

NASA Contractor Report 4234

High-Speed Civil Transport Study

Summary

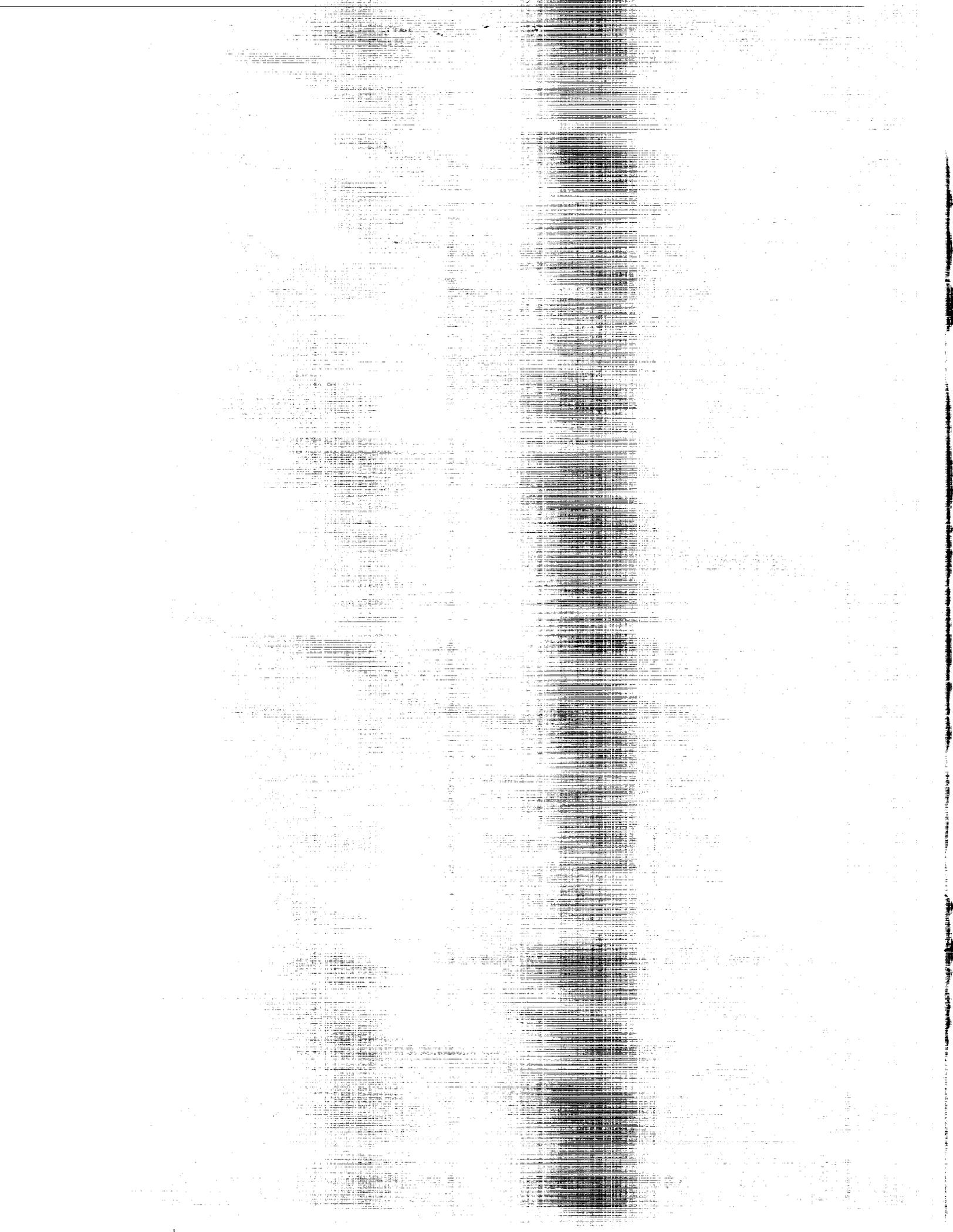
Boeing Commercial Airplanes
New Airplane Development

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High-Speed Civil Transport Study

Summary

*Boeing Commercial Airplanes
New Airplane Development
Seattle, Washington*

Prepared for
Langley Research Center
under Contract NAS1-18377



National Aeronautics and
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FOREWORD

This report documents work completed for phases I, II, and III on high-speed civil transports under NASA contract NAS1-18377. The New Airplane Development group of Boeing Commercial Airplanes, Seattle, Washington, was responsible for the study. Charles E. K. Morris, Jr., NASA Langley Research Center, was NASA program manager. Michael L. Henderson and Frank H. Brame were program managers for Boeing Commercial Airplanes. Boeing task managers were: Robert M. Kulfan for phase I and II Engineering; John D. Vachal for phase III Engineering; William H. Lee and Roger W. Roll for Marketing; and Donald W. Hayward and Edward N. Coates for Special Factors.

The Boeing team consisted of—

Manager HSCT Design Development	M. I. K. MacKinnon
Aerodynamics	D. N. Ball, T. H. Hallstaff, G. T. Haglund, J. C. Klein, S. S. Ogg, J. A. Paulson, S. E. Stark, P. F. Sweetland, T. E. Trimbath, G. H. Wyatt
Configurations	T. Derbyshire, V. K. Stuhr
Finance	G. J. Gracey
Marketing	R. E. Bateman, T. Higman, S. C. Henderson
Noise	J. G. Brown, G. L. Nihart
Payloads	D. P. Lefebvre
Propulsion	J. J. Brown, G. B. Evelyn, R. B. McCormick, J. Merrick, P. Ormiston
Special Factors	N. M. Barr, J. H. Foster, O. J. Hadaller, A. M. Momeny
Structures and Materials	J. W. Fogelman, D. L. Grande, T. E. Munns, D. G. Stensrud, R. T. Wagner
Systems	A. W. Waterman, T. Timar
Weights	J. D. Brown, M. W. Peak, J. P. Rams

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SUMMARY

A systems study of the potential for a high-speed commercial transport has addressed technology, economics, and environmental constraints. Market projections indicated a need for fleets of transports with supersonic or greater cruise speeds by the years 2000 to 2005. The associated design requirements called for a vehicle to carry 250 to 300 passengers over a range of 5,000 to 6,500 nautical miles. The study was initially unconstrained in terms of vehicle characteristics, such as cruise speed, propulsion systems, fuels, or structural materials. Analyses led to a focus on the most promising vehicle concepts. These were concepts that used a kerosene-type fuel and cruised at Mach numbers between 2.0 to 3.2. Further systems study identified the impact of environmental constraints (for community noise, sonic boom, and engine emissions) on economic attractiveness and technological needs.

Results showed that current technology cannot produce a viable high-speed civil transport; significant advances are required to reduce takeoff gross weight and allow for both economic attractiveness and environmental acceptability. Specific technological requirements have been identified to meet these needs.

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INTRODUCTION

Present projections predict that the worldwide demand for long-range air travel will double by the year 2000 and nearly double again by year 2015. This growth in the market will occur at the same time that increasing numbers of aircraft in the existing fleet will be retired due to age and noise rules.

Manufacturers must make difficult and long-lasting decisions in the next 5 to 10 years concerning future products so that sufficient time is allowed for development. One option to consider is a new generation of commercial transports that cruise at speeds of Mach 2.0 or greater and can serve both the Atlantic and Pacific markets.

Boeing Commercial Airplanes conducted a three-phase study of the potential for future high-speed civil transports (HSCT) under NASA contract NAS1-18377 between October 1986 and August 1988. The primary objectives were to identify the most promising concepts in high-speed transports and to guide the development of requisite technology that may not flow directly from the National Aero-Space Plane or other existing programs. To achieve this it was necessary to examine the environmental, operational, and nonvehicle factors that will influence the vehicle configuration, supporting facilities and systems requirements, and overall program viability. Also, it was essential to identify and account for those market and economic factors that must be considered to provide a commercially acceptable high-speed transport system.

The study examined the requirements of a future HSCT as affected by the environment, operational concerns related to other HSCTs and subsonic aircraft, and the market demand for aircraft after the year 2000. Market assumptions were developed for an HSCT operating in this timeframe. The study evaluated both supersonic and hypersonic aircraft. Initially, aircraft were evaluated through Mach 10.0; the latter phases looked at supersonic only (under Mach 6.0) (fig. 1). Propulsion concepts were investigated in conjunction with the fuel technology required. A screening process was employed to determine the best Mach number range for further investigation of the environmental issues such as community noise, effect on the ozone layer, and sonic boom. The economic impact of the configurations investigated were compared throughout the study. Figure 2 illustrates the flow of the study process through the three phases.

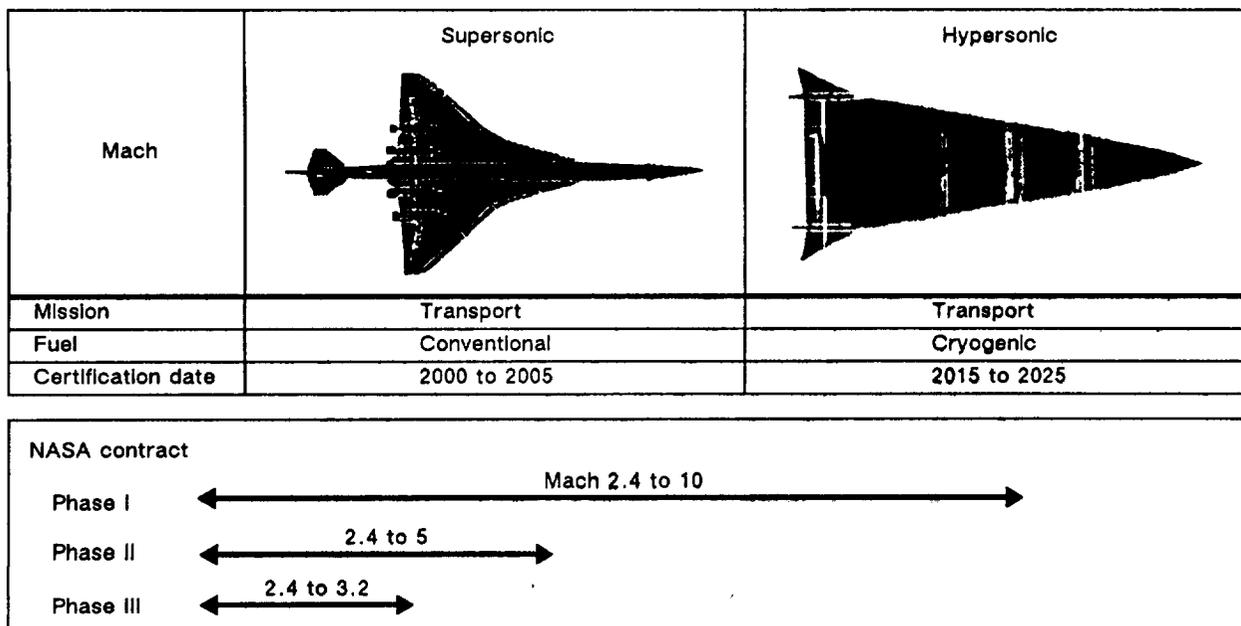


Figure 1. High-Speed Civil Transport Activities

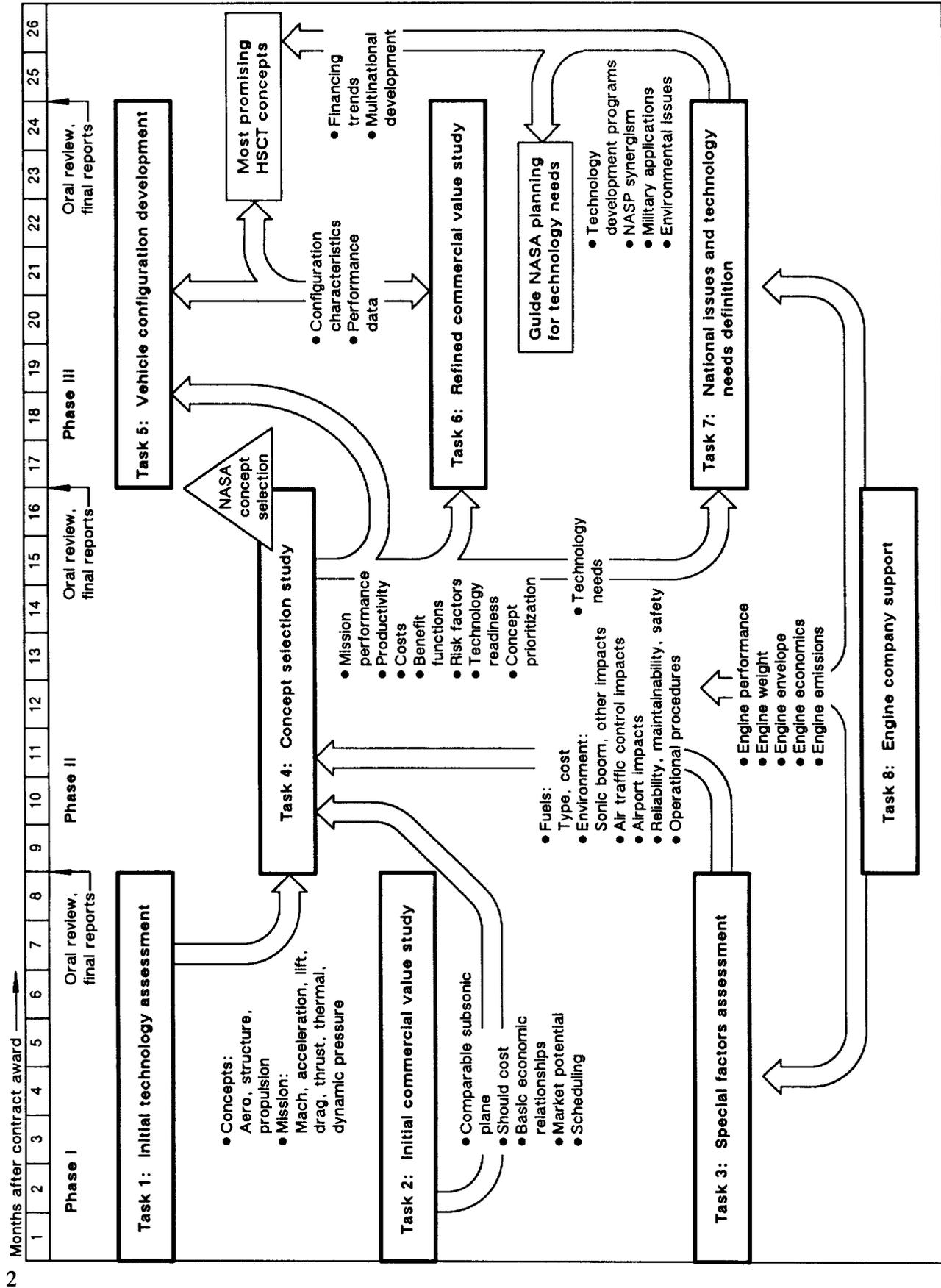


Figure 2. High-Speed Civil Transport Study Plan and Schedule

Table 1. High-Speed Civil Transport Mission Perspective

Transport type	Concorde	U.S. SST	HSCT
Year in service	1971	1975	2000-2015
Market	North Atlantic	North Atlantic	Atlantic and Pacific
Range (nmi)	3,500	3,500	5,000-6,500
Payload (passengers)	100	200	250-300
TOGW (lb)	400,000	750,000	750,000
Community noise requirements	None	Stage II	Stage III
Revenue required (cents/revenue passenger miles)	87	60	9-10

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Table 1 indicates the level of challenge posed by this goal of an economically attractive, environmentally acceptable HSCT. Passenger count must increase significantly from the Concorde to be economical, and noise and emission levels must be greatly reduced.

A capable HSCT like the one postulated in table 1 would compete well even with advanced subsonics because of reduced flight times. It is important that U.S. manufacturers understand the potential of such an airplane as a product or a competitor. Ignoring the HSCT's potential, or delaying the timely development of technology that could make it a viable product could bring about the loss of a significant national opportunity to the competition from abroad. If successful, this competition would reduce the United States' traditionally high market share in the international marketplace for large, long-range commercial transports. Even worse, commitment to a program without an adequate technological and environmental database could lead to an expensive failure. Both arguments lead to the conclusion that it is justified and highly desirable to continue research and development of key technologies for an environmentally and economically sound HSCT.

MARKET/MISSION REQUIREMENTS

Market Needs Projection

The market forecast is based on major market area passenger flows as defined in the "Boeing 1987 Current Market Outlook" (ref. 1). The Market Outlook covers the time period from 1987 through the year 2000 and projects that world air travel will grow at an average rate of 5.3% per year. The market application for an HSCT is derived from the "international scheduled" portion of this forecast that represents 22.8% of the total world demand for the year 2000.

Not all of this market is applicable for a long-range airplane, however. Figure 3 graphically depicts that portion of the international traffic allocated to the HSCT. All passenger demands less than 300 passengers per day, less than 2,500 nmi in distance, and all intraregional demands were excluded. As a result only 28% of the international demands (or about 6.4% of the world passenger forecast) are considered HSCT study markets.

The traffic forecast for 2015 was developed by assuming the individual markets are maturing, and therefore grow at 85% of their average rates from the years 1995 through 2000. This resulted in almost doubling the year 2000 demand, with the Pacific Rim area forecast increasing at a greater rate (53% of the revenue passenger miles in year 2000 and 60% in 2015) (fig. 4). The total HSCT passenger demand potential (without allowances for stimulation) is forecast to be 315,000 passengers per day by year 2000 and 600,000 per day by 2015. This is certainly adequate potential traffic to justify a commercially viable HSCT. However, if significant ticket price increases are required for HSCT configurations, market elasticity could reduce the demand for an HSCT below acceptable levels.

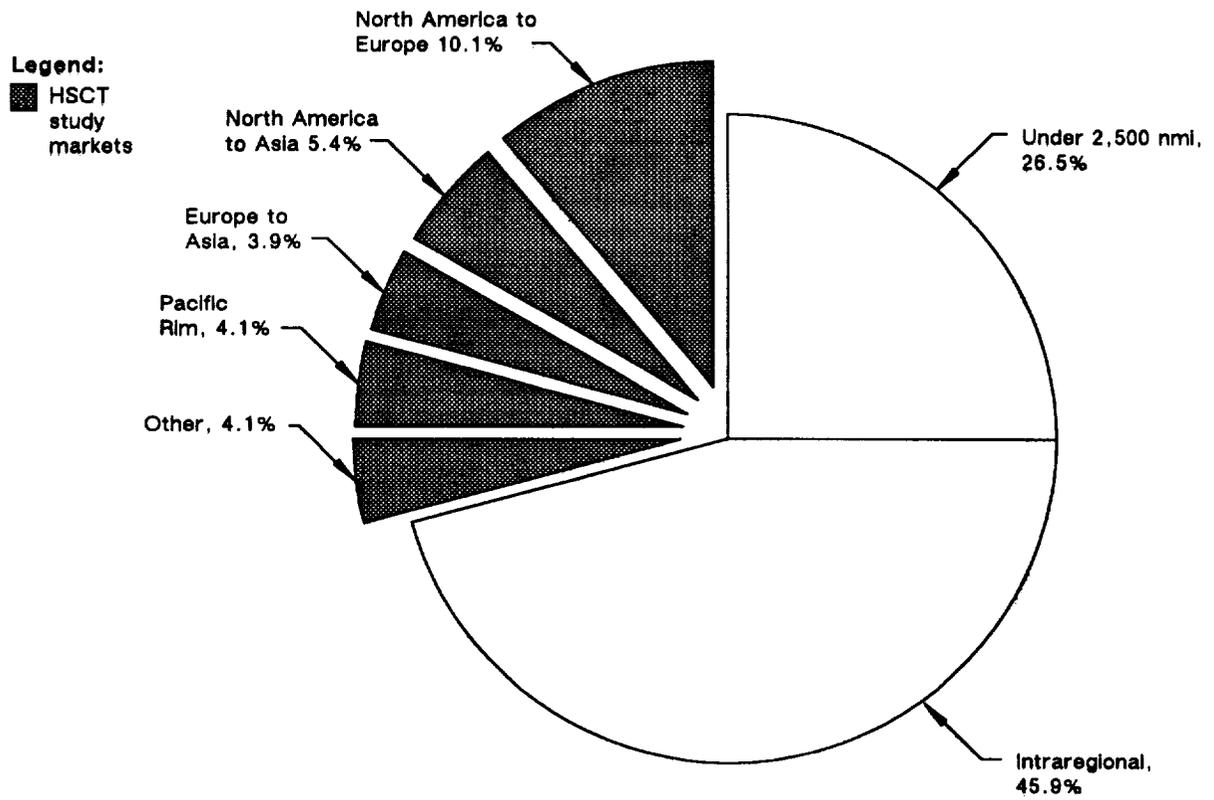


Figure 3. Year 2000 International Traffic Distribution Forecast Based on Total of 1,100,000 Passengers/Day
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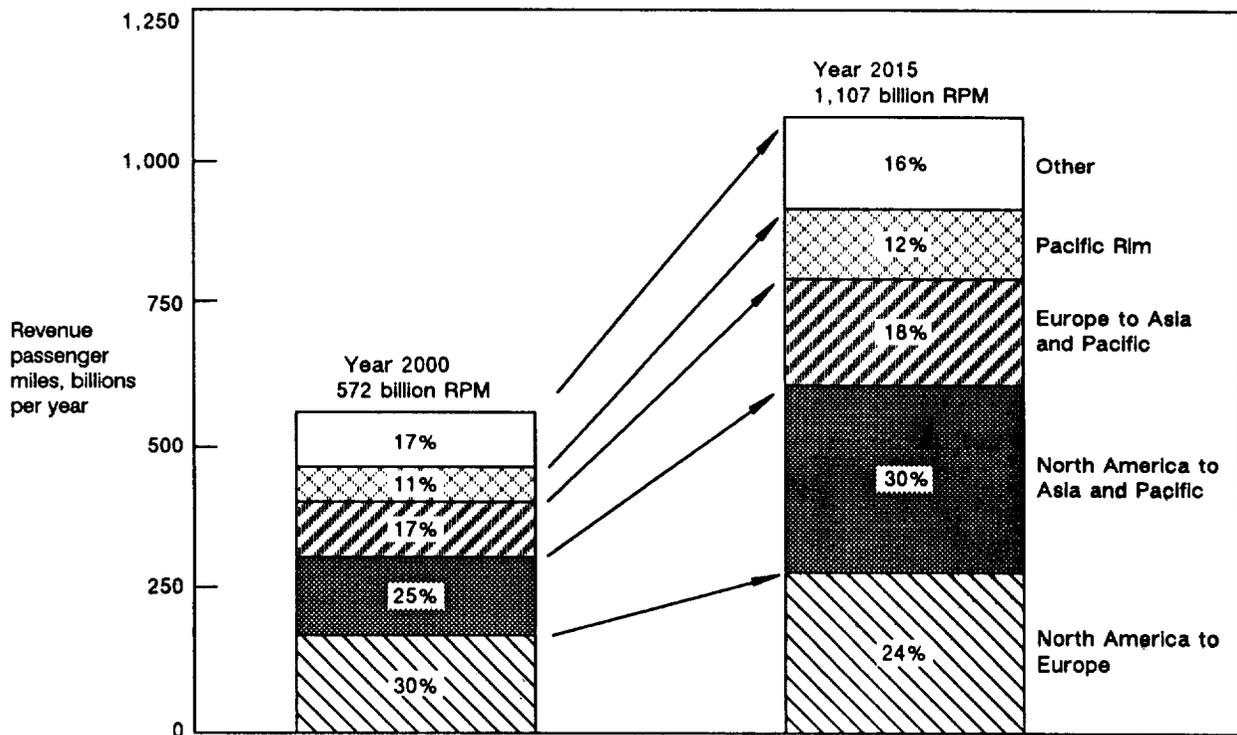


Figure 4. Revenue Passenger Mile Forecast

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Required Vehicle Characteristics

The development of HSCT market requirements demanded an assessment of not only the size and distribution of the market, but also of certain airplane characteristics. These characteristics include speed, design range, airplane through time and airport turnaround time, and passenger seat count within the market. Each characteristic was examined parametrically and then in more detail as required. The parametrics considered two basic environments: (1) an “unconstrained” environment (that is, Great Circle routing and sonic boom allowed over land), and (2) a “constrained” environment that assumed no sonic boom over land and some rerouting to maximize time spent in supersonic cruise. In both cases, existing airport curfews were observed and all the passengers were served within a postulated universal airline system.

Additionally, the market potential is subject to certain unknowns in terms of stimulated passenger demand due to shorter trip times and decreased demand due to ticket price increases over subsonic prices. Stimulation, as such, was not included in the basic study; however, the effect of ticket price was examined.

Figure 5 shows the distribution of nonstop passenger trips and revenue passenger miles. About half the passengers and 40% of the revenue passenger miles would be satisfied by a 4,000-nmi design range. Ninety percent of the passengers, representing 84% of the revenue passenger miles, could be satisfied by a 6,000-nmi design range.

A detailed analysis was conducted of 10 specific market areas in which airplane productivity and HSCT passenger trip time savings were used to evaluate design-range capabilities. Design range is important because it affects the number of intermediate stops required to serve the airline’s network. Stopovers will reduce airplane productivity and increase travel time.

As seen in figure 6, four of these ten markets have more than 85% of their routes over water and the others range from 50% to 80% over water. These same four markets represent approximately half of the passengers and 41% of the revenue passenger miles. The remaining “mostly overland” markets

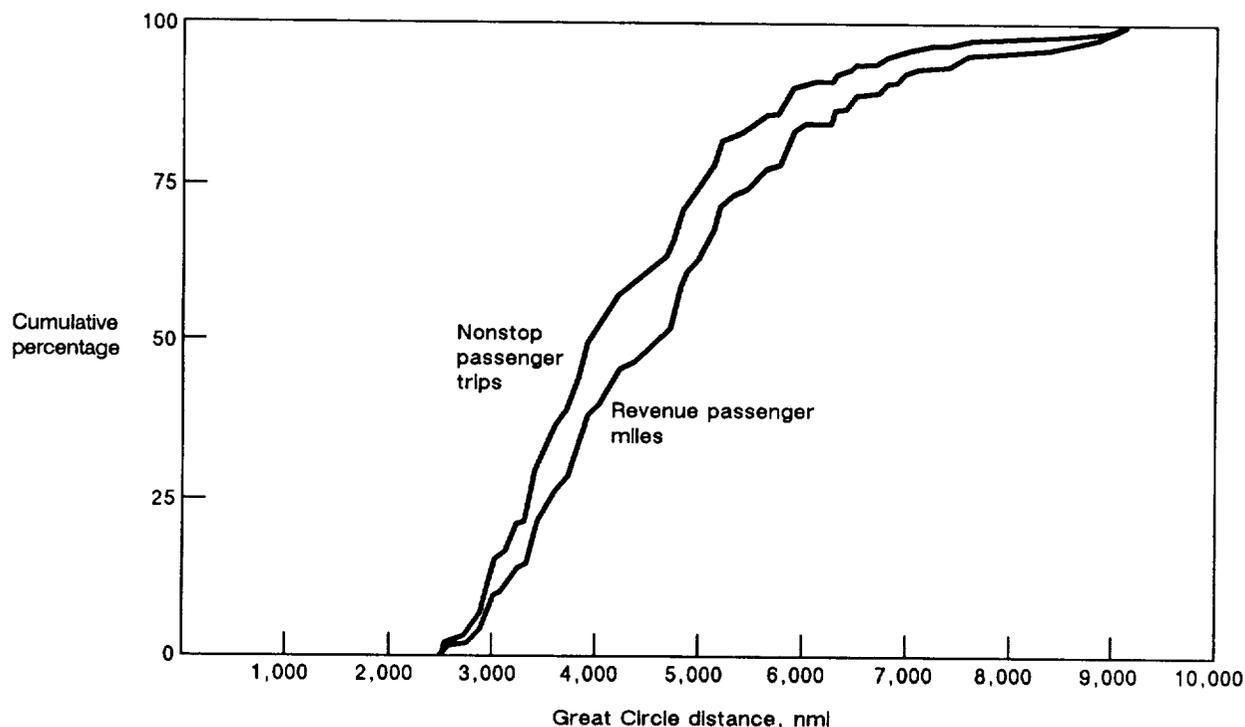


Figure 5. HSCT Traffic Distribution – Year 2000

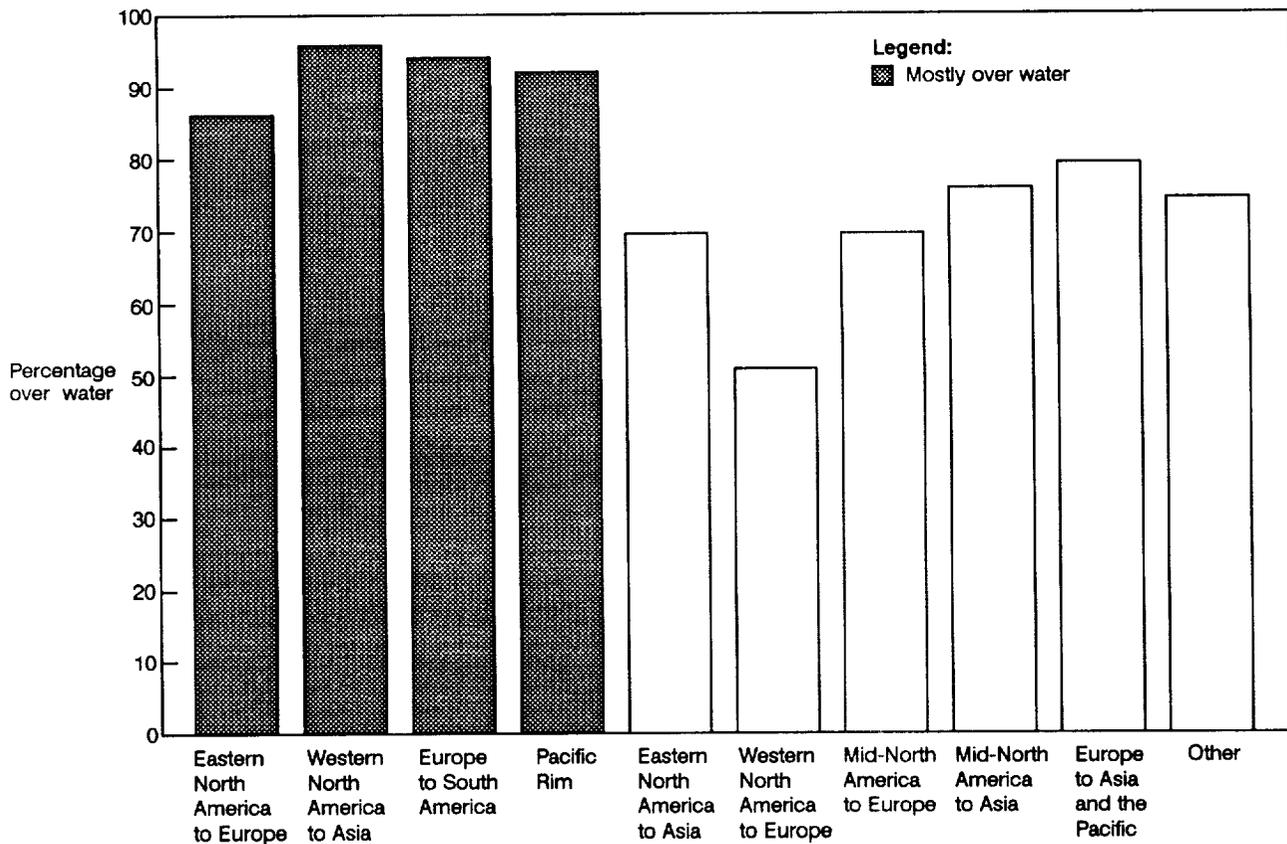


Figure 6. Overwater Distance

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cannot use an HSCT as effectively as the overwater markets if there is a constraint forbidding any overland supersonic flight. These markets, then, will require flying long distances subsonic over land and reflect the need, in many cases, to deviate from Great Circle routing to reduce overland flight distances. This natural differentiation of markets (predominantly over water versus over land) provides a useful division to evaluate the HSCT design-range requirements relative to productivity (number of airplanes required) and passenger trip time.

Figures 7 through 9 are indicative of the overall results for the best-case potential: unconstrained, supersonic, overland flight with Great Circle routing. These results indicate maximum gains in productivity between Mach 2.0 and Mach 8.0. There are, also, trades between Mach number and the other parameters. A 7,000-nmi design range, Mach 3.0 vehicle, for example, has the same productivity potential as a 4,500-nmi design range, Mach 10.0 vehicle (fig. 8).

Air Transportation System

Twenty-seven conventional airports were selected as primary candidates for use by the HSCT. A vehicle designed for a sea-level takeoff field length of 12,000 ft will impose little additional requirements to existing runways at these international airports. Airport modifications required for the fleet of subsonic vehicles anticipated for the years 2000 to 2015 would cover most of the needs of a supersonic transport in the Mach range considered most viable. Some additional modifications to taxiways and loading areas may be required because of the vehicle's length (60 ft longer than a 747).

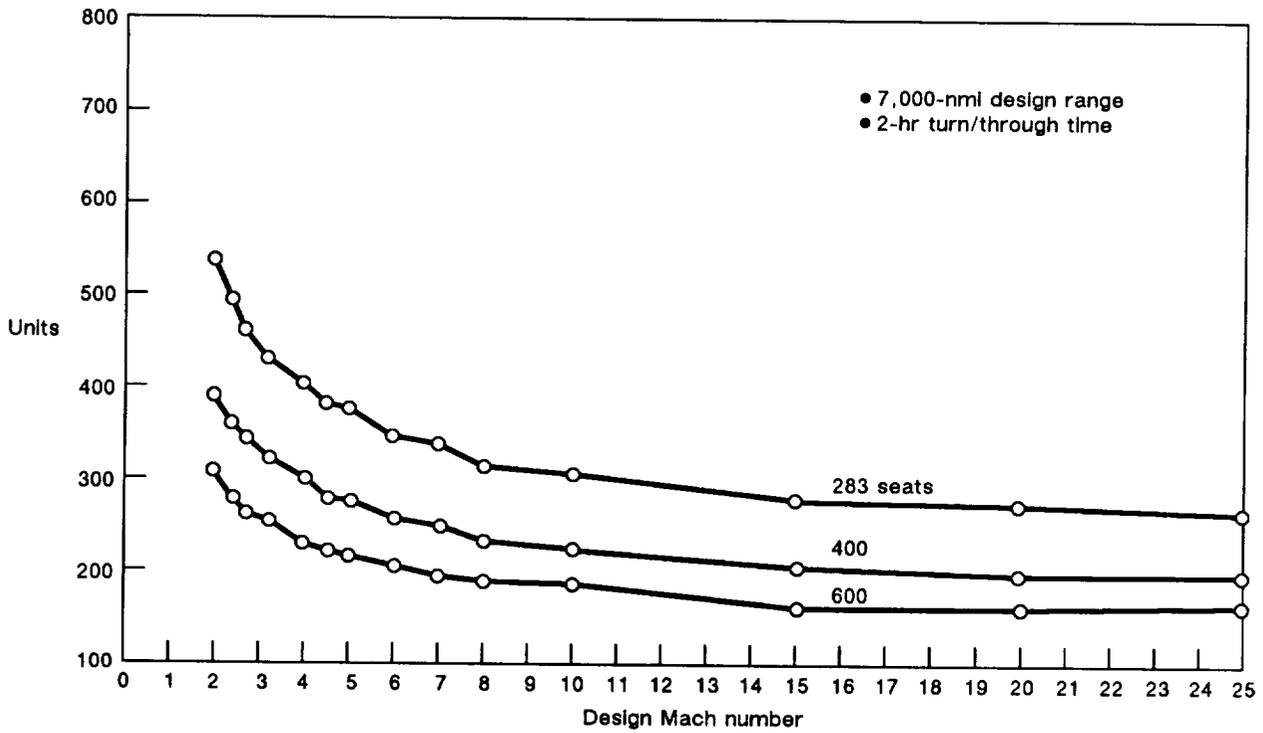


Figure 7. Fleet Size Versus Seats

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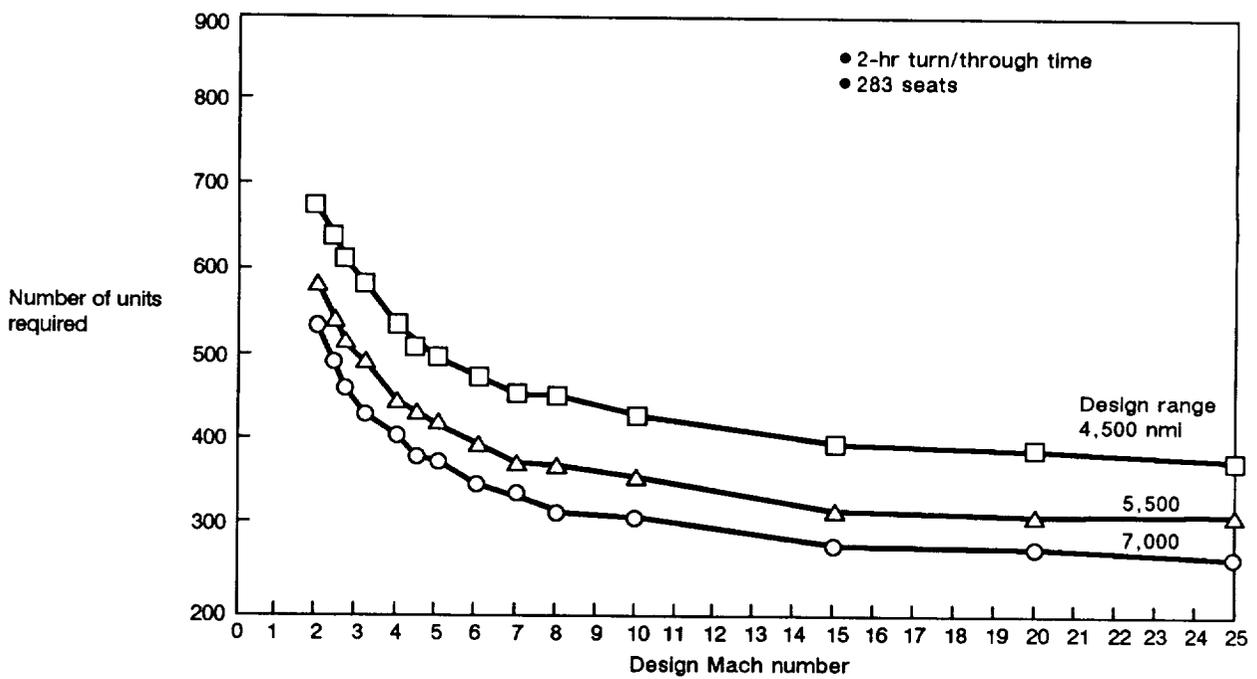


Figure 8. Effect of Design Range on Fleet Size

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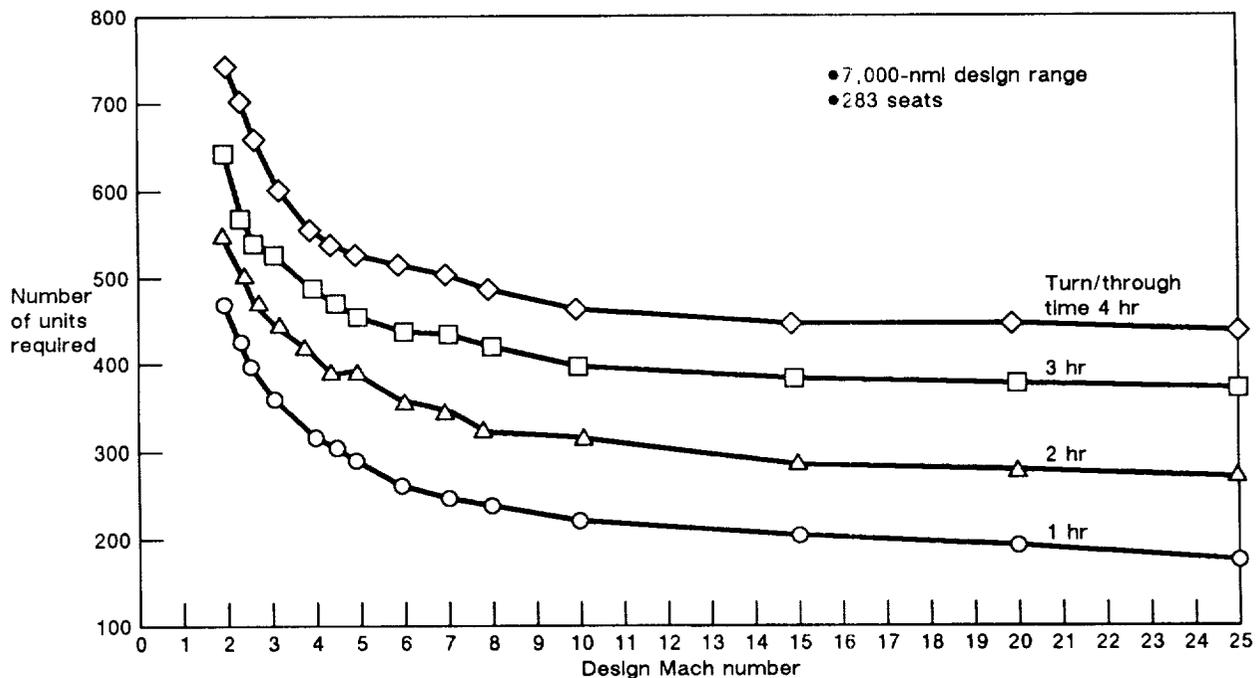


Figure 9. Fleet Size Versus Turn/Through Time

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Consideration also must be given to the influence of high-speed travel in heretofore uncontrolled airspace; however, no special Air Traffic Control electronic equipment will be required. The HSCT-era avionics systems will greatly enhance HSCT integration into Air Traffic Control environments.

Special airports would probably be required to accommodate the needs and improve the productivity of a hypersonic HSCT (airplanes with cruise Mach number of 6.0 or greater), which is expected to operate with weights greater than 1 million pounds. This higher speed vehicle will also require special fuel systems and will probably not meet community noise standards.

To improve the productivity of a hypersonic HSCT, the average stage length must be long enough to provide a substantial period of time at cruise.

A network of strategically located "superhubs," shown in figure 10, was developed to maximize the average stage length of the hypersonic HSCT. These hubs would be fed by subsonic airplanes, with service between the hubs by airplanes with cruise speeds of Mach 6.0 and greater. The productivity, measured by units required, and the average trip time for this superhub system were compared when serving the same market, with more direct routing and either an all-subsonic fleet (Mach 0.84 cruise) or an all-supersonic fleet (Mach 3.2 cruise, Mach 0.9 over land).

Figure 11 compares the units required in the year 2015 for each case. The all-subsonic system (with 525-seat airplanes) requires about 560 units, while the all-supersonic, Mach 3.2 system (with 283 seats, subsonic over land, and waypoint routing) requires 50 fewer units. The third bar in figure 11 shows that the system using superhubs requires more units (90 more than the subsonic and 110 more than the supersonic system), but 370 of these are subsonic (and less expensive) airplanes.

Figure 12 compares the average trip time for the three systems. Both the all-supersonic and the hypersonic-subsonic superhub system show significant gains over the all-subsonic system. The superhub system at Mach 6.0, however, shows no gain over a Mach 3.2 system and only a 1 hr improvement at Mach 15.0. This is because the feed portion of the trip and the passenger transfer at each end of the high-speed leg consumes almost 4 hr (even assuming an optimistic 30-min transfer time).

In conclusion, the benefits, in terms of the travel time savings of a dedicated superhub network, are minimal. Productivity gains are offset by the requirement for a large number of subsonic feed

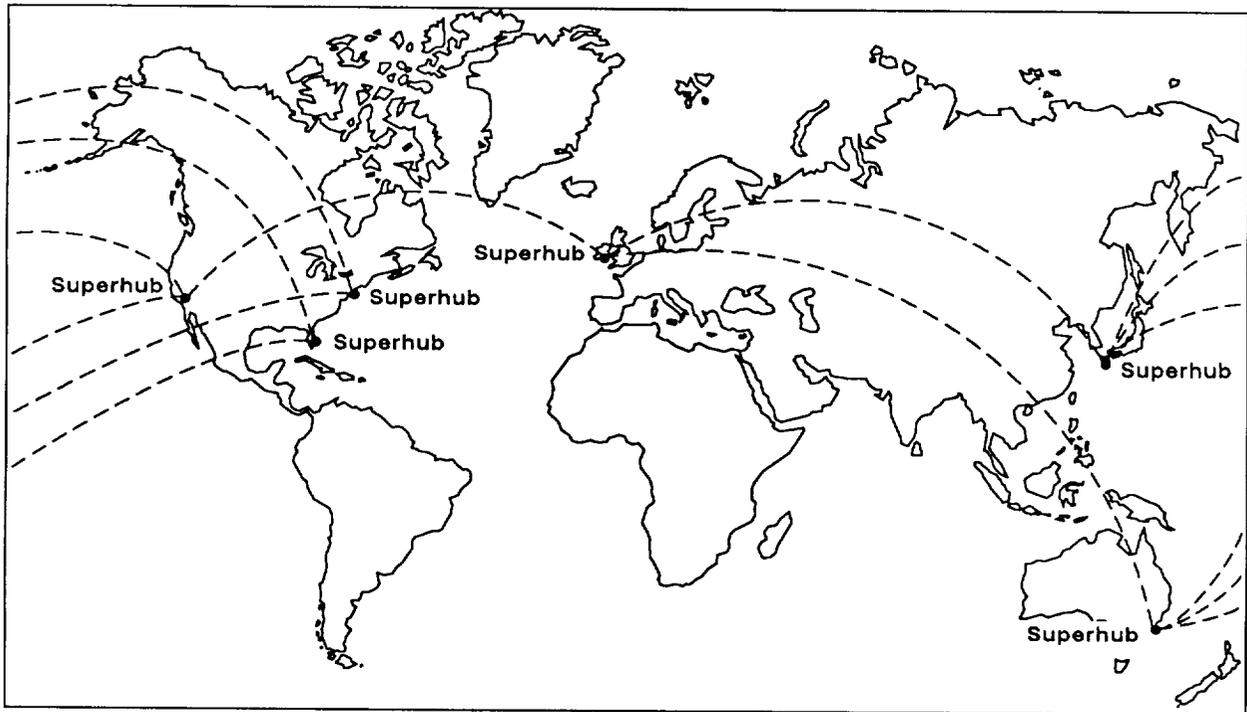


Figure 10. Superhub Airport Network

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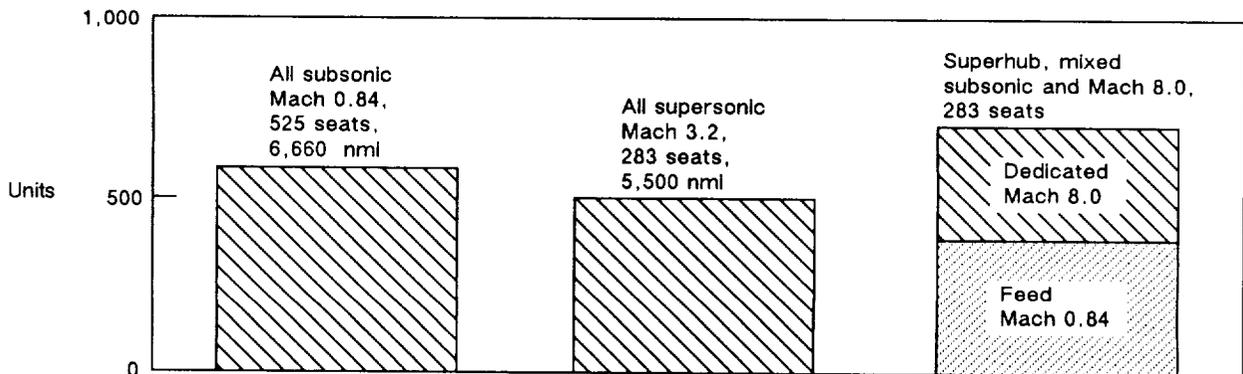


Figure 11. Units Required—Year 2015

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airplanes. The hypersonic airplanes are likely to be very expensive because of both the technology required and the small number of units needed (less than 300). Operating costs are also likely to be high. In addition, six dedicated ground facilities would have to be built, the cost of which must be included in the economic evaluation of the total transportation system.

Design Requirements

The study airplanes were designed to a set of requirements that included payload at 247 passengers; range of 5,000 nmi with a growth objective of 6,500 nmi, a maximum takeoff field length of 12,000 feet at sea level 86°F, and a maximum approach speed of 160 keas at maximum landing weight.

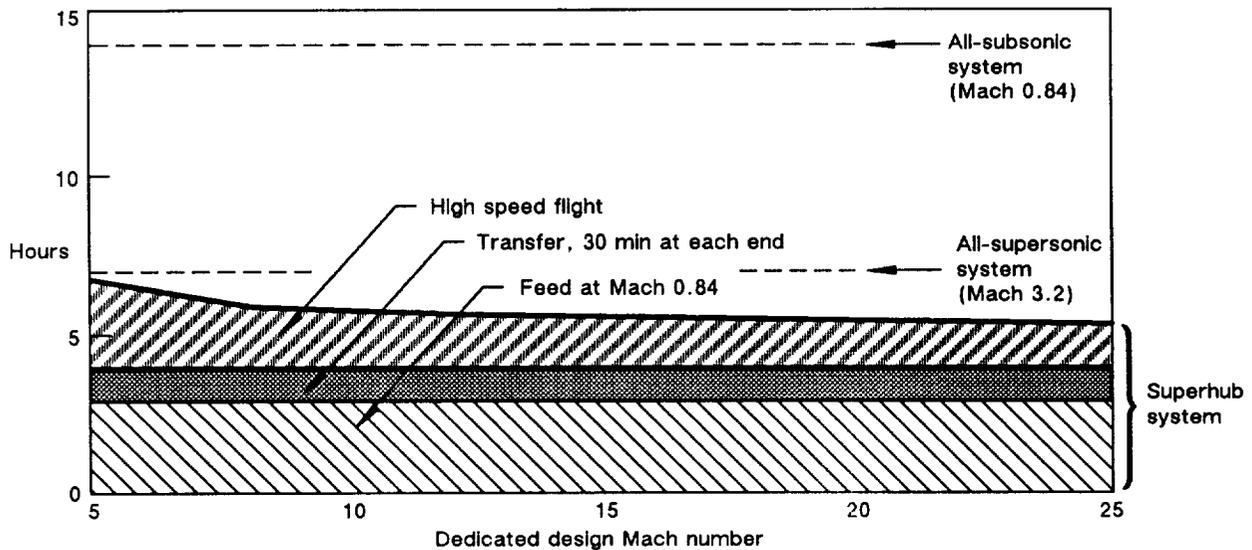


Figure 12. Average Trip Time – Superhub System

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ENVIRONMENTAL CONCERNS

Environmental acceptability is a key element of any HSCT program. If not properly accounted for in the HSCT design, environmental limitations could substantially reduce use of the vehicle and, in the most extreme circumstance, prohibit vehicle operation altogether. The primary areas of environmental impact identified by this study were engine emissions effects, community noise, and sonic boom.

A viable HSCT must be designed so that its engine emissions have no significant impact on the Earth's ozone layer. This is based on the justifiable public concern about the impact of long-term depletion of the Earth's protective ozone layer.

Operation out of conventional airports was determined to be a requirement for achieving adequate HSCT utilization. Accordingly, a viable HSCT must produce noise levels no higher than its subsonic competition. Studies indicate that, with projected suppression technology, achievement of FAR36 Stage 3 noise levels may be possible.

The sonic-boom overpressure level of a large, long-range HSCT designed for minimum weight is unacceptably high for overland flight in populated areas (overpressure of 2 to 3 lb/f²t). Commercial overland supersonic flights are, therefore, not allowed by U.S. law. The airplanes under study have been evaluated with subsonic flight profiles over land, which results in an adverse economic and market impact. Thus, there is impetus to explore low-boom designs that allow some form of overland supersonic operation.

VEHICLE DEVELOPMENT

Initial Assessment

The technical and industrial progress achieved in the last century has demonstrated that, given enough time, technical achievement is almost limitless. Thus, rational judgments on technical feasibility must be in reference to specific time scales. For HSCT development, two time periods were defined. The first timeframe was defined as the earliest date that an economically viable and environmentally safe HSCT could be produced. The certification date was judged to be the year 2000, and is consistent with projections of market needs in terms of international traffic growth and current subsonic fleet replacement. The second time period defined was the year 2015 when certain advanced

technologies would have matured, some of which could possibly be developed as part of the proposed National Aerospace Plane program.

The initial assessment of vehicle technology was organized into studies for each of several bands of Mach number (table 2). These bands were defined either by differences in technology readiness dates or in classes of airframe and engine technology.

Three engine manufacturers, Aerojet General, General Electric, and Pratt and Whitney, provided data for advanced, conceptual engines appropriate for a series of commercial transports with a cruise speed between Mach 2.4 and Mach 10.0. Turbomachinery cycles were used to power the lower Mach number vehicles. A combined turbomachinery-ramjet cycle was used at Mach 4.5, an air turboramjet at Mach 6.0, and a supersonic-combustion scramjet at Mach 10.0. Engine cycle thermodynamics and properties of the available engine materials influence the engine cycle choice for each flight Mach number. The engine concepts are illustrated in figures 13 and 14.

Mach 3.2 is near the projected upper limit of using wing-integral fuel tanks for cruise fuel. Mach 3.2 operation will require extensive development of fuels with higher thermal stability and fuel tank designs with low thermal conductivity. Mach 4.0 is near the projected upper limit for conventional turbojet-fan engine cycles and for thermally stable jet fuel (TSJF) use. Mach 4.0 is also considered to be the upper limit for a year 2000 HSCT because of very high technology risks and formidable design complexities that would need to be addressed in this relatively short development time period. For the year 2015, the continued technology development programs would provide more efficient configurations for Mach numbers up to Mach 4.0. In addition, the more advanced technology would open up design options for even higher Mach numbers.

Above Mach 4.0 it is projected that cryogenic or endothermic fuels would be required to satisfy heat sink demands. Mach 6.0 is near the upper projected limit for liquid methane, endothermic fuels, and the ramjet as the cruise propulsion system. Mach 8.0 is near the projected upper limit for uncooled structural materials. At Mach numbers below this limit, however, areas such as the wing leading edges or nacelle inlets may require localized active cooling. At Mach numbers above 8.0, active cooling of structural materials is projected. Vehicle concepts for Mach numbers of 6.0 or greater were designed for dedicated superhub operations because the design compromise for achieving both high-speed and low-speed performance would have been prohibitive.

Initial vehicle development evaluated 21 configuration concepts designed for Mach numbers between 2.4 and 10.0. A screening process was used to evaluate the concepts on the basis of risk versus benefit. Of the 21 configurations, 6 were chosen for further development (figs. 15 through 20). Based on the following trends and study results, further work was concentrated on the lower range of Mach numbers:

- a. Aircraft size and design complexity increase significantly with increasing design Mach number.
- b. The airplane maximum takeoff weight is very sensitive to projected technology improvements for the higher Mach numbers.

Table 2. Design Mach Number Selections

Region	Mach range	Year of certification	Limitation
1	2.0 to 3.2	2000	Thermally stable jet fuel in wing tank
2	3.2 to 4.0	2000	Thermally stable jet fuel
3	4.0 to 6.0	2015	Turbofan/turbojet Endothermic fuel Liquid CH ₄ Ramjet
4	6.0 to 8.0	2015	Uncooled structural materials
5	8.0 to 25.0	2015	

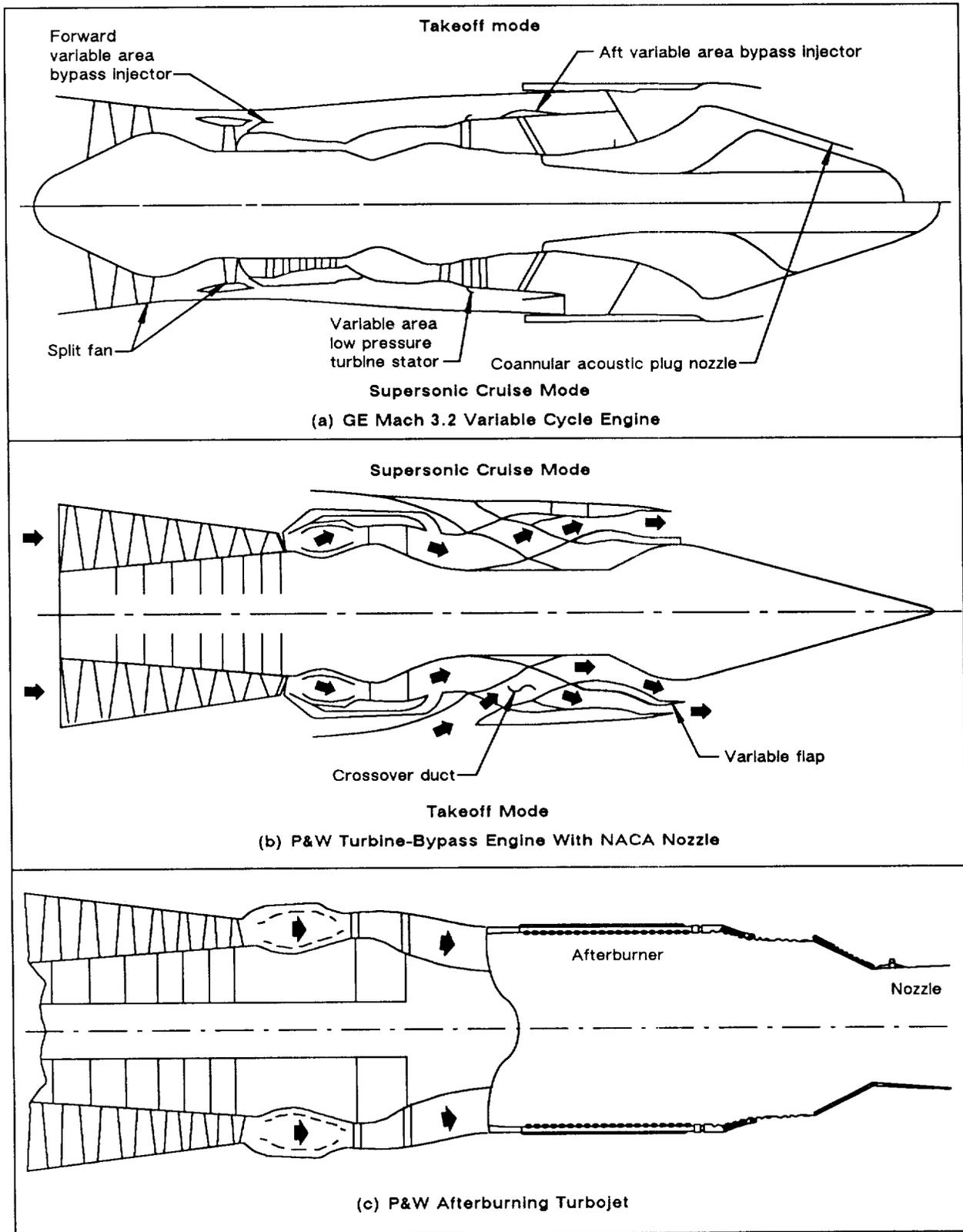


Figure 13. Conventional-Fueled Engine Concepts

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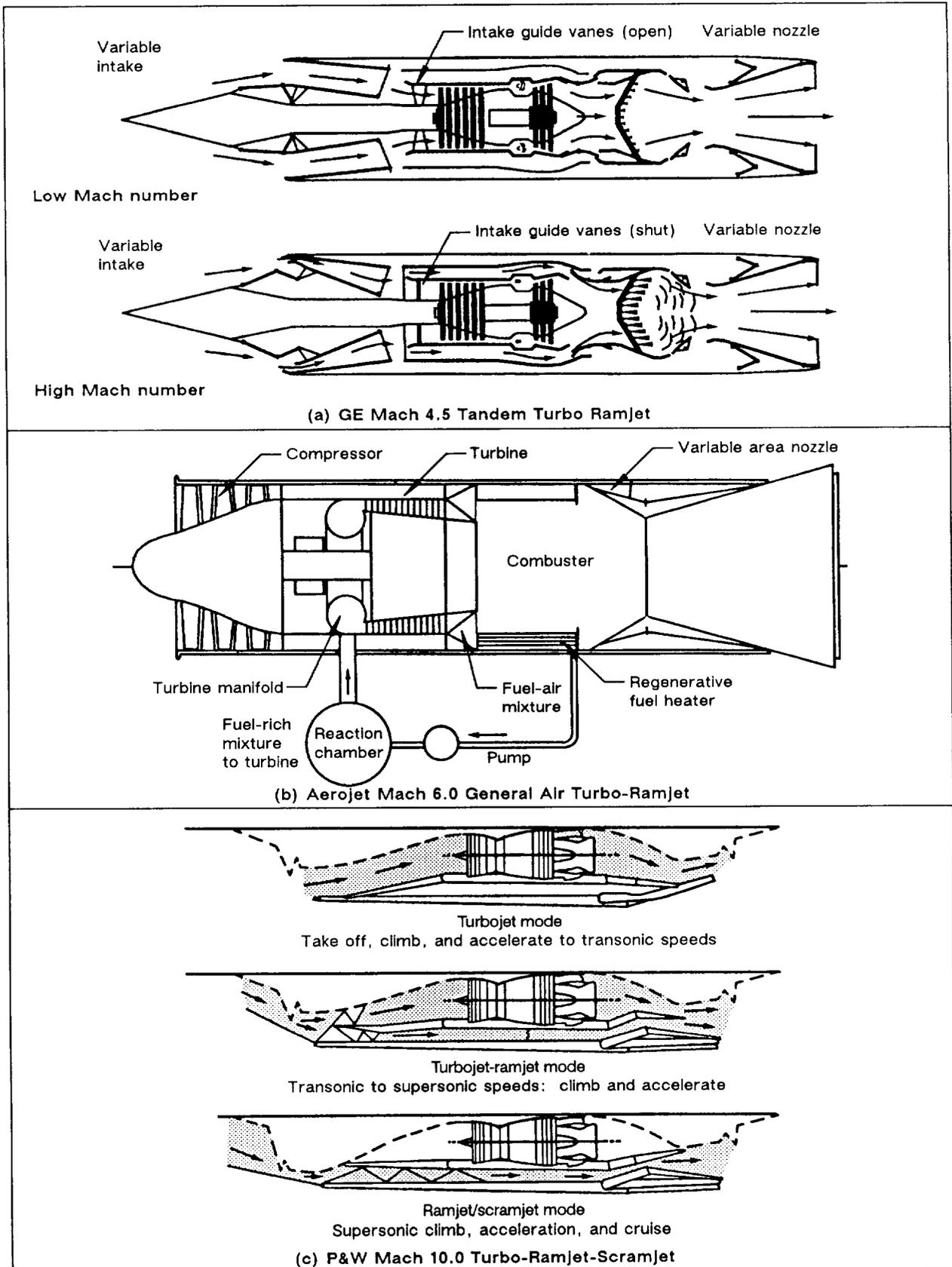


Figure 14. Cryogenically Fueled Engine Concepts

ECONOMIC EVALUATION

The concept of life cycle operating costs has been developed to satisfy the need for an economic comparison method that accounts for the actual cash direct and indirect costs incurred in operating an airplane as well as including all "ownership costs." Cost elements identified include the following:

- a. Cash direct cost elements, which include—
 1. Flight crew costs.
 2. Fuel burned.
 3. Airframe maintenance.
 4. Engine maintenance.
 5. Hull insurance.
- b. Indirect costs, which include—
 1. Airplane-related (cleaning, fueling, aircraft-handling, maintenance, and ground handling equipment).
 2. Passenger-related (food, passenger-handling, agency commissions, passenger insurance).
- c. Ownership costs.

An "economic horizon" was used to provide a reference life cycle operating cost to evaluate the economic viability of HSCT study configurations. This economic horizon is a trendline relationship of life cycle operating costs and airplane size. It was based on projected advanced derivatives of the Boeing 767 and 747 aircraft and allows comparisons of a wide variety of passenger seat counts. This economic model was used in all phases of the contract to define market value of HSCT designs and the revenue required to obtain the desired return on investment for those designs for which prices were estimated.

Economic Viability

To be economically viable, the HSCT must provide a reasonable financial return for both the airlines and the manufacturers. Any increased operating and ownership costs associated with an HSCT must be largely overcome by increased productivity due to speed. The sale price must allow an adequate return on investment and still elicit enough demand for the HSCT to justify the large investment in development and production costs. To the extent that increased costs cannot be overcome by increased productivity, higher ticket prices must be charged, thereby reducing the market. Preliminary estimates have been made of the response of the projected HSCT market to increases in price.

The impact of technology, based on this evaluation, is illustrated in figure 32. This evaluation shows that present day technology is not adequate to allow the necessary profit margin. A Mach 2.4 HSCT designed with today's technology would require a 50% to 60% increase in average ticket price over contemporary subsonic transports. This would reduce demand to the point that the total worldwide fleet requirement is estimated to be 300 units or less, an inadequate number to support a viable program. However, with technology available for year 2000-certified airplanes, the required revenues are lower, primarily because of the smaller vehicle required to perform the design mission. The result is that a ticket price increase of 18% would be required and the fleet requirement would be approximately 650 to 750 units. If year 2015-certification technology was used, ticket price would only increase by 8%. This would result in a fleet requirement of 950 to 1,050 units.

The impact of design Mach number on the market captured by the HSCT is shown in figure 33. Assuming year 2000 certification, increasing design speed from Mach 2.4 to Mach 2.8 boosts the fare increase to over 25% and reduces the market captured to 30%, requiring a fleet size of 400 to 500 units. The Mach 3.2 design does not close, as the yield required to earn the required return on investment is rising more steeply than the yield available.

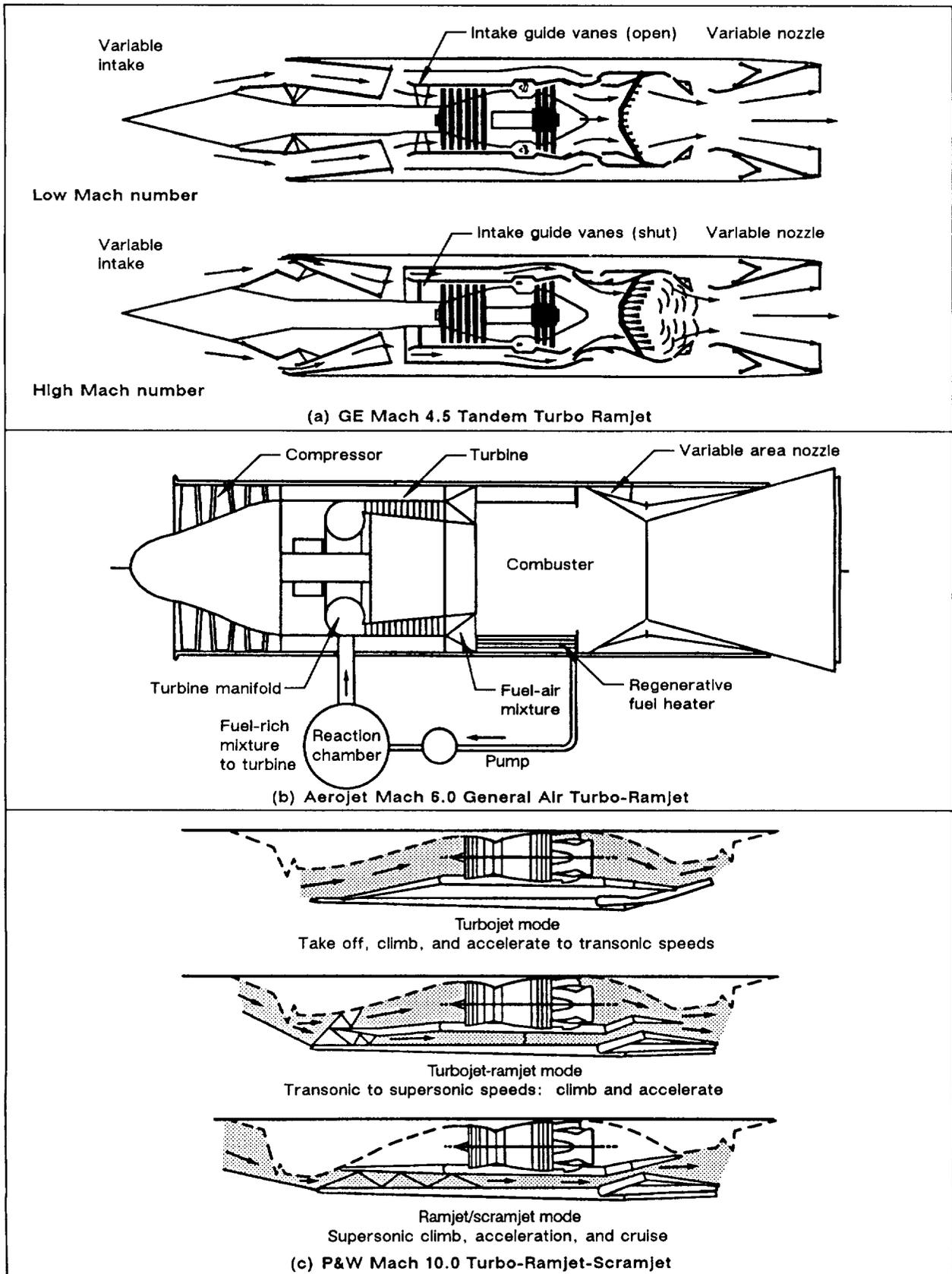


Figure 14. Cryogenically Fueled Engine Concepts

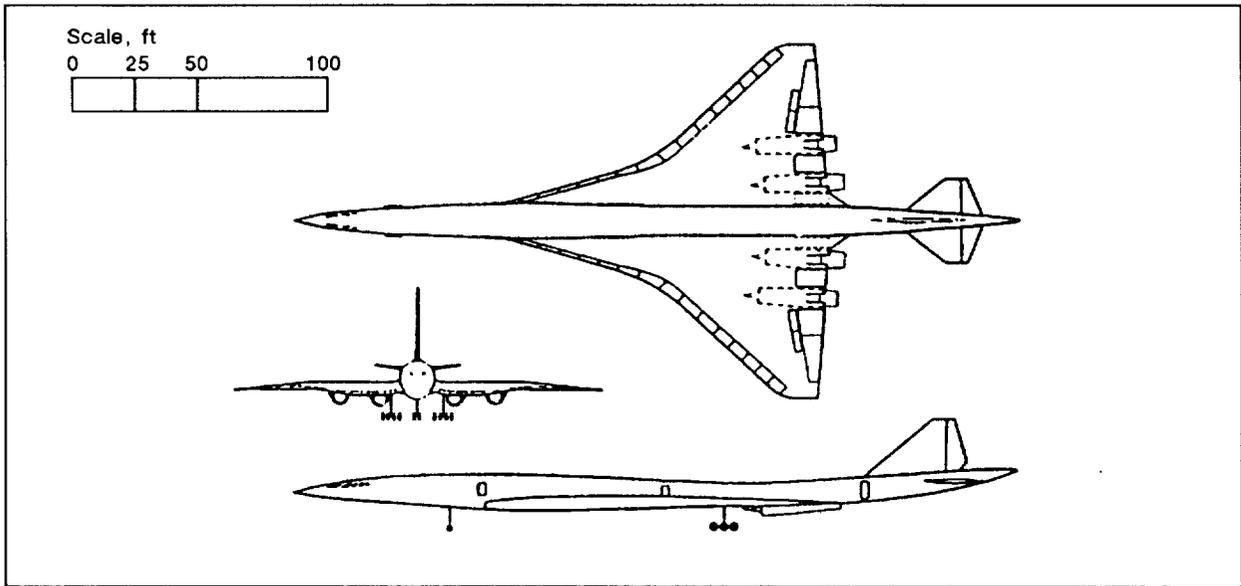


Figure 15. Mach 2.4 Configuration

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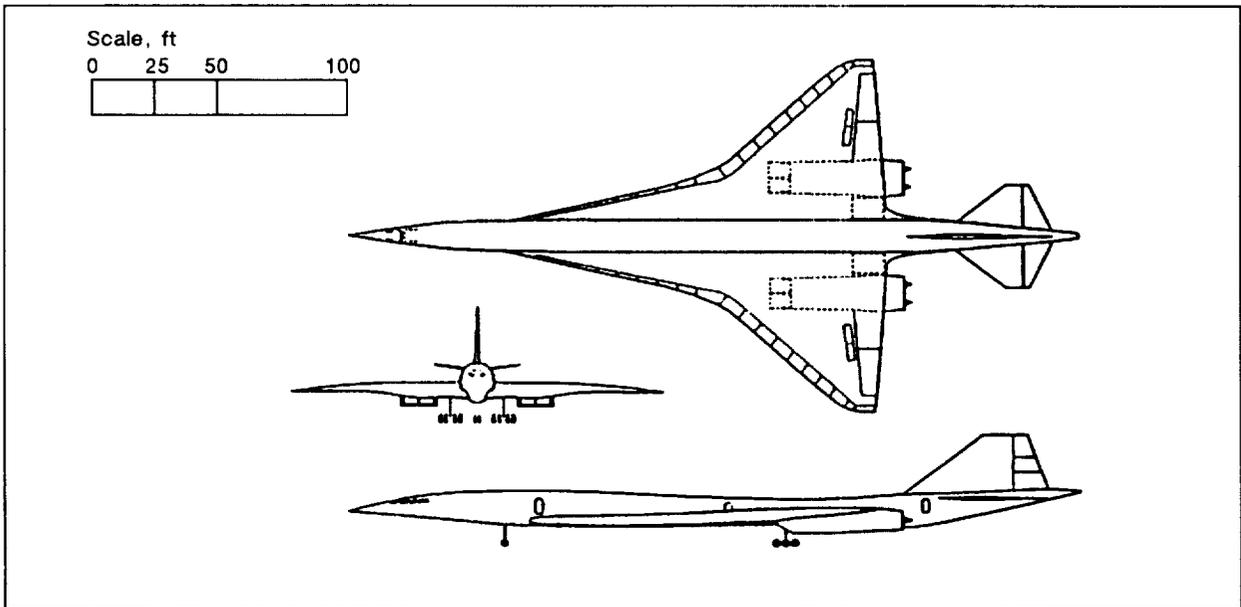


Figure 16. Mach 3.2 Configuration

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- c. Average block time decreases slowly as design cruise speed increases above a Mach number of 3.0, suggesting economic gains will not increase proportionally with design cruise Mach number.
- d. Significant technology and design advances are required for an efficient long-range HSCT, even at lower supersonic cruise Mach numbers.

Final Assessment

During the final study phase, new configurations were developed at Mach 2.4, 2.8, and 3.2. Evaluation of these configurations indicated that the lowest maximum takeoff weight, operating-empty weight, and block fuel occurred at Mach 2.4. Even though the minimum block time occurred with the

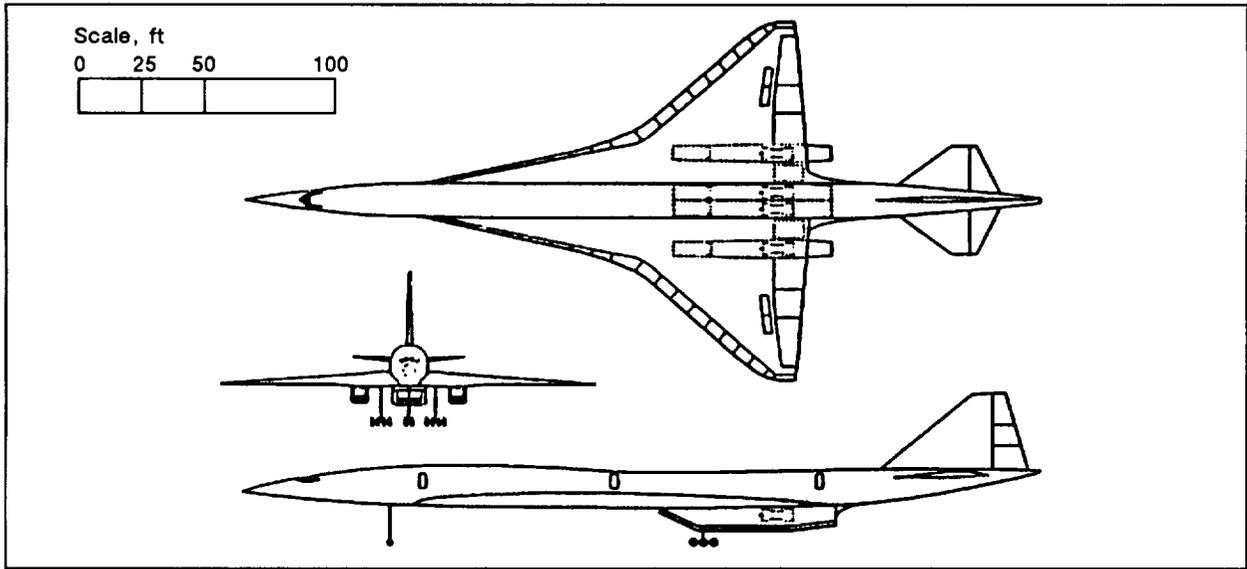


Figure 17. Mach 3.8 Configuration

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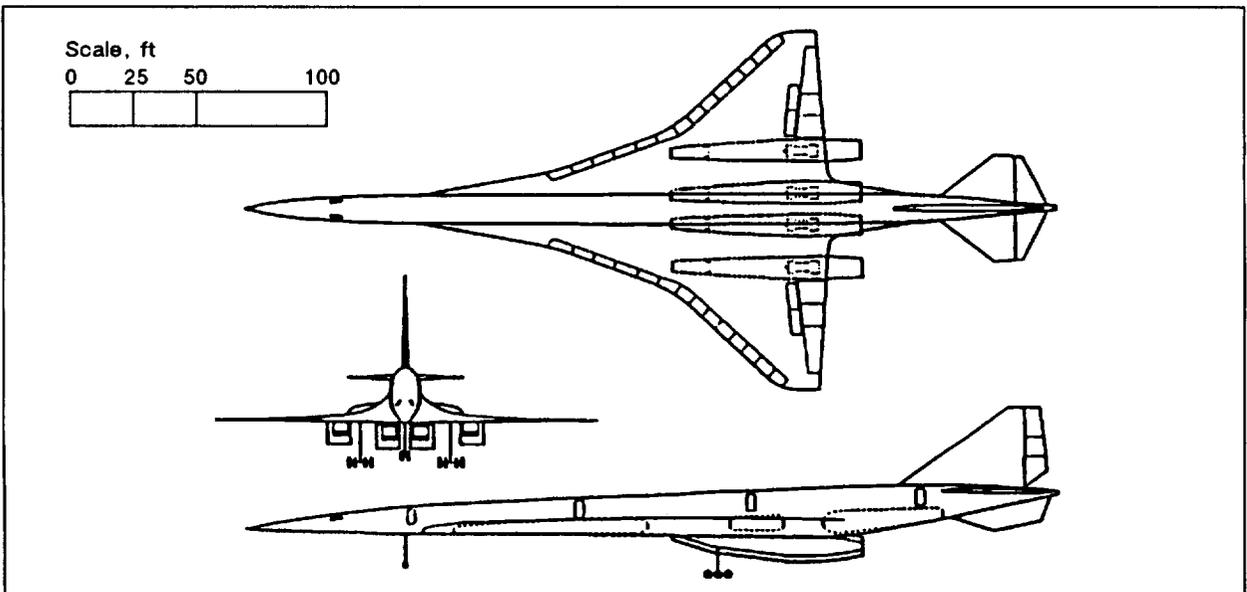


Figure 18. Mach 4.5 Configuration

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Mach 3.2 configuration, maximum economic potential occurs at Mach 2.4. This occurred because improved utilization due to reduced flight times was not enough to offset the increased cost of a heavier Mach 3.2 configuration. Technical risk evaluation in conjunction with this configuration assessment was reason to focus the environmental impact studies at the lower Mach numbers. The Mach 2.4 baseline airplane is shown in figure 21. This airplane has a maximum takeoff weight of 745,000 lb, a wing area of 7,466 ft², and an engine airflow of 582 lb/s.

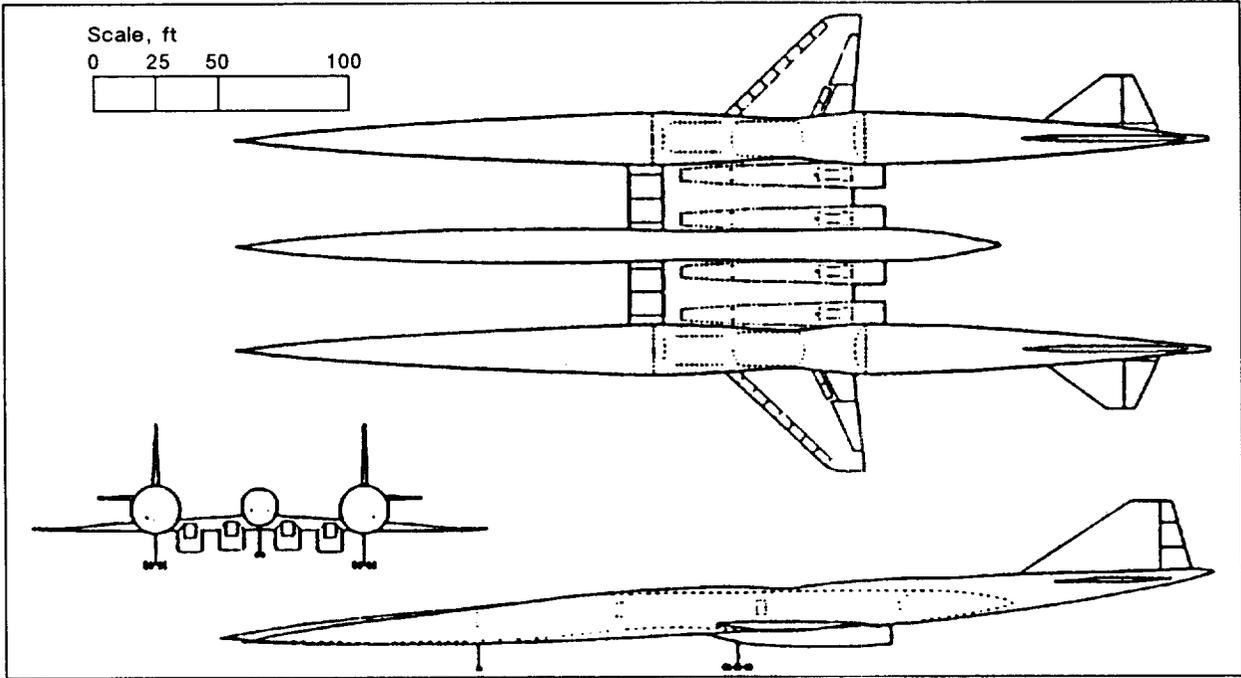


Figure 19. Mach 6.0 Configuration

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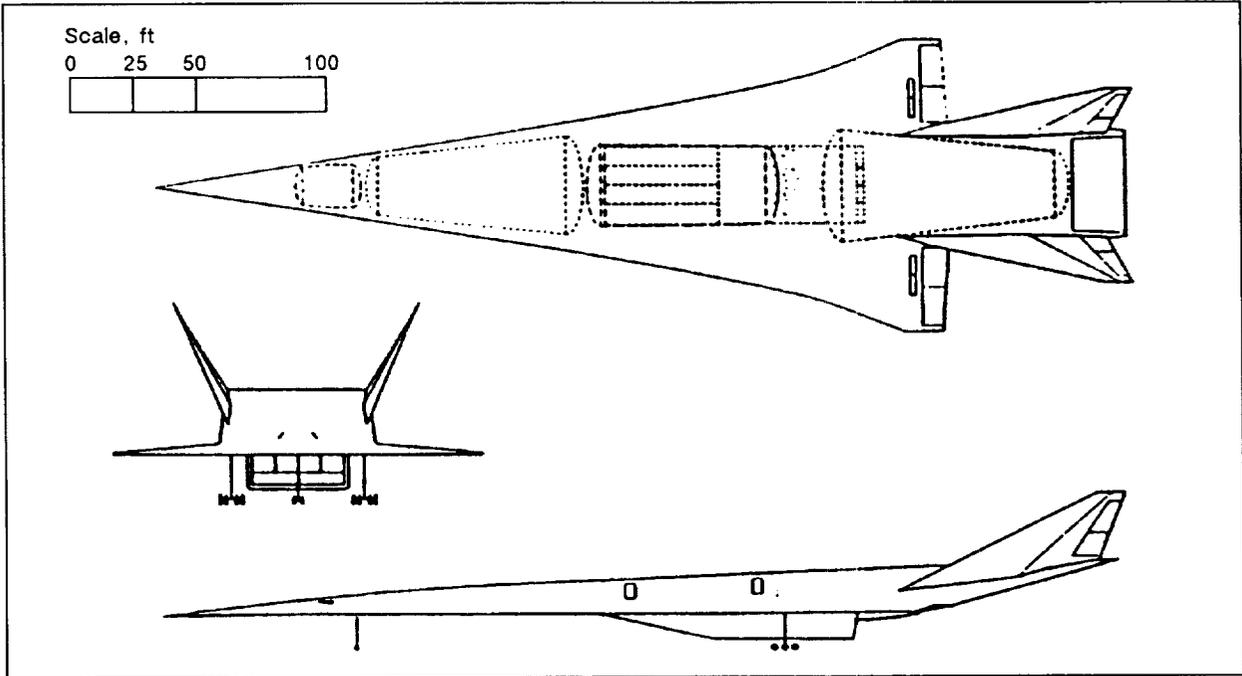


Figure 20. Mach 10.0 Configuration

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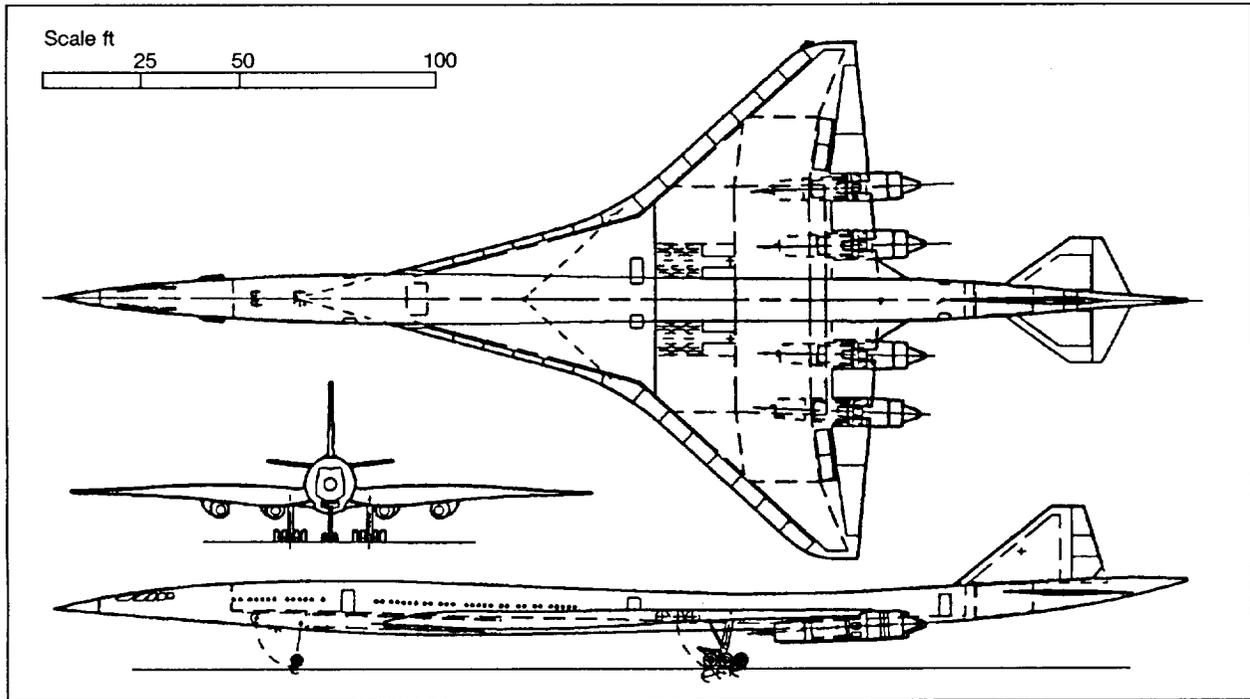


Figure 21. Mach 2.4 Baseline Configuration

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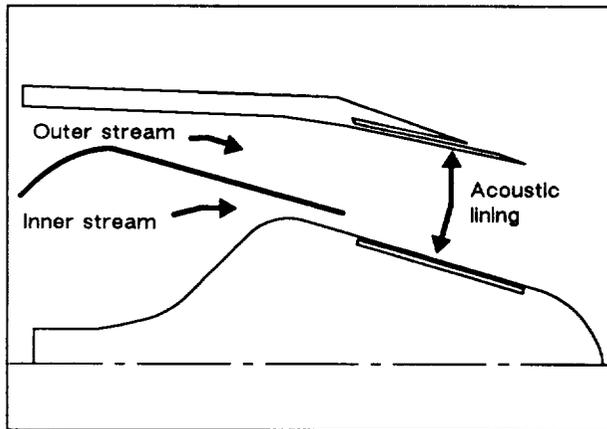
REQUIRED TECHNOLOGIES

Advanced Jet Noise Reduction Concepts

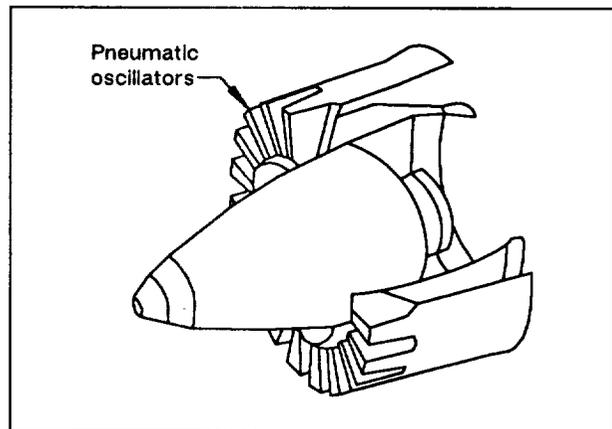
Jet noise can be diminished either by reducing the jet velocity or through nozzle noise-suppressor technology. The jet noise reduction concepts considered in this study are illustrated in figure 22. Particular attention was given to a naturally aspirated, coannular (NACA) nozzle concept. The NACA nozzle is a high-radius-ratio plug nozzle system incorporating a crossover duct, which allows ambient (secondary) air to cross inside the primary stream and be aspirated through the inner annulus of the coannular nozzle. The aspirated ambient flow is intended to provide rapid mixing on the inner boundary of the outer annulus primary stream to reduce the jet noise. The NACA nozzle has been shown to provide significant aspiration of free stream air with small performance penalties at takeoff conditions. Consequently, it is believed that the NACA nozzle offers good potential for jet noise reduction with small thrust penalties. However, this concept would require considerable development to confirm its performance and qualify it for use on a commercial airplane.

Emission Reduction Concepts

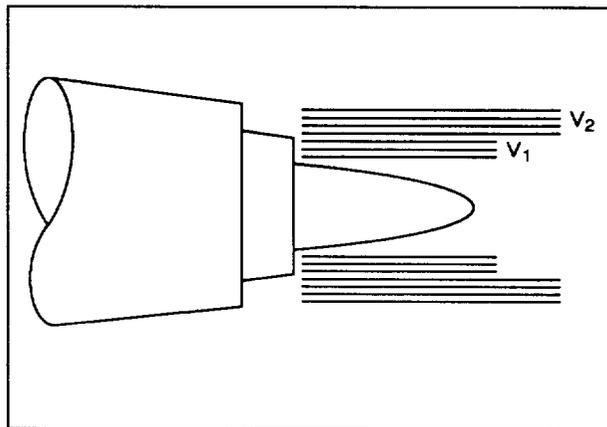
Achieving the goal of having no significant effect on the ozone layer may require the reduction of oxides of nitrogen (NO_x) engine emissions. The engine manufacturers conducted studies of derated engine cycles and high-risk, low-emission combustor concepts. The concepts considered most promising were the staged-lean combustor; rich-burn, quick-quench combustor; and lean, premixed and pre-vaporized combustor. These concepts could potentially reduce emissions in a range from three-fourths to one-sixth of the untreated level, but would require an aggressive research and development effort.



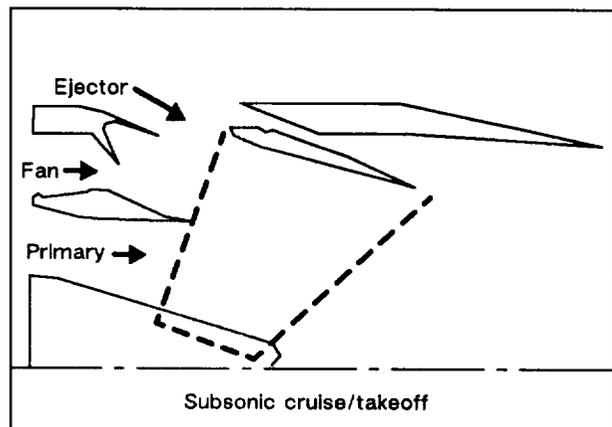
Acoustic Lining



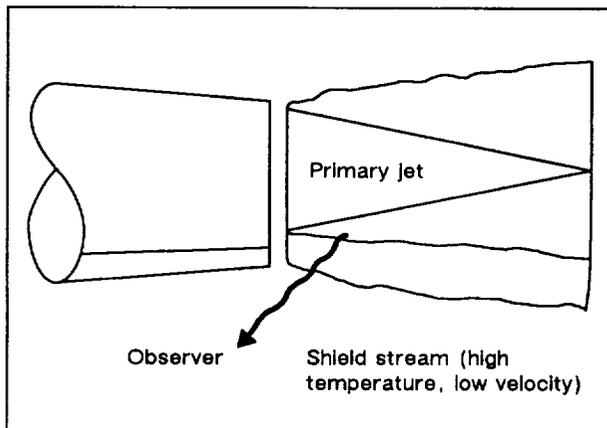
Suppressor



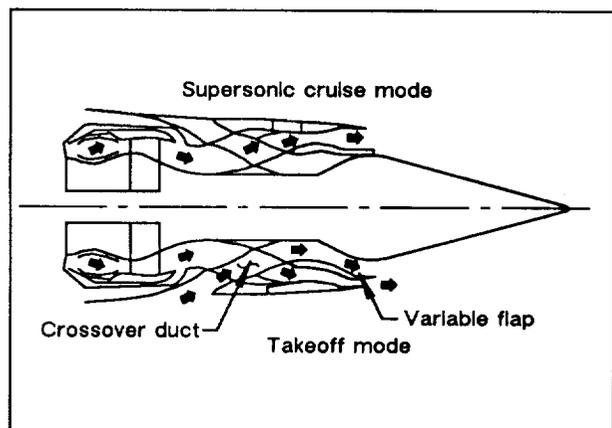
Inverted Velocity Profile



Ejector



Thermal Acoustic Shield



Turbine-Bypass Engine With NACA Nozzle

Figure 22. Jet Noise Reduction Concepts

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Fuel Technology

The fuel technology study identified and evaluated production, cost, property, and other nonaircraft system-related factors that would affect the use of both conventional and unconventional fuels in HSCTs. The fuels study included modified conventional, endothermic, cryogenic, and other fuels such as slushes and gels. The study emphasized—

- a. The availability and cost associated with modified conventional fuels (thermally stable jet fuels).
- b. Liquid methane costs (liquid methane is assumed to be the same as purified liquefied natural gas).
- c. On-airport costs for both conventional fuels and liquid methane.

Aerodynamics

The aerodynamic design of each of the study configurations included optimized camber/twist distributions and area-ruled fuselages. The wing spanwise thickness distributions and airfoil shapes were constrained by structural depth requirements. The nacelles were shaped and located aft under the wing to develop favorable aerodynamic interference subject to ground clearance, engine geometry constraints, and structural design considerations.

High-speed aerodynamic characteristics for all of the concepts were developed using the methods from earlier NASA studies. Projections for year 2000 technology improvements have been included in the drag build-ups. These projections include skin friction drag reduction resulting from the use of an outer surface treatment such as riblets over 90% of the vehicle wetted area; reduction in volume wave drag and drag-due-to-lift resulting from design methodology improvements; and incorporating an improvement in the wind tunnel to flight test drag correlation.

The drag breakdown for the baseline airplane is shown in figure 23 and lift/drag versus Mach number is illustrated in figure 24.

The high lift system is designed to increase wing lift for liftoff and touchdown. It must be designed to minimize drag during climbout and approach to reduce airport noise levels. In general, the leading-edge and trailing-edge flaps are simple hinged surfaces. Low-speed performance is improved by repositioning the flaps relative to the conventional low-drag position for higher lift. For liftoff and touchdown, leading edge flaps were raised to increase vortex lift. After liftoff, the flaps were positioned for minimum drag.

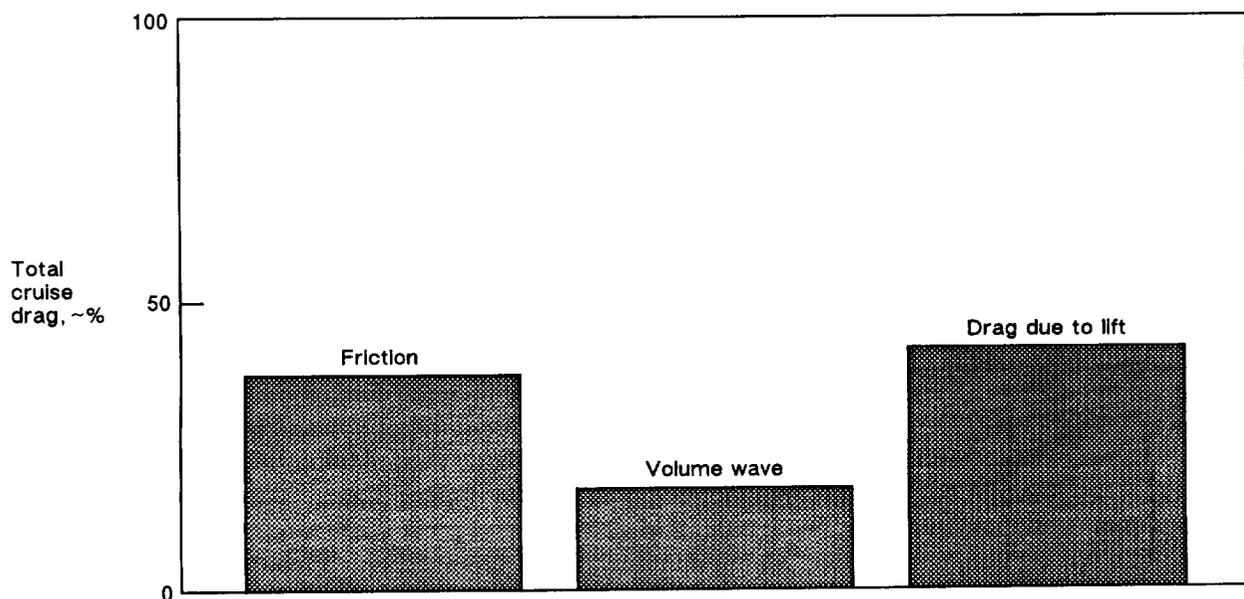


Figure 23. Drag Breakdown—Mach 2.4 Baseline

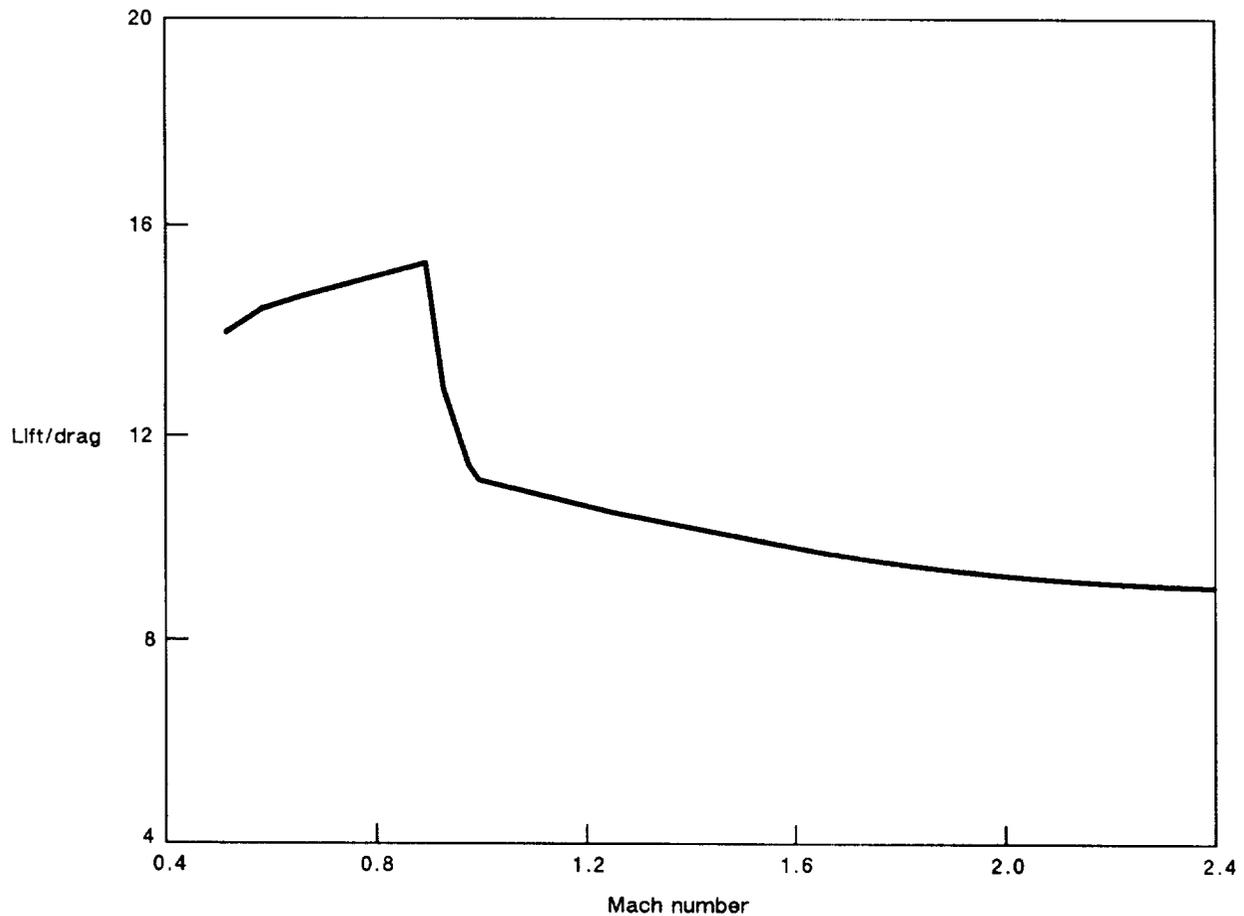


Figure 24. Lift/Drag Versus Mach—Mach 2.4 Baseline

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Stability and Control

The primary task for stability and control has been the estimation of horizontal and vertical tail size and center-of-gravity limits that satisfy critical stability and control criteria. HSCT configurations are designed using a control-configured vehicle design approach that employs the flight control system to stabilize as well as control the airplane, which results in a more efficient aerodynamic and structural configuration. The required stability augmentation system must be of sufficient capability and reliability to provide acceptable handling qualities over the operational flight envelope up to the maximum useful angle-of-attack. The flight control system will be used to limit or prevent excursions outside this envelope.

Structures and Materials

Candidate structural materials were selected by (1) surveying published research, material suppliers, and aerospace contractors to identify commercial or developmental materials with potential applicability; (2) estimating mechanical properties based on available published data and developmental goals; and (3) forecasting availability by assessing progress in development versus goals, determining technical complexity in achieving these goals, and estimating process scaling necessary to support a large production program. A significant development effort to ensure availability of technology was assumed. Potential materials, maximum use temperatures, and predicted availability are summarized in figure 25.

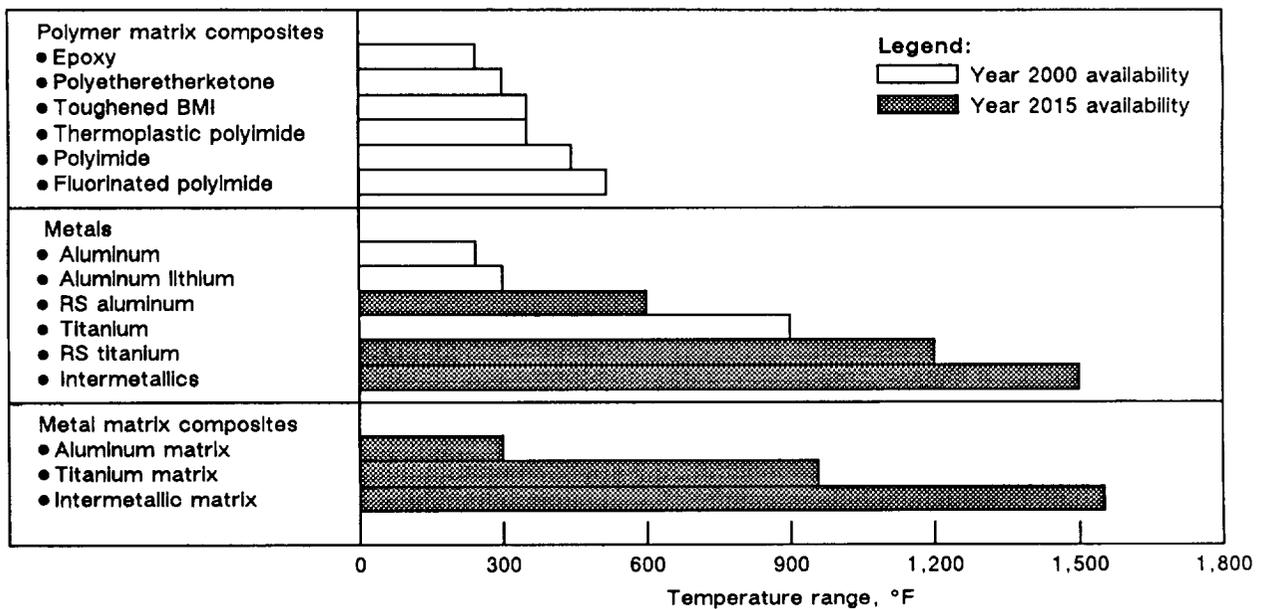


Figure 25. Structural Material Candidates and Projected Temperature Range for HSCT Application

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The structural materials for Mach 2.8 and below judged to have the most potential and to be available for year 2000 certification were identified. These materials were high-temperature thermoplastics or toughened thermosetting polyimide composites. Ingot titanium alloys were selected for the higher Mach numbers. Even though they have the most potential for a lightweight, cost-effective HSCT, polymeric composite systems for high-temperature service have inadequate processibility and unproven long-term, thermal and environmental resistance for application in a commercial program.

Significant development is required to optimize these materials, develop automated processing methods, and evaluate their long-term performance in the severe HSCT environment.

By the year 2015, it is projected that the maturation of metal matrix composite and rapid solidification technology will make them available for application on the HSCT. Current material forms, processes, and production equipment available in the industry are not adequate to produce the large structure required for an HSCT program. Development is necessary to scale processes and evaluate long-term, high-temperature performance of these materials.

Support materials compatible with the selected structural materials are required for a viable commercial program. Support materials include adhesives, seals and sealants, finishes, and lightning protection materials. Generally, support materials are available with thermal stability applicable to a cruise speed of Mach 2.8 or below. The performance and long-term durability of current support materials are necessary for their application to the HSCT. Development of improved temperature resistant materials is required for high Mach number configurations.

Structural weights for performance calculations are based on the structural concepts, arrangements, and procedures used in the study reported in "Study of Structural Design Concepts for an Arrow Wing Supersonic Transport Configuration" (ref. 2). A number of potential materials were selected for years 2000 and 2015 as described previously. Based on the projected mechanical properties of these materials, panels taken from ten locations on the fuselage and six locations on the wing were redesigned and resized for strength, making allowance for the change in operating temperature at the higher Mach numbers. These locations were selected to represent the range of typical design load conditions on the airframe structure. Based on the weights of these structural elements, the weight of the airframe for each airplane configuration was estimated for use in the performance calculations.

Weight and Balance

The weights databases of the Boeing 2707-300 (U.S. S.S.T.) and other studies have been used for baseline structural sizing, loads, systems and equipment definition, design criteria, and payload system definition. Passenger comfort level requirements according to the current Boeing and airline companies' definition were substituted for the definition used in the model 2707-300. Advanced technology materials were applied for concepts projected to be certified in years 2000 and 2015.

Impact of Improved Technology

Advanced technology is essential to achieve the desired range capability (5,000 nmi) within a realistic size limit (maximum takeoff weight of 900,000 lb). Figures 26 and 27 show the impact of technology advances projected for year 2000 certification versus that currently available for year 1995 certification. These data show that, collectively, advanced technology reduces the maximum takeoff weight from 1 million pounds to 745,000 lb (about 25%), with advanced structures and materials providing the largest single benefit. The figures also show the same data plus the impact of further technology

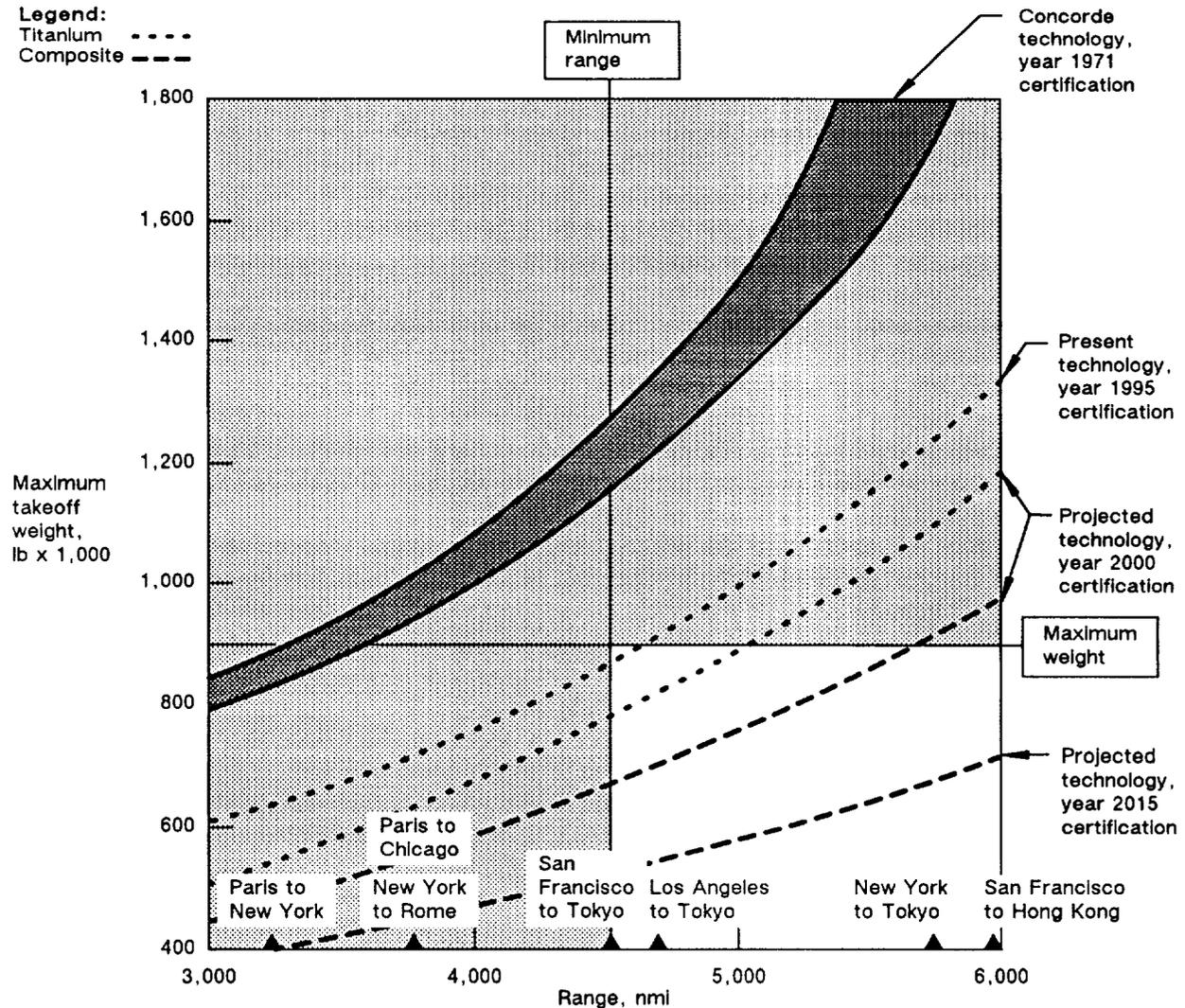


Figure 26. Impact of Technology—Mach 2.4 Baseline

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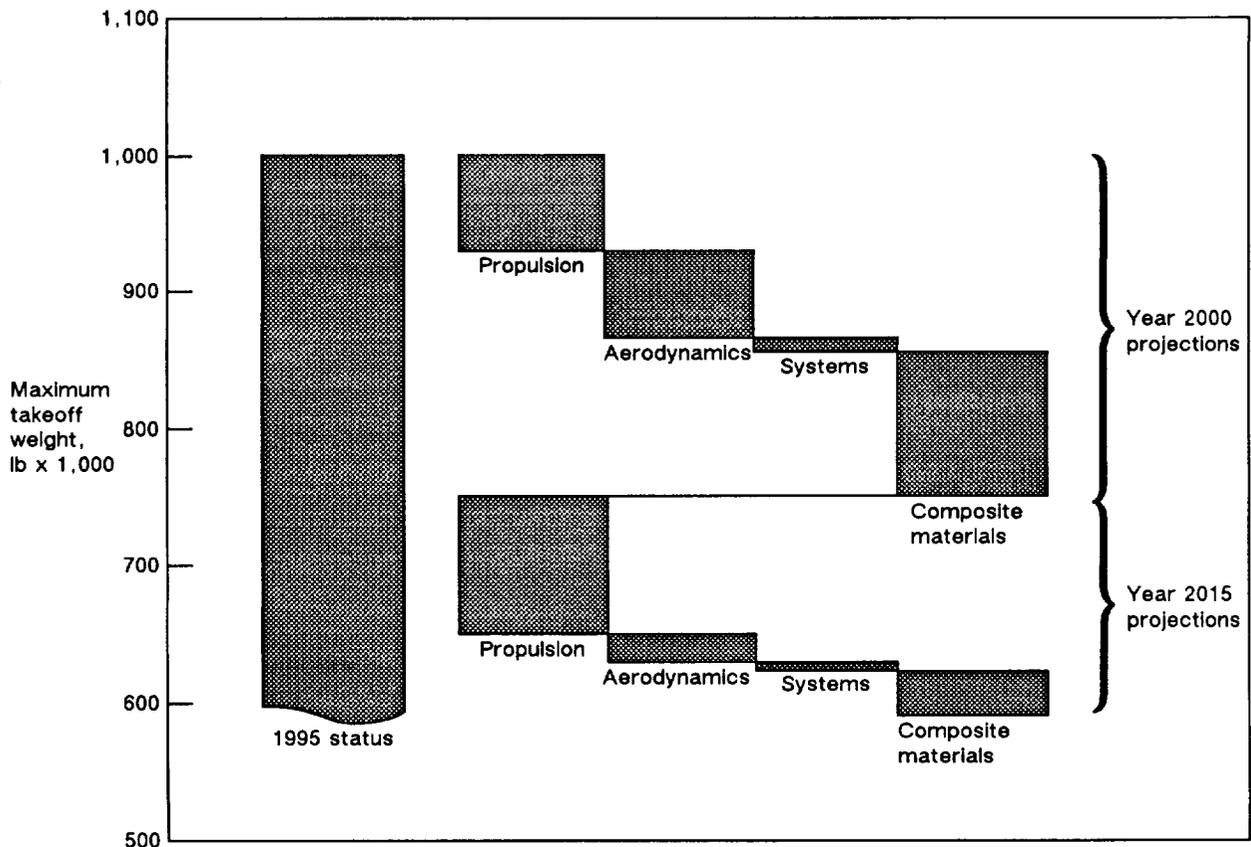


Figure 27. Impact of Technology—Mach 2.4, 247-Seat Airplane With Year 2000 Certification, 5,000-nmi Design Range

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improvements projected for year 2015 certification. The required maximum takeoff weight is reduced from 745,000 lb to about 585,000 lb (about 20%), with advances in propulsion technology providing the largest single benefit. A year 2000-certification airplane could conceivably use this technology improvement for the range growth strategy of the HSCT family concept (fig. 28).

ENVIRONMENTAL EVALUATION

Upper-Atmosphere Emissions/Ozone Impact

The study provided NASA with emissions data for representative fleets of airplanes for analyses with math models of the Earth's atmosphere. The impact on the airplane size of using reduced emission engine combustion technology was studied.

Studies to assess the effect on vehicle design of incorporating reduced-emission engines indicated that significant reduction in NO_x emissions can be obtained with a resultant 2.2% to 3.7% increase in maximum takeoff weight. Of the concepts considered, the lean, premixed and prevaporized combustor has the greatest potential for NO_x reduction (approximately one-sixth the base level), but carries the highest technical risk. The staged-lean combustor provides less NO_x reduction (approximately three-fourths the base level) with what is considered a low technical challenge. The rich-burn, quick-quench combustor may prove acceptable with a significant NO_x reduction (approximately one-fourth the base level) with a smaller maximum takeoff weight increase than either the lean, premixed and prevaporized or the staged-lean combustor and is considered to have a lower development risk.

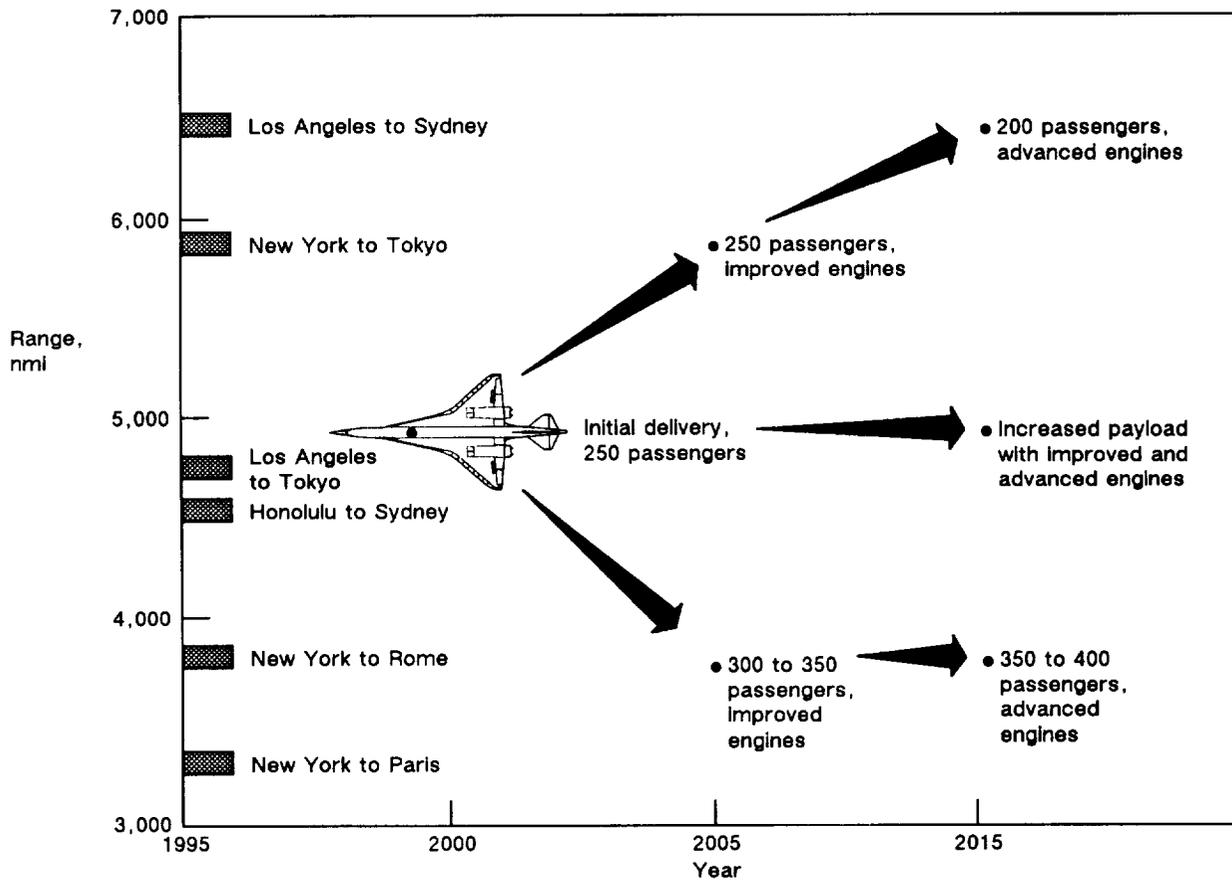


Figure 28. HSCT Growth Strategy

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Community Noise

Two different goals were pursued in two parallel studies of community noise and the HSCT. The first was to achieve compliance with FAR36 Stage 3 noise limits; the second was to produce the same overall effect on the community as a Boeing 747-200 airplane configuration, which just meets the Stage 3 criteria. The baseline configuration used very aggressive jet noise suppression technology to reduce takeoff noise levels. In addition, vehicle configurations that had oversized engines and/or wings were studied to evaluate the effects of these changes on the community noise levels, airplane weight, and economics. Oversizing the wing was not beneficial. Increasing engine size in conjunction with advanced, automatic thrust modulation reduced takeoff noise to subsonic Stage 3 requirements, but also incurred a 4.7% increase in takeoff gross weight and a significant degradation in economic potential.

In the airport study, residential noise exposure was evaluated at 18 airports; the assessments were made with 85 dBA noise contours (footprints). Two HSCT footprints were compared with the Boeing 747 footprint as shown in figure 29. The residential area exposure at levels greater than 85 dBA was nearly the same for the HSCT with a 20% programmed lapse rate procedure as the Boeing-747 (actually 6.5% less because the HSCT footprint is slightly shorter). If sideline noise requirements were somewhat reduced or trade provisions increased, maximum thrust could be used for takeoff. The use of maximum takeoff thrust was found to expose 43.2% less residential area based on an average of 18 airports. It was found that, at most airports, larger residential communities are downrange of the runway and the shorter footprint more than makes up for the increased width. A supersonic Stage 3

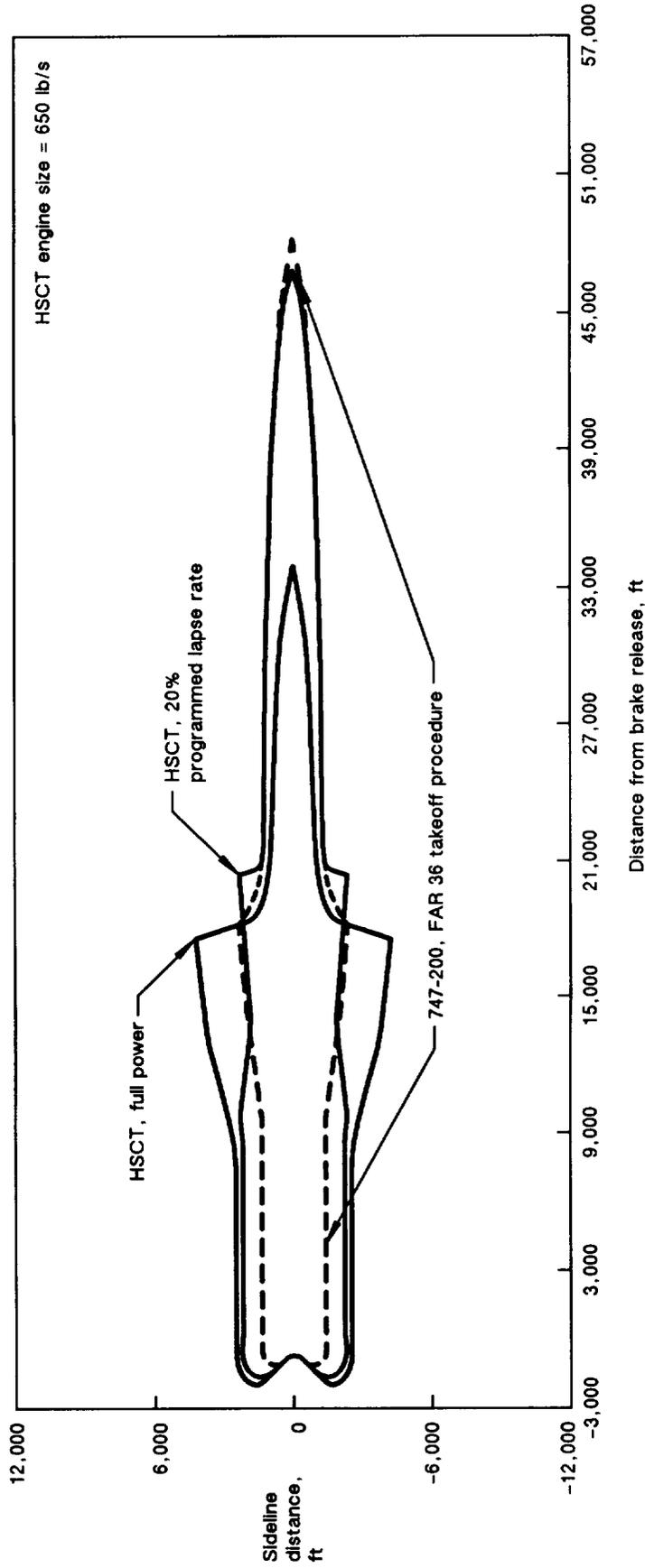


Figure 29. Noise Contour at 85 dBA—Comparison of HSCT to 747-200

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noise rule that takes into account the HSCT's unique ability to climb away from the community has the dual benefit of reducing the impact on the community and improving the economics of the airplane.

Sonic Boom

All vehicles in the viability studies were configured to fly supersonically over water and subsonically over land. However, because of the significant impact of supersonic overland flight on fleet economics, a configuration was evaluated that was designed to reduce the level of sonic boom at Mach 1.5 to a potentially acceptable level. This design would potentially be capable of cruising over land at supersonic speeds, increasing utilization and reducing flight times.

This study examined several options for reducing the sonic boom shock wave amplitude to a target overpressure of 1.0 lb/ft². This level, with a typical rise time of 6 ms, corresponds to a potentially acceptable level of 72 dBA for restricted overland flight (corridors). Acceptability is based on previously published human response testing (ref. 3).

The configuration studies focused on a Mach 1.5 overland design because the concept allowed a more reasonable fuselage length and required only minimum changes to an arrow wing. The resulting airplane is shown in figure 30. Compared to the Mach 2.4 baseline, the forebody was lengthened by 10 ft and widened slightly, a wing strake was added, nacelles were staggered, and an arrow planform was used for both the wing and horizontal tail. The maximum takeoff weight for this low-boom configuration is approximately 3% greater than the baseline aircraft.

The initial attempt at achieving a low-boom profile was only partially successful. In particular, the inexact design methods resulted in undesirable intermediate shocks and a strong tail shock. Because the human auditory system is sensitive to shock waves, only a small reduction was obtained. Pressure signature and resulting loudness predictions at Mach 1.5 are shown in figure 31. More detailed configuration design studies are required to reach the target of 72 dBA.

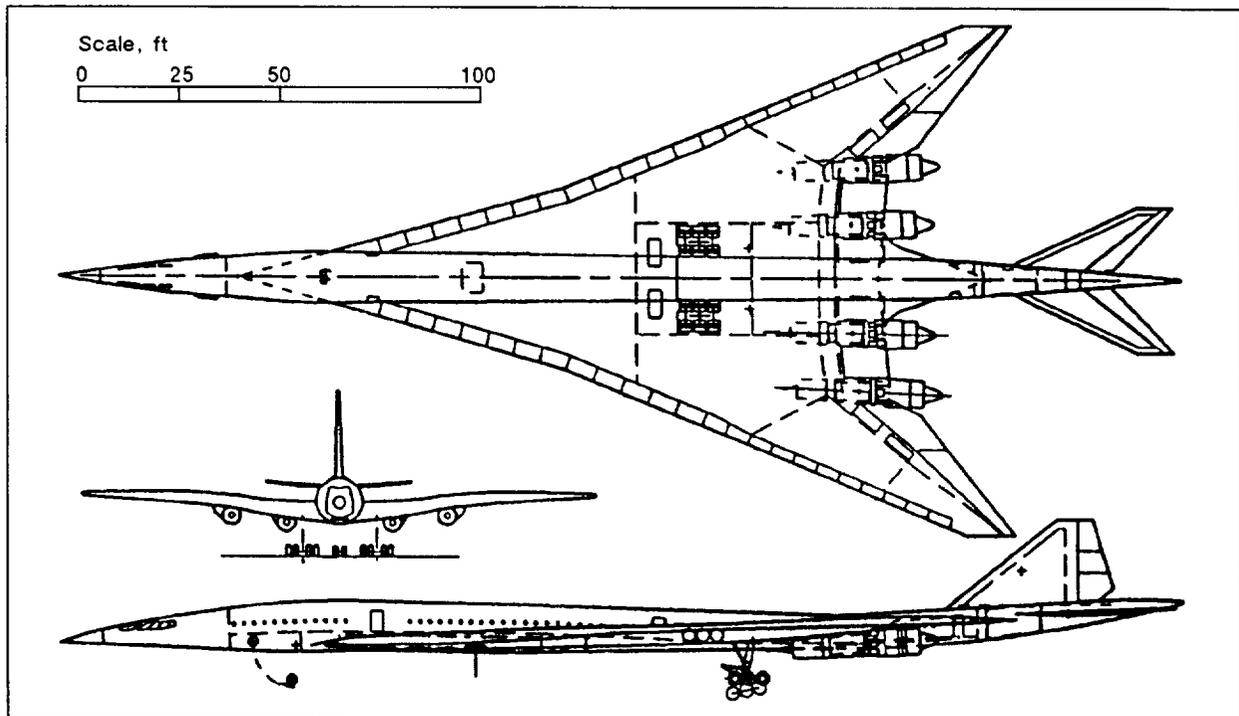


Figure 30. Low-Sonic-Boom Configuration

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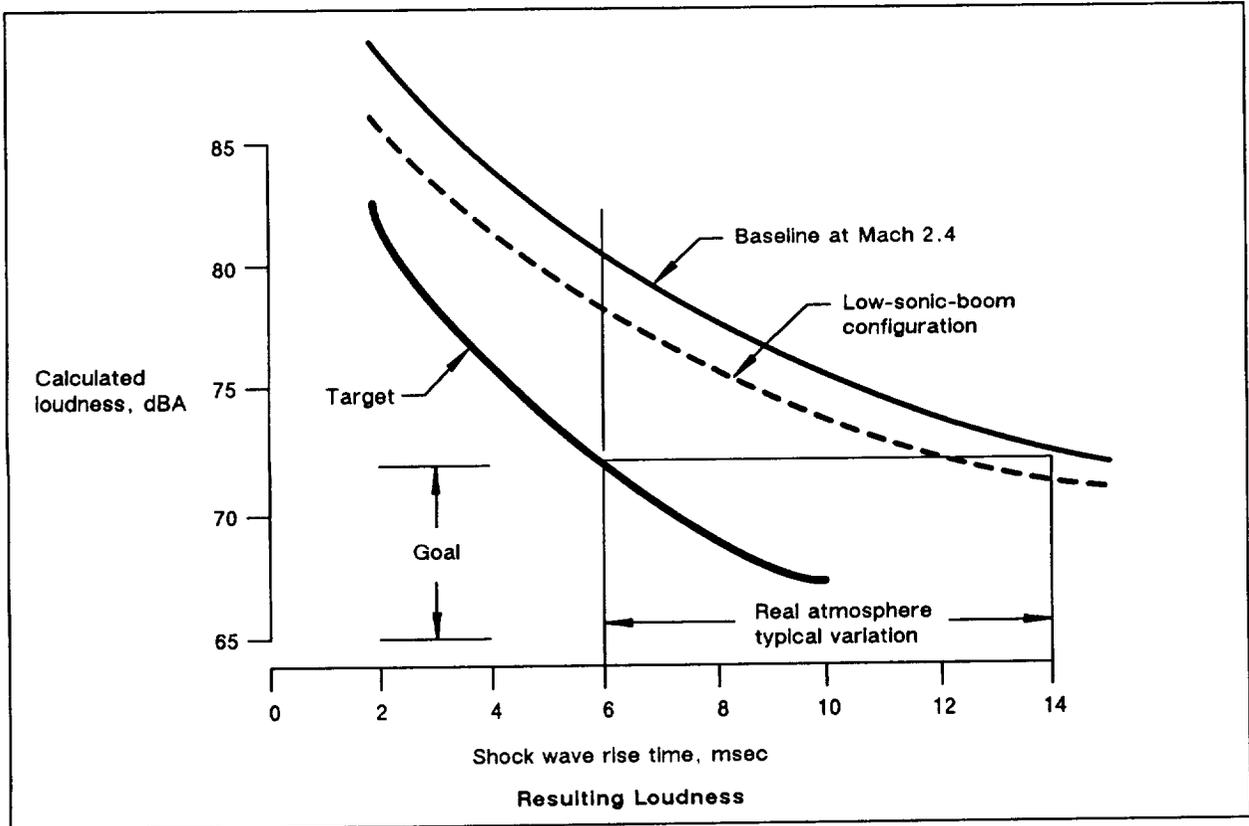
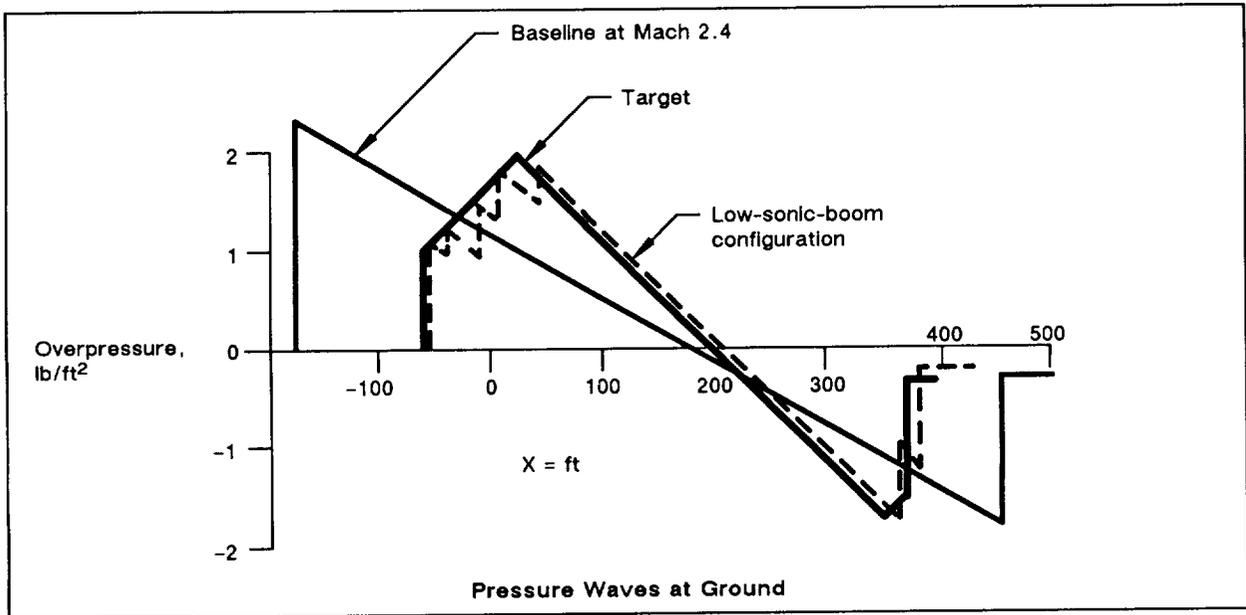


Figure 31. Mach 1.5 Pressure Signature and Loudness Predictions

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ECONOMIC EVALUATION

The concept of life cycle operating costs has been developed to satisfy the need for an economic comparison method that accounts for the actual cash direct and indirect costs incurred in operating an airplane as well as including all "ownership costs." Cost elements identified include the following:

- a. Cash direct cost elements, which include—
 1. Flight crew costs.
 2. Fuel burned.
 3. Airframe maintenance.
 4. Engine maintenance.
 5. Hull insurance.
- b. Indirect costs, which include—
 1. Airplane-related (cleaning, fueling, aircraft-handling, maintenance, and ground handling equipment).
 2. Passenger-related (food, passenger-handling, agency commissions, passenger insurance).
- c. Ownership costs.

An "economic horizon" was used to provide a reference life cycle operating cost to evaluate the economic viability of HSCT study configurations. This economic horizon is a trendline relationship of life cycle operating costs and airplane size. It was based on projected advanced derivatives of the Boeing 767 and 747 aircraft and allows comparisons of a wide variety of passenger seat counts. This economic model was used in all phases of the contract to define market value of HSCT designs and the revenue required to obtain the desired return on investment for those designs for which prices were estimated.

Economic Viability

To be economically viable, the HSCT must provide a reasonable financial return for both the airlines and the manufacturers. Any increased operating and ownership costs associated with an HSCT must be largely overcome by increased productivity due to speed. The sale price must allow an adequate return on investment and still elicit enough demand for the HSCT to justify the large investment in development and production costs. To the extent that increased costs cannot be overcome by increased productivity, higher ticket prices must be charged, thereby reducing the market. Preliminary estimates have been made of the response of the projected HSCT market to increases in price.

The impact of technology, based on this evaluation, is illustrated in figure 32. This evaluation shows that present day technology is not adequate to allow the necessary profit margin. A Mach 2.4 HSCT designed with today's technology would require a 50% to 60% increase in average ticket price over contemporary subsonic transports. This would reduce demand to the point that the total worldwide fleet requirement is estimated to be 300 units or less, an inadequate number to support a viable program. However, with technology available for year 2000-certified airplanes, the required revenues are lower, primarily because of the smaller vehicle required to perform the design mission. The result is that a ticket price increase of 18% would be required and the fleet requirement would be approximately 650 to 750 units. If year 2015-certification technology was used, ticket price would only increase by 8%. This would result in a fleet requirement of 950 to 1,050 units.

The impact of design Mach number on the market captured by the HSCT is shown in figure 33. Assuming year 2000 certification, increasing design speed from Mach 2.4 to Mach 2.8 boosts the fare increase to over 25% and reduces the market captured to 30%, requiring a fleet size of 400 to 500 units. The Mach 3.2 design does not close, as the yield required to earn the required return on investment is rising more steeply than the yield available.

The key assumption behind the economic closure trends shown in figures 32 and 33 is the trade of market share against ticket price for a 50% time savings. If the decline in market share with higher ticket price is steeper, then the "yield available" curve of figures 32 and 33 may have lower slope with

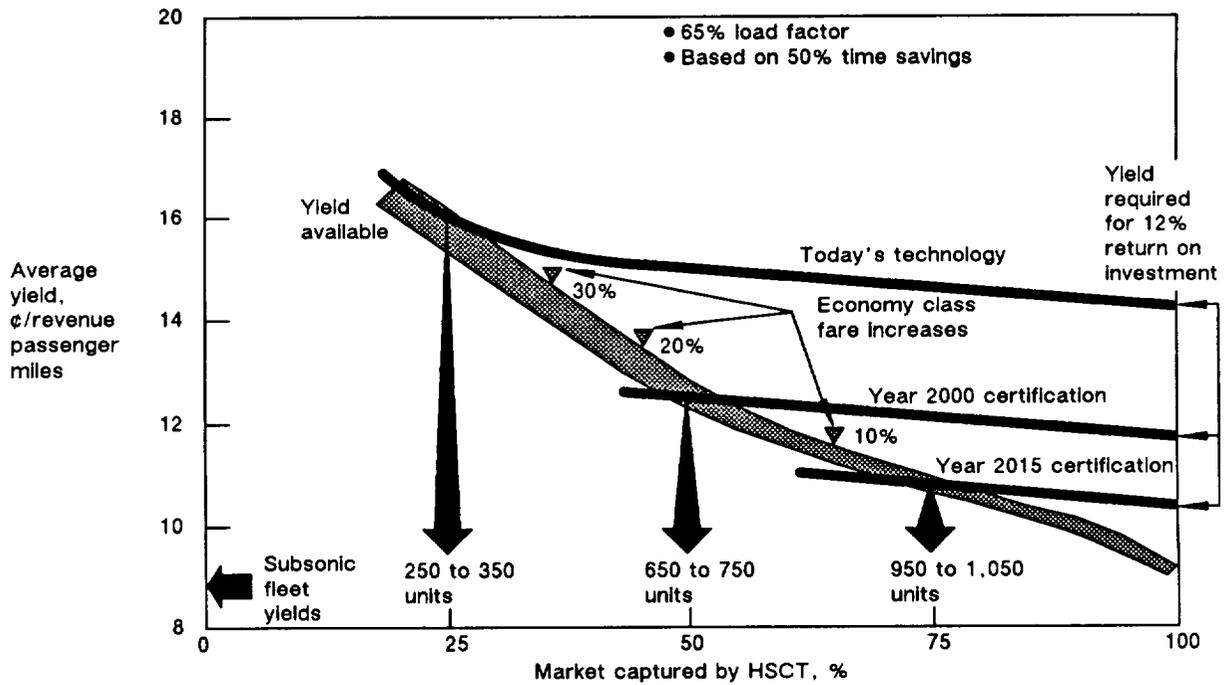


Figure 32. Economic Viability—Technology Impact on Fleet Size Based on Mach 2.4, 247-Seat Design With 5,000-nmi Range

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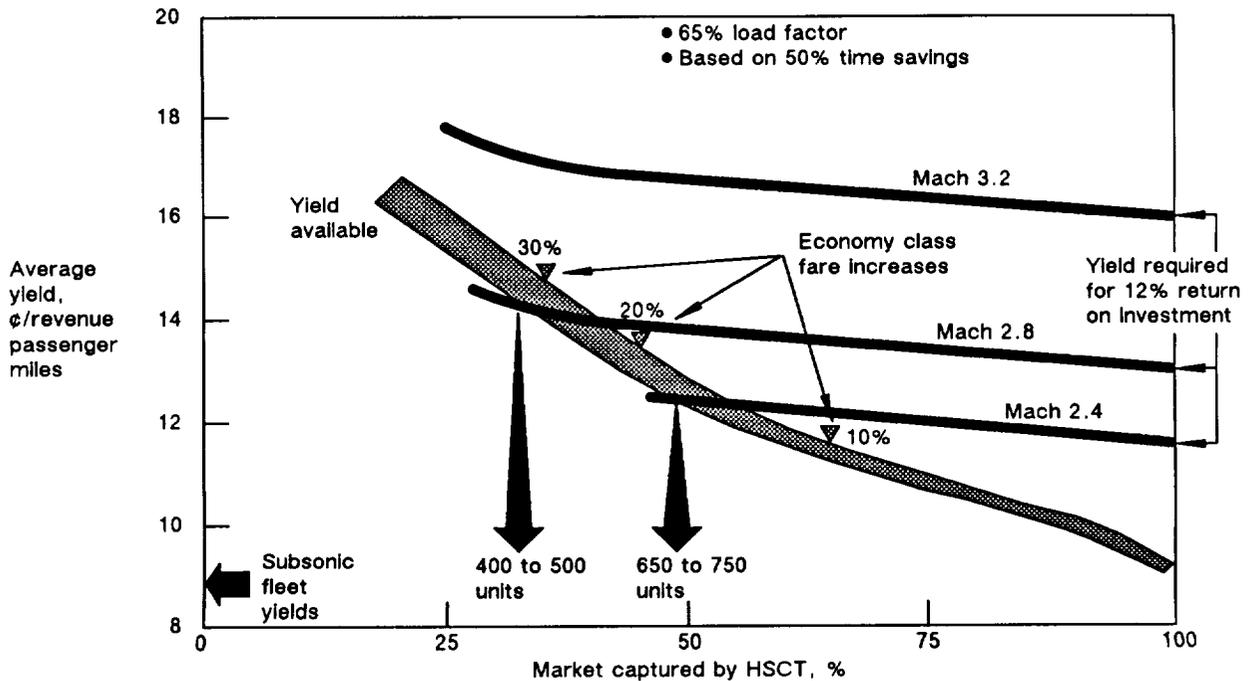


Figure 33. Economic Viability—Impact of Speed Based on 247-Seat Design With 5,000-nmi Range

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decreasing market share. This would move the closure point to even lower values of market share and sales base.

While there is considerable uncertainty in the technical projections and the economic analyses of all such studies, results indicate the Mach 2.0 to 2.5 vehicles have maximum potential for economic viability. Compared to transports with greater cruise speeds, they maximize fleet size and meet the market needs for year 2000 to 2005 introduction. Additionally, they represent reduced development investment and risk because of reduced size, complexity, and costs.

CONCLUSIONS

Market and Competition

The market results show that a viable HSCT could acquire a significant portion of the growing, long-range, worldwide market. However, to achieve this result, the airplane must have the following characteristics:

- a. Environmentally acceptable (no special operating limits other than subsonic flight over land).
- b. Adaptable to the year 2000 airport system (i.e., no superhubs for the HSCT alone).
- c. From about 250 to 300 seats (in triclass seatings). Final seat definition is a function of productivity, which depends on Mach number and design range capabilities.
- d. A range of 5,000 nmi initially with growth to over 6,000 nmi. This increase will occur through weight growth; the use of improved engines; minimizing intermediate stops, which increase airline costs and passenger trip times; and allowing maximum flexibility of the airplane within an airline's system. Maximum flexibility will be reached only if the HSCT is used on routes suited to its capabilities, rather than as a direct substitute for 747 missions.
- e. Economically competitive with a year 2000 subsonic fleet (i.e., increases in utilization must overcome increased operating and ownership costs).
- f. Cruise Mach number should be consistent with minimum operating costs and maximum productivity when considering design range tradeoffs.

An HSCT with these characteristics could justify a total fleet size of over 1,200 aircraft between the years 2000 and 2015, serving primarily the long-range (2,500 nmi and greater), high-density market.

Environmental Concerns

The primary areas of environmental impact identified by this study were—

- a. Engine emission. Projections of advanced low-emissions burner technology indicate that an NO_x emissions reduction from 30 + lb to approximately 5 lb of nitrous oxide emissions per 1,000 lb of fuel burned is possible. A clearer understanding of the effect of engine emissions on the atmosphere is being investigated using the best atmospheric models available and data from the current HSCT studies. This knowledge is essential to understanding the design requirements for an environmentally acceptable HSCT.
- b. Community noise. The study shows that with projected suppression technology, achievement of FAR36 Stage 3 noise levels may be possible. The primary issues involved in achieving Stage 3 levels are—
 1. Development of projected jet-noise suppressor technology.
 2. Possible modifications to the Stage 3 rules. The unique characteristics of an HSCT could justify a different trade between sideline noise and takeoff noise, which could further reduce noise to the majority of the community. Requirements could also focus on the area exposed to a given sound level to take into account the operating characteristics of an advanced HSCT in reducing residential area exposed to noise.

- c. Sonic boom. Subsonic, boomless overland flight was assumed for the basic technical and economic viability estimates. However, a preliminary low-sonic-boom-design study suggests that a combination of fuselage shaping, wing planform choice, and a cruise at reduced supersonic Mach has potential for reducing boom overpressure levels. Acceptable sonic boom levels have not been established. Therefore, committing a design to a reduced sonic boom level is premature at this early stage. Continued effort must be made toward developing a low-boom configuration.

Technical Feasibility

Within the Mach 2.0 to 3.2 speed range, vehicles can be operated with kerosene-based fuels, engine cycles using conventional turbomachinery, an uncooled high-temperature composite, or a titanium primary structure. These vehicles would be capable of operating from existing airports.

Based on the results of the contract studies and other independent studies focusing on lower cruise speed vehicles, maximum potential for an environmentally sound, technically feasible HSCT exists for a vehicle designed to cruise at Mach 2.0 to Mach 2.5 over water and Mach 0.9 over land.

Economic Viability

Preliminary estimates of the response of the projected HSCT market to increases in ticket cost have been measured against the revenues needed for the airplanes studied in this and other independent studies to provide adequate profit margins to the manufacturer and the airlines. Based on this evaluation, the following conclusions can be drawn:

- a. Present technology is not adequate.
- b. A year 2000, Mach 2.0 to 2.5 HSCT shows promise (potential total market of 650 to 750 airplanes). While this would be an adequate demand for a single manufacturer, it is not an adequate market for two or more.
- c. A Mach 2.0 to 2.5 HSCT with the advanced technology projected to be available for a year 2015 airplane (either as an all-new airplane or an advanced derivative of a year 2000 airplane) is more encouraging. With this technology, the potential total market is estimated at 950 to 1,050 airplanes, which clearly represents a business opportunity for two manufacturers.
- d. Technology that reduces the weight and cost at Mach 2.0 to 2.5 has a much greater impact on economic viability than technology that enables higher cruise Mach numbers.

Key areas of improvement that would directly impact economic performance are—

- a. Reduced structural weight.
- b. Improved engines available for year 2000 vehicles.
- c. Increased aerodynamic performance through improved wing planforms and hybrid laminar flow.

Finally, while the development costs of vehicles in the preferred Mach range may be considerably higher than the costs of a similar-sized subsonic vehicle, Government support of the production program for an HSCT would not be required if such a vehicle were economically viable.

RECOMMENDATIONS

Technology Development Program

Potential for a successful U.S. commercial high-speed transport exists for the year 2000 market if aggressive technology development is undertaken in the near term. It is recommended that a joint NASA-industry technology development and validation program be undertaken to address key technology areas. This program would optimize the likelihood of achieving environmental acceptability for, and economic viability of, an HSCT cruising between Mach 2.0 and 3.0. The cost of this program would be a small fraction of the total development and production costs, but could be key to receiving

the commitment from airframe and engine manufacturers necessary to achieve the timely development and production of a successful HSCT and, ultimately, to ensure the HSCT's success in the worldwide marketplace.

Technology Needs

Many technology development needs are enabling, meaning that they are essential to achieve viability, and others are high-leverage items that offer significant payoff in risk reduction or economics. The list of required and/or desirable technology developments covers virtually all technology areas and disciplines and must be prioritized. One basis for prioritization is the development of technology to demonstrate environmental acceptability, without which the HSCT program cannot be launched. (Examples of these technologies are low-emission burners and noise suppression technology.) Other factors that set priorities are the degree to which the technologies are time-critical, high-risk, or high-cost, or are potentially high in value in economic payoff.

Based on maximum potential for environmental and economic viability, the highest near-term priorities for technology development are—

- a. Low-emissions technology.
- b. Noise-suppressor technology.
- c. Variable-cycle engine technology.
- d. High-temperature, durable-composite structures and materials.
- e. High-lift aerodynamics.
- f. High-temperature metals compatible with lightweight composite structures.

These are all high-value, high-cost items that will make critical contributions to the environmental and economic factors and they are time-critical to the aircraft certification date of year 2000. Serious research and development of each of these items should be initiated by 1990.

Technology development needs for longer term, higher risk vehicles have been identified. These are considered of secondary priority to the Mach 2.4, year 2000 vehicle, but could provide enhancements in economics and possibly speed. They are applicable to a later timeframe for certification. Those areas needing development include—

- a. Advanced engine concepts.
- b. Advanced vehicle concepts.
- c. Laminar flow control.
- d. Higher temperature materials for higher speed vehicles.
- e. High-thermal-stability fuels.

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16. Abstract <p>A system study of the potential for a high-speed commercial transport has addressed technology, economic, and environmental constraints. Market projections indicated a need for fleets of transports with supersonic or greater cruise speeds by the years 2000 to 2005. The associated design requirements called for a vehicle to carry 250 to 300 passengers over a range of 5,000 to 6,500 nautical miles. The study was initially unconstrained in terms of vehicle characteristic, such as cruise speed, propulsion systems, fuels, or structural materials. Analyses led to a focus on the most promising vehicle concepts. These were concepts that used a kerosene-type fuel and cruised at Mach numbers between 2.0 to 3.2. Further systems study identified the impact of environmental constraints (for community noise, sonic boom, and engine emissions) on economic attractiveness and technological needs.</p> <p>Results showed that current technology cannot produce a viable high-speed civil transport; significant advances are required to reduce takeoff gross weight and allow for both economic attractiveness and environmental acceptability. Specific technological requirements have been identified to meet these needs.</p>					
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