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Recommended Practice

Wind Tunnel Testing — Part 2: Practitioners Volume

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Wind Tunnel Testing – Part 2: Practitioners Volume

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Abstract

This recommended practice document is the second part of a two-part series intended to provide test project management and practitioners with best practices that will maximize data value of wind tunnel test projects. Part I is designed to help managers understand the impact of decision making before and during 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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CONTENTS

Foreword vi
1 Introduction 1
2 Aircraft Program Development 1
2.1 Overview 1
2.2 Test Development 2
2.3 Key Actions Throughout All Phases of Test Projects 4
3 Pretest Planning and Preparation Phase 5
3.1 Personnel, Test Requirements, and Facility Selection 5
3.1.1 Team Participants for Pretest Planning and Preparation 5
3.1.2 Test Requirements 6
3.1.3 Facility Selection 7
3.2 Development and Management of the Project Plan 8
3.2.1 Test Project Plan Development 8
3.2.1.1 Requirements Statement 9
3.2.1.2 Basic Work Structure 9
3.2.1.3 Experimental Uncertainty Analysis 9
3.2.1.4 Risk Identification and Mitigation 9
3.2.1.5 Safety 10
3.2.1.6 Security 10
3.2.2 Test Project Plan Implementation and Management 10
3.2.2.1 Schedule Development and Control 11
3.2.2.2 Budget Development and Control 12
3.2.2.3 Communication and Reporting 13
3.3 Test Preparation 13
3.3.1 Final Instrumentation Requirements 14
3.3.2 Data Acquisition and Reduction 14
3.3.3 Calibrations 15
3.3.4 Pretest Predictions and Historical Data 15
3.3.5 Instrumentation Checks 15
3.3.6 Information Management 15
4 Model Development and Fabrication Phase 16
4.1 Team Participants for Model Development and Fabrication 16
4.2 Conceptual Design 17
4.2.1 Model/Test Facility Considerations 17
4.2.2 Model Configuration Considerations 18

4.3 Detailed Design 19
4.4 Model Fabrication 20
4.4.1 Rapid Manufacturing Processes 20
4.4.2 Virtual Manufacturing 20
4.4.3 Acceptance Criteria and Noncompliance Documentation 20
4.4.4 Instrumentation Installation 21
4.4.5 Model Acceptance 21
4.4.6 Handling, Packaging, and Shipping 22
5 Pretest Buildup and Preparation Phase 22
5.1 Team Participants for Buildup Phase 22
5.2 Model Buildup 23
5.3 Planning for Installation in the Test Section 25
5.4 Final Test Matrix Review 25
6 Test Phase 25
6.1 Test Team Communications 25
6.2 Model Installation and System Checks 26
6.3 Test Readiness Review 27
6.4 Initial Tunnel Runs 27
6.5 Testing Checks and Documentation 28
6.6 Data Processing 29
6.7 Cost and Schedule Management 29
6.8 Test Efficiency Issues 29
6.9 Test Completion Review 30
6.10 Model Removal 30
7 Post-Test Phase 31
7.1 Team Participants During the Post-test Phase 31
7.2 Hardware 31
7.3 Data 31
7.4 Documentation 32
8 Summary 32
References 34
Annex A Example of a work Breakdown Structure (WBS) for a wind tunnel test project 35
Annex B Cost/Schedule Status Report 37
Annex C Subcontracting Mechanisms for Consideration In Test Projects 39
Annex D Rapid Manufacturing Techniques 41
Annex E Issues Affecting Fabrication Cost and Schedule 43

Figures

Figure 1 Major Phases of a Wind Tunnel Test Project....4
Figure 2 Team Makeup During Pretest Buildup....23
Figure B.1 Graphic Presentation of Cost/Schedule Status....38

Tables

Table 1 Examples of Tests Used in Commercial Aircraft Development Programs....2
Table 2 Examples of tests used in a high-performance military aircraft development program....3
Table 3 Examples of Technical Objectives Stated as Top-Level Goals Versus Detailed Requirements. 6
Table B.1 Definitions Used in a Cost/Schedule Status Report....37
Table B.2 Summary of Cost/Schedule Status Report....38

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. Early on, it became apparent to the participants of the AIAA working group 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 projects require that a broader viewpoint of the wind tunnel test process be evaluated in order to develop successful techniques and methods. The two-part effort, “Recommended Practices for Wind Tunnel Testing,” is the result of that evaluation.

Part I was written to provide managers with clear insight into achieving technically focused, cost-efficient, low-risk test programs (which contain multiple test projects) that 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 projects.

Part II provides additional detail on successful methods for those directly involved in developing and executing individual tests.

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.

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The skill and leadership of Mr. Cap Catalanotto was critical to the early activities of this work group. Many others also contributed to this document during its development.

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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.

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

The AIAA Standards Executive Council (Phil Cheney, Chairman) approved this document in September 2003.

1 Introduction

The purpose of this recommended practice document is to provide the reader with increased knowledge about planning and executing highly successful wind tunnel tests. First, an overview of the test process is provided, giving a general picture of the origin, purpose, and high-level breakdown of activities that are a part of wind tunnel test development and execution. Secondly, detail is added to the overview to define the full scope of the activities and key considerations. Finally, recommended practices and lessons learned are described.

Part I of this recommended practice looked at test development from a management perspective. This volume (Part II) will provide additional detail that is more useful to participants who develop and execute testing activities. Part II is organized into sections describing activities and best practices during the various stages of test implementation:

- Program development
- Pretest planning and preparation
- Model development and fabrication
- Pretest buildup and preparation
- Testing
- Post-test activities

Part II of this recommended practice document was assembled with guidance from experts (both industry and government) who are responsible for all aspects of wind tunnel testing. Experts from airframe companies (military and commercial), as well as model makers and tunnel operators contributed best practices to help guide test personnel through the implementation and execution of a test project.

2 Aircraft Program Development

Aircraft designs continually push the state-of-the-art in technology. Advances in materials, instrumentation, and onboard computing will continue to allow the design of higher performance, lighter weight aircraft. Consequently, wind tunnel testing has become more sophisticated as demands for improved aircraft performance have increased. Relatively simple aerodynamic tests of early years have broadened to highly specialized testing. Advances in wind tunnel test facilities and techniques are also impacting testing projects by reducing cycle times and increasing the amount, quality, and versatility of the data collected.

As test requirements flow from a programmatic level to the finer detail of individual tests, activities and issues associated with the requirements are developed and refined to enable the completion of individual tests. It is often during this flow down that the success or failure of a test effort is determined.

2.1 Overview

As used in this document, an aircraft development ***program*** refers to the process by which a new aircraft or major derivative is created—from initial concept to production. The test ***project*** is the portion of the development program when testing is conducted. For this document, the test project will focus on a wind tunnel testing activity. Therefore, each test project is an integrated and important part of the entire vehicle development program.

The phase of a development program has direct bearing on the level of technical requirements for the individual test project. Traditionally, aircraft or technology development programs generally follow three phases:

- Phase 1 is the concept development and risk reduction phase. Initial configuration concepts are evaluated against program goals. Vehicle configurations change quite frequently. Parametric models, with multiple configuration variables, are investigative in nature and high-fidelity simulations are usually not required. The purpose at this phase of the program is to select an initial configuration that will meet developmental goals.
- Phase 2 is the development of the flight vehicle, often referred to as the Engineering and Manufacturing Development (EMD) or Full-Scale Development (FSD) phase. The scope and amount of wind tunnel testing increases dramatically as models are tested throughout the vehicle envelope and simulated flight conditions. Model configurations become more refined as the development phase progresses. Test and model-fidelity requirements increase as aerodynamic, propulsion, and aeroelastic goals are met.
- Phase 3 is the validation phase or production phase. In this phase, the final configuration has or is very close to being frozen, and full-scale production is underway. High-fidelity models with very stringent tolerance requirements are tested to validate aerodynamic, propulsion, and aeroelastic performance predictions. Testing is conducted throughout the proposed flight envelope and flight conditions of the aircraft.

2.2 Test Development

Traditional types of tests and models used for commercial aircraft development are presented in Table 1 and for military aircraft in Table 2. This document is presented from the perspective of testing that supports aircraft development. Other types of flight vehicles, such as missiles, helicopters, rockets, space re-entry vehicles, and V/STOL aircraft, have developed their own unique testing requirements.

Table 1 — Examples of Tests Used in Commercial Aircraft Development Programs

Model Type	Test Goals	Average Wind Tunnel Test Hours[a]
Conceptual Phase		
Low-Speed Force and Moment (High-Lift)	Take-off and Landing Performance and Stability and Control	500–1,000
High-Speed Force and Moment	Cruise Performance High Speed Stability and Control	500–1,500
Development/Validation Phase		
Low-Speed Force and Moment	Take-off and Landing Performance and Stability and Control	250–1,500
High-Speed Force and Moment	Cruise Performance High Speed Stability and Control	250–2,000
Aero Loads Model	Structural Loads	300–800
Flutter Model (Low- and High-Speed)	Flutter Clearance	500
Powered Models	Integrated Propulsion Effects	500–1,500
Icing Models	Icing Effects	500
Isolated Inlets	Inlet Performance	500

[a] Test hours, typically described as User Occupancy Hours (UOH), are the time a model occupies a test facility and is able to acquire usable data (includes model change time, but not facility down time).

Table 2 — Examples of tests used in a high-performance military aircraft development program

Model Type	Test Goals	Average Wind Tunnel Test Hours[a]
Conceptual Phase		
Low-Speed Force and Moment (High-Lift)	Take-off and Landing Performance and Stability and Control	500–1,000
High-Speed Force and Moment	Cruise Performance High Speed Stability and Control	500–1,500
Isolated Inlet and Static Inlet Model	Inlet Conceptual Design	200–700
Static Exhaust Model	Nozzle Performance	200–500
Development/Validation Phase		
Low-Speed Force and Moment	Take-off and Landing Performance and Stability and Control	250–3,500
High-Speed Force and Moment	Cruise Performance High-Speed Stability and Control	250–3,500
Aero Loads Model	Structural Loads	300–1,000
Flutter Model (Low- and High-Speed)	Flutter Clearance/Aeroelastic Effects	800–1,000
Inlet /Airframe Model	Integrated Inlet Effects/Inlet-Induction System Performance	500–1,500
Weapons Separation Model	Safe Store Separation/Accurate Delivery of Weapon	2500–5,000
Spin Models	Spin Recovery	500–2,000
Jet Effects Model	Effects of Exhaust on Aircraft Performance/Stability and Control	500–1,000

[a] Test hours, typically described as User Occupancy Hours (UOH), are the time a model occupies a test facility (including installation and removal) and is able to acquire usable data (includes model change time, but not facility down time).

Each aircraft or flight vehicle will have unique requirements in regard to the type and amount of wind tunnel testing it needs. Individual test projects during the flight vehicle development program have three main drivers:

- Data requirements
- Cost
- Schedule

Defining data requirements and when that data is needed are of utmost importance at the start of a program. This will establish and guide specific test project requirements and goals. Accordingly, the next two drivers, cost and schedule, are directly related to the selection of test hardware and test facilities. Wind tunnel test planning must carefully consider “how much” testing and fidelity are required to accomplish the stated goals. This is the starting point for individual test project development.

Individual test projects typically contain the following five key phases and activities:

- **Pretest planning and preparation** — Transition from program requirements to detailed test requirements, development of detailed plans, and preparation for testing

- **Model development and fabrication** — Planning and implementation of model-specific activities in preparation for testing
- **Pretest buildup and preparation** — Configure the test facility and install the test article in preparation for testing
- **Test** — Conduct testing
- **Post-test** — Evaluation of test results, documentation of test events, cleanup of test hardware, and final documentation, including lessons learned

The phases of a test project are shown in approximate chronology in Figure 1. Sections 3 through 6 describe in further detail the activities associated with these phases.

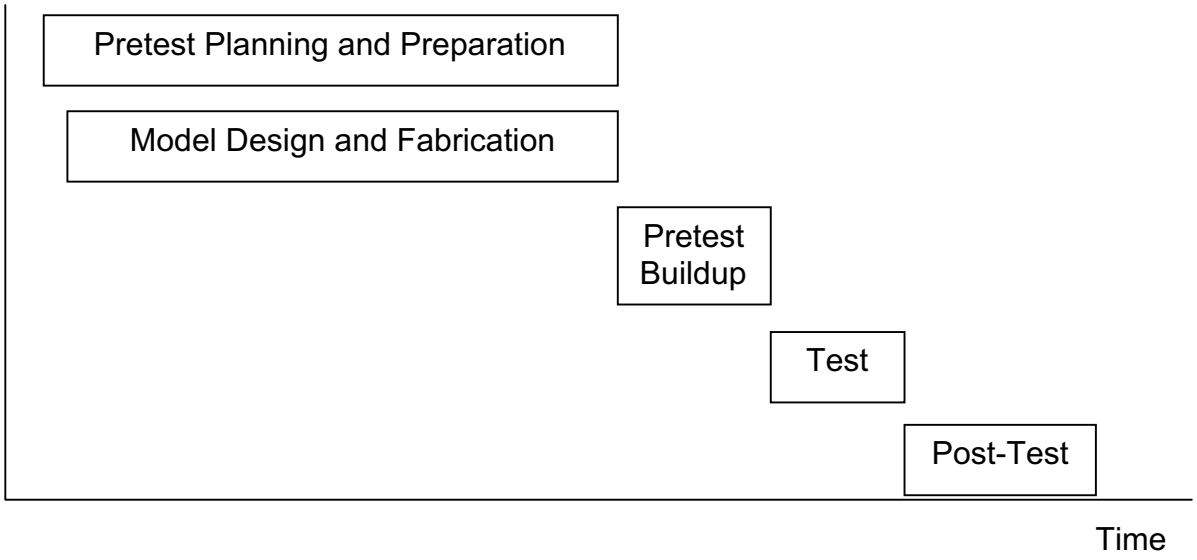


Figure 1 — Major Phases of a Wind Tunnel Test Project

As illustrated in Figure 1, most activities in the first two phases (pretest planning and preparation, and model design and fabrication) occur almost concurrently. Because many activities happen during the same time period, it puts significant stress on all involved. Many of the considerations discussed in later sections are described to illustrate the complex nature of the interactions of activities involved in testing.

During these phases, the mix of necessary personnel will evolve as the focus changes during pretest planning and preparation, model development and fabrication, pretest buildup, testing, and finally post-test activities. The dividing lines and overlap of the various activities are not precise or as easily defined as shown, but for the purposes of this document, information and key personnel will be discussed according to the phases shown.

2.3 Key Actions Throughout All Phases of Test Projects

Three critical actions are common throughout all phases of a test project. First, getting the right personnel (with appropriate authority to act) involved early helps ensure that all details and tasks are correctly planned and executed (nothing is overlooked). Secondly, organizing the personnel using a team-based model gives structure to the activities of individual participants. Finally, constant attention to the importance of communication (throughout the assembled team) gives those with the right skills the opportunity to perform at the highest level.

There is a great deal of work that must be addressed in the early stages of a test project, such as selecting and scheduling tunnels, setting up contracts with outside vendors, and selecting test equipment. It is important that those with detailed knowledge be involved in the early stages of a test project.

Organizing the participants using a team model provides a strong working structure for participation, decision-making, and project management. While this document does not provide a tutorial on the various methods of team-based organization, it does illustrate the basic functions the team should perform during the various phases of the project. Throughout this document, it is assumed that a team lead with overall authority is in place. Recommendations on team structure are provided during the critical test buildup and testing phases. Finally, regular communication between the team members is absolutely critical. Information should be disseminated throughout the entire team for the duration of the project. Remember that the personnel involved with a test project will change over time as the project moves from one phase to the next (as illustrated in Figure 1). Because of this, communication with team members associated with each test element is crucial throughout the project to ensure that vital information is transferred effectively as the project progresses.

3 Pretest Planning and Preparation Phase

Planning and preparation are critical to the ultimate success of any test project. When lead time is short, there is a tendency to abbreviate these steps and progress directly to implementation. However, investing time and resources to properly plan a project and prepare for testing will invariably pay off in terms of lower cost, reduced cycle time, and higher data quality.

Pretest planning and preparation embodies the following key areas:

- Selecting personnel, test requirements, and the facility
- Developing and managing the Project Plan
- Preparing to test

Work in each of these areas is an iterative process. As a test project develops, new information may require adjustments to the initial plan; however, laying the groundwork properly can minimize the impact of these adjustments.

3.1 Personnel, Test Requirements, and Facility Selection

The first item to be addressed in pretest planning is the creation of the test team, determination of the test requirements, and selection of the test facility. Each of these items will affect the others. Key requirements could eliminate some facilities from consideration, or conversely, a facility selected for one set of capabilities may not support other test requirements, so a trade-off may be required. In addition, the availability of expert key personnel must be considered when selecting facilities.

3.1.1 Team Participants for Pretest Planning and Preparation

During pretest planning and preparation, the key participants typically include the following:

- Customer (principal user of the test data)
- Lead test engineer
- Lead model designer
- Facility test engineer
- Fabrication engineer or foreman

Throughout this document, the customer is defined as the principal user of the test data, who converts the data to aircraft design or design validation information (such as aircraft aerodynamics, performance,

installed propulsion effects, etc.) Customer, in the context of this document, is *not* the program management team or primary user of the aircraft or flight vehicle.

Identifying the responsible test team is a task that is often left until late in the planning process. The test participants must be identified as early as possible so they can participate in all planning aspects. The most common failure in project planning and implementation is a breakdown in communication. Because communication is a critical aspect of this phase, a communication plan must be established to ensure that all team members are involved in planning and that their knowledge and experience are included in the decision-making process.

3.1.2 Test Requirements

The test project must have clear objectives and requirements that have been mutually agreed upon by the customer and the test team. Although most objectives will focus on the technical aspects of the aircraft development program, they should also address cost and schedule implications. Depending on the wind tunnel test experience of the customer, technical objectives may be stated as top-level goals or as detailed requirements. Examples of the relationship between the two are listed in Table 3.

Table 3 — Examples of Technical Objectives Stated as Top-Level Goals Versus Detailed Requirements.

Top-Level Goals	Detailed Requirements
Data Accuracy / Repeatability	Model Fidelity
	Data System Accuracy / Repeatability
	Sensor Speed and Accuracy / Repeatability
	Accuracy / Repeatability of Model Positioning System
	Uniformity of Flow Field
Reynold's Number	Model Size
	Mach No.
	Flow Environment (Pressure, Flow Medium)
Volume of Test Points	Ranges of Model Travel
	Frequency of Data Acquisition
	Model Configurations
Visualization Requirements	Facility Capability for Schlieren, Laser Doppler Velocimetry, Pressure-Sensitive Paint, etc.
Format Requirements	Test Data
	Model Design Data

Frequently, more than one customer will ultimately use the test data (e.g., design engineers, computational fluid dynamics developers, etc.). Therefore, the requirements may be a compromise or collaborative effort. The team (including multiple customers) should work together to identify opportunities for consolidating model and test requirements. Often requirements may take the form of a preliminary run schedule, which indicates Mach range, attitude range, number of configuration changes, and the number of runs at a minimum.

There are many potential problems that can arise during the development of requirements. The biggest threat to managing any test project is "requirements creep" or changing requirements as the project progresses. Although it will never be eliminated, having the customer work through the requirements as a team member is a good first step in controlling "requirements creep."

When project objectives and requirements are established, trade studies should be performed to determine the most cost-effective experiment design. This is typically an iterative process. These studies include determining model size (or scale), model configurations, instrumentation, and test facilities. Initial

aircraft analysis and computational fluid dynamics (CFD) can assist in making model hardware and scaling decisions such as model loading, support system optimization, and wall effects evaluation.

3.1.3 Facility Selection

Numerous considerations must be evaluated when selecting a wind tunnel for a specific test project. The selection of the test facility will influence every aspect of the test project, from cost to final data quality. Many points that must be considered are listed here:

- **Test section size** — This will establish possible model size. The general trend is to maximize model size for a given tunnel. This can, however, lead to large wall corrections that could compromise the data.
- **Tunnel operating conditions** — Will the tunnel operating range match desired data test goals? This includes Mach number and Reynolds number. Can tunnel test conditions be varied?
- **Tunnel flow quality** — Will the tunnel flow quality meet test goals? Uncertainty analysis of test parameters will help make this determination. Tunnel flow qualities are typically determined in ideal circumstances (no model) and should be viewed as best “possible”.
- **Tunnel costs** — This includes pretest setup, test, and post-test costs. Can lower cost facilities be used and still meet test objectives? Productivity of each tunnel should also be evaluated. Some facilities may be lower in cost on a per-hour basis, but not obtain the same amount of data per-hour as another tunnel (with a higher per-hour rate). Cost of the tunnel, coupled with the cost of the model selected, should be evaluated. Previous experience with a facility’s ability to predict or perform to cost is also an important consideration.
- **Tunnel availability** — Many facilities have full schedules. Initial planning far in advance might be required to obtain test time in a desired tunnel. Tunnel availability may remove some facilities from consideration.
- **Data acquisition capability** — What are the data acquisition capabilities of each tunnel being evaluated? Does a user have to bring his/her own data acquisition, along with support personnel, to the site? Can the data be provided directly to the user via a Web site or other means?
- **Data reduction and analysis** — What are the capabilities of each tunnel for supplying reduced data in near- or real-time while the test is in progress? What data analysis (such as plotting) capabilities are available during testing? What corrections will have to be applied for such things as test section flow quality, model support interference, wall interference, or test article geometry, and are these corrections in place at the facility?
- **Instrumentation** — Is the necessary instrumentation available to support test requirements (e.g., balances, optical access, etc.)?
- **Experience** — Does this tunnel have a proven history of successfully executing the type of test requested? Are past performance records available that indicate how the tunnel handles a particular type of test? What lessons were learned from past experiences?
- **Personnel support** — Are knowledgeable experts available to assist in interpreting test results? Are on-site model design and fabrication services available? Do tunnel personnel have experience with the required type of testing?
- **Support hardware** — Does the tunnel have existing hardware that is available for use? New model hardware, such as support systems, can be very costly, and if necessary, must be part of the overall evaluation.
- **Security** — Can tunnel and tunnel personnel meet program security requirements? Security clearances are often a long-lead issue that must be addressed.

- **Data quality/information quality** — Does the tunnel have an established capability to produce quality data? What combination of tunnel, model, and instrumentation provide the desired data quality? What information management system is in place?
- **Contractual agreements/liability** — How are the formal relationships established? Are the legal aspects of performing a test understood, and is the risk of unfavorable contract terms low? How long will it take to have contracts approved? Who is liable for damage to the facility in case of a model failure? Is export or import documentation required? Are proprietary or Memorandums of Agreement (or similar documents) in place?

3.2 Development and Management of the Project Plan

After the initial planning has been established, the next step is to develop and execute a detailed test Project Plan. This plan is the blueprint used to successfully complete the wind tunnel test project. As illustrated in the following sections, the plan is an all-encompassing document that requires input from the entire team to be meaningful and useful. The Project Plan is a living document, in that it will change to reflect changes in the scope of the test requirements or other aspects of the test project. The Project Plan is used to document all planned activities, assumptions, task assignment and responsibilities, tolerances and fidelity requirements, and expected outcomes.

The form of the Project Plan is not important, but the act of creating a detailed action plan provides a baseline for all participants and provides documented expectations for implementation. The Project Plan implies a commitment made between the team members once the plan has been established and approved. The commitment is that team members will complete their assigned duties as agreed upon in the plan. The Project Plan is also an important tool for the project leader in further defining the details of the test project and for managing the tasks, costs, and schedule associated with the test.

3.2.1 Test Project Plan Development

Developing the Project Plan is a team activity. It begins with evaluating the project requirements (technical, cost, and schedule) and identifying areas where additional information is required (such as facility schedule, procurement and fabrication lead-times, resource availability, model-to-facility interfaces, material costs, and labor) and culminates in an integrated schedule of tasks.

This activity serves two purposes. First, it develops a common understanding among the team members about the tasks to be accomplished. Secondly, it provides a road map for the team to follow and assists when making adjustments as the project develops. There are numerous software tools available to assist in this aspect of project planning, most provide the capability to produce and maintain detailed project schedules. In most cases, significant training and experience are required before the full capability of the software can be realized. Ultimately, success of the plan will depend on the depth and breadth of the content and not the sophistication of the tools used.

Project planning is not complete until the plan has been documented in a format available to all team members. It is vital to the success of the plan that all team members have an opportunity to review the plan and concur on the tasks, costs and schedules that have been listed. It is also very important that the plan be kept current. Modifications to the plan can be expected, but any changes must be carefully controlled. A well-defined process must be established for submitting, reviewing, approving, and incorporating potential changes. Any cost or schedule impacts from the changes should be negotiated before proceeding with the amended plan, and the entire team, including the customer, must understand and agree on the changes. An amended Project Plan should continue to serve as a communication tool to keep the team informed and involved in the project.

The Project Plan should include the items described in Sections 3.2.1.1 through 3.2.1.6 below. They have been separated to demonstrate the importance of each. However, they are highly dependent on each other. Decisions made in one area can have major impacts on several others. The descriptions provided focus primarily on the informational content of the major sections of the plan. The order in which

the information appears and the scope of the information will depend on the complexity of the test and the priorities of the test team.

3.2.1.1 Requirements Statement

Because the plan is based on the customer's requirements, it is important that the test requirements be included in the plan to ensure that all team members are aware of and understand the technical expectations of the test. If it is not practical to include the original requirement package as part of the plan, the requirements and objectives should at least be synopsized. It is essential that all test team members understand why the test is needed, what the test is intended to prove, and the overall importance of the test to achieving the programmatic goals. If for no other reason, this understanding will promote a sense of teamwork.

3.2.1.2 Basic Work Structure

The remainder of the Project Plan will be dedicated to describing how the objectives will be met. The tasks should flow directly from the plan and identify which function or team member is accountable. Each task must identify other tasks that are required to be complete prior to its start and have a clearly defined endpoint or product. The plan must also identify the people, budget, and equipment available to support each task. The tasks should be organized into a schedule that will provide time phasing for all tasks and resources, and it must include the dependencies between tasks. Milestones, such as the release of aerodynamic loft or contour lines, must be clearly identified. The critical path that is developed by establishing the schedule will help to identify potential risk areas. When combined in a schedule, potential resource conflicts will be identified and must be resolved. The detailed schedule becomes the basis for tracking the flow of work and budgetary issues for the life of the test project.

This schedule or Work Breakdown Structure (WBS) (Annex A), as it is commonly referred, must be designed so that costs can be tracked efficiently. Too much detail will require excessive effort to accumulate and track costs, while too little detail will make it difficult to identify problem areas. Using an Earned Value budget-tracking system (Annex B) can be very useful for monitoring costs and identifying problems that could affect project success.

3.2.1.3 Experimental Uncertainty Analysis

Once the initial decisions regarding facilities, models, instrumentation, data acquisition processes, etc., have been made, an experimental uncertainty analysis should be performed. The results will determine if the test, as proposed, has the capability to meet the test accuracy requirements. Reference 1 provides key insights into techniques that should be used.

If the initial analysis indicates deficiencies, trades between the factors mentioned in the previous paragraph can be evaluated to improve the result. The methodology of experimental uncertainty analysis also provides opportunities for improving the result by taking advantage of the interrelationships of the error sources (e.g., correlated biases). The analysis should be updated whenever plans change that impact data accuracy. In addition, data acquisition during the test and the data reduction software must be set up to enable verification of the uncertainty analysis and reporting of calculated uncertainties throughout the test.

3.2.1.4 Risk Identification and Mitigation

Potential risk areas should be identified prior to implementing the Project Plan. For each risk identified, a mitigation plan should be identified. Examples of mitigation strategies could include the assigning additional resources (budget and people) to a specific task, or removing non-critical requirements. Since they affect the Project Plan, risk mitigation plans must be approved by the entire team (including the customer) and documented as defined in Section 3.2.2.1

3.2.1.5 Safety

Safety precautions must be considered in every Project Plan. This section will identify and address safety concerns such as the use of hazardous materials (special solvents, coatings, gases, or pyrotechnics), structural design criteria and safety margins (including start and/or shock loads), procedures for using special equipment (e.g., lasers), hearing protection, etc. Most facilities will have safety documents that should be referenced in this section.

If any special certifications will be required for personnel who support the project, these must be identified and incorporated into the budget and schedule, as required.

3.2.1.6 Security

Security requirements and planning must be accounted for in all schedule, resource, and budget allocations. Often, security restrictions or requirements can easily double the difficulty of performing a task and must be anticipated and understood prior to establishing a detailed plan. Typically, many questions arise during planning about the requirements that project security may impose on the test effort.

Security requirements (including proprietary issues) can significantly affect design activities. The impact of increased security restrictions must be anticipated and planned for or disaster can occur. It is not uncommon for design times to increase by up to 50% for highly classified activities, primarily due to the adherence of strict security rules.

Significant negative impacts to model fabrication schedule and cost are the usual outcomes when security restrictions are imposed. If parts of the model system are sight-sensitive, special facilities are often required. Special clearances for fabrication personnel often take several months to obtain and must be started well before fabrication begins. The process for handling design and fabrication documentation must also be developed and implemented (up to and including special containers, alarms, and rooms).

3.2.2 Test Project Plan Implementation and Management

Once the Project Plan is established, the team can begin implementation. There are three key project management responsibilities that must be addressed to ensure that the Project Plan is successfully completed. These responsibilities are:

- developing and implementing a detailed schedule
- implementing cost or budget management
- providing proper communication with the team and management.

Detailed scheduling and budgeting control are consistent threads throughout all test activities, and these items can be extremely challenging, so careful management is important. As mentioned previously, the team is responsible for ensuring requirements creep does not impact the cost or schedule without customer authorization.

When a team lead is assigned, he/she is given the authority and responsibility for managing that job to meet the quality and schedule objectives within established budget constraints. The team lead will initially establish the schedule objectives and budget constraints by obtaining commitments from the team. Once the schedule and budget is established, the team lead will organize the necessary authorizations to engage the required resources within the established budget constraints. Team members do not have the authority to exceed that constraint, and must immediately notify the team lead any time the scope of work cannot be completed within the established constraints. It is imperative that this notification be early enough for corrective actions to be implemented to keep the job within the established budget constraints or to negotiate a change to those constraints. Recognizing that the latter is most frequently not an option, the team must seek alternative resources to complete the scope of work within the established constraints or negotiate a change of scope or schedule with the customer.

The team is responsible for establishing the baseline budget for the scope of work at the beginning of any job. Any time the customer directs a change in scope, the team is responsible for advising the customer of the impact to schedule and cost and for obtaining authorization to implement the directed changes. This authorization shall include the customer's commitment to pay invoices submitted for work performed on the change of scope. The team may not authorize additional resources to accomplish the change of scope until such approval is obtained from the customer.

At all times the team lead must know the cost and time required to complete the respective job. To do that, reliable "estimates to complete" must be obtained from the team as often as necessary to ensure budget and schedule compliance, but no less frequently than monthly.

When the team lead obtains the resources to perform a job, it is best if those resources remain assigned for the commitment period. The team lead must ensure the necessary information is supplied to the team in a timely manner to efficiently use those resources. If there are delays in receiving that information, the team must discuss schedule and cost changes with the customer and negotiate for the reassignment of the committed resources. Then, when the delayed information becomes available, the team must renegotiate to get resources reassigned.

The team lead will be responsible for reporting project status to senior management, as desired, or whenever it is perceived that the project is not going to remain within cost or schedule compliance. The team will present corrective actions that are being taken (or considered).

3.2.2.1 Schedule Development and Control

Once a general Project Plan is in place, detailed scheduling of the tasks necessary to produce the test and test hardware must be established. Typically, adding additional detail to the WBS from the Project Plan does this. The WBS may already have sufficient detail to accomplish all activities, but it is usually necessary to expand the major WBS tasks into smaller, more manageable subtasks. Annex A illustrates this point. The WBS from the Project Plan will have one or more critical paths, as will each expanded schedule. The critical path items from the general Project Plan WBS and the expanded schedules must be closely monitored to ensure that the plan will be completed as expected. Several iterations are typically required to produce a good baseline schedule.

The following are important points to consider when developing either the overall WBS or the expanded WBS at the subtask level:

- Further breakdown can assist in establishing the details of the schedule, but care should be taken to balance the level of detail with the ability to manage and ascertain status once each task is underway (more is not necessarily the right answer).
- Start and finish dates are equally important in establishing a good plan. An acceptable finish date does not in itself guarantee a schedule that can be accomplished.
- In almost all cases, establishing a timeline for fabrication and design works backward from the test date. Design milestones are established by when they must occur to support detailed fabrication. The amount and number of available resources typically dictate the critical path. As an example, in most cases numerically controlled (NC) machining is on the critical path for model fabrication. Machine availability dictates when NC programming is required, which in turn dictates when three-dimensional design data must be available. Other items that can dictate the critical path include casting availability (if used), electronic discharge manufacturing (EDM), instrumentation calibrations, instrumentation availability, and test facility availability.
- Often there may be several critical paths. As an example, part of a model may be required prior to model delivery to the tunnel for other purposes (such as balance fitting, nozzle or airflow ducting calibrations, sensor installation, etc.).

- During this development, schedule risk (and mitigation planning) should occur. When many items fall on the critical path, it is very important to anticipate potential problems and possible ways to overcome test preparation, design, or fabrication delays. Work-around plans can include using alternate processes, adding additional resources, rescheduling the flow of work, or eliminating lower priority requirements.

Once established, it is very important to closely track actual performance to the plan. Schedule changes should immediately be made based upon actual events, although the baseline should be saved for historical purposes. Scheduling issues should be considered immediately. This is particularly important if it appears that test schedules will be impacted. Most test facilities are limited in their ability to adjust test schedules.

3.2.2.2 Budget Development and Control

Developing a detailed budget plan occurs parallel to developing a detailed schedule. Budget estimates begin based upon the details determined in the initial planning. Budget breakdowns should be planned at the task level for most test activities and should be performed at the same work breakdown levels discussed in Section 3.2.2.1.

When developing a budget, many factors should be considered including:

- Historical information for similar tasks performed
- Where the work will be performed (in house or vendor)
- Experience level of the team
- Anticipated contingencies
- Bottom-line cost boundaries
- Renovation or rework costs
- Coordination time — often required at a much higher level than initially anticipated
- Management reserve (buffer for unknowns)
- Overall level of uncertainty in requirements
- Types of contracts being used (if subcontractors are used)
- Overhead, allocated costs, and labor rates (and fluctuations)
- Security cost impacts
- Shipping and handling costs
- Unique purchases of instrumentation, exotic materials, or other supplies
- Calibrations or special checkouts (such as pressure vessel proof testing) that may be required

Procedurally, planning should include a formal method to handle task or requirement changes during model development and a method to realign budgets as a result.

Typically, maintaining a status of budgetary performance on a weekly basis is the best way to keep a firm grasp on current and anticipated performance. Annex B provides additional information on cost and schedule tracking and reporting.

3.2.2.3 Communication and Reporting

Communication is one of the most important jobs of the team lead. Ensuring that accurate and detailed information is provided in a timely manner is vital to the success of the project. Communication will take several forms, from informal conversations, phone calls or emails, to formal status review presentations. Each communication form serves a purpose and is an important link in the information transfer chain.

Status reports facilitate the flow of information from the team to management (where decisions are made that can affect the test outcome). Typically, status reports are given on a weekly or biweekly basis and contain information about various aspects of the model or test status. These reports, along with budget and schedule information, keep management informed about test development status.

Progress reviews are a valuable tool during model development and test preparation. It is recommended that the following reviews occur when developing a test project:

- **Requirements Review** — A review of the overall objectives and corresponding requirements for a proposed test effort. Anticipated or proposed budgets should be identified, discussed, and approved.
- **Planning Review** — A review of the proposed detail requirements, budget, schedule, and resources that will be used to accomplish proposed testing.
- **Progress Review(s)** — Reviews during conceptual design of the model (usually called a preliminary design review—PDR), and a detailed design review (usually called critical design review—CDR)
- **Test Readiness Review** — Review to establish overall readiness of test preparations
- **Post-Test Review** — Final review to evaluate if objectives were met and to discuss lessons learned

Reviews are generally useful exercises to gather the team and appropriate management and to focus on the tasks. Reviews also help align the necessary resources to overcome problems. It is important to keep the reviews informative, but not overly formal to allow all team members and management to interact.

3.3 Test Preparation

The last key planning activity is the detailed test planning. The team will have to communicate with several other key personnel at this time to ensure that requirements are being addressed. These efforts include:

- Finalizing instrumentation requirements and locations
- Obtaining other test or predicted data for initial comparisons through discussion with the end data user
- Working with the facility test engineer to define test procedures and run sequences to optimize data/information obtained
- Arranging for pretest calibrations
- Determining data acquisition and reduction methods
- Arranging the management of information (i.e., computing resources and methods)
- Developing model boundary layer transition strategy

A pretest report or test plan document is typically produced to capture the details of the test plan. Additional information will be presented in the following sections.

3.3.1 Final Instrumentation Requirements

Finalizing the types, numbers, and locations of required instruments to acquire necessary data is a very important activity. The Project Plan (see Section 3.2) generally contains the necessary guidelines about the type and number of instruments, but the details of where and how instrumentation will be located and used must be finalized. Model design must consider type, location, number, and routing of instrumentation early in the development process; therefore, it is critical that instrumentation be finalized very early in the pretest planning phase.

Aerodynamic force testing, which typically makes up the largest percentage of wind tunnel testing, requires very careful selection of the balance(s) used to measure aerodynamic forces. Careful matching of anticipated aero loads and model weights is critical to accurate data. Too stiff a balance will results in reduced data accuracy, while too limber a balance will results in significant model dynamics during testing and in extreme cases, loss of model.

3.3.2 Data Acquisition and Reduction

Once instrumentation requirements are finalized, planning and implementation for data acquisition and reduction can be developed. Data acquisition can include:

- Obtaining special acquisition hardware
- Arranging for additional instrumentation in the test facility
- Specifying data reduction constants or methods (such as pitch/pause or continuous sweep modes)
- Identifying filter and sampling methods
- Defining recording device requirements
- Identifying acquisition device placement in a model

Data reduction can include:

- Applying calibrations to measurements to produce engineering unit data
- Calculated corrections to measured values (such as force corrections due to cavity corrections, flow angularity corrections, buoyancy and blockage corrections, etc.)
- Special statistical uncertainty data
- Special statistical data from nonsteady measurements
- Coefficient calculations
- Integrated load from pressures
- Changes in reference systems (such as model to aerodynamic axis)
- Autopilots for captive trajectory or grid separation testing
- Engine deck values from pressures on inlet /airframe integration tests

Documenting data acquisition and reduction methods is generally part of a pretest report. It is important to coordinate responsibilities and ensure that each party understands the expected data reduction requirements. Simulated test parameters are input into the system to verify data reduction methods and should be a standard part of pretest preparation.

3.3.3 Calibrations

Calibrations of instruments tunnel systems or the tunnel itself are required prior to testing. During pretest preparation, requirements, methods, and timetables for these calibrations must be established and executed. Careful scrutiny of calibration results is also critical, as these calibrations often are the basis for the final data accuracy. Typical pretest calibration requirements include:

- Tunnel calibrations (Mach, pressure, acoustics, temperature, etc.)
- Model duct airflow calibrations
- Balance or force measurement system calibrations
- Pressure transducer standard online calibration
- Heat transfer measurement system calibrations
- Angle measurement system calibrations
- Optical measurement system calibrations
- Data acquisition systems standard calibrations
- Flow measurement system calibrations
- Ground Vibration Test structure calibrations (for flutter or aeroelastic models)
- Drop model calibrations (weapon separation testing)
- Engine simulator calibrations
- Deflection calibrations for support system or aerodynamic surfaces under load

Data from calibrations should be used to update pretest uncertainty predictions and to verify if overall uncertainty remains acceptable (reference Section 3.2.1.3 Experimental Uncertainty Analysis).

3.3.4 Pretest Predictions and Historical Data

Access to pretest predictions and previously acquired data is critical when preparing for early evaluation of data during testing. Gathering data from similar tests conducted earlier and from analytical predictions provides the basis for determining if problems exist with the data and where to focus early diagnostic efforts.

Gathering and organizing this information during pretest work greatly enhances the test team's ability to understand early test results and diagnose any issues that arise.

3.3.5 Instrumentation Checks

During pretest preparation, it is often necessary to check the instrumentation that will be used during testing. Instruments, such as high-response transducers, thermocouples, and angle measurement devices must have correct operation verified (calibration, continuity checks, etc.) early to avoid last-minute "surprises."

3.3.6 Information Management

Managing information has become a major issue during test preparation. Most tests have a large mix of project-supplied and facility computers integrated to provide overall data management and information flow. Add in Web-based information management systems, virtual private networks, and hardware and software encryption, and the level of activity required to prepare these systems for use during testing becomes substantial.

Test preparation requirements for information management can include:

- Arranging for necessary computer hardware and software
- Securing necessary software and hardware for networking
- Validating networking protocols and connectivity
- Determining network access requirements and protocols
- Arranging data configuration management and protocols
- Arranging shipping and shipping containers suitable for computing equipment

Tackling these issues early is often necessary, particularly when dealing with connectivity between test site and home offices through several firewalls. Computer system security is a major issue for most sites, and connecting two diverse sites is often a major struggle.

Arranging compatible software, particularly if purchases are required, can also be a major hurdle. Most large test facilities are developing Web-based information management systems for use during testing. Early investigation into available methods and software may provide easy solutions to information management issues.

4 Model Development and Fabrication Phase

Model development and fabrication often pace the overall project schedule and make up a significant percentage of the overall budget. The quality of the model can determine the success of the test effort. Therefore, it is crucial to have these activities well planned and executed.

Using subcontractors (vendors) for model design and/or fabrication may reduce the cost and schedule of the project. The ability to design and fabricate models is a specialty that many airframe companies are eliminating in favor of relying on outsourcing.

There are associated costs that also must be considered, such as travel, procurement support, data transfer and coordination, and any additional overhead burdens placed on purchased services. The ability to be flexible on cost and schedule must be taken into account, as well as the experience and history of the sources. The maturity of the test and model plan may dictate the selection of a vendor and the type of contract used.

The cost, quality and schedule, and risk of using outside resources (versus performing the design and/or fabrication in-house) should be compared. In some companies this is part of a “Make or Buy” evaluation. Finally, overall company goals, guidelines, and regulations may have an impact on the use of such companies and should be reviewed.

If legal relationships must be established (such as subcontracting model design and fabrication), it is important to establish these ties early during model development. Many different contractual arrangements are possible, and each offers advantages and disadvantages. Annex C describes various mechanisms that are traditionally utilized and the characteristics of each.

Model conceptual development should begin at the same time test requirements are being defined. Because of the iterative nature of test planning, model concept development and early test planning occur concurrently. The key activity is to develop detailed tasks to achieve the goals of model design and fabrication and to manage their implementation based on the Project Plan.

4.1 Team Participants for Model Development and Fabrication

The key personnel typically involved in development and fabrication are:

- **Customer** — responsible for evaluating trade-offs of model capabilities versus overall test goals

- **Design engineers** — responsible for developing a model concept and the design required to meet goals
- **Test engineers** — responsible for converting testing conditions and requirements into hardware requirements
- **Fabrication personnel** — responsible for planning and executing the detailed fabrication, assembly, and validation to produce the model. It is important to have the fabrication personnel involved in the design process, as they can provide options that could make fabrication faster or less costly.
- **Numerical control programming** — responsible for converting detailed designs into machine-specific instructions to produce the bulk of the test hardware
- **Instrumentation personnel** — responsible for assisting in the development of model-related instrumentation plans
- **Tunnel personnel** — represent the tunnel perspective in model development and help insure that model and tunnel interfaces are properly incorporated into model design

These specific functions play a vital role in the success of the model development; therefore, a complete understanding of the test requirements and implementation plan is necessary.

4.2 Conceptual Design

Conceptual design of the model hardware should begin as soon as the initial details of the proposed test project are known. At this point, work begins with identifying:

- what (if any) existing hardware can be utilized;
- the most suitable model scale for facilities under consideration;
- what major model support hardware is needed and available;
- what features the model will have (simulating the required vehicle configurations)?

4.2.1 Model/Test Facility Considerations

As mentioned, the conceptual development of the model is integrally linked to the tunnel(s) under consideration. Each tunnel has specific guidelines on many of the following technical areas:

- **Model blockage** — How large can the model be (usually measured by cross-sectional area) and still enable the tunnel to provide high-quality flow over the entire test condition range?
- **Shock impingement** — How large can the model be and stay out of reflecting shocks (supersonic conditions)?
- **Support system** — What model support system will be used and what loads are created during testing (does the model stay within the tunnels operating envelope)?
- **Instrumentation packaging and location** — Where will the necessary instrumentation be located and how will wiring be routed? Who will provide the instrumentation?
- **Strength** — What model concept will meet applicable tunnel standards for model strength?
- **Operating envelope for test conditions** — What is the expected range of operating conditions (total and dynamic pressures, temperatures, etc.) for the model?
- **Starting or emergency shutdown loads** — What are the starting or emergency shutdown loads?

- **Model changes** — What is the best model development strategy to maximize efficiency during testing?
- **Existing equipment** — What exists for possible reuse?

4.2.2 Model Configuration Considerations

Typical configuration-dependent considerations during model concept design include:

- **Model breaks** — How will the model be broken into sections to provide the ability to change configurations to meet test objectives? What design features are necessary for metric/nonmetric breaks and test geometry parametrics?
- **Model systems access** — What model features are necessary for access to systems or model utilities (hydraulics, high-pressure air, instrumentation, and actuators)?
- **Internal flow paths** — If internal ducting is required (to simulate aircraft flow path), what design criteria and specific measurements will be required? What are the sealing requirements?
- **Fidelity** — How detailed must the outer mold lines (OML) and specific vehicle features be simulated? These requirements will flow from the uncertainty analysis discussed in Section 3.
- **Rapid prototyping** — Can lower strength and fidelity processes (such as stereo lithography, casting, etc.) be used to reduce cost and model part fabrication span times?
- **Remote control devices** — Are there opportunities to automate model configurations to reduce model change times during testing? What are the trade-offs for including this capability (typically trading test cost for model cost and schedule, differences in setting accuracy, operational risk)?
- **Instrumentation** — How much and what kind of instrumentation (balances, pressures, thermocouples, accelerometers, etc.) are required to meet test objectives? How will these items be included in the model and routed to the data acquisition system?
- **Overall surface finish and tolerances** — What are the required surface finishes and overall tolerances for the required configurations? As an example, wing flaps can often be designed either with cutouts for separate deflection brackets or with integral brackets as part of the flap itself. Number of parts, cost, and schedule vary greatly depending on approach. Which is required to support the test goals?
- **Propulsion system simulation** — How will propulsion systems be simulated and what special test requirements are created to support that simulation?

Other considerations for model concept development include:

- **Resource availability** — What resources (machines, people, and processes) are available to support the model development?
- **Design and fabrication concurrency** — Can the anticipated processes support highly concurrent design and fabrication, or will model development be restricted to complete design before fabrication begins? (This is often a strong issue when model fabrication is contracted to model suppliers.)
- **Loft availability** — When will final vehicle lofts be available?
- **Calibrations** — Are there any calibration requirements that will affect the design and manufacturing schedules (can include items such as balance, balance blocks, ducts, nozzles, airflow systems, etc.)? What additional calibration equipment is required (load hangars, calibration fixtures, plugs for hydrostatic leak checks/certifications, etc.)?

- **Computer-aided design (CAD) tools and loft translations** — What are the best available tools for concept and detailed design and how will lofts be translated from their original source? Are design and fabrication tools compatible, and will standard translators (STEP, IGES) work properly?

Each of these technical areas must be considered during conceptual design. From the conceptual design, detailed model design, and fabrication, schedules and budgets must be established and subsequently included in the WBS (discussed in Section 3.0). The conceptual design phase typically ends with a Preliminary Design Review (PDF).

4.3 Detailed Design

Detailed design is initiated immediately upon overall acceptance of the design and fabrication plan. Even with nearly concurrent schedules, detail design should have a head start before major fabrication begins.

Activities that occur during this phase include model strength analysis and report, drawing preparation, 3D-model data generation, inspection requirement generation, instrumentation positioning, and final facility interface documentation.

Resource availability is a key issue for model design. Management and careful task planning, based upon the scheduling described above, is critical. Design scheduling, based upon fabrication requirements, dictates the critical path for the release of design information. Resource availability and task planning must be carefully organized to accomplish activities according to planning. As previously mentioned, tracking frequent updates to schedule and budget can help avoid catastrophic surprises at a later date and give the design group the opportunity to perform adjustments during a project.

Detailed stress analysis also occurs during this stage. Stress analysis should be an integral part of the design process, not an afterthought. A small thing, such as minimizing the numbers of fasteners at a model attach point can save many fabrication hours. Conversely, one too few fasteners can spell potential disaster at the tunnel. Careful development of model loads, from predictions or similar test data, is critical to establishing model structural integrity.

Conformance to tunnel strength and stress standards is mandatory. Published design standards are established at most facilities. Careful documentation of loads used in the design (whether based upon analysis or historical data) is critical. Analysis methods should be discussed with tunnel personnel early to avoid surprises late in model development. Material certifications must be consistent with analysis assumptions. Waivers or direct load monitoring are sometimes required to meet test requirements. Careful coordination with tunnel personnel is a key.

Hazard analysis should be performed early if systems or components can produce safety or operational issues. This analysis typically involves identifying hazards and their controls. Once again, careful coordination with tunnel personnel is essential.

To ensure overall model accuracy, inspection requirements and planning must be generated. A general outline and a detailed plan must be provided to the model fabrication team. The outline should summarize the overall inspection goals, tolerances and methodologies for inspection. The detailed plan includes inspection requirements for all model components, including surface contours, location or rigging, deflection angles, balance orientation, level surfaces, instrumentation locations, base areas, duct areas, porosities, weights and center of gravities, fits, clearances, and any other special inspections. The final model acceptance review or buy-off is the best place to acquire all the measurements and data to prove that the model meets all accuracy and functionality requirements.

Common sense is also an important part of any design. The hardware should be easy to assemble and have as much access as possible to the internal instrumentation. If exotic fastener sizes or types are not warranted, they should not be used. Standard grade 8 threaded fasteners should work for the vast majority of applications.

It is also important that design reviews be conducted at predetermined stages of the design process (typical times are 30%, 60%, and 90% completion points). It is during these reviews that team members (customer, test engineering, test facility, instrumentation, and fabrication) will provide a sanity check on items like instrumentation locations, routing space for tubing and wires, and interface with support systems. It is important that any potential problem areas be identified during the design phase when the cost of modification to the original design is minimal; learning about these problems after hardware fabrication is completed is very costly to the schedule and the budget.

4.4 Model Fabrication

Model fabrication is often a critical path item, and careful attention is required to ensure that it is on time and per specifications. As is the case throughout the test project, communication is again vital to the success of this step. The team lead must stay in contact with the fabrication personnel (whether in-house or a subcontractor) and relay any potential problems to other team members so that contingency plans can be put in place quickly, if needed. If all team personnel are involved early in the design phase, then the fabrication should be a matter of turning drawings into test hardware. However, a lack of up-front participation by any part of the team could result in delays at this stage.

The following sections provide insight into methods that can reduce the overall cost, the time required to complete the model fabrication, or the risk involved with the fabrication process. Annex E provides additional information on design and fabrication issues that affect cost and schedule.

4.4.1 Rapid Manufacturing Processes

Rapid manufacturing technologies can reduce cycle times and costs significantly and should be implemented on all model systems (where practical). There are numerous rapid manufacturing technologies currently in production, application development, and research. Stereo lithography (SLA), selective laser sintering (SLS), directed light fabrication (DLF), high-speed machining, and advanced casting methods are a few that apply to manufacturing model systems. Each has advantages and disadvantages, depending on the model system requirements. Additional information about rapid manufacturing techniques is provided in Annex D.

4.4.2 Virtual Manufacturing

Virtual manufacturing is a means by which manufacturing of model systems can be simulated in virtual space before actual manufacturing begins. Virtual manufacturing allows inspection and proof checking of manufacturing processes. Additionally, virtual manufacturing allows the correction and elimination of manufacturing errors. A large reduction in manufacturing time can be achieved by reducing the errors in numerically controlled tool paths used to manufacture model systems. Most computer-aided manufacturing (CAM) codes provide the ability to simulate tool paths. This allows up-front determination of the quality of tool paths and inspection of tool path to ensure errors (such as gouging of parts and collisions between work piece and machining center) do not occur. Previously, tools paths were verified by cutting components on machining centers in materials such as foam or aluminum, which machine at much faster rates than steel or other tough machining materials. By moving verification off the machining centers and to the computer processor-using software, cycle time and errors can be significantly reduced.

4.4.3 Acceptance Criteria and Noncompliance Documentation

Model acceptance criteria are important to verify that the as-built condition of the model system meets the design specifications. Design, customer, and test facility team members typically determine model acceptance requirements. Model complexity, model fidelity, and the potential for personnel or facility harm (as a result of model failure) play a significant role in determining the procedures for model acceptance.

Requirements for model acceptance can include the following:

- Material certifications

- Heat treat certifications
- Fabrication/inspection plans (including coordinate measurement machine—CMM—evaluations)
- Control of nonconforming hardware

Typically, raw materials and components used in fabrication will be traceable through material certification reports and heat treatment certification. Components that require this level of documentation will be carried through fabrication processes with shop travelers (in-process fabrication documents). Shop travelers have all the associated documentation stated above, including all fabrication processes applied to each individual component.

Typically, materials used for critically stressed components will be subject to nondestructive testing (NDT). For metals components, surface or immersion NDT methods will be used, depending on specification or requirements. For surface inspections, a variety of methods exist including liquid dye-penetrant, magnetic particle, and eddy current techniques. Techniques for detecting cracks in the internal structure include radiographs, X-ray tomography, and ultrasonic inspections. For composite materials, visual inspections may be used during fabrication to determine delaminations, inclusions, contaminates, and fiber orientation.

A fabrication/inspection plan defines pre-manufacturing inspections, in-situ manufacturing inspections, special process inspections (such as bonding, welding, and brazing processes), contour inspections, and final assembly fit checks. Additionally, instrumentation checks can be included in the fabrication/inspection plan, such as pressure tube flow, leak checks, and pressure transducer operation.

When an article or a material does not comply with design specifications, it is identified as nonconforming and is held for disposition by a Material Review Board. Depending on the complexity of the model system, the Material Review Board will include, at a minimum, the customer and design and fabrication quality assurance personnel. The deposition of the nonconformance is documented and supplied with the associated model system documentation. In some cases, a nonconformance will have no affect on test objectives, and therefore will not be required. In other cases, corrections are required to meet engineering or testing requirements. When the deposition is complete, any design changes are captured in the documentation, as required.

During fabrication problems often occur that create parts that do not match the original designs. Maintaining “as built” drawings can substantially impact the test and future uses of the model hardware.

4.4.4 Instrumentation Installation

Instrumentation for models should be addressed in the design process. Typically, all instrumentation should be installed and fit-checked during the model fabrication phase. When this is not accomplished, valuable testing time is used for installing instrumentation into the model system. Model space is usually limited and requires that material be removed to allow instrumentation installation (model structural integrity must be carefully evaluated). Typical instrumentation installed in models are balances, angle-of-attack measurement devices, and pressure ports and temperature gauges. Installing pressure orifices into models can account for as much as 20% of fabrication time. Installing a balance into a model requires precision joints between the balance and model adapter hardware and between the balance and sting. All joints between balance and associated hardware should be fit-checked and modified accordingly before model assembly begins. All instrumentation should be calibrated and pre-fitted for installation when model assembly begins.

4.4.5 Model Acceptance

Model acceptance is the final review of the hardware and the last step before the team accepts a model. At this point the team has the opportunity to review and accept the model for delivery. All documentation such as discrepancies or nonconformance reports are reviewed and approved, or rejected and rework recommended and performed. It is recommended that the model be fully assembled to ensure all

components or configurations fit properly and all fasteners are accounted for and modified as needed. All model parts should be marked in a permanent fashion with identifying numbers. Additionally, all instrumentation should be checked and labeled with the appropriate identification labels.

It is advantageous to have test facility personnel attend the model acceptance to facilitate model buildup when it arrives at the test facility. This reduces any down time that may occur during testing or configuration changes during the test. Additionally, the test facility personnel will gain knowledge and understanding of the model assembly sequence, again reducing errors during pretest assembly.

4.4.6 Handling, Packaging, and Shipping

All hardware should be protected from damage during shipping. Any special handling, packaging, and shipping requirements for the model should be documented. Shipping containers should be designed to ensure the safe arrival of hardware to the testing facility. All components should be clearly identified. A copy of drawings should also accompany model hardware and any other supporting documentation that will be needed for handling and assembling model hardware at the test facility. Photographs of the model should be taken as it is shipped and received and included with the materials lists.

5 Pretest Buildup and Preparation Phase

Initial efforts at the test facility are the culmination of all planning and work that has occurred during the preceding period. At this point, a smaller, more focused group of personnel begins the final activities required to prepare for the experiment. These activities include:

- Getting the test team organized
- Configuring the model and test facility properly for testing
- Obtaining, installing, and checking out instrumentation
- Preparing final data acquisition and analysis capabilities (hardware and software)
- Finalizing test procedures
- Ensuring that all safety requirements have been met

The pressure and pace of activities generally increases as the test start date gets closer.

5.1 Team Participants for Buildup Phase

Careful organization and orchestration of the test personnel is an important first step in the pretest buildup activities. Members of the test team must know their role and responsibilities, the reporting path, and monitoring and status reporting methods. The pretest (and test) efforts are similar to an orchestra, with each member playing a role, directed by a conductor. When carefully planned and executed, testing occurs with little error. However, when unorganized, test preparation and testing can be pure chaos.

A model for organizing the test team during the buildup phase is presented in Figure 2. Two key personnel, the facility engineer/manager and the test project manager, are typically the focal points for pretest efforts.

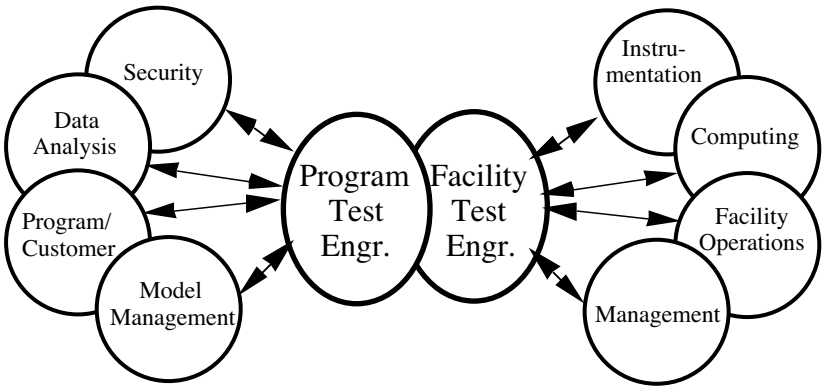


Figure 2 — Team Makeup During Pretest Buildup

Figure 2 illustrates that the facility engineer/manager and the test project manager provide the backbone for organization and communication (management) of the various personnel required to successfully perform pretest and test activities.

The test project manager is responsible for overseeing the activities that relate to meeting test objectives. These include:

- Final preparation of the model hardware
- Data reduction requirements and methods
- Organization of the test matrix or test log
- Setup of all necessary computing tools for analyzing test results
- Providing the direct interface to the test facility manager

The facility engineer/manager performs a similar function, organizing and executing the actions and activities of all the various functions within the test facility. These include tunnel operations, security, business management, data acquisition, computing, and overall scheduling.

The facility engineer/manager and the test project manager should be the center of all information and coordination during the pretest buildup. At the start of pretest activities, a meeting should be held with all participants to establish the responsibilities, reporting requirements, communication methods, and schedule of events. Multiple shift activities, typical at most wind tunnels, require that these topics be covered to coordinate the shift change of personnel.

At this point, it is also important to establish and implement a status and monitoring plan. Because test events are very dynamic, it is important to establish a process to monitor and communicate progress and to report and resolve problems.

5.2 Model Buildup

When the model arrives at the test facility, it is important to document the contents and organization of the hardware in case any damage occurred during shipment. After the hardware has been cataloged, buildup can begin. Buildup typically occurs outside the test section, in nearby areas that have been set up to provide the standard mountings and data acquisition connections. Buildup areas generally simulate the test section installation so that the majority of checkouts can be completed prior to moving the model into the tunnel. As the model is assembled, it is important to perform final fit and function checks on all configurations that will be tested. Frequently, model fit and function problems can be overcome more easily outside the test section than during testing.

During the model buildup phase, installation and checkout of all instrumentation is performed. These include:

- Fitting balances, stings, and pins
- Installing and routing pressure instrumentation
- Painting for pressure or temperature paints
- Installing boundary-layer transition devices (grit, dots, etc.)
- Installing grounding or fouling strips
- Installing high-pressure air or vacuum lines for flowing configurations
- Installing any angle measurement devices and appropriate calibration fixtures
- Installing any motion monitoring equipment (rotary differential transformer, linear variable differential transformer, potentiometers, accelerometers, etc.)
- Determining and installing mechanical and electrical limits
- Routing necessary electrical and pressure lines through the test hardware (including spares)
- Checking ground vibration or proof-loading

Tunnel, model, and instrumentation calibrations must also occur during this period. Since most tunnels are performing other tests while a model is in buildup, careful orchestration of instrumentation and acquisition must be performed to ensure that adequate test preparation can occur prior to moving the model into the test section. Typical calibrations include:

- Pressure measurement devices
- Balances and strain gage devices
- Angle measurement equipment
- Pressure measurement equipment
- Electronic monitor and measurement equipment
- Sting deflection or support system devices
- Taper fits
- Pin fits
- Limits and range of motion checks
- Model to balance relationship measurements
- Data channels, filters, and voltage settings

Safety practices are typically finalized during buildup. These can include:

- Hazardous material handling (if any)
- Training/handling of hardware for safe use
- Material safety data sheet access
- Required proof-testing

- Required safety equipment
- Required use of wire ties, locking fluid, or safety wire
- Fastener torque requirements

In many instances, additional computing capabilities are brought from other sites and must be integrated into the test facility (networks, power systems, and physical location). Tasks that must be planned for and performed during this phase include:

- Establishing communication protocols and information transfer timing
- Routing necessary wiring and networking hardware
- Establishing software connections and communications
- Establishing data transfer timing and formats
- Verifying encryption methods and/or physical security
- Validating all software functionality and accuracy (end-to-end checks)
- Cross-training personnel, as necessary

5.3 Planning for Installation in the Test Section

During buildup outside the test section, it is important to plan for the final move into the test area. Hardware and instrumentation installation and checkout should be carefully coordinated so that all work can be accomplished outside the test section prior to moving into the test section. Test facility personnel are typically responsible for planning the move from the buildup area to the test section. In many facilities, this involves heavy lift equipment and coordination among a number of test facility personnel.

5.4 Final Test Matrix Review

Prior to testing, a final test matrix should be completed and provided to all test team members to allow a last check of hardware compatibility with desired testing. Often, preliminary test matrices fail to consider the limitations of support systems, auxiliary subsystems, instrumentation, or model configurations. A final review of the test matrix facilitates a final check of model and tunnel systems to be used.

6 Test Phase

The test phase is the culmination of all the planning, hardware development, and setup work that has been completed. It is during the test phase that everything comes together, “air blows over steel,” and the required data is collected. The team composition is the same as for pretest buildup (Figure 2), with the addition of the customer. Coordination and communication continues to be key to project success, and it may even be more critical during the test phase due to the hectic pace involved with testing. It is the job of the test management team (project and facility managers) to ensure that roles and responsibilities are clearly defined and that the proper reporting and decision-making paths are defined and working.

The complexity of the test phase depends on the size of the test matrix, the amount of data to be collected, the type of model used (highly automated, propulsion simulator, loads, etc.), the number of configurations tested, and the facility. The test team is now responsible for all activities required to complete the test, including hardware installation and checkout, data collection, data verification and reduction, and test documentation.

6.1 Test Team Communications

Establishing correct and consistent lines of communication within the test team is vital to the success of the test project. The two main areas to focus on are: (1) communication of goals, procedures, and

information and (2) chain of command. Establishing and understanding the process of how information flows within the team is the first step.

- **Communication** — Figure out which team members need to know specific information and how all team members will be informed of decisions that might affect their part of the test. Be aware of reporting responsibilities that are required of the project, whether they are operational, technical, or financial, and make sure that someone has the responsibility and the information to correctly report on it. In facilities where multiple shifts are used, communication between shifts is essential for smooth transitions. Establish documentation requirements, including test logs.
- **Chain of command** — The clear definitions of responsibility and authority must be established from the very first day. As a test progresses, a clear chain of command with a good understanding of authority and responsibility will be essential. A written record of the chain of command should be distributed to all team members. It should be clear who has the authority to make decisions. This is especially important protocol for the test crew, customer, and the tunnel personnel.

The team arrangement discussed in Figure 2 continues to be the basic model during testing. The primary focal points are typically the project manager and facility engineers. As operational testing begins, the level of participation for various functions increases or decreases depending on need. Coordination between the project and facility engineers remains critical.

6.2 Model Installation and System Checks

Installing the model into the tunnel can begin only after all pretest buildup work is complete. It is very important that all model parts have been fitted prior to installation, as any mismatch between parts found after installation starts will result in lost test time and increased costs.

The individual or team assigned to complete the installation must be familiar with the test setup, model configurations, and the facility. Having these personnel involved in earlier phases of the project will now show dividends because they will be familiar with the hardware, and the input they made during the design phase will make installation and configuration changes easier.

There are calibrations or checkouts that must be performed in the tunnel prior to testing (and daily). Since each facility and test entry is unique, the test team must determine which calibrations are relevant for a particular test project. It is essential that each calibration be done with a traceable standard that is itself calibrated within inspection dates. The calibration standard used and certification should be noted in the test log. A few examples of in-tunnel calibrations are:

- **Support systems** — Test article support systems should be checked before and after mounting a test article for alignment to the axes system of the tunnel. Angular tilt should be zeroed if possible and recorded if not. A record of exact orientation of the support system should be noted and checked whenever feasible, according to the testing plan and difficulty of taking the measurement. Careful integration with the detail design of the model will overcome most of these problems.
- **Test article orientation** — As with the model support structure, the test article should also be put into the desired orientation (angle–of–attack, roll, yaw), and deviations from this position should be noted in the test log.
- **Subsystem calibrations** — If the test requires the addition of test subsystems, such as gas flow for cooling, hydraulic fluids, control, or safety devices, it is often required that calibrations be done in the tunnel with the model fully assembled. Measurements should be obtained for increased confidence that the data from the subsystem at the station required is accurate, verifiable, and controllable.

- **Check loads** — Prior to obtaining test data, check loads should be applied to confirm that tunnel measurements will be identical to the measurements obtained for the balance or other instruments during calibrations. Differences in cabling, electrical environment, or filters can change calibration coefficients. For this reason, check loads or simulated inputs will verify that the calibration is valid and accurate. In some cases, where the model is dynamically operated during the test period, check loads should be obtained dynamically to remove the inertial loading to the system.

- **Pretest tares** — Tares frequently need to be taken into account for environmental phenomenon that are specific to the test. Ideally, test data should be taken as close in time to the calibration as possible. Sensors may drift due to inherent instabilities, temperature, pressure, moisture, or sensitivity to other environmental factors. Tares are also performed to remove biases in the data such as the loading from the weight of the model or the dynamic inertial loading from a pitch system, fouling system checkout, and metric/nonmetric tare effects.

- **Instrumentation checkout** — Once all sensors are installed and model position and orientation are set, all remaining sensors should be checked by performing end-to-end checkouts. It is strongly recommended that much of this checkout be done before installation; it is usually much easier to replace broken sensors before the model buildup is complete.

- **Data acquisition system checkout** — The data acquisition system should be checked to verify that any offsets or out-of-range issues are remedied. Subsystems used as references, such as constant voltage or current sources and calibration standards, should be verified as operational and accurate.

- **Data reduction and analysis verification** — An entire (end-to-end) data run should be performed with a hand check of the sample data set. This data should use the entire data acquisition and reduction process and must verify that all systems are functioning properly.

6.3 Test Readiness Review

Just prior to testing, a test review should be held. In essence, this is a last minute check to ensure that all needed tasks have been completed and that nothing has been overlooked. Often, a third-party review is used; this is beneficial because nonpartial reviewers can sometimes catch potential problems that the team might miss because they are too close to the operation. It is important to distinguish this review from a design or safety review. This review will include all critical systems and data requirements. All team members should be at this meeting and be able to give input about test readiness. Specific discussion topics include test procedures and processes, data quality, and subsystem calibration and operation

6.4 Initial Tunnel Runs

Once pretest calibrations and checks are complete, initial tunnel runs may be performed prior to beginning actual data collection runs. The reasons for these runs vary and represent tunnel-specific characteristics. It is important that the characteristics of all critical parameters be known and found to be within required specifications prior to the start of data collection. To ensure that the model and tunnel are test ready, some initial runs may be needed to determine the following information:

- **Operational checks —** One of the first checks is the basic operation of the model in the tunnel. The model is tested through the planned operating range (airspeed, pressure level, model angles or configurations) to ensure that the model, tunnel, and support systems are behaving as expected. Other specific checks may include mass flow rate for engine simulations, control systems, data collections, and remote access systems.

- **Test section flow quality —** Since tunnel calibrations and flow quality surveys are performed without a test model installed, the presence of the model can influence the test section flow quality. Depending on the objectives of the test, the model may be tested upright and inverted to

provide an indication of the overall test section flow angularity. Other checks that may be important are Mach number tolerance, Reynolds number effects, humidity effects, background noise levels, or the usable test section area (boundary layer thickness).

- **Data acquisition and quality —** Because the collected data is the ultimate product of the test, all efforts must be made to ensure that high data quality is achieved. Some items that should be checked during the initial runs are data sample size, data filtering, and sample frequency. Settling time, or the time required to achieve steady-state conditions, must also be determined. This is important for all tests, but is particularly critical for pitch-pause sweeps for lift and drag measurements. Checking data repeatability should also be part of the initial tests. The initial checks can also be used to validate experimental uncertainty estimates.

- **Data Reduction —** Initial runs also provide a way to finally verify that data reduction methods are correct. Often, important computing errors become obvious only once the entire test procedure is used (usually for the first time during the initial runs).

6.5 Testing Checks and Documentation

Once the entire test process has been validated, testing begins on the desired aircraft configurations. Throughout the execution of test matrix, a number of important quality control checks should be included as a routine part of testing. These include:

- **Repeat runs** — Testing a configuration again after a period of time provides a measure of in-test repeatability and often gives critical insight into errors that have crept into testing that would otherwise be masked within the data being obtained. As a matter of procedure, repeat runs should be added at least daily to ensure that in-test repeatability is as expected.

- **Calibrations and check loads** — Routine instrument calibrations and occasional validation of operation through application of check loads, pressures, temperature, or known measures provide valuable ways to ensure continued operational success. Most test facilities have routine calibration schedules for typical instrumentation (for example, pressure instrumentation). Extreme caution should be used if deviations from established procedures are considered.

- **Tares** — Measuring tare effects (such as changes in model weight) should be integrated into the test matrix and be a routine part of testing whenever changes occur that could affect tares.

It is critical that data quality be monitored throughout the test. A plan should be in place to check and verify all instrumentation performance at periodic intervals. This may be done daily at the start of a shift or continuously on-line with verification instrumentation. Since model or tunnel configuration changes require changes in data reduction constants, these terms need to be monitored throughout testing, particularly when changes occur. Routine checks provide a valuable method of checking continued operational health.

Test documentation is a critical responsibility for all members of the test team. Required documentation includes:

- **Test log** — Perhaps the most critical record during testing, this log typically documents the test sequence, configurations, settings, and test conditions along with test numbering. Both test facility and project leads typically maintain logs as a crosscheck of events, with each recording the unique aspects associated with their responsibilities.

- **Test notes** — Second only to the test log, test notes contain written descriptions of the events that occur during testing. Notes about problems, solutions, events, issues, and decisions (with rationale) are usually documented in the test notes. Documentation of discussions and comments are also typically included in the test notes.

- **Configuration documentation** — Photographs and video imagery can provide import documentation and records of test events. Both should be used as much as possible to document events as they occur.
- **Detail logs** — Various functions within the test team typically maintain specific logs of test events. Examples include tunnel drive operations, computer reduction, and photography logs. These additional logs ultimately provide further documentation of test events (and problem resolution, if necessary)

Test logs and notes are often a key method for keeping personnel informed, particularly if testing spans multiple shifts. Note takers should be careful to write legible and understandable notes that can be interpreted by someone else that day (or several years later to unravel a test mystery, if necessary). Many facilities are utilizing Web-based tools to electronically maintain and share the various logs and notes typically maintained during testing.

6.6 Data Processing

The decision about how much data will be processed in real time and how much data will be processed post-test will play a major role in understanding test results. The ability to make fast and accurate decisions about the test is directly related to understanding the data. Typically, setup time and model changes account for a large portion of test costs, and therefore, every effort should be made to not repeat configurations (except for repeatability runs). Be sure that all required data is captured on-line, and enough information is gathered to determine if a configuration or particular setup can be changed.

With modern advances in computational capabilities, it is now possible to perform most, if not all, processing in near-real time. However, there will be information and processing routines that are not time critical and may be delayed (post-test processing). The identification and separation of this type of processing will be important for smooth conduct of the test and can affect the cost considerably. Care should be taken to ensure that on-line and post-test processing is fully integrated.

6.7 Cost and Schedule Management

Facility cost and schedule information must be understood to adequately manage the test. Processes to obtain “real time” cost and schedule information must be in place to properly manage the test. Typical parameters that can act as a barometer of schedule and cost overrun are:

- Tunnel occupancy and test-hour tracking
- Power costs
- Cost tracking
- Run rates
- Downtime
- Data rates
- Unscheduled maintenance charges
- Labor hours expended

Testing often involves second and third shifts to reduce power costs, and often more than one shift (which affects manpower requirements) to fit within tunnel or customer schedule requirements.

6.8 Test Efficiency Issues

Since testing is a team function, tasking order will have a large effect on project efficiency. Careful identification of tasks that can be performed in parallel, those that require a unique resource, or those that

are on the critical path will significantly improve overall test efficiency. Be aware, however, that in ground testing, changes will occur that can cause deviations from this path. Accommodations should be made to identify when this occurs, and procedures should be in place to regain control over the test under the new circumstances.

It is common for a test matrix to be established prior to a test, but to contain decision points where the matrix may be altered based on test results. This allows the test team to obtain the best total data set needed to accomplish the test goals in the most efficient manner. An established procedure should be in place that allows changes to the test matrix and provides information to each test team member about impacts. The test matrix can be part of the contract between test team and test facility; therefore, accommodations need to allow changes to that matrix without having to rescope or renegotiate contracts.

6.9 Test Completion Review

It is important to hold a test review soon after the last run to capture relevant information while the test team is assembled, the experience is fresh, and tunnel resources are available. Goals of this review should include:

- Summary of acquired data
- Discussion of test and data
- Verify test goals were met
- Definition of actions and roles and responsibilities for the pending post-test period
- Milestones for data, reports, and follow-up
- Feedback on performance during testing
- Discussion on lessons learned during testing

6.10 Model Removal

When the last run is complete and the test team has verified that no further data or post test calibrations are required, removal of the test hardware can begin. Careful consideration should be taken to allow sufficient time and resources for this period in the test project. Measurements that were taken during installation, like orientation angles, should be verified and recorded in the test log.

Before the model is removed, any necessary final calibrations should be made. These may include final position checks or transducer zero shift checks. Also, all final documentation photographs must be taken. It is also recommended that the model be thoroughly inspected before it is removed. This inspection will ensure the condition of the model at the end of the test and will guarantee that any damage later found on the model occurred after the test.

The first task for hardware removal is to develop a plan for packing all hardware. This is necessary since hardware removal tends to be somewhat chaotic, as there is a rush to get one model out and the next model in the test section. It is also essential to conduct a thorough inspection of the model and instrumentation and to catalog all hardware. This step should occur before the model is removed to ensure that no hardware is overlooked during removal. This list should also indicate the owner of each piece of hardware (tunnel or project). This list will be used later to coordinate the disposition and storage of all hardware. An agreement must be reached between all parties about the proper disposition of the test hardware; all hardware must be accounted for at this time to ensure that nothing is lost.

If possible, model and test hardware should be carefully packed in original shipping crates. It is important to document each container; photographs are particularly useful for that. Shipping and handling arrangements, including how shipping is to be paid and the expected arrival date are important subjects to be discussed among the test team. Generally, the facility accepts responsibility for arranging shipment

based upon test personnel requirements and shipping information. Shipping information such as number of boxes (including sizes and weights), carrier, shipping invoice number, and expected arrival date should be gathered and communicated promptly among the test team.

7 Post-Test Phase

The tasks that occur after the test are as important as the planning and actual test. Items such as storage of the model and test hardware, disposition of the test data, and review of the test experience and action items are very important, not just for the completed test, but also for the planning and execution of future tests. The goal of a successful wind tunnel test is accurate, usable data that can be applied to the design of an aerospace vehicle. There are many things that occur after the tunnel has been shut down that can impact the validity of test data. This section reviews important post-test activities.

Post-test activities can be divided into three areas: hardware, data, and documentation. From a project management standpoint, hardware and documentation are areas that are generally straight-forward; data is typically handled by the final data user, so the project and facility engineers may not have as much responsibility in this area. However, it is important that all three areas be addressed completely before the test is closed to ensure that all objectives are completed.

7.1 Team Participants During the Post-test Phase

Once again, the team makeup illustrated in Figure 2 continues to be the model for team organization during the post-test phase. Most activities are centered on the facility, the project engineers, and the personnel responsible for cleaning up and disposing of model hardware and instrumentation.

7.2 Hardware

Once the model hardware is returned, it is important that the hardware be restored to usable condition, repairs made (if necessary), instrumentation removed and stored, and storage documentation finalized. Photographs of model storage are particularly useful for documenting locations of the parts that comprise a model.

Design drawings should be updated to reflect any changes to the model hardware or test setup that occurred during testing. This is particularly important because most models are used many times, and poor documentation leads to errors during the next test (and lost time and money). Hardware that can be used for other purposes (examples include support system parts, adapters, instrumentation, etc.) should be separated from a specific model and stored in a central or common storage location.

Instrumentation should be returned to storage, or if maintenance is needed, that should be performed. Often, cleaning up wiring, cables, connectors, calibration hardware, etc., is required at the end of a test. Delaying final disposition of instrumentation often leads to lost or destroyed instruments.

7.3 Data

The final product of a wind tunnel test is accurate, meaningful data. Generally, the customer (end-user) will be responsible for evaluating the test data. This evaluation could include comparing the wind tunnel test results to flight test data, analysis results (including computational fluid dynamics), or to tests conducted in other facilities.

Careful review of the data can identify the need to recompute or make additional corrections to the test data. Adjustments to the collected data are often made to account for anomalies or changes found in the post-test model or instrumentation, calibrations, errors in configuration information, or tares. After the data is in its final format, the project test engineer is responsible for ensuring that all the data is properly transferred to the customer. It is important that the project test engineer maintain a good log of any changes to the test data, including rationale and background, to support the understanding of changes made between “online” and “final” data.

7.4 Documentation

The final step in the wind tunnel test process is to compile and file the final project documentation. This documentation is very important, especially in terms of effort saved in planning and executing the next test entry for a similar model. A summary report that provides details of the test project should be prepared shortly after completing the test. This report will summarize all aspects of the test project and include, at a minimum, the following information:

- Summary of test advocacy and objectives
- Description of test hardware
- Description of specialized support systems
- Status of test objectives
- List of problems encountered and solutions
- Lessons learned
- Summary of test results and collected data
- Resources used (funding, labor, and tunnel utilities)
- Scorecard of tunnel and test efficiency and performance metrics
- Final test matrix (as-run)

An archive file should be created containing all pertinent documentation for the project. This file will contain, but is not limited to:

- Test requirements
- Work plan and work breakdown schedule (showing planned and actual dates)
- Hardware drawings, stress report, parts list, and storage records
- Test installation photos
- Test and project engineering log notes, run reports, and the test summary report
- Final test matrix (as-run)

These archive files are very important for planning future tests since they transfer knowledge between test teams. The archive files should be maintained in a central filing location (perhaps at the tunnel or as part of the organization's management files) and not remain with individual team members, to ensure that the files are not lost as personnel assignments change.

Lessons learned and problems encountered are important information that should be shared within test organizations. While this information is contained in the project archives, it may go unnoticed. For this reason, lessons learned should be posted for all personnel to see. A post-test briefing should be conducted to summarize and communicate events that occurred during a test project.

8 Summary

Wind tunnel testing is a demanding activity. Several key strategies, if employed, will significantly contribute to the project's success. These include:

- Having the right personnel involved from start to finish
- Forming strong team bonds by keeping all personnel involved

- Making and maintaining a good plan based upon defined requirements
- Monitoring progress weekly against the plan (particularly budget and schedule)
- Anticipating problems (evaluating risks) and having alternate plans available
- Holding regular reviews with management
- Paying attention to detail throughout pretest activities (success or failure is usually determined by preparation)
- Calibrating tunnels and instrumentation
- Structuring the team during testing to carefully coordinate all activities between the test facility and the test crew (if different)
- Performing thorough post-test reviews of data, hardware, and documentation.

This document has provided an overview of how these strategies should be applied. Not all apply to every test, but the general strategies are fundamental to conducting a successful wind tunnel test.

References

1. AIAA S-071A-1999: *Standard for the Assessment of Experimental Uncertainty with Application to Wind Tunnel Testing.*

Annex A Example of a Work Breakdown Structure (WBS) for a Wind Tunnel Test Project

A work breakdown structure (WBS) provides an organizational strategy for events, actions, tasks, milestones, scheduling, and cost tracking. A WBS structure for wind tunnel testing typically contains at least the following major categories:

1) Requirements Review (milestone)
2) Loft availability (milestone)
3) Contracts in place for tunnel and model (milestones)
4) Planning Review (milestone)
5) Progress payments (milestones)
6) Preliminary Design Review (milestone)
7) Design by part (span)
8) Stress Analysis Report Delivery to tunnel (milestone)
9) Pretest report preparation
10) Pretest report delivery (milestone)
11) Critical Design Review (milestone)
12) Fabrication kickoff (milestone)
13) 50% Fabrication Review (milestone)
14) Major instrumentation calibrations (such as balances—span)
15) Numerically controlled programming (by part)
16) Numerically controlled machining (by part)
17) Instrumentation installation (span)
18) Systems installation and checkout (span)
19) Conventional machining (by part)
20) Hand finish (by part)
21) Assembly (by section)
22) Assembly (total)
23) Quality assessment (in process and final)
24) Model buy off (milestone)
25) Shipping (span)
26) Model delivery to test facility (milestone)
27) Pretest buildup
28) Tunnel Installation date (milestone)

29) Test window

30) Post-test activities

Annex B Cost/Schedule Status Report

Cost/Schedule/Status Reports are the most common reporting format for tracking a project. A basic understanding of the definitions listed in Tables B.1 and B.2 is necessary. With this information, a graphic representation of the project's status can be quickly understood. (Figure B.1).

Table B.1 — Definitions Used in a Cost/Schedule Status Report

Col.	Title	Definition
	Project/Task	Total Project Summary or Major Deliverable Tasks
	Contract Type	Contract Type, e.g., FFP, CPFF, T&M (Subcontracted Tasks)
(1)	Original Auth. Cost	Original Project or Task Cost Authorized
(2)	Auth. Cost Changes	Additional Cost Changes Authorized by Customer
(3)	Current Auth. Cost	(1) + (2)
(4)	Scheduled Complete Date	The Date for Project/Task Completion
(5)	% Compl.	Estimate of Project or Task Accomplished to Date
(6)	BCWS	Budgeted Costs for Work Scheduled Estimated Cost of Scheduled Work (at Reporting Date)
(7)	BCWP	Budgeted Costs for Work Performed (Completed) BCWP = % Complete * Budget at Completion/100
(8)	ACWP	Actual Cost of Work Completed Actual Cost of Work Completed (at Reporting Date)
(9)	SV	Schedule Variance SV = BCWP - BCWS
(10)	CV	Cost Variance CV = BCWP - ACWP
(11)	BAC	Budget at Completion = Current Authorized Costs
(12)	EAC	Estimate at Completion
(13)	Cost Variance	Cost Variance = BAC - EAC
(14)	Est. Complete Date	Estimated Date of Completion of Project/Task
(15)	Schedule Variance	Schedule Variance = Sched - Est. Completion Dates, Days
(16)	Action Taken	Action Code and Date Action Taken

Action Codes	
Recovery	Implemented a recovery plan that will bring costs within the contract authorization level. Mandatory to have a recovery plan if ACWP is greater than 50% of contract authorization and EAC is 10% > BAC.
Revised	Project/task has been revised and customer has authorized scope/resource change.
Notified	The program (customer) must be notified of a potential cost overrun before 75% of the authorized budget is expended. The program must decide to add resources or stop work at the authorized amount and accept delivery of work as is.
Shutdown	If ACWP > 80% of budget authorized and the EAC is 10% > BAC and the customer has been notified and has not authorized a contract change, actions must be taken to start shutting down the project to ensure that costs do not exceed the authorized contract amount. For FFP activities, a senior management review must be held to determine how to minimize cost overruns.
ECO	Engineering change orders have been negotiated with the customer and additional resources added to contract.

Table B.2 — Summary of Cost/Schedule Status Report

Column>	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	Authorization				Cumulative Date						At Completion					
Project/ Task	Contract Type	Original Auth. Cost	Auth. Cost Changes	Current Auth. Cost	Scheduled Completion Date	% Complete	BCWS	BCWP (5)*(11)/100	ACWP	SV (7) - (6)	CV (7) - (8)	BAC	EAC	Cost Variance (11) - (12)	Est. Completion Date	Schedule Variance	Action Taken

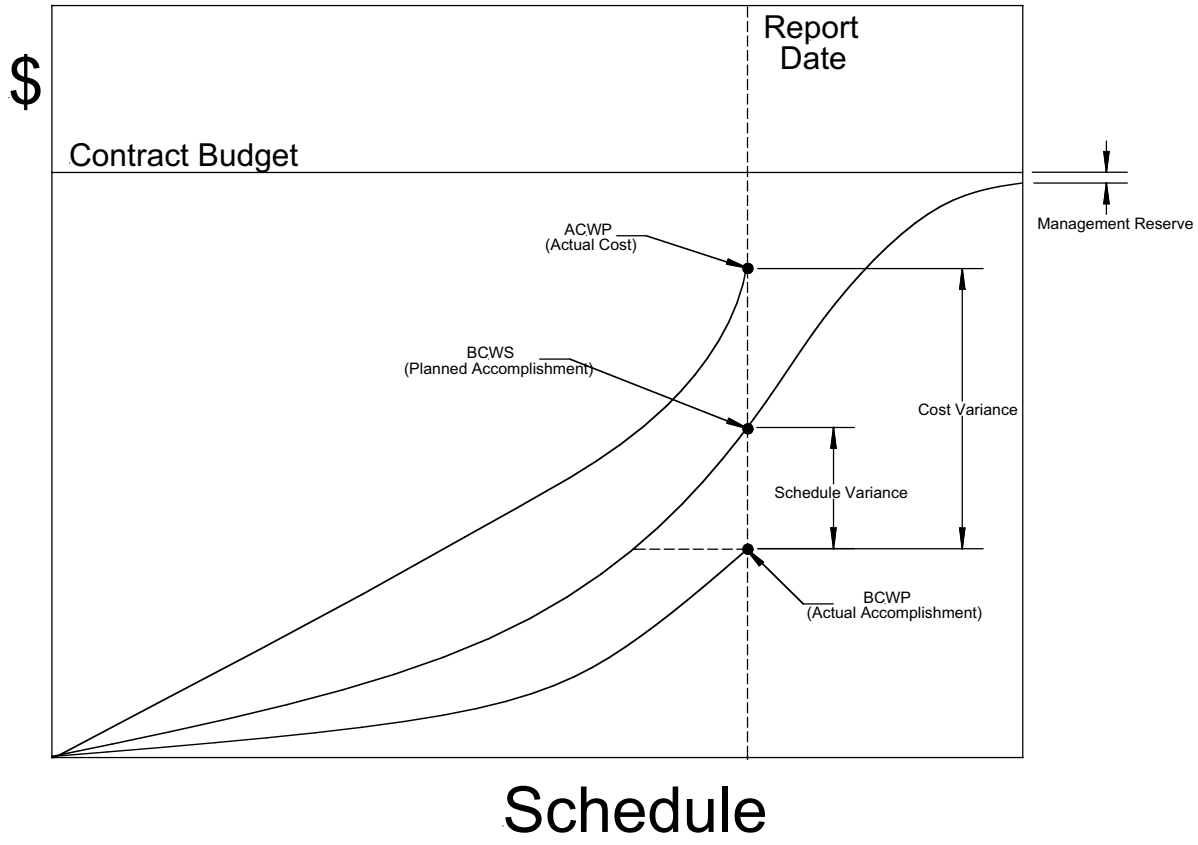


Figure B.1 — Graphic Presentation of Cost/Schedule Status

Annex C Subcontracting Mechanisms for Consideration In Test Projects

In general, using subcontractors or vendors may offer the opportunity for cost savings to a project. Vendor's ability to reduce the cost and meet schedule, and quality requirements has given rise to several qualified suppliers of wind tunnel model design and fabrication services.

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), projects that have extremely tight schedules (or are likely to change throughout the model development) may save money (and reduce risk) by using 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 projects may not be able to select the specific contract vehicle. Often, prime contracts with government agencies specify allowable subcontract mechanisms. Notwithstanding the type of contract, it is essential to maintain excellent communication with all parties, including engineering, facilities, design, and procurement.

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. Major program changes that are buyer-initiated after contract award may be accompanied by significant cost and schedule impact to the project while minor changes may be made at lower cost and possibly no schedule impact. However, a FFP can be utilized successfully in these cases by establishing good working relationships with vendors and by providing a document thoroughly describing the known and anticipated activities. The customer's ability to relate requirements to the vendor will usually be reflected in the cost quotations received. This subcontract format usually is more cost-effective when applied to more mature programs that are likely to remain relatively consistent throughout the test article development.

If a program is in early development and is likely to evolve significantly during model development, it may be more cost-effective to use a risk/cost-sharing contract vehicle such as T&M or CPFF. A 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. This must be balanced against the internal costs associated with managing a contact of this type.

If schedules are critical, the projects should consider, at the earliest possible time, formation of 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 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 in-house capability cannot support project cost and/or schedule requirements, a qualified subcontractor base must be established that will be available whenever needed. Cost and schedule impacts for various contract vehicles are as follows:

- **FFP** — Requires projects 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 proposal, (d) negotiate best and final price, and (e) award contract. Cost of competition is significant in terms of labor-hours and schedule delays during the competition phase, but is generally less than the savings generated by using the FFP. The schedule delay may vary from several weeks to several months depending on size of the procurement, but can be minimized by preparing a thorough SOW. An FFP contract will require careful tracking of SOW scope changes by both the Supplier and the Buyer.

- **T&M/CPFF** — Normally allows the projects to select one single subcontractor to support broadly defined needs by requesting submission of detailed labor-hours 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. However, these contracts provide the supplier with a somewhat “open ticket”, so their performance and accomplishments must be carefully supervised. The budget must be tracked carefully and future costs predicted to ensure that the final costs do not exceed the initial budget.

- **BOA** — Limits the subcontractor competitive field to prequalified vendors, with contract terms and conditions preset for all task/work orders. The BOA can be FFP or CPFF mixture based on program maturity. 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 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 work level (provided the vendor maintains performance with costs, schedules, 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) delay the schedule and increase cost.

Many times this final assembly occurs at the test site (to recover 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.

In summary, there is no single type of contract that fits all situations and all budgets. Each program must carefully analyze its needs and its maturity. Most vendors will work with the program to accommodate or share in the risk, provided that the contracting group or company procures services in a fair and equitable manner. No matter what type of contract is utilized, management of the subcontractor’s efforts (like they would their own) is required.

Annex D Rapid Manufacturing Techniques

Several rapid prototyping tools have significantly impacted traditional model building techniques in recent years. These include:

- Stereo lithography (SLA)
- Selective laser sintering (SLS)
- Directed light fabrication (DLF)
- Advanced casting
- High-speed machining

The following are descriptions of these techniques and processes.

Stereo lithography (SLA) parts are created by solidifying photo-reactive plastics (or epoxies) using a high-powered laser. Two-dimensional cross-section layers (from 0.003 to 0.010-in. thick) are created by directing a laser beam over the surface of a pool of liquid material. Where the laser comes in contact with the photo-reactive material, a solid is formed. By building successive layers, one on top of the other, very complex three-dimensional parts can be created. SLA components have typical manufacturing tolerances of ±0.010 in., are easily hand worked for fitting, and can be built directly from three-dimensional solid CAD models (eliminating numerically controlled machine tool programming). Unfortunately, SLA parts have low modulus of elasticity and material strength properties, limiting their use. Typical applications for SLA are parametric baseline studies of concept vehicles in near ambient temperature under low aerodynamic loads. Reduced cycles times and very low cost are the main advantages of SLA components. SLA parts can also be used when creating casting patterns (see Advanced Casting methods described in this Annex).

Selective laser sintering (SLS) is similar to SLA, but utilizes different materials. Materials vary from hard nylon and fiber-reinforced nylon to casting and soft rubber-like materials. Additionally, SLS can be used (in a several-step process) to create metal parts. Overall accuracy for SLS parts is approximately equivalent to SLA, except for metal parts. Metal parts are created by an additional step of replacing binder plastics within a matrix material with bronze in a complex arrangement of baking the SLS part in an oven and “wicking” in the bronze. Metal parts typically have overall manufacturing tolerances of approximately 0.030 in..

Directed light fabrication (DLF) is a developing technique involving high-power lasers and three-dimensional metal forming to create high-strength complex parts. Properties of this process include material strength comparable to wrought property conditions of the material, an additive process allowing complex internal features creation, tolerances of ±0.020 in., minimum size features no smaller than .040 in., and cycle times of 2 to 3 months per component. DLF is primarily still in the development/research phase and will offer a significant impact to model manufacturing in the future as the manufacturing cycle time of this process is reduced and process tolerances improved.

With the development of SLA, SLS, and similar rapid prototyping tools, the use of metal or ceramic casting has seen a significant resurgence in the fabrication of models. Using rapid, low-cost SLA or SLS patterns, castings can be made quickly and inexpensively to create highly complex metal and ceramic shapes. Accuracy for cast parts is still marginal, but cast parts can be used when high accuracy is not required, or finish machining can be done to fit cast parts to accuracy requirements. The primary advantage of casting is the ability to create very complex three-dimensional shapes very rapidly and inexpensively.

A rapid manufacturing technology in operation today is high-speed machining. Most model systems typically require numerically controlled (NC) manufacturing to create the highly contoured surfaces of model systems. Using high-speed machining, contoured metal components can be manufactured with a

50%–70% percent reduction in machine operation time and a corresponding 90% reduction in hand work (part finishing). These reductions in cycle time (and corresponding cost) can significantly improve an overall model fabrication span time (upwards of 40%) while maintaining tight dimensional tolerances (±0.003-in.) using any material.

Annex E Issues Affecting Fabrication Cost and Schedule

Various design or manufacturing issues can significantly affect test article cost and/or span time (schedule). Following are several of these key issues.

Surface treatments—Depending on requirements, there can be a multitude of surface treatments required for model systems. Surface treatments fall into two significant categories:

- Treatment required to obtain the necessary data
- Treatments required as part of the overall model fabrication strategy

Typical surface treatments mandated by test requirements include overall surface roughness and painted surfaces for global measurement techniques that include pressure and temperature-sensitive paints or flow visualization.

Overall surface roughness, usually given in micro-inches, establishes the allowable surface waviness (roughness) of the finished model or model component. Most modeling requirements utilize a reasonable compromise of 32 micro-inch finishes. However, some special model applications (such as low-turbulence boundary layer models) may require a highly polished finish, which can only be obtained by special processes. While a highly polished model looks pretty, it may not be required for a successful test, and care must be exercised not to over-specify the final surface roughness specification. Care must also be exercised to maintain dimensional accuracy when using any additional polishing processes.

Surface treatments required for fabrication processes include such things as welding, brazing, and bonding applications. Surface treatments are critical for such applications since these particular fabrication processes may be joining components that are under high load conditions, which could lead to a model failure. Other surface treatments are required to facilitate model assembly by providing different hardness and anti-galling properties between adjoining surfaces.

Technology is available today using laser energy to metallurgically join a precursor material (in the form of a slurry) with a parent material to alter the surface of the parent material while maintaining all the original mechanical properties of the parent. As an example, Chromium-rich slurry applied to the surface of mild steel and treated with the laser produces a very thin surface with the characteristics of stainless steel while the structural properties of the mild steel are retained. Many different surface properties are obtainable with a wide variety of parent materials using this technique.

Models typically require the use of fillers. Fillers are most frequently used on models to repair manufacturing errors, fill instrumentation troughs, and fill fastener holes before testing.

Primary repairs of machining imperfections (particularly gouges on external surfaces/outer mold lines) are usually accomplished using solder and welds. Solders and welds are advantageous over other methods such as epoxy fillers because of surface hardness, ductility, and the ability to re-machine and handwork to outer contour. Additionally, solder and welds match the coefficient of thermal expansion (CTE) of parent materials. This ensures that no thermal stresses develop between the parent material and the filler, preventing possible failure of models used for elevated or cryogenic environment testing. For manufacturing errors on models in which there are small errors in contour over a large area, resin systems are used due to their ease of application and ability to fair into the contour.

There are multitudes of fillers used to fill instrumentation troughs. Those include ceramics, epoxies, and resin systems. These fillers are typically chosen depending on the fabricator's familiarity with the filler and the operating requirements of the model. Ceramic fillers are commonly used for models that are tested in elevated temperature environments. Most manufacturers of ceramics fillers tailor a family of ceramics that will match the CTE of many materials, enabling them to be used on many models. A disadvantage of ceramics is they may require several applications, which may take up to a week and are substantially harder to handwork than epoxy fillers. For most models that are not tested in extreme environments, epoxy resins are the best alternative. They are easily applied and worked to contour.

The final filler requirement is after the model has been assembled and is ready for testing. Fastener holes must be filled and faired to match external shaping. The desired characteristics for fillers in this application are quick setup and low cure time. Any time used to cure the filler is time that is not used for testing. Typical fillers for this application are 5-minute epoxies, plasters, wax, and clays.

Structural bonds are commonplace in models and should be handled appropriately. Usually any design with structural bonds will include a secondary method of attachment that will prevent damage to model or facility if a bond failure occurs. Typically, structural bonds require adjoining surfaces be prepared properly to ensure maximum strength of the structural bond. Specimens should be fabricated using the same processes and tested to obtain strength data. Bond strength can vary greatly depending on bond joint thickness, surface preparation, and bond area coverage.

Fasteners are a critical component of all models and are typically some of the most highly stressed components on models. Fasteners must be checked to ensure that they meet the specified design standards. Some facilities require the test team provide certified fasteners with unbroken seals on each box. In this case, the model will be assembled (and fasteners torqued) at the facility with only the certified fasteners.

Wind tunnel models rarely involve the use of hazardous materials. However, there are exceptions. If hazardous materials are required, planning and preparation must be in place prior to model fabrication. Special handling systems, such as spray booths, respirators, disposal containers, permits, etc., may be required. Personnel screening (medical exams) and training and certification may be required. Environmental impact studies may also be required. Material Safety Data Sheets (MSDS) must be reviewed and on file. The key action for any model requirement incorporating hazardous materials is careful planning and preparation.

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