Langley Ground Facilities and Testing in the 21st Century

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A strategic approach for retaining and more efficiently operating the essential Langley Ground Testing Facilities in the 21st Century is presented. This effort takes advantage of the previously completed and ongoing studies at the NASA Agency and National levels. The integrated approach presented takes into consideration the overall decline in testing business within the nation and reduced utilization in each of the Langley facilities with capabilities to test in the subsonic, transonic, supersonic, and hypersonic speed regimes. The strategy accounts for capability needs to meet the Agency programmatic requirements and strategic goals and to execute test activities in the most efficient and flexible facility operating structure. The operating structure currently being implemented at Langley offers agility to right size our capability and capacity from a national perspective, to accommodate the dynamic nature of the testing needs, and will address the influence of existing and emerging analytical tools for design. The paradigm for testing in the retained facilities is to efficiently and reliably provide more accurate and high-quality test results at an affordable cost to support design information needs for flight regimes where the computational capability is not adequate and to verify and validate the existing and emerging computational tools. Each of the above goals are planned to be achieved, keeping in mind the increasing small industry and academic customers engaged in developing unpiloted aerial vehicles and commercial space transportation systems and their technologies.

Nomenclature

14x22	=	14-by 22-Foot Subsonic Wind Tunnel
ATP	=	Aeronautics Test Program
CFD	=	Computational Fluid Dynamics
CARS	=	Coherent Anti-stokes Raman Spectroscopy
DoD	=	Department of Defense
GFTD	=	Ground Facilities and Testing Directorate
HTT	=	High Temperature Tunnel
LaRC	=	Langley Research Center
LITA	=	Laser Induced Thermal Acoustics
MDOE	=	Modern Design of Experiments
NACA	=	National Advisory Committee for Aeronautics
NASA	=	National Aeronautics and Space Administration
NTF	=	National Transonic Facility
PLIF	=	Planar Laser Induced Fluorescence
TDT	=	Transonic Dynamics Tunnel
V&V	=	Verification and Validation
ViDI	=	Virtual Diagnostics Interface
UPWT	=	Unitary Plan Wind Tunnel

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I. Introduction

A. Ground Test Facilities at LaRC

A majority of the large ground test facilities within NASA were built 40 to 60 years ago, before and after the transition of the National Advisory Committee for Aeronautics (NACA) to the National Aeronautics and Space Administration (NASA) in 1957. The current set of the large NASA Langley Research Center's (LaRC) active aeronautical testing facilities (with the exception of the 16-Ft. Tunnel, which is scheduled for demolition) are shown in Fig. 1, along with the time period (shown in red) when each of these facilities was commissioned. Also shown in green are the years during which a facility was substantially modified or upgraded. Most of these facilities have been modernized several times during the intervening decades, and their drive systems were completely replaced. These large facilities shown in Fig. 1 receive significant support from the Aeronautics Test Program (ATP) within the NASA Aeronautics Research Mission Directorate, to sustain these facility capabilities into the future. ATP also supports several large facilities at the other NASA Centers. The full suite of 18 large and small subsonic, transonic, supersonic, and hypersonic wind tunnels at LaRC are currently a part of the Ground Facilities and Testing Directorate (GFTD), along with the landing dynamics, crash dynamics, and combined loads testing facilities.

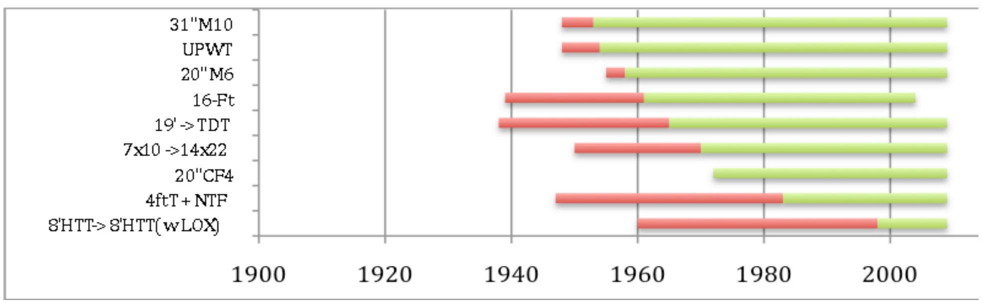


Figure 1. Relative age of NASA LaRC large test facilities.

Since they were built, the above large facilities provided unique capabilities to address aerodynamic issues associated with flight in the subsonic, transonic, supersonic, and hypersonic speed regimes, to help establish our nation as the world leader in aeronautical systems development. Almost all of the aircraft that fly today have technologies that were either developed or inspired by NASA, and these ground test facilities were a key part of it. Some of the key technological breakthroughs and advancements achieved utilizing these facilities in the last decade of the 20th century include: F/A 18 High-Alpha Research Vehicle with thrust vectoring to improve agility; high-speed research to address sonic boom, community noise, and emissions; subsonic technology development to address noise and environmental impacts; research on high-altitude, long-endurance unpiloted aerial vehicles to establish a new record for altitude; and the X-36 tailless fighter to demonstrate high-speed flight.

These large ground testing facilities continued to serve their intended purpose into the 21st century. Some key contributions during the 21st century include: F-18A active aeroelastic wing to explore flexible wings to improve maneuverability at transonic and supersonic speeds; noise reduction technology through the use of scalloped or asymmetrical chevrons on jet engine nozzles; X-43A airplane that used innovative scramjet technology to fly at Mach 10, a world record; sonic boom mitigation in supersonic flight by using a telescopic "Quiet Spike" on a F-15B aircraft; Smart Material Actuated Rotor Technology demonstration to reduce vibrations; X-1 scramjet engine technology demonstration for hypersonic flight; and the X-48B blended wing body research and technology development.

B. Large Facilities Utilization Trend

The trend of testing needs for all NASA ground test facilities over a 7-year period is shown in Fig. 2. These requirements are from NASA programs, commercial aircraft developers, and the Department of Defense (DoD). The drop in utilization from 2003 to 2010 is approximately 40 percent. This reduction is primarily due to the reduced number of aircraft developers within the nation, the reduced number of aircraft that are under development by the current U.S. aircraft manufacturers, maturity of the analytical tools to obtain aircraft design data in certain regions of the flight envelope, and the migration of some testing work to overseas facilities. It was suggested in a study from 1987[1] that the projections for testing workload, as robust as it looked at the time, would reduce as a consequence of the computational fluid dynamics (CFD) tools that are being developed within and outside of NASA. This influence is depicted in Fig. 3. The expectation of using CFD tools to reduce the cost and cycle time for vehicle configuration development and certification is consistent with other discipline areas. Although the testing community did not see the envisioned pronounced surge in wind tunnel testing efforts during the past decade, CFD tools had an influence in reducing facility utilization during this period. The facility utilization projections into the future suggest that the full capacity of all existing LaRC facilities will not be needed in their present state. However, the studies conducted [2,4] so far and the authors' personal communications with industry and the academic community to assess the influence of computational tools on testing needs also suggest that most of these facilities are needed well into the mid 21st century, at varying but reduced levels of utilization, to address the aerodynamic design challenges.

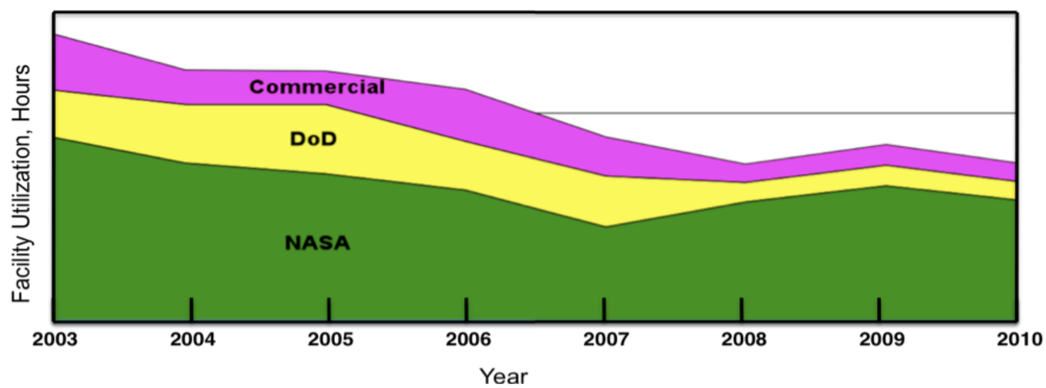


Figure 2. NASA facility utilization trend.

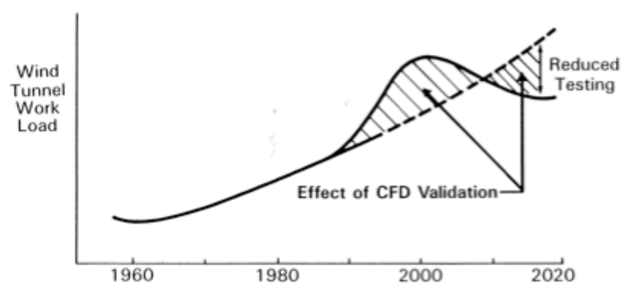


Figure 3. Influence of computational fluid dynamics tools on wind tunnel testing.

C. Current Ground Test Facilities Health

NASA is also challenged with maintaining all of their aging facilities in a state of robust health, due to resource constraints. Over the past several years, the recapitalization and maintenance investments have been well below the industry accepted levels for facilities of this type and complexity. As a consequence, these facilities are prone to occasional equipment and infrastructure failures resulting in unplanned downtime. This fiscal constraint suggests the need to retain a reduced suite of healthy facilities that are essential to meet the Agency programmatic and National needs.

D. The Future Direction of Ground Test Facilities

Based on the above realities, the question that needs to be addressed is "How can we best ensure that the facilities needed in the 21st century remain viable?" This question leads immediately to another question, "How long will it be before these facilities are no longer needed?" A host of recent studies[1,2,3,4,11,14] have attempted to answer these questions. The best approach is to devise a strategy to reduce the number of facilities and focus on the vital few. The Agency is currently formulating a facility down-select process from a national perspective. For the 18 ground test facilities at LaRC, we have developed a strategic approach to select essential testing capabilities to meet Agency programmatic and national testing needs. Our approach is to operate under progressively flexible operational models with the ability to transition into improved and advanced capabilities within the retained facilities or to emerging states of verification and validation in the 21st century. The focus of this paper is to present the influencing factors that were taken into consideration for developing the strategy and a plan to implement this strategy for the intermediate-term (2010-2015), with some thoughts for the longer-term (Year 2025 and beyond) into the 21st century.

II. Factors Influencing the Langley Ground Facilities Strategy

An integrated facility strategy requires consideration of the key factors that influence it. These factors are illustrated in Fig. 4. The primary drivers of this strategy are the Agency and National research and development program needs for testing and their facility strategies. In determining these primary drivers, the Agency and its programs will have already established the influence of computational tools (such as CFD) on their testing needs and the resources needed to establish the health and capability upgrades of these facilities. The remaining four factors (Small Facilities, Automation, Human Capital Alignment, and Test Methods and Technologies) assure operational efficiency, sustainability and excellence in the test results (i.e., quality) produced from the remaining facilities. Test technologies are identified as one area that would bring significant advancements to testing in these facilities. The contribution of these factors needs to be addressed at different levels in order to effectively address establishing an integrated facility strategy.

Figure 4. Key factors influencing an integrated facility strategy.

III. The Strategic Framework

The strategic framework utilized to implement the intermediate-term (2010-2015) plans for LaRC ground test facilities is detailed in Fig. 5. The overall plan requires reiterating the four steps shown in the framework to assure that the ground facilities and testing is relevant and effective in addressing the customer needs. The first step in this approach is to establish the essentiality of each facility based on the considerations listed in the top left box in this figure. The key considerations are the state of the analytical tools and the computing environment, as viewed by the air vehicle developers; a National perspective to assure that capability and capacity are available for testing in the needed speed regimes and flight conditions; and the health of these facilities. The approach used to determine the facilities to retain will be done collaboratively between the Agency programs and LaRC, which is not discussed

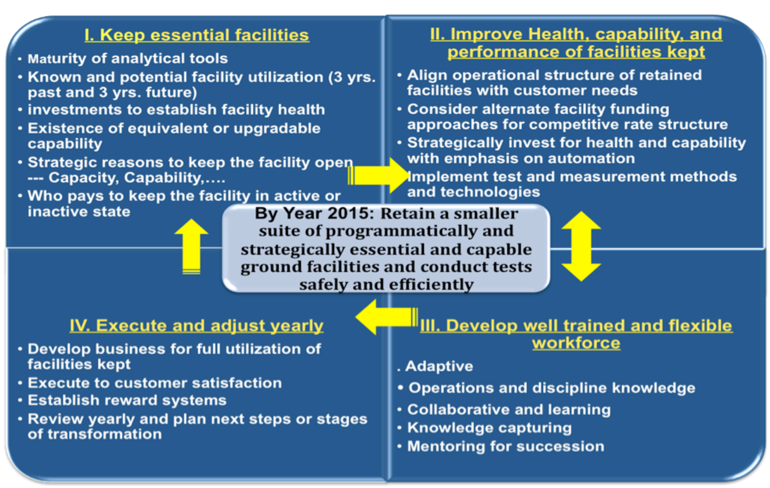


Figure 5. Strategic framework for LaRC facilities – Intermediate-term.

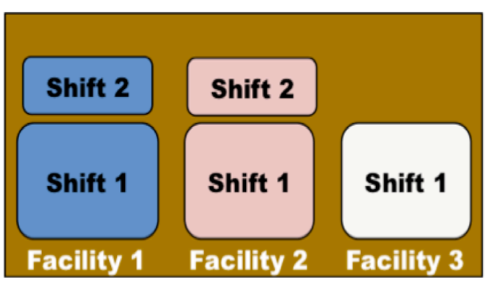
here. The second and third steps in this approach address the overall capability for these facilities and their readiness and efficiency for conducting tests to produce high-quality results for the customer. The facility operating structure, along with capability enhancements that include key facility upgrades, test technologies development, and workforce development will be discussed in the following sections of the paper. The forth step is then to execute this approach and establish processes to monitor success criteria and adjust the plan as needed with a continuing effort to develop business for full utilization of the planned facilities' capacity.

IV. Facilities' Operations Structure

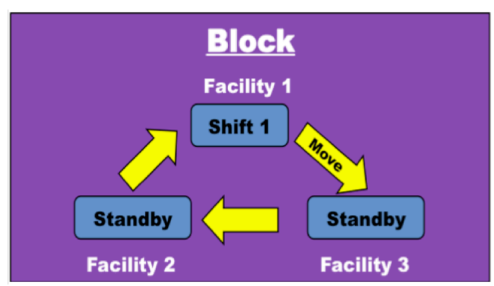
The structure within which the facilities are operated must be aligned with the program needs and is a key factor for the efficiency of operations. Assuring a minimum safe and sustainable operational capability is our primary objective in determining staffing levels for a given operational model. Specifically, this staffing resource must produce high-quality data within each of the facilities by conducting tests in a safe manner. The corresponding functions and skill sets for the workforce also must be consistent with the type of testing conducted in these facilities, such as production Vs. research. The dedication and "agility" of the workforce to conduct tests in several facilities is a key to successfully and effectively executing these operational models in a flexible manner.

A. Large Facilities

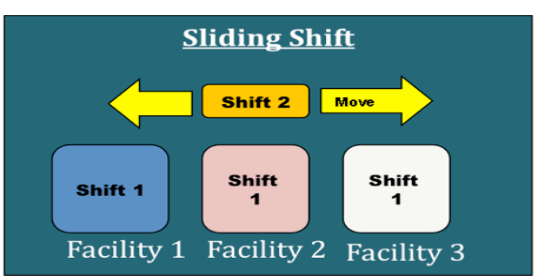
The large facilities are currently utilized to conduct "research" testing with plans for the near future to conduct a combination of research and "production" testing. The past (Year 2008) operations structure for the large facilities has been either a one- or two-shift model, as shown in Fig. 6 (a). The utilization data suggests that these structures are not sustainable for the future and needed alternate structures with flexibility to increase or decrease the operating days. The structures of Aerothermodynamics Tunnels were switched in 2009 to Model 1 (Fig. 6 (b)), where one group of workforce with skills to operate all facilities is rotated from one facility to another to conduct testing work. In establishing facility operational models for the remaining wind tunnels that will endure for at least the intermediate term (2015), the two block models shown in Fig. 6 (c-d) were considered. The challenges and risks associated with implementing this change were also evaluated. The fundamental principle is to ensure that the staffing of the facilities in the changed structure is adequate to support Minimum Safe and Sustainable Operations (MSSO) as defined in the last paragraph. Two other key aspects related to implementing these models are training and certification of the workforce to operate the facilities they work in and capture the knowledge associated with operating each of these facilities for use by the flexible workforce. Both Models 2 and 3 are "blocked models," where three facilities are grouped to provide flexibility to move the workforce with multi-facility capabilities across these facilities to accomplish tests throughout a given period. Model 3 is leaner than Model 2 in terms of the workforce needs and accommodates a reduced facility utilization scenario. Model 2 has staffing levels to conduct



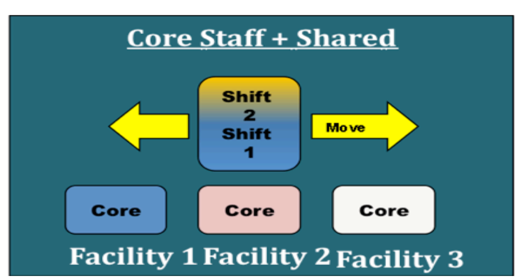
a) Current Model



b) Model 1



c) Model 2



d) Model 3

Figure 6. Operations structures for large test facilities.

one-shift operations within each facility with an additional movable block, shown in orange color, to either support facilities that use special gases to simulate flight conditions or to run second-shift operations to meet customer demand, one facility at a time. In comparison, Model 3 will have core staff in each of the facilities to attend to the maintenance and upgrade functions, with the remaining workforce residing in the movable block to support either a one-shift or a two-shift operation in one or two facilities. During 2010, GFTD is implementing Model 2, which is less risky, for the three subsonic and transonic facilities (NTF, 14x22, and TDT), and one-shift operations in each of the supersonic and hypersonic test facilities.

B. Small Facilities

Compared to the large facilities, use of the small facilities has been primarily to conduct aerodynamics research, analytical tools verification, test technology development, and perform risk reduction testing for larger-scale facilities. As shown in Fig. 7, the current strategy expands this role to include testing in support of smaller air vehicle configuration development, test methods development, current workforce development, and educating the next generation workforce. Additional work is envisioned predominantly through collaborations with small business and academic community engaged in aerosciences work, which includes applications to unpiloted and micro air vehicles and commercial space transportation systems. The expanded suite of functionalities for the small facilities and their potentially expanded customer base requires different operational models, facility cost structure,

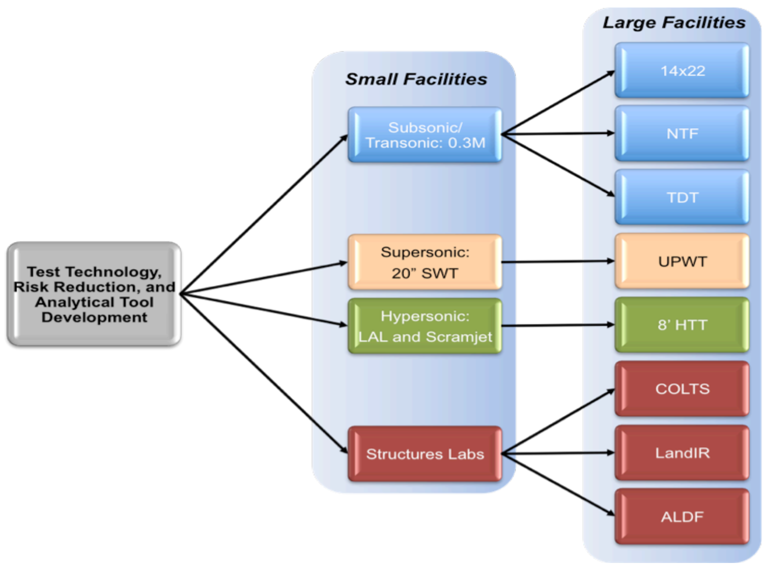


Figure 7. Anticipated future role of small facilities.

and workforce to provide less expensive and quick-turnaround testing so that many candidate concepts can be evaluated by reconfiguring the tests. Cost and time efficiencies are anticipated to come through implementation of selected automation features and information technology improvements.

IV. Facility Health and Capability Improvements

This section addresses the health and capabilities of the facilities retained for the intermediate term in the 21st century. The health of each of the existing large facilities has been assessed through Agency ATP initiatives, and available limited resources are being applied in a prioritized manner to improve the health of those facilities that are the most promising for the future. For the LaRC facilities that are not a part of the ATP, studies are currently underway to implement a similar approach. In addition, there have been ongoing and planned efforts to upgrade facility capabilities, testing strategies, test technologies, and human capital development, which are summarized below. In order to sustain essential test capabilities in the intermediate-term, it is important to have a combination of knowledge-based workforce together with initiatives to advance capabilities and automate test facilities. Some of these are discussed briefly in the following sub-sections.

A. Test Facility Capabilities

A part of the overall facility strategy must include advancing the test facility capabilities to ensure that these facilities meet future needs. These investments must be carefully planned to take advantage of the new technologies, advanced test techniques, or establish new and multi-parameter testing capabilities. To identify the appropriate investment projects, LaRC, NASA Mission Programs, and other customers work together to ensure relevant investment choices are made. At LaRC, there are several ongoing and completed upgrade efforts within the large test facilities in all speed regimes. Some key efforts within the NTF, 14x22 tunnel, and the 8-Ft. HTT are summarized below.

For the National Transonic Facility (NTF), there have been significant investments over the last several years to continually advance its testing capabilities, capacity, and performance. During 2008, the NTF completed installation of an on-site liquid nitrogen (LN2) production plant. Having an on-site LN2 production plant reduces the test costs for the customers. Through proper sizing of the production and storage systems, we are able to produce and have more LN2 available at a lower unit cost and also reduce the time required to complete a typical cryogenic test cycle. This plant was designed and optimized to be highly automated and produces only LN2, using commercially available equipment. The plant was constructed adjacent to the NTF, and is shown in Fig. 8. The total cost for this capability was minimized by utilizing the existing infrastructure, including a closed building and interface with existing LN2 piping systems. The plant has a production capacity of 430 tons of LN2 per day, a 1.5 times increase in LN2 availability compared to before. This facility improvement affords LaRC a significant

Figure 8. NTF liquid nitrogen plant.

flexibility to produce and operate the NTF in the cryogenic mode.

Additionally, the NTF is undergoing an extensive "Data Quality Study" to identify and evaluate the current level of test data quality. This study combines the analysis of historical data using statistical quality control analysis, mathematical model simulations, uncertainty analyses, and systems analysis. This study is currently underway; with several improvements scheduled for implementation, which are planned for completion before the end of 2011. The largest of these efforts is to replace its 1990's data acquisition system with a state-of-the-art system to improve the NTF's test data quality; enhance current testing techniques in the form of advanced data collection, data analysis and processing techniques; and support new testing techniques, in order to assure cost effective systems for maintainability, reliability, and data and physical security.

There are currently several projects under way at the LaRC 14- by 22-Foot Subsonic Wind Tunnel (14x22) to advance its testing capability. One such project is the installation of a test section traverse mechanism that will allow an acoustic phased array to be positioned throughout the test section. This mechanism will allow the facility to take acoustic measurements on advanced aircraft models that will include jet engine simulators. This work supports the NASA Environmentally Responsible Aviation Program to study, develop, and design diagnostics and simulation tools for a better understanding of the integration and interaction of airframe and engine acoustic signatures. A preliminary concept for this traverse mechanism is shown in Fig. 9.

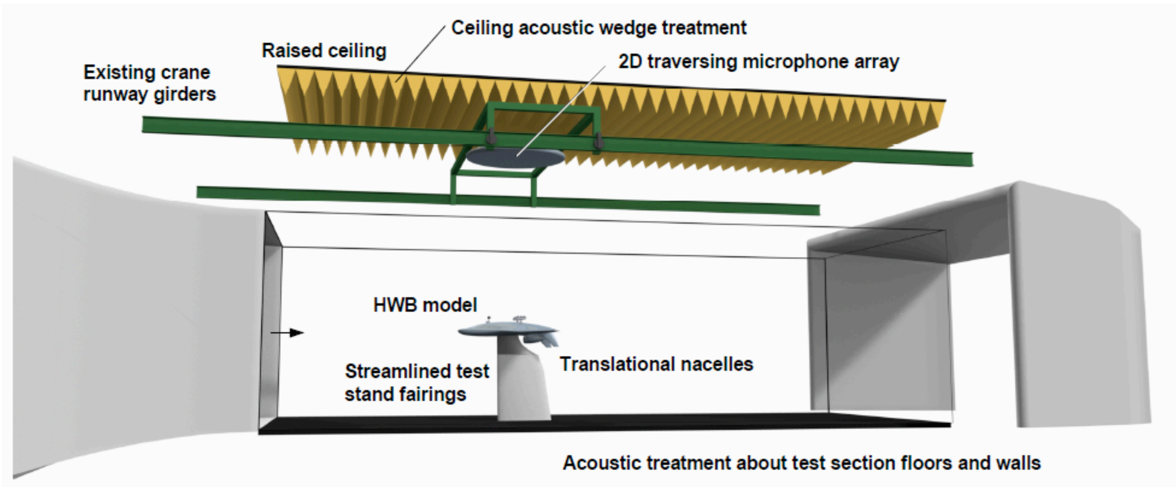


Figure 9. Conceptual design for the traverse phased array mechanism.

Figure 10. Digital control system for the high-pressure air supply system.

The new high-pressure air system at the 4-Ft. Supersonic Unitary Plan Wind Tunnel is another example of a recent strategic investment made to advance the testing capabilities of this facility. An extensive effort was undertaken in this facility to provide temperature controlled high-pressure air to the test sections for simulating jet exhausts to study reaction control jets, nozzles, and plume interactions. This work was originally planned to support the NASA Exploration Program, but the new capability provides additional testing opportunities. The system is integrated into the existing Center-wide 5000 psi high-pressure air system. Within the facility, this supply is regulated and controlled through a series of valves as it passes through a steam heat exchanger used to achieve temperature control. An advanced single digital control valve, shown in Fig. 10, is used to regulate the flow into the test section tunnel. This precision digital valve and steam heat exchanger provide accurate mass flow regulation (0.5 lb/s to 20 lb/s) and temperature control (200 ºF to 300 ºF) to the test section.

Preparing for and meeting the needs of the hypersonic ground testing community requires numerous strategic partners, in order to ensure that the national capabilities meet the needs of DoD and NASA. As a result of this strategic partnership, the 8-Ft. High Temperature Tunnel (8-Ft. HTT) is adding a fuel heating capability to the facility.

The need for this new fuel heater capability was identified several years ago and was based on the development of hypersonic air-breathing engines, where the fuel supply is used for cooling the engine structure. In order to reduce the cost of engine research and development without having to build a complex system of engine cooling passages for fuel heating, the 8-Ft. HTT has successfully integrated a fuel heater system (Fig. 11) into the facility. This system was originally a part of the Glenn Research Center's Hypersonic Test Facility and has been relocated at

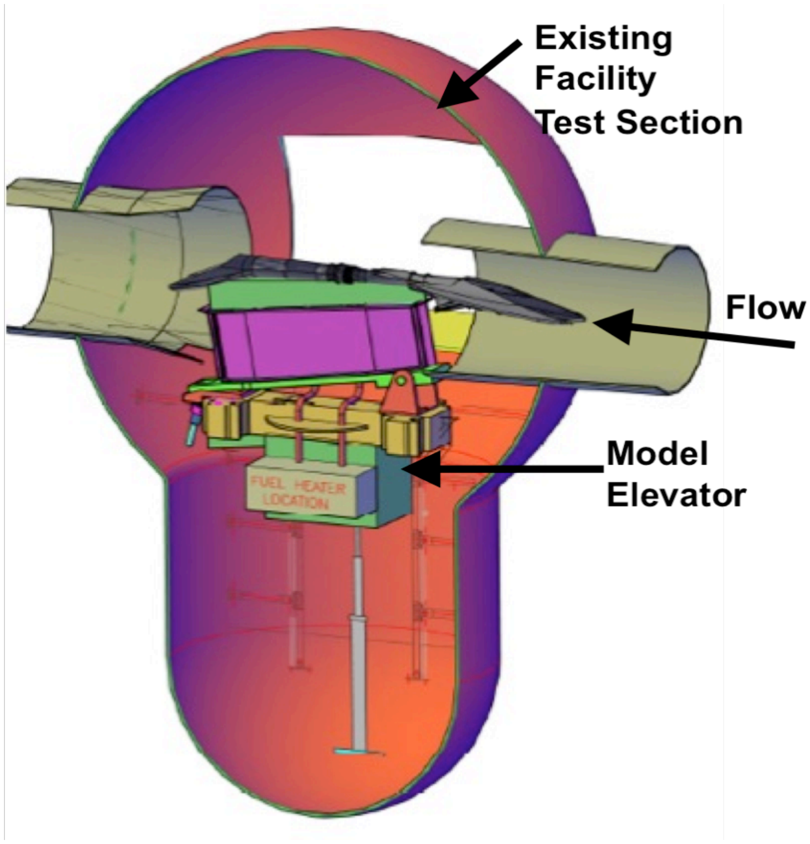


Figure 11. 8-Ft. HTT Fuel Heater System.

LaRC. This integrated system is capable of heating JP-7 fuel up to 1300ºF at full power and delivering 3.6 lbs/sec to the test article.

B. Testing Strategies

In addition to the upgrades to facility capabilities, there are also changes that need to be made to the process of conducting an experiment, most notably that due to the advancement in measurement technology and the inclusion of Modern Design of Experiments (MDOE),[5,6,7,8,9] which represents an advancement to the way traditional aeronautical testing has been done. References 5 through 9 cover the essential principles of the MDOE strategy, which must be done with much more attention to the dependent and independent variables and how accurately one needs to know them, before testing at a facility. These references provide information and examples of successful MDOE investigations. The fundamental advantages of using a MDOE approach are threefold:

1) There is a significant increase in productivity since every single data point contributes to every one of the unknown quantities in which one has interest. This has the benefit that fewer data points are required (at least 50 percent fewer within the typical test matrices, but it has often been observed that as few as 1/10 of the originally planned data is adequate).

2) An obvious benefit of taking a limited volume of data is that quality assurance tactics can be implemented directly, such as sample replication. Another benefit is that the precision of the measurement is determined during the experiment itself.

3) A third, but profound attribute of using an MDOE strategy is that one optimizes the test matrices to get data for quality needs rather than speed or quantity. This often leads to resistance to adopting this method by the aeronautical research community, since they have strived for years to obtain the largest volume of data in the least amount of time.

C. Test Technologies, Test Planning, and Data Visualization

One of the key areas that can advance wind tunnel testing is test technologies. To get the most out of each test conducted in the wind tunnels, one needs to fully optimize each test. Advanced test technologies can help obtain more and critical information from each tunnel run with the desired quality, compared to just the traditional forces, moments and pressures. This is an area with significant opportunity for innovation where using appropriate measurement technologies one can study the gas flow, not just the effect on the model. This may be accomplished through routine application of a battery of advanced instrumentation such as Planar Laser Induced Fluorescence (PLIF), Coherent Anti-Stokes Raman Spectroscopy (CARS), Laser Induced Thermal Acoustics (LITA), Rayleigh, Diode laser absorption, and other off-body flow field diagnostic techniques.

The capabilities from the wind tunnels in the 21st century will allow the researcher to fully comprehend the physics from a "global" perspective. Traditionally, a vast majority of aerodynamic data has been in the form of scalar point measurements, requiring the researcher to infer the structure and behavior of the accompanying flow field. Examples include the inferred presence and behavior of discreet features such as vortices or a boundary-layer transition. However, due to practicality, these measurements are most often made at spatial frequencies far below what is desired, and are often limited directly to the surface of the model. Through the use of advanced, global measurement techniques, with multiple techniques used in concert with one another in the same test, both the causes of and effects from such discrete elements of the aerodynamic environment can be catalogued and analyzed. The outcome goes beyond the knowledge of just resultant forces, moments, and pressures to a comprehensive understanding of the inclusive environment in which the test article is fully immersed. This is the *crucial transition* where experimental testing evolves from acquiring data to obtaining knowledge.

Additionally, advanced data processing and visualization techniques provide a means to enhance understanding of the information acquired through the measurement techniques. An example of such a technique utilized at LaRC is the Virtual Diagnostics Interface (ViDI). ViDI (see Fig. 12) is a methodology that applies two-dimensional image processing, three-dimensional computer graphics, physics-based modeling, and the handling of large data sets

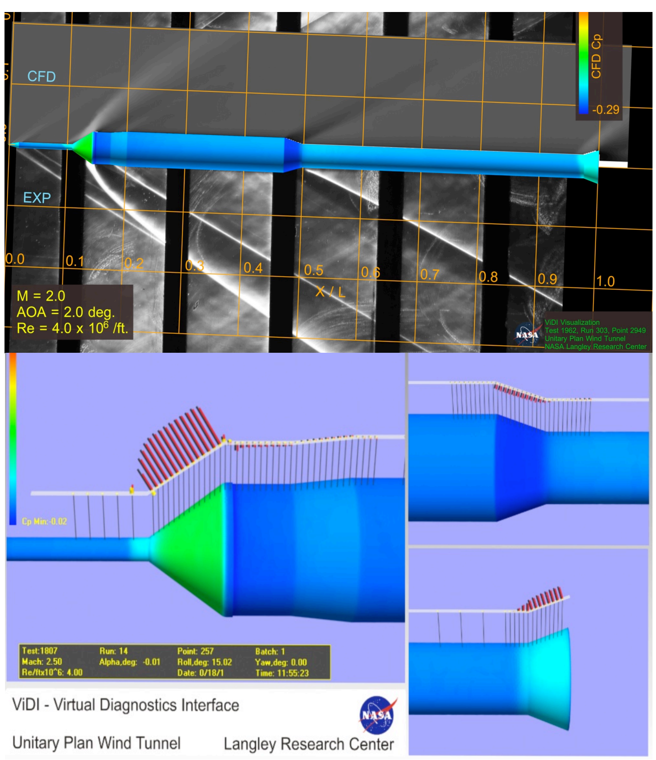


Fig. 12. Examples of ViDI use at the UPWT.

toward solving complex aerospace testing and data visualization problems. In this figure, CFD data, Schlieren images and pressure data are all combined for a better understanding of the test results.

In ground testing, ViDI is used to address three important activities. These are pre-test planning, real-time data visualization in an interactive virtual environment, and post-test data unification, where disparate forms of data are brought together *in-situ* in the virtual environment to help obtain a more global perspective on the causes and relationships of experimental parameters and the resulting physical phenomena reported by the data.[10] The same three-dimensional model used for planning the test, as described above, can be used to display data. The data is fed into the visualization system either through video cameras to incorporate live streaming video into the virtual environment, or through a facility Data Acquisition System, which provides facility conditions and instrumentation data, or both, simultaneously. The result is an interactive three-dimensional virtual environment in which hundreds of channels of data of several different formats (video, pressure, temperature, position, rotation, etc.) can be displayed *in-situ*. This allows the researcher to see the global distribution of the acquired data in real time, especially if the data sets consist of dozens to hundreds of discreet points, i.e., pressure from static ports or temperature from thermocouples.

In addition to real-time experimental data, the ViDI system can be used to display comparisons between CFD and experimental data in real time by making CFD data accessible to the ViDI system.

Detailed descriptions of advanced test technologies and simulation and visualization capabilities that are being developed and utilized at LaRC are presented in a companion paper at this conference (Ref. 11).

D. Workforce Development

Successful implementation of the LaRC facility and testing strategy requires workforce that is adequately trained to be agile and effective across several facilities. The workforce within these facilities is aging and, as people retire, their knowledge will be lost. It is not always possible to transition this knowledge through conventional approaches like mentoring the incoming workforce. Workforce skills need to be enhanced consistent with improvements to test equipment capabilities, test methods, and test technologies. Also, as the new generation of Information Technology (IT) knowledge-oriented workforce replaces the retiring workforce, advanced training methods need to be developed and institutionalized. Therefore, the workforce development strategy requires continued efforts to capture knowledge for each facility, and to train the workforce utilizing the appropriate technology media. Another aspect of workforce development in a learning organization is nurturing innovation. Opportunities need to be created for the workforce to exchange challenges and solutions within a virtual environment that offers access anytime from anywhere to a large group of people. The efforts that are underway within GFTD are summarized below.

1. *Aerospace Testing Skills Revitalization*

The planned and anticipated changes in facilities operations structure, upgrades to facility capabilities, insertion of new and advanced test methods, and testing in both research and production modes requires a dynamic approach to revitalizing the workforce aerospace testing skills. An additional goal is to impart the engineer and technician workforce both operations and discipline knowledge. This approach augments the existing training method, which uses in-class and on-the-job training followed by certifications to work in different facilities and brings forth advanced training methods and tools, which are discussed in the next several paragraphs, to facilitate this education process. It is envisioned that this activity will benefit the current workforce within GFTD, the aerosciences researchers at LaRC, and the next generation workforce in educational institutions.

A challenge in implementing the strategy outlined earlier chapters requires a workforce that is well trained in the application and operation of these advanced testing techniques. Developing IT-based training tools that use animation can be an effective way to communicate complex and advanced testing technologies. A frame out of a recently completed "Force Balance" animation pilot effort, designed to show the technicians the fundamentals of how a balance system works, is shown in Fig. 13 through Fig.17, where the key sensors measure each component of the aerodynamic forces and moments. This is a simple model used to demonstrate the power of animation tools. It shows the test section of the NTF with the side door closed (Fig. 13). These animations are easy to generate since CAD/CAM models of nearly all of our facilities and all of the test articles are always generated. This illustration utilized existing "wire frame" models of the test section, the model, and balance. The animation with an open tunnel door is shown in Fig. 14, a trivial task to do using such a model.

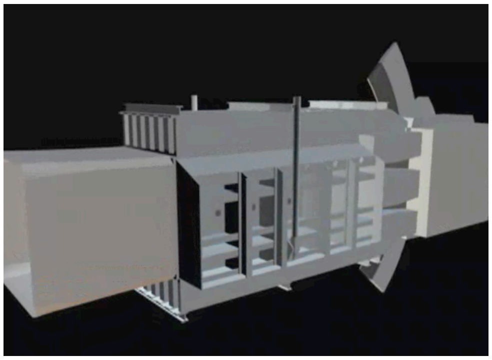


Figure 13. Image from the balance animation showing the NTF test section.

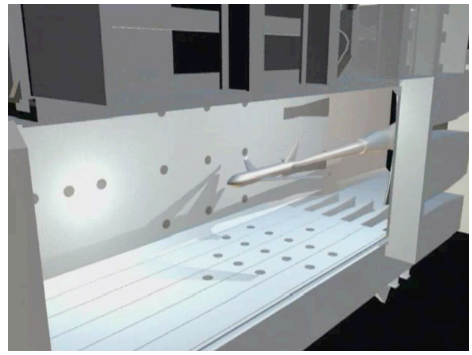


Figure 14. Image from the balance animation showing opening of the NTF test section.

Another feature of such animations, illustrated in Fig. 15, is the ability to show the model structures as "transparencies" so that it is possible to see the balance within the model. It can also show important features, such as areas of close tolerances between the model and the sting/support structure. While balances are designed to be extremely stiff, they are still manufactured such that some component within the balance flexes. The strain gauges are affixed on these flexures to register loading in each of the six principal force and moment directions.

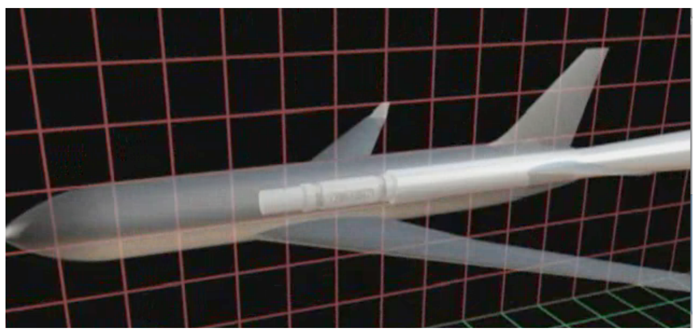


Figure 15. Image from the animation showing balance location within the model.

The locations of the flexures and gauges that detect normal force are shown in Fig. 16. The effect of positive normal force on the balance, with very exaggerated deflections of the balance flexures, is shown in Fig. 17. These types of animations can be done for any instrument, showing the salient features much better than can be done in still images (as presented in this paper).

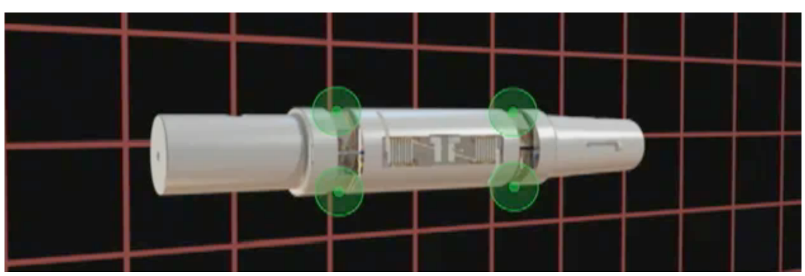


Figure 16. Image from the animation showing the gauges used to measure normal force.

It is clear that more integrated high-speed computational capabilities are central to the development and widespread use of any of these techniques. Langley plans to make investments into advancing these pilot efforts to begin this transformation. As the world's interconnectedness advances rapidly, we expect to share these training opportunities with others outside of LaRC.

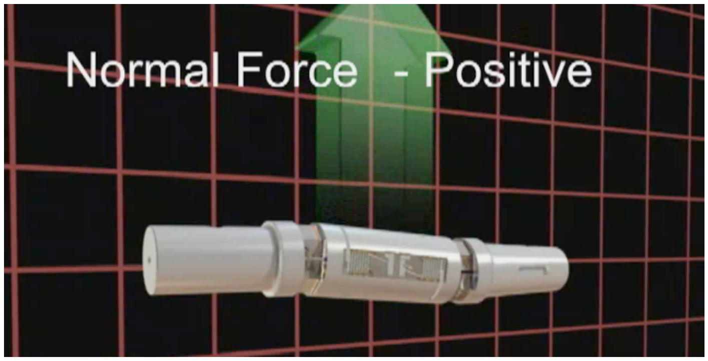


Figure 17. Image from the animation showing balance deflection due to a positive normal force.

2. Fostering creativity and innovation

Innovation is key to continued success in the 21st century and, as a learning organization, we will continuously strive to improve with time to stay relevant. These improvements could be through introduction of new or altered techniques, methods, practices, or processes. Participation of everyone within and outside of the Ground Facilities and Testing Directorate (GFTD) is important in order to provide stewardship of the ground testing facilities and their capabilities in the 21st century. A recent initiative within GFTD, "Innovathon," is a web blog where the workforce can post problems they want addressed, as well as identify potential solutions to these problems. Their unique knowledge and experience makes them ideal contributors of ideas through the website, which will eventually lead to implementing innovative solutions to our key challenges.

Some Technical Challenges identified by the participants from GFTD include:

a) Wind Tunnel Calibrations: What measurements are required to adequately characterize/calibrate a wind tunnel flow field well enough for both customer requirements and CFD development?

b) Supersonic Boundary Layers: What facilities, test techniques, and instrumentation are needed to conduct supersonic boundary layer research?

c) Complex Structural Load: Can we develop a robust, non-intrusive, measurement technique/approach to quantify the response of complex structures under complex loading conditions and environments? Complex environments could include thermal (hot or cold) or vacuum. However, the most common measurement metric across the structures discipline would be displacement or strain, so we suggest this as an initial focus.

d) Shock Wave Tomography: Can we develop 3-D tomography to identify 3-D shock shapes?

e) How can we Improve Facility Efficiency - Operations, Cost, Productivity? How can we substantially improve efficiency or reduce cost of facility operations, or substantially improve facility productivity?

f) Code Validation Experiments: What experiments and test techniques are needed to provide high quality code development/validation data for the subsonic/transonic challenges of:

- i) Laminar flow transition
- ii) Separation onset
- iii) Massively separated flow

g) Energy Independence: Can LaRC become more energy independent? Completely energy independent? How?

h) Shock Strength Measurement: Can we develop a non-intrusive method to quantify shock strength and position?

i) Equivalent Hot Wires Sensors: Can we develop a non-intrusive instrument that will get velocity fluctuations equivalent to hot-wire fidelity, but more rugged?

j) Structural Response Measurement and Visualization: Can we develop a method that takes 2-D experimental data and augments it by analysis to realize 3-D results on the fly?

V. Thoughts for the Long Term

It has been well established that computational modeling has progressed substantially over the past several decades, and computational modeling and simulation is expected to continue progressing at an ever-accelerating pace. There are, however, significant gaps that exist in the ability of the computational tools to accurately, rapidly, and inexpensively predict aerodynamic response for flight regimes that are "off-design" and the flow conditions associated with them. While it is possible to calculate simple flows quickly and efficiently, unsteady, separated, and reacting flows are considerably more challenging. Results from an unsteady calculation of the unsteady flow over an F-18 aircraft wing is shown in Fig. 18, where under certain conditions, differences in the flow over the left and right wings lead to an abrupt wing stall. This CFD prediction was done over 5 years ago, in an attempt to uncover the mechanisms behind the abrupt wing stall, a phenomena faced by many military fighter configurations. Hall[12] implemented the novel "free to roll" testing method in LaRC facilities, which proved very effective in evaluating which configurations were prone to abrupt wing stall and which were not. He identified "figures of merit" for this phenomena using experimental methods. At that time, it was not practical to use CFD to find the same "figures of merit" for these phenomena. Calculations by Forsythe[13] took many hours on the highest speed computers of that time and would still take about 25 percent of that time, making those computational solutions impractical even today, and perhaps for some time to come.

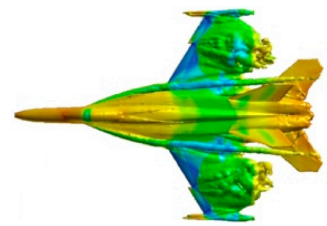


Figure 18. Illustration of unsteady flow calculation of abrupt wing stall on a F-18 aircraft.

Current and emerging computational tools need to be thoroughly evaluated to address the uncertainties in results before confidently using them for air vehicle design. Also, fast computing power is needed to rapidly execute these runs in a cost effective manner. Since rapid advances and changes are likely to continue forward in many of the areas that influence facility operations during this century, LaRC has been studying the nature of changes and preparing for the 21st century. The initial findings of this study have been published in a white paper entitled "A Future State for NASA Laboratories, Working in the 21st Century."[14] At the forefront of these findings is that computational speed has been doubling every 24 months, suggesting that the needed computing power will be available in the near or intermediate term. Depending on the progress we make in developing verified computational tools, it is conceivable that the tipping point toward using analytical tools to assess aerodynamic performance in an expanded flight regime, compared to now, could occur as soon as 2025. This state could lead to an "immersive" environment in another decade, where one could simply make configuration changes and visualize the CFD tools driven aerodynamic response in near real time. In another decade after that, it is conceivable that there could be an intelligence-based design and testing environment that, with minimum human involvement, could self-select a combination of computations and tests across multiple speed regimes to design and evaluate future advanced vehicle configurations.

Advancements in ground testing during the next decade would render a full "virtual presence" for the customer with semi-automated facilities that respond to a customer command to run the test conditions and shared viewing of the experimental and analytical results. This would be needed as we begin working globally in this area. The customer needs complete audio and video access into model preparation, instrumentation set ups, the test section, control scheme, the data being visualized, etc., to work collaboratively with the combined knowledge. A more integrated high-speed networking capability is at the heart of such virtual presence capability. The world's interconnectedness is rapidly advancing, and we could expect to get in to this collaborative mode well before 2020, if the computer security issues can be mitigated.

VI. Summary

A strategy for LaRC ground facilities and testing in the 21st century is discussed. This strategy takes into account factors that influence choices for a smaller set of the currently existing facilities, with consideration to supporting national capability needs, as outlined by the Agency and national studies. Published studies suggest that these select facilities will be needed to support air vehicle design for the next 25 to 40 years. As a part of the strategy, the suite of facilities retained will be reviewed each year based on the framework outlined here. The retained facilities will be operated in a structure that is aligned with the testing demand and staffed with skilled and agile workforce to ensure minimum safe and sustained operations. Every effort will be made to upgrade and maintain the health of these facilities and to keep the workforce skills up-to-date using advanced training methods such that needed technical data can be generated reliably and efficiently as long as these facilities are in use. The facilities that are retained need to be upgraded to support current and future testing needs for single and multi-parameter test data and by utilizing advanced test technologies, data visualization techniques, and virtual collaboration. Innovation will be a key to accomplish these advancements.

Acknowledgments

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