U.S. Supersonic Commercial Aircraft: Assessing NASA's High Speed Research Program

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U.S. SUPERSONIC COMMERCIAL AIRCRAFT

Assessing NASA's High Speed Research Program

Committee on High Speed Research
Aeronautics and Space Engineering Board
Commission on Engineering and Technical Systems
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Preface

The United States leads the world in the manufacture of commercial aircraft, and civil aviation is an important part of American life, providing safe travel and important economic benefits. However, the United States did not always hold this preeminent position in aeronautics, and there is no guarantee that the current success will last indefinitely. Continued leadership will depend upon many factors, including successful innovation in the design and manufacture of safe and affordable aircraft.

The National Aeronautics and Space Administration (NASA) is currently developing advanced technologies as a foundation for the next breakthrough in civil aviation: an economically viable, environmentally acceptable supersonic transport. The High Speed Research Program is working with industry to identify and address critical technological challenges that must be overcome to initiate commercial development of a practical supersonic transport.

In support of the High Speed Research Program, NASA requested that the National Research Council conduct an independent assessment of the program's planning and progress. Areas of particular interest include the ability of technologies under development to meet program goals related to noise, emissions, service life, weight, range, and payload.

In response, the National Research Council established the High Speed Research Committee. The study committee met five times between June 1996 and January 1997, collecting information, assessing relevant issues, and generating appropriate recommendations. As detailed herein, the committee concluded the High Speed Research Program is well organized and has made substantial progress. Even so, significant changes are needed to enable the program to meet its stated objectives.

Gen Ronald W. Yates, U.S. Air Force (retired)
Chairman, High Speed Research Committee

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Contents

APPENDICES

Tables, Figures, and Boxes

TABLES

FIGURES

BOX

Executive Summary

The legislatively mandated objectives of the National Aeronautics and Space Administration (NASA) include "the improvement of the usefulness, performance, speed, safety, and efficiency of aeronautical and space vehicles" and "preservation of the United States' preeminent position in aeronautics and space through research and technology development related to associated manufacturing processes." Most of NASA's activities are focused on the space-related aspects of these objectives. However, NASA also conducts important work related to aeronautics.

NASA's High Speed Research (HSR) Program is a focused technology development program intended to enable the commercial development of a high speed (i.e., supersonic) civil transport (HSCT). However, the HSR Program will *not* design or test a commercial airplane (i.e., an HSCT); it is industry's responsibility to use the results of the HSR Program to develop an HSCT.

An HSCT would be a second generation aircraft with much better performance than first generation supersonic transports (i.e., the Concorde and the Soviet Tu-144). The HSR Program is a high risk effort: success requires overcoming many challenging technical problems involving the airframe, propulsion system, and integrated aircraft. The ability to overcome all of these problems to produce an affordable HSCT is far from certain.

Phase I of the HSR Program was completed in fiscal year 1995; it produced critical information about the ability of an HSCT to satisfy environmental concerns (i.e., noise and engine emissions). Phase II (the final phase according to current plans) is scheduled for completion in 2002. Areas of primary emphasis are propulsion, airframe materials and structures, flight deck systems, aerodynamic performance, and systems integration.

The HSR Program is well managed and making excellent progress in resolving many key issues, especially with regard to predicting and reducing the potential impact of HSCTs on the environment. By 2002, the program will have resolved many of the foundational questions regarding the technical feasibility of producing an economically viable HSCT. Furthermore, the committee believes that Phase II will produce an important, broadly applicable technological legacy regardless of industry's decision about proceeding with commercial development of an HSCT.

To a large degree, the successes of the HSR Program are the result of committed program leadership that has made effective use of innovative management tools to overcome the challenges inherent in such a complex enterprise. Even so, the committee believes that significant changes are necessary for the program to achieve all of its stated objectives.

THE WAY AHEAD

The vision of the HSR Program is to "establish the technology foundation by 2002 to support the U.S. transport industry's decision for a 2006 production of an environmentally acceptable, economically viable, 300-passenger, 5,000 nautical mile (n.m.), Mach 2.4 aircraft."[1] This vision is understood by the committee to mean that the HSR Program will deliver critical technologies to support an industry decision to enter into HSCT engineering and manufacturing development in 2006. However, the committee views this vision statement as unattainable by the current program plan. It does not seem likely that industry will decide to launch a high risk, multibillion-dollar development program based on the enabling technology being developed by the HSR Program, even if concurrent HSCT development work by industry is taken into account. The committee has concluded that additional efforts are needed to address technology concerns and affordability issues more thoroughly.

In order to achieve the vision of the HSR Program, the committee believes it is essential that ongoing technology development be supplemented by corresponding technology maturation and advanced technology demonstration. These efforts are needed to adequately address issues, such as the impact of scaling to full size, systems integration, service life, and manufacturing, that current efforts will not resolve. This very significant expansion in the scope of the program cannot be accomplished in the time frame mentioned in the vision statement or with the resources currently available to the HSR Program. Thus, for a launch decision to be made, additional work is needed that cannot be accomplished by the 2002 deadline specified by the vision statement. The committee recommends the following approach to a product launch decision (see Figure ES-1).

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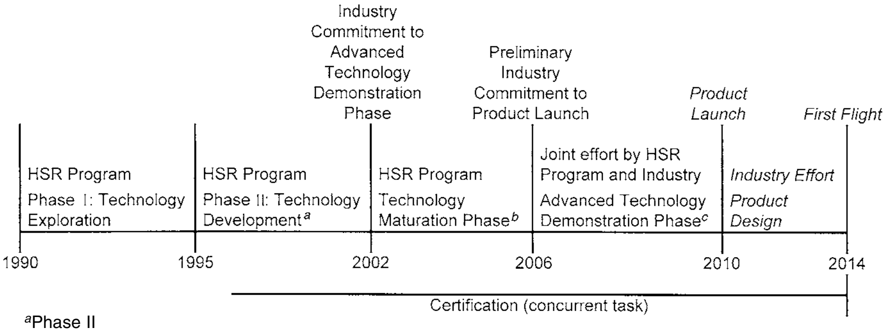
[1] By comparison, the Concorde can carry 100 passengers up to 3,000 n.m. at Mach 2.0, and it does not meet the environmental or economic goals established by the HSR Program.



[a]Phase II

- Focus more on technology development, deferring work on technology maturation, such as fabrication of full-scale components
- Focus on specific technologies related to affordability, airframe durability, APSE effects, engine service life, manufacturing and producibility, engine emissions, and range.
- Accelerate the propulsion system level of technological readiness relative to the airframe

[b]Technology Maturation Phase

- Fabricate and test full-scale demonstrator engines.
- Ground test two full-scale demonstrator engines.
- Focus on the impact of scaling to full size, integration, manufacturing and producibility, and certification planning

[c]Advanced Technology Demonstration Phase

- Flight test a full-scale advanced supersonic technology (FAST) demonstrator

FIGURE ES-1 Time line for comprehensive risk reduction program leading to program launch. Italicized program elements are industry-only efforts.

Phase II

The current Phase II program should be adjusted to sharpen the focus on technology development, especially in areas that impact affordability. Other areas of particular importance are airframe service life; dynamic interactions among the airframe, propulsion, and flight control systems; engine emissions; engine service life; manufacturing and producibility; and range. Outstanding issues in many of these areas are interrelated. For example, affordability may suffer from costs associated with proposed solutions, and development paths may be restricted by affordability concerns.

Because development of new supersonic engines almost always takes at least three years longer than development of the corresponding airframe, the Phase II program should be revised to accelerate the propulsion system's level of technological readiness relative to the airframe. In addition, to help pay for additional propulsion work, the revised Phase II program should defer work on some technology maturation issues (such as fabrication of full-scale components) that the committee believes are being addressed prematurely.

To make efficient use of available funding, Phase II should be adjusted as described above even if the recommended technology maturation and advanced technology demonstration phases are not implemented. The committee does not believe that Phase II alone can achieve the program's current goals regardless of how it is structured. The recommended changes to Phase II will maximize the quality and usefulness of its results to the eventual development of an HSCT and to other advanced aeronautics development efforts that may take place in the meantime.

Technology Maturation Phase

After Phase II, NASA should conduct a technology maturation phase that focuses on manufacturing and producibility demonstrations and ground testing of full-scale components and systems, including two full-scale demonstrator engines.

Advanced Technology Demonstration

The technical difficulty of building an economically viable HSCT is similar in magnitude to developing an advanced reusable launch vehicle, as currently envisioned by NASA. Just as flight tests of the X-33 are intended to demonstrate the feasibility of launch vehicle technology, the committee believes that flight tests of a full-scale advanced supersonic technology (FAST) demonstrator is necessary to show that the propulsion and aircraft technologies under development by the HSR Program can, in fact, be successfully integrated. Only then are they likely to be accepted as a secure foundation for launching a commercial HSCT program.

The FAST demonstrator would not be a prototype or preproduction aircraft. Instead, it would focus on the critical airframe, propulsion, and integrated aircraft technologies under development by the HSR Program. In particular, the FAST demonstrator would verify that full-scale applications of these technologies can reasonably be expected to overcome high-risk issues, such as aero/propulsive/servo/elastic (APSE) effects. Therefore, the committee recommends that NASA and industry jointly support an advanced, full-scale technology demonstration phase similar to the X-33 program. Prior to initiating the technology maturation phase, NASA and industry should each make a commitment to provide a specific level of financial support for the advanced technology demonstration phase. In addition, NASA and industry should agree on the goals and content of the advanced technology demonstration phase to ensure that the agreed-upon level of financial support will be sufficient.

The technology maturation and advanced technology demonstration phases would probably cost billions of dollars. However, even after those phases have been completed, the level of risk—and the investment required by industry to produce an operational aircraft—would still far exceed the risk and cost of any previous commercial transport development. Nonetheless, the committee believes that the FAST demonstrator would enable industry to make a program launch decision. In addition, the FAST demonstrator would serve as a classic aerodynamic demonstrator and would provide the U.S. aeronautics community with invaluable information on the utility and performance of the technologies under development by the HSR Program.

Formal product launch and product development would not occur until the end of the advanced technology demonstration phase. However, before proceeding with the advanced technology demonstration phase, industry should make a preliminary commitment to commercial development of an HSCT. Industry cofunding of the FAST demonstrator would be firm evidence of industry's confidence in its ability to use the results of the expanded HSR Program to produce a marketable HSCT.

NATIONAL IMPACT OF A SUCCESSFUL U.S. HIGH SPEED CIVIL TRANSPORT

The United States has benefited greatly from past investments in the military and civil aerospace industry. Aerospace research has created high quality jobs and stimulated advances in science and technology at many institutions of higher learning. The aerospace industry has a larger positive balance of trade than any other U.S. industry. The safety, efficiency, and affordability of the air transportation system stimulates U.S. domestic and international business and enables leisure travel, which makes an important contribution to our quality of life. Society also benefits from products and services based on aerospace technology, such as communication satellites, the Global Positioning System, and aircraft engines.

The technology being developed by the HSR Program, which could lead to development of the first economically viable supersonic transport ever built, represents another opportunity for the United States to capitalize on its leadership in aerospace technologies. Investing in advanced civil aeronautics research is especially important given recent reductions in military research. However, like many other high payoff opportunities, the HSR Program is a high risk undertaking. Success depends on a research program that properly addresses risk in all critical areas. This requires a careful and thorough effort—developing an appropriate vision, selecting system concepts and technologies necessary to achieve the vision, and executing a research program to demonstrate the technologies critical to the vision. Accordingly, the committee recommends that the HSR Program adopt a modified vision statement that focuses on the key attributes of a successful HSCT (i.e., safety, environmental acceptability, and economic viability) and provides more leeway for cost-performance trade-offs. The following example is provided for consideration:

> Develop high risk, critical, enabling technologies in conjunction with complementary industry investments to support the timely introduction of a Mach 2.0-plus HSCT. These technologies must lead to an environmentally acceptable, economically viable aircraft, with safety levels equal to or better than future subsonic transports. Successful completion of the NASA and industry programs will provide the technology foundation industry needs to proceed with the design, certification, and manufacture of an HSCT.

ADDITIONAL CHALLENGES

Dynamics of the Integrated Aircraft

The HSCT configurations being considered have a combination of structural flexibility and aerodynamic instability that, taken together, are unprecedented in aviation history. This situation raises concerns about dynamic interactions between the airframe structure, propulsion system, and flight control system. These interactions, which the committee refers to as APSE (aero/propulsive/servo/elastic) effects, will affect the HSCT in flight and on the ground. APSE effects are separate and distinct from other classic effects, such as wing flutter, and controlling them will require a tightly integrated flight-management/flight-control/propulsion-control system. Developing and certifying such a system is *completely outside industry's experience*. Addressing APSE effects will require developing analytical and test capabilities that do not exist today. Furthermore, it is possible that HSCT design requirements for dynamic performance and stability robustness may be unattainable for the conceptual aircraft design developed by the HSR Program. Clearly, controlling ASPE effects is critical to successful development of an HSCT, and the committee strongly recommends that NASA give this area increased attention and focus.

Propulsion System

The propulsion system is another very high risk area the HSR Program must address. Reducing propulsion system risk to an acceptable level is unlikely without a strenuous effort that includes tests of the following:

- a full-scale combustor early in the technology maturation phase (to validate that it can meet emission standards)
- two full-scale engines later in the technology maturation phase (to investigate interactions among engine components)
- a full-scale propulsion system (using the FAST demonstrator) during the advanced technology demonstration phase (to investigate environmental compliance and propulsion system–airframe–flight control system interactions)

Building and testing two full-scale engines during the technology maturation phase would allow the HSR Program to use one engine to focus on aerothermodynamics and aeromechanical issues, while using the other to address structures and materials issues. The second engine would also reduce risk by ensuring a backup engine would be available in case the first engine experiences a catastrophic failure. Full-scale demonstrations are also necessary to verify that proposed manufacturing processes can successfully produce HSCT components that will be unprecedented in terms of size, material composition, and/or design.

Cruise Speed

The HSR Program's decision to specify a cruise speed of Mach 2.4 greatly hampers the effort to create an affordable aircraft. Increasing cruise speed from Mach 2.0 or 2.2 to Mach 2.4 raises temperatures on the surface of the aircraft enough to require a new class of materials for the airframe. The HSR Program is making progress in the development of suitable materials, but success is still uncertain in terms of affordability, durability, maintainability, manufacturability, and availability. Furthermore, it is not clear whether the current effort to develop lower temperature materials is likely to provide a viable alternative if the effort to develop Mach 2.4 materials is not successful. Even at Mach 2.0 to 2.2, a significant materials development effort will be needed to validate the suitability of candidate materials. However, most of the current effort to develop lower temperature materials is being conducted by proprietary, industry-funded research that cannot be easily examined by NASA personnel (or this committee).

The committee did not discover sufficient evidence to support the claim that a cruise speed of Mach 2.4 would significantly enhance HSCT market demand compared to a cruise speed of Mach 2.0 to 2.2. Because economic viability is the primary variable that will ultimately determine whether industry will commit itself to commercial development of an HSCT, the committee recommends that the HSR Program take a more balanced approach that increases its effort to develop airframe materials for Mach 2.0 to 2.2.

Flight Deck Systems

Aerodynamic considerations require that a supersonic transport have a long nose that extends well beyond the front of the flight deck. This nose partly obscures the flight crew's forward visibility. This is a significant problem during approach and landing because the flight crew is unable to see the runway. Concorde supersonic transports have a moveable front section (i.e., a "droop nose") that can be lowered during approach and landing to solve this problem, but it adds significant weight and mechanical complexity to the aircraft design. The HSR Program intends to avoid these penalties by replacing the forward windows of the flight deck with artificially generated displays to create "synthetic vision." These displays are intended to provide the flight crew with superior forward visibility regardless of weather conditions. The committee believes that the flight deck technologies being considered for the HSCT have the potential to increase safety relative to the flight deck systems on existing or future subsonic transports. However, to realize that potential the HSR Program must establish improved safety throughout the flight regime as an explicit goal. The resulting increase in overall safety, especially in the terminal area, should help dispel potential concerns about the loss of forward visibility.

Supersonic Laminar Flow Control

Supersonic laminar flow control (SLFC) technology could increase aerodynamic performance of future HSCTs by 10 to 15 percent. Developing a practical SLFC aircraft is a difficult challenge that must also address manufacturing and maintenance issues. Even so, SLFC could provide an economical way to extend HSCT range. The committee recommends that NASA continue to support research in this area through the end of Phase II and beyond.

Manufacturing Technology and Durability Testing

The HSR Program should put more emphasis on manufacturing technology and service life (i.e., durability) testing for both the airframe and propulsion system. Current plans call for using surrogate materials and surrogate manufacturing processes in the full-scale tests of components of both the airframe and propulsion systems. The committee believes this will severely degrade the value of the tests, particularly with regard to durability. As indicated previously, the committee recommends postponing full-scale component testing until a future technology maturation phase. This would allow the current Phase II to develop the materials and manufacturing technology needed to conduct meaningful tests.

Technology Readiness Level

NASA has adopted a Technology Readiness Level (TRL) of 6 as a goal for the HSR Program. NASA defines a TRL of 6 as “system/subsystem model or prototype demonstrated in a relevant environment.” This seems to be the correct objective for some technologies, but not for all. In any case, not all of the technologies under development can meet this goal under the current plan because of time and/or resource constraints.

The research and development schedule for a new aircraft should ensure that all systems and technologies are ready for first flight at the same time. Some systems (such as the engines) take longer to develop, especially during the latter phases of the development process. These subsystems should be scheduled to achieve early TRL milestones before other systems, giving them a “head start.” Expecting each element of the HSR Program to achieve the same TRL at the end of Phase II is not realistic. The HSR Program should reassess the TRL goals for individual technologies in light of these concerns.

KEY PRODUCT AND PROCESS CHARACTERISTICS

Translating customer needs and objectives into key product and process characteristics (which then lead to design requirements) is essential for early technology development and product planning. This is especially true for complex systems, such as an HSCT. The committee used Quality Function Deployment (QFD) methodology for explicitly defining and prioritizing 14 customer requirements and relating them to 26 key design requirements. *The QFD analysis identified affordability as the single most critical design requirement.* The analysis identified six other areas of particular importance, which are listed below in alphabetical order (not in order of priority):

- airframe service life
- dynamic interactions among the airframe, propulsion system, and flight control system (i.e., APSE effects)
- engine emissions (i.e., ozone depletion)
- engine service life
- manufacturing and producibility (which also have a strong positive correlation with affordability)
- range

The committee recommends that the HSR Program use the QFD process to better understand the complex interdisciplinary nature of the HSR Program and the trade-offs that may be required between different design requirements. In particular, the HSR Program should ensure that current and future efforts are properly focused on the areas listed above. The HSR Program should also adopt an affordability metric—such as cost per available seat mile—that is more comprehensive than maximum takeoff weight (MTOW), which it is currently using as the primary measure of affordability. This is especially important because lightweight technologies that minimize MTOW could significantly increase total aircraft costs if they are not balanced with affordability and related factors, such as inspectability, maintainability, and repairability.

ENVIRONMENTAL IMPACT

Minimizing the environmental impact of HSCTs is an essential goal of the HSR Program. Safety and environmental standards are non-negotiable requirements that must be achieved for the program to succeed and commercial development of an HSCT to proceed. For an HSCT, the primary environmental issues are engine emissions (because of their potential impact on concentrations of stratospheric ozone) and community noise (i.e., noise during takeoff, approach, and landing—not noise associated with sonic booms).[2]

The HSR Program has made good progress in developing the basic technologies necessary to meet environmental standards, both as they currently exist and as they are expected to be modified by the time an HSCT design is ready for certification. However, it will not be possible to validate the effectiveness of

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[2] Sonic boom is less of a concern because NASA and industry agree that HSCTs will not operate supersonically over populated lands masses.

these technologies without testing full-scale, integrated systems. This will require flight tests in some cases, such as testing for community noise standards. Thus, the technology maturation and advanced technology demonstration phases are necessary to ensure that technologies developed by the HSR Program are compatible with the environment.

CONCLUSIONS

The HSR Program is complex, both technologically and organizationally. Within the HSR Program, several NASA centers, two airframe manufacturers (Boeing and McDonnell Douglas), two engine manufacturers (General Electric and Pratt & Whitney), and more than 70 other contractors are working hard to optimize a configuration baseline using joint NASA/industry assessments of technology and industry assessments of economic factors. Although industry has excellent access to NASA's work, NASA does not seem to have enough insight into industry's work. In particular, materials efforts should be better balanced so that HSR Program activities to develop Mach 2.4 materials are better coordinated with industry's internal development of materials for Mach 2.0 to 2.2. NASA and industry should develop an integrated master plan that includes development efforts by both industry and NASA and includes risk reduction paths and backup plans for critical technologies. Development of this plan should also include the Federal Aviation Administration (for certification issues).

In general, the committee finds that resource and time constraints make it unlikely that the current program will enable industry to make a product launch decision in accordance with the program's vision. Even so, the current HSR Program is making excellent progress, and additional support should enable NASA to achieve important technical objectives.

1

Introduction

The National Research Council (NRC) was chartered by the National Aeronautics and Space Administration (NASA) to conduct a focused, independent review of the High Speed Research (HSR) Program. In response, the NRC's Aeronautics and Space Engineering Board formed the High Speed Research Committee. This report is the result of the study conducted by that committee. This chapter provides an overview of the HSR Program, describes the study process, outlines the contents of the report, and previews the committee's view of how best to achieve the goals of the HSR Program.

OVERVIEW OF THE HIGH SPEED RESEARCH PROGRAM

The stated vision of the HSR Program is to "establish the technology foundation by 2002 to support the U.S. transport industry's decision for a 2006 production of an environmentally acceptable, economically viable, 300-passenger, 5,000 nautical mile (n.m.), Mach 2.4 aircraft."[1] This program vision is understood by the committee to mean that the HSR Program will deliver critical technologies to support an industry decision in 2006 to enter into engineering and manufacturing development of a commercial high speed civil transport (HSCT). The first flight could take place around 2010, and the first production airplane could be in operation around 2013.

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[1] By comparison, the Concorde can carry 100 passengers up to 3,000 n.m. at Mach 2.0, and it does not meet the environmental or economic goals established by the HSR Program.

Program Objective

The HSR Program is a high risk, focused technology program to develop enabling technologies in the areas of propulsion; airframe materials and structures; flight deck systems; aerodynamic performance; and systems integration, without which commercial HSCT development cannot succeed even for the lowest Mach numbers under consideration (i.e., Mach 2.0). NASA's legislatively mandated objectives include improving the usefulness, performance, speed, safety, and efficiency of aircraft and developing associated manufacturing processes. However, the HSR Program will *not* design or test a commercial airplane (i.e., an HSCT); it is industry's responsibility to use the results of the HSR Program to develop an HSCT.[2]

NASA and industry have a common understanding of the critical technologies that are prerequisites for initiating commercial development of an HSCT (see Figure 1-1). The committee agrees that these technologies are critical to the design of a successful HSCT. However, as discussed in Chapters 2 through 6, the committee believes there are additional technologies the HSR Program should treat as critical (e.g., technologies related to flight dynamics and control, manufacturing, and the engine).

Program Organization, Funding, and Schedule

The HSR Program is a joint research and development program involving NASA centers and industry. NASA is using no-fee contracts to fund industry. Major industry participants include Boeing and McDonnell Douglas for the airframe, General Electric and Pratt & Whitney for engine development, and Honeywell for the flight deck system. Additional participants include Lockheed Martin, Northrop Grumman, and about 70 other subcontractors. Although many of the industry participants compete against each other in some business areas, the HSR Program seems to have fostered a sense of cooperation with regard to the development of HSCT technology. This is probably because of the precompetitive nature of the HSR Program, which is many years away from commercial development. Also, the expectation is widespread that commercial development of an HSCT will involve similar teaming because of the large financial investment required. For example, General Electric and Pratt & Whitney have teamed for NASA's HSR technology program and HSCT engine development.

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[2] In this report, the term "SST" refers to first generation supersonic transports (i.e., the Concorde and the U.S. supersonic transport that was under development in the 1970s but was never fully developed); HSCT refers to the second generation aircraft that is the focus of current U.S. research and development efforts; and "supersonic commercial transport" is used as a generic term to refer to second generation supersonic transports that may be developed outside the United States. Also, in this report "HSR Program" refers to the total research and development effort funded by NASA. This includes research at both NASA and industry sites. "HSCT research" refers to separate, proprietary research and development funded and conducted solely by industry.

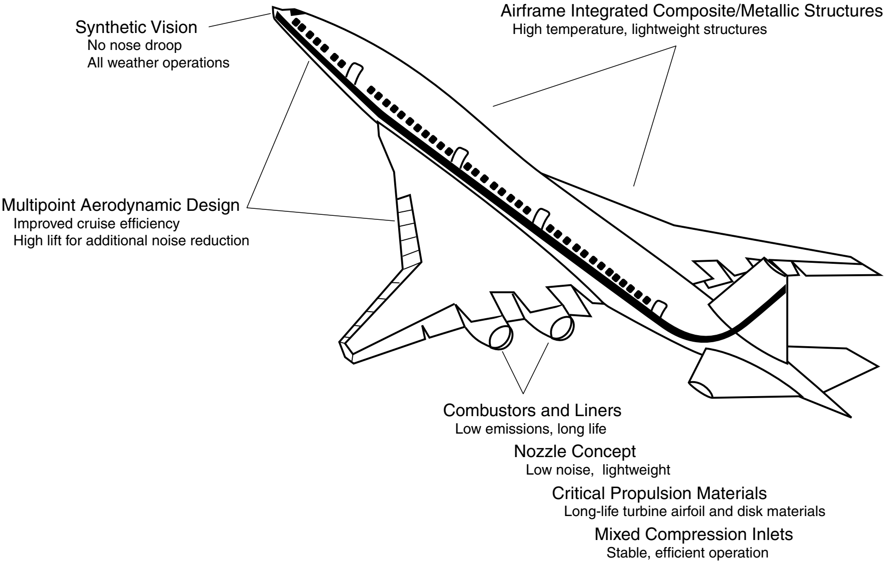


FIGURE 1-1 Critical enabling technologies for a commercially viable HSCT. Source: NASA.

The work breakdown structure for the HSR Program is shown in Table 1-1. Within NASA, about 730 NASA scientists and engineers are working on the development of HSR technology. About half of the NASA team is at Langley Research Center, a third is at Lewis Research Center, and the remainder is at Ames Research Center and Dryden Flight Research Center.

TABLE 1-1 HSR Program Work Breakdown Structure

- 1.0 Project Office Operations
- 2.0 Systems Integration
  - 2.1 Technology integration
  - 2.2 Environmental impact
  - 2.3 Environmental research and sensor technology (no longer part of the HSR Program)
  - 2.4 Tu-144
  - 2.5 Atmospheric Effects of Stratospheric Aircraft (AESA)
- 3.0 Propulsion Technology
  - 3.1 Critical propulsion components
  - 3.2 Enabling propulsion materials
- 4.0 Airframe Technology
  - 4.1 Flight deck systems
  - 4.2 Airframe materials and structures
  - 4.3 Aerodynamic performance

Source: NASA, 1997.

TABLE 1-2 Total NASA Funding for the HSR Program from Program Inception in FY 1990 through Planned Completion in FY 2002 (in millions of dollars)

Organization	FY 1990–1996	FY 1997	FY 1998–2002	Total
Lewis Research Center	442.4	110.8	273.9	827.1
Langley Research Center	345.7	112.1	318.3	776.1
Ames Research Center	84.0	17.7	43.8	145.5
Other NASA facilities	53.8	13.7	70.3	137.8
Total	925.9	254.3	706.3	1886.5

Source: NASA, 1997.

The commercial transport industry views the HSR Program as the highest priority aeronautics research program within NASA's Office of Aeronautics and Space Transportation Technology. NASA's funding for the HSR Program, from program inception in fiscal year (FY) 1990 through planned completion in FY 2002, is summarized in Table 1-2. Funding allocation among major program elements is shown in Table 1-3. In addition, Boeing and McDonnell Douglas report that they have contributed heavily to the development of HSCT technology (Henderson, 1996; MacKinnon and Bunin, 1996).

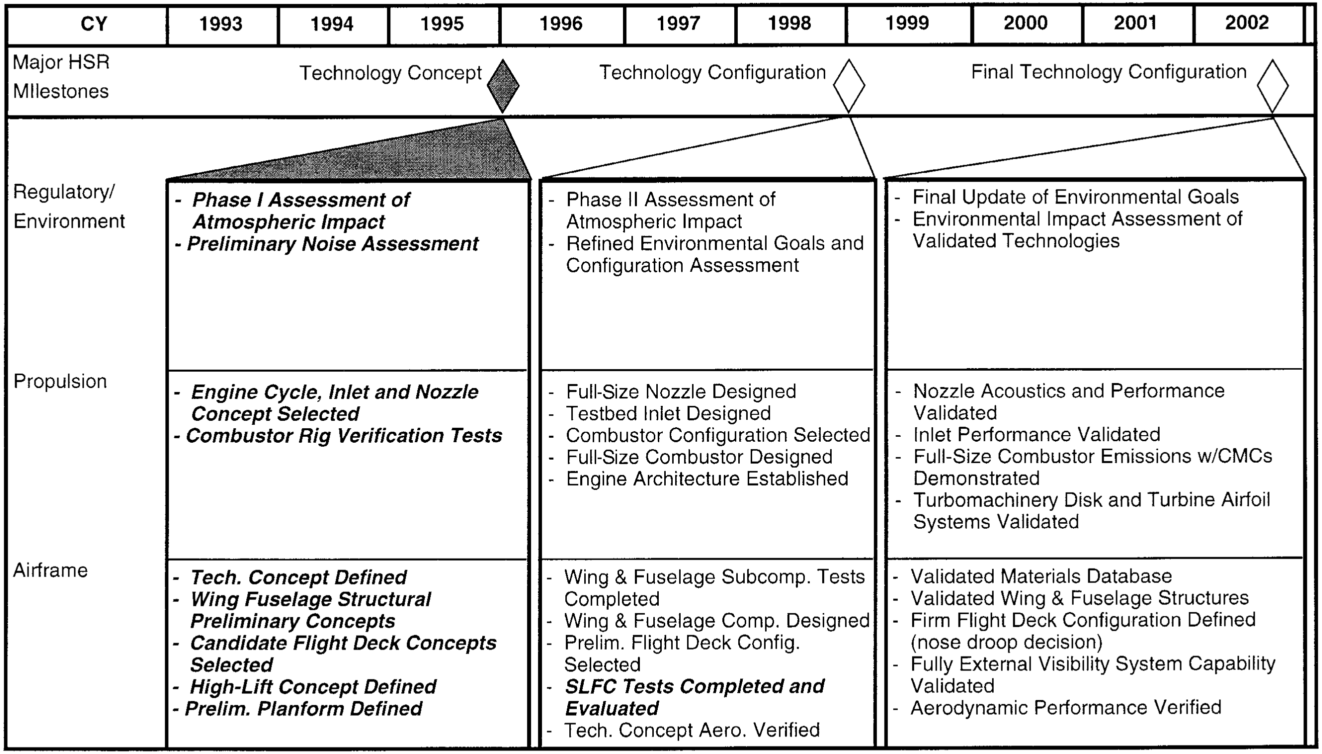
The HSR Program is divided into two phases. Phase I, completed in fiscal year 1995 with a funding level of $283 million, focused on issues of environmental compatibility. Phase II, funded through FY 2002 at $1.6 billion, is focusing on technology development. An overall program schedule, noting top level milestones and objectives, is shown in Figure 1-2.

After completion of the current Phase II program, NASA, industry, and the committee agree that additional foundational technology development and validation will be required to prepare and demonstrate that needed technologies are ready for use in a commercial transport. As discussed in the last section of this chapter and in Chapter 6, the committee is convinced that NASA can and should play a key role in this development, although NASA's involvement is currently scheduled to end at the completion of Phase II in FY 2002.

TABLE 1-3 HSR Funding Allocation by Technology (in millions of dollars)

Program Element	FY 1990–1996	FY 1997	FY 1998–2002	Total
Propulsion	459.3	114.1	312.5	885.9
Airframe	322.6	110.5	286.8	719.9
Systems Integration	144.0	29.7	107.0	280.7
Total	925.9	254.3	706.3	1,886.5

Source: NASA, 1997.



CY	1993 – 1995	1996 – 1998	1999 – 2002
Major HSR Milestones	Technology Concept ◆	Technology Configuration ◇	Final Technology Configuration ◇
Regulatory/ Environment	- ***Phase I Assessment of Atmospheric Impact*** - ***Preliminary Noise Assessment***	- Phase II Assessment of Atmospheric Impact - Refined Environmental Goals and Configuration Assessment	- Final Update of Environmental Goals - Environmental Impact Assessment of Validated Technologies
Propulsion	- ***Engine Cycle, Inlet and Nozzle Concept Selected*** - ***Combustor Rig Verification Tests***	- Full-Size Nozzle Designed - Testbed Inlet Designed - Combustor Configuration Selected - Full-Size Combustor Designed - Engine Architecture Established	- Nozzle Acoustics and Performance Validated - Inlet Performance Validated - Full-Size Combustor Emissions w/CMCs Demonstrated - Turbomachinery Disk and Turbine Airfoil Systems Validated
Airframe	- ***Tech. Concept Defined*** - ***Wing Fuselage Structural Preliminary Concepts*** - ***Candidate Flight Deck Concepts Selected*** - ***High-Lift Concept Defined*** - ***Prelim. Planform Defined***	- Wing & Fuselage Subcomp. Tests Completed - Wing & Fuselage Comp. Designed - Prelim. Flight Deck Config. Selected - ***SLFC Tests Completed and Evaluated*** - Tech. Concept Aero. Verified	- Validated Materials Database - Validated Wing & Fuselage Structures - Firm Flight Deck Configuration Defined (nose droop decision) - Fully External Visibility System Capability Validated - Aerodynamic Performance Verified

Objectives in bold italics have been completed.

FIGURE 1-2 Schedule of top-level milestones and objectives. Source: NASA.

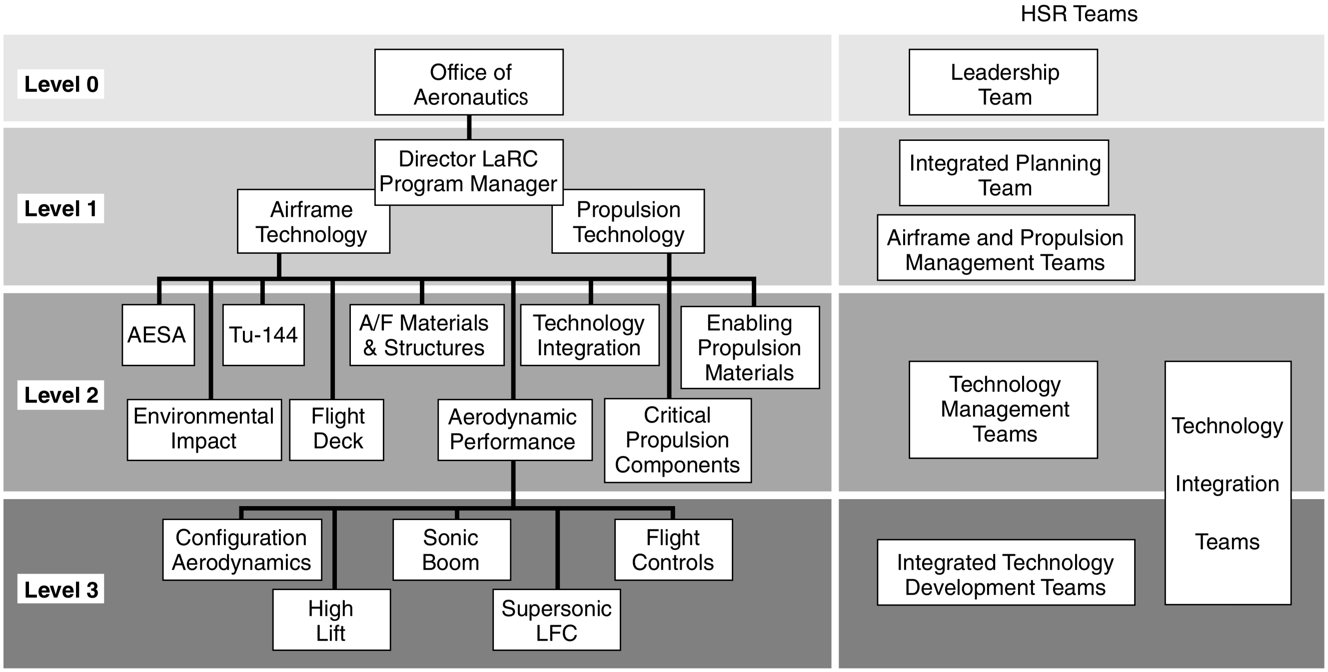


FIGURE 1-3   HSR integrated product and process team hierarchy. Source: NASA.

Program Management

The HSR Program makes extensive use of integrated product and process teams. The teams at each level consist of both NASA and industry participants, and many teams are led by industry members. Team participants have received more than 50 hours of formal training, as well as periodic refresher training in team dynamics, organizational skills, and project planning and scheduling. The four-level integrated product and process team hierarchy is shown in Figure 1-3. The Leadership Team, composed of key NASA managers and the vice presidents of the primary industry partners, is responsible for general program oversight. A total of 28 Integrated Technology Development (ITD) teams are responsible for the execution of individual technology tasks.

Figure 1-4 shows the function of the Technology Integration Team, which is composed of NASA and industry technologists with multidisciplinary expertise in analysis, integration, and optimization of individual systems and overall aircraft configurations. The goal of the Technology Integration Team is to ensure overall program integration of the HSR Program's many diverse technologies by maintaining two-way communications and coordination with the ITD teams. The Technology Integration Team serves as the overall project integrator by performing the following tasks:

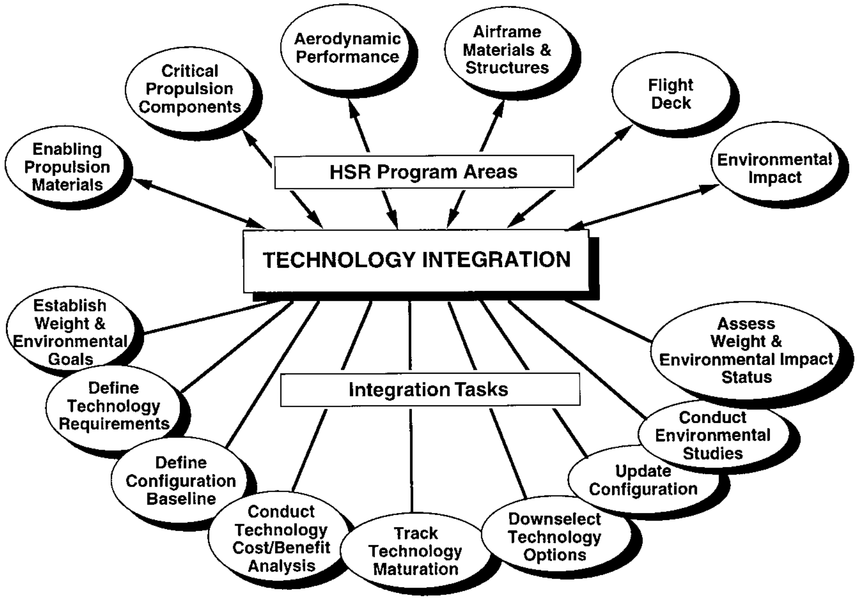
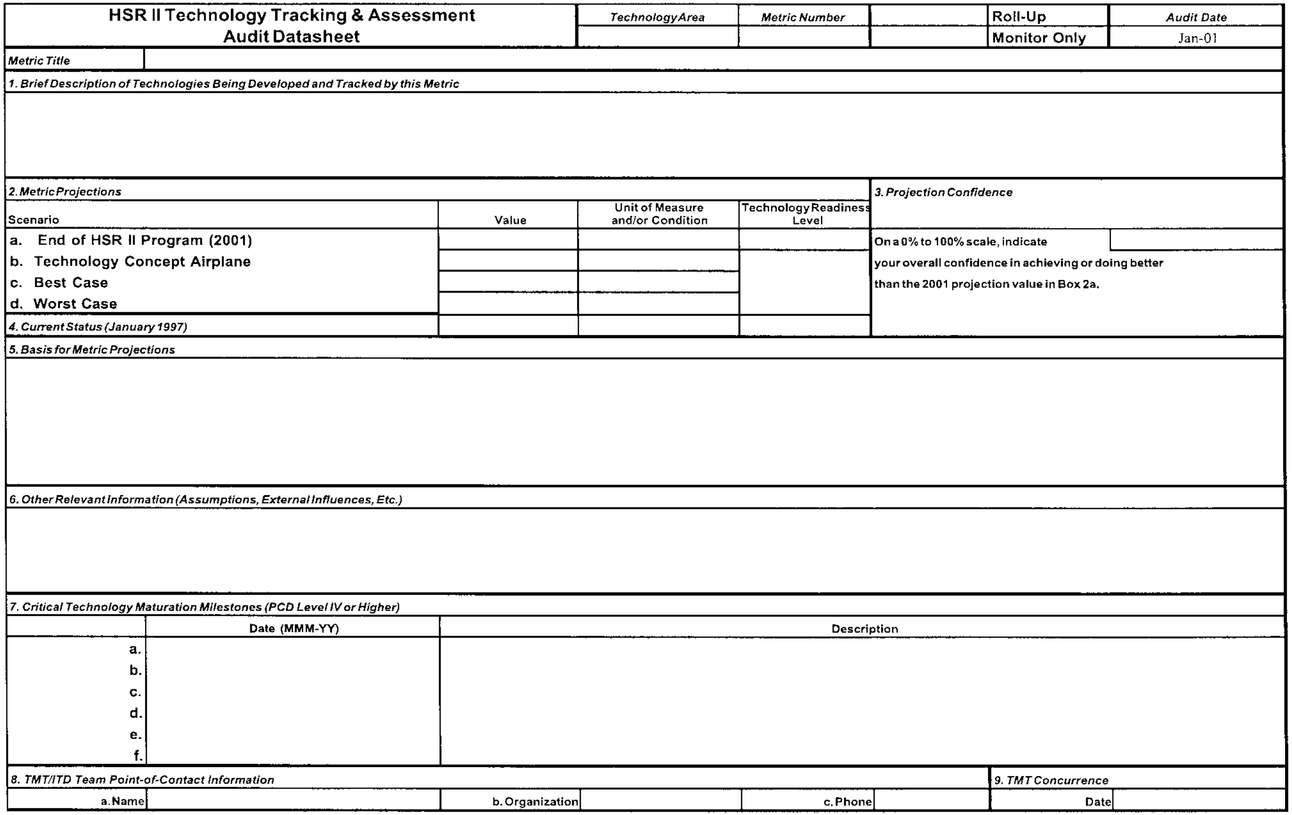


FIGURE 1-4 HSR Program technology integration. Source: NASA.



HSR II Technology Tracking & Assessment Audit Datasheet	Technology Area	Metric Number		Roll-Up	Audit Date
				Monitor Only	Jan-01

Metric Title

1. Brief Description of Technologies Being Developed and Tracked by this Metric

2. Metric Projections

Scenario	Value	Unit of Measure and/or Condition	Technology Readiness Level
a. End of HSR II Program (2001)			
b. Technology Concept Airplane			
c. Best Case			
d. Worst Case			
4. Current Status (January 1997)			

3. Projection Confidence

On a 0% to 100% scale, indicate your overall confidence in achieving or doing better than the 2001 projection value in Box 2a.

5. Basis for Metric Projections

6. Other Relevant Information (Assumptions, External Influences, Etc.)

7. Critical Technology Maturation Milestones (PCD Level IV or Higher)

	Date (MMM-YY)	Description
a.		
b.		
c.		
d.		
e.		
f.		

8. TMT/ITD Team Point-of-Contact Information

a. Name

b. Organization

c. Phone

9. TMT Concurrence

Date

FIGURE 1-5 Blank technology audit data sheet. Source: NASA.

- actively participating on other HSR technology teams
- establishing technology requirements
- assessing sensitivity to changes in requirements, technology performance, and technology readiness
- tracking the progress of technology development
- maintaining the baseline configuration
- integrating technology into the baseline configuration

Because of its many areas of responsibility, the Technology Integration Team serves as both a Level 2 and Level 3 team (see Figure 1-3).

In addition to the use of ITD teams, the HSR Program has implemented a number of innovative program and technology management tools. The ITD teams use these tools to define the total program plan—including tasks, metrics, exit criteria, schedules, and deliverables for each program element. The ITD teams use a rigorous technology auditing process to track the progress of technology development against the program plan and system requirements in terms of schedule, performance, and risk. The progress of technology development is quantified through a combination of top-level and detailed metrics. Technology tracking and assessment audit data sheets provide one-page summary assessments of each technology metric. The technology metrics and overall uncertainty analysis are used as management tools to track technology progress quantitatively, to guide future technology development, and to recommend the redirection of resources to areas that will reduce program risk the most. A blank data sheet appears in Figure 1-5.

NASA characterizes the maturity of new technology and programs in terms of Technology Readiness Levels (TRLs), which are defined in Figure 1-6. For each of the HSR Program's critical technology elements, the general goal established by the HSR Program is to demonstrate a TRL of 6: "system/subsystem model or prototype demonstrated in a relevant environment" (NASA, 1997). For each metric, the HSR Program tracks the program's current TRL and estimates the TRL at program completion in the year 2002.

In order to evaluate competing design concepts against mission requirements fairly, the HSR Program has defined a reference aircraft configuration, referred to as the Technology Concept Aircraft (TCA). This notional aircraft configuration provides the HSR Program with a common reference point for trade studies of competing system, subsystem, and component design concepts; analysis of design tools and methods; and system-level performance assessments. For example, the TCA has been used as the basis for finite-element analysis of airframe structures, materials trade studies, analysis and optimization of aerodynamic properties using computational fluid dynamics and wind tunnel testing, and technology integration trade studies.

The effort to define a viable baseline design has involved many secondary studies. For example, a study of fuels was conducted to examine the feasibility of using alternate fuels (and concluded that it is important for an HSCT to use conventional fuels that are already available at commercial airports). Details of these studies are not included in this report.

Many of the design variables specified in the TCA will continue to evolve as HSR technology matures. Multidisciplinary optimization will be used to integrate interim results and define a revised Technology Configuration (TCn) during December 1998.

The final design of an actual HSCT is expected to differ from the TCA and TCn. Boeing and McDonnell Douglas each have proprietary HSCT designs that differ from the TCA. The variations are based on internal trade studies, economic analyses, and industry-funded development beyond the scope of the HSR Program. For example, the HSR Program is not developing landing gear technology. Although clearly important to the design of an actual vehicle, the landing gear is an area where industry experience and expertise surpasses NASA's. Even so, the relevance of the TCA/TCn designs to the industry designs is assured. Industry provides direct, ongoing feedback to NASA so the TCA/TCn can be modified as necessary to preserve functional and technological links with industry designs. To continue the landing gear example, Boeing and McDonnell Douglas include a landing gear weight allowance for the TCA/TCn that is consistent with their internal designs. The same feedback mechanism ensures that the TCA structural design is compatible with design requirements related to emergency exits, seating arrangements, windows, and baggage handling.

9 – Actual system "flight proven" on operational flight
8 – Actual system completed and "flight qualified" through test and demonstration
7 – System prototype demonstrated in flight
6 – System/Subsystem (configuration) model or prototype demonstrated/validated in a relevant environment
5 – Component (or breadboard) verification in a relevant environment
4 – Component and/or breadboard test in a laboratory environment
3 – Analytical & experimental critical function or characteristic proof-of-concept or completed design
2 – Technology concept and/or application formulated (candidate selected)
1 – Basic principles observed and reported

FIGURE 1-6 Definition of TRLs. Source: NASA, 1997.

STUDY PROCESS

Statement of Task

The High Speed Research Committee was charged with the task of assessing HSR Program planning, evaluating progress to date, and recommending appropriate changes in the program. The committee determined that continuation of the HSR Program beyond the currently scheduled completion date will be required to achieve its stated objectives. Therefore, the committee's recommendations for program changes cover both the current program and the recommended continuation phases. These changes are previewed in the last section of this chapter.

As described above, the HSR Program is developing the advanced, enabling technologies that are necessary precursors to commercial development of an environmentally acceptable, economically viable supersonic transport. This study examined the technology development and the conceptual aircraft design that NASA has developed as a guide. (Assessing the proprietary HSCT designs being developed by industry was outside the scope of this study.)

The study statement of task calls for thorough investigations of the following key technical areas:

- engine emissions, fuel efficiency, service life, and weight
- community noise (i.e., noise during takeoff, approach, and landing—not noise associated with sonic booms)
- aircraft range and payload
- weight and service life of airframe structures

The statement of task also requires the committee to consider the likely market demand for HSCTs because the goal of the program is to support the development of an *economically viable* aircraft. This means the market must be large enough for industry to recoup its product development costs. Thus, the aircraft configuration selected by the HSR Program (and the technologies included in the HSR Program) must be consistent with a level of aircraft performance likely to generate a viable commercial market.

The committee reviewed the overall goals of the HSR Program to assess their relationship to the technology development effort and overall program risk. In fact, although some adjustments are suggested to mitigate that risk, a thorough reexamination and validation of program goals related to aircraft speed, range, and payload were beyond the scope of this study.

The committee also limited its deliberations to the critical, enabling technologies that are the subject of the HSR Program. For example, the noise associated with sonic booms was not included in the scope of this study because NASA and industry agree that HSCTs will not operate supersonically over populated land masses. Also, NASA plans to initiate separate research (outside the HSR Program) on softening the shock waves produced by supersonic aircraft (Sawyer, 1996). The boom-softening research by the HSR Program was closed out during FY 1995 to free funds for higher priority work. (The complete statement of task appears in Appendix C.)

Committee Operations

The High Speed Research Committee is composed of 10 members with expertise in supersonic aircraft propulsion systems, aerodynamic performance, airframe materials and structures, aircraft stability and control, flight deck systems, aircraft design, and airline operations. Biographical sketches of committee members appear in Appendix B.

To accomplish its task, the full committee met five times at Langley Research Center, Lewis Research Center, and National Research Council facilities. Small groups of committee members conducted additional fact-finding trips to Lewis Research Center, Ames Research Center, Boeing, McDonnell Douglas, and General Electric. Participants in committee meetings and trips are listed in Appendix D.

Rather than develop quantitative estimates of risk, the committee used the Quality Function Deployment (QFD) process to identify risk areas and evaluate them against the HSR Program plan. This process allowed the committee to identify areas where the level of risk was relatively high and to determine whether activities under way to mitigate those risks were appropriate for the particular risk. As described in Chapter 2, QFD is a powerful tool that identifies risk areas by comparing customer requirements to key product and process characteristics and assigning weighting factors to their interaction. The resulting matrix quickly highlights important risk areas and interrelationships. The QFD process enabled the committee to identify areas in the current HSR Program that should have greater emphasis, now and in the future.

ORGANIZATION OF THIS REPORT

The organization of this report loosely follows the HSR Program's work breakdown structure (see Table 1-1). However, it does not include a comprehensive discussion of each program activity. For example, the report does not address TU-144 flight tests; although these tests have the potential to provide valuable information, they are not central to the technical issues specified in the committee's statement of task because of fundamental differences between the design of the TU-144 and technologies under development by the HSR Program.

Chapter 2 sets the stage for the rest of the report by describing the key market drivers and system characteristics. Chapter 2 also documents the results of the committee's QFD analysis. Chapter 3 addresses key issues, findings, and recommendations pertaining to the propulsion system. Chapter 4 addresses airframe materials and structures. Chapter 5 addresses areas related to the integrated aircraft: flight deck systems; systems integration, flight dynamics, and control; community noise, certification, and airline operations. Chapter 6 concludes the report with a summary of issues related to general program planning and program execution. The appendices provide a summary list of the committee's findings and recommendations (Appendix A), member biographies (Appendix B), statement of task (Appendix C), and list of meeting participants (Appendix D).

For a period of five years, industry has limited exclusive rights to the data generated from research funded by the HSR Program. These data can be shared with other participants in the HSR Program, and NASA can use the data for its own purposes. However, they are protected from public disclosure. The committee was given access to these data and used them to formulate its findings and recommendations. However, to avoid public disclosure, limited exclusive rights data do not appear in this report.

PREVIEW OF THE WAY AHEAD

This section provides an overview of the report's major conclusions as a frame of reference for the discussions of specific program areas in Chapters 2 through 5. The stated vision for the HSR Program is to "establish the technology foundation by 2002 to support the U.S. transport industry's decision for a 2006 production of an environmentally acceptable, economically viable, 300-passenger, 5,000 n.m., Mach 2.4 aircraft." However, the committee views this vision statement as over-specified and unattainable by the current program plan.[3] It seems unlikely that industry will make a launch decision for a high risk, multi-billion-dollar development program based on the enabling technology being developed by the HSR Program, even if concurrent HSCT development work by industry is taken into account. Based on the considerations documented in Chapters 2 through 6, the committee has concluded that additional efforts are needed to address technology concerns and affordability issues more thoroughly.

In order to achieve the vision of the HSR Program, the committee believes it is essential that ongoing technology development be supplemented by corresponding technology maturation and advanced technology demonstration in the future. Continued efforts are needed to address issues, such as the impact of scaling to full size, systems integration, service life, and manufacturing, that current efforts do not adequately address. This very significant expansion in the scope of the program cannot be accomplished in the time frames in the vision statement or with the resources currently available to the HSR Program. Thus, the dilemma is that additional work will be needed before a launch decision can be made, but the work cannot be completed by the specified deadline of 2002.

Nevertheless, the current program is making valuable progress in developing important technologies. By 2002, many of the foundational questions facing the HSR Program will have been resolved. Furthermore, the committee believes

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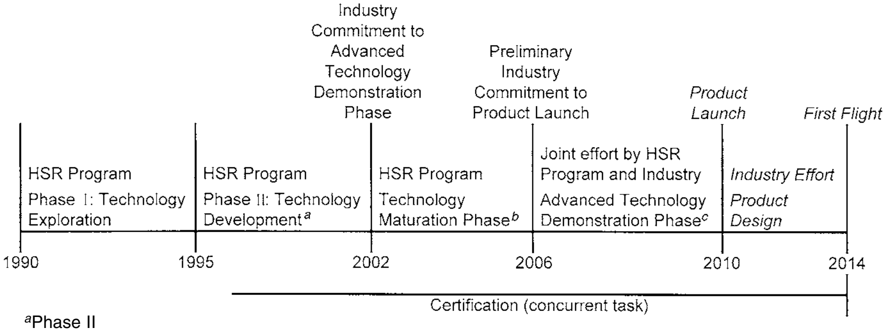
[3] A modified vision statement proposed by the committee appears in Chapter 6.



[a]Phase II

- Focus more on technology development, deferring work on technology maturation, such as fabrication of full-scale components
- Focus on specific technologies related to affordability, airframe durability, APSE effects, engine service life, manufacturing and producibility, engine emissions, and range.
- Accelerate the propulsion system level of technological readiness relative to the airframe

[b]Technology Maturation Phase

- Fabricate and test full-scale demonstrator engines.
- Ground test two full-scale demonstrator engines.
- Focus on the impact of scaling to full size, integration, manufacturing and producibility, and certification planning

[c]Advanced Technology Demonstration Phase

- Flight test a full-scale advanced supersonic technology (FAST) demonstrator

FIGURE 1-7 Time line for a comprehensive risk reduction program leading to program launch.

that much of the work scheduled for completion by 2002 will have many applications outside of the HSR Program. As further explained in the following chapters, the committee endorses the following approach to a product launch decision (Figure 1-7).

Phase II. The current Phase II program should sharpen its focus on technology development, especially in areas that impact affordability. Because the development of new supersonic engines almost always takes at least three years longer than the development of the corresponding airframe, the Phase II program should be revised to accelerate the level of technological readiness of the propulsion system relative to the airframe. In addition, the revised Phase II program should also defer work on some technology maturation issues (such as fabrication of full-scale components) that the committee believes are being addressed prematurely.

Technology Maturation Phase. After Phase II, NASA should conduct a technology maturation phase that focuses on manufacturing and producibility demonstrations and ground testing of full-scale components and systems, including two full-scale demonstrator engines. Prior to initiating the technology maturation phase, NASA and industry should both make commitments to provide a specific level of financial support for the advanced technology demonstration phase (see below). In addition, they should agree on the goals and content of the advanced technology demonstration phase to ensure that the agreed-upon level of financial support will be sufficient.

Advanced Technology Demonstration Phase. The technical difficulty of building an economically viable HSCT is similar in magnitude to developing an advanced reusable launch vehicle, as currently envisioned by NASA. Just as flight tests of the X-33 are intended to demonstrate the feasibility of launch vehicle technology, the committee believes that flight tests of a full-scale advanced supersonic technology (FAST) demonstrator will be necessary to show that the propulsion and aircraft technologies under development by the HSR Program can, in fact, be successfully integrated. Only then are they likely to be accepted as a secure foundation for the launch of a commercial HSCT program. There are some important differences between the X-33 program and the proposed advanced technology demonstration phase. For example, the X-33 program is not building a full-scale vehicle. However, the X-33 program does provide an example of NASA and industry jointly funding construction of an important technology demonstration vehicle. Therefore, the committee recommends that NASA and industry jointly support an advanced technology demonstration phase similar to the X-33 program.

After the completion of the technology maturation and advanced technology demonstration phases, the level of risk—and the investment required by industry to produce an operational aircraft—will still far exceed the risk and cost of any previous commercial transport development effort. Nonetheless, the committee believes that the FAST demonstrator would enable industry to make a launch decision. In addition, the FAST demonstrator would serve as a classic aerodynamic demonstrator and would provide the United States with invaluable information.

Formal product launch and product development would not occur until the end of the advanced technology demonstration phase. However, before proceeding with the advanced technology demonstration phase, industry should make a preliminary commitment to the commercial development of an HSCT. The requirement for industry to co-fund the FAST demonstrator would provide firm evidence of industry's confidence in its ability to use the results of the expanded HSR Program to produce a marketable HSCT.

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2

Requirements Analysis

Using the results of the HSR Program to develop an HSCT is entirely the responsibility of industry. However, the technology being developed by the HSR Program will have value only to the extent that it is relevant to design requirements for an economically viable HSCT. This chapter examines the important links between HSR technology and HSCT requirements. In particular, the chapter examines expected HSCT market demand and the key performance parameters (i.e., aircraft speed, range, and payload) that impact market demand; international aspects of HSCT development; and the results of the QFD analysis the committee used to identify key HSCT design requirements.

MARKET DEMAND

The study statement of task calls for reviewing "existing studies of the likely demands for supersonic transports in light of the dependence of these demands on aircraft characteristics." Accordingly, the committee examined the methodology used in market demand studies, the basis for key assumptions (such as fuel costs), and the areas of risk inherent in those assumptions.

An important element of the vision statement (see Chapter 1) is development of the necessary technologies for an economically viable HSCT. Economic viability means that the aircraft can be operated profitably on enough routes that the airline industry will purchase enough units to make the program profitable for the airframe and engine manufacturers. The number of routes an airline can operate profitably with an HSCT is a function of aircraft performance, cost structure, and passenger demand.

Forecasting program size is industry's responsibility because industry will be designing the actual aircraft and taking the financial risk of launching and building it. Nonetheless, these forecasts are also important to NASA and the HSR Program to ensure that funds allocated to the HSR Program are spent on technologies with an acceptable probability of commercial application and to ensure that technology development is focused on related risk areas, such as economic viability and environmental acceptability.

Forecasts of HSCT Program Size

Proponents and opponents of the HSR Program have generated vastly different estimates of program size for an HSCT. The long-term forecasting horizon creates significant uncertainty in the forecasts and contributes to differences among the estimates.

Industry has indicated that a minimum program size of approximately 300 to 500 units will be required for them to make a launch decision (MacKinnon and Bunin, 1996). The market forecasts produced by industry range from 925 aircraft (Metwally, 1996) to 1,270 aircraft (MacKinnon, 1996) through the year 2025. In other words, industry believes an economically viable market is likely to exist for an HSCT aircraft that meets the performance specifications of the TCA.

Industry forecasts are based on several assumptions that limit the number of routes considered eligible for HSCT travel. Eligible routes must allow HSCTs to provide significant time savings over subsonic flights. This occurs between city-pairs[1] connected by long-haul routes, mostly over water. (Because of sonic boom, HSCTs will cruise subsonically over populated land masses.) In some cases, routes may be altered to avoid flying over land, but such diversions should be minimal. Eligible routes must also be forecast to have sufficient passenger demand to support daily flights. Refueling stops (called technical stops in the airline industry) are assumed on routes longer than the aircraft's range of 5,000 n.m.

Underlying these forecasts is the assumption that airlines will obtain a 20 percent yield premium on HSCTs compared to subsonic aircraft. (That is, passengers will be willing to pay 20 percent more for an airline ticket on a supersonic aircraft.) This premium is needed to cover the HSCT's higher operating costs per seat mile. Industry has spent approximately $1 million on market research, including in-flight surveys and focus group discussions regarding surcharges for tickets on a supersonic aircraft. This research indicates that both business and leisure travelers would accept surcharges of up to 20 percent (relative to actual, discounted fares in any given class) to realize the time savings associated with travel on a supersonic aircraft.

The committee has reviewed industry's market forecasts, and the assumptions used appear to be reasonable for the specified time horizon and consistent

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[1] City-pairs refer to the arrival and destination airports that define a given route.

with aviation industry practice. The committee did not find any credible market forecasts that contradicted industry's forecasts. However, there are several risks or uncertainties in these forecasts.

Reliability of Market Research. The reliability of market research supporting the surcharge that passengers are willing to pay is uncertain. Travelers and corporate travel departments have never had the option of supersonic flights at an affordable price, so it is difficult for them to estimate accurately what their consumption will be. Also, the results from in-flight surveys of passengers are of limited value because many passengers do not pay for their own tickets, particularly high-fare business travelers. Focus groups with business managers were also used to examine this issue, but the results are not statistically sound.

Airline Economics. The impact of HSCTs on subsonic aircraft economics and the resulting impact on total airline system profits are not fully understood nor do they seem to be accounted for in current market forecasts. If HSCTs are not able to command the expected surcharge, airlines may be reluctant to adopt HSCTs because they may deteriorate the economics of their route systems by adding costs without adding revenue. In other words, the same revenue would be spread across a more expensive asset base.

Subsonic International Flights From Inland Cities. HSCTs will be best suited for operation to and from coastal cities. HSCT forecasts for routes between coastal cities assume that a portion of traffic transfers from connecting flights from inland cities. However, the number of inland cities with international flights has increased in recent years. Inland airports, such as Dallas/Fort Worth and Chicago, have nonstop service to Europe, Asia, and South America. Passengers in these cities will have the choice of taking a subsonic nonstop flight or a subsonic connection to a supersonic flight. Available market research does not address consumers' preferences in this situation. Increasing the range of subsonic aircraft and improving in-flight communications and entertainment may reduce passengers' perceived "lost time" during subsonic travel and mitigate their willingness to pay premium fares for supersonic speed. Current forecasts do not seem to account accurately for this competition for passengers.

Technical Stops. Technical stops can be effectively used on some long-range routes that exceed HSCT range. Even with a technical stop, the projected time savings over a subsonic flight on a transpacific route exceeds four hours—or 30 to 50 percent of the elapsed time—depending on the route. Nonetheless, technical stops may not be competitive, especially on routes like Los Angeles to Sydney on which subsonic aircraft can make the trip nonstop. A technical stop increases costs and uncertainty. The technical stop is probably not on the shortest approved nonstop route, increasing the distance of the trip. The additional takeoff and landing incurs additional landing fees and requires additional fuel and ground staff. Weather or runway conditions, air traffic congestion, or maintenance problems identified during required ground inspections can all cause delays. Thus, technical stops may be viewed as a disadvantage by both airlines and passengers, potentially reducing passenger demand on long-range HSCT routes.

Utilization. Market forecasts are based on average aircraft utilization (in terms of flight hours per day) on a few high profile routes. This may be a poor representation of the actual aircraft utilization that can be achieved for a large airline network. Lower utilization would seem to increase the number of required aircraft, but the relationship is not that simple. Lower utilization increases capital costs per seat mile, possibly reducing the number of routes an HSCT can serve profitably.

Scheduling. The method used to calculate the number of eligible routes ignores some operational and marketing constraints that affect schedules. Factors such as the availability of landing and takeoff slots, airport curfews, and marketable departure and arrival times have been analyzed only on an anecdotal basis for selected routes, not for a global airline network. These constraints may lower HSCT utilization to an unacceptable level on some routes now included in the list of profitable HSCT opportunities.

Resolving the above uncertainties will require additional studies of market demand. This will also allow the quality and reliability of market studies to keep pace with technological development. As investments by NASA and industry increase, continued market studies will confirm that the HSCT performance characteristics targeted by the HSR Program remain consistent with a viable market.

Finding 2-1. Industry forecasts of market demand indicate that an HSCT consistent with TCA performance specifications will have a market size large enough to be economically viable. The assumptions in these market forecasts appear to be reasonable, although not certain or risk free. Generalizations in the forecast assumptions may overstate the projected market size.

Recommendation 2-1. Industry should conduct further market research and simulations to reduce the uncertainties associated with current forecasts and to validate that performance specifications used by the HSR Program to guide technology development are consistent with the design of an economically viable HSCT.

Impact of Cruise Speed

The HSR vision statement specifies a cruise speed of Mach 2.4. The Concorde, designed in the 1960s, has a cruise speed of Mach 2.0. The block time (i.e., the time between leaving the gate at the departure airport and arriving at the gate of the destination airport) for a trip between Los Angeles and Tokyo with a Mach 2.4 aircraft is 35 to 45 minutes less than with a Mach 2.0 aircraft. On transatlantic routes, the difference is less noticeable: both Mach 2.0 and 2.4 aircraft can cross the Atlantic four times per day, and the difference in block times between New York and London is about 15 minutes.

TABLE 2-1 HSCT Schedule between New York City (NYC) and London Heathrow (LHR) (local times)

Mach 2.4 (Elapsed time: 3 hours, 18 minutes each way)

New York to London		London to New York	
Depart NYC	Arrive LHR	Depart LHR	Arrive NYC
8:00 (Day 1)	16:18 (Day 1)	17:50 (Day 1)	16:08 (Day 1)
22:00 (Day 1)	6:18 (Day 2)	8:00 (Day 2)	6:18 (Day 2)

Mach 2.0 (Elapsed time: 3 hours, 40 minutes each way)

New York to London		London to New York	
Depart NYC	Arrive LHR	Depart LHR	Arrive NYC
8:00 (Day 1)	16:40 (Day 1)	18:05 (Day 1)	16:45 (Day 1)
21:50 (Day 1)	6:30 (Day 2)	8:05 (Day 2)	6:30 (Day 2)

Source: MDA, 1995

Both Mach 2.0 and Mach 2.4 allow for marketable arrival and departure times on transpacific and transatlantic routes (MDA, 1995). Tables 2-1 and 2-2 show schedules for a single aircraft on these routes at Mach 2.4 and Mach 2.0. Aircraft turn times (i.e., the time between aircraft arrival and departure that allows for unloading passengers, servicing the aircraft, and boarding new passengers) are assumed to be 90 minutes at each airport. This appears to be consistent with airline industry practice for an aircraft of this size and for routes of this length.

One of the key justifications for building a Mach 2.4 HSCT, instead of a technically less challenging Mach 2.0 HSCT, is to maximize HSCT productivity in terms of passenger miles per day.[2] On the routes from the U.S. west coast to Japan, a Mach 2.4 aircraft can make four crossings in 24 hours, while a Mach 2.0 aircraft can make only three crossings. However, scheduling four crossings with a Mach 2.4 HSCT provides very little slack in the schedule to absorb delays caused by weather, congestion, or maintenance. Also, a fleet of Mach 2.0 HSCTs could be scheduled so that individual aircraft alternate between different routes, maximizing their utilization and providing a total number of seat miles that may not be significantly lower than the total number of seat miles provided by an equivalent fleet of Mach 2.4 HSCTs.

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[2] Although building a Mach 2.0 HSCT would be less challenging than building a Mach 2.4 HSCT, it would still be a formidable challenge to build a Mach 2.0 transport that can successfully compete with subsonic transports on economic terms.

TABLE 2-2 HSCT Schedule between Tokyo (NRT) and Los Angeles (LAX) (local times)

Mach 2.4 (Elapsed time: 4 hours, 29 minutes each way)

Tokyo to Los Angeles		Los Angeles to Tokyo	
Depart NRT	Arrive LAX	Depart LAX	Arrive NRT
9:00 (Day 2)	21:29 (Day 1)	23:00 (Day 1)	19:29 (Day 2)
21:00 (Day 2)	9:29 (Day 2)	11:00 (Day 2)	6:29 (Day 3)

Mach 2.0 (Elapsed time: 5 hours, 5 minutes each way)

Tokyo to Los Angeles		Los Angeles to Tokyo	
Depart NRT	Arrive LAX	Depart LAX	Arrive NRT
9:00 (Day 2)	22:05 (Day 1)[a]	23:35 (Day 1)	20:40 (Day 2)
22:10 (Day 2)	11:15 (Day 2)	12:45 (Day 2)	9:50 (Day 3)[b]

[a] The aircraft crosses the international date line during the flight and arrives on the night of the day before it left.

[b] More than one Mach 2.0 aircraft would be required to fly this pattern because the first leg of the next cycle leaves Tokyo at 9:00, before the last leg is completed—illustrating that a Mach 2.0 aircraft can complete only three crossings in a 24-hour period.

Source: MDA, 1995

Finding 2-2. From an airline scheduling perspective, an HSCT with a cruise speed as low as Mach 2.0 is likely to have productivity similar to a Mach 2.4 HSCT, assuming similar maintenance and servicing requirements.

Impact of Design Range and Payload

Aircraft range and payload correlate in an adverse way: increasing payload decreases range and vice versa. Early in the design synthesis phase, trading off range and payload is the traditional approach used to understand and evaluate aircraft design sensitivities and margins. Recently, greater emphasis has been placed on economically robust design processes, which Dieter (1991) has defined as "the systematic approach to finding *optimum values* of design factors which result in *economical designs* with *low variability*" (emphasis added). This definition and approach seem particularly applicable to the development of an HSCT.

Most recent analyses of potential HSCT designs have targeted payloads from about 200 to 350 passengers and ranges from about 4,000 to 6,500 n.m. A sensitivity analysis by Mavris, Bandte, and Sebrage (1996) shows that increasing the number of passengers from 220 to 300 would substantially increase economic performance, whereas increasing range from 5,000 to 6,500 n.m. would decrease economic performance, although not to the same degree.

A Japanese study (Mizuno et al., 1991) examined payloads of up to 400 passengers and concluded that the economic viability of a supersonic transport is not improved when the payload is increased beyond 300 passengers. As a result, that analysis focused on payloads of 200 to 300 passengers. The same study also focused on a design range up to 6,500 n.m., which would enable nonstop flights between Tokyo and New York.

The HSR Program has fixed payload and range at 300 passengers and 5,000 n.m., respectively. The nominal range of 5,000 n.m. was selected to allow a TCA-like HSCT to provide nonstop service between Los Angeles and Tokyo, based on typical assumptions for the weight of passengers and their baggage, winds aloft (which are quite low at HSCT cruise altitudes), etc. Developing a precise range estimate for the TCA is unnecessary. NASA and industry participants in the HSR Program currently work together to ensure that the technology developed in accordance with the TCA design is compatible with the separate industry designs for an HSCT. Ultimately, industry will define the range and payload of any HSCTs that are built, based on its assessments of up-to-date market analyses and technological maturity. For example, an HSCT could be designed with a smaller payload to increase range. However, for payloads of less than 250 passengers, economic viability is expected to be unsatisfactory despite the increase in range. An aircraft with longer range would be optimized for longer routes, but it would provide less-than-optimum economic performance on the larger number of routes serviceable by a 5,000 n.m. HSCT.

As illustrated by the range formula given in the aerodynamic design section of Chapter 4, either a 1 percent decrease in the lift-to-drag ratio (L/D) during supersonic cruise or a 1 percent increase in specific fuel consumption would reduce range by 1 percent. Also, because fuel weight is slightly more than 40 percent of maximum takeoff weight (MTOW) (for the TCA), and because the structural weight fraction is approximately 20 percent of MTOW, the range formula predicts that a 1 percent increase in structural weight would cause about a 0.5 percent reduction in range. Alternatively, maintaining the same range despite a 1 percent decrease in L/D would require an increase in MTOW of 8,500 pounds (about 1 percent) above the TCA's estimated MTOW of 740,000 pounds.

Another factor that complicates discussions of range is reserve fuel requirements. The TCA design includes some reserve fuel for operational diversions in case of hazardous weather at the destination airport. However, the full impact of reserve fuel requirements has not been estimated. Reserve requirements for over-ocean engine failure and cabin depressurization, in particular, have not been examined, even though they could significantly reduce the effective range of a TCA-like HSCT.

The technological challenges faced by the HSR Program are similar in magnitude to the challenges faced by development programs for highly advanced military aircraft, where experience indicates that the initial development effort does not enable new aircraft to achieve performance goals in every area. When shortfalls do occur, their impact must be managed through trade-offs with other parameters (where performance exceeds the design goal) to provide an acceptable level of overall system performance. With an HSCT, a shortfall in any of the key performance parameters (L/D, specific fuel consumption, range, structural weight fraction, or MTOW) would jeopardize overall economic viability unless one or more of the other parameters exceed their goals. And that seems unlikely because of the technical challenges that must be overcome to develop and manufacture an HSCT that meets the current goals of the HSR Program.

Finding 2-3. There is general agreement within industry and the HSR Program that a payload of about 300 passengers is required for an economically viable HSCT. A similar level of agreement does not exist regarding what design range (between 4,500 n.m. and 6,500 n.m.) will maximize economic viability.

Recommendation 2-2. The HSR Program should conduct further market research and economic simulations to capture the impact of payload and range on HSCT utilization and economics. These simulations should be based on a comprehensive analysis of specific city-pair routes rather than a top-down analysis.

Finding 2-4. Achieving the range, payload, and MTOW goals established by the HSR Program (i.e., 5,000 n.m., 300 passengers, and 740,000 pounds) depends on full attainment of goals for supersonic cruise L/D, specific fuel consumption, and structural weight fraction.

Recommendation 2-3. The HSR Program should establish design margins to allow for possible shortfalls in key performance parameters. The HSR Program should also establish a management system to make trade-offs among these parameters to maintain an acceptable level of overall system performance.

INTERNATIONAL CONSIDERATIONS

There is considerable interest around the world in developing a new, economically viable, supersonic commercial transport. In Europe, Aerospatiale, British Aerospace, and Deutsche Aerospace are working together to develop advanced technology for a supersonic commercial transport. Publicly presented concepts focus on a cruise speed of Mach 2.0, but the Europeans are also developing airframe materials for higher speeds.

The experience of the European community with certification and flight testing of the Concorde is an important advantage relative to U.S. industry. However, the Europeans do not yet have the propulsion or airframe technology needed for a Mach 2.4 transport, and developing an improved Mach 2.0 transport would still require a major financial investment. Therefore, there seems to be little likelihood that the Europeans will be ready to initiate a new supersonic commercial transport soon.

Since 1987, the Japanese Ministry of International Trade and Industry has supported technical and market feasibility studies for a supersonic commercial transport. At the 1996 World Aviation Congress, the Japan Aircraft Development Corporation (JADC) released the results of a government-supported conceptual design study that reviewed specifications for a next-generation supersonic commercial transport (Takasu et al., 1996). This study examined cruise speeds from Mach 2.0 to 2.4 and ranges from 4,000 n.m. (the minimum range for transatlantic routes) to 6,000 n.m. (to accommodate a variety of transpacific routes). Payload was fixed at 300 passengers. Design concepts for engines for Mach 2.0, 2.2, and 2.4 were developed and applied to a supersonic-commercial-transport sizing and performance-prediction tool developed by JADC. MTOW for different configurations were surveyed to find the best combination of cruise speed and range, which were determined to be Mach 2.2 and 6,000 n.m., respectively.

The JADC study selected a mixed-flow turbo-fan engine similar to the baseline engine concept selected by the HSR Program (see Chapter 3). JADC estimated that MTOW could be minimized by using an engine bypass ratio of 0.7 to 1.0 for a Mach 2.0 aircraft, or 0.4 to 0.5 for Mach 2.4. (Lower bypass ratios are necessary to maximize specific fuel consumption at higher speeds. The bypass ratios used by an HSCT engine will probably be similar.)

It is interesting to note that JADC could not find a combination of wing planform (i.e., wing cross section) and engine thrust for a Mach 2.4, 6,000 n.m. aircraft that did not exceed a maximum takeoff distance of 11,000 feet.[3] This indicates that additional enabling technologies are needed to reduce MTOW for a Mach 2.4, 6,000 n.m. design.

JADC recommended using the study results as the basis for market research that could optimize aircraft performance parameters in terms of economic viability. Future work planned by JADC includes flight tests using subscale models launched from a subsonic aircraft.

Elsewhere in the Pacific rim, China, South Korea, Taiwan, and Indonesia also have the potential to participate in development of a supersonic commercial transport. These countries have strong and growing economies, and they are interested in developing their aerospace industries. For example, Korean manufacturers already rank twenty-first in aerospace trade, and the Korean government has ambitions of reaching the top 10 by the year 2000.

Finding 2-5. Europe has the technical expertise to compete in developing a next-generation supersonic commercial transport. Japan and other Pacific rim countries

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[3] Based on the length of runways at existing airports, a maximum takeoff distance of 11,000 feet is a practical constraint. This constraint is also accepted by the HSR Program and U.S. industry.

could contribute financially and, to a lesser extent, technically. Because of technical challenges and financial requirements, it seems unlikely that foreign interests will initiate a program to develop an economically viable supersonic commercial transport during the next 5 to 10 years. However, political factors could spur earlier action.

Recommendation 2-4. NASA should continue to track the development of supersonic commercial transport technology worldwide.

KEY PRODUCT AND PROCESS CHARACTERISTICS

Translating customer needs and objectives into key product and process characteristics (which then lead to design requirements) is essential for early product planning (including technology development). This is especially true for complex systems like an HSCT. The committee used the QFD (Quality Function Deployment) methodology for defining and prioritizing customer requirements and relating them to key design requirements. QFD is a way of making the "voice of the customer" heard throughout an organization.

Description of the QFD Matrix

A QFD matrix is sometimes called a "house of quality" because of its house-shaped structure. The structure has various "rooms" as illustrated in the HSCT/HSR QFD product planning matrix (see Figure 2-1).

Customer Requirements and Importance

Customer requirements (the "whats") appear in the left side room (Room 1) of Figure 2-1. The committee established four categories of major customers for the HSR Program and, ultimately, for the HSCT that will incorporate the results of the HSR Program. The four customers are society, manufacturers, airlines, and passengers. Society's major requirements concern safety, noise, and emissions; major requirements of the manufacturers (primarily, the airframe and propulsion system manufacturers) are mature technology and return on investment; major airline requirements are airport compatibility, direct operating costs, acquisition cost, economic range, and payload (i.e., number of passengers); and major passenger requirements are comfort, ticket price, dispatch reliability, and time savings/schedule.

The column next to the customer requirements room is the customer importance room. The importance rating (1 through 5) is typically based on customer surveys. For this study, members of the committee provided this input, along with airline and FAA personnel who participated in study meetings. The committee rated the following areas as the highest priority customer requirements:

- society: safety, noise, and emissions
- manufacturers: mature technology and return on investment
- airlines: direct operating costs
- passengers: ticket price and time savings/schedule

Design Requirements

Design requirements are specified as key product and process characteristics (the "hows") in the upper center room (Room 2) of Figure 2-1. The key product and process characteristics are grouped into three major categories: propulsion technologies, airframe technologies, and integrated aircraft. (These categories correspond to Chapters 3, 4, and 5 of this report and roughly correspond to the organizational structure of the HSR Program.)

Wherever practical, the committee used characteristics in the QFD matrix that are also being tracked by the HSR Program. However, in some cases the characteristics used by the committee are at a higher level, as in the propulsion technologies category. More importantly, the committee has included additional characteristics. Many of these, such as certification, manufacturing, utilization, and affordability, are related to processes that can only be addressed by a combination of technologies.

QFD methodology requires selecting key product and process characteristics that can be quantitatively measured. Target values for each characteristic are located a row below Room 1 labeled "HSR Technology Targets, End of Phase II."

The committee included MTOW and affordability as characteristics of the final technology configuration because the committee believes that minimizing MTOW by itself is not sufficient to meet the program objective of developing technology that will lead to an economically viable HSCT. The committee endorses the view of the Boeing chief executive officer that "enabling technologies must be developed to permit the airplane to be built at affordable costs" (Condit, 1996).

Cost per available seat mile is a useful measure of affordability. The committee estimates that a cost of less than 7.8 cents per available seat mile would accommodate a fare surcharge of 20 to 30 percent relative to the fares for future subsonic transports.

Risk Levels

Immediately below Room 1 (the customer requirements room) of Figure 2-1, is a row labeled "Risk Level." The perceived risk level is a function of (1) the probability that the HSR Program will fail to reach the specified technology target value by the end of Phase II with a TRL (Technology Readiness Level) of 6 and (2) the impact that failure would have on the development of a successful HSCT. To indicate areas of high risk clearly, the committee used a nonlinear

FIGURE 2-1 FOLDOUT

FIGURE 2-1 HSCT/HSR QFD product planning matrix.

FIGURE 2-1 FOLDOUT

TABLE 2-3 Risk-Weighting Factors

Perceived Level of Risk	Risk-Weighting Factor
low	1
low-medium	2
medium	3
medium to high	5
high	9

weighting scale (see Table 2-3). This scale helped to illuminate high risk characteristics, such as environmental constraints, and to identify clearly the key product and process characteristics. The risk levels in Figure 2-1 are based on information provided by the HSR Program, as modified by the committee's assessment of current risk for each product and process characteristic.

Finding 2-6. The key product and process characteristics with the highest risk are engine emissions, engine service life, airframe service life, range, affordability, community noise, APSE (aero/propulsive/servo/elastic) phenomena,[4] and manufacturability.[5]

Relationships

The center room, called the relationship room, shows the relationships between all the "whats" and "hows." To determine the strength of a relationship, the committee considered the impact that achieving a specific product or process characteristic would have on the customer's assessment of how well a specific customer requirement had been satisfied. One of three relationship symbols is used to define the strength of a relationship: a filled circle implies a *strong* relationship; an empty circle implies a *medium* relationship; and a triangle implies a *weak* relationship. No symbol appears if there is no relationship.

The triangular "roof" of the QFD matrix, called the correlation room, is used to identify correlations between pairs of product and process characteristics. A filled circle implies a *strong positive* correlation; an empty circle implies a *weak positive* correlation; an "X" implies a *weak negative* or adverse correlation; and an "XX" implies a *strong negative* or adverse correlation. If there is no correlation, the space is blank.

Negative correlations identify where trade-off decisions may be needed because of conflicts between individual product and process characteristics. In other

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[4] APSE phenomenon are associated with the highly interactive, dynamic nature of the HSCT airframe, propulsion, and flight control systems. See Chapter 5.

[5] These characteristics are listed in the order they appear in Figure 2-1.

words, it may be possible to accomplish one product or process characteristic only at the expense of another. If a strong negative correlation cannot be eliminated, research may be needed to reduce the strength of the correlation.

The row directly below the roof indicates whether an increase or decrease in numerical value of each process or product characteristic would be beneficial. The information in this row is important for clarifying whether the correlations between the characteristics in the roof are positive (reinforcing) or negative (adverse). Three of the characteristics (range, payload, and cruise Mach number) have circles rather than arrows because the HSR Program has fixed these values.

The roof of Figure 2-1 illustrates the importance of the process characteristics (certification, manufacturing, utilization, and affordability). Most HSCT product characteristics have a strong relationship with one or more of the four process characteristics.

Finding 2-7. Most of the advanced technologies the HSR Program is developing to support an HSCT product launch decision are very process dependent, especially from the point of view of affordability.

Absolute and Risk-Weighted Importance

The "Absolute Importance" row near the bottom of the QFD matrix is used to record the calculated values indicating the importance of each product and process characteristic. The absolute importance of each characteristic is calculated as follows:

1. In the relationship room, a strong relationship (a filled circle) is assigned a numerical weight of 9, a medium relationship (empty circle) is assigned a numerical weight of 3, and a weak relationship (triangle) is assigned a numerical weight of 1.
2. The importance of each customer requirement (1 through 5) is multiplied by the appropriate weighting factor (1, 3, or 9) in the relationship room (based on the strength of the relationship between the customer requirement and the key product and process characteristic of interest).
3. The results of steps 1 and 2 (for every customer requirement that has a relationship with the key product and process characteristic of interest) are then added.

The resulting levels of absolute importance do not reflect the risk levels for each key product and process characteristic. The "Risk-Weighted Importance" row corrects this. Risk-weighted importance is calculated by multiplying the absolute importance of each key product and process characteristic by its assigned risk level. The key product and process characteristics from Figure 2-1 are ranked according to risk-weighted importance in Table 2-4. The ranking based on absolute importance is also listed in Table 2-4.

TABLE 2-4 Key Product and Process Characteristics Ranked by Risk-Weighted Importance

Characteristic	Risk-Weighted Importance Score	Absolute Importance Ranking
1. Affordability	3006	2
2. Manufacturing and Producibility	2745	6
3. Range	2718	7
4. Airframe Service Life	2601	9
5. Engine Emissions	2565	10
6. Engine Service Life	2529	12
7. APSE	2466	13
8. Supersonic L/D	1780	1
9. Cruise Speed	1670	3
10. Community Noise	1620	24
11. MTOW	1600	4
12. Structural Weight Fraction[a]	1565	5
13. Engine Reliability	1330	15
14. Thrust/Weight Ratio	1285	16
15. Multi-Loop Stability Robustness	1265	17
16. Handling Qualities	1200	18
17. Fuel Efficiency	1055	20
18. Flight Deck System Software Development Cost	1050	21
19. Traffic Avoidance	930	25
20. Payload	906	8
21. Certification	852	11
22. Utilization	822	14
23. High Lift L/D	678	19
24. Subsonic L/D	597	22
25. Flight Deck System Weight Savings	588	23
26. Fan Containment Weight	184	26

[a] Structural weight fraction is the ratio of the weight of the airframe structure to the total weight of the aircraft (MTOW).

Results of the QFD Assessment

The scores in Table 2-4 indicate that risk-weighted importance divides key product and process characteristics into three groups of about the same size. In the most important group, affordability stands alone as the single most important characteristic. As shown in the "roof" of the QFD matrix, affordability is related to most other key product and process characteristics. Thus, even though some characteristics, such as certification and utilization, individually have low risk-weighted importance, their cumulative impact is reflected in the high importance of affordability. In the least important group, fan containment weight takes a distant last place in both absolute and risk-weighted importance.

Much of the information used to complete a QFD matrix is subjective, especially where there is little or no objective data available. For example, the committee did not have the resources to conduct surveys of customer requirements. Nevertheless, the committee believes the results are generally valid and support the findings and recommendations that appear elsewhere in this report. Even so, the importance rankings should not be considered entirely objective.

In many cases, the results of the committee's QFD analysis are driven by the values assigned by the HSR Program to the top-level aircraft performance requirements: cruise speed of Mach 2.4, range of 5,000 n.m., and payload of 300 passengers. For example, a cruise speed of Mach 2.4 mandates the use of unproven materials for the airframe structure. With a lower cruise speed, using less risky materials would probably remove airframe service life from the most important group in Table 2-4.

A more sophisticated QFD analysis could be used to provide additional insights into product and process relationships. For example, a two-stage approach could be used. One QFD matrix could examine the relationship between (1) customer requirements and (2) propulsion and airframe design requirements. A second QFD matrix could use propulsion and airframe requirements as customer requirements and relate them to integrated aircraft design requirements (range, payload, MTOW, affordability, etc.). This two-stage analysis could provide a more accurate assessment of key product and process characteristics for the integrated aircraft.

Recommendation 2-5. The HSR Program's Integrated Planning Team should use the HSR/HSCT QFD planning matrix in Figure 2-1 to examine the complex interdisciplinary nature of the HSR Program and the trade-offs that may be required among design requirements.

Recommendation 2-6. The HSR Program should ensure that current and future efforts are properly focused on the most important, highest risk areas. The single most critical design requirement is *affordability*, and the HSR Program should adopt an affordability metric—such as average yield per available seat mile—that is more comprehensive than MTOW. The other areas of greatest importance, many of which are closely linked to affordability, are as follows:

- airframe service life (durability)
- dynamic interactions among the airframe, propulsion, and flight control systems (i.e., APSE effects)
- engine emissions (ozone depletion)
- engine service life
- manufacturing and producibility
- range

MARKET, TECHNOLOGY, AND FINANCIAL RISKS

Before making a product launch decision, industry must determine that the technological, market, and financial risks are acceptable. Technological risk is the risk that efforts to develop new technologies will not yield anticipated results. A new technology may fail altogether, may not perform to specification, or may be too expensive to be profitable. Technological risk has traditionally been a relatively minor concern for commercial aircraft programs because they have drawn on proven military aircraft technologies. However, developing an HSCT will require many technological advances that have no parallel in military aircraft design. For example, there are no supersonic military transports; supersonic military aircraft do not have the long-range, supersonic cruise capability that will be essential for an HSCT.

Market risk is the risk that new aircraft will not sell as well as expected. The market success of an HSCT will depend upon its high productivity on relatively long, over-ocean flights. For a given seating capacity and utilization (flight hours per day), the supersonic speed of an HSCT produces higher productivity (passenger miles per day) than subsonic transports. The profitability of HSCTs will also depend upon the number of suitable routes, payload (seating capacity), fuel efficiency (at supersonic and subsonic speeds), acquisition costs, and operating costs. For example, the relatively low subsonic fuel efficiency and low seating capacity of the Concorde have contributed to its high cost per seat mile.

Financial risk is the risk of receiving an unsatisfactorily low return (or a loss) on investment. Both technological development and market trends will influence levels of return. Thus, financial risk captures the influence of both technological and market risk (see Figure 2-2). Because developing a new aircraft requires a large investment before sales generate any revenue, it can take 10 to 15 years to recover the initial investment, even for an aircraft that sells well (OTA, 1980).

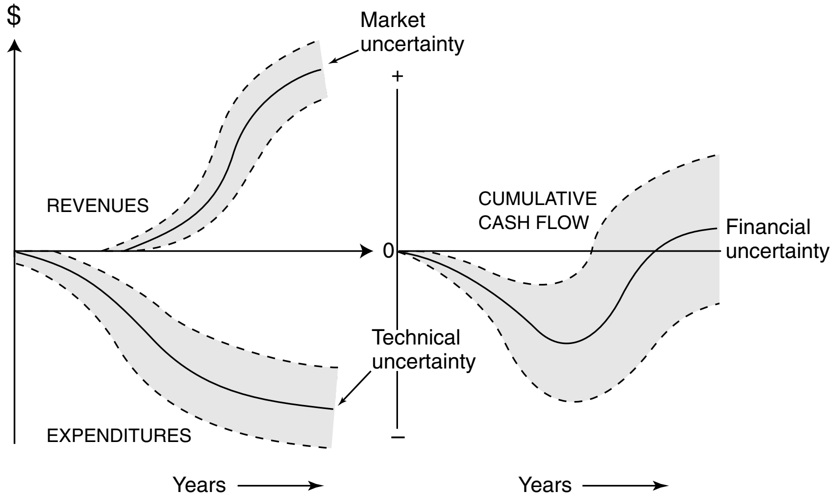

FIGURE 2-2 Market, technology, and financial uncertainties. Source: OTA, 1980.

The HSR Program is focusing on research and development to overcome the technological challenges associated with a conceptual aircraft design (the TCA). Considerably higher costs are likely to result if industry decides to develop an operational HSCT. Industry would need to include full-scale manufacturing processes and the associated capital equipment costs. However, as illustrated in the roof of the HSR/HSCT QFD product planning matrix (Figure 2-1), there are strong negative (adverse) correlations between many of the propulsion and airframe product technologies and the integrated aircraft process technologies, such as manufacturing/producibility and certification. The resulting technological risk, together with market risk, make it quite unlikely that HSCT airframe and engine manufacturers will make a product launch decision in 2006, based on the deliverables the HSR Program plans to make available before the program terminates in 2002.

Finding 2-8. The strong negative (adverse) relationships among high-priority design requirements and the risks associated with these requirements (especially with regard to affordability) support the committee's recommendation for a substantial effort beyond the current Phase II.[6]

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[6] See Chapters 1 and 6.

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3

Propulsion

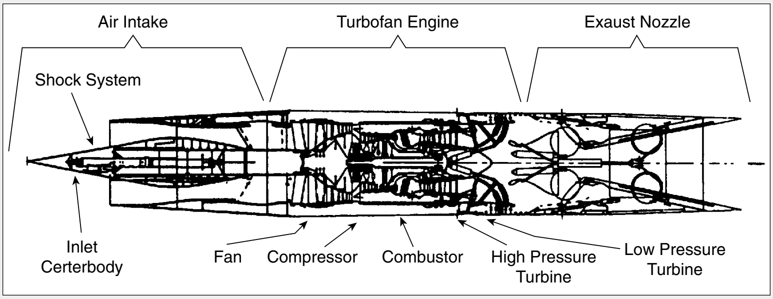
Developing a propulsion system for an HSCT will be more technically challenging than for any other civil aircraft engine ever attempted. Generating an economically viable design is a daunting problem for propulsion scientists and engineers. Revolutionary advances, especially in engine materials and combustor technology, will be required to design a propulsion system that satisfies performance requirements in terms of emissions, noise, vibration, thrust, weight, fuel efficiency, service life (durability), and reliability. The manufacturing technology base will be significantly challenged as well, given the physical size of the engine components and the need to provide production quantities of materials that do not yet exist. Box 3-1 describes a conceptual propulsion system.

Phase I of the HSR Program, which has been completed, focused on defining critical environmental compatibility requirements with regard to noise and emissions. Phase II, which will continue through 2002, is concentrating on enabling propulsion materials, critical propulsion components, and propulsion system technology integration. In other words, Phase II—in conjunction with separate HSCT development by industry—is intended to provide a propulsion technology base for full-scale engineering and manufacturing development shortly after the turn of the century.

Many supersonic aircraft, including the SR-71 Blackbird and Concorde, are powered by turbojets with afterburners. These aircraft were designed at a time when turbofan technology was relatively immature, and afterburners (which are fuel inefficient) were needed to meet performance requirements. After evaluating the capabilities of modern engine technology, the HSR Program selected low-bypass turbofan engines as the primary engine concept. The small amount of bypass air provides cooling to the region exterior to the engine and improves

BOX 3-1
Conceptual Propulsion System

A conceptual propulsion system suitable for a supersonic commercial transport such as the HSCT is shown in the drawing below. The main elements of the system are the mixed compression air intake, turbofan engine, and convergent-divergent ejector-type exhaust nozzle.



Conceptual propulsion system for a supersonic commercial transport. Source: NASA.

The air intake is axisymmetric. The movable "centerbody" controls the position of the oblique shock waves, which compress the air flowing into the inlet duct. Air flow compression through the inlet duct is terminated with a normal shock, which allows subsonic flow into the diffuser. The subsonic diffuser further reduces the flow velocity for entry into the main engine.

Engine "unstart" is an operational problem that occurs when air flow disturbances at the propulsion system inlet move the shock system out of the inlet duct. When that happens, inlet compression is reduced, and thrust is suddenly reduced to a small fraction (less then half) of its previous value. Restoration of full power requires reducing flow disturbances to move the inlet shock waves back into position.

The turbofan engine consists of a fan section, compressor section, combustor, high pressure turbine, and low pressure turbine. The air flow is compressed through the fan and split into two parts. The bypass air flows through the fan duct. The core flow passes into the core engine, where it is further compressed in the compressor. The core flow then passes into the combustor where it is mixed with fuel and burned.

Unlike combustors on conventional engines, an HSCT combustor will likely use staged burning of fuel to minimize emissions. For example, a rich fuel-air mixture could be burned in the first stage. For the second

continued

BOX 3-1—continued

stage, additional air could be added to enable combustion of fuel remaining from the first stage.

The core air flow then passes through the turbine section of the engine. The mechanical energy produced in the high pressure turbine turns the compressor through a shaft, and the mechanical energy produced in the low pressure turbine turns the fan. Air flow from the core and fan duct then mix in the exhaust section of the engine and pass into the exhaust nozzle.

The exhaust nozzle shown is an ejector type, with a convergent section and a divergent section to maximize thrust produced by the exhaust gases. The ejector feature draws in outside air to reduce exhaust velocity and thereby reduce noise during takeoff and climb-out, the phases of flight where noise standards are hardest to meet.

subsonic fuel efficiency. Also, because the amount of bypass air is low, supersonic performance approaches that of a turbojet (which has no bypass air).

Each HSCT propulsion system unit—which consists of an air intake, turbofan engine, and exhaust nozzle—would be about 50 feet long, weigh 8 or 9 tons, and produce on the order of 60,000 pounds of thrust. (Figure 3-1 illustrates the size of an HSCT propulsion system.) The design of the TCA (Technology Concept Aircraft) has four of these units, two under each wing. The TCA is not intended to serve as the design for a production HSCT, but it does allow propulsion technologists to design experimental hardware close in size to a production HSCT engine.

The most critical engine technologies, which require revolutionary advances, are in the materials and combustor areas. The economic viability of an HSCT

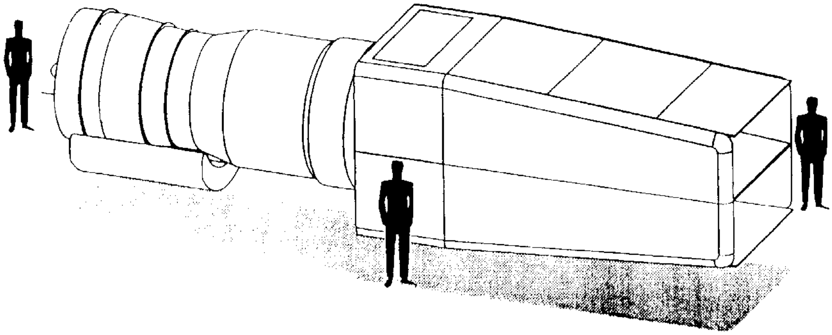


FIGURE 3-1 Conceptual HSCT engine and nozzle (without air intake). Source: NASA.

propulsion system will depend on lightweight, high-temperature materials that have not yet been developed. For example, meeting the stringent noise restrictions for commercial aircraft will require revolutionary lightweight materials and structures that can be fabricated into a long-life, low-noise, ejector-type exhaust nozzle. Also, achieving engine emission goals will require entirely new concepts in combustor design. In addition, very challenging advances of an evolutionary nature will be needed throughout the engine to meet overall HSCT weight and performance requirements. This chapter examines these technical issues; program planning and execution are discussed in Chapter 6.

CRITICAL PROPULSION MATERIALS

This section discusses critical materials issues the HSR Program is addressing to enable development of turbine airfoils and disks for the compressor and turbine sections (see Figure 3-2). The materials and associated manufacturing demands for combustor and exhaust nozzle components are addressed later in this chapter.

Two fundamental factors must be recognized to appreciate the material and manufacturing challenges of developing HSCT propulsion system components. First, individual components will be much larger than propulsion system components currently used in military or commercial aircraft. (The technology used in the Concorde's Olympus engines is generally incompatible with the weight, noise, and emission requirements an HSCT propulsion system will need to meet.) Second, HSCT propulsion system components will be required to operate at

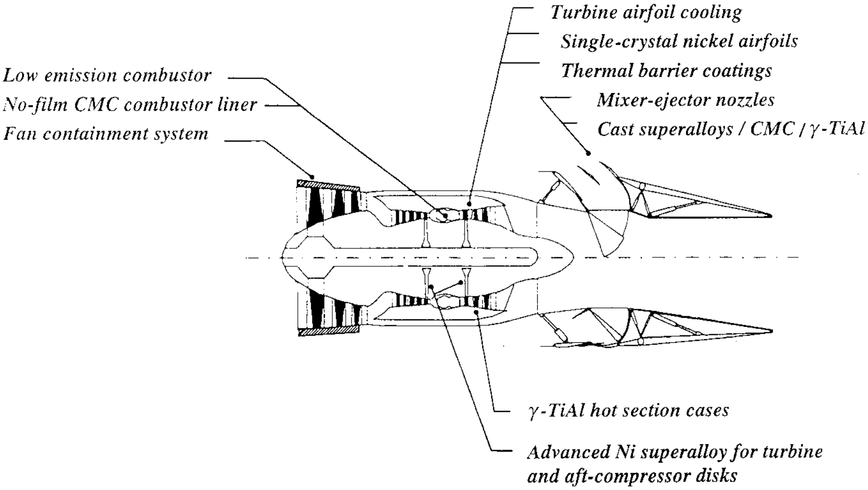


FIGURE 3-2 HSCT engine and exhaust nozzle. Source: NASA.

maximum temperature for an unusually long time; annual operating time at maximum temperature (component "hot time") will be more than 10 times longer than the hot time of components of subsonic commercial or supersonic military aircraft engines. This is because the mission cycle of an HSCT results in turbine inlet temperatures that are close to the maximum throughout the supersonic cruise portion of a flight and because commercial transports have much higher utilization than military aircraft. An average utilization of 14 hours per day is anticipated for an HSCT.

In some applications, the number of temperature cycles is more life limiting than hot time. However, this is not likely to be the case with materials for an HSCT engine. Problems with the number of cycles can usually be addressed through changes in the mechanical design to accommodate thermal stresses better. Failure modes associated with hot time, however, are more difficult to control. High engine efficiency requires temperatures higher than the melting point of metals. Cooling air can prevent melting but can be quite difficult to supply to some hot surfaces. The committee believes that the HSR Program has properly focused on hot time instead of cycles as the primary life-limiting factor.

Turbine Airfoils

HSCT turbine airfoils (both vanes and blades) will likely consist of intricately cooled single-crystal castings of an advanced, oxidation-resistant nickel-based superalloy with a thin ceramic coating. The ceramic coating will serve as a thermal barrier to reduce the average metal temperature in the airfoil. Research is under way to improve the temperature capability of the superalloy substrate and the insulating quality and durability of the ceramic thermal barrier coating. The life goal for the turbine airfoils is 18,000 hours. The life goal for the thermal barrier coating is shorter, and it is anticipated that airfoils will be replaced and reused, as necessary, following refurbishment and the application of a new thermal barrier coating.

Airfoils are, perhaps, the most demanding application for a structural material. The single-crystal alloys that are the HSR Program's airfoil system of choice will probably be alloys with low sulfur content that contain active elements to resist oxidation spallation. The alloys will be formulated to provide creep, thermal fatigue, and melting point advantages.

Manufacturing large, complex, actively cooled single-crystal turbine airfoils will be difficult. However, other programs are conducting important research in the areas of superalloy airfoil manufacturing related to large, subsonic engines and stationary gas turbines, and some results will be applicable to development of HSCT engine technologies. Thus, the committee believes that the risk associated with airfoil manufacturing is relatively low, assuming that required materials will be available.

Thermal barrier coating systems are needed to insulate airfoils from the high-pressure, high-temperature gases exiting the combustor. The durability of the thermal barrier is a major challenge because of the requirement for long life at maximum temperature. In addition, decreasing the thermal conductivity of the ceramic coating is important to allow a reduction in the thickness of the thermal barrier, which would reduce blade weight, thereby reducing the creep stresses on rotating turbine airfoils. Continued development of ceramic coatings and the layers that bond the coatings to the superalloy substrate and contribute to oxidation resistance is essential.

The HSR Program's baseline approach for manufacturing ceramic thermal barrier coatings is electron-beam physical-vapor deposition. The performance of thermal barrier coatings and related manufacturing technologies is also being addressed by other government- and industry-funded research and development programs. Although these programs will probably contribute to the creation of a thermal barrier system suitable for an HSCT, continued work by the HSR Program is still needed.

The HSR Program has made notable progress toward development of an alloy with enhanced creep-rupture characteristics at conditions representative of the critical airfoil stress and temperature. However, the current turbine airfoil development effort is still about a factor of three short of demonstrating the life goal. The alloy chemistry must also be balanced to achieve acceptable thermal fatigue and oxidation resistance in addition to superior creep resistance. The committee believes meeting these important goals by end of the current Phase II is unlikely. Shortcomings in these areas could be offset by reducing turbine inlet design temperature. However, this would reduce fuel efficiency to an unacceptable level. Another option would be to leave the temperature unchanged and replace the turbine airfoils and thermal barrier coatings more frequently. However, this would increase operational costs.

Finding 3-1. The HSR Program's turbine airfoil system development effort is a high risk endeavor that is unlikely to demonstrate the specified level of technology readiness (TRL 6) by the end of Phase II.

Recommendation 3-1. The HSR Program should expand its efforts to develop suitable alloys and thermal barrier systems during Phase II to increase the probability that the airfoil system will satisfy durability and lifetime requirements and to prepare for the recommended technology maturation phase.

Disk Materials and Manufacturing

The HSR Program is developing special nickel alloys (using powder metallurgy) for the HSCT compressor and turbine. Alloy compositions are being tailored for the HSCT mission cycle, which will subject the disks to high temperatures for long periods. Thus, both high-temperature creep life and cyclic, fatigue durability are important.

The life goal for HSCT engine disks is 18,000 hours. The HSR Program is making progress in developing an improved alloy that can satisfy this goal. If the target lifetime is not achieved, then a fallback position would be to replace the disk more frequently.

The manufacturing portion of the disk development activity is particularly challenging. The size of the disks envisioned for an HSCT propulsion system is at or beyond the maximum size capability of existing extrusion and forging presses. The capability to consolidate and forge preforms from which the disks can be machined must be demonstrated to show that manufacturing such large disks is feasible. Furthermore, the ability to achieve requisite materials characteristics in preforms of such a large diameter and thickness needs to be validated. As part of the manufacturing technology effort, the possible effect of powder segregation in large extrusion cans, the effect of thermal gradients and variations in furnace and quench treatments, and the effect of the quench on distortion and residual stress must all be determined. Current efforts will not resolve these issues by the end of Phase II.

Finding 3-2. The HSR Program's disk manufacturing development effort will not demonstrate a necessary level of technology readiness (TRL 6) by the end of Phase II.

Recommendation 3-2. Early in the recommended technology maturation phase, which would follow Phase II, the HSR Program should manufacture and destructively test representative full-scale disk components to verify that manufacturing technologies are feasible and that measured material properties are consistent with design data generated from small samples. Disk performance should be demonstrated in a full-scale engine later in the technology maturation phase.

COMBUSTOR

Developing the technology needed to design an advanced combustor that emits ultralow levels of nitrogen oxides (NO_x) is a key objective of propulsion system development. Meeting this objective is necessary to enable the development of an environmentally acceptable HSCT. Because the NO_x emissions discharged by an HSCT fleet during supersonic cruise are a potential threat to the stratospheric ozone layer, combustor design technology that meets the target NO_x emission level is critical.

Key Considerations

When the HSR Program was initiated, it examined available environmental impact assessments and set an NO_x emission index goal of 5 grams per kilogram (g/kg) of fuel burned. Extensive efforts were then initiated as part of the HSR

TABLE 3-1 Calculated Steady-State Total Column Ozone Change between 40°N and 50°N Averaged over a Year[a]

	Ozone Column Change (%)			
	Average of Five Different Model Predictions		Range of Five Different Model Predictions	
NO_x Emission Index at Cruise Speed(g/kg)	Fleet of 500 HSCTs	Fleet of 1,000 HSCTs	Fleet of 500 HSCTs	Fleet of 1,000 HSCTs
5	–0.15	–0.40	–0.30 to +0.20	–0.7 to +0.1
10	–0.35	not available	–0.50 to +0.07	not available
15	–0.69	–1.67	–0.80 to +0.06	–2.3 to –0.6
45	–5.20	not available	–8.30 to –2.80	not available

[a] Assumptions: cruise Mach number of 2.4; background chlorine concentration of 3.0 parts per billion in the atmosphere.

Source: NASA, 1995a; NASA, 1995b.

Program to assess the environmental impact associated with the exhaust emissions of an HSCT fleet. This assessment, which is still in progress, is called the Atmospheric Effects of Stratospheric Aircraft Project (AESA). The latest results suggest that the original goal of 5 g/kg is still appropriate (see Table 3-1).

The data shown in Figure 3-1 are for a Mach 2.4 aircraft. For best aerodynamic efficiency, slower HSCTs would cruise at altitudes lower than the cruise altitudes of a Mach 2.4 HSCT. Atmospheric models predict that operating at lower altitudes would mitigate the ozone depletion caused by engine emissions (or add to the net increase in ozone).[1] This effect could provide some trade-off space to mitigate the technical and economic risks associated with development of a very-low-NO_x (5 kg/g) combustor. However, the expected change is not large enough to justify changing program goals from Mach 2.4 to Mach 2.0 (as long as a practical combustor with an emissions index of 5 g/kg can be developed).

In a turbine engine equipped with a conventional combustor, the NO_x emission level is highly dependent on the compressor discharge air temperature and, to a much lesser extent, on the compressor discharge air pressure. Because of this strong dependence, the NO_x emissions from an HSCT engine equipped with a conventional combustor would be very high, in the range of 40 to 50 g/kg during supersonic cruise operation. (During cruise, the compressor discharge air temperature is very high—in excess of 1200°F.) Attaining the goal of 5 g/kg will require technological advances that can reduce NO_x emissions by as much as

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[1] The effect of HSCT emissions on the atmosphere is the result of many complex chemical interactions. Although some processes increase atmospheric ozone, the net effect is generally negative. However, as shown by the range of model results in Table 3-1, a fleet of low-emission HSCTs could have no net effect on the ozone.

90 percent compared to conventional technology. To do this, the HSR Program is developing advanced combustor concepts that do not require high (stoichiometric) flame temperatures anywhere in the combustor. This would mitigate the effects of the high compressor discharge temperatures associated with supersonic cruise operation.

Besides producing low levels of NO_x emissions, the combustor technology being developed by the HSR Program must meet the same demanding performance, operability, reliability, structural integrity, and durability requirements that current combustors meet. Further, ultralow-NO_x-emission combustors must produce equally low levels of other emissions (e.g., smoke, carbon monoxide, and unburned hydrocarbons). Meeting all of these requirements is a formidable challenge.

There are two basic combustor design concepts with known potential for achieving ultralow NO_x levels: a lean premixed, prevaporized (LPP) combustor, and a rich, quick mix, lean (RQL) combustor. Both of these concepts embody features that are substantially different from those of combustors in modern aircraft engines.

The LPP concept involves premixing the fuel and combustion air upstream from the combustion zone. Premixing and prevaporizing the fuel produces a lean, homogeneous mixture, which significantly reduces NO_x emissions. Combustor designs of this kind are very complex because they require sophisticated hardware for proper staging of the combustion process. Also, preventing autoignition of the fuel-air mixtures is difficult. At supersonic cruise conditions, autoignition can occur very quickly, typically within one to four milliseconds after the start of premixing. Thus, the premixing process must be accomplished very quickly. This is difficult with liquid fuels because of practical limitations on the number of fuel injection points that can be used.

In RQL combustors, all of the fuel is injected into the first stage to produce rich fuel-air mixtures. Combustion of such mixtures suppresses the formation of NO_x. However, the combustor liners must be cooled without film air cooling, which is used in current combustors. Film air cooling is unacceptable because the cooling air would create stoichiometric fuel-air mixtures, which produce high levels of NO_x in regions close to the liner. Most of the air flow in RQL combustors bypasses the rich first stage and is introduced further downstream to complete the combustion process. The bypass air must be mixed very rapidly with the combustion products from the rich first stage to suppress NO_x formation as the rich gases are diluted. Suppressing NO_x formation during this rapid mixing process is especially difficult during high power operation because of the high combustor inlet air temperatures.

Development Status of Ultralow NO_x Combustors

To date, the HSR Program has made extensive efforts to evolve promising versions of both ultralow NO_x combustor concepts (LPP and RQL). Considerable

TABLE 3-2 Concerns and Risks Associated with Ultralow NO_x Combustors

LPP Concepts	RQL Concepts
Complexity associated with the much larger number of fuel injection points (compared to a similarly sized conventional combustor)	NO_x emission goal not demonstrated simultaneously with acceptable performance and operability capabilities
Complexity of fuel injection point staging and associated controls	Complexity of variable geometry features needed to modulate the quantity of air admitted to the rich first stage
Potential for carbon buildup in fuel injectors and distributor valves	Need for unique high temperature liner materials for the rich first stage to eliminate the need for film air cooling
Potential for autoignition and flashback in the premixer elements	
Need for unique high-temperature liner materials to minimize the need for cooling air	

progress has been made and aggressive efforts are continuing. Testing is in progress using module and sector test rigs, and NO_x emission levels at or near the target value have been demonstrated with versions of both concepts. The HSR Program expects to collect enough data to select a preferred combustor design concept by the scheduled date of May 1998.

Nonetheless, several concerns still exist regarding the viability and acceptability of using either an LPP or RQL combustor in an operational engine (see Table 3-2).[2] The committee believes that these concerns can be addressed and resolved only by additional testing involving both combustor rigs and full-scale engines.

As noted above, using film air cooling in the rich first stage of RQL combustors is unacceptable. With LPP combustors, minimal film air cooling of the liner is necessary to obtain sufficiently low NO_x levels. Thus, both concepts require combustor liner materials that can withstand high operational temperatures with little or no film air cooling. The HSR Program is pursuing advances in liner materials that can meet this need. To date, efforts have focused on ceramic matrix composite (CMC) materials because of their relatively low thermal expansion characteristics and their resistance to thermal distortion and fatigue. Accomplishments to date include demonstration of a CMC material with improved thermal conductivity. In 1996, the HSR Program selected a silicon carbide CMC as the liner material of choice.

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[2] The technical concerns described in this chapter have been identified by the HSR Program and are shared by the committee.

As with other propulsion system components, long hot times are a major durability challenge. The combustor life goal is 9,000 hours of hot time, with periodic refurbishment of the liners. To meet this goal, the hot (inner) surface of liners fabricated with silicon carbide CMC will probably require a ceramic thermal barrier coating. Specific durability concerns for this type of liner include oxidation-induced ductility loss, inadequate resistance to crack growth, and spallation of the thermal barrier coating.

Processing experiments conducted thus far indicate that manufacturing silicon carbide CMC liners may be technologically feasible. However, the availability of such liners for use in HSCT engines is at risk because of the likely absence of other engine applications. Without a broader base of applications, unit costs would probably be prohibitive. This problem could be mitigated if engine development by NASA, the U.S. Department of Defense, or the U.S. Department of Energy lead to other applications for silicon carbide CMC liners.

In recognition of the immaturity of CMC material in terms of both performance capabilities and manufacturing possibilities, the HSR Program has selected nickel alloy materials with thermal barrier coatings as a backup. Nickel alloy materials are widely used in operational engines and, thus, are already proven and available. However, nickel alloy liners may not achieve life goals in HSCT applications because of oxidation-induced coating spallation; thermal fatigue and distortion; creep; and melting.

Combustor Conclusions

The development of ultralow NO_x combustor technology will require major advances in both combustor design and associated material technologies. For this reason, combustor development is a high risk element of the HSR Program, and the results will have a significant impact on the HSCT product launch decision. Any HSCT built *must* be environmentally acceptable, and engine emissions are a direct function of the combustor design.

In an effort to resolve combustor material and design issues, a subscale core engine test is planned for 2000 and 2001. This test will provide a much-needed opportunity to evaluate the performance and operability characteristics of the selected combustor design. Combustor characteristics that require engine testing for meaningful assessments include ground starting; altitude relight; autoignition tendencies, flashback tendencies, and combustion stability during engine thrust transients; and liner cyclic life.

Even if the subscale core engine testing has promising results, the viability of the selected combustor design will remain in doubt because of uncertainties about how these characteristics may change as a function of scale. Testing a full-scale demonstrator engine will be needed to reduce the magnitude of these uncertainties and lower propulsion system risk to an acceptable level. Thus, dedicated tests of a full-scale demonstrator engine should be conducted during the recommended

TABLE 3-3 Suggested Time Line for Combustor Development

Time Period	Task
5/98[a]	Select a single combustor and liner material concept
6/98 to 12/99	Continue testing selected concepts using existing test rigs
3/99 to 12/99	Design combustor for full-scale engine tests Design test rig for testing full-scale combustor components
1/00 to 6/01	Fabricate two full-scale combustors Fabricate full-scale combustor test rig
6/01 to 12/02	Conduct rig tests of combustor to evaluate and refine operability, emission, and structural integrity characteristics
7/02 to 12/02	Design engine control features for combustor operation (in parallel with combustor testing)
1/03 to 12/03	Install combustor and associated engine control features into demonstrator engine
2004 to 2006	As part of the recommended demonstrator engine test series, conduct *dedicated tests* of the combustor to assess performance, operability, emission, and service life characteristics

[a] Existing Milestone

technology maturation phase to evaluate and, as necessary, guide continued development of the selected combustor design. If a commitment is made to conduct full-scale testing, it may be feasible to eliminate the subscale core engine tests planned for Phase II. A suggested schedule is presented in Table 3-3.

Finding 3-3. Significant uncertainties regarding the viability of potential ultralow NO_x combustor designs—and the materials needed to implement those designs—are likely to remain at the conclusion of Phase II, as currently planned.

Recommendation 3-3a. During the recommended technology maturation phase, the HSR Program should test a full-scale demonstrator engine to reduce uncertainties regarding the viability of the selected ultralow NO_x combustor design. Combustor development during Phase II should focus on preparations for full-scale tests.

Recommendation 3-3b. In order to increase the potential market for silicon carbide CMC liners—and thereby ensure their availability for use in HSCTs—the HSR Program should encourage other engine research programs sponsored by NASA, the Department of Defense, and the Department of Energy to include more CMC materials.

EXHAUST NOZZLE

The engine exhaust nozzle envisioned for an HSCT propulsion system is quite large, about 18 feet in length. In order to meet aircraft and propulsion system weight goals, the HSR Program has established performance and weight goals for the nozzle that cannot be achieved using materials, designs, or manufacturing processes typically used for engine exhaust nozzles.

The main components of the engine exhaust nozzle are the primary structure, convergent flaps, divergent flaps, noise absorption system, and thermal blanket. The current HSR nozzle concept features a large nickel-base superalloy primary structure with a thin-walled casting to meet weight goals. Although complex, this design appears to be manufacturable, and the mechanical and thermochemical properties of the superalloy seem to be acceptable.

Candidate materials for the convergent and divergent flaps are thin-walled castings of a nickel-base superalloy and a titanium aluminide intermetallic, respectively. Secondary processes to remove material from the initial castings will be required to achieve weight goals. Casting demonstrations indicate such structures are feasible. Areas of ongoing concern include joining, which will be important during manufacture and repair; the impact of thermal fatigue, oxidation, and creep on the durability of the superalloy convergent flaps; and the impact of acoustically driven high cycle fatigue, oxidation, and creep on the durability of the titanium aluminide divergent flaps.

The exhaust nozzle design also includes an internal noise absorption system constructed from CMC acoustic tiles and an insulating thermal blanket. The durability of the CMC in the harsh environment within the exhaust nozzle is a major concern. Failure can result from interfacial oxidation, acoustic fatigue, thermal fatigue, or erosion. Moisture can also degrade the CMC acoustic tiles.

The life goal for the primary exhaust nozzle structure is equal to engine life, about 36,000 hours. The life goal for the acoustic liner and thermal blanket is one-half engine life or about 18,000 hours.

Finding 3-4. Development efforts for the exhaust nozzle may achieve the specified level of technology readiness (TRL 6) by the end of Phase II. Nonetheless, uncertainties about nozzle materials and manufacturing processes will require additional work during the recommended technology maturation phase.

Recommendation 3-4. The HSR Program should fabricate and test full-scale nozzles during the recommended technology maturation phase to validate nozzle manufacturing technology, noise levels, and material performance.

FUEL EFFICIENCY

The fuel efficiency of the HSCT propulsion system will depend largely on the efficiency of the air intake, engine turbomachinery components, and exhaust nozzle. The HSR Program should assess fuel efficiency using full-scale component tests and, ultimately, full-scale engine tests and propulsion system flight tests. Component performance necessary to meet HSCT fuel efficiency goals is generally consistent with currently available technology, although marginal improvements may be needed in some areas. Overall, the committee believes that fuel efficiency is an area of relatively low risk.

SYSTEM INTEGRATION AND TESTING

Phase II is developing and testing technologies at the component level, often in subscale form. However, the highly complex nature of supersonic jet engines can produce component interactions that can not be predicted by full-scale component tests or by subscale engine tests. For this reason, and because of the historical risk involved in developing advanced supersonic engines, an HSCT program launch decision seems quite unlikely unless risk is reduced by demonstrating satisfactory performance of a full-scale, fully integrated engine (during the proposed technology maturation phase) and a full-scale, fully integrated propulsion system (during the proposed advanced technology demonstration phase).

Also, the HSR Program is currently structured with a high degree of concurrence between development of the engine and airframe; both are scheduled to reach the required level of technology readiness at about the same time. However, jet engines are mechanically more complex; involve processes that are more difficult to model compared to the corresponding airframes; are more difficult to manufacture, assemble, and test; and require more time to redesign, remanufacture, and retest than corresponding airframes. In fact, history has shown that engine development takes about three years longer than airframe development. Thus, to ensure that the engine and airframe are ready for first flight at the same time, engine development must lead airframe development. The present HSR Program does not reflect this imperative. Testing full-scale engines during the recommended technology maturation phase would resolve this issue.

Finding 3-5. Fabrication and testing of full-scale engines are needed to validate engine technologies, particularly with regard to emissions and noise requirements. Early action leading to this goal is required to ensure that the propulsion system technologies will be ready for flight testing at the same time as airframe and integrated aircraft system technologies.

Recommendation 3-5. It is critical that the HSR Program build and test two full-scale, instrumented engines during the recommended technology maturation phase. Testing of one engine should focus on aerothermodynamics and aeromechanical issues (e.g., thrust, emissions, noise, and vibration); testing of the other should focus on structures and materials issues (e.g., reliability, service life, and weight). The second engine would also reduce risk by ensuring a backup engine is available in case the first engine experiences a catastrophic failure.

The full-scale demonstrator engines will be too large to test in a facility that can simulate high altitude conditions. Although sea-level tests will be an important milestone in the development of new supersonic engines, some important questions will remain unanswered. Flight demonstrations are needed to determine propulsion system responses to atmospheric conditions and disturbances, including turbulence and wind gusts. A full-scale technology demonstration aircraft will also be needed to verify critical angles for engine unstart to investigate the impact of engine unstart on the aircraft and its occupants.

Similarly, flight demonstration would verify the ability of the integrated airframe and propulsion systems to meet noise and emissions goals. For example, as part of the AESA project, NASA has made in-flight measurements of emissions from the Concorde. However, an HSCT engine is likely to have a very different thermodynamic cycle from the Concorde's Olympus engines, and NO_x emissions from an HSCT engine are expected to be considerably different (NRC, 1997).

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4

Airframe

This chapter discusses the process the HSR Program is using to select and develop candidate materials, to characterize and improve the service life of materials in an HSCT environment, to identify and resolve manufacturing issues associated with new materials, to develop and validate low-weight structural designs, and to develop a feasible aerodynamic design that will enable the TCA to meet its weight and range goals.

BACKGROUND

The goals of the HSR Program require development of an advanced airframe structure that significantly outperforms conventional aluminum skin-stringer designs (i.e., designs consisting of discretely stiffened, monolithic structures). For 300-passenger subsonic airframes, structural weight fractions of 25 percent are common. In other words, the airframe structure typically weighs 25 percent of MTOW (maximum takeoff weight). The HSR Program, however, has established a goal of less than 20 percent for structural weight fraction. This goal—along with the additional design requirements and conditions encountered in the supersonic flight regime—is driving the selection of material and structural concepts toward high risk, high payoff designs (Velicki, 1995). These designs must have simultaneous improvements in material properties at elevated temperatures and in structural design efficiencies. These improvements will be especially difficult to accomplish given other program objectives related to affordability, risk reduction, and service life. In fact, the committee believes that the primary airframe structural design will have more impact on HSCT affordability than any other technological area. Economically feasible materials, structural designs, and manufacturing processes are essential.

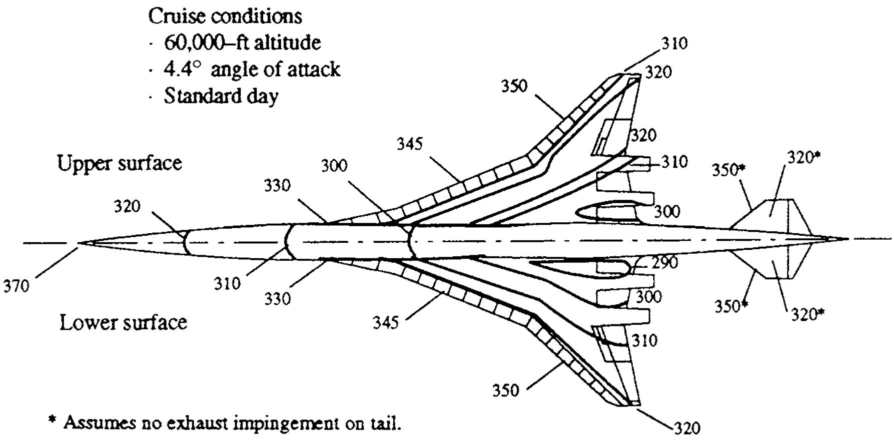

FIGURE 4-1 Predicted equilibrium skin temperatures for a Mach 2.4 HSCT. Source: Johnson, 1994.

The skin of a high-speed aircraft is heated during flight by friction with the atmosphere. However, the relationship between temperature and cruise speed is not linear; skin temperature increases more rapidly at higher speeds. Figure 4-1 shows predicted equilibrium skin temperatures for a Mach 2.4 HSCT configuration. Except for the nose (radome) and leading edge structures on the wing and tail, the maximum effective skin temperatures estimated for the primary airframe structure on the fuselage, wing, and tail are 320°F. (The radome will use special radar transmitting materials, and leading edges will use titanium alloys.) Skin temperatures are somewhat lower at lower cruise speeds: 250°F at Mach 2.2 and 210°F at Mach 2.0 (NRC, 1996; Johnson, 1994).

Two types of materials are generally available for airframe structures: composites, such as polymeric matrix composite (PMC) resin systems using carbon fibers; and metals. The estimated thermal stability of potential HSCT structural metals and polymeric matrix composite (PMC) resin systems is shown in Figure 4-2 (Smith, 1996).[1] As indicated, the basic polymer systems available for HSCT applications above 250°F are more limited than at lower temperatures. The availability of suitable adhesives, sealants, and paints follows the same pattern (Smith, 1996). Thus, the goal of developing technologies compatible with a cruise speed of Mach 2.4 critically affects development related to airframe materials, structures, and

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[1] PMCs suitable for high temperature airplane structure consist of high strength, high modulus carbon fibers embedded in a high-temperature-resistant polymeric matrix (i.e., the resin). Two main categories of matrix materials are thermosets and thermoplastics. The epoxy, bismaleimide, and cyanate ester materials are of the thermoset family. The thermoplastic family includes polyarylene (arylene-ether) and polyimide matrices.

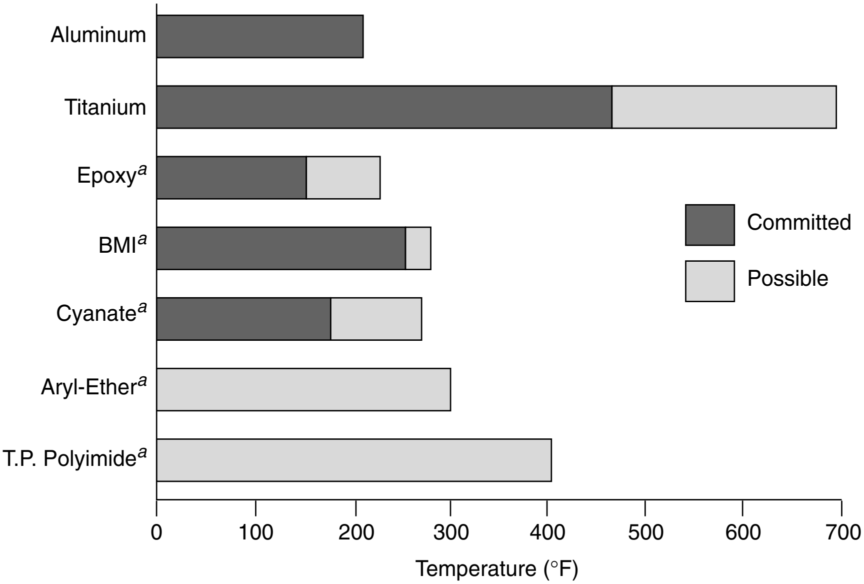

FIGURE 4-2 Estimated thermal stability of potential HSCT structural materials (20-year service life). Source: Smith, 1996.

[a]The potential for using these materials at the upper end of the indicated temperature band is based on short-term experimental data.

processes. This is not the case with regard to airframe aerodynamics, the propulsion system, or integrated aircraft systems. Although those areas also face extremely difficult technical challenges, the level of risk is essentially the same for cruise speeds between Mach 2.0 and 2.4.

SELECTION OF MATERIALS

This section discusses the HSR Program's approach to developing advanced materials, followed by comments on aluminum alloys, titanium alloys, PMCs, structural adhesives, sealants, coatings and finishes, and the supplier base.

Development Approach

Materials and processes currently used by the aerospace industry cannot satisfy the performance and cost requirements of a Mach 2.4 HSCT. Materials and processes for an economically feasible Mach 2.0 to Mach 2.2 HSCT would also require significant technology development, but developing lower speed materials (such as aluminum alloys and polymer materials) would involve lower risks and costs.

Operating temperature and structural weight are key variables that will determine the viability of an HSCT. The Mach 2.4 materials under development by the HSR Program must perform adequately at temperatures from –65°F to 320°F (350° for leading edge structures), for a minimum of 60,000 hours at maximum temperature. The nose structure, which will encounter maximum temperatures of 370°F, will be designed for in-service replacement and is exempt from this lifetime requirement.

The objective of the HSR Program's materials effort is to develop (1) key technologies for metallics, composites, adhesives, and sealants and (2) associated fabrication processes to provide a technological foundation for the production of a commercially viable Mach 2.4 HSCT. Environmental compliance, worker safety, and acceptable cost for the final structure are also important considerations. The specific goals are very aggressive. For example, one goal is to improve critical mechanical properties of candidate materials by 20 percent over baseline metals (such as Ti-6 Al-4 V titanium alloy) and composites (such as composite material AS4/5250).

Specified deliverables in the area of materials, processes, and structures are as follows:

- database of material properties, durability, fabrication processes, etc.
- finite element models of airframe structures
- test data on wing and fuselage components

The HSR Program will use these deliverables to evaluate the feasibility of meeting the weight and performance goals of the TCA and to support development of a refined aircraft configuration (the TCn).

The materials development effort assessed the applicability of existing and experimental materials with potential applicability to an HSCT. However, work on coatings, finishes, hydraulic fluids, and other enabling materials is not included in the HSR Program. As discussed below, this significantly increases the overall program risk. The key finding and recommendation related to the development of materials follow. Additional justification for this finding and recommendation appear in subsequent sections.

Finding 4-1. Different families of materials (e.g., resins, adhesives, sealants, coatings, and finishes) are required for use at sustained temperatures above 250°F (i.e., for aircraft designs with cruising speeds above Mach 2.2) than for use at temperatures below 250°F. Therefore, the focus of the HSR Program on a speed of Mach 2.4 critically influences materials technology development. General classes of polymeric materials and manufacturing processes suitable for a Mach 2.0 to 2.2 HSCT are available but have not demonstrated the life requirement and require significant technology development.

Recommendation 4-1. The HSR Program should retain a cruise speed of Mach 2.4 as an important baseline objective to encourage development of advanced materials and to develop a fundamental understanding of high temperature material responses and degradation mechanisms. However, the HSR Program, with appropriate support from the airframe manufacturers and material suppliers, should also identify and develop critical enabling technologies to protect the viability of developing a Mach 2.0 to Mach 2.2 HSCT. This effort should start during Phase II and continue until risks associated with a Mach 2.4 design are substantially reduced.

As with any backup program, resources devoted to the backup reduce the resources available for pursuing the primary approach. Resources devoted to development of the backup approach should be balanced against the risk that the primary approach will fall short. In the case of the HSR Program, the committee believes the backup effort should be enhanced to achieve appropriate balance.

Aluminum Alloys

Aluminum alloys, such as 2618, operate at temperatures up to 220°F and are used in the Concorde. Alcoa and Reynolds are developing stronger and tougher aluminum alloys, but fracture toughness and creep resistance are continuing challenges. Also, improved alloys will still be limited to a maximum operating temperature of about 220°F. Thus, the HSR Program is interested in aluminum alloys primarily as a backup material in case the speed requirement is reduced from Mach 2.4 to about Mach 2.0. However, the HSR Program discontinued funding for the development of aluminum technology in December 1996. As a result, Alcoa and Reynolds anticipate stopping or greatly curtailing efforts to develop advanced aluminum technology applicable to an HSCT.

Titanium Alloys

Titanium is an attractive material for a Mach 2.4 HSCT because of its thermal stability at the 350°F maximum skin temperature. In addition, titanium and its alloys are not susceptible to degradation in the environment of a Mach 2.4 HSCT. In spite of the high strength-to-weight ratio of current titanium alloys, however, an all-titanium HSCT would not be economically viable because of excessive weight. Even so, titanium alloys are the prime candidates for wing and tail leading edge structures, the main wing box, foil for honeycomb sandwich core structures, and, perhaps, higher temperature fuselage structures. Therefore, the HSR Program includes a significant effort to develop titanium alloys with a 15 to 20 percent improvement in strength and other key properties. Achieving these improved properties would probably result in more complex and costly processing, such as hot forming (for higher strength alloys) and heat treatment after processing. Thus, the HSR Program is studying the effects of complex thermomechanical processing and how to optimize alloy composition and manufacturing processes to reduce processing costs and risks. The cost reduction effort is exploring innovative fabrication technologies, such as forming, machining, joining, net-shape extrusions, metallurgical and adhesive bonding, laminated titanium alloy structures, and superplastic forming and diffusion bonding of structural honeycomb sandwich.

The committee believes that the HSR Program's titanium alloy and process development plan is properly scoped and does a good job of integrating work by NASA and the airframe manufacturers with work by materials suppliers and academia.

Polymer Matrix Composites

The effective application of PMCs using carbon fibers has long been recognized as the key to producing an economically viable HSCT. Currently, the leading candidates for Mach 2.4 applications are thermoplastic polyimide resin systems, such as Dupont's Avimid-K and NASA's PETI-5. Testing of carbon-fiber-reinforced PMCs using these systems has shown favorable performance (in terms of thermal resistance, open-hole compression strength, and compression-after-impact strength), even compared with the toughened PMC systems currently used on subsonic aircraft. However, manufacturing components from the proposed new materials can involve complex fabrication processes for long periods of time (up to 24 hours) at high temperatures (up to 700°F) and high pressure (up to 200 psi). In addition, solvents added to provide "tack" for wet-layup fabrication processes must be volatilized, removed, trapped, and recovered for reuse and recycling. (Volatile contents can be as high as 20 percent weight fraction.) Automated lamination processes (e.g., advanced tow placement) may be applicable if a solvent-free, "dry" PMC layup material can be developed to eliminate the solvent-removal challenge. However, constraints imposed by the stringent processing requirements (i.e., long time, high temperature, and high pressure) preclude using potentially more affordable manufacturing methods, such as resin transfer molding, pultrusion, resin film infusion, and nonautoclave processing. Further, the processes currently proposed will likely require expensive tooling, increasing the risk that they may not be compatible with the manufacture of an affordable HSCT.

PETI-5, which was developed and patented by NASA, is currently the HSR Program's primary composite matrix baseline. PETI-5 is a lightly cross-linked thermoplastic polyimide that offers potential improvements in solvent resistance and mechanical properties over earlier thermoplastic polyimides. The HSR Program is also evaluating modifications of the PETI-5 system, such as PTPEI-1.

In limited testing to date, PETI-5 composites appear to have reasonable properties and durability, but they are difficult to process, and devolatization of large, complex parts presents a major challenge. Thus, the HSR Program plans to develop a "dry" PETI-5 material form to simplify processing. PETI-5 coupon testing has accumulated more than 5,500 hours of isothermal aging at elevated temperature without degradation in mechanical performance.

The focus of the HSR Program on a single, high-risk PMC material system (PETI-5) optimized for Mach 2.4 (as opposed to lower speeds) increases overall program risk, as does the ambitious schedule. In fact, NASA and industry participants in the HSR Program understand that the airframe materials and structures being developed by the HSR Program involve significant cost and risk and may not be optimal for a lower-speed HSCT design. Nonetheless, the HSR Program is not pursuing the development of alternate materials technology for lower speeds.

The rationale for maintaining the technical focus of the materials effort on Mach 2.4 is based on the desire to push the state of the art as far as possible and the presumption that the materials and structures for a Mach 2.4 design could be used for a lower-speed design, if necessary. Materials for a Mach 2.4 aircraft, if successfully developed, would certainly satisfy the less-stressing requirements of a Mach 2.0 or Mach 2.2 design. However, several factors would probably favor the selection of other materials for lower-speed applications. A lower design speed would allow consideration of PMC resins, adhesives, sealants, and paints that have substantially lower developmental risks; are generally easier to manufacture, repair, and maintain; cost less; and have a larger supplier base. For example, some thermoset and thermoplastic material systems are currently used in subsonic aircraft, and it may be possible to modify them for use on an HSCT operating between Mach 2.0 and Mach 2.2. These materials can be processed at moderate temperature (350°F to 400°F) and pressure (approximately 80 psi), and they would be more compatible with lower-cost manufacturing methods, such as lamination, resin transfer molding, and nonautoclave processing.

In summary, the HSR Program's focused effort to develop Mach 2.4 PMC materials, if successful, would produce high performance materials that could be used at temperatures from 200°F to 350°F. However, even if the HSR Program can overcome the high developmental risks for these materials in a timely fashion, high manufacturing costs and a limited supplier base may create economic limits on their use. Furthermore, the nearly exclusive focus of the HSR Program on Mach 2.4 does not seem to be justified based on Finding 2-2, which concludes that a Mach 2.0 HSCT is likely to have productivity similar to a Mach 2.4 HSCT. The committee believes additional efforts during Phase II to develop alternative materials for Mach 2.0 to 2.2 designs are crucial. Funding could be obtained by reducing funding for full-scale components, as suggested in Recommendation 4-7.

Finding 4-2. The focus of the HSR Program on a single basic PMC system (PETI-5) is a major program risk that could have a catastrophic effect on the HSR Program if the development effort falls short in critical areas, such as processing, properties, or durability. This risk underscores the importance of developing alternative materials technologies for Mach 2.0 to Mach 2.2.[2]

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[2] Finding 4-1 and Recommendation 4-1 further explain the committee's conclusions regarding efforts by the HSR Program to develop PMCs.

Structural Adhesives

The development of structural adhesives and surface preparation and bonding processes are critical for effective manufacture of composite and metallic components for the TCA. The primary research conducted by the HSR Program for honeycomb sandwich skin-to-core bonding, laminated hybrid composites, and metal bonding is a supported-film adhesive based on the chemistry of NASA's PETI-5. The most crucial technical issues are related to processing (e.g., surface preparation and secondary bonding).

Consistent and reliable surface preparation processes for adhesive bonding and repair of titanium and composite substrates are critical to the development of durable bonded structural components. Historically, the key to the structural bonding of titanium has been the development of a stable oxide surface layer. However, the processes used by the HSR Program to achieve these surface conditions with titanium alloys have proven to be unacceptable under production conditions for commercial airplanes and involve environmentally harmful etching and conversion solutions. Therefore, the HSR Program is currently investigating more complex processes, such as silicate coatings and chromium sputtering surface treatments. Chromium sputtering results to date are promising, although this process requires an enclosed chamber, which is a major concern for the manufacture of large, complex parts.

During secondary operations and bonding repairs, the high temperatures and pressures required to process PETI-5-type adhesives could damage or degrade previously cured laminates. This could be a major challenge during secondary processing or component repair procedures. It should be noted that adhesive bonding of primary structure on subsonic commercial aircraft continues to be a processing challenge.

The committee believes the development of structural adhesives is well scoped and is technically well directed. However, there is high risk associated with achieving the desired level of technology readiness within the current schedule, particularly with regard to titanium surface preparation.[3]

Sealants

The HSR Program has accepted the difficult challenge of developing sealants (especially fuel tank sealants) that can survive environmental conditions associated with a Mach 2.4 aircraft. The combinations of critical performance characteristics, such as elongation at low temperatures (down to –65°F) and high-temperature oxidation resistance, have proven extremely difficult to achieve.

Fluoroelastomer systems, such as fluorosilicones, have been the leading candidates for Mach 2.4 applications. However, condensation-cured fluorosilicones

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[3] Finding 4-1 and Recommendation 4-1 summarize the committee's conclusions regarding efforts by the HSR Program to develop structural adhesives.

do not have sufficient thermal stability for long-term applications at Mach 2.4 conditions. Addition-cured fluorosilicones have performed better but tend to degrade after long times at elevated temperatures. New materials and blends are being developed and evaluated.

Fuel tank sealants have additional requirements for low-temperature elongation and long-term exposure to jet fuel at elevated temperatures. The development of fuel tank sealants for the SST and SR-71 in the 1960s and 1970s was only marginally successful, and potential suppliers have expended little effort since then because of the difficulty of meeting these performance requirements, high development costs, and the small potential market.

Using an HSCT design speed between Mach 2.0 and 2.2 would significantly improve the ability of fluoroelastomer systems to meet sealant performance requirements. A design speed of Mach 2.0 would also allow using modified nonfluorinated polymers (e.g., high-temperature polysulfides), which would significantly reduce sealant cost and weight. Additional testing, however, would be required to validate specific formulations of polysulfide sealants for use at the elevated temperatures associated with Mach 2.0 and above.

The HSR Program had no sealants suitable for Mach 2.4 available for testing in 1996. The best technology in this area appears to reside with foreign suppliers, who are not eligible to participate in the HSR Program. Therefore, U.S. airframe manufacturers must use their own funds to collaborate with foreign suppliers on the development of advanced sealants. Overall, the prospects for success remain uncertain.[4]

Coatings and Finishes

PMCs require surface coatings for protection from the environment, including ultraviolet radiation from the sun. In addition, estimates of HSCT equilibrium skin temperature are dependent on specific surface emittance and absorptance properties. However, it is extremely difficult to develop satisfactory coatings and finishes that can withstand the high skin temperature of a Mach 2.4 HSCT. Currently available coating technology would not be economical for commercial applications at speeds above Mach 2.0. Thus, material and structural design decisions are currently being made based on a temperature profile that may not be achievable with the coatings and finishes that will be available.

Efforts to develop improved coatings and finishes must carefully consider microcracking that can be caused by environmental cycles related to temperature or moisture. Microcracks can begin in coatings, such as paints, primers, and fillers, and propagate into the PMC substrate. This has occurred periodically in the PMC structures of the existing fleet of commercial subsonic aircraft.

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[4] Finding 4-1 and Recommendation 4-1 summarize the committee's conclusions regarding efforts by the HSR Program to develop sealants.

The HSR Program views the development of advanced coatings and finishes as a low priority and is not funding any research in this area. However, the challenge and risk of developing coatings and finishes increase significantly for long-term applications above Mach 2.2. [5]

Recommendation 4-2. The HSR Program should make development of PMC-compatible coatings and finishes an integral part of its PMC development effort.

Supplier Base

Development of an HSCT will be a major commercial endeavor. Commercial programs of this type typically attract a significant level of direct funding and technical commitment by suppliers of key materials, such as resins, adhesives, sealants, coatings, and finishes. This support reduces the research burden that the airframe manufacturers must carry and helps ensure that required materials will be available in production quantities when needed. However, material suppliers do not appear yet to have made a substantial investment in the development of materials needed for an HSCT, and it is not clear when or if such a commitment will be forthcoming. This increases the challenge faced by the HSR Program as it attempts to develop materials that meet technical performance requirements *and are likely to be commercially available*.

The HSR Program has selected a PMC and adhesive baseline material (PETI-5) that is patented by NASA. This discourages the materials industry from developing its own materials for HSCT applications because the HSR Program has already indicated a preference for PETI-5. Furthermore, by retaining the patent rights for PETI-5, NASA discourages industry investments in the development of PETI-5 because industry may be disinclined to invest its own funds in improving someone else's materials. The Mach 2.4 polymeric materials are also likely to have a more limited supplier base than alternate materials for lower-speed designs.

The ability to create and manufacture new materials is inherently a global resource, one that is not confined to the United States. For a high-risk technology development effort, such as the HSR Program, involving foreign technology in selected areas could make an important contribution to the success of the total program. However, as noted previously, foreign companies are not eligible to participate in the HSR Program. Thus, it is up to the airframe manufacturers—as part of their internally funded HSCT research—to involve foreign technology in situations where it is more advanced than U.S. technology.

Finding 4-3. The adequacy of the materials supplier base could become a critical issue when industry considers whether to make an HSCT program launch decision. Factors that interfere with establishing the necessary supplier base include

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[5] Finding 4-1 and Recommendation 4-1 summarize the committee's conclusions regarding efforts by the HSR Program to develop coatings and finishes.

restrictions on the involvement of foreign industry and NASA's ownership of a major structural material (PETI-5). These factors lower the incentive for large suppliers of aerospace materials to develop materials on their own.

Recommendation 4-3. HSR Program managers and airframe industry executive managers should meet with material suppliers to solicit financial and technical commitments to participate in the overall effort to develop materials needed for an HSCT. The HSR Program should also ensure that the ability of foreign industry to reduce risk in critical areas is adequately considered, either through the independent actions of industry participants in the HSR Program or through direct action by the HSR Program (after obtaining necessary exemptions to NASA policy restrictions on the involvement of foreign industry). This is especially important for the cost-effective development of required sealants.

SERVICE LIFE

A major technical issue in the selection and evaluation of structural materials for the HSCT is the characterization of long-term thermomechanical durability to verify a minimum service life of 20 years. Currently, there are no methods for predicting 20-year end-of-life behavior for PMC materials.

The results of the committee's QFD analysis (see Figure 2-1) indicate that a strong adverse relationship exists between airframe service life and the downstream processes of "manufacturing and producibility" and "certification." This adverse relationship exists because advanced, new materials and structures necessary to increase service life typically are—at least initially—more difficult and expensive to manufacture and certify than existing, proven materials.

The key service life technology areas being investigated by the HSR Program are (1) long-term real-time testing, (2) accelerated testing, and (3) life prediction methodologies. Currently, predictions of end-of-life properties for developmental materials are based on accelerated test techniques. Real-life testing to date has been limited and will not be able to validate end-of-life properties until many years after the HSR Program has selected the materials and structural design of airframe test articles.

The durability of candidate PMC materials is being defined by ongoing thermomechanical fatigue tests of material element and specimen forms. These tests simulate the mechanical and thermal cycles that materials will experience in operation. Various materials are being tested in a variety of test conditions, but not all materials are being tested in all test conditions. For example, as development of new material resins progresses, the use of new resin formulations in the design of test articles depends largely on predictive methods that can correlate the results of modeling and accelerated testing with long-term durability.

Some multiyear service life tests are being conducted in real time, and some are being accelerated. When the current Phase II program is completed in 2002, it will have conducted about half-a-lifetime of isothermal testing, but those tests will not address durability in the total environment. Real-time tests are being used to supplement and measure the accuracy of accelerated tests. However, accelerated testing is not yet a proven tool for screening candidate HSR materials and structures; more real-time tests must be completed and correlated with accelerated tests.

The history of high-temperature PMC components indicates that matrix microcracking is a more severe problem than creep or thermal oxidation. *Accelerated Aging of Materials and Structures* (NRC, 1996) points out that matrix cracking accelerates most PMC degradation mechanisms, especially oxidation. This could create problems for both thermoplastic polyimides, such as PETI-5 (because of the high residual stresses from high processing temperatures) and even moderate temperature thermosets (because of their lower strengths and elongation). The hygrothermal (i.e., cyclic moisture and temperature) sensitivity of thermoset and thermoplastic polyimides is of particular concern with regard to microcracking. In addition, each parameter traditionally used to accelerate testing (such as temperature, pressure, and moisture) is also a degradation mechanism for PMCs. Therefore, acceleration strategies may be material specific.

Ongoing test programs at Lawrence Livermore National Laboratory are studying accelerated thermomechanical degradation and its relationship to real-time testing. Results of that test program are currently being produced for K3B thermoplastic polyimide and 5260 bismaleimide thermoset materials. However, differences between those materials and the PMC materials being developed by the HSR Program make it difficult to apply the results of those tests to the HSR Program.

Life prediction methodology involves correlating long-term PMC behavior with postmortems on tested specimens and specific property data (e.g., viscoelastic creep behavior) to develop predictive analyses. The ability of the HSR Program to develop accurate life prediction methodologies is limited because no actual service life data are available. Specific challenges include the following:

- accounting for hygrothermal effects
- interpreting the results of PMC durability tests of materials (K3B and bismaleimide) that may not accurately model the baseline PMC materials selected by the HSR Program (PETI-5)
- applying the results of PMC durability testing of specific laminates to HSCT components that are designed with laminates with a different layup orientation

Finding 4-4. The HSR Program's materials specimen and element testing is well planned. The testing schedule, however, extends beyond the end of the current program and is generally limited to thermomechanical testing of the PMC material being developed by the HSR Program (PETI-5) and thermoset materials that are commercially available. Risk associated with the selection of structural concepts is increased by the need to rely on (1) predicted end-of-lifetime material properties based on less than one lifetime of real-time test data and (2) accelerated durability test methods that have not been validated by adequate real-life tests. An improved scientific understanding of individual composite degradation mechanisms is needed to reliably predict lifetime performance and to design accelerated tests.

Recommendation 4-4. During Phase II, the HSR Program should conduct a focused, critical, detailed, technical assessment of alternatives for including new PMC materials in the durability testing of specimens and elements. This assessment should include personnel from inside and outside the HSR Program, and it should use the findings and recommendations of *Accelerated Aging of Materials and Structures* (NRC, 1996) as a guide. The assessment should include the results of ongoing real-time testing, and it should be oriented toward understanding aging characteristics and accelerated testing techniques suitable for a broad class of materials applicable to HSCT development.

MANUFACTURING

Industry has assumed responsibility for the development of manufacturing technology needed to address producibility issues specific to their HSCT designs. Even so, it is incumbent upon the HSR Program to ensure that the materials technologies it is developing are compatible with affordable manufacturing processes.

As noted earlier, airframe structural design, including economically feasible materials and manufacturing processes, will have more impact on HSCT affordability than any other technological area. As discussed in more detail below, a NASA-sponsored study (Marx et al., 1996) examined the effect of alternate structural concepts for an HSCT wing on vehicle life cycle cost. That study emphasized the importance of considering airframe manufacturing and economic issues concurrently with technology development. For example, the effort to meet HSR Program goals for MTOW, range, payload, and cruise speed will tend to favor a highly specialized airframe design that would be difficult—and expensive—to manufacture.

Processing Polymeric Matrix Composites

Manufacturing costs are the single largest contributor to the cost of composite components (JTEC, 1994). Manufacturing costs include processing costs (e.g., cure cycle) and nonrecurring costs for factory tooling, computerized controls, and other equipment, such as autoclaves. Costs can rapidly escalate if complex tools, large production rates, or complicated processes are required.

For subsonic aircraft, only 8 to 10 percent of the cost of composite components is attributable to the materials from which they are manufactured (DeVault, 1993). Similarly, the material costs for HSCT structural components are expected to be significantly less than manufacturing costs. Thus, widespread use of composites in an HSCT will be contingent upon the maturation of innovative, affordable composite manufacturing processes, such as advanced tow placement, resin transfer molding, resin film infusion, pultrusion, and nonautoclave processing (NRC, 1995).

Twenty years of experience with carbon-fiber PMCs indicates that the successful use of PMCs in commercial aircraft very much depends upon industry's ability to integrate PMCs efficiently into the aircraft design philosophy. For example, for both subsonic and supersonic commercial aircraft, the materials technology should be low risk and cost effective. Thus, PMC systems with little or no in-flight service testing and no proven manufacturability are unlikely to be adopted by manufacturers or accepted by airlines (Seferis and Condit, 1995). This supports the committee's conclusion that flight testing a full-scale technology demonstrator is necessary to reduce risk enough to enable industry to make an HSCT program launch decision (see Chapters 1 and 6).

A successful materials development program is best supported by a philosophy that combines basic science (e.g., microstructures, processing, and properties) and basic economics (e.g., design, performance, and manufacturing) (Seferis, 1988). Applying this philosophy to evaluation of PMCs that could be developed for a near-term HSCT clearly shows that new PMC systems that incorporate unproven chemistries will have a difficult time competing as a low-risk, affordable alternative to systems and composite manufacturing schemes that can be connected to an existing database (Miller, Lovell, and Seferis, 1993; Seferis and Carrega, 1991).

PMC processing and manufacturing methods are crucial because they drive manufacturing costs and affect the structural integrity of the finished component. The committee shares the concerns of some HSR Program engineers that manufacturing demonstrations of small (3-foot by 3-foot) flat panels will not be able to identify and resolve manufacturing problems that could arise during production of actual wing and fuselage structures. Production experience with subsonic commercial airplanes has repeatedly demonstrated that the lessons learned from manufacturing small test articles often do not apply to the manufacture of full-size production parts. The committee believes that new materials and structures technologies developed for the HSR Program are likely to experience the same problems. Thus, the committee recommends reallocating HSR Program funds to develop more robust producibility demonstrations (see Recommendation 4-5).

The high temperature processing required for PMCs, such as PETI-5 and other thermoplastic polyimides, may preclude the use of more affordable processing. Further, stringent processing requirements (in terms of time, temperature, and pressure) are likely to create a need for expensive and complex tooling systems. Overcoming the processing limitations of PETI-5, particularly for large components, is a major challenge and involves considerable risk.

Hybrid Structure

New hybrid titanium-composite materials may have significant promise for HSCT applications. One candidate uses alternating layers of titanium foil and carbon fiber composites. The titanium provides excellent compressive strength, while carbon-fiber composites provide stiffness, tensile strength, and fatigue resistance. Potential advantages include light weight and increased damage tolerance. In addition, a titanium laminate with a high modulus boron fiber is under consideration. However, from a materials technology standpoint, applying either of these materials to the TCA design must overcome major problems associated with (1) reliably bonding titanium-PMC surfaces over large areas (2) complex laminate processing, (3) industry and airline inspectability and maintainability, and (4) repairability.

Structural Sandwich Construction

The HSR Program has made a major effort to develop a honeycomb-core sandwich structure tailored for application to a Mach 2.4 HSCT. Structural honeycomb sandwich (metallurgically and adhesively bonded) will be used to fabricate major components of the HSCT wing and possibly the fuselage structure (see Figure 4-3).

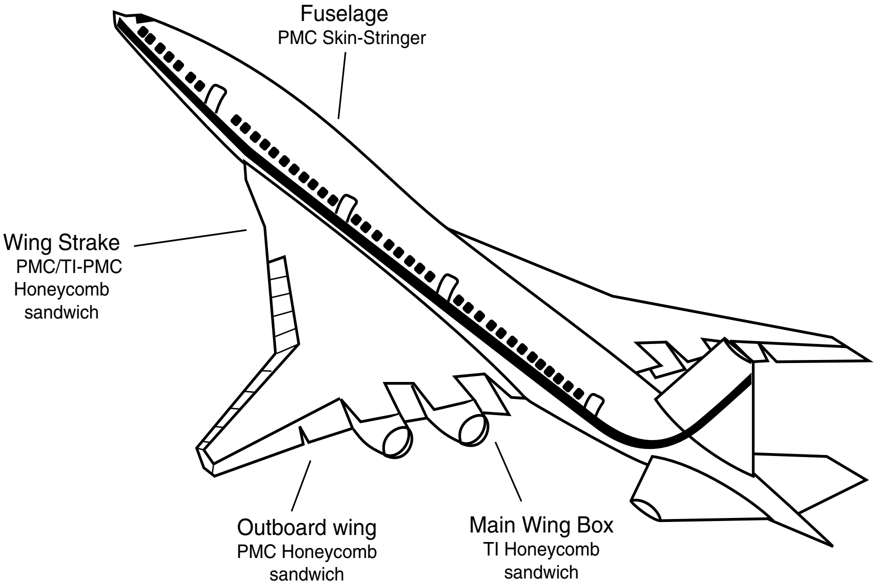

FIGURE 4-3 Materials and structures baselines for the TCA. Source: Boeing.

Adhesively bonded titanium-sandwich structure with a titanium-alloy core is a primary design concept for the HSR main wing box. As previously mentioned, current surface preparation techniques for adhesive bonding of titanium alloys are not acceptable. Surface preparation processes need to be developed to ensure the long-term durability of the adhesive bonds for Mach 2.4 applications.

Fabrication methods for titanium-sandwich structure that use metallurgical bonding also have the potential to provide lightweight, high-performance airframe structures. The high thermal conductivity of aluminum-brazed honeycomb panels limits their application on thermally sensitive wing fuel-tank structures where it is not feasible to install additional thermal insulation. However, these panels could be used for other fuselage applications where it is feasible to install additional insulation. The high temperature brazing-diffusion process and "Stresskin" concepts (which are based on resistance-welding of titanium core to titanium skin) can provide metallurgically bonded honeycomb-sandwich structure as well, although further heat treating in a vacuum furnace or retort would be needed to meet the high mechanical-property requirements of HSCT airframe structures. Substantially more work is needed to demonstrate these high-temperature processes on subscale components compatible with TCA requirements.

In the past 20 years, superplastic forming and diffusion bonding processes have been developed for fabricating titanium sandwich structures, primarily for military airplanes (NRC, 1995). These processes, however, need to be validated for new titanium alloys. Processes for adhesively bonded structural honeycomb structure with titanium core and PMC laminates also require extensive work with regard to development of filler, paste, and film adhesives; scale-up; and characterization.

Conclusions on Manufacturing

As discussed in the following section, the HSR Program intends to fabricate and test full-size components (viz., a fuselage barrel section and an inboard wing box) to validate the fuselage and wing structural designs, respectively. These components will be constructed using hand layup fabrication processes (which would be uneconomical for a production aircraft) instead of automated manufacturing processes. As a consequence, the results may not indicate how components manufactured using commercial processes would behave. In other words, the committee does not believe the proposed testing will determine if the structural designs are compatible with the manufacturing processes that will ultimately be used to build an HSCT.

High temperature composites are notoriously hard to process, and industry has no experience using automated manufacturing processes with the candidate materials. The HSR Program currently plans to use automated manufacturing processes to construct small (3-foot by 3-foot) sections of the airframe structure. However, fabrication of such small sections is not adequate for manufacturing validation. Producibility demonstrations are generally conducted using full-scale test articles in order to accurately assess the effects of outgasing, viscosity variability, resin flow, porosity, etc. Although large, these test articles need not have the complexity of parts intended for assembly into a structural component like a wing box. In other words, full-scale manufacturing test articles may be simpler in design than parts for full-scale component tests, even though they would be about the same size. Therefore, the manufacturing test results would accurately characterize the effect of interactions between candidate materials and the proposed, automated manufacturing processes.

Finding 4-5. In the areas of manufacturing, processing, and producibility, the HSR Program is focused on developing processing methods for the fabrication of small numbers of subscale and full-scale components to support the materials testing program. However, this will not resolve issues associated with how to affordably manufacture components in production quantities. In addition, manufacturing processes for PMCs required for a Mach 2.4 HSCT, such as PETI-5, will be complex and costly because of handling characteristics, high volatile content, and high temperatures and pressures (up to 700°F and 200 psi).

Recommendation 4-5. The NASA and industry participants in the HSR Program should jointly place greater emphasis on the development of manufacturing technology and producibility demonstrations so the HSR Program can properly support the HSCT product launch decision. NASA and industry should develop an integrated manufacturing technology plan that enables the HSR Program's materials technology development efforts, which currently seem to be focused on near-term component fabrication, to adequately consider overall, long-term manufacturing issues. Development of this plan should be closely coordinated with the wing and fuselage design teams. The HSR Program should also review and incorporate the integrated design and manufacturing approach described by Marx et al. (1996), which is based on a combined performance and economic perspective. Implementation of this recommendation will require changes to the Phase II program and approval of the recommended technology maturation phase.

STRUCTURAL DESIGN

The structures challenge is shown graphically in Figure 4-4. The HSR Program goal of reducing vehicle weight by one-third compared to a comparable Concorde-type aircraft requires a structural weight fraction of less than 20 percent. By comparison, the structural weight fraction of typical 300-passenger subsonic transports is 25 percent or more, and the B-2 bomber, which contains the highest percentage of advanced composite primary structure in flight today, has only achieved a weight fraction of 23.9 percent (Hargrave, 1996). Thus, the effort to achieve a goal of 20 percent must be viewed as high risk, even with the planned

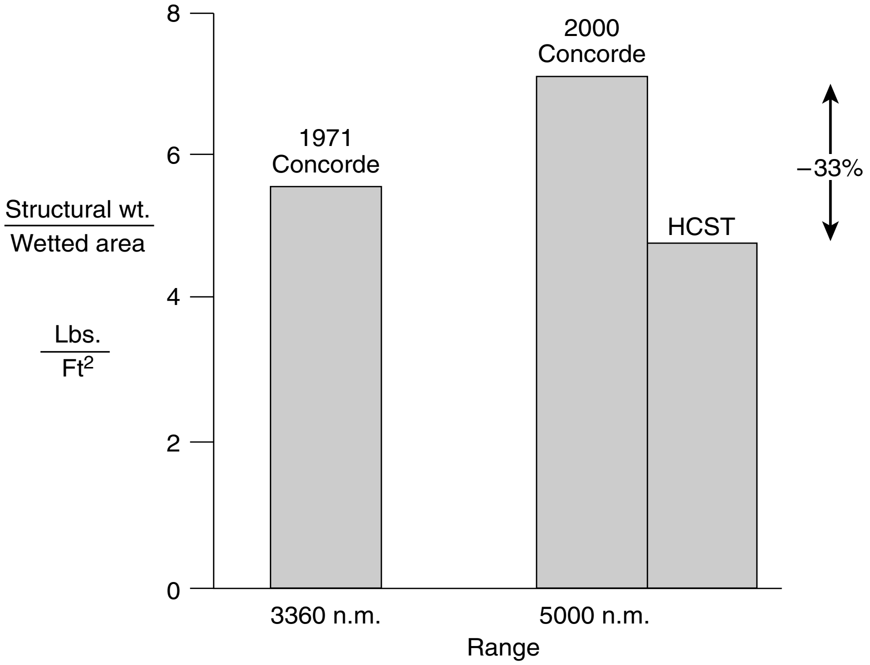

FIGURE 4-4 Structures challenge. Source: Boeing.

use of advanced materials and improved structural design efficiencies. Also, the structures technology issues, which are discussed below, cannot be effectively addressed without considering the materials issues identified in the previous section.

As mentioned in Chapter 2, structural weight alone is not an adequate metric for determining economic viability, which also depends on the affordability of materials, structural designs, and manufacturing processes. This lesson was demonstrated in a recent NASA-sponsored study (Marx et al., 1996), in which several wing structural arrangements for a 1970s Lockheed SST design were compared for total system fly-away costs using two cost models: a weight-based model and a process-based model. The differences between the results produced by these two models become increasingly acute as structural concepts become more dependent on advanced materials and manufacturing processes.

The specific goal of HSR structures technology development is to develop and validate structural designs for the TCA. Specifications for the TCA include an MTOW of about 740,000 pounds and a minimum service life of 20 years. The strategy to accomplish this task involves identifying aspects of current subsonic structural design concepts that can be improved and developing new, lighter-weight design concepts. The process includes the following:

- design trade studies to develop preliminary weights for new and existing concepts
- a building-block test approach that reduces technology maturation risk by sequentially testing coupons, elements, subcomponents, and components
- selection criteria to reduce the number of concepts carried forward at each step

The current materials and structures baselines for the TCA are shown in Figure 4-3. Critical material and structural issues considered during the selection process include the durability of PMCs, adhesives, and sealants; the ability of sandwich structures to contain damage; the residual strength of damaged structures; the availability of nondestructive evaluation methods; and repairability. The committee believes that this overall strategy is sound and well planned. The committee identified some areas of concern as well as some innovative solutions. Findings and recommendations are detailed below.

Dependence on Materials Development

Weight management techniques evident in the structural concepts being developed by the HSR Program include the use of advanced lightweight composite materials; the aggressive use of sandwich structure for large areas in the wing and, perhaps, in the fuselage; and the elimination of structural joints and fasteners through bonded integral construction. These innovative structural concepts are strongly dependent on the maturity and success of materials development. The use of advanced composite materials, especially the baseline PETI-5 structural composite, is key to achieving areal weight goals for structures in the fuselage, outer wing box, and strake. However, success of the structural assembly is equally dependent on the concurrent availability of adhesives, cores, caulks, fillers, potting compounds, and compatible tooling materials. In terms of TRL (Technology Readiness Level) these materials are not at a comparable level of maturity (see Figure 4-5). As discussed in the earlier sections of this chapter and in Chapter 6, developing these materials is a high risk endeavor because of the technical challenges and time constraints imposed by the current program schedule.

Honeycomb sandwich structure can provide a very efficient, lightweight method for supporting large structural loads and is considered a candidate for the main wing box and fuselage. Concerns about damage tolerance have restricted the use of sandwich structure over very large area, because it does not have the crack arrestment features inherent in skin-stringer designs. Some innovative sandwich tear strip concepts have been developed by the HSR Program to address this concern.

A more fundamental issue in sandwich construction is joining the core to the facesheet. Skin-to-core integrity for the titanium sandwich depends on the development of reliable preparation methods for titanium surfaces. Skin-to-core integrity for PMC sandwich depends on the availability of compatible adhesives.

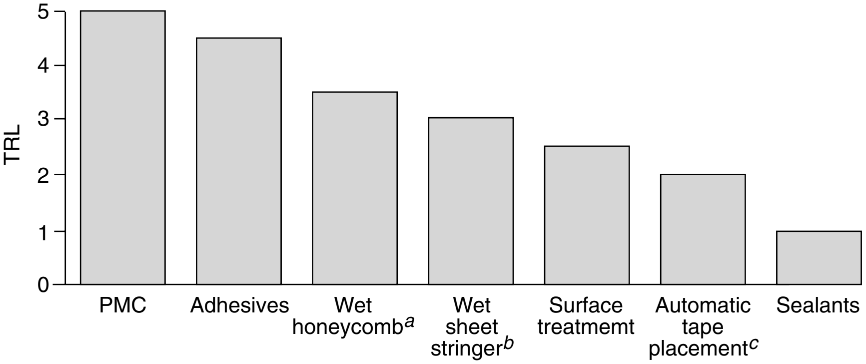

FIGURE 4-5 Current levels of technology readiness of composite materials are unequal, jeopardizing development of structural concepts.

[a] Honeycomb is a method of hand fabricating composite structures that produces a sandwich-type construction.

[b] Sheet stringer is a method of hand fabricating composite structures that produces panels with reinforcing stiffeners.

[c] Automatic tape placement (also known as automatic tape laying) is a machine method of laying up composite structures. Robotics automatically place either a tape or a rope (tow) of fiber.

Both technologies are currently under development in the HSR Program, as discussed above.

Unitized construction of large integral structural components reduces total part count, eliminates structural joints and fasteners, and reduces assembly costs. The success of this construction approach is strongly dependent on PMC processing characteristics, the availability of compatible tooling and materials for cobonding, and the availability of adhesives and shimming materials.

Finding 4-6. The performance of innovative structural concepts depends on successful development of the materials upon which they are based. It is virtually impossible to separate the structures design effort from the materials and manufacturing development effort. The materials development program and the structural concept development program are both well planned. However, the current schedule of the HSR Program does not facilitate a sequential approach that would reduce overall risk by validating the performance of proposed new materials before they are incorporated into new structural concepts.

Design Analysis Methodology

Design trade studies are important for managing technology maturation, resource allocation, and risk reduction. Currently, the HSR Program uses weight as the key metric in design trade studies to guide its evaluation of competing concepts. But the objectivity and outcome of design trade studies also depend on the maturity of the design tools and design database.

Early on, the HSR Program identified a problem with design analysis methodologies. The FY 1994 HSR Planform Study concluded that there were significant differences between the design practices and assessment methods used by McDonnell Douglas and Boeing. For example, one assessment method might predict that a given design change would increase MTOW, whereas another method would predict a decrease in MTOW. In order to understand and resolve these differences, the HSR Program developed the TCA (Technology Concept Aircraft), a notional aircraft configuration that is used as a common base for technology assessments, integrated system-level trade studies, vehicle-level tracking, and technology cost-benefit prioritization. The TCA is intended to provide an appropriate balance between risk, performance (payload, range, and speed), and environmental compliance (noise and emissions). Although Boeing and McDonnell Douglas are continuing to develop and refine their own proprietary aircraft designs, industry participation on the HSR Program management and technology teams ensures that technology developed to support the TCA configuration will also be applicable to the industry designs. Assigning responsibility for maintaining the TCA finite element master model to one company (Boeing) further reduced the differences between the design analysis methodologies. Thus, even though differences will persist in the structural optimization codes for some detailed models, this problem has largely been solved.

During the course of the program, many different teams have estimated weights using numerous methods, and it is not clear if all of the teams have cooperated very well. There is still some residual uncertainty in tracking component, system, and total aircraft weights. Overall vehicle weight targets were established using a parametric weights method called ATLAS. Weights of competing design concepts were calculated using both Boeing (ELFINI) and McDonnell Douglas (non-optimum) methodologies. Weight estimates have also been generated using structural finite element models. The uncertain relationships between some of these methods have hampered the evolution of a precise vehicle weight assessment. Also, the relationship of MTOW to the fuselage and wing areal weight metrics is unclear.

Finding 4-7. The use of multiple weight estimation methods has confounded weight tracking and obscured HSR Program successes in using innovative structural concepts to reduce vehicle weight. There is no longer a clear relationship between structure areal weights and MTOW, which are both top-level audit metrics used by the HSR Program.

As noted previously, the HSR Program has attached great importance to a design speed of Mach 2.4. This speed requirement has dictated the structural temperature profile of the vehicle, which in turn has driven the aggressive materials development effort and the equally aggressive test program for characterizing high temperature materials. However, the ability to predict the thermomechanical response of new structural concepts accurately is just as important to the overall success of the HSR Program. Based on past experience, the committee believes that the lack of accurate thermal structural analysis is often a stumbling block in major aircraft development programs. There was a notable lack of information on this topic in HSR documents reviewed by the committee and in discussions with HSR Program personnel. Also, during individual discussions at Boeing, McDonnell Douglas, and Northrop Grumman, structural engineers involved in the HSR Program identified thermal structural analysis as an area of concern.

Structural engineers involved in the HSR Program also identified long design cycle time (i.e., the inability to evaluate new configurations in a timely manner) as an issue. Using current design tools, it takes a full year to go through a complete vehicle-level analysis, from external loads to finite element modeling to static and dynamic structural analysis. This long cycle time jeopardizes the schedule for evaluating alternate structural designs and selecting a single configuration. An iterative, feature-based, preliminary sizing tool is needed to permit quicker evaluations of the details of various structural concepts in a small portion of the structure (for example, going from honeycomb sandwich structure to skin-stringer structure in the wing box) within an overall vehicle master model.

Finding 4-8. Structural design and analysis tools vary from company to company. Improvements are needed in these tools, including life prediction tools, weight estimation tools, thermal stress analysis tools, and rapid preliminary sizing tools. These improvements would give the U.S. aerospace industry a distinct competitive advantage.

Structural sizing is dependent on the accuracy of the structural design allowables as well as the fidelity of the finite element model.[6] As shown in the HSR Program schedule (see Figure 1-2), validation of materials databases will not occur until 2001, long after structural concepts have been downselected and committed to full-scale testing. Thus, the structural analysis properties on which the selection process will be based must be developed from incomplete databases of material characteristics. This will affect the accuracy of service life and weight estimates. For example, overestimating the durability allowable for an experimental titanium alloy and underestimating the durability allowance for an equally experimental PMC material could, in an extreme case, lead to selection of the wrong design concept.

Recommendation 4-6. During Phase II, the HSR Program should concentrate more resources on developing structural design tools tailored for HSCT applications.

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[6] Structural design allowables are design limits based on the strength, toughness, durability, etc. of materials used in the structure.

These tools should include validated materials databases, rapid preliminary sizing tools, validated thermal stress analysis tools, and validated analytical life prediction tools. Resources could be reallocated to this task from full-scale component tests.[7]

Structural Concept Selection

The HSR Program is using the results of ongoing research to evaluate the TCA in preparation for defining the follow-on design configuration (the TCn) in 1998 and conducting large component fabrication and testing around the year 2000.

The TCA evaluation includes separate analyses using vehicle-level models for four structural concepts in the fuselage, three in the main wing box, two in the strake, plus additional analyses, as required by updates to the materials databases and non-optimum factors. In addition to these vehicle-level models, detailed analyses of finite element models of the fuselage and wing box structural test components are also planned. These analyses are prerequisites for selecting preferred designs for the structural test components.

Finding 4-9. The large amount of work needed to carry forward and analyze the many design concepts still under consideration increases the risk of not meeting the program schedule.

Structural Test Program

The airframe materials and structures effort currently plans full-scale component tests of a fuselage barrel section and the inboard wing box to validate the fuselage and wing structural designs, respectively (see Figure 4-6). These tests are intended to develop confidence in proceeding from technology development to engineering and manufacturing development. This emphasis on large-scale component fabrication and testing leads to the perception that the design and testing of a commercially viable airplane is overwhelming the development of enabling technology.

Structural issues that would be addressed by full-scale component tests include major load paths, thermal-structural interactions, failure loads and modes, fuselage pressurization, large-scale durability and damage tolerance, limited fabrication scale-up, and major structural repairs. However, *these issues are vehicle specific*. Design drivers, such as minimum gage, damage tolerance, compression and tension strength, and deflection, will vary from location to location for each vehicle design. Full-scale testing of the notional TCA components *will not negate*

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[7] See Finding 4-10 and Recommendation 4-7.

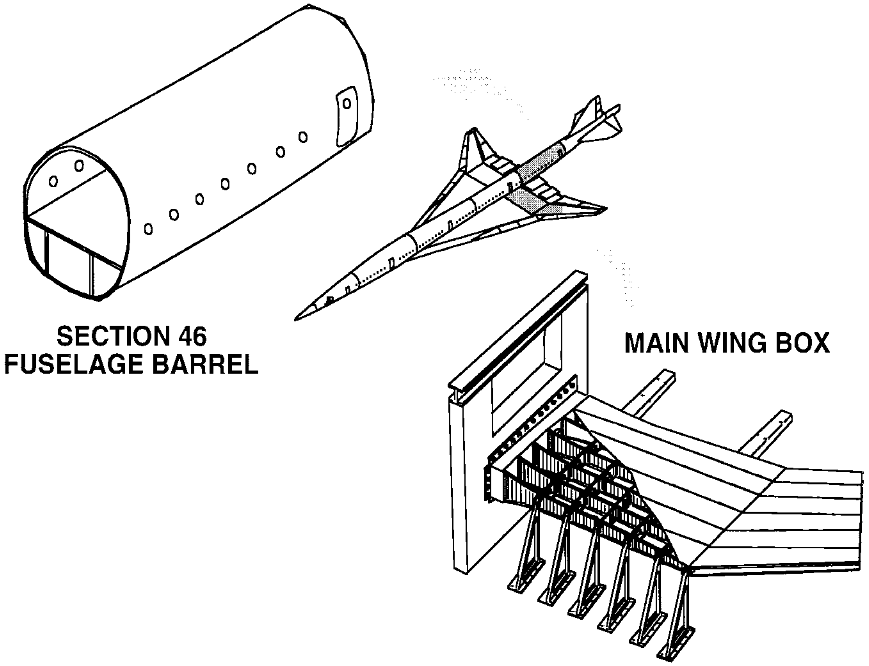

FIGURE 4-6 Full-scale large component test articles. Source: NASA.

the need, cost, schedule, or risk for industry to perform full-scale tests of their design for a commercial vehicle.

The full-scale component tests that are planned will not eliminate the need for real-time tests to measure long-term durability and end-of-life strength and stiffness. In addition, the thermal compatibility of the wing-fuselage joint and the joint in the outboard wing crank, which involve dissimilar materials and extremely high loads, will not be tested. Thus, the most critical structural issues for the full-scale vehicle will not be addressed. Furthermore, cost considerations seem likely to limit the full-scale tests to static loading only, with no thermal or durability testing. Even with these simplifications, the estimated cost of testing full-scale fuselage components is nearly $38 million.

Finding 4-10. Full-scale testing of large components, because of the cost and time involved, is more appropriate to the final structural validation of a specific vehicle point design. Large component tests, as currently planned, would not address critical structural issues for the full-scale vehicle or major structural joints. Nor would they validate that fabrication methods used for component tests would be representative of the manufacturing methods that will be used during production.

Thus, full-scale testing of large components during Phase II would probably add little value to the technology development process.

The HSR Program intends to construct component test articles using materials, tooling, and fabrication processes that may not be representative of the production components. Even though test materials will be from the same family as those planned for the TCn and test article fabrication processes are expected to have a known relationship to production processes, the committee views this as a notable risk. As indicated previously, the structural integrity and quality of a structural article cannot be separated from the material product forms or the processes and fabrication methods used in its construction. PMC layup material and automated tape laying (which are expected to be used for production) yield structures with inherently different properties than structures formed using wet layup hand fabrication processes (which are proposed for test components). In addition, there is currently a nationwide shortage of carbon fibers. For example, current production of IM7 fibers, which are used in the HSR Program's baseline PMC (PETI-5), is dedicated to the F-22 and C-17 programs. This could mean that HSR test components will have to be manufactured from a different PMC material system.

Finding 4-11. Using surrogate materials and fabrication processes for components in large-scale tests could significantly reduce the ability of those tests to assess objectively the economic viability of the proposed design approaches. Correlation of component test results with analytical predictions would be complicated by inherent differences between the "as-designed" and the "as-tested" materials and fabrication processes.

For the reasons stated above, the committee believes that full-scale component tests of a point design from the notional TCA configuration would be premature. Subcomponent tests would be a compromise in terms of cost and structural complexity. Subcomponents would be quicker and less costly to fabricate and test, thus allowing more tests for more in-depth investigations of fundamental issues, such as damage tolerance, repair, load interaction, environmental exposure, material variability, process repeatability, fabrication defects, etc. Subcomponent test articles are large enough to incorporate key structural concepts, address fabrication and handling issues, investigate some load interactions, and calibrate analytical models. For example, testing the outboard wing splice joint would investigate substantive issues, such as dissimilar material joining, highly loaded joints, static strength, thermal-structural interaction, and durability. Because the analytical model for subcomponents is greatly simplified compared to the model required for full-scale structural assemblies, the model would not cloud discovery of fundamental science and would facilitate the often difficult task of correlating the results of analytical predictions with actual structural responses.

The more fundamental investigation afforded by structural tests of elements and subcomponents would provide an opportunity to achieve higher levels of maturity in the key enabling technologies (which is the key objective of Phase II) rather than validating a single point design for a structural concept that, in the end, may not even be applicable to the ultimate commercial product.

Finding 4-12. Structural issues should be resolved in a cost-effective manner, which means using the smallest and simplest tests that can provide the required information. Addressing materials and structures issues using tests at the coupon, element, and subcomponent levels during Phase II may offer a higher payoff than testing full-scale components.

Recommendation 4-7. Testing of full-scale components should be deferred to the recommended technology maturation phase. Funds allocated for testing full-scale components during Phase II should be reallocated to achieve higher levels of technology readiness in the critical enabling materials and structures technologies, including the following:

- materials characterization and life prediction methodologies
- rapid, efficient design and analysis tools
- robust structural concepts
- technical criteria related to dynamic interactions among the airframe, propulsion, and flight control systems (APSE effects) and the relationship of these criteria to structural concepts

This redirection of the Phase II test program would go a long way toward banishing the perception that the development of hardware is leading technology development.

AERODYNAMIC DESIGN

The HSR Program has pursued the systematic development of an aerodynamic design by a combination of linear theory, nonlinear computational simulations, and wind-tunnel testing. This has culminated in the current TCA configuration, which represents a compromise between the requirements of (1) maximizing L/D (lift-to-drag ratio) during supersonic cruise, (2) achieving sufficient L/D for reasonably efficient subsonic cruise for overland route segments, and (3) achieving takeoff and climb performance compatible with noise requirements.

The range achievable in long-range cruise at constant speed is proportional to

$$\frac{V(L/D)}{C}\log\left(\frac{W_1}{W_2}\right)$$

where V is the cruising speed, C is the specific fuel consumption, and W_1/W_2 is the ratio of the initial weight (at takeoff) to the final weight (at landing). Achieving the HSR Program's performance goals requires a combination of low specific fuel consumption, very low structure weight fraction (on the order of 20 percent), and an improvement in L/D on the order of 10 percent relative to the L/D of the current TCA baseline configuration.

The committee conducted a careful review of the HSR Program's aerodynamic design, details of which are not included in this report because of restrictions on the release of this information. Based on that assessment, the committee believes that there is little prospect of achieving specific fuel consumption or weight fractions beyond the current goals of the HSR Program. Consequently, a shortfall in the L/D ratio would seriously compromise the projected 5,000 n.m. range of the aircraft. This would, in turn, degrade economic viability.

The committee believes that the aerodynamic research being conducted by the HSR Program is well planned and managed. The results of wind-tunnel tests are in close agreement with computational simulations. However, scaling factors and other corrections necessary to project wind-tunnel test data to the flight conditions of a full-scale aircraft total about 40 percent. This large correction factor raises some uncertainty about the accuracy of the projected L/D.

A separate analysis based on fundamental considerations of minimum wave drag (which is associated with the shock waves generated during supersonic flight), minimum drag due to lift, and minimum skin friction also suggests that the aerodynamic performance goals are within the range of possibility, but close to the attainable limit. Successful use of nonlinear optimization techniques should bring the performance within 3 to 4 percent of the goal. Other improvements are predicted in detailed refinements, but there is still some risk of a shortfall of several percent.[8]

Ongoing research on supersonic laminar flow control (SLFC), including flight testing, has shown promising results. If successful, SLFC offers the prospect of significantly improving the L/D ratio, on the order of 10 to 15 percent. This would provide a margin against shortfalls in the specific fuel consumption or weight fraction. It would, however, require a complete aerodynamic redesign of the proposed configuration.

Even if SLFC research is not successful in the time frame needed to benefit initial production of an HSCT, development of practical SLFC technology could benefit a variety of supersonic aircraft, including future-generation HSCTs, and continued SLFC research is consistent with NASA's mission to develop advanced aeronautical technologies.

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[8] The committee conducted a detailed review of the projected L/D ratio. Details of that review are not included in this report because disclosure of L/D values and other aerodynamic design parameters are restricted by NASA as limited exclusive rights data.

Finding 4-13. The current estimate of drag for the TCA is reasonable. However, there remains some uncertainty (on the order of 3 to 5 percent) about the actual drag of an HSCT in flight.

Finding 4-14. The projected 10 percent improvement in L/D (relative to the L/D of the current TCA design) is optimistic. Design optimization can be expected to yield about 5 to 6 percent. Some of the other projected improvements may be offset by drag increments on the real production aircraft.

Finding 4-15. SLFC has the potential to improve L/D by 10 to 15 percent, which could offset shortfalls in the attainment of predicted L/D, specific fuel consumption, or structural weight fraction, and would provide a margin for attaining performance goals in terms of aircraft range.

Recommendation 4-8. NASA should continue to conduct SLFC research as part of a long-term commitment to HSR technology. This research could also have significant payoffs for other aeronautical projects. Long-term planning by the HSR Program should provide for the possible incorporation of SLFC in future configurations, including the full-scale technology demonstrator the committee recommends flight testing during the advanced technology demonstration phase.

AIRFRAME SUMMARY

Development of material and process technologies by the HSR Program is well managed, but very aggressive. Also, the program as currently scoped faces high risks with regard to meeting performance and schedule goals. This is particularly true for the baseline material technologies, including PMCs, adhesives, sealants, coatings, and finishes. The committee recommends retaining the Mach 2.4 performance goal to drive material and process technologies. However, to protect the goal of commercial viability, additional funding should be devoted to development of alternative technologies for lower-speed (Mach 2.0 to 2.2) HSCT designs. This is necessary in case the aggressive Mach 2.4 materials technology does not result in levels of risk, cost, and performance that satisfy HSR Program goals and schedules. In addition, airline economic factors do not seem to support the tight focus on a speed of Mach 2.4 (see Finding 2-2).

The materials supplier base, including foreign suppliers, should be critically assessed with regard to prospects for establishing crucial financial and technical commitments in partnership with airframe manufacturers, parts suppliers, NASA, and academia. Such a partnership is needed to ensure appropriate materials, technical expertise, and fundamental data are available to support an HSCT program launch decision.

The ability to develop materials, particularly PMCs and adhesives, that can meet the long-term thermomechanical durability requirements for an HSCT is a major concern. The ability to produce reliable life prediction analyses within the existing HSR schedule is another. More time for technology maturation, as described in Chapters 1 and 6, could significantly reduce these risks.

Airframe manufacturability will be the major factor in determining HSCT affordability. The committee recommends placing greater emphasis on plans for developing basic manufacturing technology. These plans should be coordinated with ongoing development of material technologies, and they should be structured to help identify how decisions involving concurrent manufacturing, materials, and structural design efforts affect the critical issues of producibility, performance, and affordability.

Efforts to achieve the HSR Program's structural design goals are high risk, even with advanced materials and improved structural design efficiencies. The structural integrity of innovative concepts depends on the success of material and process technology development. In addition, using weight as the key structural selection criterion ignores the equally important effect of manufacturing feasibility and affordability on the economic viability of the selected design.

The committee recommends that the HSR Program defer plans to produce full-scale components and provide additional funding during Phase II to mature enabling technologies for material and process development; structural design; validation of accelerated durability tests; and modeling tools for rapid preliminary sizing, thermal analysis, and analytical life prediction.

Additional funding is also needed to investigate real-time, long-term durability, end-of-life properties, robust structural concepts, and fabrication techniques that could be used for full-scale production—before full-scale test components are designed, fabricated, and tested. The committee believes that this approach would shift the focus to technology development and away from validation of point design concepts that may have limited applicability to the final design of an HSCT.

In summary, the committee is concerned about the tight schedule of the current program, which encourages the research program to focus prematurely on unproven materials while simultaneously developing and testing structural concepts. A more appropriate focus for the Phase II materials and structures effort would be technology development to provide an understanding of materials behavior, processing science, material characterization, and structural analysis methods to aid suppliers and airframe manufacturers in their development of materials and processes for an HSCT. This approach would also defer the need to focus on a discrete speed and configuration.

The aerodynamic research being conducted by the HSR Program has resulted in systematic development of an aerodynamic design and aerodynamic goals that are within the range of possibility. Optimization techniques should result in aerodynamic performance within 3 to 4 percent of the goal. However, a shortfall in L/D would seriously compromise airplane performance. The committee recommends the HSR Program and NASA continue long-term SLFC research because of its significant potential and broad applicability to the aerospace industry.

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5

Integrated Aircraft

This chapter concentrates on technology and systems integration—combining disparate units into a unified whole to achieve a common goal.[1] The biggest systems integration challenge faced by the HSR Program is designing an integrated aircraft with acceptable flight dynamics and handling qualities. Achieving this goal requires overcoming adverse interactions involving the pilot, airframe, propulsion system, and flight control system. This report refers collectively to the last three as the APSE (aero/propulsive/servo/elastic) system.

Additional challenges are associated with the flight deck system (particularly with regard to the external visibility system [XVS]), community noise requirements (because minimizing noise involves design of the airframe, flight control system, and propulsion system), certification (because the FAA and industry need to understand how to certificate an aircraft that incorporates the advanced technologies being developed by the HSR Program), and aircraft operations (to examine the impact of HSCT characteristics, such as length, wingspan, and speed, on airline, airport, and air traffic control facilities and operations). Many of these integration issues are exceedingly complex, and final resolution will require in-flight testing (which would occur during the advanced technology demonstration phase recommended by the committee).

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[1] Additional information on program planning issues associated with systems integration appears in Chapter 6.

SYSTEMS INTEGRATION, FLIGHT DYNAMICS, AND CONTROL

Background

The design of the TCA, which is representative of the HSCT designs currently envisioned by NASA and industry, specify a very large aircraft. The structural weight and aerodynamic drag of this aircraft must be minimized to meet the flight performance requirements established by the HSR Program. As a result, aerodynamic stabilizing surfaces (such as the horizontal stabilizer) will be relatively small, and the vehicle will be dynamically unstable in one or both axes over at least a portion of the flight envelope. Thus, the flight control system will need to include high-authority, multiloop feedback control systems, both for basic attitude stabilization and for tailoring the vehicle's dynamic responses. This tailoring must deliver maximum range performance, superior handling characteristics, and excellent ride qualities.

The large size of the HSCT will also result in structural vibration mode frequencies[2] lower than for any existing aircraft. In fact *some vibration frequencies will be within the bandwidth of the pilot and the flight control system*. Hence, dynamic interactions between rigid-body and elastic responses of the airframe will be significant; piloted, ground-based simulations have already verified that these interactions will have an enormous and unfavorable impact on HSCT handling characteristics (Waszak, Davidson, and Schmidt, 1987; Coleman, 1996). Furthermore, these low-frequency elastic effects can lead to *catastrophic* pilot-vehicle dynamic coupling, and even low levels can produce unacceptable passenger discomfort. However, there is a dearth of flight-control design criteria (flying qualities criteria) for highly elastic aircraft, which further complicates the design challenge.

Gain stabilization[3] of low-frequency structural vibration mode frequencies will not be possible because of fundamental limitations on the achievable performance of feedback systems. (For the HSCT, the essential problem is the small difference in frequency between the unstable attitude mode[4] and the lowest structural vibration mode frequency, as shown schematically in Figure 5-1.) As a result, some active structural mode control[5] will be necessary. This mode control system would be *in addition to* any other higher-frequency active flutter-suppression system that may be required.

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[2] Structural vibration mode frequencies are the oscillatory frequencies of structural vibration. A given structure vibrates at certain frequencies unique to that structure.

[3] Gain stabilization is a technique employed in designing feedback control systems. It involves reduction of the gain, or amplification factor, of the feedback loop at certain frequencies.

[4] All dynamic systems can be described in terms of a combination of unique natural modes of motion (i.e., rotations and translations). If an aircraft is aerodynamically unstable, its fundamental rotational-attitude mode of motion is unstable, which in turn is characterized mathematically by a system eigenvalue that is a positive real number.

[5] Active structural mode control refers to a special feedback control system designed specifically to dampen structural vibrations.

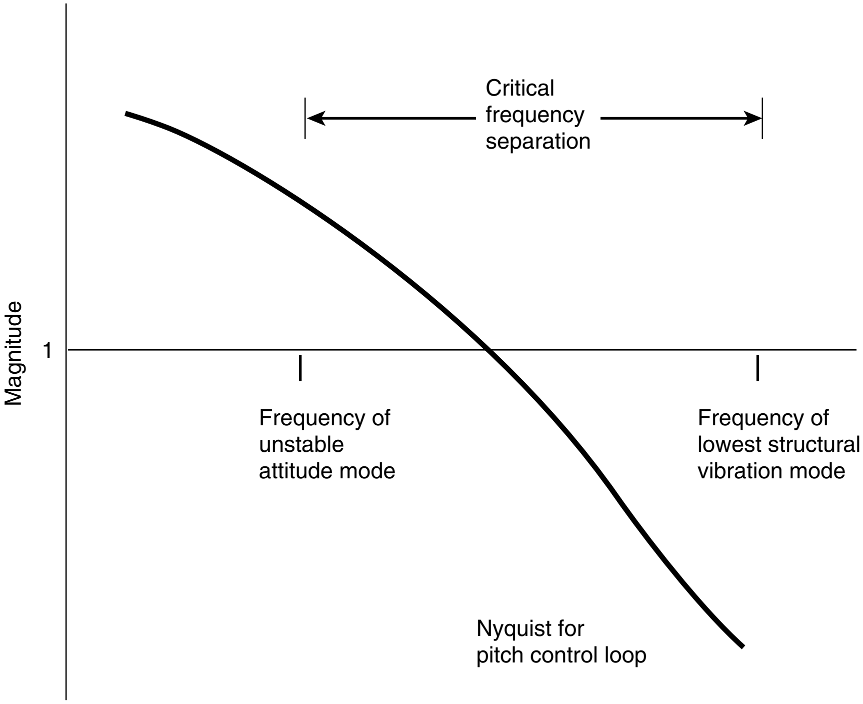

FIGURE 5-1 Difference in frequency between unstable attitude mode and the lowest structural vibration mode frequency of the TCA design.

Another area of concern is the amount of flow distortion at the engine inlets caused by non-zero side-slip angle or angle of attack. This distortion can induce an engine unstart.[6] The sudden loss of thrust caused by an engine unstart would cause additional excursions in side-slip angle and angle of attack, possibly causing other engines to unstart. To avoid this, either flow distortion must be regulated or the response of the aircraft to an unstart must be tightly controlled. In the event of an unstart, the ability to provide the necessary control depends a great deal on both the integrated feedback-system design and the magnitude of elastic deformations of the aircraft structure following the disturbance created by an unstart. A recent simulation study of an HSCT-like vehicle concluded that "structural flexibility effects are expected to be significant for aircraft controllability during unstarts" (Shelton and Harris, 1994).

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[6] See Box 3-1 for an explanation of engine unstart.

Aero/Propulsive/Servo/Elastic Phenomenon

Integration of the HSCT airframe, propulsion system, and flight control system produces a highly interactive multidisciplinary dynamic system, herein referred to as the APSE (aero/propulsive/servo/elastic) system. The ability of the flight crew to control the APSE system requires a tightly integrated flight-management/flight-control/propulsion-control system. Developing and certifying such a system is *completely outside industry's experience base*. Existing vehicles are either aerodynamically stable (e.g., the Concorde and B-1) or much smaller and rigid, with much higher structural vibration mode frequencies (e.g., fighter aircraft). HSCTs will be both unstable and highly flexible, with very low mode frequencies. This combination creates an incredibly difficult technical and organizational challenge.

Industry's limited experience base is not the only problem. The effort required to resolve APSE problems is huge and requires the close integration of a wide variety of technologies and organizations within the HSR Program. Flight-control design criteria are virtually nonexistent for highly flexible vehicles, and it is physically impossible to make a flexible structure behave dynamically as if it were rigid. In addition, the frequency spread between the TCA's unstable attitude mode and its first elastic mode may be too small to create a safe and effective control system because of a fundamental limitation on feedback control systems (i.e., Bode's integral). As a consequence, it is *possible* that the APSE system incorporated in the TCA may have design requirements for dynamic performance and stability robustness that are *unattainable*.

In other words, the structural flexibility of the TCA design simply may be too great. If this is true, (1) the flight control design requirements must be relaxed (e.g., to reduce the stability gain/phase margins[7]), which would make certification more difficult; (2) the level of aerodynamic instability must be reduced, which would reduce cruise L/D—perhaps as much as 4 percent; and/or (3) structural stiffness must be increased, which would almost certainly lead to an unacceptable increase in structural weight. For example, increasing stiffness enough to produce structural vibration mode frequencies similar to the B-1 would probably *more than double* the structural weight of the TCA design. In any case, the efficacy of the TCA design would be severely diminished. The committee believes that *this is an area of significant technical risk* and urges the HSR Program to develop and implement appropriate risk abatement strategies (including full-scale flight tests during the proposed advanced technology demonstration phase).

The HSR Program seems to perceive flight control and flight management as an area of low risk. For example, the HSR Program's list of top-level enabling

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[7] Feedback control systems must always meet certain design specifications on the degree of dynamic stability inherent in the feedback system. The degree of stability is measured in terms of "gain margins" and "phase margins." The greater the margins, the greater the degree of stability.

technologies (see Figure 1-1) does not include the development of analysis and design tools, techniques, or criteria applicable to dynamic control of a highly interactive aircraft design. Furthermore, structural-dynamic effects and APSE interactions were not included in either the process used to select the TCA design configuration or the piloted simulations used to define the desired dynamic characteristics of and specifications for the flight control system. As a result, the committee believes that the current TCA configuration does not adequately address APSE effects.

Although APSE effects may be of great concern to some members of the HSR flight-control technical community, control-law design activities in the HSR Program include little consideration of elastic effects. Also, the structures portion of the HSR Program has not identified low-frequency structural-dynamic interactions as a critical issue, and APSE considerations seem to be absent from the HSR Program's weight assessments.

APSE effects also seem to have been left out of the planning for the HSR Program's Aeroelastic Concept Engineering (ACE) Project, which only considers static-elastic deformations and classical aeroelastic flutter. APSE effects are related to entirely different phenomena, are much broader in scope, and have greater significance than the factors considered in the ACE project (see Figure 5-2). Addressing static deformations and traditional flutter adequately will be impossible until basic research discovers how to solve problems caused by APSE

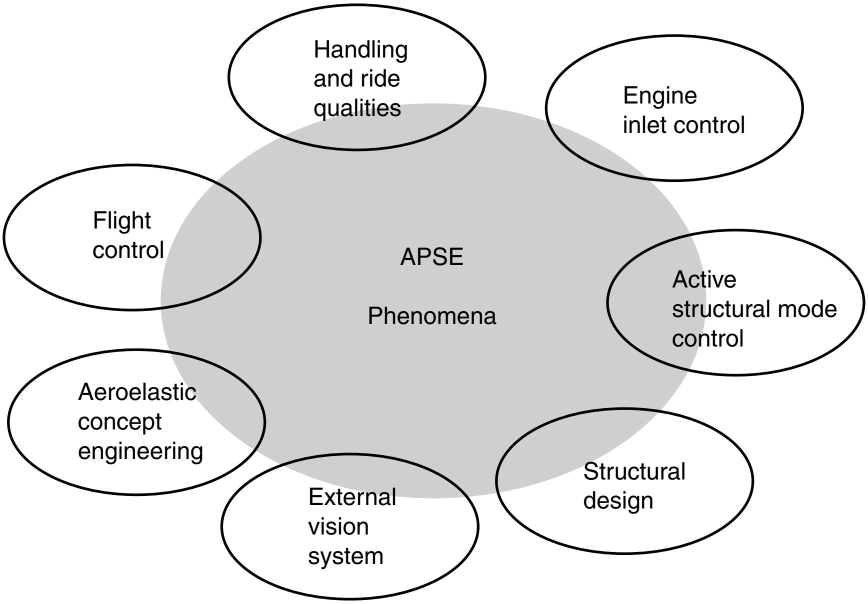


FIGURE 5-2 APSE effects interact with many other issues and design activities.

effects. The next step will be to develop techniques to incorporate this newly discovered fundamental knowledge into an appropriate (and perhaps quite different) multidisciplinary design methodology.

The committee noted that development of guidance and control systems is organizationally separate from the development of control laws; the former is in the flight deck organization, and the latter is in the aerodynamic performance organization. The committee could not ascertain why these groups, which have very closely related technical responsibilities, are not in the same organization. The organizational distance between the groups increases the possibility of miscommunication and unclear delineation of responsibilities.

Finding 5-1. An HSCT similar to the TCA will experience complex dynamic interactions involving the pilot and the APSE system, which includes the airframe (e.g., aerodynamic effects and elastic properties of the airframe structure), the propulsion system, and the flight control system (including the XVS). It is not yet clear how to design an HSCT that overcomes these effects and provides safe flying and handling qualities. Furthermore, the current HSR Program does not adequately address this problem.

Finding 5-2. The impact of APSE effects on flight dynamics and handling qualities may require changes in the aerodynamic and/or structural design of the TCA that would significantly reduce aerodynamic efficiency and/or increase structural weight, thereby reducing maximum range.

Finding 5-3. It is unlikely that the technical risk associated with APSE effects can be adequately addressed without building and flight testing an aircraft like the FAST (full-scale advanced supersonic technology) demonstrator.

Recommendation 5-1. The development of design tools and techniques for synthesizing and validating a highly integrated flight and propulsion control system and for properly addressing APSE effects on flight control and flight management systems should be established as a top-level research issue within the HSR Program during Phase II and the subsequent phases proposed by the committee. How to address APSE effects early in the aircraft-design cycle, before detailed structural models are developed, requires special attention.

Recommendation 5-2. The HSR Program should reevaluate the current TCA configuration in light of APSE effects. Because structural mode control will almost surely be required to achieve adequate flight dynamics and handling qualities, the optimum vehicle configuration may include additional and/or nontraditional aerodynamic surfaces. If necessary, such “control-configured” concepts should be included in future evaluations of aircraft design configurations.

Recommendation 5-3. An interdisciplinary team should be formed to fully address relevant aspects of the APSE problem, and the organizational distance between the groups responsible for (1) guidance and control systems and (2) control laws should be reduced or eliminated.

FLIGHT DECK SYSTEMS

Background

Aerodynamic considerations require that supersonic transports have a long nose that extends in front of the flight deck. This nose partly obscures the flight crew's forward vision. This is a significant problem during approach and landing because the flight crew cannot see the runway. Concorde supersonic transports have a moveable front section (i.e., a "droop nose") that is lowered during approach and landing to solve this problem (see Figure 5-3). This solution, however, adds significant weight and mechanical complexity to the aircraft design. The HSR Program intends to avoid these penalties by developing an XVS for the flight deck. The XVS would consist of external video and radar sensors, digital terrain databases, and displays mounted on the front bulkhead and instrument panels. The system would provide the flight crew with "synthetic vision" equal to or better than the unaided human eye through all phases of flight, including approach, landing, and ground operations. Like the flight deck systems on other large commercial transports, HSCT flight deck systems will be highly reliable and multiply redundant.

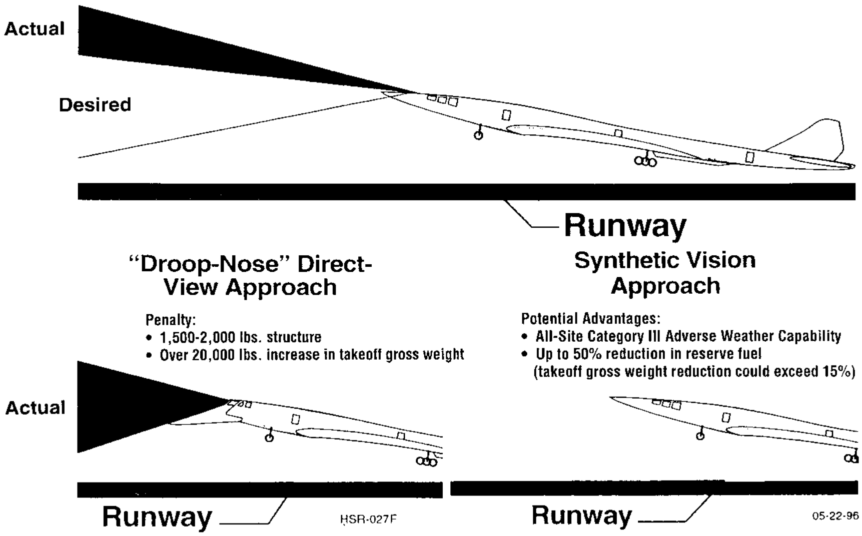


FIGURE 5-3 Droop nose versus synthetic vision for approach and landing. Source: NASA.

Flight Deck Displays

Two areas of the flight deck will display information to the flight crew: the forward bulkhead, which will be used in lieu of the front windows, and the front instrument panel. The front instrument panel will contain a series of displays similar to those found on today's newest subsonic aircraft, (e.g., the B-777 or A-340). Because this type of display is already in service, it poses minimal risk. The HSR design concept for the bulkhead displays uses a projection system (see Figure 5-4). Bulkhead displays have never been used on a commercial aircraft, and manufacturing a suitable projection display system will require technology that does not yet exist. Both types of displays are discussed in detail in the following sections.

Panel Mounted Displays

The HSR Program has selected active matrix liquid crystal displays (AMLCDs) as the baseline concept for the front instrument panel. AMLCDs are included in the designs of every new commercial and military aircraft, both fixed and rotary wing. In addition, a new display technology (field emission displays) may be mature by 2002 (Marticello and Hopper, 1996) and could be included by industry in the design of a commercial HSCT.

FIGURE 5-4 Artist's concept of one possible flight deck. Source: Boeing.

Because the HSCT flight deck will have a solid forward bulkhead instead of windows, the levels of sunlight will be somewhat reduced compared to conventional aircraft. As a result, HSCT flight deck displays will probably have reduced luminance requirements. Luminance requirements will be further reduced if the HSR Program succeeds in its effort to develop side windows that will darken automatically as a function of ambient light.

Bulkhead Displays

There are two alternatives for the design of the bulkhead display: (1) projection or (2) a "video wall" consisting of multiple panel-type displays (such as AMLCDs). Both alternatives are expected to be viable by 2002 (Hopper, Blanton, and Marticello, 1995). The HSR Program currently favors a projection system because of its potential to overlap the scenes from individual projectors, thereby creating a single, continuous, wide field-of-view image. A video wall of AMLCDs, on the other hand, would have visible seams between each AMLCD in the wall.

Display Resolution Requirements

HSCTs must provide a level of safety and performance that is equal to or better than other commercial transport aircraft in order to meet certification requirements and win the trust of airlines and airline passengers. This means the resolution of XVS displays must be comparable to the human eye. That is, the detail depicted by the XVS displays must enable the flight crew to see other aircraft and airfield features just as well (or better) than they could by looking through the windows of a conventional flight deck.

The resolution limit of the eye is 0.5 minutes of arc (Gille et al., 1994). However, empirical research within the HSR Program has determined that a resolution of 1 arc minute should be sufficient for visual tasks associated with the flight deck. Therefore, the XVS must have picture elements (pixels) that are no more than 1 minute of arc in size (as viewed by the flight crew), or 60 pixels per degree. Based on the field of view required by the TCA flight deck design, a minimum of about 7 million pixels will be required for the bulkhead displays.

The highest-resolution high-definition television (HDTV) requirement is 1,920 horizontal lines of video by 1,280 pixels per line, which corresponds to a total of about 2.1 million pixels (FCC, 1995). Four such displays would provide more than the 7 million pixels required for the XVS. In fact, the XVS concept currently under development by the flight deck contractor (Honeywell) fuses the output of four HDTV-quality cameras with four projectors into a tiled mosaic projection. If either the cameras or the projectors cannot provide the expected resolution, additional cameras and/or projectors will be required. This would increase system complexity and make it harder to create a single display image without unacceptable variations in brightness or discontinuities between the scenes created by individual projectors.

As an alternate approach for achieving HDTV-level resolution, the XVS could employ digital micromirror devices, which are under development by Texas Instruments. These devices use millions of micromirrors as the image-producing "engine" in the projector—one micromirror for each pixel. By 2002, advances in micromirror technology may enable construction of an XVS bulkhead display by combining four devices for each bulkhead display (just as four projectors would be combined to create a single bulkhead display large enough to meet the requirements of the HSR Program).

No full-scale, flight testable XVS system will be built as part of the HSR Program; Honeywell is demonstrating component feasibility only. A full resolution system (60 pixels per degree) will be simulated during ground tests at Langley Research Center. The HSR Program will also conduct flight tests of XVS technology using the Air Force's Total Inflight Simulator (TIFS) aircraft. These flight tests will use the highest resolution displays that can be obtained at a reasonable cost (i.e., commercially available displays). However, these displays will not offer the full resolution required for an operational HSCT system. As a result, the display configuration on the TIFS will require more than four projectors, which could make it more difficult to create a single, consistent display image.

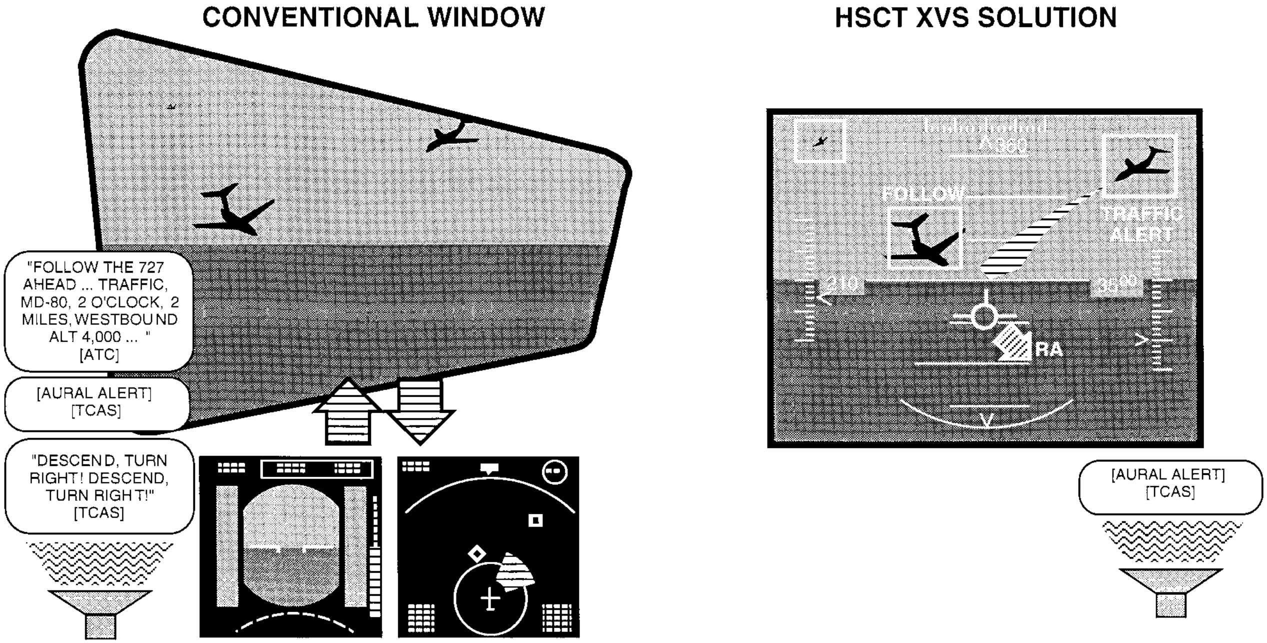
Flight Deck Program Challenges

The XVS will have the potential to help make the HSCT *safer* than current or future subsonic aircraft by creating visual meteorological conditions for the flight crew regardless of actual weather conditions. In order to achieve this goal, the XVS and other flight deck systems must, at a minimum, enable the flight crew to accomplish three crucial functions: avoid collisions with other aircraft; land the aircraft (even in adverse weather); and perform ground operations (e.g., taxi and position the aircraft at the gate).

Aircraft Avoidance

Three key components of the XVS will help the flight crew avoid collisions with other aircraft (see Figure 5-5):

- video cameras—high resolution cameras for takeoff, approach, and landing; and low resolution cameras for cruise
- Traffic Collision and Alerting System, which is currently available on subsonic aircraft
- X-band weather and windshear radar modified to detect noncooperative targets (i.e., aircraft not equipped with transponders) as small as a Cessna 150



- Head-down/head-up, eye refocus delays
- Requires dual alert modality (voice/visual)
- Visual search space not well defined
- Delays induced by pilot integration of head-down, head-up, and aural information
- Separate lateral and vertical terrain collision avoidance system (TCAS) resolution advisories (RAs)
- Difficult to validate RAs due to head-down/head-up transitions
- Often difficult to discriminate visually between threats and benign traffic

- All information head-up, eye refocus not required
- All critical information presented visually
- Visual search space minimized via calculated traffic designators and threat trajectories
- All information integrated in head-up format
- Integrated lateral and vertical TCAS RAs
- Easy to validate RAs with traffic search aids
- Reduced ambiguity by differentiating threats from other traffic
- Can be readily adapted for system to detect non-transponder equipped threats

FIGURE 5-5 Object detection and collision avoidance—conventional window versus external visibility system. Source: NASA.

As part of the HSR Program, a combined NASA-industry team headed by Langley Research Center has already flown variations of the X-band radar, and it plans to flight test an integrated system in 1999.

Studies by the HSR Program indicate that flight crew visual searches (with conventional windows) locate only 45 to 55 percent of other aircraft within terminal areas. The goal for the XVS is 99 percent; achieving this goal would constitute a significant safety improvement relative to conventionally equipped subsonic aircraft.

Ground Operations

Because the HSCT flight deck (and flight crew) is positioned so far forward of the nose gear (54 feet for the TCA design, compared to just 12 feet for the B-777), and because the HSCT flight crew will have no direct forward view, ground operations—such as taxiing—could pose a problem. The flight crew will not be able to see either the taxiway centerline or the taxiway itself during turns.

To investigate ground operations, the HSR Program is developing the Surface Operation Research and Evaluation Vehicle (SOREV) (see Figures 5-6 and 5-7).

The XVS on the SOREV will have bulkhead displays with a full field of view (as specified for the TCA). Like the TIFS, the SOREV XVS will use cameras, projectors, and displays with the highest resolution that is economically feasible (i.e., commercially available). Thus, the resolution of the SOREV XVS will probably be less than the goal of 60 pixels per degree. A lower resolution should be adequate for the SOREV, however, because ground tasks are less visually demanding than flight tasks. Construction of the SOREV is scheduled for completion during the summer of 1997. Initial testing will take place at a Boeing test facility in Seattle, Washington.

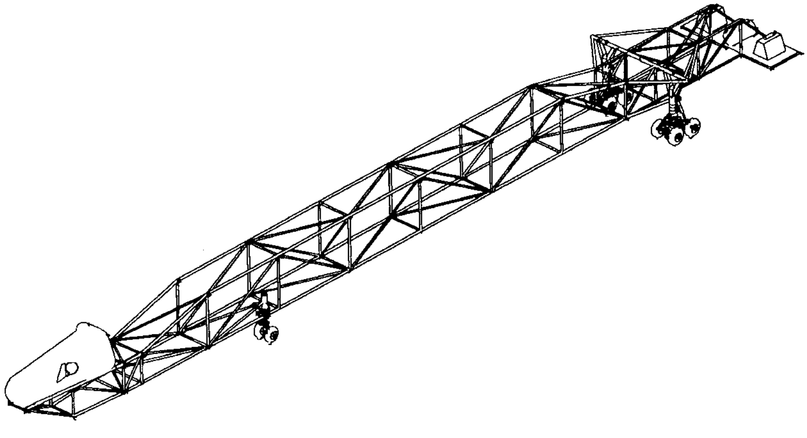


FIGURE 5-6 Surface Operation Research and Evaluation Vehicle (SOREV). Source: NASA.

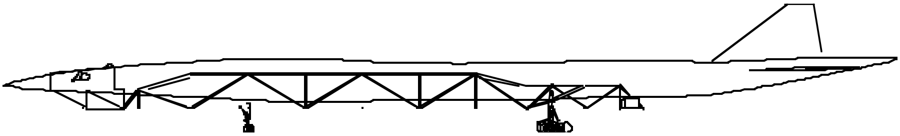


FIGURE 5-7 Comparison of the SOREV and TCA designs (side view). Source: NASA.

Adverse Weather Landing

Many aircraft landings have been made with limited or no external visibility. In the 1920s, Jimmy Doolittle made more than 100 landings with a hood to eliminate external visibility, and in 1929 he made a successful instrument landing in thick fog (Glines, 1989). Because of limited visibility through the cockpit windows, Charles Lindbergh used a periscope to land after his historic flight across the Atlantic Ocean. The Royal Air Force's Blind Landing Unit and the U.S. Air Force's All Weather Landing Program both have made numerous landings with severely restricted or no external visibility. All of these landings were made under very special circumstances (Lindbergh) or as part of research efforts designed to explore landing in poor visibility. There was no intention to develop a cockpit design that eliminated forward visibility during routine flight operations in clear weather. However, numerous landings have been made on blacked out runways at night by U.S. Air Force F-15E and F-16C aircraft using infrared images generated by the LANTIRN (landing, navigation and targeting–infrared, night) system.

The flight deck technology under development by the HSR Program is intended to enable HSCTs to land regardless of visibility. Under the worst visibility conditions (known as Category IIIc), the HSR Program anticipates that HSCT flight crews will monitor their aircraft while the on-board automatic landing system lands the aircraft. Subsonic transports already use similar systems, but the flight crew of an HSCT will have a visual image of the runway. In less severe conditions, the XVS is expected to allow flight crews to control their aircraft manually during approach and landing.

Redundancy and Graceful Degradation of the External Visibility System

The XVS will be the sole means of providing HSCT flight crews with forward visibility. Therefore, the XVS must be designed to operate reliably, with no catastrophic, total failures. (The level of reliability specified by the FAA for flight critical systems is 10^{-9}: one failure per billion flight hours.) One way to achieve this level of reliability is to provide redundancy with multiple backup components and subsystems. For the XVS, these would include multiple cameras, software processors, and projectors. In addition, the displays would be independent for each member of the flight crew to ensure that a failure in the displays for one pilot would not affect the displays for the other pilot.

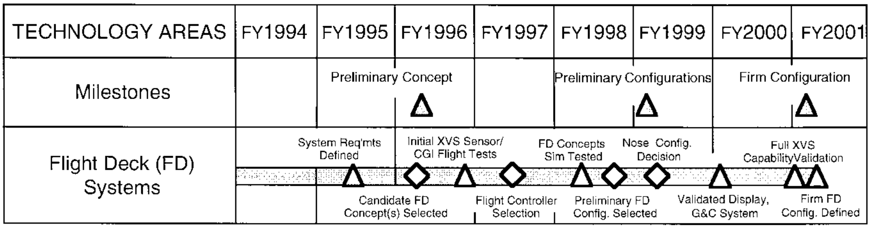
It is also critical that the XVS demonstrate graceful degradation so that failure of an individual component or subsystem would have minimal impact on the overall operation of the aircraft. For example, suppose each bulkhead display had two projectors, one showing primary flight control symbology on the upper portion, the other displaying a navigation map on the lower portion. If the display projector for the top portion fails, the other projector should automatically shift function and display primary flight symbology instead of the navigation map, because the map is of lower priority. Validating that the XVS includes adequate redundancy and graceful degradation would be done during the HSCT design, development, test, and certification process.

Flight Deck System Conclusions

Almost all HSCT flight deck system technologies already exist or will be developed by industry and government programs other than the HSR Program. Even so, determining how to integrate these technologies into a system that can provide the required levels of performance and reliability is a formidable challenge. The HSR Program expects the flight deck development schedule (see Figure 5-8) to achieve its goals by 2002. The committee views this as an aggressive schedule and believes that the flight deck will remain a high risk area until flight testing validates technical feasibility.

Finding 5-4. Validating the performance of the XVS and other key flight deck technologies being developed by the HSR Program is crucial to the public acceptance and economic viability of an HSCT. Flight testing XVS technology using displays with lower resolution than the resolution needed for an operational HSCT increases the risk that test results will be unsatisfactory, which could reduce public acceptance of the XVS design concept.

Recommendation 5-4. To address flight deck system risk adequately, the preliminary flight tests planned during Phase II of the HSR Program should be supplemented by additional flight tests during the proposed technology maturation and advanced technology demonstration phases. These additional flight tests should use displays with resolution equal to the resolution needed for an operational HSCT.



CGI = computer-generated imagery

FIGURE 5-8 Flight deck system program schedule. Source: NASA.

COMMUNITY NOISE

Community noise refers to noise during takeoff and landing, not noise associated with sonic booms. Because the HSCT will operate subsonically over populated land masses, the major noise requirements being addressed by the HSR Program are associated with certification standards and community noise levels. Determining whether noise levels of a particular aircraft satisfy certification standards is based on three ground measurements: sideline noise (which is measured during takeoff at a specified point to the side of the runway); cutback noise (which is measured at a specified point under the aircraft after takeoff); and approach noise (which is measured at a specified point under the aircraft prior to landing).

Allowable levels of aircraft noise are defined in Federal Aviation Regulations (FARs); current levels are referred to as "FAR 36 Stage 3." More restrictive noise requirements (a hypothetical and yet-to-be-defined "Stage 4") could be in place by the time an HSCT is ready for certification. Thus, the HSR Program is striving to meet *and exceed* Stage 3 noise goals.

All major U.S. airports have filed environmental impact statements for community noise. These statements are based on Stage 3 noise standards, but they are community specific because they define the ground area that is impacted by aircraft noise. Airports are required to file a revised impact statement if the size of this area increases by more than 17 percent. The HSR Program has established noise goals for the HSCT that will not exceed this threshold, based on a traffic analysis of five major airports and assuming a global fleet of 500 HSCTs. These noise goals are more restrictive than Stage 3 noise limits and are referred to as "Stage 3-X," where "X" represents the amount of additional reduction (in decibels) that is required in sideline, cutback, or approach noise. The HSR Program's current noise goals are Stage 3-1 for sideline noise, Stage 3-5 for cutback noise, and Stage 3-1 for approach noise. Cutback noise is currently the limiting condition driving noise-reduction efforts.

High-specific-thrust engines optimized for supersonic cruise have high jet velocities and are inherently noisy. Thus, unconventional designs for the engines and/or nozzles are required to meet the HSR Program's noise goals while providing acceptable subsonic and supersonic cruise performance. The HSR Program is using a multidisciplinary approach to meet these goals without exceeding the MTOW for an economically feasible design. This approach combines advanced engine cycles (such as a mixed flow turbofan) with a high thrust-to-weight ratio; advanced nozzle designs (mixer-ejector technology); advanced high lift devices (flaps); and specialized operational procedures (that allow engine power—and noise—to be reduced as soon as possible after takeoff).

The committee believes that the greatest risk associated with noise is not technical; it is the political risk that during the time it will take to develop an HSCT, noise standards will be lowered beyond the point that is feasible for an economically viable HSCT design.

Finding 5-5. HSCTs must be able to meet applicable regulatory noise standards. However, the HSR Program has established appropriate noise goals and is using an effective approach to achieve them.

CERTIFICATION

Certification is a critical issue for the HSR Program. Before making a product launch decision on any aircraft, industry must be confident that the FARs will permit timely certification of the aircraft design. For certification of an economically viable HSCT design, however, some regulations will need to be modified. This can be a lengthy process, especially in situations involving advanced technologies (such as those under development by the HSR Program) if additional data is needed to determine what certification standards are appropriate and how industry and the FAA can ensure that an aircraft design meets those standards. Thus, early action should be taken to understand and resolve certification issues associated with HSR technologies.

In January 1994, the FAA prepared a proposal for developing a long-range plan for certification of an HSCT. On September 13, 1995, NASA and the FAA signed a memorandum of agreement to formally initiate a cooperative program to address certification issues. The agreement states that the FAA will form a team of certification specialists to do the following:

- Evaluate HSR Program technologies for safety, reliability, regulatory compliance, and economic impact relating to certification.
- Work with NASA to plan research necessary to develop a certification basis for new and unique HSCT technologies.[8]
- Develop a preliminary certification basis by 1998 and a final basis by 2001.

NASA agreed to do the following:

- Provide the FAA with research data to support development of an HSCT certification basis.
- Integrate key certification issues into the HSR Program.
- Establish a certification issues program element in each of the key technical disciplines (viz., aerodynamics, structures and materials, flight deck, propulsion, and environmental impact).

As of April 1997, the FAA had established Certification Issues Coordination Teams (CICTs) for the flight deck, propulsion, structures, and noise/emissions (i.e., environmental impact); a fifth CICT for aerodynamics will be established

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[8] A certification basis consists of (1) a minimum set of airworthiness standards that an aircraft system design is required to meet and (2) the acceptable means of demonstrating compliance with those standards.

later. The CICTs are identifying specific certification issues related both to the designated system areas (e.g., flight controls and propulsion system) and to broader areas (e.g., safety, manufacturing, and operations). For example, the CICT for the flight deck is using ground simulators (at Langley Research Center, Ames Research Center, Boeing, and McDonnell Douglas) and the TIFS aircraft to examine HSCT certification criteria for collision avoidance, ground operations, manipulation of control surfaces during takeoffs,[9] and other areas related to certification of an HSCT flight deck and the XVS. However, it is not clear how future activities by the CICTs will relate to other HSR Program activities.

Even when appropriate regulations are in place, the certification program for an advanced aircraft can be a lengthy and costly process, typically lasting five years for a subsonic commercial transport. Resolving critical technology issues is required to support timely approval of an HSCT certification basis and to avoid excessive delays during the HSCT certification program. This is especially important because of competitive pressures on manufacturers to shorten the aircraft design and development time and get products to market quickly.

Recommendation 5-5. The FAA and NASA (i.e., the HSR Program) should develop and periodically update a master certification plan that supports timely resolution of key HSCT certification issues and shows how the activities needed to resolve these issues are related to other HSR Program efforts.

AIRCRAFT OPERATIONS

The TCA design anticipates an HSCT that is significantly different from any subsonic aircraft because of its extended length (more than 80 feet longer than the largest subsonic aircraft currently in commercial operation), large delta wing, and high speed. Differences like these could have a significant impact on airline, airport, and air traffic control operations.

To be successful, the technologies developed by the HSR Program must be compatible with an HSCT design that is reasonably compatible with existing airline operating procedures, airport facilities (including taxiways), and air traffic control procedures. This does not mean that an HSCT should not require any modifications to current facilities, systems, or procedures. However, before an airline commits to purchasing HSCTs, and before a manufacturer agrees to build them, incompatibilities will need to be identified and evaluated. Industry has conducted several studies for this purpose. Although often anecdotal in nature, these studies have identified several areas of concern, including the following:

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[9] As noted in the previous section, special operational procedures are one approach to minimizing cutback noise. These procedures would allow the throttles and flaps to be continuously repositioned after takeoff, maximizing aerodynamic performance of the wing and reducing engine power (and noise). Although these practices are standard on some military aircraft, they are not allowed on commercial transports for safety reasons.

- *Deicing.* Deicing fluids are used to remove snow and ice from the wings of aircraft prior to takeoff. Holdover time is the maximum allowable time between the completion of deicing and takeoff. Holdover times are reduced for large aircraft because there is more time for snow and/or ice to accumulate on portions of the aircraft that were deiced first. The TCA design configuration has a delta wing with about twice as much surface area as a large subsonic aircraft, such as a Boeing 777. It will take more time to deice HSCTs than subsonic aircraft, and new equipment or procedures may be needed to ensure holdover times are not reduced below operationally acceptable times.
- *Fueling.* The HSCT will require four in-ground fuel pits per gate; subsonic transports require just one.
- *Airport gates.* The HSCT will fit in a Boeing 747 gate when parked at an angle. However, 747 gates used for HSCT operations will probably require modifications for jet bridge positioning (in addition to the extra fuel pits), and these modifications may reduce the number of aircraft positions at some airports. Also, HSCT door sill heights, which are significantly higher than subsonic transports, will require modifications to existing jet bridges. However, there is ample precedent for airports to modify existing gates or to construct new gates to accommodate new classes of aircraft.
- *Taxi.* The distance between the cockpit and nose gear (see the previous section on XVS ground operations) will probably require new taxi procedures. Also, depending on the taxi philosophy adopted, many taxiway turns may require fillets.
- *Air traffic control.* The difference in cruise and climb speed between HSCTs and subsonic transports will require changes in current procedures and regulations.

Studies to date do not indicate that conceptual changes in the TCA design are required to meet operational needs of airlines, airports, or the air traffic control system. However, the committee believes that additional studies are needed to assess potential incompatibilities accurately, and the time, cost, and impact of corrective action. These studies should include dialogues with airlines, airport operators, and air traffic controllers to develop cost-effective, community-acceptable solutions. These solutions may not impact the TCA/TCn design, but they are likely to improve the prospects for early acceptance of HSCTs by airlines, airport operators, and air traffic controllers.

Lessons learned from operating experience with the Concorde will provide some useful information for addressing HSCT compatibility issues. However, an HSCT will be quite different from the Concorde in terms of design, the size of the expected fleet (500 for an HSCT, whereas only 13 Concorde aircraft remain in commercial service), and environmental requirements (the Concorde is exempt from community noise standards, and NO_x engine emissions are four times higher than the goal for the HSCT). Thus, solutions used for the Concorde will not necessarily apply to an HSCT.

Finding 5-6. The design and operating characteristics of an HSCT will require some changes in airline, airport, and air traffic control system facilities and procedures. However, making changes to airport facilities (including taxiways) and air traffic control procedures, although technologically simple, may be difficult from a funding and environmental/community acceptance perspective. Failure to anticipate problems and make required changes could reduce HSCT market demand below current estimates.

Recommendation 5-6. During the recommended advanced technology demonstration phase, industry and the HSR Program should identify and evaluate changes in airline, airport, and air traffic control system facilities and procedures that may be required to accommodate an HSCT. In particular, industry should conduct a detailed study of infrastructure issues at key airports worldwide that an HSCT is expected to service. As a first step, these issues should be included in the recommended effort to validate HSCT market size (see Chapter 2).

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6

Summary of Program Planning Issues

The HSR Program is well managed and is making excellent progress in resolving many key issues, especially with regard to predicting and reducing the potential impact of HSCTs on the environment. By 2002, the program will have resolved many foundational questions regarding the technical feasibility of producing an economically viable HSCT. Furthermore, the committee believes that Phase II will produce an important, broadly applicable technological legacy regardless of industry's decision about proceeding with commercial development of an HSCT.

To a large degree, the successes of the HSR Program are the result of committed program leadership that has made effective use of management tools to overcome the challenges inherent in such a complex enterprise. Even so, the committee believes some changes are necessary if the program is to achieve all of its stated objectives.

The HSR Program is developing technologies that support both products and processes. Product technologies tend to represent traditional engineering and research disciplines, such as aerodynamics, thermodynamics, structures, and materials. These areas are all important, but so are the process technologies that will be essential for the technologies developed by the HSR Program to find practical application on an HSCT. Process technologies, such as system integration, manufacturing, and certification, will be critically important to industry as it prepares to make an HSCT product launch decision. To be effective, development of process technologies must be guided by metrics, such as affordability and producibility, that are not key factors in many research programs.

The committee found that the HSR Program has made excellent progress with most product technologies. Additional efforts are needed, however, to make the same sort of progress with process technologies, which in many cases is significantly more difficult, especially with the resources currently available to the HSR Program. For example, the difficulty of resolving system integration issues involving the engine, flight deck, and APSE system has led the committee to conclude that Phase II (which is scheduled to be the final phase of the HSR Program) should be followed by two additional program phases. Moreover, the second of these new program phases should include flight testing of a full-scale technology demonstration aircraft.

This chapter contains the committee's major recommendations for enhancing the effectiveness of the HSR Program. Implementing these recommendations will require reallocating resources within the HSR Program and, in order to continue the program after Phase II, obtaining additional resources.

GENERAL PROGRAM PLANNING ISSUES

National Importance of Aeronautics Research

The United States has benefited greatly from past investments in the military and civil aerospace industry. Aerospace research has created high quality jobs and stimulated advances in science and technology at many institutions of higher learning. The aerospace industry produces a larger positive balance of trade than any other U.S. industry. The safety, efficiency, and affordability of the air transportation system stimulates U.S. business activity domestically and internationally and enables leisure travel that makes an important contribution to our quality of life.

The technology being developed by the HSR Program represents another opportunity for the United States to capitalize on its leadership in aerospace technologies. Investing in advanced civil aeronautics research is especially important given recent reductions in the level of military research. Also, although the HSR Program is focused on the development of an HSCT, the committee believes that the advanced engine and airframe materials, flight deck systems, and other technologies would be readily applicable to other commercial and military aircraft. Nonetheless, like many other high payoff opportunities, the HSR Program is a high-risk undertaking. Success depends on a vigorous research program with the time and resources to reduce risk significantly in all critical areas.

Major Finding 1. The current HSR Program is making excellent progress. Achieving program objectives is a necessary precursor to the development of a U.S.-built HSCT and would develop important new technologies with broad applicability throughout the aeronautics industry.

Vision Statement

As noted in Chapters 1 and 2, the committee views the HSR Program's vision statement as over-specified and unattainable by the current program plan.

The vision statement requires the technology under development to enable industry to make a product launch decision in 2006 for an "environmentally acceptable, economically viable, 300-passenger, 5,000 n.m., Mach 2.4 aircraft." This vision does not allow for necessary trade-offs. The essential qualities of a successful HSCT will be environmental acceptability and economic viability. Yet the vision statement includes a timetable and a specified set of payload, range, and speed requirements as equally important parameters. Although the timetable and performance requirements help to focus technology development, the committee believes they increase overall program risk by threatening the ability to achieve the most important objectives—environmental acceptability and economic viability. For example, a cruise speed of Mach 2.4 provides some operational advantages over lower speeds, such as Mach 2.0 or 2.2. However, as discussed below and in Chapter 4, Mach 2.4 also requires developing a new class of airframe materials. However, the HSR Program simply may not be able to develop materials in this class suitable for application to an HSCT. A revised vision statement could help guide the allocation (or reallocation) of resources to the most critical tasks.

Major Recommendation 1. The HSR Program should adopt a new vision statement that emphasizes top-level *requirements* (i.e., safety, environmental acceptability, and economic viability) to encourage a more balanced technical approach to achieving aircraft performance *goals* (i.e., speed, range, and payload). The committee suggests the following:

> Develop high risk, critical, enabling technologies in conjunction with complementary industry investments to support the timely introduction of a Mach 2.0-plus HSCT. These technologies must lead to an environmentally acceptable, economically viable aircraft, with safety levels equal to or better than future subsonic transports. Successful completion of the NASA and industry programs will provide the technology foundation industry needs to proceed with the design, certification, and manufacture of an HSCT.

Revised Program Plan

The HSR Program is scheduled to end in 2002 when Phase II is completed. As discussed in previous chapters, the magnitude of the technical challenges—along with schedule and resource constraints—will prevent Phase II from achieving important aspects of the program vision (based on either the current vision statement or the revised statement suggested by the committee).

The most effective way to overcome this problem is to adjust the content of the Phase II program and, more importantly, extend the HSR Program by instituting two new phases: a technology maturation phase and an advanced technology demonstrator phase. These new phases would enable the HSR Program to implement the committee's other recommendations for mitigating program risk in specific technology areas. Most importantly, however, the new phases would allow the HSR Program to achieve its ultimate objective of enabling industry to make an HSCT product launch decision.

Phase II

The Phase II program, as currently planned, is conducting technology research, development, and demonstration. All three are needed to meet the technical challenges generated by the vision statement and to enable industry to make a product launch decision. However, the existing schedule, which is driven by the program end date of 2002, does not allow enough time to validate new technologies before beginning component fabrication and testing. Adding a technology maturation phase would allow the HSR Program to reduce greatly the overlap in technology development and technology demonstration, thereby significantly reducing the risk inherent in both. In other words, the committee believes Phase II should focus more tightly on technology development and defer work on some technology maturation issues (such as fabrication of full-scale components) that the committee believes are being addressed prematurely.

As discussed in Chapter 2, affordability is the most important parameter the HSR Program should address. The other areas of greatest importance, many of which are closely linked to affordability, are as follows:

- airframe service life
- dynamic interactions among the airframe, propulsion system, and flight control system (APSE effects)
- engine emissions
- engine service life
- manufacturing and producibility
- range

Experience with high risk, technology-driven development programs for advanced supersonic aircraft has shown that development of engine technology must lead development of airframe technology by at least three years in order for the propulsion system to be ready for first flight at the same time as the airframe. Thus, the Phase II program should also be revised to accelerate the propulsion system's level of technological readiness relative to the airframe.

To make efficient use of available funding, Phase II should be adjusted as described above, even if the recommended technology maturation and advanced technology demonstration phases are not implemented. The committee does not believe that Phase II alone can achieve the program's current goals regardless of how it is structured. The recommended changes to Phase II will maximize the quality and usefulness of its results for the eventual development of an HSCT and for other advanced aeronautics development efforts in the meantime.

Technology Maturation Phase

The technology maturation phase would continue the work of Phase II by ground testing full-scale components and systems—including two full-scale demonstrator engines. Areas of special emphasis would be the impact of scaling to full size, integration, manufacturing and producibility, durability, and certification planning.

Integration and testing of full-scale engines is especially important to ensure that the propulsion system technologies will be ready for flight testing at the same time as the airframe and integrated aircraft systems. Providing the resources necessary to integrate and test two full-scale demonstrator engines is essential, even if this means lowering the TRL goals for some lower priority and lower risk program elements.

Advanced Technology Demonstration Phase

The technical difficulty of building an economically viable HSCT is similar in magnitude to the difficulty of developing the advanced reusable launch vehicles currently envisioned by NASA. Just as flight tests of the X-33 are intended to demonstrate the feasibility of launch vehicle technology, the committee believes that flight tests of a FAST (full-scale advanced supersonic technology) demonstrator are necessary to show that the propulsion, airframe, and system technologies under development by the HSR Program can, in fact, be reasonably counted on to form the basis for a fully integrated vehicle that can meet commercial standards for reliability, maintainability, and availability. Therefore, the committee recommends that NASA and industry jointly support an advanced, full-scale technology demonstration phase similar to the X-33 program.

The FAST demonstrator would not be a prototype or preproduction aircraft; it would primarily address critical HSR technologies. After the completion of the technology maturation and advanced technology demonstration phases, the level of risk—and the investment required by industry to produce an operational aircraft—will still far exceed the risk and cost of any previous effort to develop a commercial transport. Nonetheless, the committee believes that the FAST demonstrator would enable industry to make a launch decision. In addition, the FAST demonstrator would serve as a classic aerodynamic demonstrator and provide the U.S. aeronautics community with invaluable information on the utility and performance of the technologies under development by the HSR Program.

Formal product launch and product development would not occur until the end of the advanced technology demonstration phase. However, before proceeding with the advanced technology demonstration phase, industry should make a preliminary commitment to commercial development of an HSCT. The requirement for industry to co-fund the FAST demonstrator would provide firm evidence of industry's confidence in its ability to use the results of the expanded HSR Program to produce a marketable HSCT.

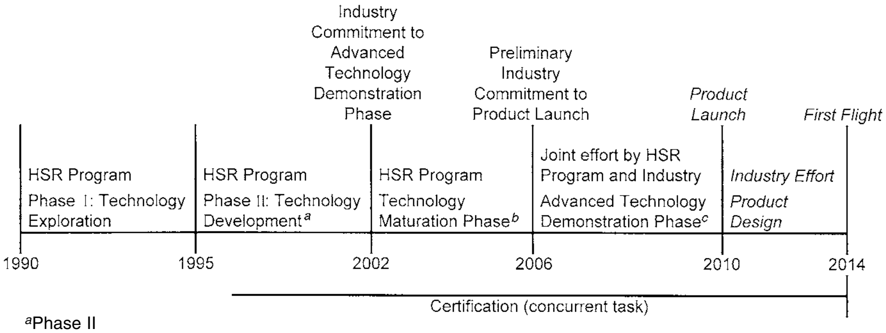
The current HSR Program is expected to cost a total of about $1.9 billion. Completion of the technology maturation and advanced technology demonstration phases would probably cost additional billions. Although the committee believes the HSR program is technologically worthwhile, a final decision to make an expenditure of this magnitude requires careful consideration of economic and budgetary factors that were outside the scope of this study and are not examined in this report.

Major Finding 2. The goal of the HSR Program is to provide the technology foundation that industry needs to make an HSCT product launch decision. Without an extended period of technology maturation and advanced technology demonstration, the HSR Program will not achieve this goal.

Major Recommendation 2. To accomplish HSR Program objectives, the program should be restructured in accordance with Figure 6-1. The recommended changes to Phase II should be implemented without waiting to determine if the technology maturation and advanced technology demonstration phases will be approved and funded.

AFFORDABILITY

The HSR Program should put more emphasis on affordability. Currently, the program concentrates on weight as the primary metric for economic viability. However, in many cases lowest weight does not equate to minimum cost, especially



[a]Phase II

- Focus more on technology development, deferring work on technology maturation, such as fabrication of full-scale components
- Focus on specific technologies related to affordability, airframe durability, APSE effects, engine service life, manufacturing and producibility, engine emissions, and range.
- Accelerate the propulsion system level of technological readiness relative to the airframe

[b]Technology Maturation Phase

- Fabricate and test full-scale demonstrator engines.
- Ground test two full-scale demonstrator engines.
- Focus on the impact of scaling to full size, integration, manufacturing and producibility, and certification planning

[c]Advanced Technology Demonstration Phase

- Flight test a full-scale advanced supersonic technology (FAST) demonstrator

FIGURE 6-1 Comprehensive risk reduction program leading to program launch.

for flight deck systems and the lightweight, high-strength, high-cost materials under development by the HSR Program. For example, weight-based assessments of economic viability could favor the selection of a design approach that does not adequately consider issues such as inspectability, maintainability, or repairability, even though these factors can have a significant impact on affordability. The committee believes that the HSR Program's integrated product teams should use affordability as a primary evaluation criteria and technology objective. For example, the economic viability of the HSCT will primarily be a function of cost per available seat mile;[1] this parameter is of vital interest to the airline industry (i.e., the customer), and it should be of equal importance to the HSR Program. As shown in the "roof" of the QFD matrix (Figure 2-1), affordability is related to most other key product and process characteristics, and developing an accurate estimate of cost per available seat mile will involve almost all HSR technologies.

Cost per revenue passenger mile (i.e., the cost of transporting a single fare-paying passenger one mile) is an economic parameter that has an even more direct impact on airline economics than cost per available seat mile. However, unlike cost per available seat mile (which is based on the seating capacity of the aircraft), cost per revenue passenger mile depends on the average number of seats occupied by fare-paying passengers. Thus, cost per revenue passenger mile is a function of airline-specific variables, such as route structure and pricing policy, and it would be difficult for the HSR Program to use cost per revenue passenger mile as a design parameter. In addition, individual airlines prefer to generate their own estimates of cost per revenue passenger mile (based on an accurate estimate of cost per available seat mile provided by the aircraft manufacturer).

Major Recommendation 3. The HSR Program should increase the role of affordability (and related factors, such as inspectability, maintainability, and repairability) in evaluating the merit of alternate technology approaches, system design concepts, and vehicle configurations. Cost per available seat mile should be adopted as the key affordability metric. The technology management teams and ITD (Integrated Technology Development) teams should understand the impact of their technology and system choices on affordability/cost per available seat mile.

Technology Audit Metrics

The HSR Program uses technology audit metrics for each program element to set goals and track progress in terms of TRL (Technology Readiness Level). The stated goal of the HSR Program is to advance all technologies under development to a TRL of 6, which is defined as "system/subsystem model or prototype

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[1] An available seat mile is a measure of aircraft utility proportional to seating capacity, speed, and the average number of flight hours per day.

demonstrated in a relevant environment." Advancing all technologies to the same level of technology readiness does not account for variations among different technologies in terms of technical risk, integration difficulties, or the manufacturing and test lead times required for first flight.

Cost and schedule constraints have made it impossible to achieve TRL 6 for all program elements during Phase II. However, the decision to lower the TRL goals for some areas seems to have been driven by cost and time rather than by a systematic assessment of overall program priorities, relative risk, etc. Such an assessment might indicate that TRL goals should be lowered for some additional elements in order to free resources for more important elements.

The committee believes that the tracking process should be simplified by selecting broader top-level metrics in some areas. For example, the status of airframe structures and materials is currently tracked using areal weights for four different aircraft sections; a single top-level metric would probably suffice. In other cases, the tracking process should use more sophisticated audit metrics; as already discussed, affordability should be tracked using an economic factor (cost per available seat mile) in addition to weight.

The committee used its own metrics in the QFD analysis documented in Chapter 2 (see Figure 2-1). Wherever practical, the committee used characteristics in the QFD matrix that are also being tracked by the HSR Program. However, in some cases the characteristics used by the committee are at a higher level, as in the propulsion technologies category. More importantly, the committee determined that additional characteristics should be used to track the overall progress of the HSR Program. Many of these, such as certification, manufacturing, utilization, and affordability, are related to processes that can only be addressed by a combination of technologies.

Major Recommendation 4. The HSR Program should reevaluate the TRL goals assigned to each technology audit metric and ensure that they are coordinated across the program. NASA should conduct a QFD analysis (see Chapter 2) to validate the choice of metrics and their assigned TRL goals.

Interdependencies

The HSR Program plan does not seem to account adequately for interdependencies among the technologies and processes needed for an environmentally compatible and economically viable HSCT. As indicated by the results of the committee's QFD analysis, there are a great many of these interdependencies. Consider the following examples:

- Airframe and engine durability are functions of the manufacturing processes required to produce the new materials under development. Thus, the impact of manufacturing requirements on technical risk and affordability should be considered in conjunction with the development of new materials. In fact, the economic viability of the HSCT design envisioned by the HSR Program cannot be determined without an integrated materials development and manufacturing technology program.

- Airframe flexibility affects flight control design and handling qualities. Thus, to achieve satisfactory handling qualities, it may be necessary to increase airframe stiffness, which would increase structural weight.
- Flight control problems caused by engine unstarts impose stringent requirements on the flight controls system and on aircraft stability.

Major Recommendation 5. The HSR Program plan should be revised to place more emphasis on the interdependencies inherent in the program. The revised plan should explicitly identify major interdependencies between the propulsion system, airframe, integrated aircraft systems, and process areas, such as certification and manufacturing. These interdependencies should be reflected in a time-phased, integrated plan that takes into account industry-funded research and development, as appropriate. Early emphasis should be put on technologies with longer development lead times. The plan should also specify a risk reduction approach for each program element with moderate or high risk.

Industry Data Sharing

As described in Chapter 1, the HSR Program uses integrated product and process teams to plan, execute, integrate, and oversee program activities. Industry participation in these teams improves the coordination and communication between NASA and industry, providing industry with excellent insight into activities by NASA personnel and the data they generate.

On the other hand, the committee noted a less-open attitude by industry partners regarding the sharing of data from their internal research. Although industry-funded HSCT research is not a formal part of the HSR Program, it is important to coordinate HSR Program activities with research by industry to avoid duplication of effort and to ensure that the design concepts, technologies, and processes under development are compatible. To a large extent, industry participation on the integrated product and process teams accomplishes this because the industry participants are familiar with HSCT research by their companies. However, this still limits the ability of NASA managers to make fully informed decisions or verify that the government's money is being spent most effectively.

Industry concerns about releasing proprietary information place some limits on how much HSCT research data industry will divulge to the government. Nonetheless, the joint government-industry aspect of the HSR Program could be significantly enhanced by giving greater visibility to industry's HSCT development activities. In particular, the proposed revision to the program plan (see Major Recommendation 5) should be jointly developed by NASA and industry, and it should reflect industry's investment in HSCT research.

Major Recommendation 6. Industry participants in the HSR Program should grant NASA increased access to internal HSCT research, and the HSR Program should include appropriate information in its planning and oversight process.

PROGRAM EXECUTION

This section discusses issues associated with execution of the airframe, propulsion, and integrated aircraft elements of the HSR Program.

Airframe[2]

Full-Scale Component Tests

Currently, the HSR Program plans to conduct full-scale tests of airframe and engine components using surrogate materials and surrogate manufacturing processes. For example, hand layup is being used in lieu of machine layup for testing some airframe composites, even though this changes the fundamental characteristics of the material. And in the engine, tests of both the combustor and nozzle will use surrogate materials. The primary objective of full-scale tests is to verify the functionality and durability of candidate materials in their intended use. Using surrogate materials and processes misses the point and minimizes the relevance of the test results (especially if the candidate material cannot be successfully developed). Component tests are expensive, and they should be timed to maximize the value of the data they generate.

Major Recommendation 7. Instead of using surrogate materials, full-scale component tests should be delayed until ongoing material development efforts can supply the materials intended for use in those components. The HSR Program should work with industry to develop preproduction manufacturing processes to manufacture test components. Implementing the recommended technology maturation phase would provide the time needed to implement this strategy.

Manufacturing Technology and Materials Durability

The HSR Program should significantly increase the emphasis on manufacturing technology and material durability. The committee does not believe that the program can obtain a satisfactory understanding of the cost and durability of new airframe and engine materials without testing full-size components that have been subjected to the rigors of the manufacturing process. (As discussed above, it is essential for this testing to be preceded by successful development of materials and manufacturing technology.)

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[2] Additional information on the airframe appears in Chapter 4.

Life prediction techniques for new HSR materials are not yet available. Until they are, the resulting uncertainty makes an HSCT launch decision unlikely. In particular, little is known about the durability of CMCs (ceramic metal composites) and other coated materials for the propulsion system or about the durability of structural composites and adhesive bonding for the airframe. During Phase II, the HSR Program only plans to develop the capability to fabricate subscale components, with only a hand layup capability for composites. The committee believes that this is inadequate because it does not accomplish the objective of TRL 6, nor does it provide the technology base needed for industry to make a program launch decision.

Major Recommendation 8. The HSR Program should demonstrate adequate materials durability and complete the development of manufacturing technology during the recommended technology maturation phase. In particular, the HSR Program should develop test methodologies suitable for validating an airframe service life of 60,000 hours. These methodologies would have wide application throughout the aeronautics industry.

Propulsion[3]

Combustor and Emissions

As discussed in Chapters 2 and 3, engine emissions is one of the most important HSCT design requirements. An advanced combustor that provides satisfactory engine performance while ensuring ultralow levels of NO_x emissions is an *essential* element of an environmentally acceptable HSCT. This is a challenging technical problem, and developing an acceptable combustor is the HSR Program's most critical propulsion technology.

The development of ultralow NO_x combustor technology requires major advances in both combustor design and material technologies. Testing a subscale core engine, which is part of the current Phase II program plan, will provide a much needed opportunity to evaluate combustor performance and operability. However, these tests will not address uncertainties about how these characteristics change as a function of scale. Thus, dedicated tests of a full-scale demonstrator engine should be conducted during the recommended technology maturation phase to evaluate and, as necessary, guide continued development of the selected combustor design.

It is also important to establish a phased development schedule that verifies material performance before moving ahead with combustor fabrication and testing. This approach will mitigate the high risk inherent in this effort by identifying and resolving problems as early as possible, ensuring that unsuitable materials

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[3] Additional information on the propulsion system appears in Chapter 3.

are not used in component or system testing. The current schedule does not provide enough time for such an approach.

Major Recommendation 9. The HSR Program should develop a more comprehensive testing and risk mitigation strategy for the combustor that extends into the recommended technology maturation phase and includes combustor testing in a full-scale demonstrator engine. Because satisfactory combustor performance is essential to program success, additional resources should be devoted to development of combustor technology during Phase II, if necessary.

Component Scale-Up and Integration

The HSR Program does not seem to recognize the critical importance of engine component scale-up and integration. The committee firmly believes that testing a full-scale engine is absolutely necessary to verify that the new materials, technologies, and design concepts developed by the HSR Program are feasible—and to enable industry to make an HSCT product launch decision. Based on experience with the development of other supersonic engines, full-scale tests of the engine are needed to make reliable assessments of material durability, system interactions, and other factors that can prevent new engines from meeting overall goals in terms of performance, service life, weight, and cost. A lack of suitable test facilities will prevent the testing of full-scale engines in a flight environment (in terms of atmospheric pressure, temperature, and Mach number). Even so, sea-level testing will ensure that engine components have been tested in a full-scale functioning engine, which is the "relevant environment" for them.

Major Recommendation 10. As a high priority, the recommended technology maturation phase should fabricate and test two fully instrumented, full-scale engines in static sea-level conditions. In order to bring the engine to a TRL of 6, this effort should include aerodynamic and aeromechanical testing, 1,000 hours of accelerated mission endurance testing, acoustic tests, and a 150-hour simulated mission profile test.

Integrated Aircraft[4]

Aero/Propulsive/Servo/Elastic Effects

An HSCT will be aerodynamically unstable. The airframe will be highly flexible, with structural vibration mode frequencies well below those of existing aircraft. This combination represents a particularly acute problem for an HSCT because the flight control system will be required to overcome severe disturbances

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[4] Additional information on the integrated aircraft appears in Chapter 5.

that may arise during an engine unstart.[5] To reduce the risk of engine unstarts, HSCTs must maintain tightly controlled flight conditions in a flight regime where aeroelasticity may significantly reduce the effectiveness of aircraft control surfaces. An HSCT flight control system must also account for APSE effects, which present a completely new class of technical problems that is outside the experience of the technical community. Furthermore, fundamental limits on control system design could make it impossible for the flight control system to provide adequate flying qualities and an acceptable level of aircraft stability without significant changes to the aircraft design.

Major Recommendation 11. The HSR Program should form an integrated product team to develop a plan for identifying and resolving APSE issues. This team should investigate the critical interrelationships among the following: airframe structural stiffness; the level of aerodynamic instability; the feasibility, performance, and complexity of the flight and engine control systems; and aircraft structural weight.

Design Cruise Speed

The actual speed of a commercial HSCT will be determined by industry based on its own assessment of economic factors, technological risk, operational costs, etc. The HSR Program's technology development efforts assume a design cruise speed of Mach 2.4. Although the primary goal is to support development of an economically viable HSCT, the selection of Mach 2.4 as the baseline cruise speed (as opposed to a cruise speed of Mach 2.0 to 2.2) does not seem to be substantiated by an objective assessment of economic and technical factors.

The economic performance and technological risk of the propulsion and avionics systems do not change very much between Mach 2.0 and 2.4. However, there does appear to be a sharp increase in technological and economic risk for aircraft structures as speed increases past Mach 2.2. Higher cruise speeds create higher temperatures on the skin of the aircraft. Mach 2.2 creates a maximum temperature of 250°F. Above this temperature, HSCT airframes will need to use a new, higher-risk family of polymeric materials. As discussed in Chapter 4, candidate materials in this class have not demonstrated an ability to meet service life requirements and require significant technology development.

The HSR Program anticipates that industry will fund development of materials and structures necessary to preserve the option of selecting a lower cruise speed (Mach 2.0 to 2.2). However, the limited ability of the HSR Program (and this committee) to assess industry's internal HSCT research makes it difficult to determine the extent to which industry activities are preserving a lower cruise speed as a viable alternative.

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[5] See Chapter 3 for a description of engine unstart.

Major Recommendation 12. The HSR Program should ensure that structural materials suitable for lower cruise speeds (Mach 2.0 to 2.2) will be available in case a lower-speed design turns out to be more economically viable than a Mach 2.4 design, based on technical and economic factors.

Desired Payload and Range

The range and payload goals established by the HSR Program are important factors that drive the overall aircraft configuration, including the selection of specific technologies. The range goal of 5,000 n.m. would allow nonstop flights between Tokyo and the west coast of the United States. The TCA (Technology Configuration Aircraft) is configured to carry enough fuel for this range, with some reserve fuel for operational diversions in case of hazardous weather at the destination airport. However, the full impact of reserve fuel requirements has not been estimated. Reserve requirements for over-ocean engine failure and cabin depressurization, in particular, have not been examined, even though they could significantly reduce the effective range of a TCA-like HSCT.

A shortfall in effective range (or the key performance parameters that impact range: L/D [lift-to-drag ratio], specific fuel consumption, and structural weight fraction) would jeopardize overall economic viability unless one or more of the other parameters exceed their goals. That, however, seems quite unlikely. Thus, reserve fuel requirements that substantially change effective aircraft range could have a significant impact on the ability of the technology under development by the HSR Program to support a product launch decision. Furthermore, concerns about operational issues, such as reserve fuel requirements, will become increasingly important as the program nears the point when industry senior executives are asked to decide if the technology is ready to support development of an operational aircraft.

Major Recommendation 13. The HSR Program, industry, and the FAA should determine if reserve fuel requirements for an operational HSCT in airline service will significantly reduce the effective range of a TCA-like HSCT. If so, the HSR Program should assess how to address that shortcoming in the context of an economically viable HSCT concept. The HSR Program should also determine the sensitivity of payload and range to key HSR technologies.

Technology Margins

As indicated above, the projected performance of the TCA provides little or no margin for shortfalls in the key range parameters: L/D (especially during supersonic flight), specific fuel consumption, and structural weight fraction. In fact, the lack of performance margins is one indication of the high risk nature of the HSR Program. Nonetheless, requiring all areas of the program to succeed in order to meet the overall objectives significantly increases the possibility that the integrated design will be less than satisfactory. The HSR Program should reexamine its performance goals and technological alternatives to provide some margin for error.

As discussed in Chapter 4, one of the most promising possibilities for increasing aircraft performance is through SLFC (supersonic laminar flow control). This technology has the potential to improve supersonic L/D by 10 to 15 percent, which would enable the conceptual aircraft design to meet range goals even with a shortfall in weight and/or specific fuel consumption.

Major Recommendation 14. The HSR Program should develop risk abatement plans that include additional research in selected technology areas to counter possible shortfalls in L/D, specific fuel consumption, structural weight fraction, and other critical parameters (which the HSR Program should identify).

Flight Deck

The HSR Program is developing revolutionary concepts for the flight deck, particularly with regard to the use of "synthetic vision" for forward visibility. There is likely to be much public discussion and, possibly, some reluctance to accept these concepts. The inability of the pilot to view the runway directly during approach and landing could cause unfavorable media attention unless the potential for these systems to improve safety in all weather conditions is understood and accepted. Thus, it is imperative that flight demonstrations of the flight deck's XVS (external visibility system) succeed. However, the initial flight evaluations will be conducted with displays having only one-half of the required resolution.

Major Recommendation 15. The HSR Program should ensure that the flight deck system concepts under development can provide a level of safety superior to conventional systems used by subsonic transports. To ensure flight tests are successful, preliminary flight tests planned during Phase II of the HSR Program should be supplemented by additional flight tests during the proposed technology maturation and advanced technology demonstration phases. These additional flight tests should use displays with resolution equal to the resolution needed for an operational HSCT.

Certification

Certification is a critical issue for the HSR Program. In some cases, certification standards that are reasonable and appropriate for subsonic transports are inappropriate for an HSCT and, if applied as is, they would make development of an economically viable HSCT unattainable with the technology under development by the HSR Program. For example, current standards require designing the entire exterior of a transport to withstand the highest temperature encountered at any point on the aircraft. This is not a burdensome requirement for a subsonic transport. However, because of the elevated temperatures on an HSCT, and because the temperatures vary widely from point to point on the airframe, imposing this standard on an HSCT would significantly increase MTOW and result in an unaffordable aircraft.

Because of the long time required to modify certification standards, early action is needed to understand and resolve certification issues associated with HSR technologies. NASA, FAA, and industry responsibilities should be clearly delineated. The FAA and NASA have agreed to establish five CICTs (Certification Issues Coordination Teams) to investigate certification issues and establish a certification basis in designated technical areas. Four of the teams are in place, and the FAA plans to establish the fifth CICT when necessary. Even so, it is not yet clear if the pace of activity will be able to provide timely resolution of all key issues. For example, establishing a standard for NO_x engine emissions will be a lengthy process that involves environmental assessments and negotiating international agreements in addition to the normal, lengthy process of changing certification standards in the FARs (Federal Aviation Regulations). Although the HSR Program has selected a specific, seemingly reasonable goal for engine emissions (an NO_x emissions index of 5 grams per kilogram of fuel burned), there is no assurance that the International Civil Aviation Organization will approve that goal as an international standard. Also, there is no firm timetable for approving a standard. Without that assurance, industry will never proceed with commercial development of an HSCT because a more stringent emissions requirement could require developing a new propulsion system.

The certification effort must also resolve testing issues. For example, new certification standards must be developed that specify the tests required to certify the flight deck and flight control systems, approve flight control procedures, and validate airframe service life. Although certification standards exist in all these areas, they are inconsistent with the technologies under development by the HSR Program. As the investment in HSR technologies increases, it is becoming increasingly important to ensure that certification issues do not prevent these technologies from finding useful application on a viable HSCT.

Major Recommendation 16. The FAA, NASA (i.e., the HSR Program), and industry should support timely resolution of certification issues—including dedicated certification-related research—to ensure that technology under development by the HSR Program can be applied to development of an HSCT.

APPENDICES

APPENDIX
A

List of Findings and Recommendations

A complete list of the committee's findings and recommendations appears below. The major findings and recommendations from Chapter 6 are listed first. Other findings and recommendations are listed in the order they appear in the body of the report.

MAJOR FINDINGS AND RECOMMENDATIONS

Major Finding 1. The current HSR Program is making excellent progress. Achieving program objectives is a necessary precursor to the development of a U.S.-built HSCT and would develop important new technologies with broad applicability throughout the aeronautics industry.

Major Recommendation 1. The HSR Program should adopt a new vision statement that emphasizes top-level *requirements* (i.e., safety, environmental acceptability, and economic viability) to encourage a more balanced technical approach to achieving aircraft performance *goals* (i.e., speed, range, and payload). The committee suggests the following:

> Develop high risk, critical, enabling technologies in conjunction with complementary industry investments to support the timely introduction of a Mach 2.0-plus HSCT. These technologies must lead to an environmentally acceptable, economically viable aircraft, with safety levels equal to or better than future subsonic transports. Successful completion of the NASA and industry programs will provide the technology foundation industry needs to proceed with the design, certification, and manufacture of an HSCT.

Major Finding 2. The goal of the HSR Program is to provide the technology foundation that industry needs to make an HSCT product launch decision. Without an extended period of technology maturation and advanced technology demonstration, the HSR Program will not achieve this goal.

Major Recommendation 2. To accomplish HSR Program objectives, the program should be restructured in accordance with Figure 6-1. The recommended changes to Phase II should be implemented without waiting to determine if the technology maturation and advanced technology demonstration phases will be approved and funded.

Major Recommendation 3. The HSR Program should increase the role of affordability (and related factors, such as inspectability, maintainability, and repairability) in evaluating the merit of alternate technology approaches, system design concepts, and vehicle configurations. Cost per available seat mile should be adopted as the key affordability metric. The technology management teams and ITD (Integrated Technology Development) teams should understand the impact of their technology and system choices on affordability/cost per available seat mile.

Major Recommendation 4. The HSR Program should reevaluate the TRL goals assigned to each technology audit metric and ensure that they are coordinated across the program. NASA should conduct a QFD analysis (see Chapter 2) to validate the choice of metrics and their assigned TRL goals.

Major Recommendation 5. The HSR Program plan should be revised to place more emphasis on the interdependencies inherent in the program. The revised plan should explicitly identify major interdependencies between the propulsion system, airframe, integrated aircraft systems, and process areas, such as certification and manufacturing. These interdependencies should be reflected in a time-phased, integrated plan that takes into account industry-funded research and development, as appropriate. Early emphasis should be put on technologies with longer development lead times. The plan should also specify a risk reduction approach for each program element with moderate or high risk.

Major Recommendation 6. Industry participants in the HSR Program should grant NASA increased access to internal HSCT research, and the HSR Program should include appropriate information in its planning and oversight process.

Major Recommendation 7. Instead of using surrogate materials, full-scale component tests should be delayed until ongoing material development efforts can supply the materials intended for use in those components. The HSR Program should work with industry to develop preproduction manufacturing processes to manufacture test components. Implementing the recommended technology maturation phase would provide the time needed to implement this strategy.

Major Recommendation 8. The HSR Program should demonstrate adequate materials durability and complete the development of manufacturing technology during the recommended technology maturation phase. In particular, the HSR Program should develop test methodologies suitable for validating an airframe service life of 60,000 hours. These methodologies would have wide application throughout the aeronautics industry.

Major Recommendation 9. The HSR Program should develop a more comprehensive testing and risk mitigation strategy for the combustor that extends into the recommended technology maturation phase and includes combustor testing in a full-scale demonstrator engine. Because satisfactory combustor performance is essential to program success, additional resources should be devoted to development of combustor technology during Phase II, if necessary.

Major Recommendation 10. As a high priority, the recommended technology maturation phase should fabricate and test two fully instrumented, full-scale engines in static sea-level conditions. In order to bring the engine to a TRL of 6, this effort should include aerodynamic and aeromechanical testing, 1,000 hours of accelerated mission endurance testing, acoustic tests, and a 150-hour simulated mission profile test.

Major Recommendation 11. The HSR Program should form an integrated product team to develop a plan for identifying and resolving APSE (aero/propulsive/servo/elastic) issues.[1] This team should investigate the critical interrelationships among the following: airframe structural stiffness; the level of aerodynamic instability; the feasibility, performance, and complexity of the flight and engine control systems; and aircraft structural weight.

Major Recommendation 12. The HSR Program should ensure that structural materials suitable for lower cruise speeds (Mach 2.0 to 2.2) will be available in case a lower-speed design turns out to be more economically viable than a Mach 2.4 design, based on technical and economic factors.

Major Recommendation 13. The HSR Program, industry, and the FAA should determine if reserve fuel requirements for an operational HSCT in airline service will significantly reduce the effective range of a TCA-like HSCT. If so, the HSR Program should assess how to address that shortcoming in the context of an economically viable HSCT concept. The HSR Program should also determine the sensitivity of payload and range to key HSR technologies.

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[1] APSE phenomena are associated with the highly interactive, dynamic nature of the HSCT airframe, propulsion, and flight control systems. See Chapter 5.

Major Recommendation 14. The HSR Program should develop risk abatement plans that include additional research in selected technology areas to counter possible shortfalls in L/D, specific fuel consumption, structural weight fraction, and other critical parameters (which the HSR Program should identify).

Major Recommendation 15. The HSR Program should ensure that the flight deck system concepts under development can provide a level of safety superior to conventional systems used by subsonic transports. To ensure flight tests are successful, preliminary flight tests planned during Phase II of the HSR Program should be supplemented by additional flight tests during the proposed technology maturation and advanced technology demonstration phases. These additional flight tests should use displays with resolution equal to the resolution needed for an operational HSCT.

Major Recommendation 16. The FAA, NASA (i.e., the HSR Program), and industry should support timely resolution of certification issues—including dedicated certification-related research—to ensure that technology under development by the HSR Program can be applied to development of an HSCT.

CHAPTER 2
REQUIREMENTS ANALYSIS

Finding 2-1. Industry forecasts of market demand indicate that an HSCT consistent with TCA performance specifications will have a market size large enough to be economically viable. The assumptions in these market forecasts appear to be reasonable, although not certain or risk free. Generalizations in the forecast assumptions may overstate the projected market size.

Recommendation 2-1. Industry should conduct further market research and simulations to reduce the uncertainties associated with current forecasts and to validate that performance specifications used by the HSR Program to guide technology development are consistent with the design of an economically viable HSCT.

Finding 2-2. From an airline scheduling perspective, an HSCT with a cruise speed as low as Mach 2.0 is likely to have productivity similar to a Mach 2.4 HSCT, assuming similar maintenance and servicing requirements.

Finding 2-3. There is general agreement within industry and the HSR Program that a payload of about 300 passengers is required for an economically viable HSCT. A similar level of agreement does not exist regarding what design range (between 4,500 n.m. and 6,500 n.m.) will maximize economic viability.

Recommendation 2-2. The HSR Program should conduct further market research and economic simulations to capture the impact of payload and range on HSCT utilization and economics. These simulations should be based on a comprehensive analysis of specific city-pair routes rather than a top-down analysis.

Finding 2-4. Achieving the range, payload, and MTOW goals established by the HSR Program (i.e., 5,000 n.m., 300 passengers, and 740,000 pounds) depends on full attainment of goals for supersonic cruise L/D, specific fuel consumption, and structural weight fraction.

Recommendation 2-3. The HSR Program should establish design margins to allow for possible shortfalls in key performance parameters. The HSR Program should also establish a management system to perform trade-offs between these parameters to maintain an acceptable level of overall system performance.

Finding 2-5. Europe has the technical expertise to compete in developing a next-generation supersonic commercial transport. Japan and other Pacific rim countries could contribute financially and, to a lesser extent, technically. Because of technical challenges and financial requirements, it seems unlikely that foreign interests will initiate a program to develop an economically viable supersonic commercial transport during the next 5 to 10 years. However, political factors could spur earlier action.

Recommendation 2-4. NASA should continue to track the development of supersonic commercial transport technology worldwide.

Finding 2-6. The key product and process characteristics with the highest risk are engine emissions, engine service life, airframe service life, range, affordability, community noise, APSE phenomena, and manufacturability.[2]

Finding 2-7. Most of the advanced technologies the HSR Program is developing to support an HSCT product launch decision are very process dependent, especially from the point of view of affordability.

Recommendation 2-5. The HSR Program's Integrated Planning Team should use the HSR/HSCT QFD planning matrix in Figure 2-1 to examine the complex interdisciplinary nature of the HSR Program and the trade-offs that may be required among design requirements.

Recommendation 2-6. The HSR Program should ensure that current and future efforts are properly focused on the most important, highest risk areas. The single most critical design requirement is *affordability*, and the HSR Program should adopt an affordability metric—such as average yield per available seat mile—

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[2] These characteristics are listed in the order they appear in Figure 2-1.

that is more comprehensive than MTOW. The other areas of greatest importance, many of which are closely linked to affordability, are as follows:

- airframe service life (durability)
- dynamic interactions among the airframe, propulsion, and flight control systems (i.e., APSE effects)
- engine emissions (ozone depletion)
- engine service life
- manufacturing and producibility
- range

Finding 2-8. The strong negative (adverse) relationships among high-priority design requirements and the risks associated with these requirements (especially with regard to affordability) support the committee's recommendation for a substantial effort beyond the current Phase II.[3]

CHAPTER 3
PROPULSION

Finding 3-1. The HSR Program's turbine airfoil system development effort is a high risk endeavor that is unlikely to demonstrate the specified level of technology readiness (TRL 6) by the end of Phase II.

Recommendation 3-1. The HSR Program should expand its efforts to develop suitable alloys and thermal barrier systems during Phase II to increase the probability that the airfoil system will satisfy durability and lifetime requirements and to prepare for the recommended technology maturation phase.

Finding 3-2. The HSR Program's disk manufacturing development effort will not demonstrate a necessary level of technology readiness (TRL 6) by the end of Phase II.

Recommendation 3-2. Early in the recommended technology maturation phase, which would follow Phase II, the HSR Program should manufacture and destructively test representative full-scale disk components to verify that manufacturing technologies are feasible and that measured material properties are consistent with design data generated from small samples. Disk performance should be demonstrated in a full-scale engine later in the technology maturation phase.

Finding 3-3. Significant uncertainties regarding the viability of potential ultralow NO_X combustor designs—and the materials needed to implement those designs—are likely to remain at the conclusion of Phase II, as currently planned.

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[3] See Chapters 1 and 6.

Recommendation 3-3a. During the recommended technology maturation phase, the HSR Program should test a full-scale demonstrator engine to reduce uncertainties regarding the viability of the selected ultralow NO_x combustor design. Combustor development during Phase II should focus on preparations for full-scale tests.

Recommendation 3-3b. In order to increase the potential market for silicon carbide CMC liners—and thereby ensure their availability for use in HSCTs—the HSR Program should encourage other engine research programs sponsored by NASA, the Department of Defense, and the Department of Energy to include more CMC materials.

Finding 3-4. Development efforts for the exhaust nozzle may achieve the specified level of technology readiness (TRL 6) by the end of Phase II. Nonetheless, uncertainties about nozzle materials and manufacturing processes will require additional work during the recommended technology maturation phase.

Recommendation 3-4. The HSR Program should fabricate and test full-scale nozzles during the recommended technology maturation phase to validate nozzle manufacturing technology, noise levels, and material performance.

Finding 3-5. Fabrication and testing of full-scale engines are needed to validate engine technologies, particularly with regard to emissions and noise requirements. Early action leading to this goal is required to ensure that the propulsion system technologies will be ready for flight testing at the same time as airframe and integrated aircraft system technologies.

Recommendation 3-5. It is critical that the HSR Program build and test two full-scale, instrumented engines during the recommended technology maturation phase. Testing of one engine should focus on aerothermodynamics and aeromechanical issues (e.g., thrust, emissions, noise, and vibration); testing of the other should focus on structures and materials issues (e.g., reliability, service life, and weight). The second engine would also reduce risk by ensuring a backup engine is available in case the first engine experiences a catastrophic failure.

CHAPTER 4
AIRFRAME

Finding 4-1. Different families of materials (e.g., resins, adhesives, sealants, coatings, and finishes) are required for use at sustained temperatures above 250°F (i.e., for aircraft designs with cruising speeds above Mach 2.2) than for use at temperatures below 250°F. Therefore, the focus of the HSR Program on a speed of Mach 2.4 critically influences materials technology development. General classes of polymeric materials and manufacturing processes suitable for a Mach 2.0 to 2.2 HSCT are available but have not demonstrated the life requirement and require significant technology development.

Recommendation 4-1. The HSR Program should retain a cruise speed of Mach 2.4 as an important baseline objective to encourage development of advanced materials and to develop a fundamental understanding of high temperature material responses and degradation mechanisms. However, the HSR Program, with appropriate support from the airframe manufacturers and material suppliers, should also identify and develop critical enabling technologies to protect the viability of developing a Mach 2.0 to Mach 2.2 HSCT. This effort should start during Phase II and continue until risks associated with a Mach 2.4 design are substantially reduced.

Finding 4-2. The focus of the HSR Program on a single basic PMC system (PETI-5) is a major program risk that could have a catastrophic effect on the HSR Program if the development effort falls short in critical areas, such as processing, properties, or durability. This risk underscores the importance of developing alternative materials technologies for Mach 2.0 to Mach 2.2.[4]

Recommendation 4-2. The HSR Program should make development of PMC-compatible coatings and finishes an integral part of its PMC development effort.

Finding 4-3. The adequacy of the materials supplier base could become a critical issue when industry considers whether to make an HSCT program launch decision. Factors that interfere with establishing the necessary supplier base include restrictions on the involvement of foreign industry and NASA's ownership of a major structural material (PETI-5). These factors lower the incentive for large suppliers of aerospace materials to develop materials on their own.

Recommendation 4-3. HSR Program managers and airframe industry executive managers should meet with material suppliers to solicit financial and technical commitments to participate in the overall effort to develop materials needed for an HSCT. The HSR Program should also ensure the ability of foreign industry to reduce risk in critical areas is adequately considered, either through the independent actions of industry participants in the HSR Program or through direct action by the HSR Program (after obtaining necessary exemptions to NASA policy restrictions on the involvement of foreign industry). This is especially important for the cost-effective development of required sealants.

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[4] Finding 4-1 and Recommendation 4-1 further explain the committee's conclusions regarding efforts by the HSR Program to develop PMCs.

Finding 4-4. The HSR Program's materials specimen and element testing is well planned. The testing schedule, however, extends beyond the end of the current program and is generally limited to thermomechanical testing of the PMC material being developed by the HSR Program (PETI-5) and thermoset materials that are commercially available. Risk associated with the selection of structural concepts is increased by the need to rely on (1) predicted end-of-lifetime material properties based on less than one lifetime of real-time test data and (2) accelerated durability test methods that have not been validated by adequate real-life tests. An improved scientific understanding of individual composite degradation mechanisms is needed to reliably predict lifetime performance and to design accelerated tests.

Recommendation 4-4. During Phase II, the HSR Program should conduct a focused, critical, detailed, technical assessment of alternatives for including new PMC materials in the durability testing of specimens and elements. This assessment should include personnel from inside and outside the HSR Program, and it should use the findings and recommendations of *Accelerated Aging of Materials and Structures* (NRC, 1996) as a guide. The assessment should include the results of ongoing real-time testing, and it should be oriented toward understanding aging characteristics and accelerated testing techniques suitable for a broad class of materials applicable to HSCT development.

Finding 4-5. In the areas of manufacturing, processing, and producibility, the HSR Program is focused on developing processing methods for the fabrication of small numbers of subscale and full-scale components to support the materials testing program. However, this will not resolve issues associated with how to affordably manufacture components in production quantities. In addition, manufacturing processes for PMCs required for a Mach 2.4 HSCT, such as PETI-5, will be complex and costly because of handling characteristics, high volatile content, and high temperatures and pressures (up to 700°F and 200 psi).

Recommendation 4-5. The NASA and industry participants in the HSR Program should jointly place greater emphasis on the development of manufacturing technology and producibility demonstrations so the HSR Program can properly support the HSCT product launch decision. NASA and industry should develop an integrated manufacturing technology plan that enables the HSR Program's materials technology development efforts, which currently seem to be focused on near-term component fabrication, to adequately consider overall, long-term manufacturing issues. Development of this plan should be closely coordinated with the wing and fuselage design teams. The HSR Program should also review and incorporate the integrated design and manufacturing approach described by Marx et al. (1996), which is based on a combined performance and economic perspective.

Implementation of this recommendation will require changes to the Phase II program and approval of the recommended technology maturation phase.

Finding 4-6. The performance of innovative structural concepts depends on successful development of the materials upon which they are based. It is virtually impossible to separate the structures design effort from the materials and manufacturing development effort. The materials development program and the structural concept development program are both well planned. However, the current schedule of the HSR Program does not facilitate a sequential approach that would reduce overall risk by validating the performance of proposed new materials before they are incorporated into new structural concepts.

Finding 4-7. The use of multiple weight estimation methods has confounded weight tracking and obscured HSR Program successes in using innovative structural concepts to reduce vehicle weight. There is no longer a clear relationship between structure areal weights and MTOW, which are both top-level audit metrics used by the HSR Program.

Finding 4-8. Structural design and analysis tools vary from company to company. Improvements are needed in these tools, including life prediction tools, weight estimation tools, thermal stress analysis tools, and rapid preliminary sizing tools. These improvements would give the U.S. aerospace industry a distinct competitive advantage.

Recommendation 4-6. During Phase II, the HSR Program should concentrate more resources on developing structural design tools tailored for HSCT applications. These tools should include validated materials databases, rapid preliminary sizing tools, validated thermal stress analysis tools, and validated analytical life prediction tools. Resources could be reallocated to this task from full-scale component tests.[5]

Finding 4-9. The large amount of work needed to carry forward and analyze the many design concepts still under consideration increases the risk of not meeting the program schedule.

Finding 4-10. Full-scale testing of large components, because of the cost and time involved, is more appropriate to the final structural validation of a specific vehicle point design. Large component tests, as currently planned, would not address critical structural issues for the full-scale vehicle or major structural joints. Nor would they validate that fabrication methods used for component tests would be representative of the manufacturing methods that will be used during production.

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[5] See Finding 4-10 and Recommendation 4-7.

Thus, full-scale testing of large components during Phase II would probably add little value to the technology development process.

Finding 4-11. Using surrogate materials and fabrication processes for components in large-scale tests could significantly reduce the ability of those tests to objectively assess the economic viability of the proposed design approaches. Correlation of component test results with analytical predictions would be complicated by inherent differences between the "as-designed" and the "as-tested" materials and fabrication processes.

Finding 4-12. Structural issues should be resolved in a cost-effective manner, which means using the smallest and simplest tests that can provide the required information. Addressing materials and structures issues using tests at the coupon, element, and subcomponent levels during Phase II may offer a higher payoff than testing full-scale components.

Recommendation 4-7. Testing of full-scale components should be deferred to the recommended technology maturation phase. Funds allocated for testing full-scale components during Phase II should be reallocated to achieve higher levels of technology readiness in the critical enabling materials and structures technologies, including the following:

- materials characterization and life prediction methodologies
- rapid, efficient design and analysis tools
- robust structural concepts
- technical criteria related to dynamic interactions among the airframe, propulsion, and flight control systems (APSE effects) and the relationship of these criteria to structural concepts

Finding 4-13. The current estimate of drag for the TCA is reasonable. However, there remains some uncertainty (on the order of 3 to 5 percent) about the actual drag of an HSCT in flight.

Finding 4-14. The projected 10 percent improvement in L/D (relative to the L/D of the current TCA design) is optimistic. Design optimization can be expected to yield about 5 to 6 percent. Some of the other projected improvements may be offset by drag increments on the real production aircraft.

Finding 4-15. SLFC has the potential to improve L/D by 10 to 15 percent, which could offset shortfalls in the attainment of predicted L/D, specific fuel consumption, or structural weight fraction, and would provide a margin for attaining performance goals in terms of aircraft range.

Recommendation 4-8. NASA should continue to conduct SLFC research as part of a long-term commitment to HSR technology. This research could also have significant payoffs for other aeronautical projects. Long-term planning by the HSR Program should provide for the possible incorporation of SLFC in future configurations, including the full-scale technology demonstrator the committee recommends flight testing during the advanced technology demonstration phase.

CHAPTER 5
INTEGRATED AIRCRAFT

Finding 5-1. An HSCT similar to the TCA will experience complex dynamic interactions involving the pilot and the APSE system, which includes the airframe (e.g., aerodynamic effects and elastic properties of the airframe structure), the propulsion system, and the flight control system (including the XVS). It is not yet clear how to design an HSCT that overcomes these effects and provides safe flying and handling qualities. Furthermore, the current HSR Program does not adequately address this problem.

Finding 5-2. The impact of APSE effects on flight dynamics and handling qualities may require changes in the aerodynamic and/or structural design of the TCA that would significantly reduce aerodynamic efficiency and/or increase structural weight, thereby reducing maximum range.

Finding 5-3. It is unlikely that the technical risk associated with APSE effects can be adequately addressed without building and flight testing an aircraft like the FAST (full-scale advanced supersonic technology) demonstrator.

Recommendation 5-1. The development of design tools and techniques for synthesizing and validating a highly integrated flight and propulsion control system and for properly addressing APSE effects on flight control and flight management systems should be established as a top-level research issue within the HSR Program during Phase II and the subsequent phases proposed by the committee. How to address APSE effects early in the aircraft-design cycle, before detailed structural models are developed, requires special attention.

Recommendation 5-2. The HSR Program should reevaluate the current TCA configuration in light of APSE effects. Because structural mode control will almost surely be required to achieve adequate flight dynamics and handling qualities, the optimum vehicle configuration may include additional and/or nontraditional aerodynamic surfaces. If necessary, such "control-configured" concepts should be included in future evaluations of aircraft design configurations.

Recommendation 5-3. An interdisciplinary team should be formed to fully address relevant aspects of the APSE problem, and the organizational distance between the groups responsible for (1) guidance and control systems and (2) control laws should be reduced or eliminated.

Finding 5-4. Validating the performance of the XVS and other key flight deck technologies being developed by the HSR Program is crucial to the public acceptance and economic viability of an HSCT. Flight testing XVS technology using displays with lower resolution than the resolution needed for an operational HSCT increases the risk that test results will be unsatisfactory, which could reduce public acceptance of the XVS design concept.

Recommendation 5-4. To address flight deck system risk adequately, the preliminary flight tests planned during Phase II of the HSR Program should be supplemented by additional flight tests during the proposed technology maturation and advanced technology demonstration phases. These additional flight tests should use displays with resolution equal to the resolution needed for an operational HSCT.

Finding 5-5. HSCTs must be able to meet applicable regulatory noise standards. However, the HSR Program has established appropriate noise goals and is using an effective approach to achieve them.

Recommendation 5-5. The FAA and NASA (i.e., the HSR Program) should develop and periodically update a master certification plan that supports timely resolution of key HSCT certification issues and shows how the activities needed to resolve these issues are related to other HSR Program efforts.

Finding 5-6. The design and operating characteristics of an HSCT will require some changes in airline, airport, and air traffic control system facilities and procedures. However, making changes to airport facilities (including taxiways) and air traffic control procedures, although technologically simple, may be difficult from a funding and environmental/community acceptance perspective. Failure to anticipate problems and make required changes could reduce HSCT market demand below current estimates.

Recommendation 5-6. During the recommended advanced technology demonstration phase, industry and the HSR Program should identify and evaluate changes in airline, airport, and air traffic control system facilities and procedures that may be required to accommodate an HSCT. In particular, industry should conduct a detailed study of infrastructure issues at key airports worldwide that an HSCT is expected to service. As a first step, these issues should be included in the recommended effort to validate HSCT market size (see Chapter 2).

APPENDIX
B

Biographical Sketches of Committee Members

Ronald W. Yates (chair), U.S. Air Force, retired, is an independent consultant to the aerospace industry. Gen Yates spent 35 years in the U.S. Air Force. He is a fighter pilot and test pilot and has 5,000 flying hours in more than 50 different types of aircraft. He has extensive experience in the acquisition business having served as program director of both the F-15 and F-16 System Program Offices. He was also a test wing commander. He served as Air Force Director of Tactical Programs in the Pentagon and as Deputy Assistant Secretary of the Air Force for Acquisition. He was the Commander of both the Air Force Systems Command and the Air Force Materiel Command, where he was responsible for all Air Force research, development, acquisition policy, and logistics. He is a member of the Society of Experimental Test Pilots; a commissioner for the National Research Council (NRC) Commission on Engineering and Technical Systems; and a member of the Ballistic Missile Defense Office Advisory Group. He is a graduate of the U.S. Air Force Academy and holds a masters degree in systems management from the University of Southern California.

Donald W. Bahr was Manager, Combustion Technology at GE Aircraft Engines for more than 20 years prior to his retirement in 1994. He joined GE Aircraft Engines in 1956 as a combustion research engineer. As Manager, Combustion Technology, he was responsible for the design, development, and certification of a variety of combustion systems used in both commercial and military aircraft turbine engines, as well as combustion systems used in industrial turbine engines. A major aspect of these responsibilities was the evolution of low pollutant emission combustors. Mr. Bahr graduated from the University of Illinois with a B.S. in chemical engineering and from the Illinois Institute of Technology with M.S.

degrees in chemical engineering and gas technology. He is a fellow of the American Society of Mechanical Engineers (ASME) and the American Institute of Aeronautics and Astronautics (AIAA). He is a member of the National Academy of Engineering and the General Electric Propulsion Hall of Fame.

James B. Day is a private consultant in the aircraft propulsion industry. He spent 34 years working in propulsion research and development for the U.S. Air Force at Wright-Patterson Air Force Base, Ohio. During his tenure, he had major responsibilities during the development of engines for the F-15, F-16, A-10, B-1B, B-2A, C-17, and F-22 aircraft. He was chief engineer for Air Force engine development for 10 years and spent two years as general manager for development engines. He received B.S. and M.S. degrees in mechanical engineering from the University of Kentucky, Lexington.

Antony Jameson is the Thomas V. Jones Professor of Engineering in the Department of Aeronautics and Astronautics at Stanford University. He is also professor emeritus at Princeton University and, until 1996, he was the James S. McDonnell Distinguished University Professor of Aerospace Engineering at Princeton. During the last decade, Professor Jameson has devised a variety of new schemes for solving the Euler and Navier-Stokes equations for inviscid and viscous compressible flows and has written a series of computer programs that have been widely used in the aircraft industry. Dr. Jameson has also served as the director of Princeton University's Program in Applied and Computational Mathematics. Before joining the faculty of Princeton University in 1980, he was a professor of computer science at New York University, where he concentrated on developing models to predict transonic flow. During the 1960s, Dr. Jameson worked for Hawker Siddeley Dynamics in Coventry, England, and Grumman Aerospace Corporation in Bethpage, New York, where he applied automatic control theory to the development of stability augmentation systems. Dr. Jameson studied engineering at Trinity Hall, Cambridge University, obtaining a Ph.D. in magnetohydrodynamics. He is a recipient of the NASA Medal for Exceptional Scientific Achievement, the Gold Medal of the British Royal Aeronautical Society, the American Institute of Aeronautics and Astronautics Fluid Dynamics Award, and the ASME Spirit of St. Louis Medal. He is a foreign associate of the National Academy of Engineering, a fellow of the AIAA, an honorary fellow of Trinity Hall, Cambridge, and a fellow of the Royal Society of London for Improving Natural Knowledge.

Donald T. Lovell was Chief Engineer of Structures Engineering, Boeing Materials Technology, until he retired in 1995. This group is responsible for research, development, design analysis, production, and airline support for all materials and processes used on Boeing commercial airplanes. Mr. Lovell worked at Boeing for more than 38 years. He had direct engineering involvement with key programs including KC-135, B-52, Minuteman, "Man on the Moon" Saturn/Apollo, Supersonic Transport (SST) Prototype, and the 707, 727, 737, 747, 757, 767, and 777 airplanes. After termination of the U.S. SST Prototype Program, Mr. Lovell was program manager of the Department of Transportation's SST Technology Follow-On Program. The objective of this program was to transfer advanced technologies developed by the SST program to other U.S. government and industry programs. He led the implementation of major new aluminum alloys, titanium alloys, and composites for the 757, 767, and 777 airplanes. Mr. Lovell attended the GMI Engineering and Management Institute, obtaining a BSME, and the University of California, Berkeley, completing the Executive Management Program. He is a fellow of ASM International (formerly the American Society of Metals); served on materials committees of the ASM, AIAA, and Society for the Advancement of Materials and Process Engineering; and is a scholar emeritus at the University of Washington.

John M. Reising is an engineering psychologist in Wright Laboratory's Vehicle-Pilot Integration Branch located at Wright-Patterson Air Force Base, Ohio. His current research centers around advanced cockpit design, with a special emphasis on blending the many new cockpit technologies so the pilot can use them optimally. Currently under examination are 3-D stereo cathode ray tubes, flat panel displays, touch sensitive overlays, voice controls, and programmable switches. The focus of Dr. Reising's research is developing cockpit technologies that will facilitate and maximize effective communication between the pilot of the future and the artificially intelligent computers that will be housed in tomorrow's aircraft. Dr. Reising is a Wright Laboratory Fellow and a fellow of the Human Factors and Ergonomics Society. He is also an adjunct professor in the Engineering Management Department of the University of Dayton, where he has taught human factors engineering since 1978. He has published more than 100 papers, journal articles, and technical reports.

David K. Schmidt is a professor of aerospace engineering and Director of the Flight Dynamics and Control Laboratory at the University of Maryland at College Park. He has been with the University of Maryland since 1993. Previously, Dr. Schmidt was a member of the faculty of Arizona State University (for five years), as well as a member of the faculty of Purdue University (for 14 years). In addition to his academic experience, Dr. Schmidt has also been a member of the technical staffs of McDonnell Douglas Astronautics Corporation in Huntington Beach, California, and the Stanford Research Institute, Menlo Park, California. He has also held visiting research positions with the U.S. Air Force Flight Dynamics Laboratory and with NASA's Langley Research Center. His area of expertise is the dynamics, guidance, and control of aerospace vehicles. He is an associate fellow of the AIAA and a member of the American Astronautical Society, the Institute of Electrical and Electronic Engineers, the American Society for Engineering Education, the Aerospace Control and Guidance Systems Committee of the Society of Automotive Engineers, and the Aerospace Technical Committee of the International Federation for Automatic Control. He is past chairman of AIAA's technical committee on guidance, navigation, and control, and a past associate editor of the Journal of Guidance, Control, and Dynamics. Finally, he recently served on the U.S. Air Force Scientific Advisory Board's Review Panel for Science and Technology.

Daniel P. Schrage is a professor in the School of Aerospace Engineering at the Georgia Institute of Technology. He also serves as the Director of the Georgia Tech Center of Excellence in Rotorcraft Technology and as the Codirector of the Georgia Tech Aerospace Systems Design Laboratory. He has been at Georgia Tech since 1984. Prior to his current academic position, Dr. Schrage served as an engineer, manager, and senior executive with the U.S. Army Aviation Systems Command (AVSCOM) from 1974 to 1984. His final position at AVSCOM was Director for Advanced Systems and while at AVSCOM he served on four major Army Aviation Source Selection Evaluation Boards and co-chaired the concept exploration effort for the LHX (Light Helicopter Experimental), now RAH-66 Comanche. In 1983, Dr. Schrage also served on a temporary assignment as the chief scientist for the Army's Combined Arms Center. Dr. Schrage also has considerable Army operational experience, having served as an Army aviator for nine years, with combat experience in Southeast Asia and as a field artillery battery commander in Europe. He recently retired as a colonel in the U.S. Army Reserve. Dr. Schrage has served on a number of advisory boards, such as the Army Science Board, the Air Force Studies Board, NASA Aeronautics Research Technology Subcomittees, and several NRC committees.

Charlotte H. Teklitz is Vice President of AMR Training and Consulting Group (AMRTC). Ms. Teklitz has more than 10 years of experience specializing in planning and analysis. At AMRTC, she has overseen aviation consulting projects in the United States, Central America, Venezuela, the Philippines, Hawaii, Uruguay, and Australia. Projects include strategic planning, due diligence, schedule optimization, slot negotiations, executive information systems, start-up business plans, hub feasibility studies, revenue accounting, and fleet planning. Prior to AMRTC, Ms. Teklitz held analytical positions at American Airlines in pricing yield management, international planning, and corporate development. She has represented American Airlines in bilateral negotiations with Singapore and Thailand. Other major projects included investigation of route potentials between North American gateways and Fukuoka and Nagoya, Japan, and an evaluation of hubbing potential in Europe. Previously, she worked in finance and marketing at General Electric and Progressive Insurance. Ms. Teklitz is a graduate of the University of Virginia, where she received her B.S. degree in electrical engineering. She earned a Master of Management degree, with concentration in marketing and finance, from Northwestern University's J.L. Kellogg School of Management.

Earl R. Thompson is Director of the Materials and Structures Department of United Technologies Research Center in East Hartford, Connecticut. Dr. Thompson has been a staff member of the Research Center for more than 30 years. His research contribution has been primarily in the area of high temperature, structural materials. He is a fellow of ASM International and a member of the Connecticut Academy of Science and Engineering. He is a previous member of the NRC's National Materials Advisory Board. His B.S. and M.S. degrees in metallurgical engineering are from North Carolina State University, and his D.Sc. in materials science is from the University of Virginia.

Dianne S. Wiley is the Manager of Airframe Technology in the Business and Advanced Systems Development Organization of Northrop Grumman's B-2 Division. She oversees five departments responsible for research and development in materials and processes, structural design and analysis, and manufacturing technology development. She has been with Northrop for 15 years. As Director of the Corporate Center of Excellence for Materials and Processes, she is responsible for coordinating the expertise and resources of the corporation to address the materials- and processes-related needs of major programs and to aggressively pursue developments in innovative and affordable materials and processes to address emerging needs of future weapon systems. Previously, as manager of the Advanced Structures Department, Dr. Wiley was responsible for directing a team of design engineers developing advanced structural concepts for aerospace applications. As a team member with Rockwell International on the Reusable Launch Vehicle NASA Research Agreement, she has used her aircraft structures experience to transition advanced organic composites to launch vehicle structures. She is also involved with Rockwell on preliminary design of wing and intertank structures for the X-33 advanced technology demonstrator. She is a member of the NASA-Industry Structures Synergy Team for Access to Space. Previously, she was a senior technical specialist on the B-2 program, responsible for developing and implementing innovative structural solutions to ensure the structural integrity of the B-2 aircraft. She draws on 20 years of experience in advanced structures research and development. Her technical experience includes durability and damage tolerance, advanced composites (organic and ceramic), high temperature structures, smart structures, low observable structures, concurrent engineering, and rapid prototyping.

APPENDIX
C

Statement of Task

The High Speed Research Committee will conduct a 12-month study of the HSR program. This study will include thorough investigations of the following key technical areas:

- engine emissions, fuel efficiency, service life, and weight
- community noise
- aircraft range and payload
- weight and service life of airframe structures

The committee will prepare a report that accomplishes the following:

(1) assesses NASA's HSR planning
(2) evaluates progress to date
(3) recommends appropriate changes in the HSR program

To accomplish this task, the committee will meet approximately five times. Some meetings will take place at NASA centers and industry facilities where HSR research and development are under way.

The committee will receive extensive programmatic and technical briefings from NASA and relevant industry participants. The committee will review existing studies of the likely demands for supersonic transports in light of the dependence of these demands on aircraft characteristics. The committee may also request information on the extent of foreign programs from the Department of Commerce, NASA, and others.

The committee will take into consideration and build on relevant National Research Council reports issued by the ASEB, the Board on Atmospheric Sciences and Climate, and the National Materials Advisory Board.

APPENDIX
D

Participants in Committee Meetings

Between June 1996 and January 1997 there were five meetings of the full committee. There were also numerous smaller meetings of one or more committee members with representatives of Boeing, General Electric, Honeywell, McDonnell Douglas, NASA, and Northrop Grumman. The small meetings were called to obtain additional information on aerodynamics, airframe structures and materials, flight deck systems, market analysis, and the propulsion system (including propulsion materials).

In addition to committee members and staff, participants in committee meetings included the following:

Dave Alldredge, Boeing
Doug Ball, Boeing
George Boucek, Boeing
Michael Brunner, McDonnell Douglas
Bruce Bunin, McDonnell Douglas
Leigh Koops, General Electric
Steve Csonka, American Airlines
Bill Corwin, Honeywell,
R.E.G. Davies, Smithsonian Institution
Ravi Deo, Northrop Grumman
Jeff Erickson, McDonnell Douglas
Tom Galloway, NASA Ames Research Center
William Gilbert, NASA Langley Research Center
Sam Gilkey, General Electric
Ed Graber, NASA Lewis Research Center
Mike Henderson, Boeing
John Hickey, Federal Aviation Administration
Dick Hines, Pratt & Whitney
Joe Jackson, Honeywell
Michael Lewis, NASA Langley Research Center
Dave Lund, Boeing
Malcolm MacKinnon, Boeing

Virginia Marks, NASA Langley Research Center
Ron McIntyre, United Airlines
Munir Metwally, McDonnell Douglas
Matt Miller, Boeing
Chet Nelson, Boeing
Thomas Odell, Boeing
Robert Plencner, NASA Lewis Research Center
June Rickey, NASA Lewis Research Center
Rodney Ricketts, NASA Langley Research Center
Wallace Sawyer, NASA Langley Research Center
John Shaw, Boeing
Robert Shaw, NASA Lewis Research Center
Jay Swink, McDonnell Douglas
William Troha, NASA Lewis Research Center
Howard Wesoky, NASA Headquarters
Allen Whitehead, Jr., NASA Langley Research Center
Alan Wilhite, NASA Langley Research Center

Acronyms

ACE	Aeroelastic Concept Engineering (Project)
AESA	Atmospheric Effects of Stratospheric Aircraft
AMLCDs	active matrix liquid crystal displays
APSE	aero/propulsive/servo/elastic
CICT	Certification Issues Coordination Team
CMC	ceramic matrix composite
FAA	Federal Aviation Administration
FAR	Federal Aviaiton Regulations
FAST	full-scale advanced supersonic technology (demonstrator aircraft)
FY	fiscal year
HDTV	high-definition television
HSCT	high speed civil transport
HSR	High Speed Research
ITD	Integrated Technology Development
JADC	Japan Aircraft Development Corporation
L/D	lift-to-drag ratio
LPP	lean premixed prevaporized (combustor)
MTOW	maximum takeoff weight

n.m.	nautical miles
NASA	National Aeronautics and Space Administration
NO_X	nitrogen oxides
NRC	National Research Council
PMC	polymeric matrix composite
QFD	Quality Function Deployment
RQL	rich, quick mix, lean (combustor)
SLFC	supersonic laminar flow control
SOREV	Surface Operations Research and Evaluation Vehicle
SST	supersonic transport
TCA	Technology Concept Airplane
TCn	Technology Configuration (airplane)
TIFS	Total Inflight Simulator (airplane)
TRL	Technology Readiness Level
XVS	external visibility system