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A 2025+ View of the Art of Wind Tunnel Testing

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The maturation of several technologies (e.g., computational power, information storage and transfer, physics-based modeling and simulation (M&S), automation sciences, optical-based instrumentation, micro-electromechanical devices, signal processing, telecommunications) applicable to wind tunnel testing offers the possibility of acquiring test information of quality and quantity that is impossible today. A confluence of this mature technological capability, new wind tunnel features designed to support this technological capability, personnel skills, and a test process to match can make the future possibility a reality. The real challenge as we see it is defining the development needs in ground test, M&S, and flight test and merging these results into a managed database and repository system of maturation requirements. A view of this future possibility being a reality in 2025+ is developed and discussed. This article captures considerations and recommendations gleaned from several efforts external to the Arnold Engineering Development Center that look at the future for requirements.[1]

Key words: Computational capability; future projected workload; investment; personnel development; wind tunnel infrastructure; workforce stability.

As recent assessments (Melanson 2008; Kraft and Huber 2009) show to those of us associated with wind tunnel testing, the use of wind tunnels is not seen as being replaced by computational capability. However, the rise of computational capability has had an impact on wind tunnel utilization and is expected to do so in the future. Based on some approximate physics-based models, flow field and surface conditions are computed for a specified shape at an ideal set of conditions, generally assuming an unconstrained outer boundary. At the present time, a few test points (full aircraft-viscous-time averaged) can be computed in a few days, with a few polars in a couple of weeks. In comparison, a typical wind tunnel test can be thought of as an analog computer that has all of the physics of aerothermodynamics and structural response embodied in the computation and produces more than 11,000 accurate time-averaged computations for the existing boundary conditions in a matter of days to weeks (not counting the time to fabricate the test model and prepare the test systems). Neither is perfect. However, both have their uses *(Figure 1)*, and when applied together they provide the best information, which is the direction needed for the future.

Admittedly, growth in computational power and physics-based modeling will have a dramatic effect on the design of the test program and test article, productivity, the cost of the test, and the information value derived. This growth, combined with advances in instrumentation and data processing, will have an impact on the design of a wind tunnel, principally the test section geometry (size, wall-boundary features) and sensor suite. The benefit potential from incorporating existing or emerging technology into the art of wind tunnel testing is seen as tremendous in terms of value-addition to the process of transforming a concept into a fielded system. The Testing and Evaluation (T&E) activities associated with acquisition, processing, and sharing of data as well as computation modeling have a much higher potential for change in the next 20 years. To maximize the benefits of future technologies to wind tunnel testing, it is critical that

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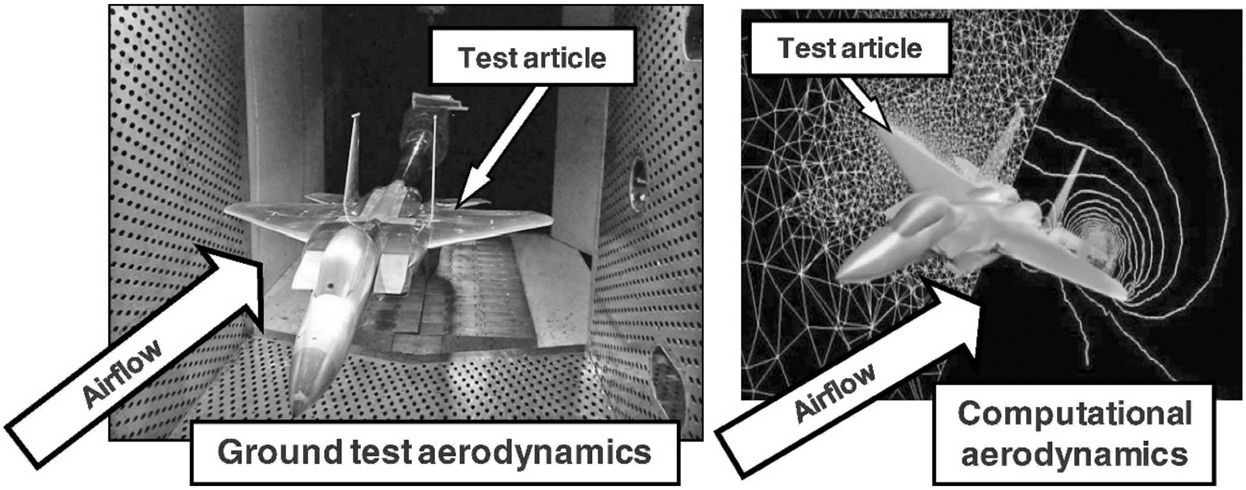


Figure 1. Wind tunnel and computation. The right-hand picture was accessed September 2009 at http://www.pointwise.com/images/app_f-15e_256px.png.

the wind T&E process be managed (guided) to take full advantage of the rapidly advancing changes in information technology, communication, and remote operations previously mentioned. And, if only the wind tunnel test portion is optimized, there will be unrealized benefit. Therefore, improving the entire test process, from first contact to final transmittal of information, should provide maximum cost-effective benefit to the product development purpose.

The 2025+ horizon selected for this presentation is predicated on the notion that starting a program today to either develop a new facility or make a major modification to an existing facility and associated systems and processes to revolutionize the contribution of wind tunnel testing would take from now to 2025 for concept and requirements definition, advocacy, securing of funds, detailed design, construction, and operational readiness for the facility and a similar parallel effort for personnel expertise development and process maturation. The need for growth in personnel skills and experience is seen as a critical element. The suggested goals for 2025 wind tunnel total capability to provide maximum cost-effective benefit and maintain preeminence are as follows.

Develop expertise and tools

Collectively, the wind tunnel facility staff should have key personnel that are knowledgeable in the aeronautical sciences, in how the test-derived information is to be used in the product development, and in its impact on product program risk. They should know how to safely and efficiently get the most out of the test facility to meet program objectives. They should have state-of-the-art knowledge of the use of computational capability and modeling and simulation (M&S) as it applies throughout the test process to plan, design, correct for non-ideal conditions, and analyze test results. The ability to track and understand new features in wind tunnel test facilities and techniques on the part of others is critical to being in the forefront of test ability. Personnel with this acumen must be developed over time and a sustained investment in their skill development is vital.

Develop wind tunnel infrastructure

Ensure suitable wind tunnels (existing and/or new) with test section size, performance range, support systems, productivity, test methodology, instrumentation, M&S tools, and operational readiness needed for product development testing with required information quality without adding to cost, performance, and schedule risk. A sustained investment for each tunnel is required for maintenance and appropriate improvement in capability, reliability, and technology to support future T&E needs.

The 2025+ view developed herein of the art of wind tunnel testing starts with discussion of the test process. Then, in succession, projected workload, test types and the classes of expected vehicles to be developed, the 2025 wind tunnel suite, the role of M&S, and a concept of operations is introduced and discussed. The bottom line is that a national strategy is needed, and the time to start investing is now.

2025 Test process

It is appropriate for this discussion to define some terms before proceeding:

- Benefit (improved performance, utility, productivity, information quality and quantity);
- Risk (likelihood of added cost, delay in schedule, insufficient performance or capability, etc.);

- Facility (wind tunnel, support systems, instrumentation, computational power, M&S capability, personnel expertise, secure high-speed communications, customer interface, information archival);
- Modeling and Simulation (M&S) Capability (M&S effect of flow nonuniformity, wall interference, test article deformation and distortion, boundary-layer state, Reynolds number, exhaust plume, etc.);
- MDOE (application of M&S termed Modern Design of Experiments used to optimize the test points in a wind tunnel program consistent with test objectives);
- Wind Tunnel Capacity (number of tunnels and occupancy hours provided annually);
- Productivity (quantity of data air-on, e.g., polars, or sweeps, or runs, etc., acquired in a given amount of time, such as polars per hour);
- Throughput (time, hours or days, required to complete installation and de-installation of a single test program);
- Test Condition (simulated or duplicated flight condition such as Mach number, Reynolds number, altitude, temperature, etc.);
- Test Simulation Fidelity (degree to which a test article simulates the flight vehicle including the test conditions, test section/model size, external and internal detail features, structural characteristics, and information quality);
- Information Content (test conditions, body and component forces and moments, pressures, temperatures, test article shape/distortion, test article attitude, flow vectors, etc.);
- Information Quality (relationship to flight vehicle at flight conditions including wind tunnel measurement or computational simulation uncertainties);
- Test Type Capabilities (capability of a wind tunnel to perform selected types of tests such as aero-performance, jet exhaust effects, inlet-performance, inlet-airframe integration, powered simulators, half model, weapon/store/stage separation, trajectory simulation, mission simulation, etc.);
- Harvesting (identification and capture of technology to enable advances in wind tunnel testing and M&S);
- One-stop shopping (aerodynamics center as a single source for the multitude of tasks associated with producing the required data, analysis, and information, including its relationship to flight duplication);
- LVC (Distributed Live, Virtual, and Constructive);
- UAV (Unmanned Aerial Vehicle); and
- SOS (System of Systems).

Figure 2, which is Version 1.1 of the Capability Test Methodology process for Joint Test and Evaluation Methodology (Bjorkman and Gray 2009), is useful for discussion because the sequence depicted in Blocks 0 through 5, including the 14 processes, applies to how wind tunnel test capability in support of product development (manned aircraft, UAVs, missiles, space access vehicles, weapons launch, etc.) and of integrated test and evaluation activities ought to exist and function. Table 1 shows a brief comparison.

For the product development effort, the central focus of the joint mission environment becomes the integrated product development environment. Here, it seems appropriate that the wind tunnel test portion should be integrated into the development process at the earliest point that a positive contribution could be made. Suppose, for the sake of clarity, in a general application without regard to a specific test that the title of Block 0 is changed to read “Select Optimum Development and T&E Strategy.” Then, from a national perspective, with due consideration for cost, benefit, and risk, a concept of the facility and how it should function in an integrated environment is defined and enabled in time to support a specific test need. The premise here is that today wind tunnel facilities are underutilized compared with the role that they could play. A view is presented herein of what the art of wind tunnel testing could be like in 2025 and beyond, after the objective of Block 0 is achieved in general, but with modification for wind tunnel application.

If at first energy is spent on looking at product development for air vehicles from initial concept to fielded product with the idea of identifying the best approach to take in the future, then out of that thinking can evolve a vision for the best use of the wind tunnel as part of that process. The first process for a wind tunnel application, Develop Capability/SOS Description, implies a definition of needed wind tunnel facility capability. Constraining thinking to existing facilities with some investment will lead to one answer. Removing that constraint will lead to a different mix of wind tunnels and functions for future programs. The capability thus defined would encompass the following:

- test performance for a suite of wind tunnels including test conditions, test simulation fidelity, and information quality;
- test type capability;
- wind tunnel capacity, productivity, and throughput;

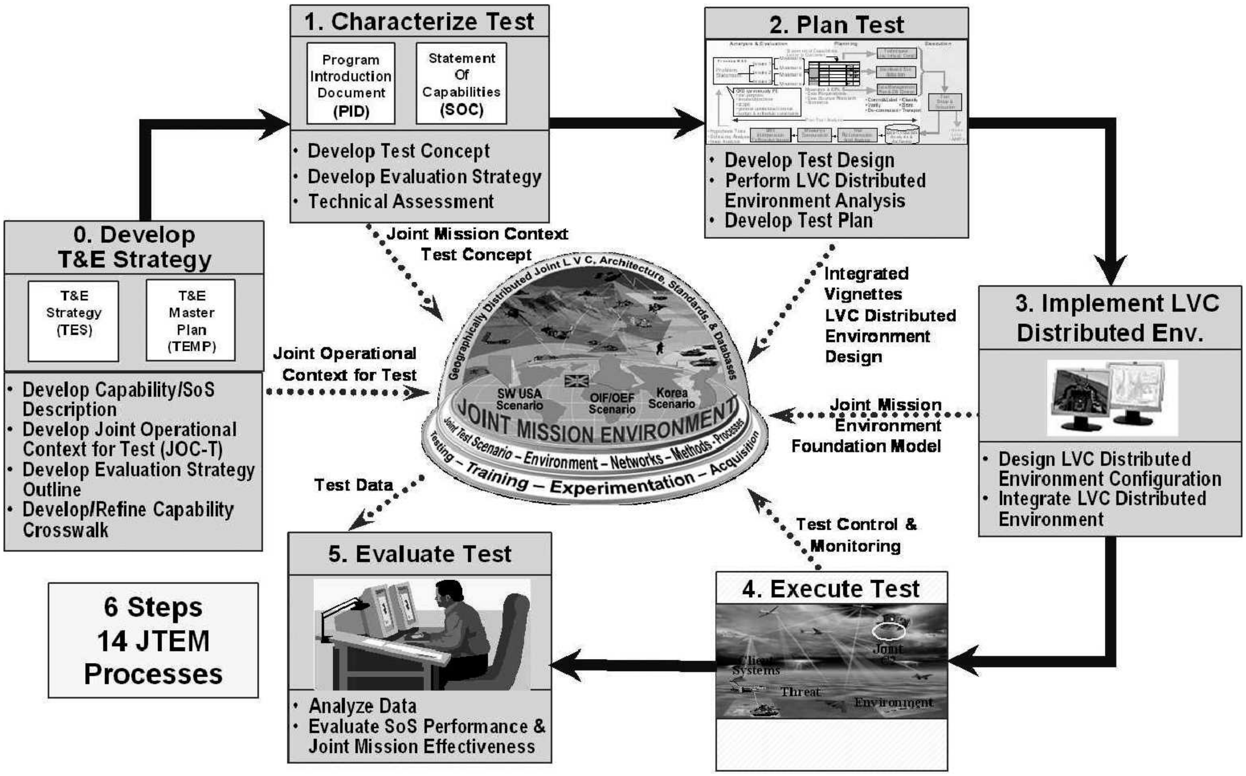


Figure 2. Capability test methodology version 1.1 for joint test and evaluation methodology.

- test operations concept (local and remote interface, full automation for operations and safety, security, monitoring, conferencing, maintenance and repair, sustained funding);
- test information (instrumentation and metrology, data acquisition and processing, data storage and handling, integration of M&S, real-time analysis, high-speed information transfer, continuity); and
- test personnel and expertise.

2025 Block 0 test process – needed wind tunnel facility capability

The product development cycle should utilize wind tunnel staffing capability starting with the inception of a product concept and following through the life cycle of the product to ensure planning and information quality and to promote optimum investment in test capability, M&S application, and personnel expertise. The Block 0 test process objective pertaining to testing is to forecast the test program—timing, facility, objective, test features, pretest M&S, test support systems, distributed control/monitoring, data acquisition and handling, analysis required, etc. From this early involvement, cost and schedule, required facility modifications, and operational readiness are coordinated; investments in hardware, software, and personnel are identified; and the process of implementation is initiated. The goal is for the required test and analysis to be executed as efficiently as possible to support confirmation of flight vehicle performance or reduce the risk prior to flight testing. Both objective and subjective measurement of performance, assessment, and appropriate investment budget to ensure continuous improvement of the Block 0 process is essential and can be included as part of the Block 5 test process.

Table 1. Block 0 joint test and evaluation methodology and wind tunnel comparison.

Capability test methodology, Block 0	Select optimum development and T&E strategy, Block 0
Develop capability/SOS description	Develop wind tunnel facility capability description
Develop joint operational context for test	Develop optimum joint operation concept
Develop evaluation strategy outline	Develop evaluation support concept
Develop/refine capability crosswalk	Develop/refine overlap capability protocol

T&E, test and evaluation; SOS, system of systems.

Other test process blocks in *Figure 2* relate as follows:

- Block 1, Characterize Test, is identical for an application to wind tunnel testing.
- Block 2, Plan Test, which contains the abbreviation LVC joint test environment to evaluate system performance and joint mission effectiveness, is a parallel to integration of the product developer and the wind tunnel test and M&S communities. The parallel is in an activity to run a simulation of the test program and expected analysis of results methodology to ensure that the test design and planned analysis protocol (who, what, when, where, and how) is optimum.
- Block 3, Implement LVC distributed environment, is interpreted as setting up and verifying the communications links, information transfer, and analysis prior to test execution.
- Block 4, Execute Test, is identical for a wind tunnel test application.
- Block 5, Evaluate Test, lists the two processes, Analyze Data and Evaluate SOS Performance & Joint Mission Effectiveness. It is assumed that some action planning for continuous improvement opportunity is part of that evaluation. These processes are essentially the same for the wind tunnel process of the future. A renaming could be Process Effectiveness Evaluation & Improvement. This is a link, which today in the lean environment is very weak as there is no affordable impetus for continuous improvement instead of just identifying and fixing something that did not work as well as it should. A particular weakness that would still exist, even with funding for continuous improvement, is lack of a working link from flight test back through the predicted flight results to the wind tunnel test information base to identify what needs to be improved.

2025 Projected workload

A strategy for reshaping the national wind tunnel infrastructure should include an analysis of historical wind tunnel usage to provide a basis for estimating future requirements. Combining current testing requirements with anticipated technology advances and vehicle development scenarios can shape this vision for the "future" portfolio of U.S. wind tunnels in terms of workload capacity, test condition simulation, and test technologies, i.e., testing or data types, sensors, etc. Strategists should consider the suitability of the future wind tunnel portfolio in relation to the development process for major/complex flight vehicles (aircraft, missiles, armament, space access vehicles) since these programs typically drive the demand for the midsized and large U.S. wind tunnels. Midsized tunnels are defined as having test sections from 3 to 6 feet (linear cross-section dimension), and large tunnels are those having test sections of more than 6 feet. High productivity continuous-flow and intermittent tunnels such as blow down currently fulfill this role and are expected to remain as primary sources into the future. Research activities, although important, are typically conducted in a variety of smaller, more cost-effective facilities and are not considered as primary national capabilities.

The amount of wind tunnel testing required to develop an aircraft has been constantly increasing (AIAA 2009) since the 1950s, although it is possible that this trend may have reached a maximum (Kraft and Huber 2009) for some flight vehicle types and missions, i.e., subsonic/transonic transports. Until now, flight vehicle complexity and the need for more exacting determination of flight performance have driven developers to require increasing quantities of aerodynamic data, and these data have been historically provided by wind tunnels. Several factors may be contributing to a perceived leveling off of testing hours for some vehicle types: the maturity of the aeronautical development processes, the increase in wind tunnel productivity, development of small subsonic UAVs, and the rise of M&S capabilities. However, because future flight vehicles may continue the trend towards increasing complexity, operating speed, and mission capabilities, there could be a corresponding need for more information (data) to be supplied by wind tunnels and M&S. The time frame for M&S significantly impacting wind tunnel utilization is not clear, although flight vehicle developers are seeking ways to use M&S to reduce the amount of wind tunnel testing prior to flight (and improve data quality). According to data from AIAA, 2009, approximately 35,000 to 45,000 hours would be required in the future to develop a typical modern transonic/low supersonic military aircraft (the F-35 required 63,000 hours for three variants) (AIAA 2009). The current estimate for a modern subsonic transport wind tunnel test program, using data from AIAA 2009, is somewhat less and on the order of 15,000 to 20,000 hours. The average ratio of high-speed testing to low-speed wind tunnel testing for Lockheed Martin aircraft development programs was 30 percent (low-speed) to 70 percent (high-speed) (AIAA 2009). (The Lockheed-Martin data are biased in the direction of military aircraft testing.) These trends emphasize the importance of high-speed wind tunnels to the future of flight vehicle development in the U.S.

Furthermore, because the U.S. sustains a high level of aerospace activity, wind tunnels support multiple concurrent development programs. A 5-year average annualized estimate of this test demand was produced in 2007 by the AIAA Ground Test Technical Committee (GTTC) (AIAA 2009) and is shown in *Table 2*. This estimate was considered a near-term baseline and was not all-inclusive (did not include the testing directly conducted by the Department of Defense [DoD] or National Aeronautics and Space Administration [NASA]). The GTTC considered wind tunnel testing a foundational activity for aeronautical vehicle development, and wind tunnels will continue to fulfill this role for the near term and beyond the 2020 horizon.

The bulk of the 38,600 estimated average annual wind tunnel hours in *Table 2* supports subsonic and transonic vehicle development since both the military and commercial industry produce vehicles that operate through this speed range (e.g., F-22, F/A-18E/F, and F-35 military fighters, military unmanned aerial vehicles, and commercial subsonic transports, such as 777, 787, and business jets). Supersonic airliners, business jets, and military aircraft and hypersonic aircraft have been proposed, although none have reached full-scale development (i.e., the DoD Blackswift program was cancelled in 2008). The demand for supersonic tunnel hours is less and typically is in support of missiles and space vehicles, and the hypersonic wind tunnel infrastructure supports the smallest workload. The total annual workload is currently satisfied by a range of tunnels owned by industry, commercial companies, government, and academic institutions. The AIAA GTTC also indicated that there is a potential for a change in the mix of required tunnels and test types as new flight vehicle development programs explore higher speeds and different missions. Their near-term (5-year) prediction was for increased propulsion systems aerodynamic and high-speed testing and decreased aircraft and reconnaissance platform testing.

Although there is a substantial annual requirement for wind tunnel hours, this workload is highly variable because of the cycles of major national programs. NASA recently reported in the Newport News (Newport News Daily Press 2009) that their wind tunnel workload dropped from 10,000 hours in 2003 to 2,500 hours in 2008. And even though need for test hours per vehicle has increased, the number of vehicle development programs has decreased over the last few decades, resulting in an overall reduction in wind tunnel testing hours (compared with the 1960s–1980s). This decreasing and variable demand has resulted in the loss (or inactivity) of several major tunnels since that peak period, including the Commercial North American Rockwell Trisonic Wind Tunnel (demolished); the DoD Supersonic Tunnel 16S (inactive); the NASA Langley 8-Foot Transonic Pressure (closed and probably to be demolished), Low Turbulence Pressure (closed), 30 × 60 Full Scale (closed and scheduled for demolition), and 16-Foot Transonic (closed) tunnels; the NASA Glenn Altitude Wind Tunnel (demolished) and Hypersonic Tunnel Facility (on standby); and the NASA Ames 8 × 7 Supersonic (non-operable), 14-Foot Transonic (demolished), 6-Foot Supersonic (closed and abandoned), 12-Foot Pressure (closed) and 3.5-Foot Hypersonic (non-operable and abandoned) tunnels.

Wind tunnel usage in 2020 and beyond will be shaped by the previously noted trends. Although wind tunnels will continue to be required for flight vehicle development, it is expected that there will be significant variability in tunnel usage, and a real probability exists that the national annual wind tunnel workload may decline as M&S capabilities increase. Therefore, the future portfolio of U.S. wind tunnels will need to be optimized for this expected (potentially lower) utilization while retaining the competency (during minimal utilization periods) to provide adequate response times. While a definitive estimate of U.S. wind tunnel usage past 2015 is beyond the scope of this report, a conservative estimate would be to plan for a similar level of national wind tunnel workload in the midterm, 5 to 10 years, and for a somewhat reduced workload for 2025 and beyond. Significant variations in this workload can be expected, and if the U.S. embarks on the development of a large transonic, supersonic, or hypersonic aircraft, these estimates could grow substantially. In addition, if supersonic and hypersonic airbreathing flight vehicles are to be developed, considerable testing in tunnels with aeropropulsion capabilities will be required.

The expected reduction of the number of test programs runs counter to the expected need of those programs for higher data quality, productivity, and availability of wind tunnel testing. Under the current wind tunnel operational scenario, the decrease in programs will force wind tunnel managers to reduce workforce, reduce available wind tunnels, and curtail maintenance. The skill level of the remaining workforce will be diminished because of reduced test experience. It will also be difficult to attract the "best and brightest" to a career of this highly variable (layoff-prone) type. This dichotomy demonstrates the need for a national strategy to fund retention of key facilities and expertise within the required wind tunnel portfolio.

As M&S results are increasingly inserted into the development process, it is expected that some of the

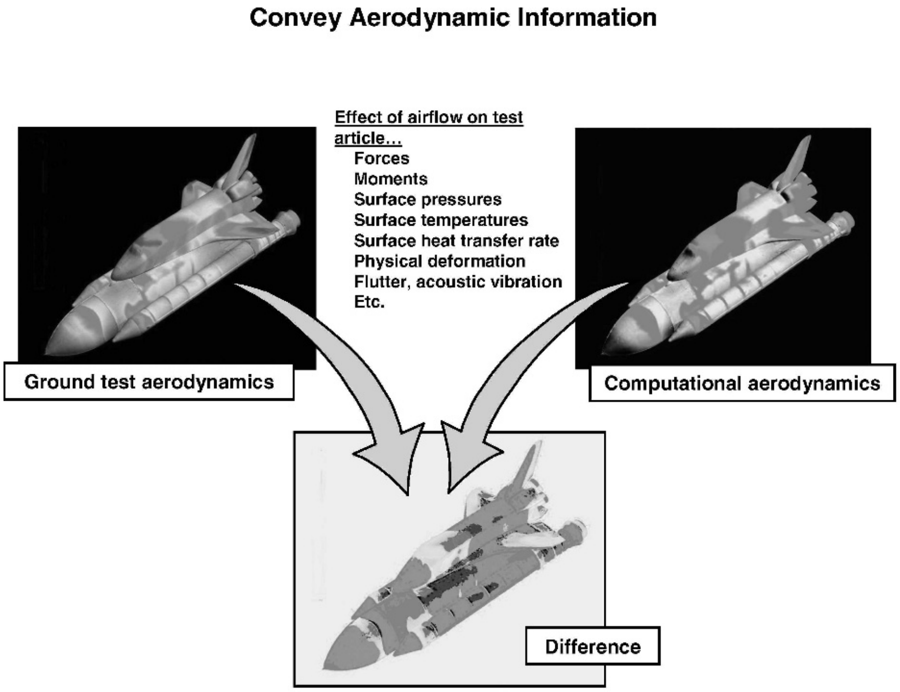
Table 2. 2007 Estimated 5-year annualized near-term workload[4](user occupancy hours).

Class	Low speed (M<.4)	Transonic (M<1.6)	Supersonic (M<5)	Hypersonic (M>=5)	Notes
General aviation	200	0	0	0	
Business jets (5–20 pass)	1,250	1,250	150	0	
Regional jets	500	550	0	0	
Commercial aviation	2,850	4500	0	0	Includes large business jets
Tactical aircraft fighters	2,400	2,900	900	450	Includes UAVs
Military transports and tankers	2,050	1,400	0	0	
Bombers, strategic	1,250	1,100	350	0	Includes UAVs
Suborbital aircraft	0	0	0	0	No forecast available
Orbital access/reentry	200	600	950	350	Industry requirements only (prime), no NASA- or DoD-conducted testing; includes launch vehicles
Conventional helicopters	2,050	150	0	0	
High-speed rotorcraft (TiltE)	1,200	0	0	0	
Air-breathing weapons	350	850	150	0	Includes targets
Rocket or unpowered weapons	400	1000	900	700	Includes targets
Propulsion systems	750	1400	750	200	Includes internal aerodynamic testing/ integration
Technology development/other	300	350	150	0	Test technology, etc., not tied to a program
Recon platforms	900	850	50	0	
Totals	16,650	16,900	4,350	1,700	

UAVs, unmanned aerial vehicle; NASA, National Aeronautics and Space Administration; DoD, Department of Defense.
*Author-date

wind tunnel workload will be displaced by computational hours. It is also expected that there will be increased use of wind tunnels to verify and investigate M&S results as well as provide data where M&S tools are not well suited. To meet this challenge, wind tunnels must become a place for verification of M&S results and merging of these two data sources through use of current tools and those developed in the future. An example of this combination is depicted in *Figure 3*. The differencing scheme between computation and experiment shown can be used as a check for the wind tunnel results by computing a case that simulates a wind tunnel test condition and model configuration. The combined (differenced) wind tunnel and computational results can be used for verification of the expectations for vehicle features that were predetermined. In the latter case, wind tunnel test results corrected by the use of M&S for differences between the wind tunnel test and the computational model are compared. The developer's emotions could vary anywhere between comfort and panic, depending on the severity of the difference. Actions to modify the test plans are a natural result of seeing something that is troubling. Everyone benefits from this process. In addition to providing the requisite air-on time, e.g., workload, a primary set of testing types critical to flight vehicle development will comprise a substantial portion of the wind tunnel workload. These wind tunnel testing types, developed to meet the data needs of flight vehicle designers, have been refined over the last 50 years of testing and require specialized support equipment, i.e., pressure sensors, force and moment balances, data acquisition systems, optical systems, model support systems, etc. Some test types require wind tunnel models specifically configured to meet the needs of the flight vehicle developer's force accounting system (Skelley, Langham, and Peters 2004). Many U.S. wind tunnels have current expertise in multiple testing types, but because of specialization and/or reductions in the wind tunnel infrastructure, some techniques are available in only a few U.S. facilities, i.e., large model store separation testing in Arnold Engineering Development Center (AEDC) 16T, Calspan 8-Foot Transonic Wind Tunnel (Calspan 2009). An example of a primary set typically used for subsonic, transonic, and supersonic flight vehicle development is shown in *Figure 4* (Skelley, Langham, and Peters 2004).

Future wind tunnel programs are expected to continue to require the services of multiple wind tunnels with various capabilities based on program goals and budget (potentially with less frequency and duration). Multiple entries into these wind tunnels will be required to acquire the various types of data (test types) for configuration refinement and validation. As an example, a portion of the F-35 development



* Notional image created by AEDC Technology Engineering Department

Figure 3. Notional concept of merging wind tunnel and computational results.*

program was conducted in two AEDC wind tunnels over a 6-year period as documented in Skelley et al. (2007). Over 8,000 wind tunnel hours were conducted and more than 30 individual tests were accomplished. The workload was distributed between the various test types as follows: 28 percent High Speed Aerodynamics, 12 percent Aerodynamic Loads, 29 percent Weapons Separation, 18 percent (exhaust) Jet Effects, 5 percent Inlet, 5 percent Acoustic, 2 percent Store Loads, and 1 percent Air Data. The test types listed in *Figure 4* are not all-inclusive as there are additional testing types needed to support the data requirements of vehicle designers, i.e., dynamic stability, aerodynamic loads, engine testing, etc., as well as for the various types of flight vehicles and missions, i.e., heat transfer and materials response test types for high-speed vehicles. It is expected that advances in sensor technology, computing power, and testing methodologies will enhance this set of test type capabilities and should be supported; however, it is essential that these capabilities are sustained for future flight vehicle programs across the full spectrum of the national wind tunnels (where appropriate) or flight vehicle developers will face increasing risks.

While the aggregate future wind tunnel test hours and test types needed to support “general” vehicle development can be estimated, we believe that the long-term outlook for the mix of tunnels and test type capabilities is much less certain. Development of supersonic and hypersonic airbreathing vehicles will also place emphasis on the need for aerodynamic propulsion integration test types.

As part of the evolving process of utilizing computational data in a larger degree for the air vehicle performance database, the detailed plan for the force and moment accounting systems will be altered. As part of the development of any vehicle performance database, the integrated force and moment accounting system will have to be transitioned to include computational pieces of data to replace or represent the results from both the wind tunnel and also the engine test facilities. Currently, AEDC wind tunnels 16T, 4T, and 16S and AEDC’s analysis and computational fluid dynamics (CFD) tools have been extensively employed for developing large portions of the ground test and evaluation database used for recent U.S. Air Force and Navy aircraft such as the F-22, the F-18E/F, and the B-1. A comprehensive force accounting system was developed for each of these aircraft by the airframe prime developer to assist in defining and building a total air vehicle performance database prior to flight testing. A depiction of such a force accounting system for a transonic fighter aircraft is shown in *Figure 5* (Skelley, Langham, Peters, and Frantz, 2007). An example of the diversity of candidate flight vehicles is provided in *Table 3*. This list was gleaned from several sources by the AEDC staff and represents typical programs

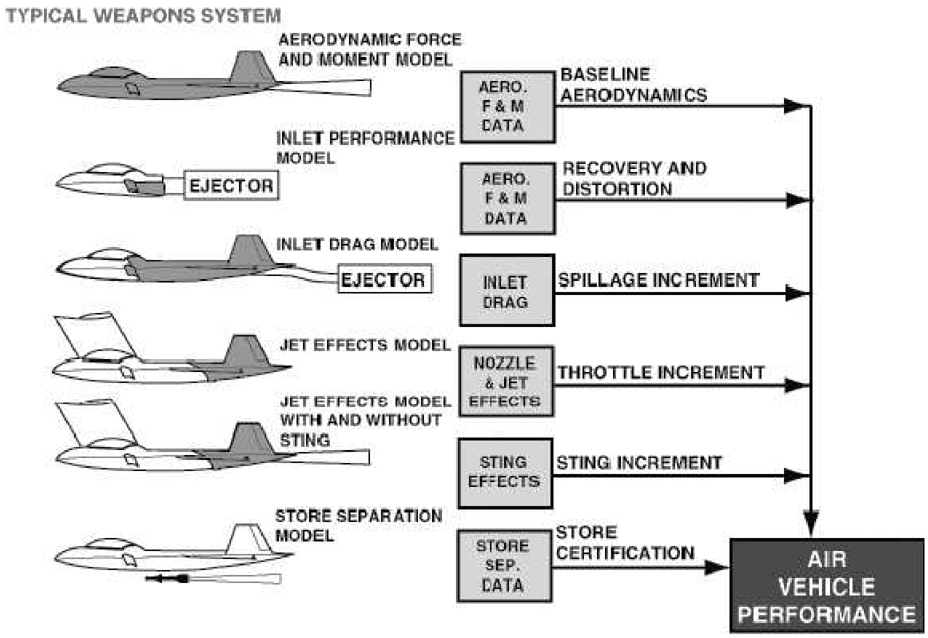


Figure 4. Typical test types providing workload for subsonic, transonic, and supersonic wind tunnels.

that could require the use of mid- to large-sized U.S. wind tunnels (government, industry, commercial, and academic) in the 2025 time frame.

Development of both civilian and military transport aircraft is expected to continue well into the future with new subsonic types being developed. There is also a continued potential for commercial supersonic aircraft such as supersonic business jets or airliners. The need for rapid mobility using high-speed transports (supersonic) has been considered, although their future is less certain. Initiation of several large (transport, bomber) vehicle programs could drive the demand for large test section wind tunnels that provide subsonic through transonic speeds. If the nation pursues hypersonic weapons delivered from supersonic platforms and delays replacing transonic fighters, the demand for supersonic and hypersonic tunnels could increase dramatically, and the transonic workload could be reduced. The U.S. has several hypersonic technology demonstration programs ongoing including hypersonic airbreathing propulsion concepts that will require access to large supersonic and midsized tunnels with propulsion simulation capability. The NASA Ares and the DoD interest in the Military Space Plane could also increase demand for supersonic and hypersonic wind tunnel testing over current levels. It is expected that these future vehicle concepts will continue to drive the demand for mid- to large-size subsonic, supersonic, and hypersonic wind tunnels. However, the resultant mix of tunnels, i.e., speed ranges or Mach capabilities, needed to satisfy the future needs of specific flight vehicles, e.g., subsonic transports versus the hypersonic Military Space Plane, within this diverse set of flight vehicles is less certain and makes strategic planning of the U.S. wind tunnel infrastructure based on vehicle programs difficult.

Therefore, even allowing for gains in wind tunnel productivity and computational effectiveness by 2025, the nation will continue to need access to a diverse set of wind tunnels that can provide up to thousands of hours of testing necessary across a wide range of expected velocities needed for a diverse set of flight vehicle programs. These tunnels must maintain the capability to provide high-quality data through competent application of key testing type methodologies when needed, e.g., timely response with validated methods. The strategy to maintain and improve the key testing types needed by flight vehicle developers should be somewhat straightforward since a radical departure from current tools is not anticipated. However, since a clear picture of the mid- to far-term requirements for wind tunnels is uncertain and the current viability of the wind tunnel portfolio seems to be based on tactical response to current programs, a national strategy is needed to ensure the viability of the wind tunnel infrastructure to meet the needs of future programs in the same manner proposed by Dr. Theodore Von Kármán for the Army Air Forces (HQ Air Force Systems Command Historians Office, 1992). In this document, Von Kármán stated that "the Air Forces must be authorized to expand existing AAF research facilities and create new ones to do their own research and also

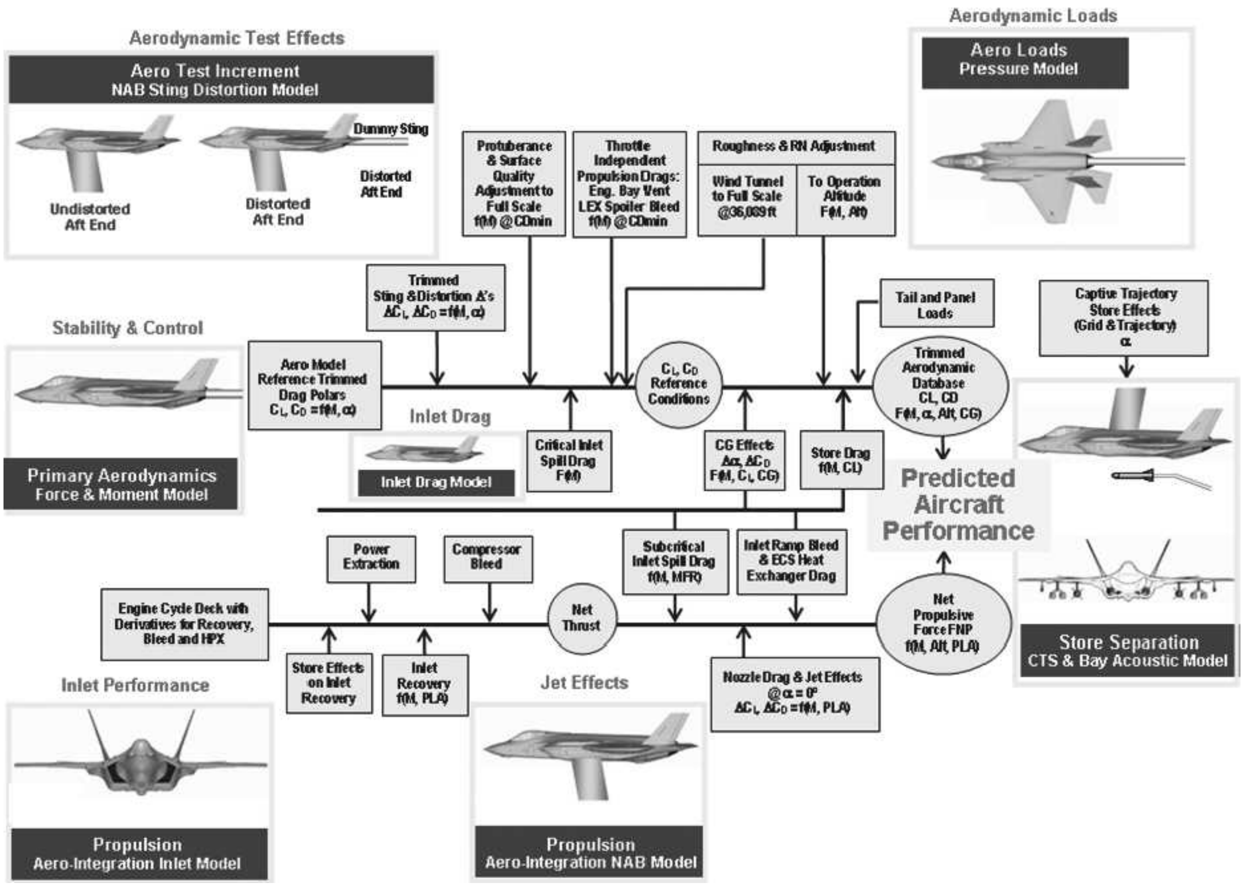


Figure 5. Typical aircraft force and moment accounting system.

to make such facilities available to scientists and industrial concerns working on problems for the Air Forces" and that "scientific planning must be years ahead of the actual research and development work." (Von Kármán 1992). Because most of the national aeronautical ground-test infrastructure is over 50 years old and faces a critical strategic decision, (Kraft and Huber 2009), it seems logical that long-term strategic planning should be initiated to reformulate the wind tunnel infrastructure that can efficiently meet the future demands of a combined ground-test and M&S environment.

The 2025 wind tunnel suite

Given that future programs will require substantial wind tunnel testing comprising a variety of principal test types, and the velocity range of interest may not be fully known, a primary policy question will be how to ensure a U.S. tunnel facility portfolio (government, industry, commercial, and academic) that can meet the future workload demand. The AIAA GTTC made several recommendations for strategic planning of the U.S. wind tunnel infrastructure that are pertinent to this discussion (AIAA Ground Test Technical Committee, 2009).

1. "Development of a knowledgeable test workforce is critical for the national infrastructure."
2. "Improved test technology is crucial to enabling future system development."
3. "Maintenance and improvement of key test assets is a vital component of enabling future test capabilities."
4. "Divestment of redundant and nonessential test infrastructure is required to focus limited resources on critical capabilities and new infrastructure requirements."
5. "New high-speed test infrastructure is required to meet anticipated requirements for future systems."

In addition, several guiding principles suggested by the authors of this report are as follows.

1. A "core" national asset wind tunnel set should be identified such that capability sustainment and

Table 3. Expected future classes of flight vehicles.

Vehicle class	Range	Mach	Development term†
Large aircraft			
1. Space access vehicle (Source: Fetterhoff, et al. 2006)	Low Earth Orbit	7–15	Far
2. High-speed aircraft (Source: Fetterhoff, et al. 2006 and DARPA Program Web site: http://www.darpa.mil/tto/programs/falcon/index.htm)	9,000 to 12,000 nm	4–7	Far
3. Military cargo, example: unmanned large military aircraft for air mobility, airlift, air-refueling (MQ-Lc in USAF Unmanned Aircraft Systems Flight Plan 2009–2047) and speed agile (Sources: USAF Unmanned Aircraft Systems Flight Plan 2009–2047 and Federal Business Opportunities Web site, Solicitation Number: BAA-07-07-PKV, respectively)	N/A	Transonic	Mid–Far
4. Transport aircraft, example: blended wing body (Source: Aviation Week, Jan 13, 2009 Article "NASA Pushes Blended Wing/Body")	N/A	<1	Mid–Far
5. Disk rotor craft (Source: DARPA, http://www.darpa.mil/tto/programs/discrotor/index.htm	N/A	<1 (~400 knots)	Far
6. Supersonic airliner (Source: Flight Global Article Aug 10, 2008, "NASA to spend millions on future supersonic airliner technology" http://www.flightglobal.com/articles/2008/10/08/317118/nasa-to-spend-millions-on-future-supersonic-airliner.html)	N/A	2+	Far
7. Subsonic commercial transport (2030–2035 Concepts) (Source: NASA Aeronautics Research Mission Directorate Web site article "Aircraft and Technology Concepts for an N+3 Subsonic Transport (Awardee Abstract)" http://www.aeronautics.nasa.gov/nra_awardees_10_06_08_c.htm	N/A	<1	Far
8. USAF next generation long range strike (Sources: Armed Forces Journal 26 Feb 2009 Article: Strike Now Next Generation Long Range Strike System Provides Strategic Options: web address: http://www.northropgrumman.com/analysis-center/images/pdf/Strike-Now-02-26-2009-Armed-Forces-comb.pdf and Aviation Week article: "Supersonics Remain Long-Range Strike Option" 12 January 2009, from http://www.aviationweek.com)	N/A	<1 (~2018 bomber), also potential for M>1 bomber after 2018 is fielded	Near–Mid
Medium aircraft			
1. High-speed aircraft (Source: Fetterhoff, et al. 2006)	2,300 nm	2–4	Near–Mid
2. Strike/attack (Source Fetterhoff, et al. 2006)	5,000 nm	3–6	Near–Mid
3. Strike/attack, prompt global reach aircraft (Sources: USAF Unmanned Aircraft Systems Flight Plan 2009–2047 & Fetterhoff, et al. 2006)	~5,000 nm	3–6	Mid
4. Strike/attack/surveillance, unmanned aircraft (Source: USAF Unmanned Aircraft Systems Flight Plan 2009–2047)	N/A	N/A	Mid–Far
5. Navy UCAS (Source: Northrop Grumman News, http://www.northropgrumman.com/review/005-us-navy-ucas-d-program.html#requirements)	N/A	<1	Mid–Far

N/A, not applicable.
†Near term indicates 0–5 years; Mid term, 5–15 years; Far term, 15+ years.

improvement resources can be directed, even if there are no near-term flight vehicle programs dependent on these capabilities.

2. A basic set of wind tunnel capabilities (infra structure, test-type support, techniques, personnel skills, distribution or sharing of capabilities) should be identified for each core facility and maintained at a national level.
3. A process to develop, retain, and transfer validated wind tunnel testing capabilities should be implemented, e.g., a center of excellence for a given test technology.

4. A process linking the wind tunnel personnel and test capabilities from the inception of a product through operational test and evaluation should be developed to ensure that continuous improvement is achieved.
5. It should be noted that if the suite of U.S. wind tunnels is selected and optimized in relation to a single scenario of projected future flight vehicle programs, a different future scenario may not be satisfied by these tunnels, resulting in a national strategic failure. Alternately, the development of future flight vehicles could be constrained to some extent by the available suite of wind tunnels and thus be limited. To guard against this event, a statistical analysis of reasonably probable scenarios is recommended followed by the approach recommended in the Unitary Plan Act (U.S. Code, Title 50,511), which focused on having a suite of national facilities that could be employed to develop flight vehicles across the speed range expected. It also seems logical that the need for the various types of tests (or types of data) developed for the last 50 years will remain, though modified through technological advances. An example is the emergence of pressure-sensitive paint technology within the last decade, which has the potential to reduce the complexity of wind tunnel models while providing increased data content. Other emerging nonintrusive diagnostic technologies will provide more physics-based understanding and validation for computational M&S.

Wind tunnels of the future must deliver the workload "on-demand," which places constraints on the reaction time of individual facilities to provide robust and quality testing services and usually flexible scheduling practices. This means the infrastructure must be preplanned to be ready for envisioned operating "space" (speed, vehicle size, and mission) of future vehicle programs. The event horizon for individual vehicle programs is typically too short to drive major investment in facility capability, but it is long enough to be a factor in any decision for activation of currently non-operating facilities such as the NASA Ames 8 × 7 Supersonic (Mach 2.5–3.5) and the AEDC 16S Propulsion (Mach 1.6–4.75) tunnels, provided they are maintained in a sufficient condition to allow this.

Assuming that AIAA GTTC recommendation No. 5 above is to be given serious consideration, the forecasted programs, coupled with a defined optimum development methodology and associate trade study involving new and existing facilities, is needed to support a decision to acquire a new 2025 wind tunnel facility. To perform this study, the attributes of a new 2025 wind tunnel facility (capability, performance, tools, etc.) should first be defined. The following is an attempt at a first-order definition of the attributes of a new 2025 wind tunnel facility that would support optimum development of high-speed flight vehicles.

A new 2025 wind tunnel facility

For a new high-speed facility, the two major issues are cost and capability. Recent events have shown that if the national need is truly there, the investment cost of several hundred million dollars is virtually a nonissue. What creates a problem is an initial proposed cost that later turns out to be inadequate. Thus, it is important to have as mature a concept of a wind tunnel facility as practical for costing purpose before advocacy begins. Key factors in a wind tunnel facility concept are size, performance, propulsion capability, test types, productivity, instrumentation, operating capability (continuous versus intermittent), and cost of operations. *Table 4* lists key features of one such concept being considered by AEDC that will cover a broad range of required conditions. The major consideration is reducing the size of the test section to where it is the best compromise for a trade between information risk and cost of operation. Information risk drives the test section size to something larger than 4 × 4 feet and cost drives the test section size to significantly less than 16 × 16 feet because, all other parameters being equal, power cost is proportional to test section area. Moreover, the smaller the test section, the lower the capital cost investment for the basic tunnel circuit and drive system. However, from a program point of view, smaller test sections mean smaller test articles, which compromise the fidelity of small features and the ability to automate the test article for a gain in productivity.

The use of M&S for correcting test results (wall interference, inertial forces, test article distortion, flow quality, thermal effects for test article and instrumentation, scale effects, etc.) reduces the risk of a smaller test section. Consideration for transonic development and semi-span testing leads to a test section that is taller than it is wide for high subsonic testing and for high angle of attack. Full automation means that a test program can be conducted quicker and at less total power than for conventional pitch-pause testing; hence, throughput is increased and cost of testing is reduced. With increased air-on productivity, installation and de-installation time becomes a larger factor in the throughput of a facility. This then leads to the need for an interchangeable test section cart system. Test section instrumentation must support use of flow diagnostics technology (e.g., optical access, wake imaging, pressure-sensitive paint). Climate-controlled access to the test section for model inspection

Table 4. 2025 Trisonic facility considerations.

Wind tunnel characteristic	Option/goal	Additional options/goals
Test section size	9-ft-wide × 12-ft-high	
Continuous mach range	0.01–2.4+	
Intermittent mach range	2.4–4.5	
Propulsion simulation	Cold and heated air	
Stagnation pressure	0.1 atm to 2 atm	
Test section walls	Ventilated and adaptive	Optical access
Control capability	Full automation	Remote monitoring/control
Test section access	Cart system (2)	Model injection consideration
Model support systems	Conventional and semi-span	Secondary for CTS
M&S integration	State of the art	
Communications	Secure satellite, high speed	Video conferencing

CTS, captive trajectory system; M&S, modeling and simulation.

or change must be rapid to reduce time for test article change and avoid lost test time to dry the test environment. A test-article injection system does have certain advantages that are worthy of consideration. Propulsion testing capability has a major impact on the size, acquisition cost, and cost of operations for a tunnel. The facility attributes shown in *Table 4* are assumed to be for an aerodynamic facility without propulsion capability since adequate propulsion test capability exists today.

M&S

The wind tunnel facility product is information, which supports the integrated T&E development process. *Figure 6* makes the point that the information features required must be relevant to answering the need for the test, have the requisite quality, and be of sufficient quantity to meet the required program value. The dominant issues for each of these three interrelated features all benefit from the use of modeling. *Table 5* shows where the use of M&S tools can contribute to achieving all three desired features and result in acceptable cost and risk to meet the product development need.

Numerous codes can produce a useful result applicable to wind tunnel testing, and the ability to do so is growing because computational power is continuing to grow at a rapid rate. Physics-based modeling is not growing as quickly, and it seems that codes are not structured so that the relatively uninitiated can quickly become adept at obtaining a reliable solution. The ability to easily generate a computational grid for a particular code is somewhat lacking as well. It is also believed that there will be an increasing need for validation of the growing number of computational (M&S) results and tools. Focused effort on institutionalizing a suite of useful codes for wind tunnel testing and on their ease of use and gridding by the relatively uninitiated would be highly beneficial to moving the use of a suite of selected M&S tools for the various purposes shown in *Table 5* to an efficient and low-cost routine state.

Concept of operations

The technology today makes it possible to reliably and safely operate anything from a remote location. The wind tunnel of 2025 (if not sooner) should have the capability to be operated from where it adds the most value to the test purpose. Likewise, the handling of test data should take place where the information can be delivered in finished state to where it is needed soonest. These two needs lead to the following list of operations concepts:

- product development schedule visibility that shows critical path schedule and wind tunnel test process status and expected period;
- trained staff that bridges gap (test program design through data/analysis delivery) between developer and test engineer;
- “One-stop shopping with distributed resources,”
    - ○ test article validation and management,
    - ○ plug and play model hardware, onboard model data acquisition,

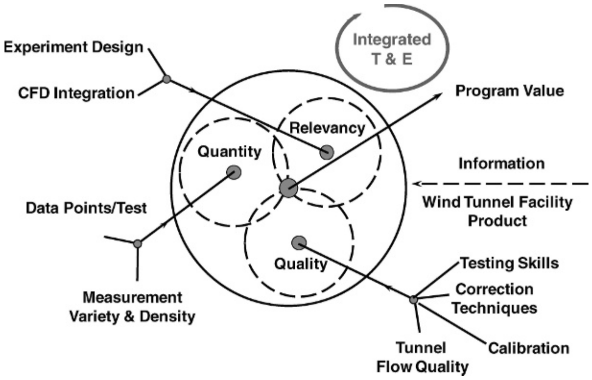


Figure 6. Features affecting desired wind tunnel test information quality.

Table 5. Use of modeling and simulation tools.

	Relevancy	Quantity	Quality
Structural—stress, deformation	X		X
Structural—modal, inertial effects			X
CFD—loads, instrumentation	X	X	X
CFD—wall interference correction	X		X
CFD—flow quality correction	X		X
CFD—model deformation	X		X
CFD—Reynolds number extrapolation	X		X
CFD and automation sciences—control		X	X
CFD—exhaust plume correction	X		X
CFD—after-body closure	X	X	X
CFD—support interference	X		X
MDOE—test matrix	X	X	X
Conjugate CFD—instrument response	X		X
Operations simulation—training and safety	X		

CFD, computational fluid dynamics; MDOE, modern design of experiments.

  - hardware-in-the-loop, and
  - M&S integration;

- design of instrumentation suite and experiment;
- corrections for tunnel effects, non-flight representative model configuration, deformations, scale, inertial and thermal effects, instrumentation installation;
- enhanced visualization to merge and compare wind tunnel and/or flight data and computational results,
  - enhanced visualization tools;
- use of graphical tools for test setup, data reduction, data visualization, data mining and presentation, etc.;
- data reduction visualization and comparison,
  - automated operations;
- virtual operations center at any location via satellite;
- full-spectrum automation sciences and adaptive learning,
  - real-time data management, including acquisition, storage, processing, and transfer;
- satellite technology for data transmission;
- security, encryption;
- virtual customer presence at tunnel operations center;
- standardized test process tools; and
- uncertainty model for final data output.

Summary

This article has attempted to cover major issues in arriving at a 2025+ view of the art of wind tunnel testing. The term "art," overshadowing the term "science," was used on purpose. To acquire and integrate the applicable science and technology and to properly apply it to the wind tunnel testing process is viewed as an art that has both training and experience at its base. The notional main ideas put forth are as follows:

- Wind tunnels are here to stay, but they must change for the future to meet national needs.
- Wind tunnel personnel as a whole should possess a wide range of skills that ought to contribute to the entire vehicle development process from initial concept through operational (flight) test and evaluation.
- Full use must be made of M&S and automation sciences in the testing process for optimum results.
- A national strategy is needed to optimize the wind tunnel facility capability, its use, its sustainment, and its continuing improvement.
- Time restrictions are such that investment in facilities, people, and techniques to meet the challenges of product development programs in 2025+ must start now. ❑

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Endnotes

[1] Approved for public release; distribution is unlimited.

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