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Recommended Practice

Wind Tunnel Testing — Part 1: Management Volume

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Abstract

This recommended practice document is the first of a two-part series intended to provide test project management and practitioners with best practices that maximize the data value of wind tunnel test projects. Part I help managers understand the impact of decision making before and during the development of a test project and provides key activities to help improve the timeliness and cost-effectiveness of future wind tunnel test projects. Part II provides those responsible for test execution with best practices to employ when preparing for and implementing tests.

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Foreword

The American Institute of Aeronautics and Astronautics (AIAA) Ground Test Technical Committee (GTTC) began looking at best practices associated with test article development as a way to recommend improvements in wind tunnel test efficiency, cost, and cycle time. It became apparent early on that trying to separate test article development from overall wind tunnel test process was not a productive and useful activity. The highly integrated nature of the processes, organizations, and personnel involved in wind tunnel test programs requires that a broader viewpoint of the wind tunnel test process be evaluated in order to develop successful techniques and methods. This two-volume effort, “Recommended Practice for Successful Wind Tunnel Testing,” is the result of that evaluation.

Part I was written to provide test program managers with clear insight into achieving technically focused, affordable, and low-risk test programs to support the development of aerodynamic vehicles and technologies. This recommended-practices document will help managers understand the impact of decision making before and during the development of a test program and will provide key activities to help improve quality, timeliness, and cost-effectiveness of wind tunnel test programs.

Part II provides additional detail about successful methods for personnel who are directly involved in developing and executing test programs.

Neither volume is intended to be a totally comprehensive document on successful wind tunnel testing. Instead, they represent a compilation of best practices to provide a strong foundation for the successful development of a test program or test effort. While these practices focus on wind tunnel test processes, the information is applicable to many other ground test activities.

The GTTC Test Processes Working Group consisted of a diverse group of industry and government experts in the fields associated with wind tunnel testing. During the development of these documents, this group consisted of:

Mr. Mark Melanson, Chairman	Lockheed Martin Aeronautics
Mr. Tom Aiken	NASA Ames Research Center
Mr. Allen Arrington	QSS Group Inc./NASA Glenn Research Center
Mr. Chris Athaide	Tri Models Inc.
Mr. Rene Barakett	Bombardier Aerospace
Mr. Mark Betzina	NASA Ames Research Center
Ms. Jean Bianco	NASA Glenn Research Center
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Many others also contributed to this document during its development.

On the recommendation of the Test Processes Working Group, the following knowledgeable individuals reviewed this document and provided valuable critiques. Approval of the document was unanimous.

Mr. Roger Chamberlin	NASA Glenn Research Center
Mr. Rick Crooks	Allied Aerospace Inc.
Mr. Chester DeCesaris, Jr.	BMDO Test Resources
Mr. Ralph Klestadt	Raytheon Missile Systems
Mr. David Miller	NASA Langley Research Center
Mr. Gerald Pounds	Lockheed Martin Aeronautics Company
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Mr. Joe Strong	Boeing, Retired
Mr. Jeff Haas	NASA Glenn Research Center
Mr. Robert Voisinet	AEDC White Oak
Mr. Scott Winship	Northrop Grumman

The AIAA Ground Test Technical Committee approved this document (Mr. Allen Arrington, Chairman) in July 2002.

The AIAA Standards Executive Council (Mr. Phil Cheney, Chairman) accepted this document for publication in September 2003.

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1 Introduction

Wind tunnel testing is a critical component in the development of aerodynamic vehicles and associated technologies. While the time and expense of wind tunnel testing is significant, it is an essential risk reduction tool before progressing air vehicles and technologies to the more expensive, technically risky flight tests. Decisions made during the evolution and execution of wind tunnel test programs can have far-reaching performance, financial, and schedule implications throughout the life cycle of an air vehicle.

Efforts are being made across all air vehicle development activities to reduce technical risk, cost, and cycle time. Since wind tunnel test programs are critical to those development activities, any successful reductions in wind tunnel risk, cost, or cycle time can have significant positive impacts on the overall air vehicle program.

To accomplish a successful program, managers of wind tunnel test programs must carefully balance the testing needs (objectives), schedules, and cost of the test program. Activities such as developing test requirements, test articles, test preparation, testing, and analysis require significant resource investments and must be carefully managed to accomplish technical goals with minimum resource expenditure.

This volume describes the broader aspects of test program development, implementation, and management. It provides managers with a set of tools (key activities) to help navigate and develop a balanced, successful test program.

1.1 History and Background

Wind tunnel testing has been critical to aircraft development since it was first performed by Frank H. Wenham in Great Britain in 1871. Beginning in 1901, the Wright Brothers utilized a tunnel of their own design to increase their understanding of aerodynamic lift and control, which helped them produce the first powered aircraft in 1903.

In today's highly competitive commercial aviation world, small improvements in aerodynamic performance can translate into range and payload gains and, therefore, sales. Wind tunnel testing to develop air vehicle configurations involves extensive aerodynamic testing. Loads, flutter, and propulsion interaction testing are also important aspects of test programs. Military air vehicle development may include additional focus on testing of broad test envelopes, weapons carriage, and highly integrated propulsion effects.

Wind tunnel testing has historically provided the primary ground test mechanism for establishing air vehicle performance prior to committing designs to flying hardware. With increasing emphasis on lower air vehicle development costs and cycle time, people in the test community have been asked to produce higher quality test results, quicker and for less cost.

The desire to reduce cycle time (and cost) seemingly necessitates reductions in allotted span time for wind tunnel model design, fabrication, test preparation, testing, and test analysis. Unfortunately, these pressures can negatively affect the quality and cost of test programs. Therefore, it has become increasingly difficult for test service providers to perform test work in a manner that is consistent with schedule pressures (at a minimum cost) while providing the quality necessary to ensure a totally successful test program.

The tradeoffs between cost, quality, quantity of data, and schedule response, along with the processes employed during test program activities, are the key focus areas for today's wind tunnel test management. To provide managers with the best tools available, it is important to first understand the tradeoffs and techniques that will yield successful test programs. These techniques include:

- Understanding technical goals (therefore data needs) before embarking on a test program
- Getting the right people involved early to minimize risk and cost (including early selection of the test facility and test facility personnel)

- Managing model and data fidelity to minimize costs and schedules
- Using a systematic process to develop, plan, and manage test programs
- Integrating test changes with minimum impact.

2 Managing Today's Wind Tunnel Test Programs

2.1 Planning Issues in Wind Tunnel Test Programs

Many significant factors ultimately influence the success of a test program. In the commercial aviation market, time-to-market is critical, driving measures of success in the direction of reduced cycle time. Of course, cost is always of special importance. When developing defense articles, technical issues may be of overriding concern. Despite the potential priority differences for every type of development program, careful attention to the planning issues discussed below will significantly enhance the probability of success.

Communication is a cornerstone activity within any test program. Early involvement of test community personnel will facilitate the best (and lowest risk) planning. Careful generation and flow down of overall objectives help the test personnel understand and execute the best possible plan. It is also critical that management be involved during the test activities to help keep objectives and activities aligned and to encourage the test participants.

2.1.1 Test Requirements

Test objectives must be documented and approved before any test-related activities are initiated. Test requirements must be clearly defined at the beginning of a test program and should be a direct result of test objectives. These requirements must contain information such as measurements and accuracy needed, time allotted to conduct test program, resources available (budget, people), security, model suppliers, test facilities, special contractual issues, etc.

2.1.1.1 Integrated Test Programs

The project developmental test program should optimize the benefits of flight test, wind tunnel test, and modeling and analysis (Annex A.1, Integration of Testing and Computational Fluid Dynamics).

Wind tunnel test programs often encompass multiple test entries at many different facilities. Efficiencies can often be gained (both schedule and budget) through careful integration across an entire test program. Examples of integration include using a single model for both low- and high-speed testing, using common model scales (and potentially, parts) for several model types, and using a single test article to acquire several types of data (e.g., force and pressures), etc. These economies are not without risk, since test schedules and goals frequently change, and conflicts can arise. Risk and payoff must be carefully balanced when assessing the optimum test program.

2.1.1.2 Test Article Size and Fidelity

Size and fidelity requirements of the test article should be carefully evaluated during the planning stages. Careful matching of model size, test facility capability (including blockage and test conditions), instrumentation (i.e., a force balance), and required data accuracy are important. It is also important to keep in mind uses for the model (including potential test facilities) beyond what is immediately known or required.

Size requirements are developed from test feature requirements (i.e., what is being simulated and at what level of detail), instrumentation size and volume requirements, test article and test facility matching, support system requirements, and manufacturing methods to be used (which relate to cost and schedule). Model design and fabrication experts are the best source of advice for optimizing model sizing.

Fidelity is associated with such items as tolerances, surface finish, model alignment, etc. Defining required test article fidelity will have a bearing on design and fabrication methods used and, hence, associated cost and schedule. Fidelity requirements should be directly related to type of testing required. If a program is in the conceptual stage, fidelity requirements may be low. As a program evolves through developmental and validation stages, fidelity requirements generally increase. An example of this might be whether a model replicates complete fuselage geometry. Early conceptual models may not include all the detailed geometry since overall accuracy of the test program does not require such fine detail.

2.1.1.3 Data and Instrumentation Requirements

Data required from each test vary greatly, as do associated impacts of obtaining that data. Data are generally acquired from various types of sensors such as internal strain gage balances, pressure transducers, inclinometers, and thermocouples. Cost to install and hook up a particular piece of instrumentation in a test article is only part of the instrumentation cost. Associated costs such as cabling, signal conditioning, filtering, calibration, checkout, data reduction, data presentation, etc., can be added factors.

Evaluation of instrumentation cost is generally expressed in terms of unit cost per instrumentation installed. Cost per unit of instrumentation should include test article installation, acquisition, checkout and calibration, reduction, and presentation. Costs of acquisition, checkout, calibration, reduction and data presentation may be buried in the facility costs and difficult to determine.

Increasing the amount of instrumentation can cause a substantial increase in cost, schedule, and complexity and should be weighed carefully during program planning. However, it is much more cost-effective and schedule-friendly to include all needed instrumentation during model design and fabrication instead of adding instrumentation at the test site.

Required data accuracy should also be used to carefully select instrumentation and calibration requirements that will meet accuracy goals at minimum cost. Proper calibration can be critical for use of required instrumentation and must be planned for during testing preparation.

It is important to consider any additional instrumentation that may be required to validate the overall quality of the test results. Different test types require additional instrumentation for correlating or correcting basic data (i.e., wall corrections, internal drag, tunnel noise levels, etc.), and these requirements must be included and planned for early in the testing. Comparing data to analytic methods (such as computational fluid dynamics) may require specific instrumentation for accurate comparisons. See Annex A.1 for additional details.

Finally, a detailed uncertainty analysis (for example, bias and precision—AIAA S-071A-1999 *Assessment of Wind Tunnel Data Uncertainty*) should be completed early in the development of a test program to ensure that proper instrumentation and sensor accuracy are available to achieve program goals.

2.1.1.4 Facility Selection

Test facility costs represent 1/2–2/3 of total test program costs and are usually the driving force behind schedules. Therefore, selecting a test site requires careful consideration and planning.

Test facilities are typically determined by mission suitability, cost, type of data required, program constraints (facility provided as part of contract), and availability. The first consideration should be performance capability (e.g., Reynolds number, Mach range, size, flow quality, etc.). Additional considerations such as high-pressure air, vacuum systems, etc., that are needed to support models systems are also important. Selecting a test facility that can provide appropriate simulation parameters is of primary importance. Cost should be a secondary consideration after test facilities have been identified that meet the basic technical simulation requirements.

Many similar facilities vary greatly in cost for a variety of reasons. With similar test facilities, a cost comparison is typically made based on what is generally known in the industry as UOH, or user-occupancy hour. This alone is not enough to determine true facility cost. An evaluation should be made in regard to the efficiency or productivity of each facility. Actual facility costs should be evaluated in terms of cost per test program (including installation/removal) for the type of testing required.

Other factors affecting test cost and span time that are directly related to the facility include:

- Test article support system availability—Are existing support systems available (or adaptable) for use, or does a new system need to be designed and fabricated?
- Data acquisition/data reduction hardware and software programming capabilities—What are the facility's on-site acquisition and programming capabilities, and will they meet test requirements? Does the user need to provide their own data-acquisition systems and computing support personnel at the facility?
- Remote access capabilities and requirements (Annex A.4)
- Facility requirements—What safety, documentation, and lead time requirements are necessary to comply with the facility processes?
- Facility on-site support—Are tunnel personnel available to assist with conducting the test (including test technology expertise)?
- Off-site travel costs—What airfare, rental car, hotel, and per diem expenses are required for test support personnel?

The test community has a wealth of knowledge about facilities' capabilities and is a critical resource when selecting a test facility.

2.1.2 Planning and Scheduling

Proper planning and scheduling are essential to ensuring a successful test program. The ability to adapt to rapid change is a vital attribute of proper planning. All tasks that are necessary to accomplish test objectives must be accounted for and planned for early in the program to ensure that such things as adequate experiment, model, and instrumentation development time, test facility preparation, checkout and calibration time, pretest uncertainty analysis, testing, and test results analysis are included.

A risk assessment of experiment design may highlight the need to add flexibility into test article design or test facility preparation. Technical risks, including such items as potential changes in configuration, program resources (budget, time available), data requirements, or accuracy, etc., should be considered in the planning stages to devise contingencies in the test approach prior to implementation.

Improper planning can have very adverse affects. In the case of the test article, insufficient design and fabrication time can result in increased cost due to required overtime, increased supervision, and productivity inefficiencies. This also applies to efforts required for test facility preparation. Careful planning of all tasks (budget, schedule, resources) early in a program helps control cost and schedule.

After the start of a program, making changes to the test article definition and/or test requirements can significantly escalate test span times and cost. Such changes can compress design and fabrication schedules, resulting in increased overtime and work force resource problems. Changes can result in major re-work of the test article with additional associated costs. Requirement changes during testing can have similar effects.

Before implementing requirements changes, overall program impacts should always be carefully evaluated. With proper up-front scheduling and planning, the adverse effect of changes can be kept to a minimum.

2.1.3 Special Issues

2.1.3.1 Security

Security requirements can have a major impact on test program cost and span times. Security classifications can range from proprietary to top-secret and above. Each can have varying levels of requirements to safeguard program information. Associated costs may include secure areas for designing and fabricating test articles, clearances for personnel (including vendors and suppliers), and systems to monitor their access into those areas. Other costs can include data and document management, and securing test sites.

2.1.3.2 Contracting and Procurement

When subcontractors build models, terms and conditions of contracts may be an important determinant of ultimate test article cost and schedules. Various contractual mechanisms are typically used for test article subcontracts; the specific type and advantages of each are noted in Annex B.

It is important to recognize that subcontracting takes time and effort and must be included in test planning and development. Getting subcontract participants involved as early as possible provides a means to minimize risk for test article development. The specific contract mechanisms selected can be important in allowing early prime/sub teaming.

2.1.4 Advanced Tools and Technologies

When planning a new test program, it is of utmost importance to be aware of new technologies and methodologies for the design of the experiment, the manufacture of test articles, and the execution of wind tunnel test programs. Improved and new techniques in test technology can have dramatic affects on accomplishing test objectives (including cost, schedule, and data quality).

Annex A describes potential high-impact tools and technologies that may be considered during program and test activity planning.

2.2 Keys to Managing a Successful Test Program

Thorough planning of test programs is crucial for project success or failure. The question in wind tunnel testing is not whether testing is required, but what is the minimum required to satisfy critical objectives, how quickly is it needed, and how much can a program afford? The test community is the key resource to answer these questions.

Key elements in developing a test program are similar to systems engineering approaches used for new product design. These phases are program test planning, detail test planning and execution, and test project close out. The three distinct phases must be orchestrated carefully while maintaining alignment with overall program goals. Across these three phases, key activities are addressed to assist in developing and executing a successful test program. Figure 1 provides an illustration of the flow of the test process and how the key activities fit into the process.

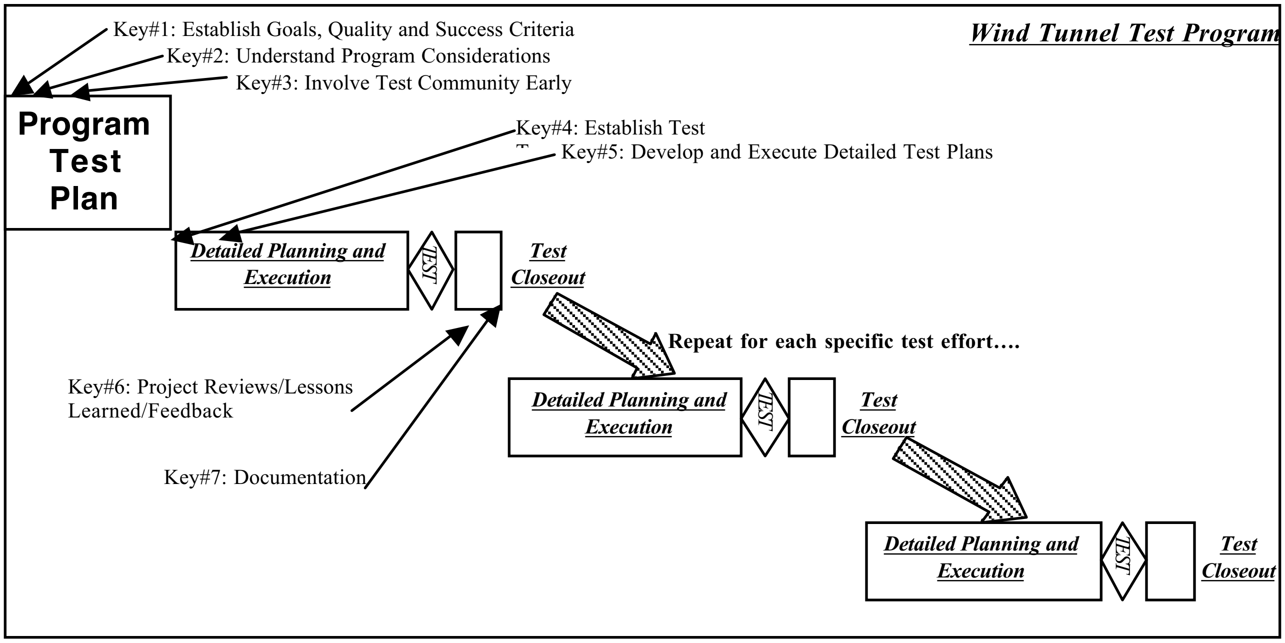

Figure 1 — Key Activities and Their Alignment to Test Program Phases

2.2.1 Program Test Plan

This phase establishes a top-level test plan to support program development and identifies the tests to be performed.

2.2.1.1 Key #1: Establish Goals, Quality, and Success Criteria

A thorough understanding of technical requirements for the test program and how they relate to program milestones is critical and provides the basis for all future activity. This initial clear understanding of test goals will assist in keeping the test focused and avoiding costly changes and false starts. Aspects of these goals include:

- Primary/essential requirements—What must be accomplished to qualify the testing as successful?
- Secondary requirements—What additional information could be beneficial but not necessary?
- Data accuracy/uncertainty—What accuracies are required to meet the stated goals, and what test program will provide those results? (Uncertainty analysis in the early stages will help drive decisions.)
- What are the expected test results?
- Success criteria—What criteria will be used to determine if objectives have been completed successfully?

2.2.1.2 Key #2: Understand Program Considerations

It is essential to develop and communicate a working knowledge of acceptable risks levels associated with the development program. The business structure may influence technical decisions associated with the test program. For example, fixed-priced programs typically limit the use of high-risk processes or test plans. Important aspects include:

- Program type—Is the program independent research and development (IR&D), contracted research and development (CR&D), or program development (contract)?

- Contract type—What is the contracting mechanism (firm fixed price, cost-plus-fixed-fee, cost sharing)?
- Overhead burdens—What overhead, indirect, or allocated burdens apply?
- Contractual reporting requirements—What cost or technical reporting and milestones apply?
- Flow-down requirements (terms and conditions)—What other special conditions might apply to test requirements (e.g., government-provided test facilities, termination clauses)?

2.2.1.3 Key #3: Involve Test Community Early

A critical element is the early involvement of the test community. Participation of key members from the test community (test engineering leads, data analysis groups, computational fluid dynamics, test facility leadership, and model design/manufacturer) is critical to developing an achievable, realistic test program. Test personnel are the best people to plan the tests. Involving the test community facilitates efficient solutions for issues such as:

- Test concept development
- Risk management (identification and mitigation)
- Test and analysis concept—What activities are required prior to, during, and after testing to make the data serve its purpose?
- Model design/manufacture cost and schedule trade studies
- Test facility cost/schedule/risk trade studies
- Resource allocation—What resources are required to ensure test completion (personnel, budget, computing, facilities, hardware)?
- Identification of long-lead items—What items will pace the test program (materials, model, test facility)?
- Identification of existing hardware and software—What is available, and what must be purchased/developed to support test objectives?
- Schedule development—What task schedules are required to meet the stated goals?
- Timely implementation of special requirements—Has planning included (schedules for) security, procurement, and other special considerations?

2.2.2 Detailed Test Planning and Execution

This phase involves planning and executing tests.

2.2.2.1 Key #4: Establish Test Teams

Establishing a test team is critical to the success of a test program, and the distinct phases of team activity may affect the team composition. These phases are requirements definition, test planning and preparation, and test execution.

While planning and preparing for a test, this team will be made up of key individuals that lead each of the necessary major activities, as illustrated in figure 2.

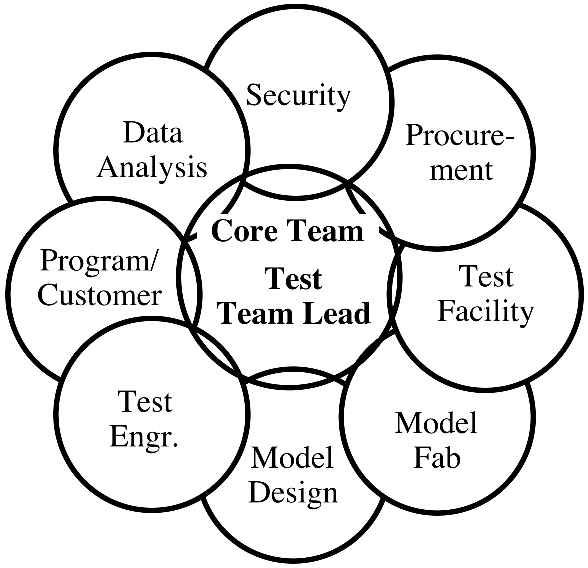

Figure 2 – Illustration of a Test Team Structure during Preparation Activities

Each team participant in the core area must be authorized to make decisions for the organization or function that he/she represents and must provide the connection to that function for planning, communication, task execution, and problem resolution. It is critically important that the interaction protocols and interface methods are established up-front to avoid confusion, wasted effort, and poor performance. Traditional team techniques such as consensus decision-making, scheduled meetings (with agendas and meeting documentation), and responsibility/coordination matrices can be important tools in establishing and maintaining effective communication during test preparation.

Changes to requirements during test preparation should be managed with full awareness of cost, schedule, and other impacts to the original goal. Impacts should be assessed prior to implementation. If changes are significant, original goals (requirements, budgets, and schedules) may have to be renegotiated. A change process should be established to manage changes.

During test execution, a slightly smaller and more rigid team structure should be established to manage the test activity, as shown in figure 3.

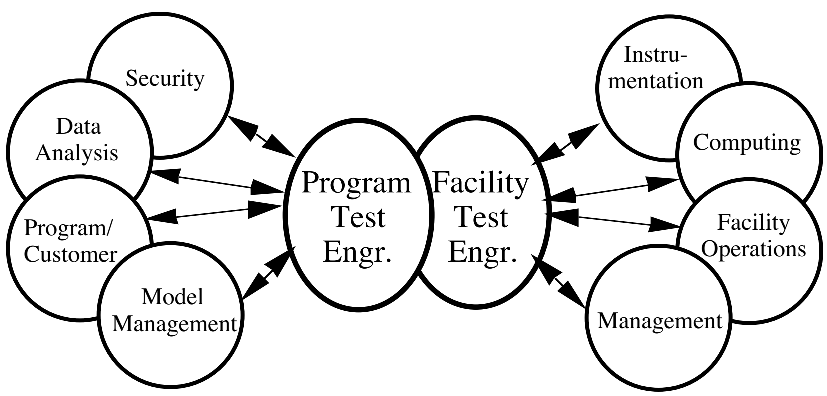

Figure 3 – Illustration of a Team Arrangement During Testing

Because test periods are frequently high-stress, fast-paced activities, extra measures should be established to define and implement specific decision-making and coordination protocols. It is important that each person involved understands his/her responsibility and authority and how to coordinate with the the rest of the team. Many difficult tests have suffered significant loss due to unclear roles and responsibilities, particularly from those not at the test site. Pretest meetings and discussions should be used to address roles, responsibilities, and interface protocols that will be used during testing.

2.2.2.2 Key #5: Develop and Execute Detailed Test Plans

Developing a plan that defines requirements and how they will be achieved should be a collaborative effort of the test preparation team, and frequently requires several iterations to achieve a consensus. A carefully thought-out plan forms the foundation for effective communication and coordination throughout preparation and testing. While developing the plan may seem time-consuming when everyone is anxious to “get started,” this step defines what needs to be accomplished, and therefore, it must be completed before initiating significant preparation activities. Essential elements include:

- Test advocacy—Why is the test program needed, who is it for, what program does it serve? This is particularly important for the test facilities to understand the overall linkage of a specific test to a major program or objective.
- Prioritized test objectives
- Schedule—Integrated timelines for all activities (including major milestones and inputs required to perform test activities)
- Configuration definition—Specific test configurations with descriptions and designations
- Test matrix—Speed range, alpha, beta, flow rates, configuration variables, etc.
- Measurement requirements—Specific instrumentation types and location including accuracy requirements; also should consider facility operating environment
- Conceptual model design—Preliminary model layout to ensure that all major items have been considered
- Data acquisition and reduction requirements
- Acceptance criteria/reviews—How will progress be monitored?
- Roles and responsibilities—Who is responsible for each activity, and what are the correct interfaces?
- Resources—What budget and staffing resources are required?
- Risks—Best assessment of risks and potential problems based on the approach described by the plan. Develop appropriate mitigation plans.
- Change control procedures—How are changes to the plan handled, and how are decisions made to authorize changes?
- Status and reporting requirements—Define status and reporting requirements (including milestones, reviews, and acceptance criteria) prior to project go-ahead.
- Test evaluation procedures—Determine what test data will be compared to and the methods of comparison

Once the plan is accepted, execution proceeds using the plan to initiate activities, gather required resources, work issues, and measure progress.

2.2.3 Post-Test Activities

2.2.3.1 Key #6: Project Reviews/Lessons Learned/Feedback

A post-test review is an essential step in the test process. These reviews are an important instrument for assessing how well the test met program goals and determining opportunities for improvement. Another important aspect in this phase is the opportunity to give recognition, in the form of individual or team awards, to anyone who made valuable contributions. All team participants should be encouraged to review performance at the conclusion of the test, including:

- Review of test results
- Test facility performance
- Instrumentation performance
- Model design and as-built performance
- Participant reviews (individual or as a group)
- Process assessment (including experiment design)
- Budgetary performance (estimates vs. actual—refine estimating factors)
- Technical performance and lessons learned
- Schedule performance during preparation and testing
- Post-test analysis feedback of data obtained.

2.2.3.2 Key #7: Documentation

Several important activities are strongly recommended at the conclusion of testing. Funding of these activities should be included in the initial planning, and staffing should be left in place to perform the work.

Documentation of test development activities, test methods, results, and lessons learned (as-run log, test hours, test event logs, data analysis) should be compiled and stored for later use. This information is vital for planning and use on future tests, and it can be an enormous time- and money-saving activity. Detailed test results' reporting is frequently required for documentation purposes.

Frequently, test articles are different from design drawings and/or have been modified during testing. All model documentation should be updated to the current status of the model at the conclusion of testing.

Model and instrumentation status and inventory are also important activities to be completed before a project is ended. Delicate instrumentation should be removed, refurbished, and stored for future use. The effort to perform these tasks at this stage of a project is usually at least half of what would be required to resurrect a model for later use.

3 Summary

Wind tunnel testing is a difficult and critical activity in the development of an air vehicle or technology. Effective communication, early involvement of the test community, and early and thorough planning are fundamental ingredients for success. When the key activities (described above) are imbedded in the test program development and testing, a smoother, more effective test program will result, with lower costs and reduced cycle times. These keys will help shift focus from test "fire drills" to test successes.

Annex A Advanced Tools and Methods for Consideration in Test

The following lists emerging technologies (at the time of publication) that offer potential improvements over conventional methods and are either currently available or hold high promise. These have been included to stimulate thought during test program planning.

Investing in these types of tools and techniques can yield significant benefits in the cost and quality of testing.

A.1 Integrating Testing and Computational Fluid Dynamics (CFD)

Improved CFD techniques and advances in computing power have made CFD a powerful screening tool. While it is not likely that CFD will replace wind tunnel testing in the foreseeable future, the two provide highly synergistic tools for obtaining required data. Using CFD in the test planning process provides the ability to optimize the experiment's design (with potential for major cost savings and risk reduction). Evaluating as-built model hardware to assess tolerance issues is becoming a practical and useful tool to help prepare for wind tunnel testing and reconciliation of test data anomalies..

Planning for integrated CFD and wind tunnel testing must allow for screening time and cost necessary to run the selected CFD configurations prior to test article design and fabrication. It is also important that all instrumentation needed to correlate/validate CFD and wind tunnel results (such as pressure ports) be coordinated and planned before either the CFD or test article development begins.

A.2 Rapid Prototype Tools

Over the last decade, advances in rapid prototype techniques have provided an additional tool that can be used in developing low-cost test articles. Rapid prototype devices provide the ability to produce three-dimensional hardware directly from computer design files. Hardware produced ranges from soft plastics to wood-like materials to metals and may be used directly on wind tunnel models.

Many companies have also developed techniques to extend the use of rapid prototype parts by applying special coatings (composites, metal plating, etc.) over the rapid prototype part. Parts made by rapid prototype tools and treated with special coatings can be utilized over a broader range of operating conditions (loads and temperatures).

If the environment does not allow use of rapid prototype-produced parts, these representations can be used as casting patterns for metal casting. Care must be exercised to accommodate inherent inaccuracies in these processes, but the technique is sound and can be selectively applied to reduce model costs.

A.3 Effective Use of Computer-Aided Design (CAD)

New CAD tools provide the means to greatly streamline processes to produce test articles. Advances in automation, associativity (such as parametric design, virtual manufacturing), and product data manager (PDM) software allow databases to be used across the entire range of engineering and manufacturing activities.

While implementation of specific systems is dependent on the test article designers, the opportunity exists to share design and development data across the test team. The opportunity to share information should be discussed early in the development of a test program to identify and eliminate the duplication of effort.

A.4 Remote-Access Testing

When planning a test program that will be conducted at a remote location, there will be a tradeoff between funding for support personnel and the skill mix of the support personnel needed to successfully complete the test. Recent advances in video conferencing and innovative use of computer networks have made it possible for remote users to access wind tunnel control room data and video systems from their home sites. These types of systems provide the wind tunnel user a great amount of flexibility in staffing a test program and facilitate the establishment of the optimum skill mix at the test site, while at the same time reducing travel costs. Test facilities are strongly pursuing this capability, and it is anticipated that most test facilities across the country will offer this capability in the near future.

The most immediate impact of remote test participation is the reduction of travel dollars spent to support a test at a distant facility. An added benefit to productivity is the ability to increase the number of participants without increasing travel expense (the data can be available in real time at the user's home facility for complete and immediate analysis). Additional user input during testing can facilitate more timely decision making during testing, which can result in better tests

A.5 Advanced Instrumentation

Onboard data acquisition systems have the potential to reduce or eliminate the number of wires, pressure tubes, cables, etc., that must cross over from the test article to the test facility systems. By reducing or eliminating these interfaces, models potentially could be used for several purposes such as force and pressure testing, or other combinations. Onboard systems are being developed, including telemetry of data from model to tunnel systems, which could facilitate multiple-use models and potentially eliminate whole classes of model types.

Tremendous advances are also being made in the use of non-intrusive flow visualization and pressure measurement. Laser systems can be used to measure wind tunnel velocity at a point, or (by forming a laser sheet) large areas of the flow field around the test article may be viewed. Pressure- and temperature-sensitive paints have been developed that allow measurement of pressure and temperature distributions over entire test articles, greatly reducing the amount of conventional measurements required, thus opening up the possibility of using a single model for many purposes. Using these systems requires additional planning in test article development, model handling, and facility selection to ensure that the needed systems can be supported and that optical access is available.

Micro Electro-Mechanical Systems (MEMS) technology utilizes manufacturing techniques from the computer chip field to produce specialized micro-miniature systems. These systems can potentially take the form of tiny pressure or temperature sensors, including telemetry capability to a nearby receiver. As this technology matures and wind tunnel implementations evolve, significant test hardware and technique changes may develop.

A.6 Model Automation

Automating test articles is one way to dramatically increase test productivity. Although cost (and complexity) of the test article is increased, data acquisition rates during testing can be dramatically increased, thus recovering any added costs to the test article. The decision to automate selected model configurations must include consideration of overall test program costs, data accuracy requirements, model loads and test configuration variables, and tunnel operational scenarios during testing (with and without automation).

The added cost of model automation can be significant, but usually results in greater savings at the test site. A cost trade study should be implemented early in the conceptual design phase of the test article to assess potential costs and savings that might result with automation.

Contractual arrangements sometimes pose particular problems with a decision to automate selected model configurations. Frequently, with contracts that provide a test facility at no direct cost, contractors will chose to sub-optimize the overall test program and not automate a model configuration for which they must pay directly. Even though the overall test program cost is greater, the model cost (borne under the contract) is reduced. Care should be exercised early in programs to provide contractual mechanisms to allow total optimization of test program costs (model plus test).

A.7 Test Simulation Tools

It is now easier to build effective tools to simulate the end-to-end test process. These tools can simulate proposed testing to determine overall accuracy, test efficiency, and instrumentation selection prior to testing

Annex B Subcontracting Mechanisms

When vendors build models, terms and conditions of the contract may be an important determinant of ultimate cost and schedules for the test article. While a firm-fixed-price (FFP) contract may be perceived as the least expensive (or financially risky), programs that have extremely tight schedules (or are likely to change throughout the model development) should use other contract vehicles. These include time-and-materials (T&M), cost-plus-fixed-fee (CPFF), basic ordering (BOA), or partnership (BOA with only one subcontractor) agreements. It should be noted that program managers may not be at liberty to select a specific contract vehicle. Often, prime contracts with government agencies specify allowable subcontract mechanisms.

The FFP contract vehicle forces model vendors (in order to secure a contract) to bear all risks for the design and/or manufacture of the model while bidding very aggressively during the competition phase. Program changes that are buyer-initiated after contract award usually are accompanied by significant cost and schedule impacts to the final cost of the model. This subcontract format usually is more cost-effective when applied to more mature programs that are likely to remain consistent throughout the test article development.

If a program is in an early state of development and is likely to evolve significantly during model development, it is frequently more cost-effective to use a risk/cost-sharing contract vehicle such as T&M or CPFF. Where the FFP contract tends to foster an adversarial relationship between buyer and seller, the cost-sharing contract fosters a teaming relationship because the subcontractor is assured of a reasonable fee while trying to incorporate changes within cost and schedule constraints.

To maximize subcontractor availability for outsourcing to meet critical schedule and quality requirements, the program manager should consider, at the earliest possible time, forming a teaming arrangement via the BOA or a partnership. The BOA approach will establish a limited number of approved subcontractors for fast-response competitive quotes using any combination of fixed or cost-type task orders. The partnership arrangement is a new concept that establishes a task order contract for a specific period of time, with options for extension with one subcontractor. This forms a risk-sharing team for maximum support from the prime model subcontractor.

When a program manager determines that in-house capability cannot support program cost and/or schedule requirements, he/she must establish a qualified subcontractor base that will be available whenever needed. Cost and schedule impacts for various contract vehicles are as follows:

- FFP—Requires the program manager to (a) develop a very detailed statement of work; (b) solicit subcontractors' responses via requests for proposal (RFP) or requests for quotation (RFQ); (c) evaluate the proposal; (d) negotiate best and final price; and (e) award the contract. The cost of competition is significant in terms of labor-hours and schedule delays during the competition phase. The schedule delay will vary from several weeks to several months, depending on the size of the procurement.

- T&M/CPFF—Normally allows the program manager to select one single subcontractor to support his broadly defined program needs by requesting detailed labor-hour and cost estimates that are negotiated during the time of contract award. This approach provides for a fast response with predetermined T&M rates or cost burdens for all follow-on changes. Even large procurements can be completed within several weeks using a cost-type contract vehicle.

- BOA—Limits the subcontractor competitive field to pre-qualified vendors, with contract terms and conditions preset for all task/work orders. The BOA can be FFP or CPFF mixtures, depending on the maturity of the program. This approach limits bidders to those of proven capability with the basic contract in place for fast implementation of any number of task orders.

- Partnership—Establishes a true team arrangement between buyer and seller for the equivalent "in-house" support of the program manager's needs. After completing the partnership agreement, the buyer is assured of immediate access to the subcontractor's resources, and the vendor is assured of a known level of work (provided he/she maintains performance within cost, schedule, and quality expectations).

Model parts may be fabricated at various locations and by different contractors (although this is not recommended). If this is the case, it is extremely important to have one organization (the organization originating the test effort or a contractor) responsible for model assembly and fit. While all parts (coming from different sources) may meet drawing specifications, problems generally occur in the final assembly phase. If this is not properly planned and coordinated, it can (and often does) result in schedule delays and cost increases.

Many times this final assembly occurs at the test site (to recoup lost schedule time). If the model parts are not right or do not fit, the time to correct the hardware occurs during the more expensive tunnel occupancy time. Additionally, the test site may not have the capabilities to perform the needed modifications. In this case, the model must be returned to the manufacturer or a new contractor source obtained. Both add cost and require additional time.

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