detailed, and extensive as possible.

While not formally a product of the CECDG, the NASA Juncture Flow tests highlighted how a deliberate effort to conduct CFD model validation experiments following such practices resulted in many new insights and a future development focus [35, 36]. These procedures support the following CECDG philosophical guidelines:

- CFD code developers and experimentalists should jointly design validation experiments and work closely together throughout programs.
- Validation experiments should be designed to capture the essential flow physics, including all relevant boundary conditions, assumed by the code.
- Validation experiments should strive to emphasize inherent synergisms between two approaches.
- Although experiments jointly designed, complete independence must be maintained in obtaining both CFD and experiment results.

- CFD validation must be conducted through a hierarchy of experiments.
- An Uncertainty Quantification (UQ) analysis procedure should be employed that delineates and quantifies systematic and random error sources by type.
- Invest in careful quantification of all relevant experiment parameters needed for comparison of CFD predictions to validation experiments.

As will be seen, these procedures and guidelines have not fundamentally changed. However, the importance of assembling a joint CFD and physical testing team and having that team jointly write a "Goals Document" [35] cannot be overstated. In 2018, members of the GTTC and APA TCs came together to help promote this type of interaction.

III. GTTC/FoGT Briefing Products

During the many GTTC FoGT meetings leading the development and presentation of the work products noted in part II, additional materials were developed to facilitate meeting discussions. This section presents some of these materials – largely unpublished and not fully vetted – as inputs to the future work of the new Focus Group, namely a problem definition, a need statement, and a draft vision statement.

A. The Problem

A generalized goal, arising from "Toward New Horizons," is that United States domestic aeronautics and aerospace industry – commercial and government – research, development, test, and evaluation capabilities be available when needed at sufficient levels of quality and throughput. The current national state of being able to achieve this goal is at significant risk based on the following key challenges:

1. Physical experimental and computational capabilities are often thought of as a suite of national capabilities, but instead are owned by independent organizations (across the government, industry, and academia) and subject to support based on local workloads, priorities, and budgets. Despite some efforts to share both workloads and R&D for new capabilities, there is no overall framework to prioritize needs and make investments.
2. U.S. federal fiscal year budgets have been created via a combination of continuing resolutions and omnibus bills every year since 1996. Strategic (10-20 years out) thinking on long-term needs is limited (it can take 10+ years to bring a significant new ground test capability online), with an emphasis on near-term needs and payback.
3. Physical ground testing infrastructure has a long history and since the 1980s recapitalization and other sustainment and investment needs have far outpaced available funding – exacerbating the tendency to shut down or mothball capabilities in times of low workload.
4. It is observed by the authors that many key decision-makers, with backgrounds and education outside of aerospace and in the absence of any authoritative predictive doctrine, do not have a strong understanding of the RDT&E capabilities required to produce new and/or upgraded air vehicles. Thus, decisions are made on the capabilities themselves, rather than the effect each has on the larger system. The larger system control volume payback often results in a vastly different capability keep or lose business case.
5. Air vehicles are becoming ever more complex and development cycle times are significantly increasing for new product development – the above challenges tied to using existing and new ground testing and CFD technologies (and how they integrate for system development risk management) are surmised to be a key reason for product development time and quality issues.
6. The combination of short-term budgets and industry consolidation since the 1990s, program changes and stops resulting from changing political leadership, and the projectized nature of accomplishing work leads to forms of boom-bust cycles that impact workforce numbers and expertise with knowledge loss.

B. Defining the Need

1. Aerospace research and development tools primarily consist of ground testing, flight testing and computational capabilities – with a wide application range from component to full vehicle and from early research through fielded systems.
2. Computational tools have steadily developed in recent decades to first augment ground test capabilities and then to either use both in tandem or to replace physical testing for some applications.
3. Limitations, strengths, and weaknesses exist for both sets of tools and are changing with advancements in computing power, software development, and test technique and measurement improvements.
4. Advancing the state-of the art for research and development of increasingly complex aerospace systems to achieve improved technical quality, expanding (targeted) capabilities, and improved efficiency requires that ground test and computational capabilities be utilized as an integrated tool kit by researchers and developers.

The need is for aerosciences researchers and developers to have the right/best ground test and computational tools (sufficient quality, at reasonable cost, and available), when needed, to do their work.

C. Developing the Vision

Once it became clear that the FoGT working group could not define the future of ground testing without the complementary integration of CFD, the team collaborated with others from across the AIAA technical community to develop and initially vet the following vision statements.

Ground Testing: Ensure the availability of a suite of critical national ground test facilities capable of providing relevant and seamless test environments supporting both the pursuit of new technologies and development of new systems:

- Sustain needed core capabilities;
- Develop and field targeted experimental and measurement improvements; and
- Implement and integrate computational/CFD tools in physical experimental processes.

CFD: Enable fast, efficient design and analysis of advanced aviation systems from first principles by developing physics-based tools/methods and cross-cutting technologies, provide new MDAO (multidisciplinary analysis and optimization) and systems analysis tools, and support exploratory research with the potential to result in breakthroughs:

- Physics-based methods for revolutionary analysis and design capability; and
- Critical tools and technologies to enable transformative aeronautics concepts.

Integration: Combine CFD with ground testing to:

- Improve the prediction of aerodynamic flight physics while reducing the development cycle time and cost; and
- Provide researchers and developers access when needed to the appropriate ground test and computational tools.

IV. Transitioning to a Multi-TC Focus Group

Aerospace RDT&E capabilities tend to be expensive to acquire and maintain and, while being able to make clear technical cases for existing and supporting R&D for new/updated flight systems, the business case payback in terms of defense protection, homeland security, and commercial returns may not be clear until those systems are operational and making a difference. Predictions of future needs have a fairly wide uncertainty and affect/limit resource allocations based on better understood near-term needs:

- Time from a large capability investment decision to operation can be ten years or more;
- Sustaining/maintaining existing capabilities and making targeted improvements is often a function of near-term workload, while competing for limited investment resources; and
- Some decision makers lack understanding of function and purpose of the RDT&E capabilities and lead times required to field updated and new aerospace air vehicles.

National RDT&E capabilities – both physical and computational – tend to be segmented by ownership and largely focused on owner needs. Increasingly, experimental ground testing needs are tied to integration with computational modeling for code verification and validation, gathering data where CFD is inadequate, and offering alternative sources of data due to cost and availability factors.

Capability owners and users regularly network and many deep relationships have developed over many cycles of R&D projects and programs. Yet, organizational stove pipes within and between capability owners limits current knowledge and sharing of needs. The AIAA technical community, via the many technical and integration committees organized by disciplines, provides forums for exchange – albeit in forms of discipline stove pipes. The authors found from leading respective TC groups that meetings regularly draw session participants from across the technical community. The forming of a Focus Group hosted by two complementary TCs and supported by many is the logical next step toward advancing dialog, sharing, and facilitating collaboration.

The Focus Group is still being developed from the 2023 SciTech meeting, and the following are the initial guidelines:

- Coordinate purpose, process, and products across the AIAA tech community.
- Provide a platform to share and leverage – not just talk about topics, but to facilitate and support advancement of capabilities (including workforce).

- Follow a general vision such that researchers and developers – both service providers and users – will have the best ground test/computational tools available to them when needed, even as capability advances due to robust investment and expanded applications.

Success for this Focus Group is directly correlated to usefulness to the Institute's technical community. All involved are busy and the work of this FG must be more important than some of people's current work. Just talking about things isn't good enough – there must be a measurable positive impact. At a minimum, this FG will support networking across TCs and sponsor invited sessions on related topics with published key points and takeaways. The FG will reach out across the AIAA technical community to gather needs, challenges/barriers/roadblocks, best practices, examples of ICE methods and application (with points of contact) and other useful information to share across the larger community.

Output from collaborative activities can support improved teaming on research, technology development, physical and computational tool development – especially relative to design and use in an integrated manner, and building reliance and trust for using other's capabilities during product RDT&E. As this matures, the group can also be a source of information that supports advocacy for targeted investments in RDT&E capabilities (including workforce) that especially addresses current and projected gaps and weaknesses from a national perspective.

A. Focus Group (FG) Structure

The proposed mission of the Integrated Collaborative Experiment (ICE) Focus Group is to provide a place within the AIAA technical community to share and leverage needs, use cases, and tools to integrate physical ground testing and computational modeling and simulation public domain information, advance interactions via facilitated technical sessions and workshops, and be a meaningful source for advocacy for capability investments to decision-makers and stakeholders. The expertise to draw from in this technical community is vast, though most are working in their particular areas of interest via the TC structure – the ICE focus group can bring them together to coordinate purposes, processes, and products using an integrated toolkit. **The FG leadership is agnostic on driving specific advancements – it is about the opportunity to help bring interests together to define needs and approaches and then to advance together.**

Figure 1 presents a draft structure to support the proposed mission needs. It is organized in two branches:

- Connectivity, Information, and Advocacy – designed to facilitate paths and places and provide opportunities for communicating and connecting.
- Technical Activity Groups (TAGs) – for teams to leverage and work specific topical areas.

Each of these functional boxes must provide a service that makes enough difference to be a draw from an already very busy volunteer community. This layout is likely to change as the participants bring needs and thinking to bear and create processes that make that difference.

The Connectivity, Information, and Advocacy branch currently utilizes AIAA tools and processes. An AIAA Engage website is being designed as a collaboration hub, providing participant connections, documentation from meetings and work products, highlights of ongoing public domain integrated experimental/computational efforts, and (at some point) the ability to blog on particular topics. Advocacy is already occurring via the AIAA Public Policy Committee – which is advancing the visions of space and aeronautics. Achieving these visions require, foundationally, that researchers and developers have access to cutting edge ground/flight test and computational tools and capabilities. A role of the GTTC FoGT working group was to develop and provide information for informing and advocating via recommendations for specific needs and issues to decision makers. Inputs were made to the AIAA Public Policy Committee for vetting and prioritization/integration with other key issues. As this Focus Group matures, it is expected that advocacy and providing information about key ground testing and CFD capabilities, and integration of both that are needed to produce future air vehicles will become a significant purpose.

The TAG branch is for specific topical areas and, as of this publication, one effort is very active and growing, including sponsoring invited technical sessions, "Validation Dialog and Mutual Accountability." Progress and direction are discussed in some detail in section B. The "Cross-training" TAG is in the early planning stage and the "TC Community+" TAG should provide outreach with the ability to highlight the maturity of particular topics/initiatives.

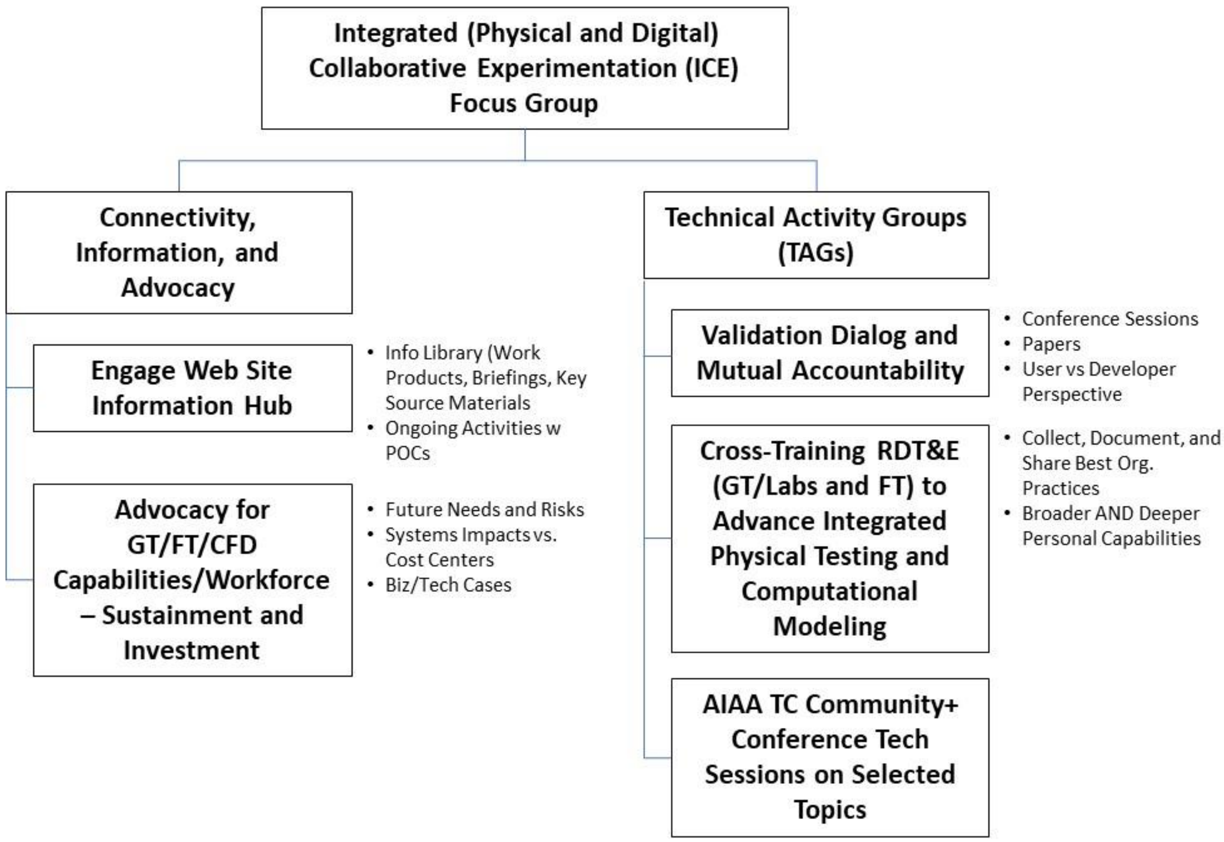

Fig 1. Proposed ICE Focus Group Structure.

B. Initial focus on Validation

Vision: Advance “Validation of Numerical Models.” Determine what each research domain (physical tests and computational simulations) need 1) to measure and why and, 2) to verify data to flight physics within (defined) acceptable limits.

Approach: Foster cooperation and collaboration between numerical, ground test and flight test communities to help determine causes for differences in results, with an intention to improve “best practices” within each community and overall.

A primary goal is to derive a validation approach for a future state and, via a gap analysis, develop an ordered/prioritized investment program for integrated RDT&E capabilities leading to accelerated product development. Starting with SciTech 2023, the FG sponsored the invited session “Improving Aerosciences Modeling and Simulation through Experimental and Computational Integration (IC&E).” Jim Ross' (NASA Ames) presentation "CFD and Wind-Tunnel Test Integration," highlighted two "big" integration challenges: wind tunnel geometry documentation and tunnel boundary conditions. While as-built drawings were often available, they didn't always represent as-built geometry, and even recent modifications didn't match existing documentation. He also noted the lack of information with respect to the flow in the settling chamber or at the downstream end of the diffuser. Diffusers pose a particular challenge since they are often designed to operate at or near insipient separation, and these are difficult areas to model in CFD. Additional computational complexity is introduced as many tunnels were designed with vortex generators downstream of the test section to stabilize the flow.

Nigel Taylor (MBDA UK Ltd) complimented these observations with a presentation introducing Validation Dialog and Mutual Accountability using factors taken from ASME V&V 20-2009 [37], “Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer.” These factors include model form, model input parameters, numerical aspects, and physical measurements. Together they can be used to capture the difference between the simulation and experimental error. Some of the key components of each of these factors for computing error and uncertainty include [37, 38]:

- Model form
  - "Weak form" = general mathematical formulation e.g., incompressible Navier-Stokes equations.
  - "Strong form" = "Weak form" plus all parameter values and boundary and initial conditions.
  - Modeling assumptions and approximations.
  - Models typically defined in a continuous sense, therefore, don't include discretization errors (part of verification).
- Model input parameters
  - Measured and assigned values such as measured experimental conditions (density, temperature, volume flow rate, thermal conductivity, etc.).
  - Estimated uncertainty in simulation input parameter values; by combining systematic and random contributions, where *systematic* implies error sources that remain fixed during the measurement process, as opposed to *random* or errors, which contribute to the variability of a measurement.

Note: There is an intimate connection between model form and model input in the sense that some, possibly all, parameters in the model formulation may be considered fixed/permanent values inherent to the model, and as such, these "parameters" do not contribute to model input/parametric uncertainty.

- Numerical aspects
  - Arise from numerical solution of the mathematical model such as discretization (including grid convergence), incomplete iterative convergence, and round-off error.
  - Solution verification assesses/estimates the numerical accuracy of a particular calculation, typically measured in terms of convergence, consistency, and stability.
  - Coupling of discretization schemes (e.g., grid and time-step) depends on physics being modeled [39].
- Physical measurements
  - Ideally, input standard uncertainty values come from prior experiments.
  - Trades (number and spacing of nodes, number of repeat measurements, quality of measurements, quality of corrections from simulating physics).

During the discussion portion of the session, additional observations of the validation problem were put forward. First, there is a difference in perspectives between a *user* of CFD codes/simulations and the *developer* of a CFD/simulation code or alternatively, the model user versus the model developer. Second, current validation efforts are limited in applicability to a "specified variable at a specified point" as opposed to "interpolation/extrapolation in a domain of validation." And finally, uncertainty quantification is a critical process being addressed in multiple venues within the aerospace community, but for a developer of new systems, and in particular a design engineer, quantification of uncertainty (model credibility) as an output with confidence intervals is desired.

An invited session and several working meetings at AVIATION 2023 served to develop relevant topics for SciTech 2024 sessions such that the community could more actively engage with this new validation paradigm of Validation Dialog and Model Validation. In particular, it was felt that the dialog would be served best at this time by a more in-depth discussion of the terms being used with an emphasis towards applications and the users' perspective, and this introductory paper is intended to set that stage. The FG also wanted to leverage the excellent work that has been done through the CFD Vision 2030 effort and focus on one of the Grand Challenges (GC), "Advancement of Numerical Prediction of High Lift (HL) Aerodynamics." Other GCs were considered, but HL was chosen in part due to the linkage with the HL-CRM (High Lift – Common Research Model) and CbA (Certification by Analysis) initiatives. While this was a rather ambitious attempt to bring relevance to the dialog, it also reinforced core interpretations of validation as "The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model," where "uses of the model" is being interpreted as the end use, such as "the critical low-speed (high-lift) maneuver typically performed for airplane certification" [40]. Ultimately, a leaner topic was chosen in which several panelists will discuss the current state and future of CFD turbulence modeling. In particular, what are the limitations of Reynolds-averaged Navier-Stokes (RANS) models, and what are their prospects for future improvement? How can wind tunnel experiments be used to improve turbulence models? Or as Philippe Spalart has stated, "... finding ANY way new knowledge can translate into better models" [41].

In addition, the invited session is aiming for the members to speak to the importance of establishing baselines (with associated uncertainty), the extension of techniques and methodologies for quantifying V&V/UQ for field data (as opposed to point data), confidence intervals for extrapolation (and interpolation) of V&V at the subsystem and system level, and multidisciplinary/sub-system integration for system V&V/UQ. The tone for the panel is to present some ideas and experiences that help bridge the interactions between the computational and ground test communities.

V. Summary

The authors are excited to join efforts from multiple TCs by creating a space for making connections, leveraging multiple current efforts, creating new initiatives, joining to advocate for investment in the future, and having stimulating and learning interactions. This initiative grows from the vision and subsequent application over decades of Toward New Horizons, supported by many great advancements from industry, academia, and government.

Over the last ten plus years the GTTC and APATC put considerable effort into sharing, connecting, and advocating as a means of feeding forward into the future – these integrated RDT&E capabilities are foundational to creating new technologies and utilizing those technologies in new and upgraded air vehicles. This paper was written to be a form of knowledge capture with some great ideas and observations from many skilled and eminent people from different backgrounds that can be used as the ICE focus group moves forward. It also provides the initial design of the focus group as a way of reaching out to readers that their support and participation is key to making the future happen. At its core the FG goal is to establish a place and process for a "validation dialog" - sharing and iterating on overall context and goals as well as the "technical" details of how to "get 'er" done by utilizing AIAA's technical community and role as an unbiased, apolitical entity will create a public domain clearinghouse for sharing, leveraging, and advocating.

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Appendix 1

Findings and recommendations from “CFD Vision 2030” [16].

<u>Findings</u> <u>(bold as shown in the original document)</u>

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.** Advancing simulation capabilities will be important for both national aeronautics and space goals and has broad implications for national competitiveness. This will require advances in foundational technologies, as well as increased investment in software development, since problem and software complexity continue to increase exponentially.
2. **HPC hardware is progressing rapidly and technologies that will prevail are difficult to predict.** However, there is a general consensus that HPC hardware is on the cusp of a paradigm shift that will require significantly new algorithms and software in order to exploit emerging hardware capabilities. While the dominant trend is toward increased parallelism and heterogeneous architectures, alternative new technologies offer the potential for radical advances in computational capabilities, although these are still in their infancy.
3. **The use of CFD in the aerospace design process is severely limited by the inability to accurately and reliably predict turbulent flows with significant regions of separation.** Advances in Reynolds-averaged Navier-Stokes (RANS) modeling alone are unlikely to overcome this deficiency, while the use of Large-eddy simulation (LES) methods will remain impractical for various important applications for the foreseeable future, barring any radical advances in algorithmic technology. Hybrid RANS-LES and wall-modeled LES offer the best prospects for overcoming this obstacle although significant modeling issues remain to be addressed here as well. Furthermore, other physical models such as transition and combustion will remain as pacing items.
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.** As more capable HPC hardware enables higher resolution simulations, fast, reliable mesh generation and adaptivity will become more problematic. Additionally, adaptive mesh techniques offer great potential, but have not seen widespread use due to issues related to software complexity, inadequate error estimation capabilities, and complex geometries.
5. **Revolutionary algorithmic improvements will be required to enable future advances in simulation capability.** Traditionally, developments in improved discretizations, solvers, and other techniques have been as important as advances in computer hardware in the development of more capable CFD simulation tools. However, a lack of investment in these areas and the supporting disciplines of applied mathematics and computer science have resulted in stagnant simulation capabilities. Future algorithmic developments will be essential for enabling much higher resolution simulations through improved accuracy and efficiency, for exploiting rapidly evolving HPC hardware, and for enabling necessary future error estimation, sensitivity analysis, and uncertainty quantification techniques.
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.** These include effective, intuitive, and interactive visualization of high-resolution simulations, real-time analysis, management of large databases generated by simulation ensembles, and merging of variable fidelity simulation data from various sources, including experimental data.
7. **In order to enable increasingly multidisciplinary simulations, for both analysis and design optimization purposes, advances in individual component CFD solver robustness and automation will be required.** The development of improved coupling at high fidelity for a variety of interacting disciplines will also be needed, as well as techniques for computing and coupling sensitivity information and propagating uncertainties. Standardization of disciplinary interfaces and the development of coupling frameworks will increase in importance with added simulation complexity.

<u>Recommendations</u>

1. NASA should develop, fund, and sustain a base research and technology (R&T) development program for simulation-based analysis and design technologies.
2. NASA should develop and maintain an integrated simulation and software development infrastructure to enable rapid CFD technology maturation.
3. NASA should make available and utilize HPC systems for large-scale CFD development and testing.

4. NASA should lead efforts to develop and execute integrated experimental testing and computational validation campaigns.
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.
6. NASA should attract world-class engineers and scientists.

Appendix 2

Key takeaways from two panel sessions documented in 2016: "Direction and Integration of Experimental Ground Test Capabilities and Computational Methods" [20]. The take-aways were organized from near to longer term and are noted below.

Current/Near-Term

Experimental Fluid Dynamics (EFD) and CFD have complementary roles in the characterization of aerospace systems, and there are some blurred areas of overlap.

Sustainment of EFD infrastructure is a challenge in today's funding environment – some form of an enterprise solution that maintains critical capability and sustains it properly is needed. Discussions on how to pay for the sustainment of capability need to continue.

1. We must overcome the mentality that little-used wind tunnels should be closed. There needs to be a value proposition that allows for low usage but critical infrastructure along with a way to properly sustain (or replace it). The true value of wind tunnel testing is not proportional to how much they are being used, but rather to the reduced risk of developing aeronautical products with advanced capabilities. National investments should be made on what is needed for national defense and not what is expected to be used on a frequent basis.
    a. "I don't think documenting the regret about certain facilities having been declared obsolete (AEDC 16S) is productive. Rather, it is striking that the discussion of solid criteria for obsolescence and future need is rather thin, although the convincing argument that it is not the rate of occupation of a facility but the added value it provides to a product is recorded."

KEY IDEA: We are concerned with the metrics of comparing experimental and CFD results, but the big challenge is to predict what's going on in flight.
KEY IDEA: Need to concentrate investments on facilities for production capability to stay ahead of the rest of the world.
KEY IDEA: It is a problem that we are currently only trying to make what we already do less expensive.
KEY IDEA: Whether it is experimental or computational, it is just a tool.

Near- to Mid-Term

1. Individual engineers need to work both CFD and EFD for the industry to make greater progress toward advancing the state of the art. The "stove-piping" needs to be eliminated.
    a. We need to train engineers to understand both EFD and CFD so that better decisions can be made as to which tool to use at any given time. Attention needs to be given to the future testing workforce. Efforts to increase workforce technical ability through efforts like STEM and training alone have proven unconnected and unreliable. A robust and directed program to equip, train and technically nourish the workforce is required for a vibrant and impactful enterprise. We need to pass graybeards' knowledge to the young workforce.
    b. On the other hand, "we need specialists to take full advantage of the possibilities of the developing technologies. Only specialists in specific technologies can produce the result needed at the current stage of maturity in aeronautics. One doesn't become a specialist on a part-time basis."
    c. "What we also need, in addition to the specialists, are people at responsible levels who can understand, combine and synthesize the different streams of information."

KEY IDEA: What was missing from the whole discussion was the development of measurement techniques and data acquisition. . . ; it could be extrapolated that a new specialty is evolving in addition to the numeriscist and the experimentalist, that of the data reductionist. (NOTE: The rationale was provided that data mining or data extraction is needed to drive cost down and quality up.)
KEY IDEA: Level the playing field between disciplines on tool cost and provide a means of allocating sometimes scarce (and costly) tool availability.
KEY IDEA: The process of handling data and converting it to knowledge is critical.
KEY IDEA: There is a need to educate and train engineers to be competent in both EFD and CFD.
KEY IDEA: The driving consideration is for risk reduction in flight, even if the GT/CFD capability is used only once.

Mid- to Long-Term

1. EFD (e.g., wind tunnels) will be needed for a long time to come to validate CFD solutions and to provide data where CFD can't.

2. The primary CFD limitations (turbulence models and grid generation) are well-known and “won’t be resolved in the next several decades, or maybe ever”.

KEY IDEA: Need methods that will help get the product to market faster.

KEY IDEA: Need to develop and advance experimental capabilities that enable data acquisition for use in CFD to assist better modeling for better predictions.

KEY IDEA: Need to stop thinking of two separate communities (i.e., EFD and CFD) and think in terms of a “prediction community.” Put the needs on the table and then decide what investments are needed. In most cases we will need a joint response from the computational and experimental communities working the problem together.

KEY IDEA: Do not overestimate CFD and therefore overlook the continued need for experimental capability. This would risk premature facility closure and it would lead to unrealistic expectations for CFD.

KEY IDEA: We can talk about all the things we need to do things, but there is no commitment to a national capability. Without the commitment, we’re stuck in the cycle of determining what to divest ourselves of. Unfortunately, this country lacks then necessary leadership needed in this area.

Appendix 3

GTTC ground testing meta-analysis [21] observations and recommendations.

Observations

1. The US experimental ground test industry is coming out of a long post-cold war downturn. Research is down, maintenance has long lagged and is lagging, and investment in new capabilities is limited.
2. The future of ground testing is an integrated, interdependent process with computational methods. It is clear to the authors and the FoGT working group that the future of ground testing is completely intertwined with the development and implementation of computational methods (and vice-versa).
3. Uncertainty quantification (UQ) is more robust in experimentation, but computational UQ is improving.
4. There is a move toward recognizing and valuing capabilities as tools – sustaining and investing **in** the experimental and computational tools required to accomplish the research and development for different classes of aerospace products (as opposed to treating capabilities as cost centers).
5. The major defects frequently found late in the development cycle for a flight system usually occur at the interface of major subsystems, e.g., aerodynamically induced structural failures. Finding and fixing major defects early, which requires both funding and expertise for experimental and computational testing, results in significantly lower time and cost in the development life cycle and, potentially, gains in product performance.
6. Stove-piping has been and remains a significant issue in advancing both the computational and experimental state of the art. Research and development in experimental/measurement/sensing and computational techniques tend to be protected within the originating organization

Recommendations and Future State Needs

1. Saving money on tests is not the right metric. Rather, the proper metric is acquiring enough information to improve quality, resulting in fewer defects and shorter product development times. It is noted that improved quality of the research process also positively affects product development.
2. Data management/data fusion is not addressed much in this paper but must be addressed for EFD/CFD integration to proceed and to meet future development needs – possibly the most important element of integration. Rather than generating large amounts of data, sufficient planning for managing the data sets and leveraging computational strengths must be undertaken to develop fused data sets that go beyond what either resource can provide independently.
3. Computational modeling will not replace wind tunnel testing in the foreseeable future. Product complexity, flight-envelope expansion, risk aversion, and extensive flight-control systems are the additional drivers for the continued use of the wind tunnel.
4. Future workforce will require the right combination of generalists (broad-based skills) and specialists (deeply skilled in specialty areas).
5. Capabilities must have sustained investment or services will decline, even as needs (accuracy, data quality, timeliness, more) increase due to product complexity. This includes experimental tools (wind tunnels, propulsion facilities, and measurement and sensing technologies), computational tools (hardware, software, and processes), and data management (acquisition, processing, mining, fusing, organizing, and information output).
6. Improved (new and better) test techniques are needed for verification and validation of codes and to provide information that may lead to new theories that can be numerically solved in the future.
7. Additive manufacturing and rapid mesh/grid generation have the potential to provide rapid responses to new information – shortening the research time required for new designs and concepts.
8. Data security was only touched on in this paper but is recognized as a pressing investment requirement, especially as test campaigns become integrated experimentally and computationally, in real time, across geographic locations.