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High-Speed Civil Transport Study

Boeing Commercial Airplanes
New Airplane Development
Seattle, Washington

Prepared for
Langley Research Center
under Contract NAS1-18377

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Space Administration
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GLOSSARY

ALT	altitude
APU	auxiliary power unit
ASM	available seat miles
ASTM	American Society for Testing and Materials
ATC	Air Traffic Control
ATFE	advanced technology fighter engine
ATR	air turbo-ramjet
ATTCS	automatic takeoff thrust control system
BMI	carbon fiber toughened bismaleimide
BTU	British thermal units
CC	conventional combustor
CD	aerodynamic drag coefficient
Cfg	nozzle gross thrust coefficient
CG	center of gravity
CH_4	methane
CL	lift coefficient
CL APP	aerodynamic approach lift coefficient
CL LOF	aerodynamic liftoff lift coefficient
CO	carbon monoxide
C/T-BMI	high modulus carbon fiber reinforced toughened bismaleimide
C/TPI	high modulus carbon fiber reinforced thermoplastic polyimide
dB	decibels
dBA	A-weighted decibels
DOT	Department of Transportation
ENG	engine
EPNdB	effective perceived noise decibels
EST	estimated
FAR 25	Federal Aviation Regulation, part 25
FAR 36	Federal Aviation Regulation, part 36
FL600	60,000 foot altitude
Fn	net thrust per engine
(Fn-D)/q	thrust minus drag over dynamic pressure
g	acceleration of gravity
GE	General Electric
HL	high-lift system
HSCT	high-speed civil transport
Hz	hertz
IATA	International Air Transport Association
IFR	instrument flight rules
JFTOT	jet fuel thermal oxidation tester
JP	jet petroleum fuel
keas	knots equivalent air speed
kias	knots indicated airspeed
kn	knots
lb/ft^2	pound per square foot
lb/s	pounds per second
L/D	lift to drag ratio
L/Dc/o	climbout lift to drag ratio
LH_2	liquid hydrogen
LHV	lower heating value
LNG	liquefied natural gas
LO_2	liquid oxygen
LPP	lean, premixed, and prevaporized
mi	statute mile
MLW	maximum landing weight
MMC	metal matrix composite
ms	millisecond
MTOW	maximum takeoff weight
MV	market value
NA	not available
NACA	naturally aspirated, coannular
NASA	National Aeronautics and Space Administration
NASP	National Aero-Space Plane
nmi	nautical miles
N/M^2	newtons per square meter
NOx	oxides of nitrogen

OEW	operating empty weight
OL	over land
OPCOST	Operation Cost Program (computer program)
OPR	overall pressure ratio
OW	over water
P&W	Pratt & Whitney
PLR	programmed lapse rate
PNL	perceived noise level
PNdB	perceived noise decibels
R&D	research and development
RAM	revenue aircraft miles
RBQQ	rich-burn, quick-quench
ROI	return on investment
RPM	revenue passenger miles
RS	rapid solidification
RSR	rapid solidification rate
SCR	supersonic cruise research
SFC	specific fuel consumption
SJ	scramjet
S/L	sea level
SL	staged lean
SLS	sea level static thrust
SST	supersonic transport
TBE	turbine bypass engine
TF	turbofan
THC	total hydrocarbon
TJ	turbojet
TOFL	takeoff field length
TOGW	takeoff gross weight
TP	technology projections
TSFC	thrust specific fuel consumption
TSJF	thermally stable jet fuel
TT3	combustor inlet temperature
TT4	combustor outlet temperature
T/W	thrust to weight ratio
VAT	variable-area turbine
VCE	variable-cycle engine
VCHJ	turbofan ramjet
VFR	visual flight rules
Wa	engine airflow
W/S	weight to wing area ratio
Wt	weight

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.

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SUMMARY

Boeing Commercial Airplanes has conducted a study of the potential for high-speed civil transports. The primary objectives of the study were to identify the time frame and technologies required for such aircraft in order to guide plans for appropriate technology development. To achieve these objectives, the study had to address economics and technology as well as environmental constraints. The technology included factors beyond the vehicle itself, such as airport infrastructure and fuel-handling systems. Analyses assessed the economic impact of all these factors on the commercial attractiveness of such vehicles.

The study progressed in three phases. The first phase allowed consideration of a broad range of vehicle and system characteristics. Initial results allowed a reduction of the range of vehicle concepts to those flying with cruise speeds of Mach 4.5 or less. The second phase allowed for more direct and specific integration of technology and economics. The final phase focused on the impact of environmental constraints and refined analyses on the value of cruise speed. In this final phase, cruise speed ranged from Mach 2.4 to Mach 3.2.

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-class 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. Potential ozone depletion. Projections of advanced low-emissions burner technology indicate that an NOx 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 overland 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.
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. 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-cyle engine technology.
d. High-temperature, durable composite structures and materials.
e. High-lift aerodynamics.
f. High-temperature metals compatible with lightweight composite structures.

1.0 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). 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 1-1 illustrates the flow of the study process through the three phases.

Table 1-1 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 1-1 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 promote 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 the development of key technologies for an environmentally and economically sound HSCT.

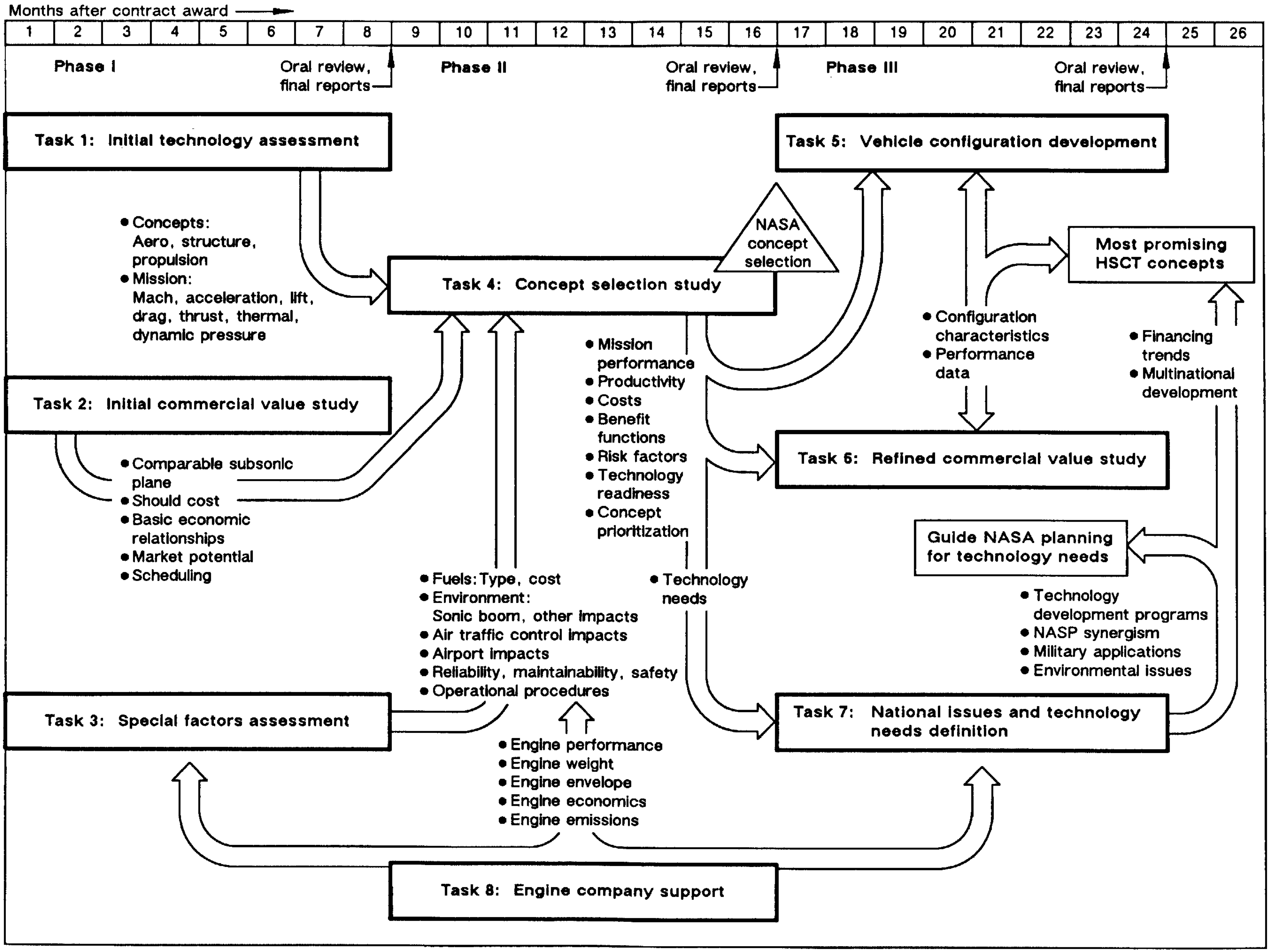

Figure 1-1. High-Speed Civil Transport Study Plan and Schedule

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Table 1-1. 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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2.0 ENVIRONMENTAL, OPERATIONAL, AND MARKET REQUIREMENTS AND MARKET ASSUMPTIONS

The objective of this study was to determine the requirements for a successful, commercially viable high-speed civil transport (HSCT) that is environmentally acceptable and technically feasible.

Certain environmental, operational, and marketing requirements were driving issues in the evolution of the designs. The framework was established by combining the unique requirements for a supersonic environment and the market with those for commercial-airplane safety, comfort, and durability. Merging this with the projected levels of airframe, propulsion, and systems technology permitted specific designs to be established. Assessments were then made regarding the aircraft's technical feasibility and market viability for certain calendar-year windows.

2.1 ENVIRONMENTAL REQUIREMENTS

Ozone. One of the environmental goals of this study is to identify the technologies that will allow future operation of an HSCT that will cause no significant impact on the ozone layer.

An HSCT will cruise at a higher altitude and in a different environment than present commercial air traffic. Because of this, depletion of the stratospheric ozone by oxides of nitrogen (NOx) is a possibility. Thus, it is paramount to understand the technology and operational procedures required to minimize the effects of the HSCT engine effluents in the stratosphere.

Two engine companies (Pratt & Whitney and General Electric) have estimated the cruise emissions on several engine/combustor concepts. Total emissions based on projected fleet size and route structures were then established. NASA will use this information to assess the impact on the environment. Research and technology will be applied to ensure that emissions be reduced to the level required.

Community Noise. Achieving the noise levels of subsonic noise rule FAR36 Stage 3 is the goal for airport sideline and community noise. When further test data and analyses are available, it will be more appropriate to decide on the most beneficial noise rule criteria, taking into account options afforded by the difference between performance characteristics of the HSCT and conventional, subsonic transport aircraft.

Sonic Boom. A further goal for the future HSCT is to operate with an acceptable boom over populated areas. Large supersonic aircraft typically produce sonic booms that have shock waves with intensities of 2.0 to 3.0 lb/ft^2. Commercial overland supersonic flights are not allowed by U.S. law. The airplanes under study have been evaluated with subsonic flight profiles over land, which results in a significant economic and market impact. Thus, there is impetus to explore low-boom designs that allow some form of overland supersonic operation.

Based on a review of human response testing, design criteria of 72 dBA for corridors and 65 dBA for unconstrained flight are suggested. The 72 dBA criterion suggests that 1.0 lb/ft^2 shock waves may be acceptable. Parameters that significantly influence the effect of sonic boom pressure waves include rise time, duration, maximum overpressure, and initial overpressure.

2.2 OPERATIONAL REQUIREMENTS

Operational requirements include the use of suitable airports and design constraints based on the speed and altitude of the mission.

Two types of airports were considered: the conventional airport for subsonic and supersonic vehicles, and a special airport constructed to support the heavy, hypersonic (Mach 6.0 or greater) vehicle. If the HSCT were to operate from a conventional airport, the effect on airport construction and capacity must be assessed. Furthermore, the vehicle's performance requirements in terms of field length and low-speed characteristics must be defined. The very high weight of the hypersonic HSCT makes use of a conventional airport impossible. This limitation, along with the hypersonic's special fuel system, dictates the need for a customized airport.

The speeds and altitudes to be flown by the HSCT could produce flight operation requirements unlike those for subsonic aircraft in terms of both controlled airspace and the influence of cruise speed and altitude on vehicle design.

Operation From Conventional Airports. Operation from conventional airports requires that the vehicle must meet anticipated weight and field-length constraints, as well as operate compatibly with subsonic vehicles during approach to avoid system degradation.

Twenty-seven airports were selected as primary candidates for use by the HSCT. The airports, along with their runway characteristics, are listed in table 2-1. 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.

The pavement strength at eight of these candidate airports is inadequate to support a 750,000-to 900,000-lb HSCT without additional strengthening. However, the larger subsonic aircraft that are

Table 2-1. Selected High-Demand Airports

City	Country	Runway	
		Width x length, ft	Elevation, ft
Anchorage, AK	United States	150 x 10,897	44
Bahrain	Bahrain	200 x 13,000	6
Bombay	India	150 x 11,455	27
Buenos Aires (EZE)	Argentina	262 x 10,824	66
Caracas	Venezuela	150 x 11,483	235
Chicago, IL (ORD)	United States	150 x 11,600	667
Dallas/Fort Worth, TX	United States	200 x 11,388	596
Frankfurt	Germany	150 x 13,123	328
Hong Kong	Hong Kong	200 x 10,930	15
Honolulu, HI	United States	150 x 12,360	13
Johannesburg	South Africa	200 x 14,495	5,557
Los Angeles, CA	United States	150 x 12,091	126
Lisbon	Portugal	150 x 12,483	374
London (LHR)	United Kingdom	150 x 12,802	80
Madrid	Spain	150 x 13,451	1,998
Mexico City	Mexico	150 x 12,796	7,341
Miami, FL	United States	150 x 13,002	11
Manila	Philippines	200 x 11,004	75
New York, NY (JFK)	United States	150 x 14,572	12
Paris (CDG)	France	150 x 11,860	387
Rio de Janeiro (GIG)	Brazil	150 x 13,124	30
Rome (FCO)	Italy	200 x 12,795	14
Seattle, WA	United States	150 x 11,900	429
Singapore (Changi)	Singapore	200 x 13,123	21
Sydney (Kingsford)	Australia	150 x 13,000	21
Tel Aviv	Israel	150 x 11,998	135
Tokyo (NRT)	Japan	200 x 13,120	135

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anticipated to be in concurrent operation with the HSCT will require that the pavement strength be increased by at least 20% over current levels.

The HSCT may have some effect on the pavement fillet radius because of the anticipated length of the vehicle. Some modifications to the runway fillets may be necessary to maintain an acceptable runway-edge safety margin while maneuvering an HSCT on the ground from the runway to the taxiway with the cockpit over the center line. Again, modifications must be made to accommodate the subsonic vehicles anticipated for the years 2000 to 2015.

To avoid an increase in the takeoff and landing separation between subsonic and supersonic airplanes, a design approach speed of 145 kias (with a wake vortex system similar to that of a Boeing 747) will ensure that impact is no more serious than a "heavy jet." If the vehicle had an approach speed of 185 kias or a significantly stronger wake vortex field, there would be a significant incremental impact. Table 2-2 summarizes airport throughput sensitivities for flight rules (instrument flight rules (IFR) and visual flight rules (VFR)), approach speeds, and approach path variants.

Operation From Special Airports. Special airports are envisioned 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 require special fuel systems as well 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 2-1, 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 2-2 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 2-2 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 2-3 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 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 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.

Flight Operations. The high speed of travel and the high altitude of HSCT flight require special consideration of uncontrolled airspace. Currently, only the Concorde and special military vehicles use the airspace above 60,000 ft. A new definition of airspace above this level is required to ensure that the Air Traffic Control (ATC) services and standards provide the HSCT with safety levels equivalent to conventional, subsonic commercial operations. There are currently no known ATC services at the higher altitudes for civil aircraft.

No special considerations for ATC electronic equipment are required. The HSCT-era avionics systems will greatly enhance HSCT integration into ATC environments. The avionics, with improved

Table 2-2. *Summary Throughput Change With 10% HSCT Airplanes*

Operating condition	Change, %	Relative change, %									
Addition of HSCT or heavy jet arrivals only, 145 kn, VFR	-4.2	Base				Base					
Addition of HSCT or heavy jet arrivals only, 145 kn, IFR	-2.5		Base				Base				
Addition of HSCT or heavy jet 50% arrivals, 145 kn, VFR	-4.9			Base							
Addition of HSCT or heavy jet 50% arrivals, 145 kn, IFR	-2.1				Base						
185 kn approach speed, arrivals only, VFR	-5.5	-1.3									
185 kn approach speed, arrivals only, IFR	-1.5		+1.0								
185 kn approach speed, 50% arrivals, VFR	-4.9			0							
185 kn approach speed, 50% arrivals, IFR	-0.3				+1.8						
+1.4 nmi wake vortex separation, arrivals only, VFR	-4.2					-4.2					
+2.0 nmi wake vortex separation, arrivals only, IFR	-3.8						-1.3				
15 nmi common approach path, arrivals only, 145 kn, VFR	0.0							Base			
15 nmi common approach path, arrivals only, 145 kn, IFR	-0.6								Base		
15 nmi common approach path, arrivals only, 185 kn, VFR	-7.0							-7.0			
15 nmi common approach path, arrivals only, 185 kn, IFR	-5.5								-4.9		
15 nmi common approach path, 50% arrivals, 145 kn, VFR	0.0									Base	
15 nmi common approach path, 50% arrivals, 145 kn, IFR	0.3										Base
15 nmi common approach path, 50% arrivals, 185 kn, VFR	-1.2									-1.2	
15 nmi common approach path, 50% arrivals, 185 kn, IFR	-4.2										-4.5

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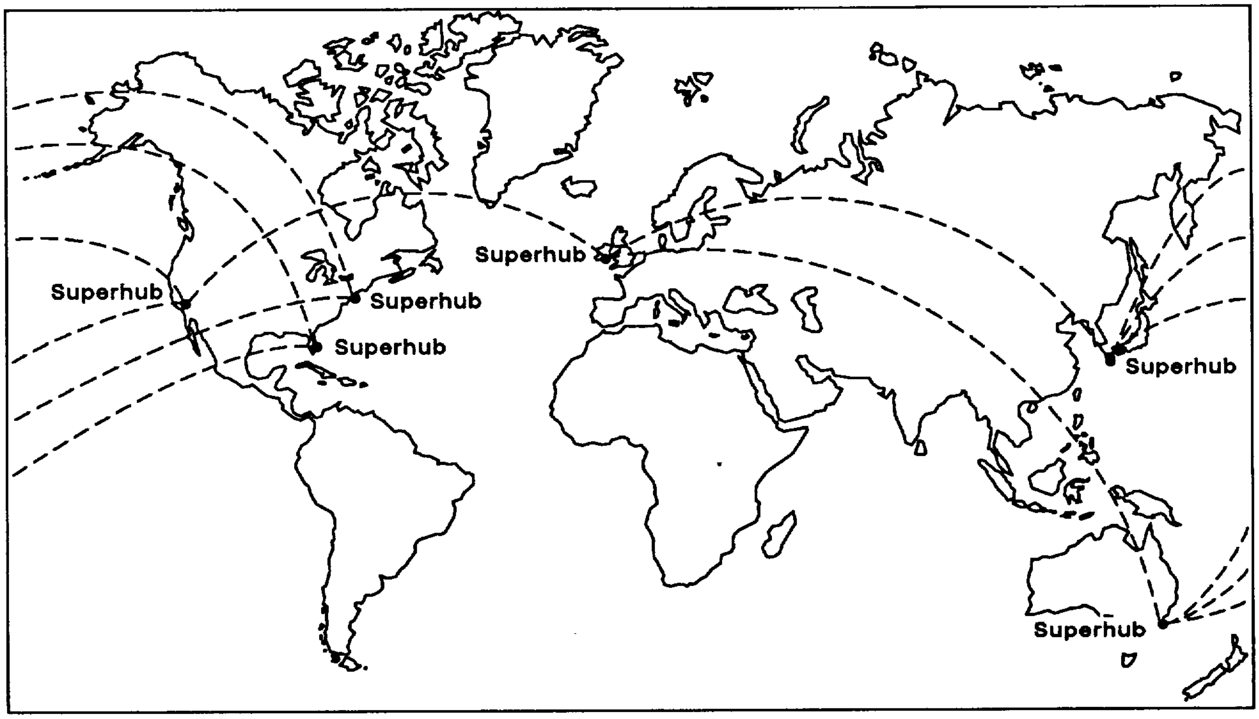

Figure 2-1. Superhub Airport Network

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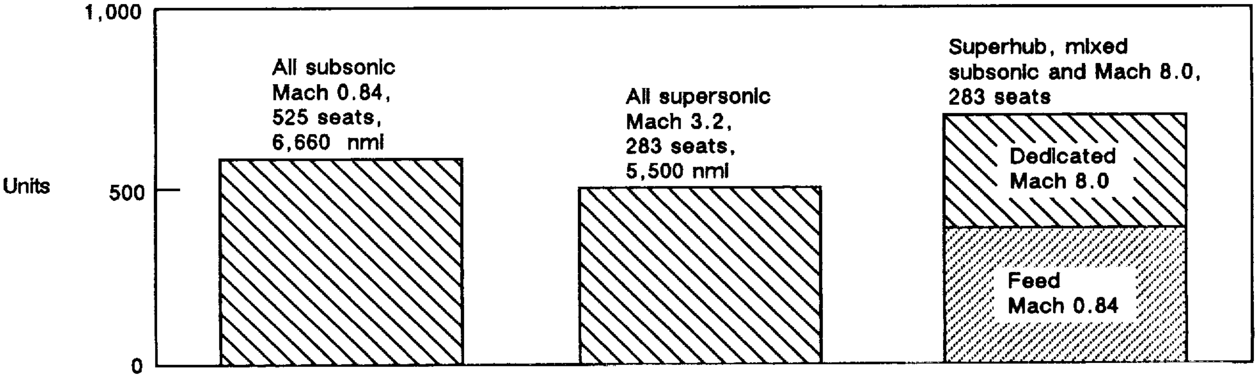

Figure 2-2. Units Required—Year 2015

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navigation accuracy, will permit a reduction in the separation standards used in oceanic and remote areas. Tighter separation standards will lead to increased flight capacity and easier access to the system.

2.3 MARKET REQUIREMENTS AND ASSUMPTIONS

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 turnaround time at an airport, 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

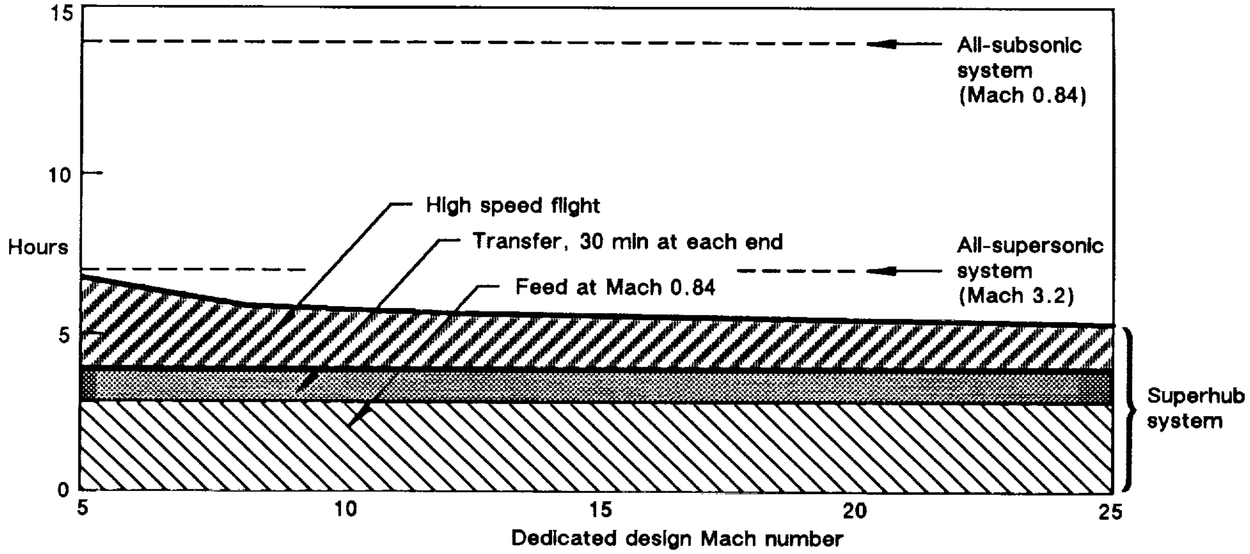

Figure 2-3. Average Trip Time – Superhub System

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prices. Stimulation, as such, was not included in the basic study; however, the effect of ticket price was examined.

Market Forecast. The market forecast is based on major market area passenger flows as defined in the "Boeing 1987 Current Market Outlook" (ref. 2.1). The Market Outlook covers the 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 (fig. 2-4).

Not all of this market is applicable for a long-range airplane, however. Figure 2-5 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 intra-regional 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 year 2015 was developed by assuming the individual markets are maturing, and therefore grow at 85% of their average rates from years 1995 through 2000. This resulted in almost

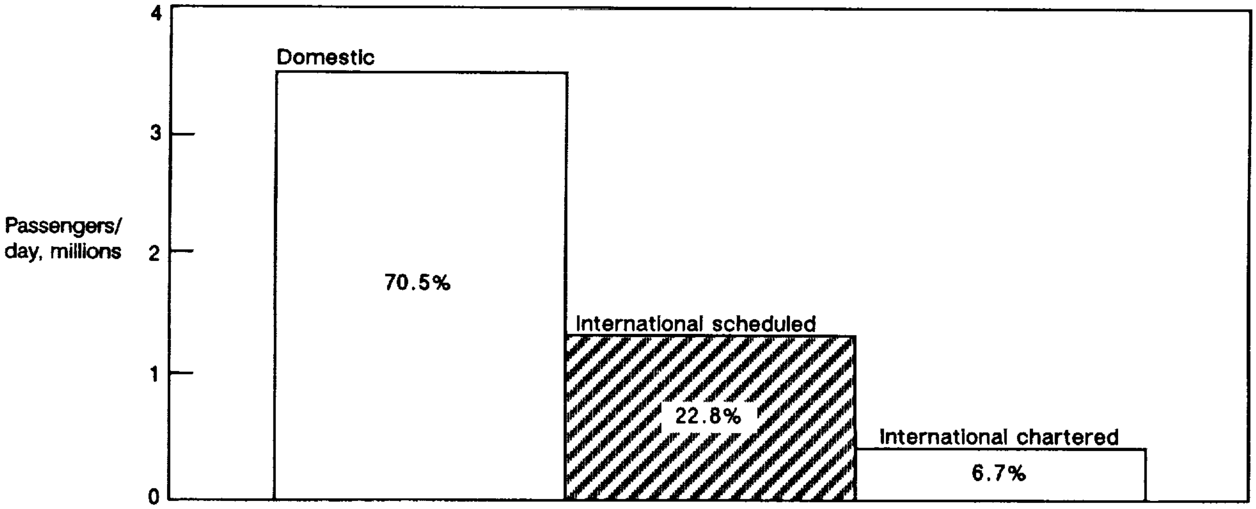

Figure 2-4. World Air Traffic Demand Forecast – Year 2000

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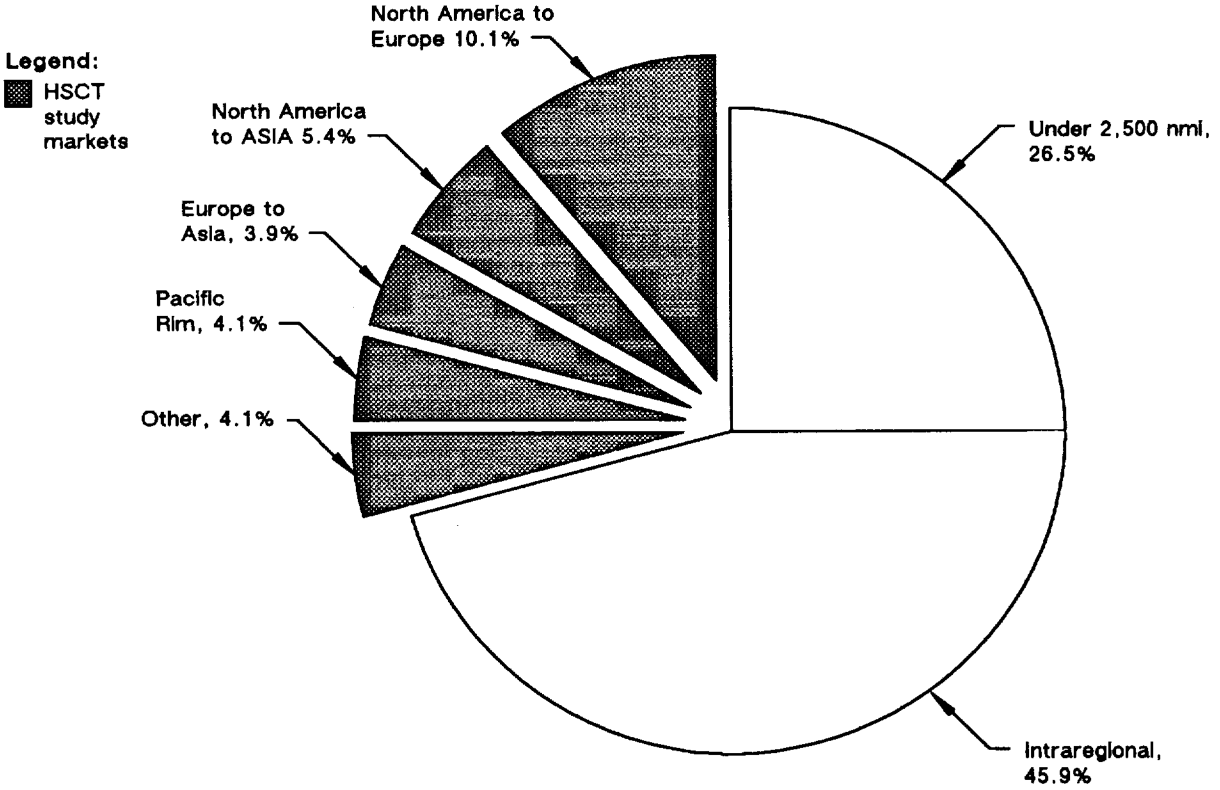

Figure 2-5. Year 2000 International Traffic Distribution Forecast Based on Total of 1,100,000 Passengers/Day

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doubling year 2000 demand, with the Pacific Rim area forecast increasing at a greater rate (53% of the revenue passenger miles (RPM) in year 2000 and 60% in 2015) (fig. 2-6). The total HSCT passenger demand potential (without allowances for stimulation) is forecast to be 315,000 passengers per day by 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.

The resulting market forecast becomes the potential market for the HSCT. The fleet sizes discussed in this report represent various degrees of penetration of the potential market. However, airlines will have on-order subsonic aircraft that will satisfy a significant portion of the lift requirement. The HSCT market is the "open" lift market, which is the total market less the market satisfied by on-hand or on-order aircraft plus the market created by aircraft retirements or transfers (fig. 2-7). The economic viability of the HSCT can affect all the elements of the open lift market. An economically viable HSCT can affect the total market by stimulation. It can also affect near-term purchases of new subsonic aircraft; retirements of older, marginal subsonic aircraft; and transfers of subsonic aircraft to other markets.

Passenger Trip Distance and Airplane Design Range. Figure 2-8 shows the distribution of nonstop passenger trips (no intermediate stops) and RPM. About half the passengers and 40% of the RPM 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.

The following discussion summarizes a detailed analysis of 10 specific market areas in which airplane productivity and HSCT passenger trip time savings were used to evaluate design-range

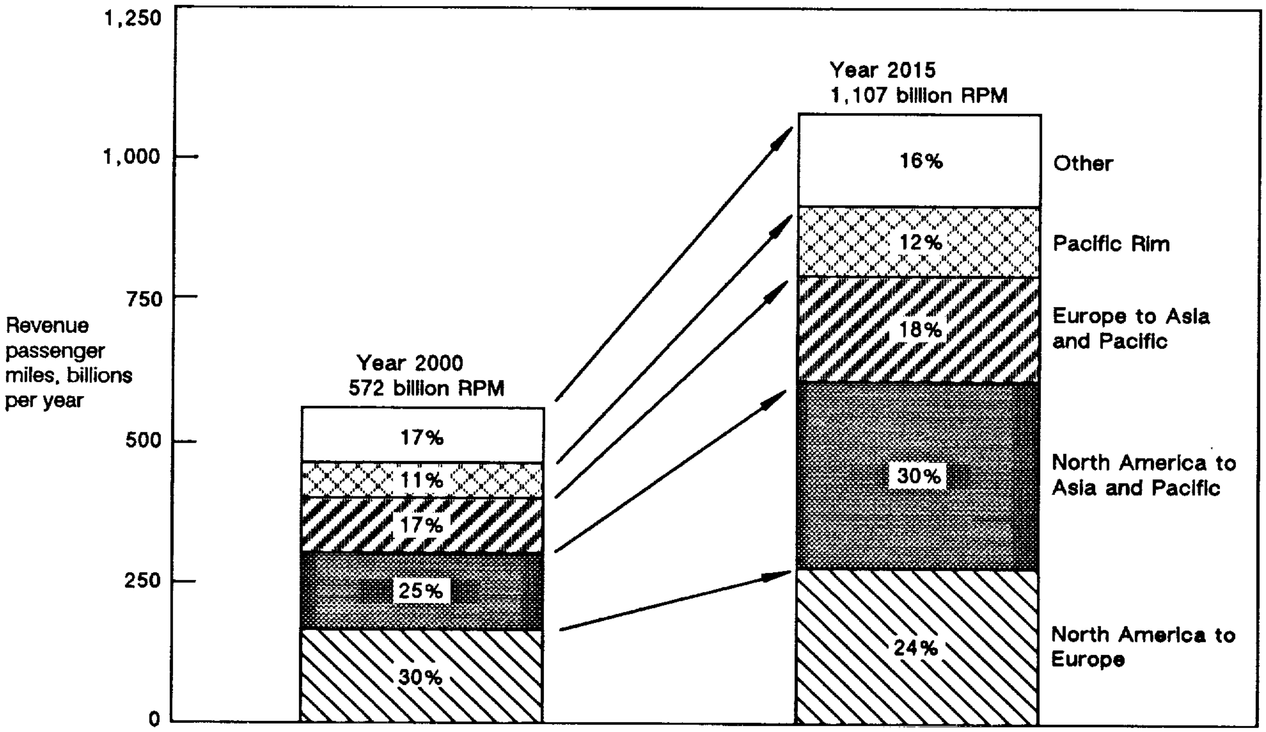

Figure 2-6. Revenue Passenger Mile Forecast

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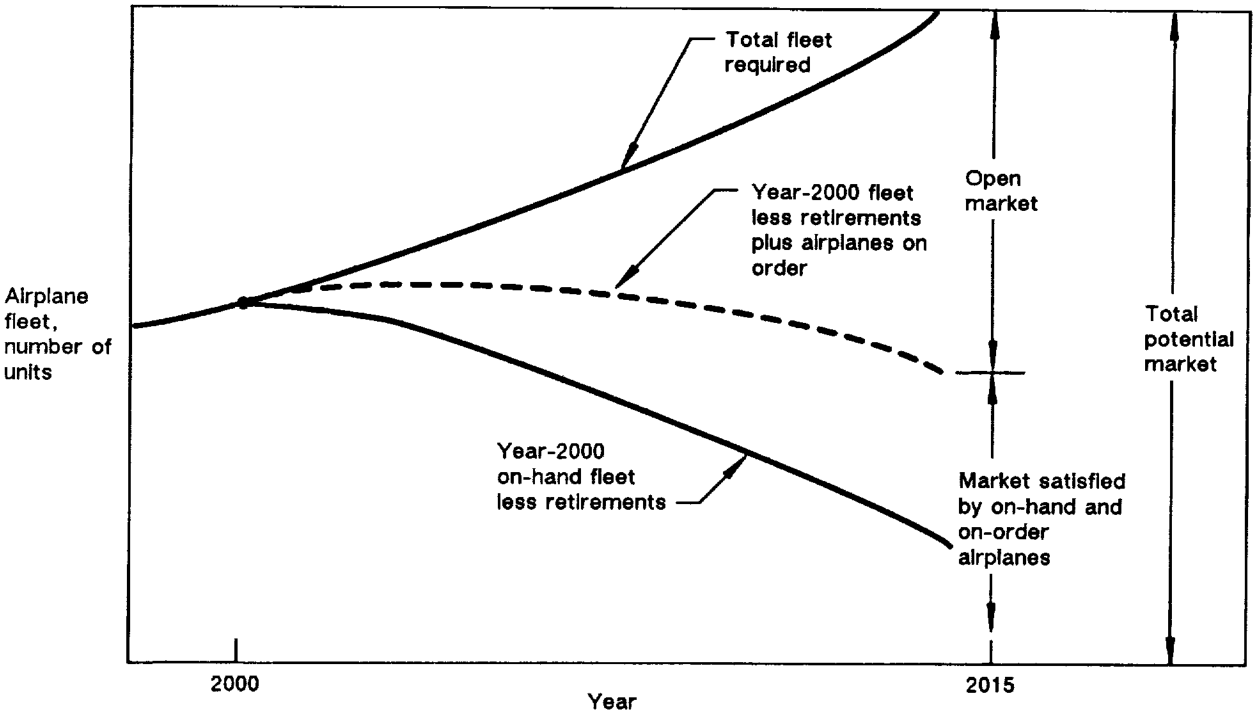

Figure 2-7. Potential Market for the HSCT

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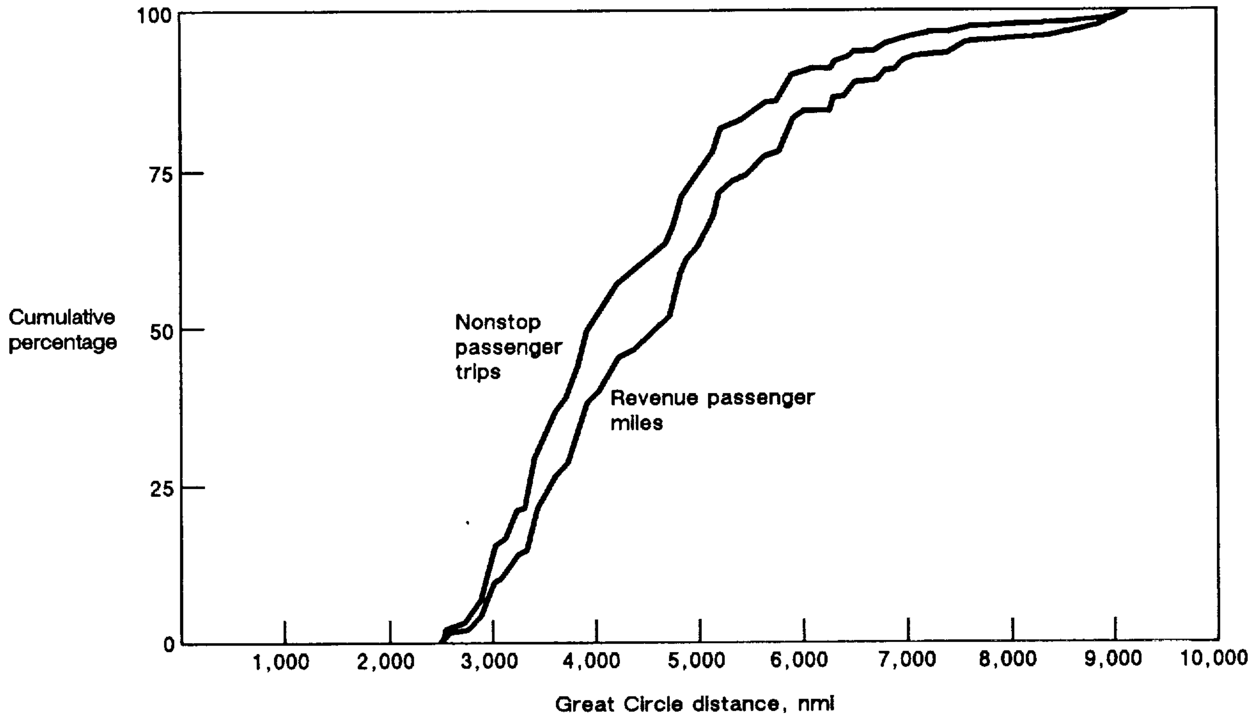

Figure 2-8. HSCT Traffic Distribution – Year 2000

4-U90027R2-10

capabilities. Design range is important because it affects the number of intermediate stops required to serve the airline's network. Stopovers reduce airplane productivity and increase travel time.

The market area groups used to evaluate design range capabilities are—

a. Eastern North America to Europe.
b. Eastern North America to Asia/Pacific.
c. Mid-North America to Europe.
d. Mid-North America to Asia/Pacific.
e. Western North America to Europe.
f. Western North America to Asia/Pacific.
g. Europe to South America.
h. Europe to Asia/Pacific.
i. Pacific Rim (intra-Asia/Pacific).
j. Miscellaneous.

As seen in figure 2-9, four of these ten markets have more than 85% of their routes over water and the others range from 50% to 80% over water. Further, figure 2-10 indicates that these same four markets represent about half the passengers and about 41% of the RPM.

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. Using year 2000 technology, figure 2-11 reflects the number of units (with 247 seats and a 2-hr through time) required to serve each "mostly overwater" market at both Mach 2.4 and Mach 3.2 cruise speeds. Most of these markets do not show any significant productivity gain beyond a design range of 5,000 nmi. This same trend is apparent in the relative travel-time analyses (fig. 2-12) for the Eastern North America to Europe and the Pacific Rim markets; however, travel time saved continues to improve with increased design range for the other two markets and, most markedly, the Western North America to Asia arena.

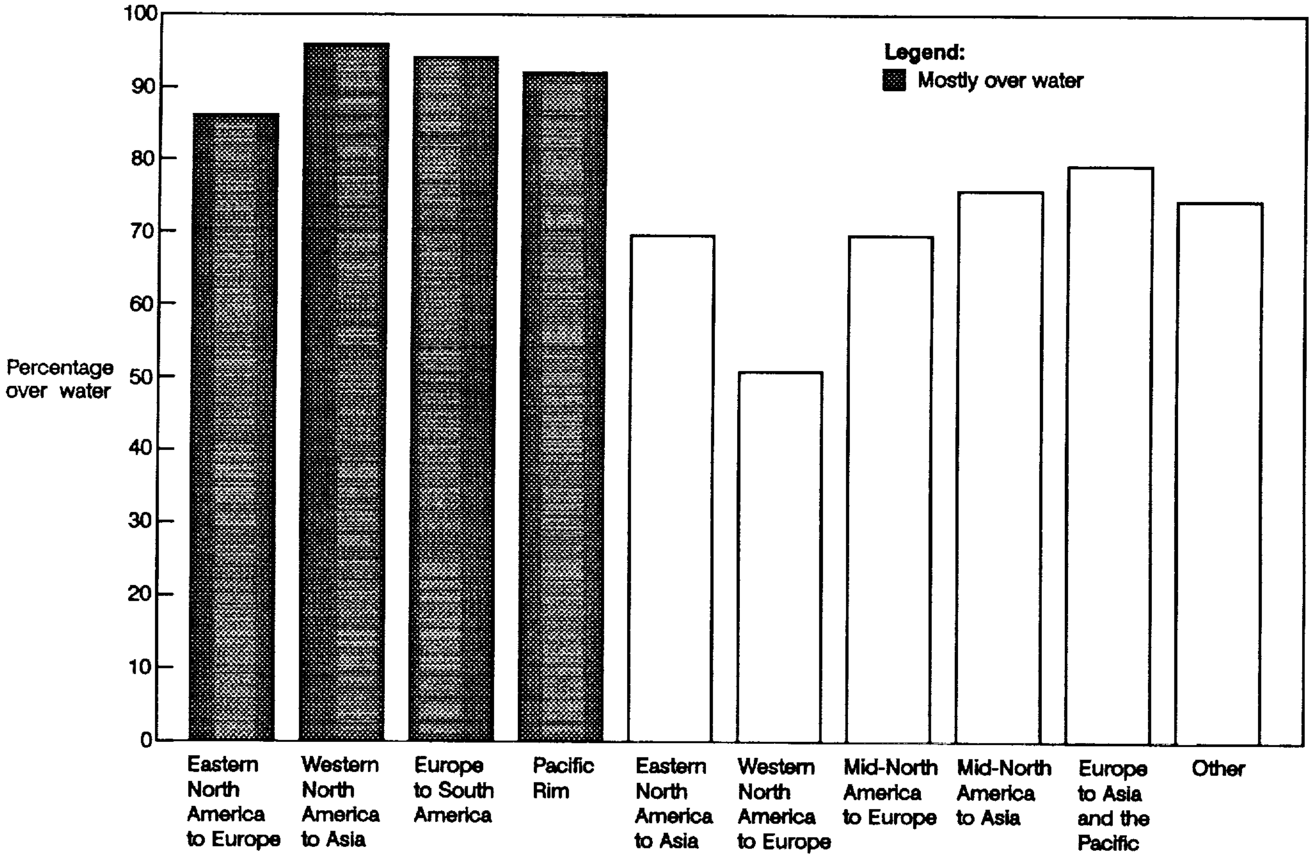

Figure 2-9. Overwater Distance

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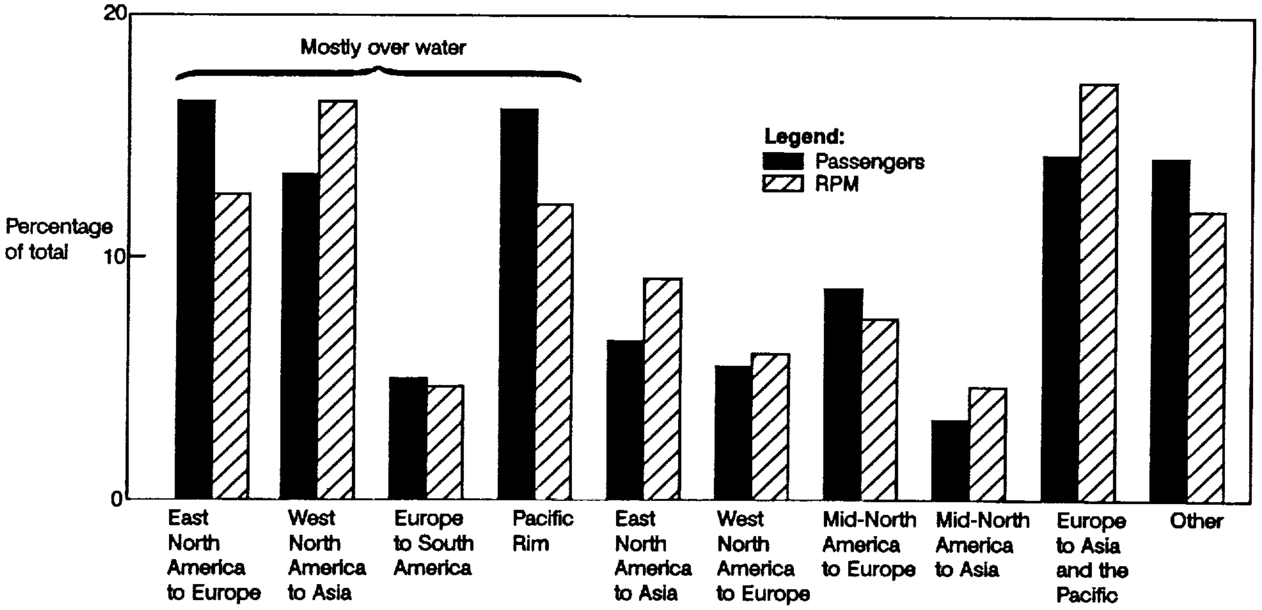

Figure 2-10. Major HSCT Markets-Year 2015

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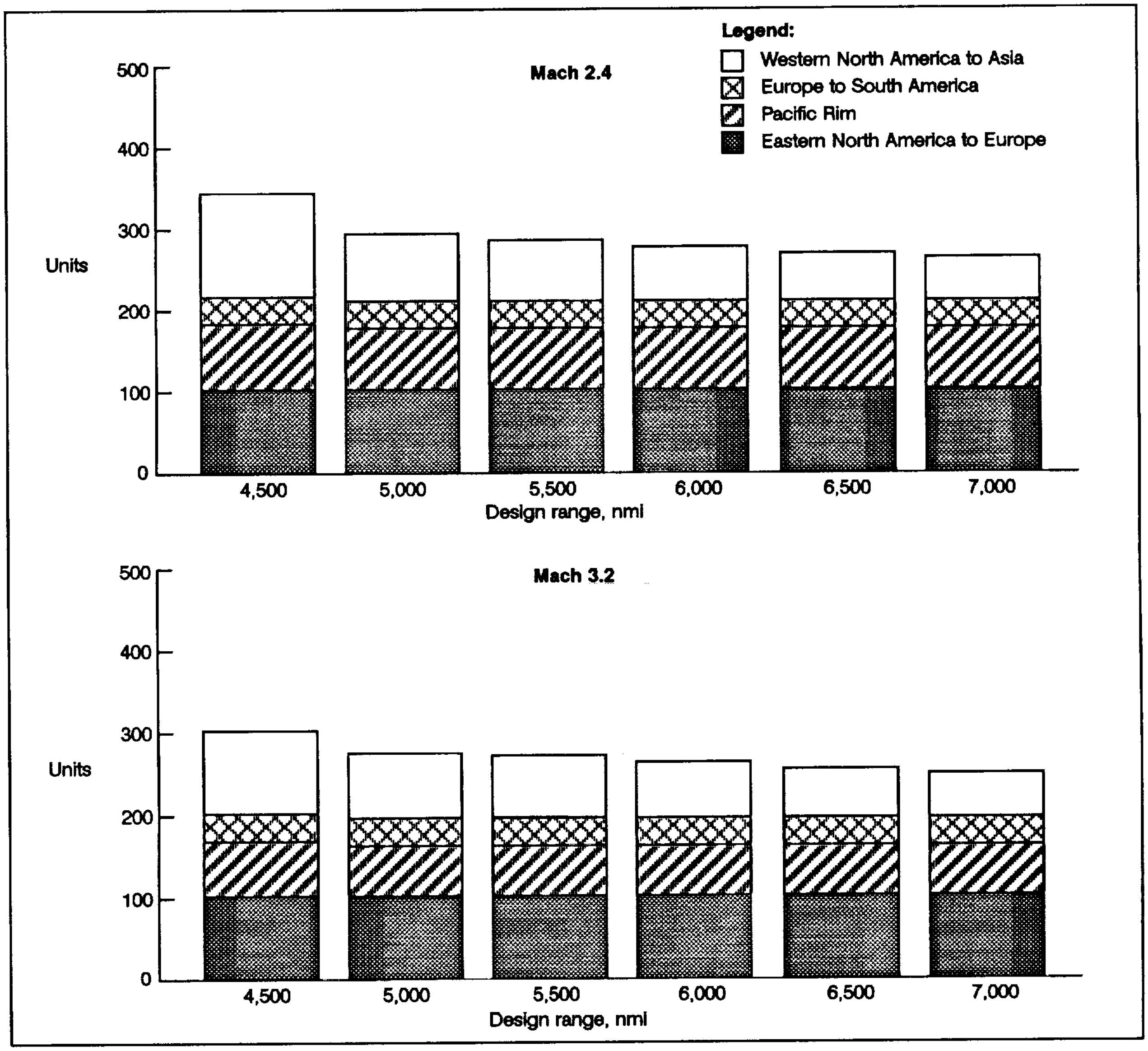

Figure 2-11. Units Required—Overwater Markets

4-U90027R1pk33-13

The remaining markets cannot use an HSCT as effectively as the mostly overwater markets if there is a constraint forbidding any overland supersonic flight. This constraint is an inherent assumption in all Boeing market analyses. Therefore, these markets 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. These markets require about 65% of the total airplanes, while carrying only 50% of the traffic. Figures 2-13 and 2-14 represent these markets and show that a design range of 6,500 nmi would capture most of the productivity. However, even with a 7,000 nmi design range, the average time saving over a subsonic airplane is barely 40%.

Specific Airlines. The two key benefits of an HSCT to an airline are increased utilization and revenue. The most important aspect of the scheduling portion of the marketing analysis is the determination of utilization as a function of the various design parameters. The HSCT universal system was created to exploit the benefits of HSCT long-range markets where the relative time savings are greatest and where dense markets allow excellent passenger flow opportunities. This is a good environment

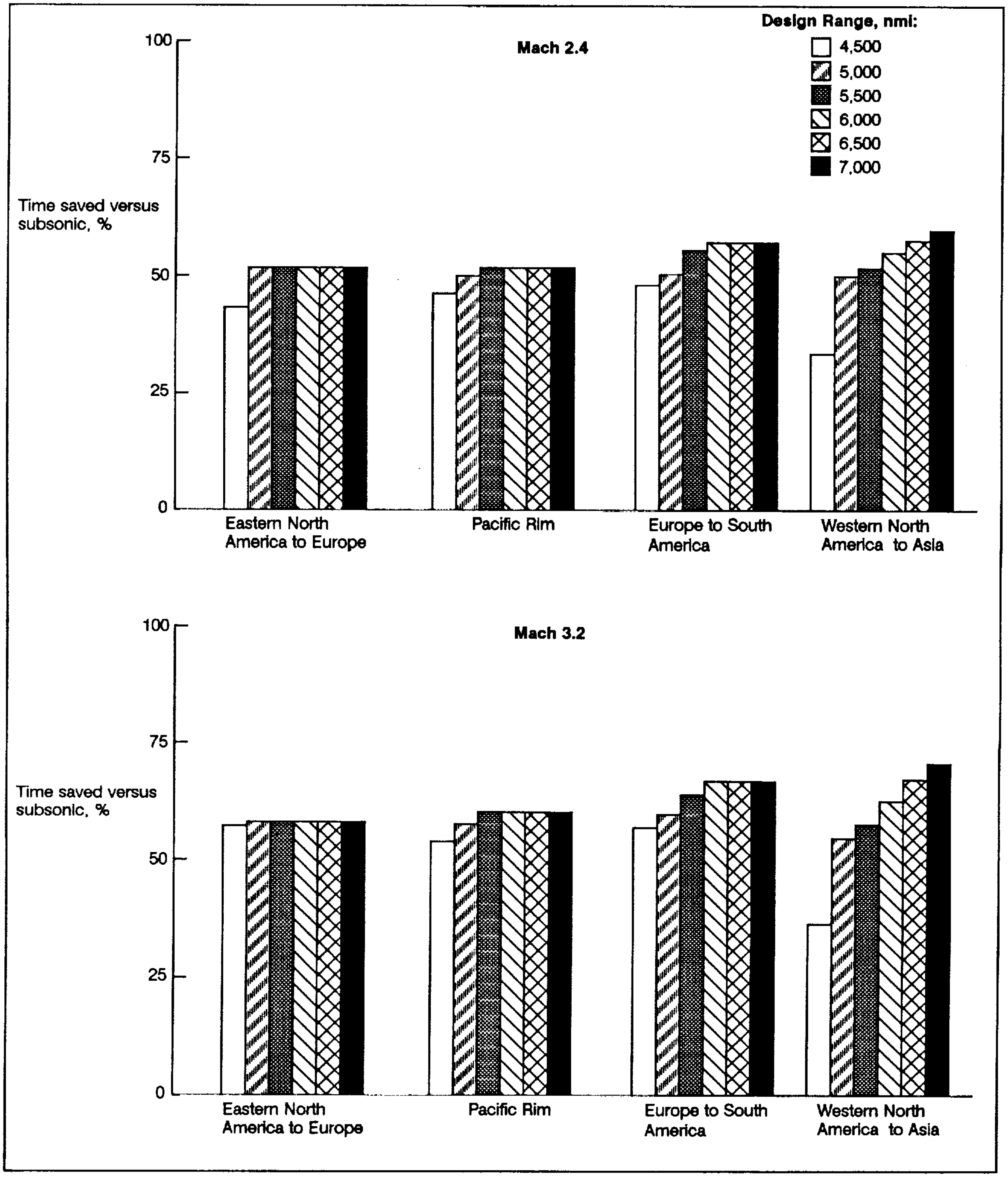

Figure 2-12. Relative Travel Time – Overwater Markets

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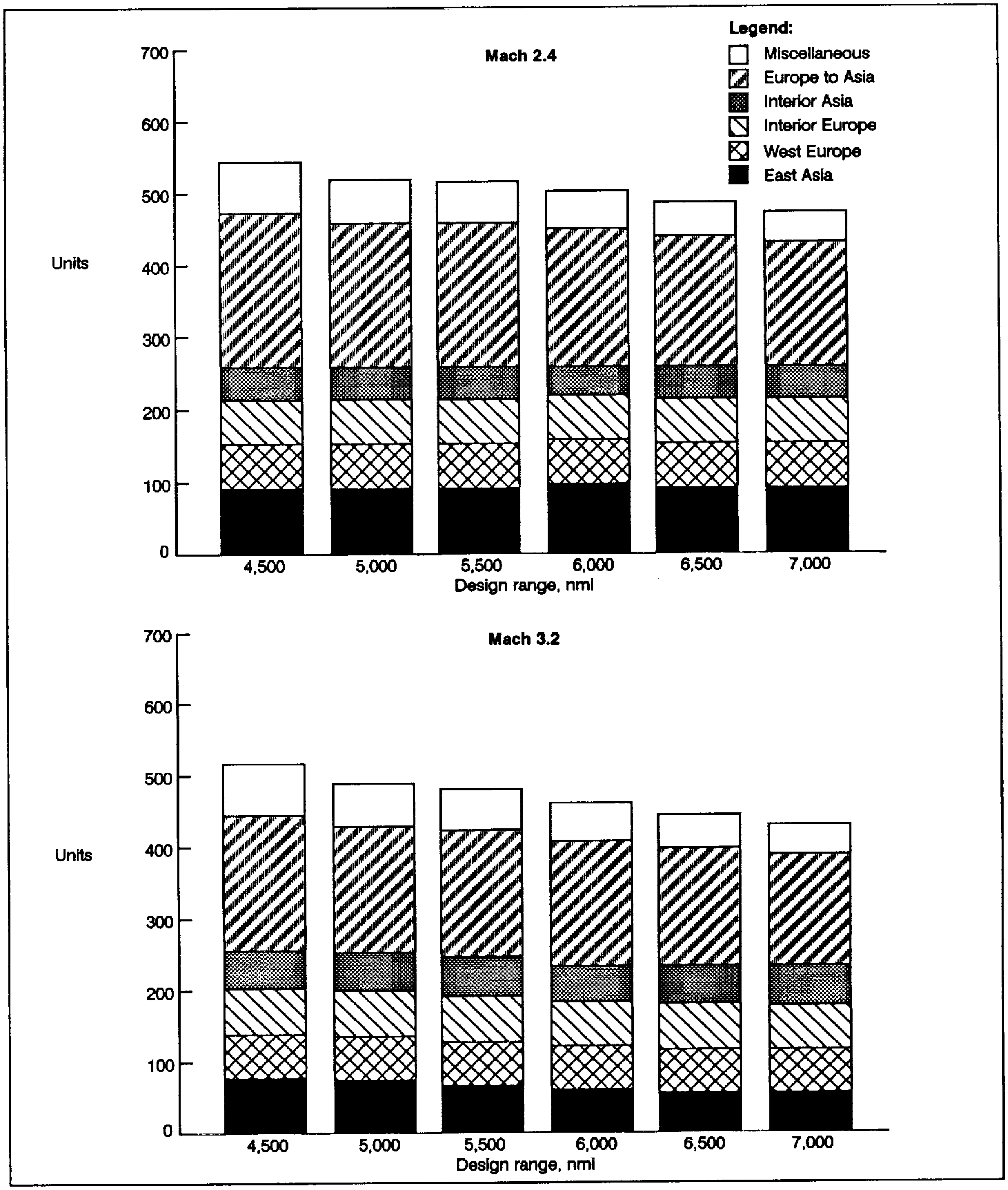

Figure 2-13. Units Required—Other Markets

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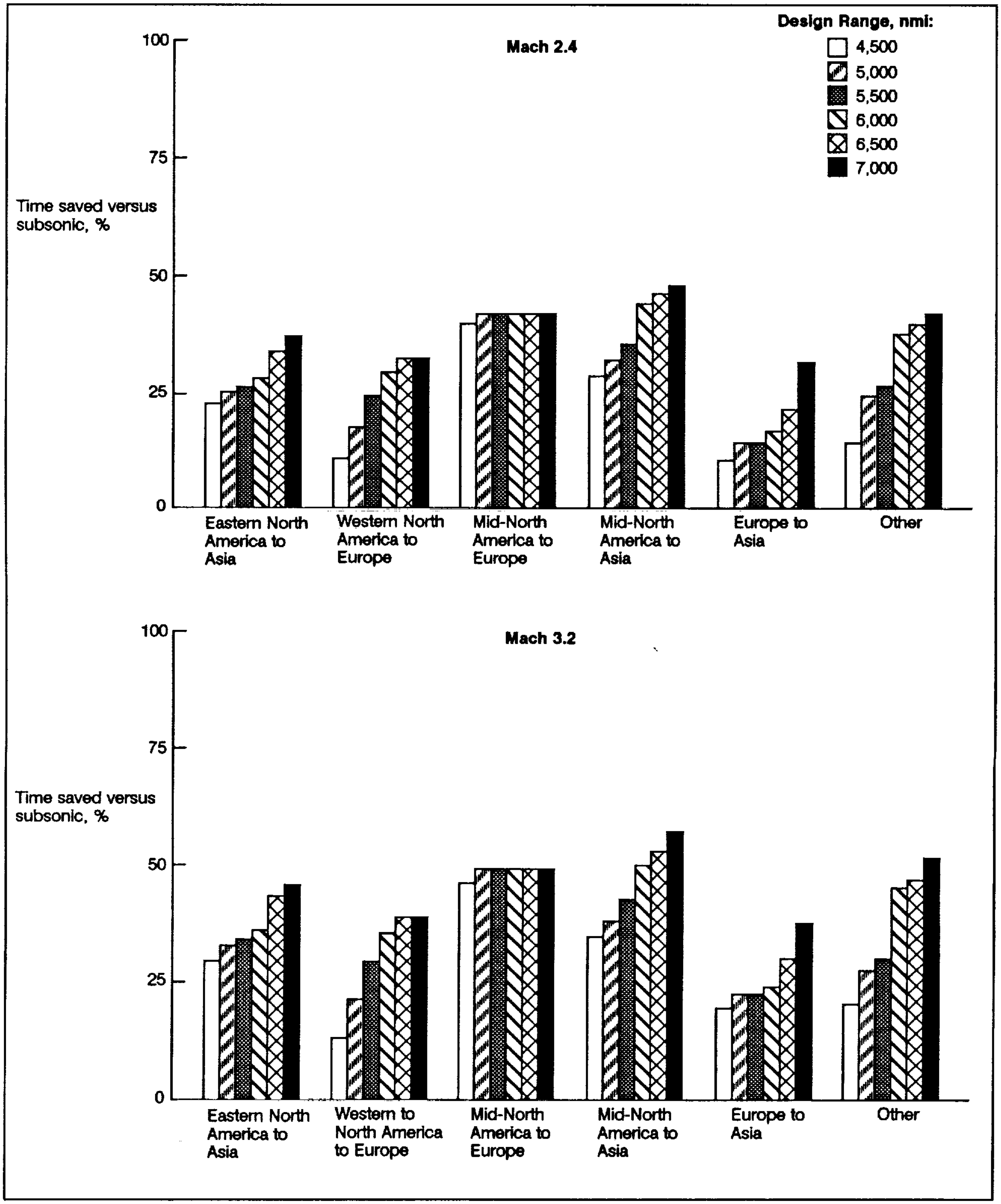

Figure 2-14. Relative Travel Time—Other Markets

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to examine design sensitivities and the resulting utilization levels are high. In the real world, however, it is important to understand how an airline system might differ from the universal system, primarily from the standpoint of utilization and workrate differences.

HSCT Universal Utilization. The HSCT universal system utilization levels were established by running the various HSCT configurations through the HSCT universal system. Figure 2-15 shows the utilization levels for the following set of conditions:

a. Year 2000 HSCT universal system.
b. Seating of 247 seats.
c. A 5,000-nmi design range (3,583-nmi average range).
d. Mixed waypoint routing for Mach numbers greater than 0.84.
e. Two-hour turn time.

The trend of utilization (as indicated by the dotted lines in the figure) as a function of average stage length is based on analyses of trends derived from Department of Transportation (DOT) Form 41 scheduled U.S. international airline reported data. The trends indicate that, as average stage length decreases, utilization increases. Notice that the utilization level of the Mach 0.84 aircraft is about 30% greater than the Boeing standard level that represents actual airline utilization. This again reflects the fact that the HSCT system is specifically designed to exploit utilization. The results of alternative-design-range HSCTs are superimposed on the utilization trends. These results indicate that the utilization levels for the alternative design ranges follow the trend lines, except for the high Mach number-short design ranges where, because the climb and descent are a greater proportion of the total mission, the resulting utilization levels are below trend.

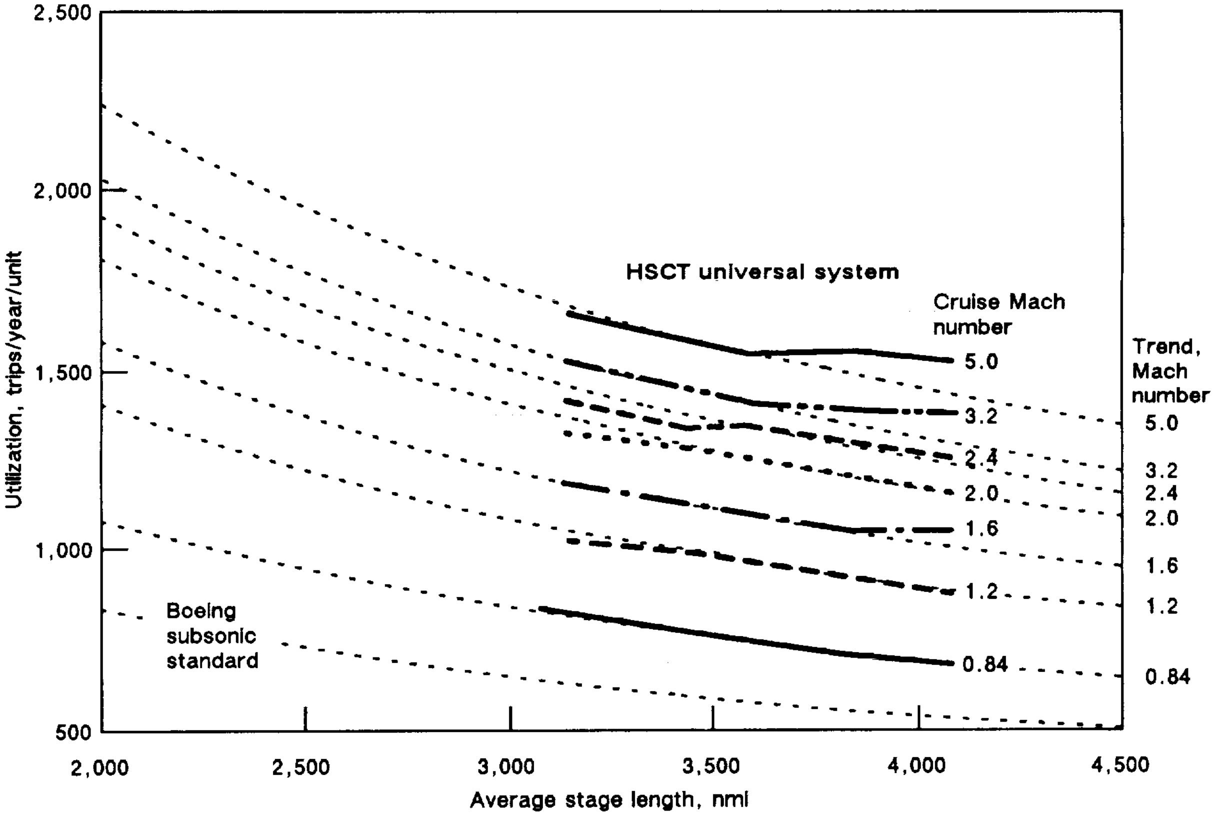

Figure 2-15. HSCT Utilization Results

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HSCT Airline Utilization. The next steps were to (1) examine the schedules of seven airlines that expressed interest in HSCT activity, (2) determine how an HSCT might fit into these airline networks, and (3) establish the resulting utilization levels. The general approach was to start with a recent wide body schedule for each of the airlines as reported in the Official Airline Guide. The schedule was converted to a daily schedule (each flight operating 7 days a week). Also short-range, overland domestic flights were excluded. This resulting route structure is referred to as the modified schedule. A reduced route structure was then created in which most of the short-range, tag-end segments were eliminated to increase average range and to improve utilization.

The resulting HSCT utilization levels for a "typical" airline are shown in figure 2-16. Notice that the average stage lengths for the typical airline are considerably less than for HSCT universal network. While it is difficult to generalize airline systems because of the unique characteristics of each system, some general observations are appropriate. A key comparison can be made between the utilization of an HSCT within an airline system with that of an HSCT operating within the HSCT universal system. The Mach 2.4 HSCT results in figure 2-16 demonstrate that the HSCT "airline" utilization, as measured in terms of trips per year, is about 20% below the Mach 2.4 Universal trend for the modified airline systems and about 10% below the Mach 2.4 Universal trend for the reduced airline systems. As Mach number increases, the utilization shortfall also increases, because of the short average stage lengths in the airline systems.

The utilization levels for the specific airlines differ. The main causal variables are—

a. Average stage length. The greater the average stage length, the less the utilization shortfall.
b. System size. The more the system is pared back to routes that are suited to the HSCT, the closer the utilization will align with the trend. However, this lessens the requirement for an HSCT, and creates a requirement for a complementary airplane.

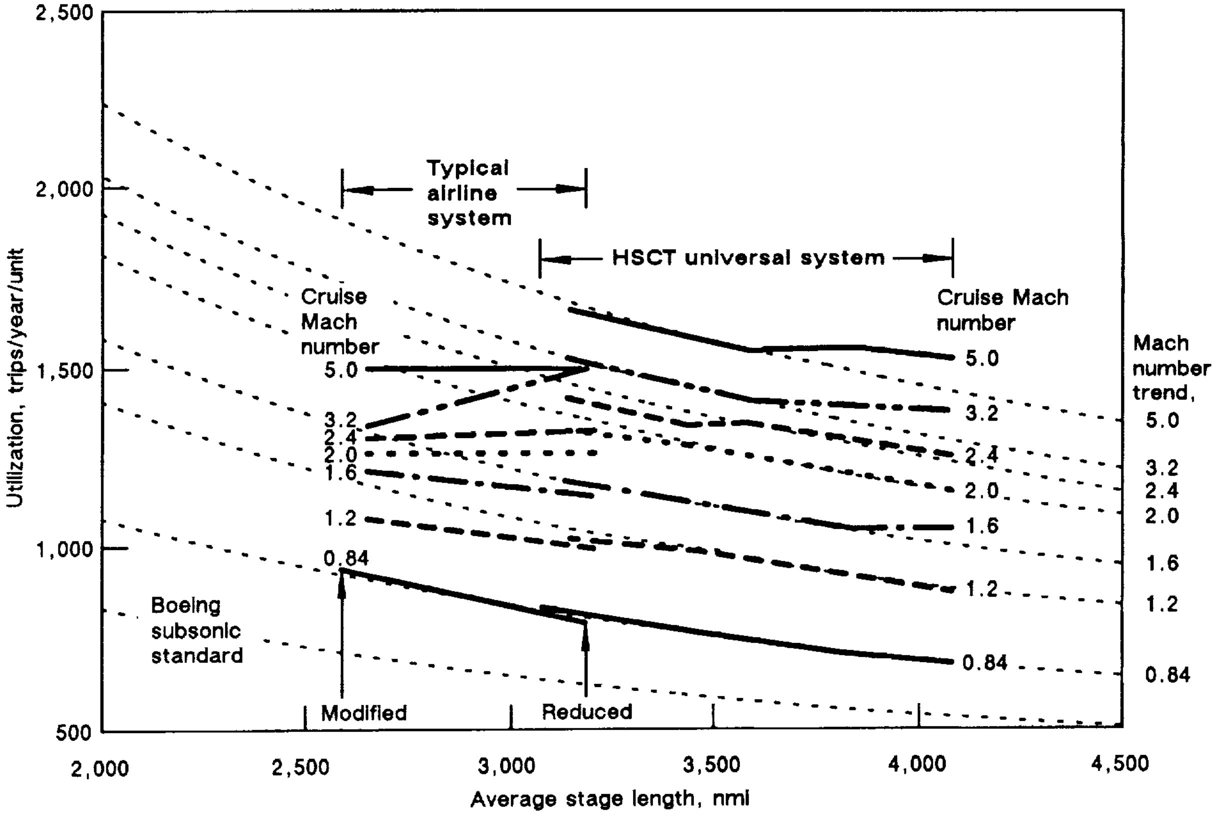

Figure 2-16. HSCT Utilization Results for Typical Airline System

5-U90027R3-18

c. Short-range segments. The smaller the proportion of short-range segments, the more likely the resulting utilization will be closer to trend.
d. Overwater percentage. The greater the overwater percentage, the more likely the resulting utilization will be closer to trend.

The results indicate that if an HSCT is directly substituted for a Boeing-747 mission, the resulting utilization levels may be 20% below the levels achieved in the HSCT universal system. This is primarily because of the many short, overland, tag-end segments that the subsonic aircraft typically perform. To minimize the utilization loss in an airline system, the HSCT should be used on routes more suited to its capabilities. However it is a delicate balancing act because the more the system is tailored to the HSCT, the less the requirement will be for the HSCT, and the less desirable the service becomes from a passenger service point-of-view (i.e., more connect stops). Only by working with the airlines can a determination be made as to how far the system can be tailored to favor the HSCT.

Market Physics. One of the first study tasks was to scope or focus the airplane design effort through parametric marketing applications. A universal airline system was postulated using the defined passenger flow forecast. The airplanes flown in this system were varied in size (seats), design range, and cruise Mach number. Acceleration rates were varied between 0.1g and 0.5g, based on "Evaluation of Routing and Scheduling Considerations for Possible Future Commercial Hypersonic Transport Aircraft" (ref. 2.2). The turnaround and through stop times varied from 1 to 4 hr. Figures 2-17 through 2-19 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 and, of course, using the longest design range and the higher number of seats. Of additional interest are the obvious trades between Mach number and the other parameters

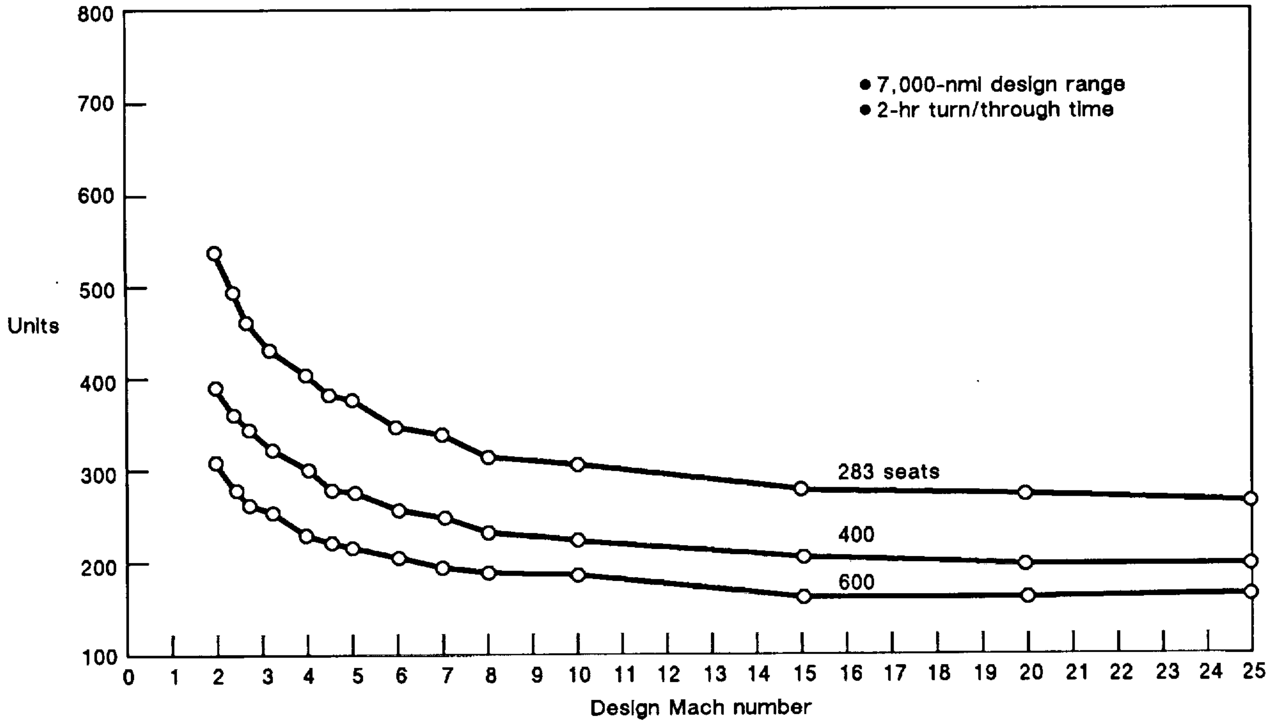

Figure 2-17. Fleet Size Versus Seats

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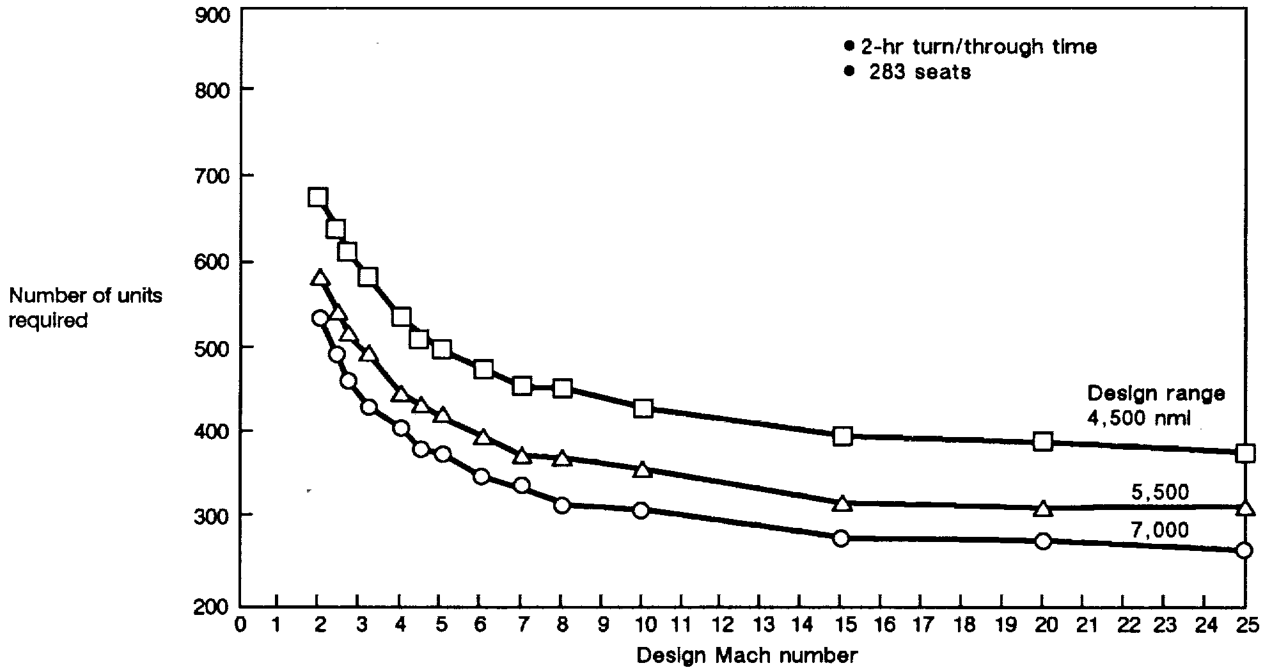

Figure 2-18. Effect of Design Range on Fleet Size

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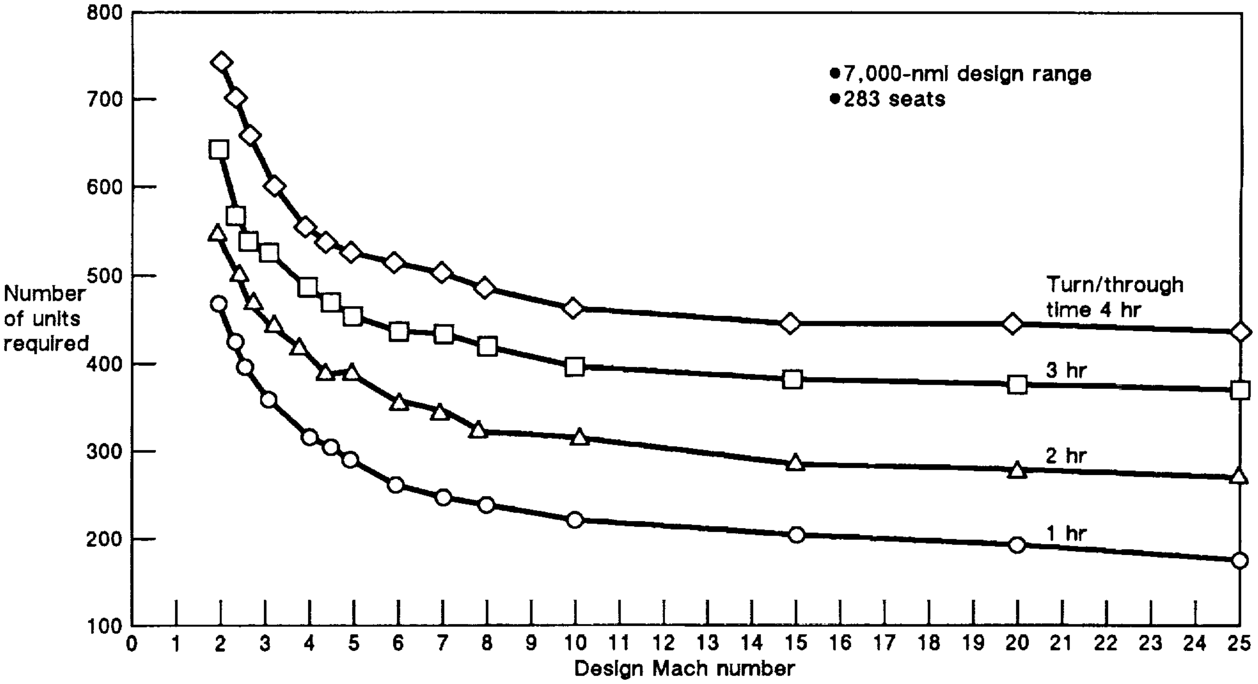

Figure 2-19. Fleet Size Versus Turn/Through Time

4-U90027R1-21

(e.g., fig. 2-18 demonstrates that a 7,000-nmi design range, Mach 3.0 vehicle has the same productivity potential as a 4,500-nmi design range Mach 10.0 vehicle).

While figures 2-17 through 2-19 used an average acceleration rate of (0.02 x Mach) g, figure 2-20 shows that significant gains in average Mach number are possible (in the unconstrained environment) by accelerating at high rates up to certain Mach limits. The prime explanation for the limitation lies in the climb and descent portions of the flight. For example, a Mach 25.0 airplane accelerating at 0.5g

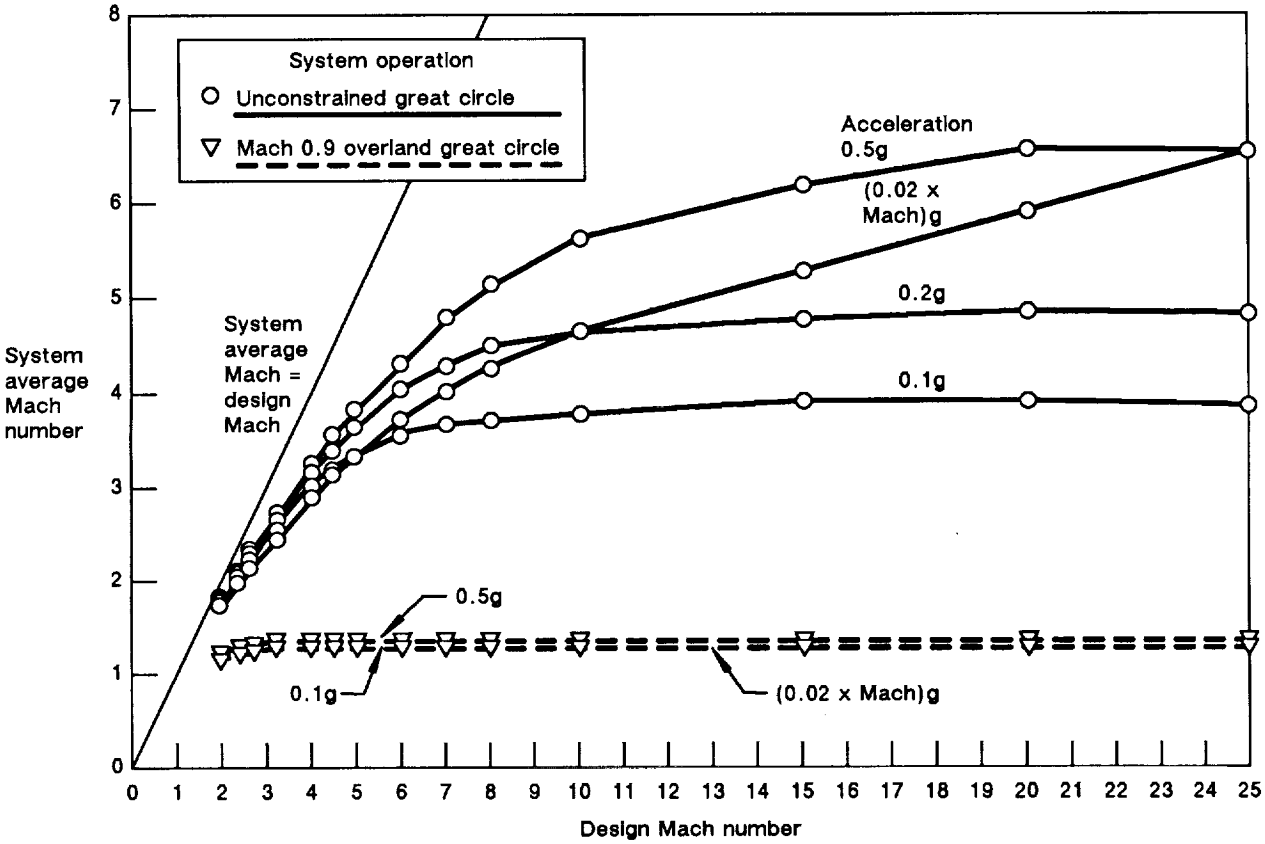

Figure 2-20. Effect of Acceleration Rate on Average Mach Number (7,000-nmi Design Range)

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requires 7,000 mi to climb and descend. That same airplane accelerating at only 0.1g (a more reasonable comfort level for the passengers) requires 35,000 mi to climb and descend. In either case, very few city-pairs are far enough apart to allow proper use of the higher Mach numbers. When the "no sonic boom over land" constraint is applied (see lower curves in fig. 2-20) no gain is received from the higher acceleration rates. Further, the average system Mach number never reaches Mach 2.0 even for a Mach 25.0 airplane. The explanation for this low average Mach number is that almost 50% of the Great Circle routes are over land, and flying that percent of distance subsonically allows very little, if any, cruise at the higher Mach numbers.

One solution for this problem is to reroute appropriately to minimize the overland distances. This application reduced the overland portion to less than 20% of the total distance and had a significant effect. Figure 2-21 shows the result using a 7,000-nmi design range vehicle with 283 seats and 2-hr turn/through time (acceleration (0.02 x Mach)g). However, system average Mach number still did not exceed Mach 3.0 and these results indicate that design Mach numbers above 3.5 to 4.0 probably do not justify further consideration for airline use.

Market Elasticity. HSCT revenues can be increased by charging more for the faster service; however, air travellers (particularly economy class) are sensitive to ticket price. Any significant increase in ticket price will result in loss in market share for the HSCT. A reduction in market share means fewer units produced to serve the market with a subsequent increase in the price of each unit to recapture the development and manufacturing costs. Therefore, the tradeoff between a ticket price increase and time savings becomes an important issue in the economic viability of an HSCT.

A determination was made for the market study of the class mix of passengers within the forecast time period. This was accomplished by analyzing the DOT 10% U.S. ticket sample for 1985 and

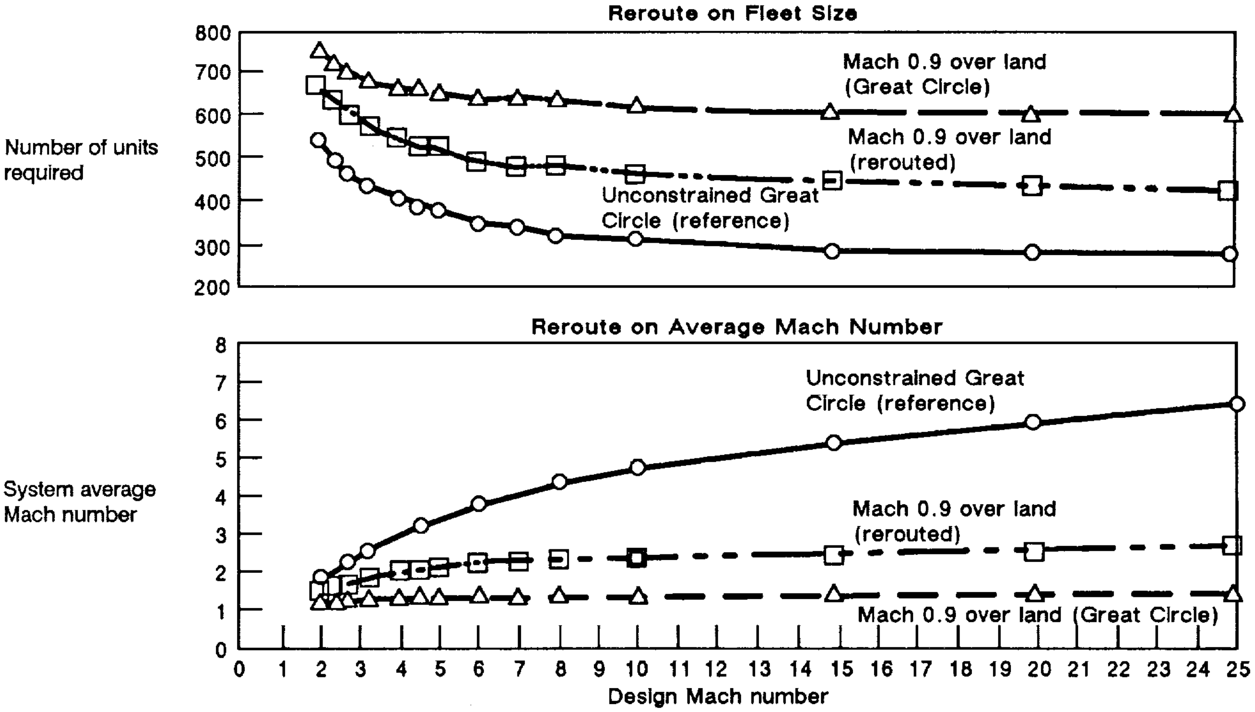

Figure 2-21. Effect of Reroute on Fleet Size and Average Mach Number

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allocating the results to establish first, business, and economy passengers in each of 14 markets. Figure 2-22 shows that, as expected, the mix of classes varies widely by market with the proportion of economy passengers varying from 62% to 79% within each market. For the purpose of market evaluations, the following class mix was assumed:

a. First class	5.7%.
b. Business class	17.8%.
c. Economy class	76.5%.

It was then necessary to collate the results of previous passenger surveys conducted for or by The Boeing Company relative to supersonic travel and the passenger's reaction to speed and ticket price. Four surveys were reviewed with the consolidated results illustrated in figure 2-23. These data are for a 50-50 mix of business and personal travellers in economy class. The results are completely consistent and indicate that the percentage of passengers choosing the supersonic flight decreases substantially as the price is increased; however, the percentage also increases as the time saved increases. The survey data were cross-plotted (with extrapolations to 40% time savings) to give the relationship of ticket price to market share as a function of time saved (fig. 2-24). Note that for a 40% time savings, a 10% ticket price increase reduces the market share by over 65%.

In order to put this in perspective, figure 2-25 summarizes the time savings provided by year 2015, Mach 2.4, 247-seat airplane with a 5,000-nmi design range. Only 50% of the scheduled RPM have time savings of 40% or more as compared to a subsonic airplane flying the same routes. While this seems disconcerting, figure 2-26 shows that those markets would require over 500 airplanes by the year 2015, which is certainly an adequate production opportunity.

Another view of the market share impact on units required is provided by figure 2-27. In this analysis, it was assumed that the HSCT would capture 100% of the first-class passengers. The number of

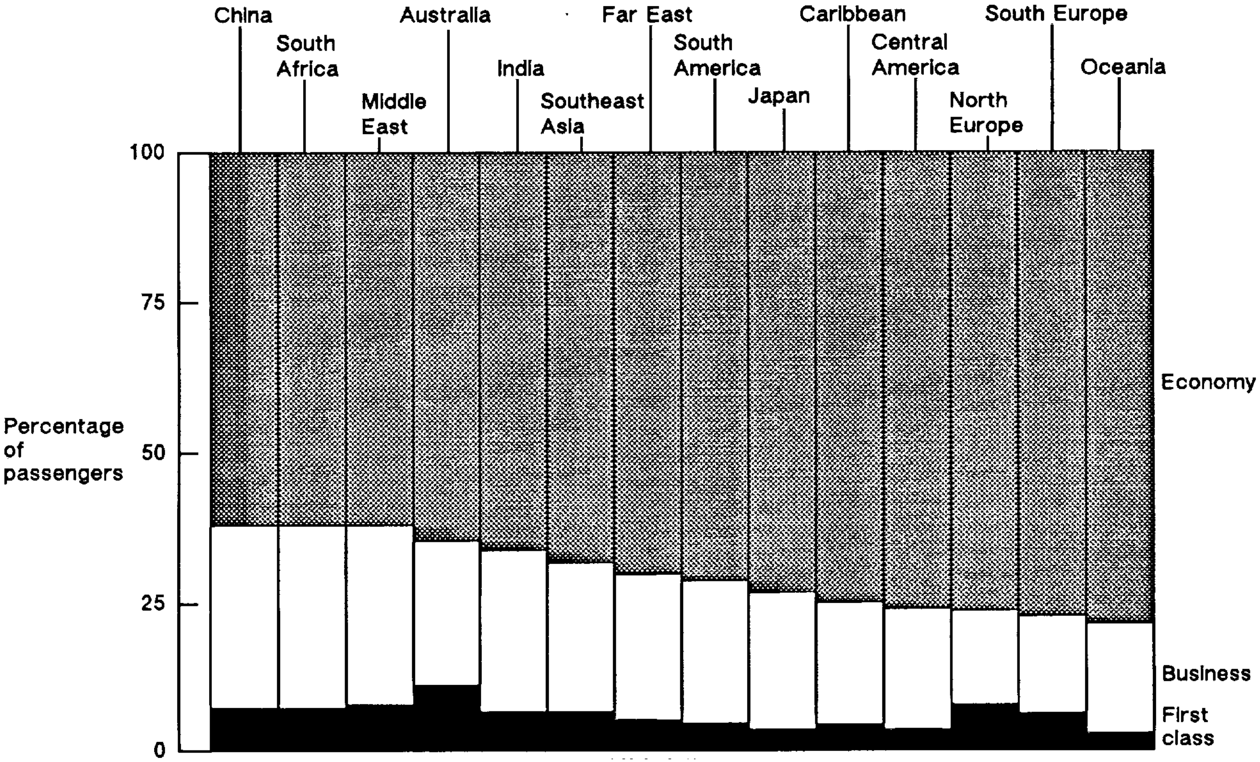

Figure 2-22. Class Mix From the United States

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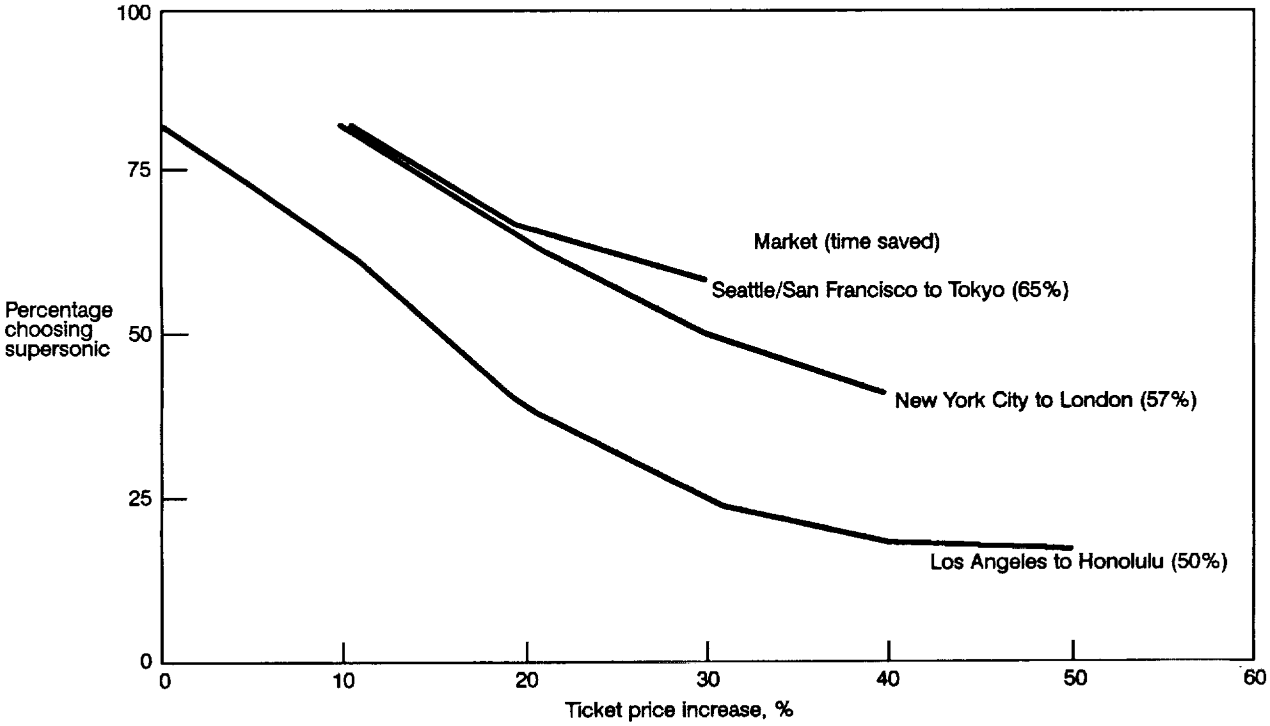

Figure 2-23. Time and Price Trades for High-Speed Air Travel

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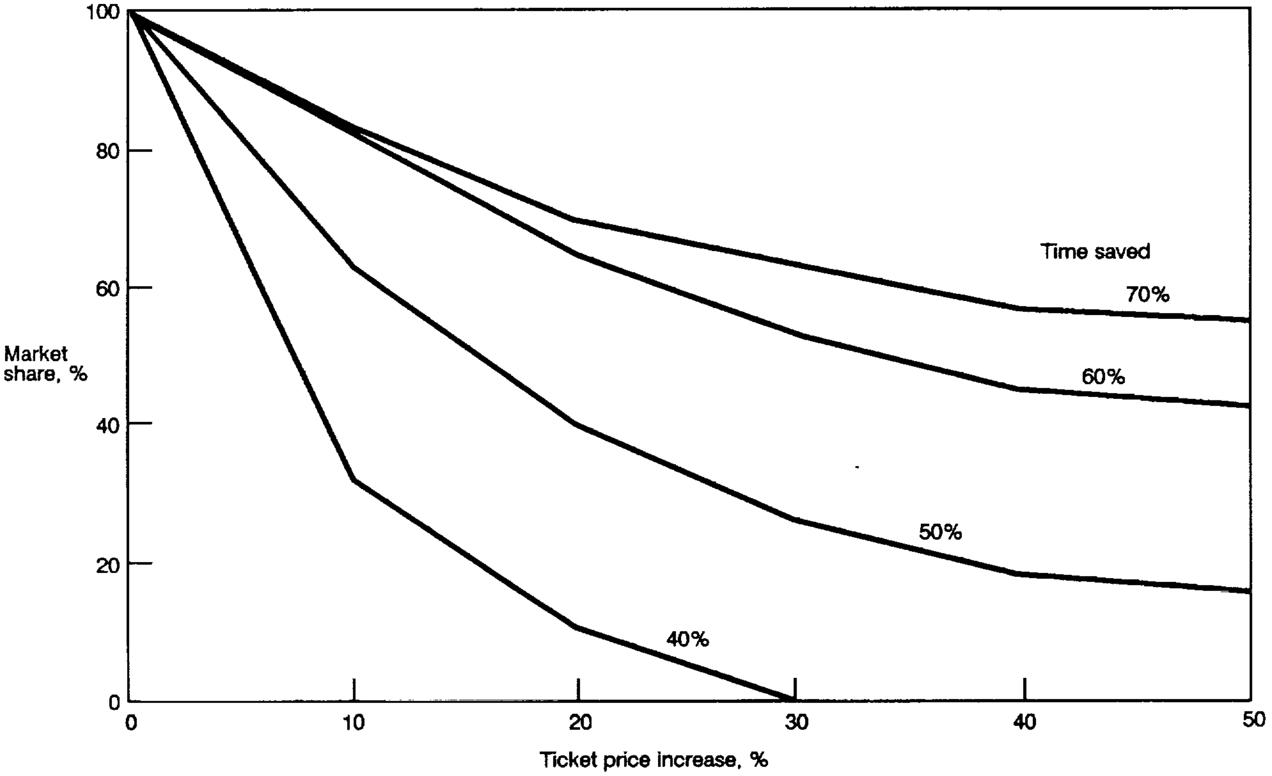

Figure 2-24. Estimated Market Share Versus Ticket Price

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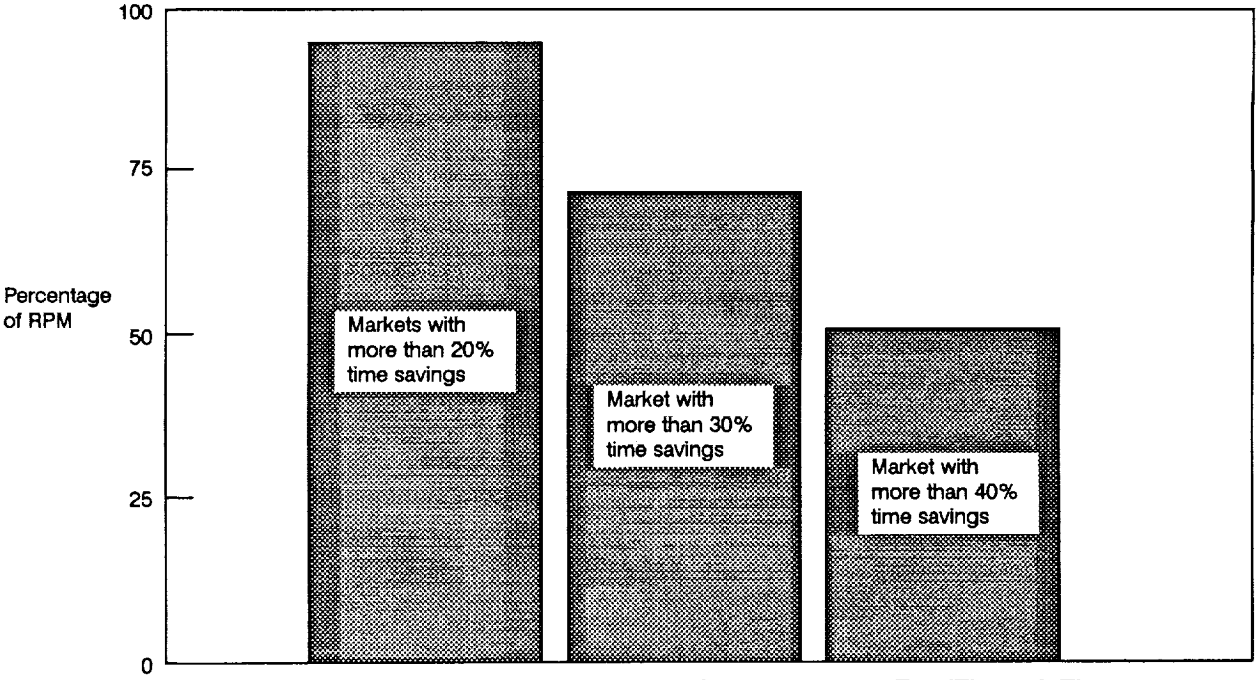

Figure 2-25. Impact of Time Savings on Traffic Carried – 1-Hour Turn/Through Time

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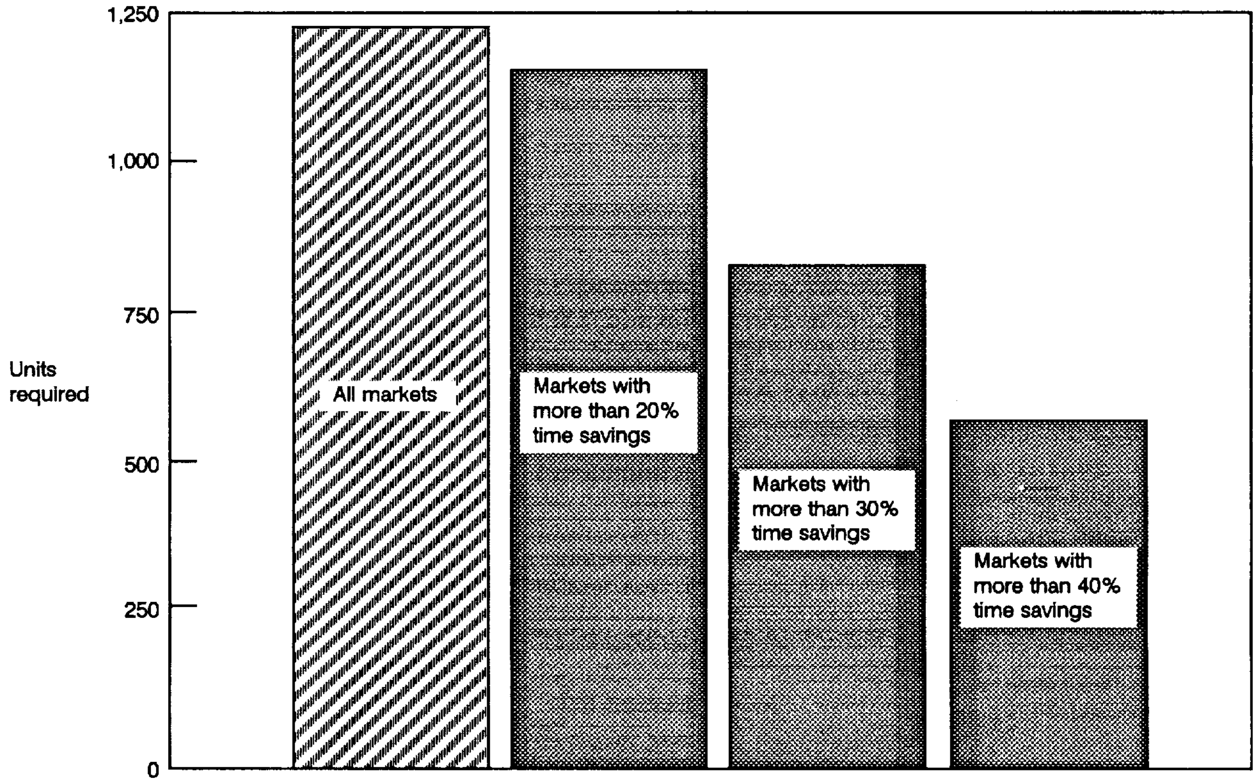

Figure 2-26. Impact of Time Savings on Market Size

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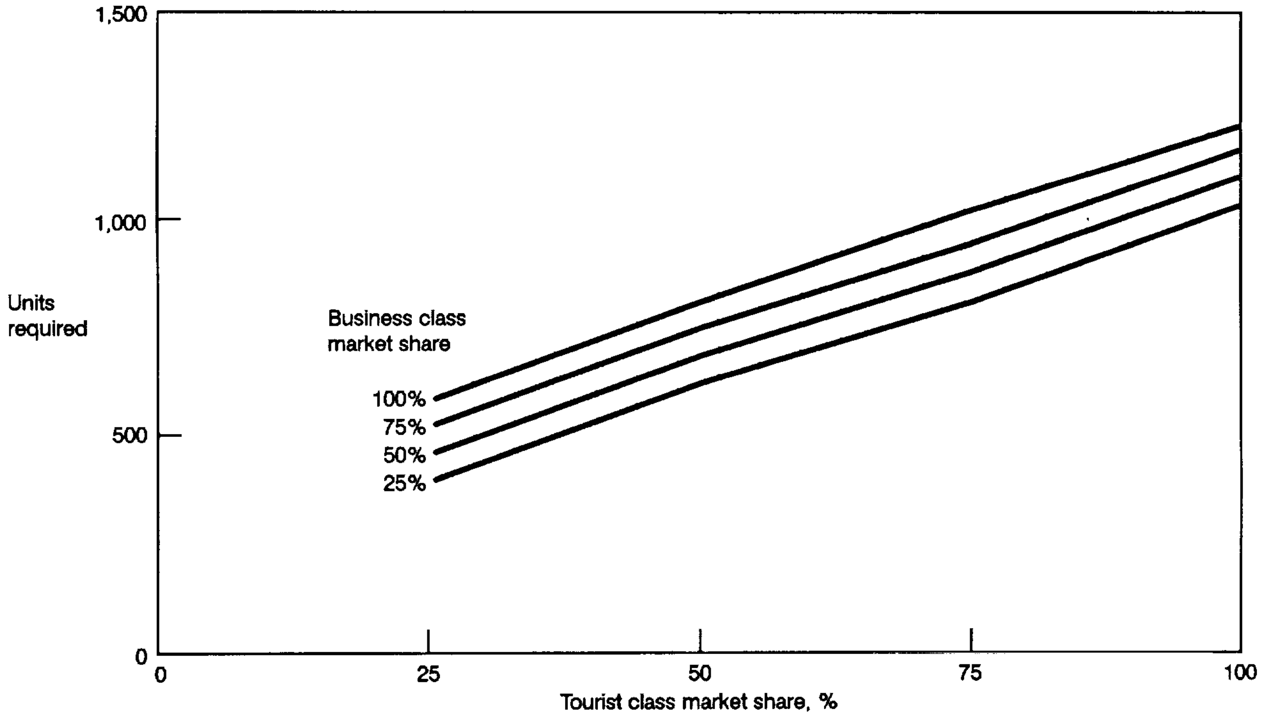

Figure 2-27. Units Required Assuming 100% of First-Class Market– 1-Hour Turn Time

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business- and economy-class passengers carried was varied in each market. The airplane seating mix was changed to correspond with the assumed demand. The number of units required was then determined by scheduling each configuration to carry the demand. As expected, the tourist market share has a major impact on the number of units required (a 25% decrease in tourist-class market share results in a 230-unit decrease in airplanes while a like percentage decrease in business-class market share only reduces the number of units by 50). If 100% of the first-and business-class passengers and only 25% of the economy-class passengers are captured, there is a potential requirement for over 600 Mach 2.4 vehicles. This is, again, an adequate production opportunity.

2.4 CONCLUSIONS

From a marketing standpoint, there is substantial potential for an HSCT. However, in order to capture 100% of the available market, the vehicle must achieve operating cost levels that require no increase in ticket price. Any increase in pricing will, in mature competition, reduce the number of passengers willing to choose the HSCT and could possibly repeat the Concorde experience. The vehicle should exhibit the following characteristics:

a. Design range. Initial introduction should be mainly in the overwater markets with a range of 5,000 nmi to be quickly increased to 6,500 nmi to minimize intermediate stops (which increase airline costs and passenger trip times) and to allow maximum flexibility of the airplane within an airline's system.
b. Seats. Initial target is 250 to 300 seats in a tri-class configuration. Final seat definition is a function of productivity, which depends on Mach number and design range capabilities.
c. Mach number. Between Mach 2.0 and 3.5, but consistent with minimum operating costs and maximum productivity when considering design-range tradeoffs.

3.0 PROPULSION TECHNOLOGY

The NASA contract provided for technical and economic viability assessments to be made on several high-speed civil transport (HSCT) concepts over a wide Mach number range. The assessments required the definition of appropriate engine concepts for each airplane configuration. The engines were provided by three engine manufacturers, Aerojet General, General Electric Aircraft Engines (GE), and Pratt & Whitney (P&W), who were subcontracted for specific support tasks. Two timeframes were considered: the year 2000, providing the earliest viable introduction date combined with a favorable market assessment, and the year 2015, allowing for a maximization of technological advances. Descriptions of the engine concepts, and a summary of the performance results are provided in the following sections.

So that the technical and economic viability of each of the airplane configurations could be thoroughly evaluated, the engine manufacturers were required to supply performance, weight, geometry, and economic data for both the engine and the exhaust system. Technology projections for improved performance and reduced weight beyond the initial certification date were also required to support the airplane growth strategy.

In the performance assessment of the airplane configurations it was necessary to scale both the engine and the airplane to correctly size the airplane for the design range. It was, therefore, necessary that scaling laws governing engine weight, dimensions, and economics also be provided by the engine manufacturer.

An important factor in the overall viability of the airplane is the growth strategy for increased passenger loads on the shorter Atlantic routes and decreased passenger loads for the longer Pacific routes. Here the technical projections for improved engine performance and reduced engine weight beyond the initial airplane certification play an important part. This is where an early, extensive commitment to research by NASA will play a significant role in the viability of a U.S. HSCT.

Performance and economic predictions were initially supplied for six engine concepts. In later phases of the evaluation, three additional variations on these engine concepts and technology projections were provided at the lower Mach numbers. These engines were representative of a broad spectrum of applicable cycles and fuel types as shown in table 3-1. Three engine concepts (representing flight Mach numbers less than 4.0) are "conventional" kerosene-fueled, while the other three (for Mach numbers greater than 4.0) are fueled by cryogenic fuels. The conventional-fueled and the cryogenic-fueled engine concepts are discussed in the following sections.

Table 3-1. Engine Data Packs for Airplane Configuration Studies

Company	Certification Date	Design Mach number						
		2.4	2.8	3.2	3.8	4.5	6.0	10.0
Aerojet General	2015						ATR (LH_2)	
General Electric	2000 2015	VCE (JET A)		VCE (TSJF) VCE (TSJF)		VCHJ (CH_4)		
Pratt & Whitney	2000 2015	VCE (JET A) TP	VCE (TSJF) TP		VCE (TSJF)			VCE/SJ (LH_2)

Abbreviations:

VCE	variable cycle engine	(JET A)	kerosene type	TP	technology projections only
VCHJ	turbofan ramjet	(TSJF)	thermally stable jet fuel		
ATR	air turbo-ramjet	(CH_4)	liquid methane		
SJ	scramjet	(LH_2)	liquid hydrogen		

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3.1 CONVENTIONAL-FUELED ENGINE CONCEPTS

The three conventional-fueled engine concepts are the variable-cycle engine (VCE) turbofan from GE, and the turbine-bypass turbojet (TBE) and the afterburning turbojet from P&W. General features of the engine concepts are discussed, and performance and weight comparisons are made in this section. Additionally, the effects of technology improvement on engine performance and weight from the years 2000 to 2015 is presented. Each of these engine concepts requires noise suppression technology in order to operate from conventional airports. (A discussion of noise suppression technology is presented in section 3.3.)

The GE VCE turbofan uses variable geometry front and rear flow diverters along with variable geometry in the fan, low-pressure turbine, and exhaust nozzle to provide optimum performance (ref. 3.1). The double variable-area bypass feature allows increased engine airflow for reduced noise at takeoff, reduced inlet spillage drag at part power, and good inlet operation at approach. Low-pressure turbine-stator variable geometry increases core power and dry thrust at inlet scheduled airflow during the climb-accelerate portion of the mission and reduces the augmentation required. This significantly reduces thrust-specific fuel consumption (TSFC) and noise (as a result of lower exhaust jet velocities).

The VCE turbofan aft mixer operation provides increased climb thrust at the maximum power setting by permitting the fan to be controlled to a minimum stall margin. The aft mixer also provides for best fan operation at takeoff power and high-bypass duct bleed rates for reduced noise.

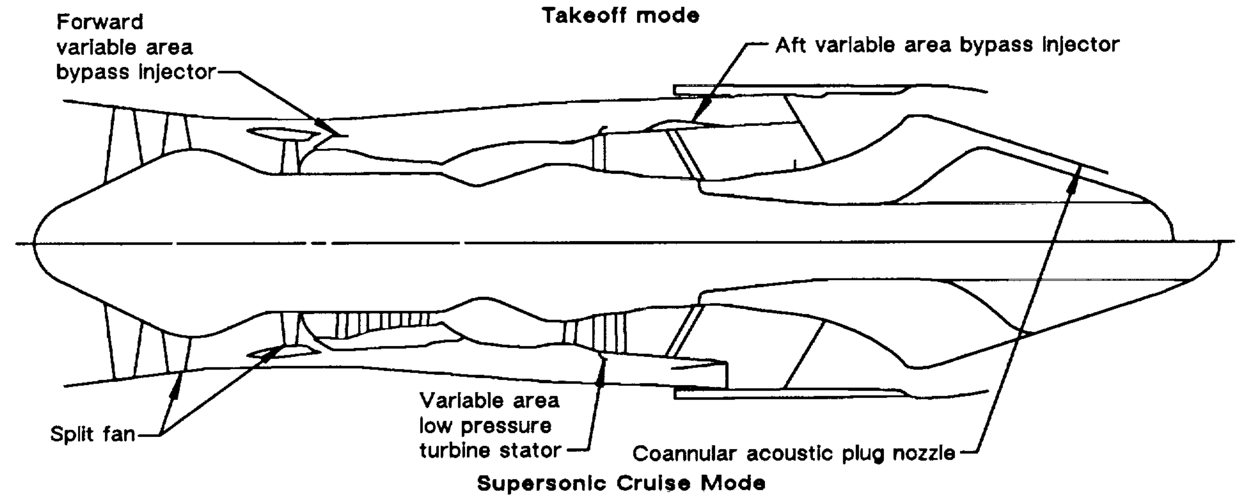
GE provided performance, weight, and economic predictions for the Mach 2.4 and Mach 3.2 engines. Engine performance and weight predictions are based on overall engine dimensions and flow path definition. The GE Mach 3.2 engine used in the aircraft speed study, is shown schematically in figure 3-1(a); the Mach 2.4 engine concept is similar. The Mach 3.2 engine is an augmented 0.3 bypass ratio turbofan with a 14.6 overall pressure ratio (OPR) and a 3.8 fan pressure ratio. The Mach 2.4 engine is a 0.35 bypass ratio turbofan with a 22.5 OPR and a 4.5 fan pressure ratio. This latter engine was used to assess engine emission reduction technology. All of these engines use advanced technology fighter engine military technology in the core components.

The P&W TBE, as the name implies, bypasses a percentage of the compressor flow around the combustor and turbine to provide near optimum performance at high-power settings. Generally, a turbojet operates with the turbine choked over a wide range of operating conditions. For variations in turbine inlet temperature, the compressor will operate at pressure ratios and airflows to satisfy the constant value of turbine-corrected airflow. For a prescribed compressor airflow, the compressor operates at increasing pressure ratios with increasing turbine inlet temperatures. The compressor surge margin places an upper limit on the turbine inlet temperature. Consequently, the selection of a particular compressor-turbine combination places limits on the turbine inlet temperature excursion that a turbojet engine can achieve. Matching a compressor to a large annulus-area turbine reflects a high-temperature design that is capable of high thrust levels. For the same engine airflow, matching the same compressor to a small annulus area turbine reflects a low-temperature design and low thrust. The smaller turbine could not be operated at the same high turbine inlet temperature as the large annulus area turbine without surging the compressor.

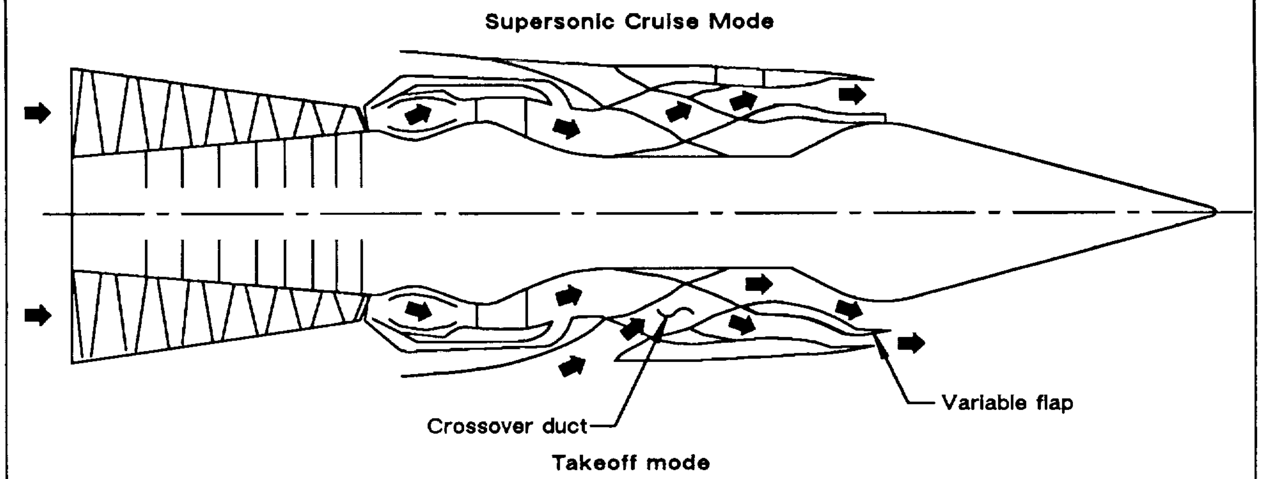
One means of removing the restrictions associated with the choked turbine is by using a variable area turbine (VAT). With the ability to vary the turbine area, the turbine corrected flow can vary, thus permitting wider excursions in the operating turbine inlet temperature. Typically, at Mach 0.9 the turbine area varies by 30% from low throttle to maximum climb thrust, while the compressor operating points do not vary significantly.

In practice, a VAT is difficult to achieve because of the complexities involved in providing variable area capability in hot structures. The TBE varies the turbine airflow rather than the turbine area with the same performance benefits as the VAT (ref. 3.2), but without the complexities.

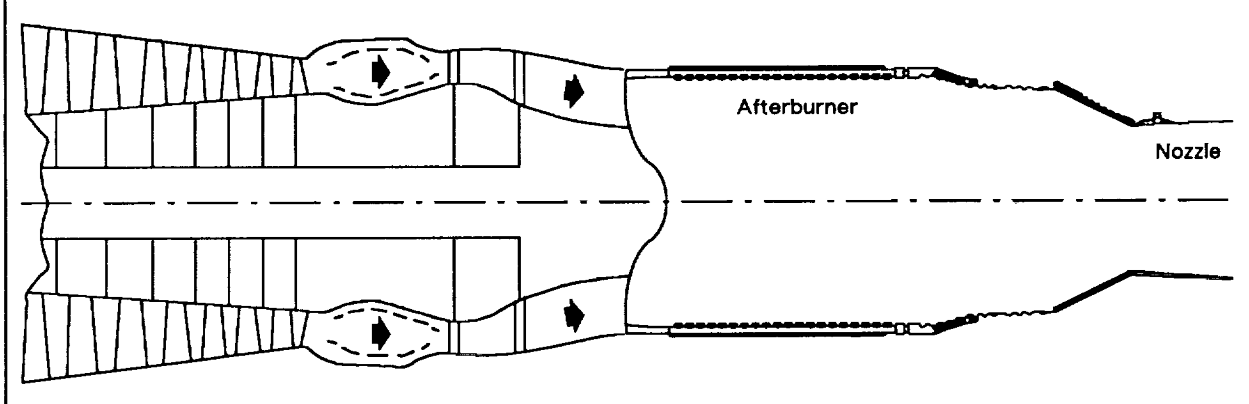
P&W provided performance, weight, and economic predictions for the Mach 2.4 and Mach 2.8 TBE engines. Engine performance and weight predictions are based on overall engine dimensions and



(a) GE Mach 3.2 Variable Cycle Engine



(b) P&W Turbine-Bypass Engine With NACA Nozzle



(c) P&W Afterburning Turbojet

Figure 3-1. Conventional-Fueled Engine Concepts

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flow path definition. A schematic drawing of the P&W TBE engine is shown in figure 3-1(b). The Mach 2.4 engine features a seven-stage, high-pressure compressor that is driven by a two-stage, high-pressure turbine with a turbine-bypass bleed capability; the engine OPR is 15.5. The baseline combustor technology is similar to that employed on the PW4000 commercial engine. The Mach 2.8 engine is similar except that it incorporates a six-stage compressor with an OPR of 10.5. As with the GE study, the P&W Mach 2.4 engine was also used to assess engine emission reduction technology.

As the vehicle Mach number increases, a turbomachinery cycle becomes less efficient. The higher freestream stagnation pressures and temperatures associated with the higher Mach numbers restrict the amount of energy that can be added to the captured air and still meet the temperature limits of the engine material. To assess the Mach number effect, P&W supplied performance and economics predictions for an afterburning turbojet designed to operate at Mach 3.8. A schematic drawing of the P&W Mach 3.8 engine is shown in figure 3-1(c). The Mach 3.8 engine features a five-stage, high-pressure compressor that is driven by a single-stage, high-pressure turbine; the engine OPR is 7.75. This engine was used in the initial aircraft screening study.

Installed performance variations for the conventional-fueled engines are shown in figure 3-2. Figure 3-2(a) presents the installed subsonic (Mach 0.9) cruise performance for each engine, while figure 3-2(b) presents the installed supersonic cruise performance for each engine at their respective cruise Mach numbers. Year 2000 technology is used for the Mach 2.4, 2.8, and 3.2 engines' performance, while the Mach 3.8 engine uses the available technology of year 2015 (the turbine inlet temperature requires the later technology materials). Table 3-2 presents the engine size and weights for each hydrocarbon-fueled engine. The initial engine size and the final mission-sized engine are included.

Performance and weight sensitivities for technology improvement from the years 2000 to 2015 were provided by the engine companies for the Mach 2.4 and 3.2 engines (fig. 3-3). The graphs illustrate the subsonic and supersonic cruise performance relative to the performance of the 1971 U.S. SST turbojet, which is a good representation of the available technology at that time. The improved performance of the year 2000 TBE is shown along with the projected year 2015 improvement. The performance

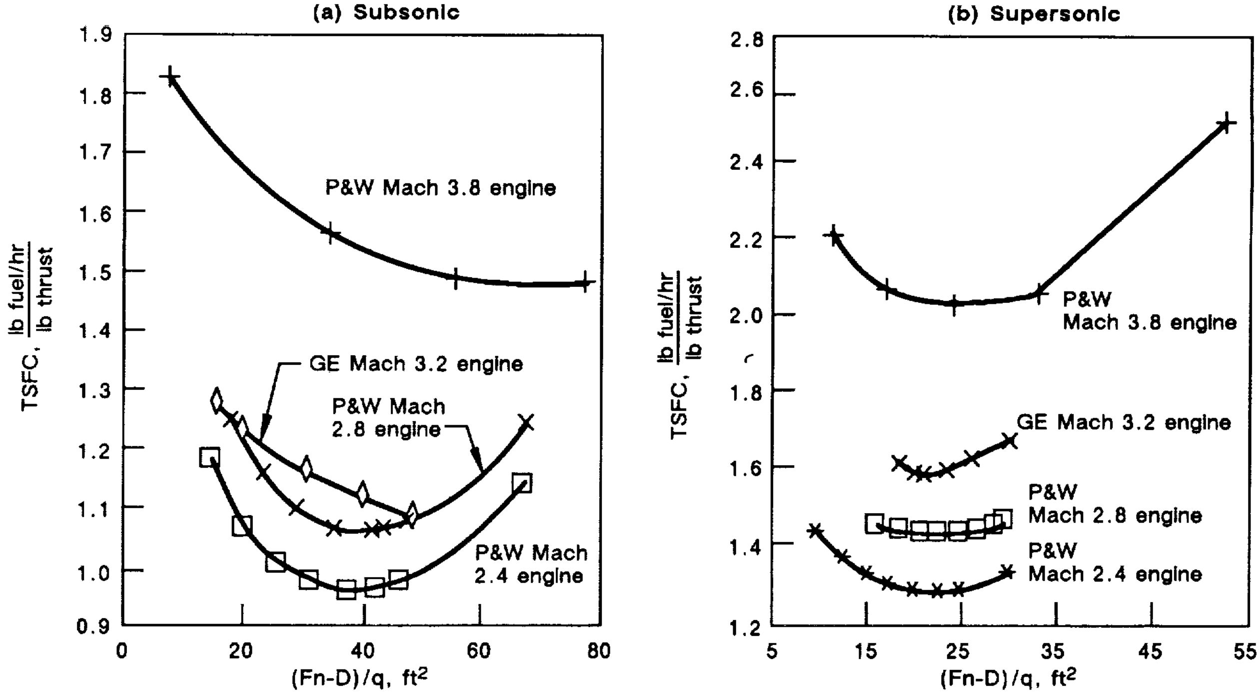

Figure 3-2. Conventional-Fueled Engine Cruise Performance Comparison

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Table 3-2. Conventional-Fueled Engine Weights

Flight Mach number	Engine company	Initial engine size		Mission-sized engine	
		Wa, lb/s	Weight, lb	Wa, lb/s	Weight, lb
2.4	P&W	630	13,770	604	13,150
2.8	P&W	650	15,400	745	17,890
3.2	GE	700	15,927	870	20,320
3.8	P&W	650	10,200	875	13,730

Note: Engine weight is per engine and includes base engine + nozzle + reverser + suppressor.

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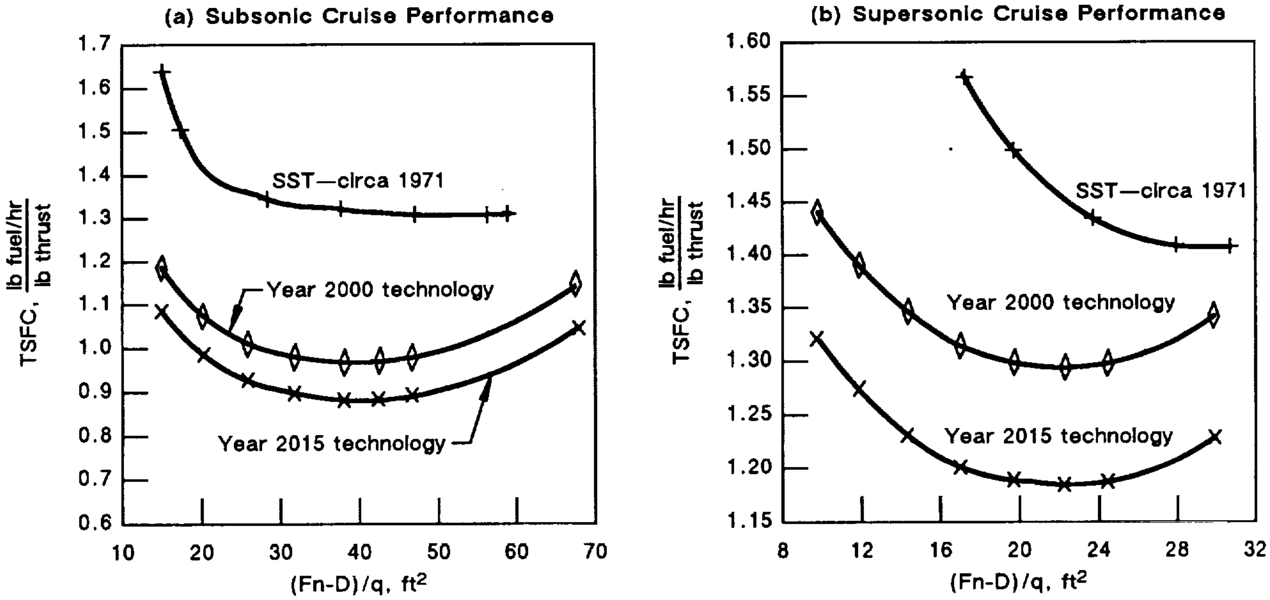

Figure 3-3. Engine Technology Improvements

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improvement from 1971 to 2015 is largely because of the variable-cycle improvement; the primary technological improvement is the materials used. The propulsion pod is projected to weigh 30% less with year 2000 technology than a similar pod with 1971 technology would weigh. Technology in the year 2015 reduces the pod weight by another 11%. Advanced lower weight alloys and composites will allow higher temperature limits that, in turn, will yield improved performance from the reduced cooling flows. Advanced combustor designs will be incorporated to reduce emissions and aerodynamic blade design improvements will improve performance.

The trend is toward increasing levels of TSFC with increasing flight Mach number at constant values of the ratio of thrust minus drag to the dynamic pressure. Engine performance and weight each have a significant impact on vehicle takeoff gross weight (TOGW). Preliminary estimates indicate that 1,000 lb of engine weight becomes 24,000 lb of TOGW for the Mach 2.4 aircraft sized for a 5,000 nmi range. Additionally, 1% in TSFC is equivalent to 360 lb of engine weight, which yields 8,640 lb of TOGW.

The engine weights for the initial engine concepts were estimated using aerodynamic flowpath models. The studies of emission reduction concepts and detailed engine designs in the third phase of the contract had mixed results, and showed the need for indepth studies. The emission study by P&W revealed the need to increase the length of the combustor section for the baseline Mach 2.4 engine, requiring a moderate engine weight increase. The weight study by GE identified design approaches that achieved a significant weight reduction of their baseline engine.

3.2 CRYOGENIC-FUELED ENGINE CONCEPTS

Three cryogenically fueled engine concepts were analyzed for potential hypersonic cruise vehicles. All three were year 2015 technology engines: a Mach 4.5 tandem turbo-ramjet from GE, a Mach 6.0 air turbo-ramjet (ATR) from Aerojet General, and a Mach 10.0 turbo-ramjet-scramjet from P&W.

Engine cycle thermodynamics and the properties of the engine material influence the choice of engine cycle for each flight Mach number; the freestream stagnation temperature increases with Mach number. In the Mach number range of 3.0 to 4.0, the gases entering the engine have such a high temperature that no further energy can be added by turbomachinery without exceeding the temperature limits of the projected engine materials. In that situation, no net thrust is possible. Eliminating the ability to raise the material temperature limits leaves two possible modifications: (1) minimizing or canceling the turbomachinery work output requirements, or (2) making the turbomachinery work output independent of flight Mach number.

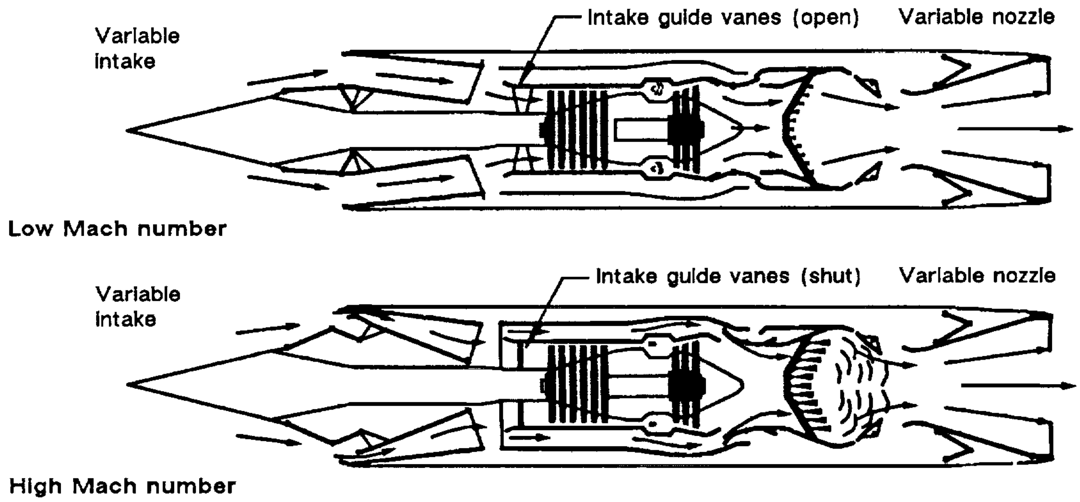
As airplane Mach number increases, the inlet diffuser compression ratio becomes high enough that mechanical compression can be minimized or eliminated. Minimizing the mechanical compression ratio can lead to either a very low compression ratio, a variable mechanical compression process, or a turbomachinery bypass process. The complete elimination of mechanical compression leads to the ramjet, but because a pure ramjet is not effective at subsonic and low supersonic speeds, a second turbomachinery engine is required. This combined engine cycle, known as a turbo-ramjet, is used for the Mach 4.5 airplane. At this Mach number the heat sink capability of kerosene-type fuels may be inadequate; therefore, cryogenic liquid methane was selected for use.

The second modification, having the turbomachinery work output independent of flight Mach number, leads to the ATR engine. The exhaust energy from a source independent of flight speed is expanded through a turbine; the turbine work output is used to drive a compressor. The thrust is produced by the combined expansion of the compressed air and the turbine exhaust products, which is the engine cycle used for the Mach 6.0 airplane. At flight speeds above approximately Mach 7.0, the pressure losses incurred while decelerating the supersonic flow to subsonic speeds for combustion are too high. This is overcome by burning the fuel in a supersonic stream, which removes the normal shock losses; this engine cycle is known as a scramjet. To burn supersonically, it is necessary to use a fuel with a high flame speed. For the Mach 10.0 engine, liquid hydrogen was selected for its improved heat sink capability and higher flame propagation speed.

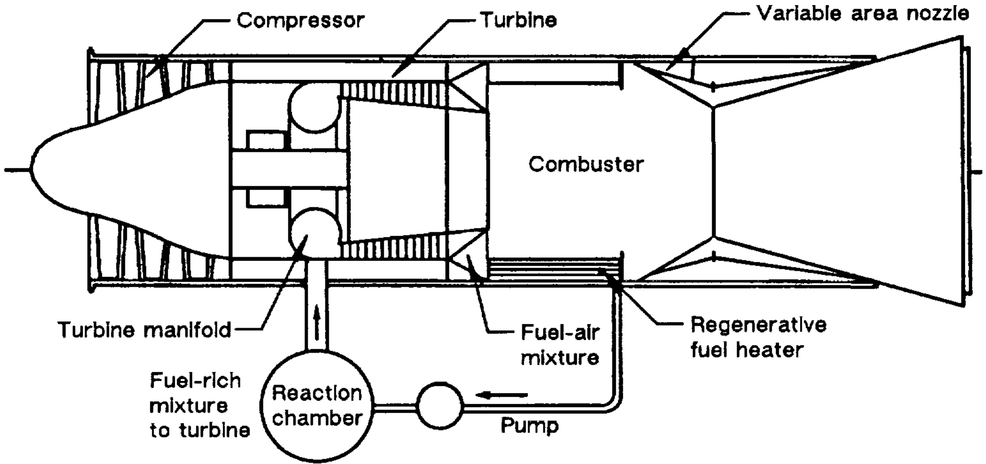
Performance and economic estimations for a liquid methane (CH4) fueled tandem turbo-ramjet were presented by GE. A schematic drawing of the engine concept is presented in figure 3-4(a). At takeoff and subsonic climb, the core intake-guide-vanes are open, and the engine operates as an afterburning turbojet engine. As the engine climbs transonically and at low supersonic speeds, the bypass begins to open allowing a portion of the inlet flow to divert around the turbomachinery and to mix with the core flow before the afterburner. At Mach 4.5 cruise, the intake guide vanes are closed, the bypass is fully open, and the engine operates as a pure ramjet.

Aerojet General provided a liquid hydrogen (LH_2) fueled, dual-regenerator ATR for a Mach 6.0 aircraft. A schematic drawing of the engine concept is shown in figure 3-4(b). The ATR is a continuous flow airbreathing engine that involves air compression (ram plus mechanical), constant pressure heat addition, and expansion through a thrust nozzle. The unique feature of the engine is that the turbine of the turbocompressor is driven by high-temperature, fuel-rich gas from a separate gas generator rather than by the heated air from a fuel-air combustor as in a turbojet. After passing through the turbine, this fuel-rich gas is mixed with the airflow from the turbocompressor and burned in a burner before expansion through the nozzle. This gas is formed by heating and vaporizing the LH_2 fuel in a dual-regenerator process. The first heat exchanger is located at the turbine exit; the second uses waste heat from the combustion chamber.

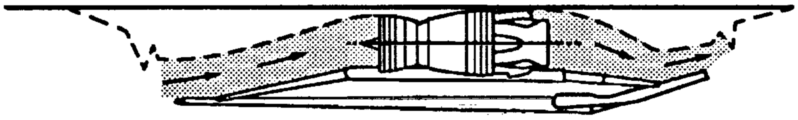
P&W provided an LH_2-fueled turboramjet-scramjet for evaluation of a Mach 10.0 aircraft. A schematic drawing of the engine concept is shown in figure 3-4(c). The concept employs a turbojet installed above the ramjet-scramjet. Initially, the ramjet-scramjet is closed off and the turbojet provides the



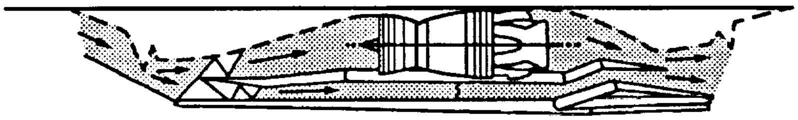
(a) GE Mach 4.5 Tandem Turbo Ramjet



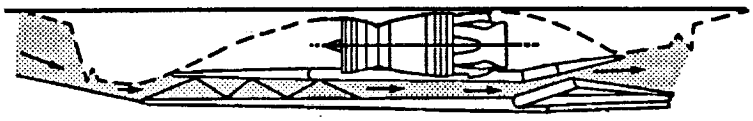
(b) Aerojet Mach 6.0 General Air Turbo-Ramjet



Turbojet mode
Take off, climb, and accelerate to transonic speeds



Turbojet-ramjet mode
Transonic to supersonic speeds: climb and accelerate



Ramjet/scramjet mode
Supersonic climb, acceleration, and cruise

(c) P&W Mach 10.0 Turbo-Ramjet-Scramjet

Figure 3-4. Cryogenically Fueled Engine Concepts

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thrust for takeoff, climb, and acceleration to transonic speeds. The inlet geometry is varied to provide for combined turbojet/ramjet operation for initial supersonic climb. Between Mach 3.5 and 4.0 the turbojet is completely closed off, and the engine operates as a ramjet for climbing to Mach 6.0. For the remainder of the climb to the Mach 10.0 cruise altitude the engine operates as a scramjet.

Installed supersonic cruise performance variations are shown in figure 3-5 for the year 2015, cryogenically fueled engines studied. Table 3-3 presents the size and weight of each engine, including the initial engine size and the final mission-sized engine.

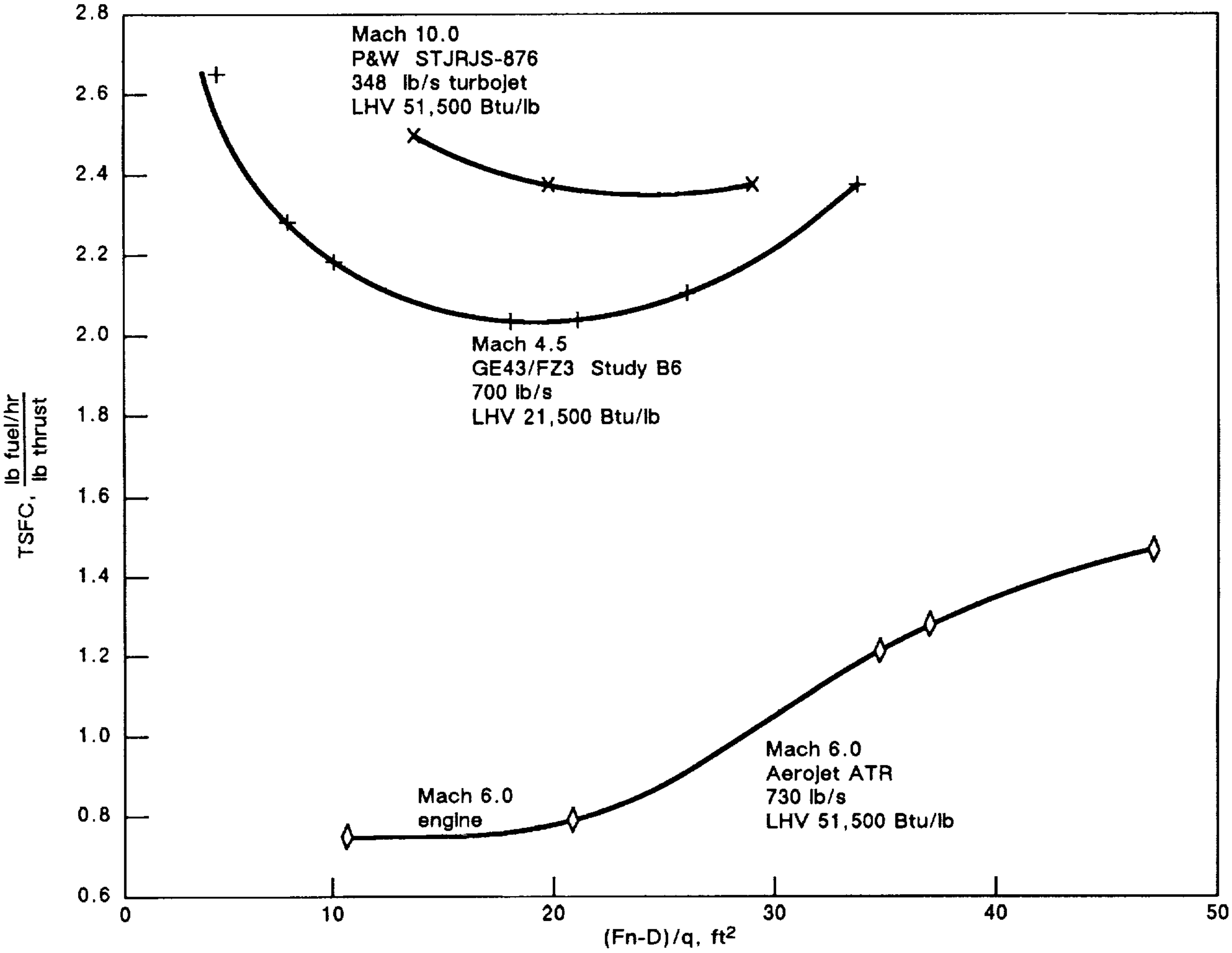

Figure 3-5. Supersonic Cruise Installed Performance Comparison—Year 2015 Cryogenically Fueled Engines

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Table 3-3. Cryogenically Fueled Engine Weights

Flight Mach number	Engine company	Initial engine size		Mission-sized engine	
		Wa, lb/s	Weight, lb	Wa, lb/s	Weight, lb
4.5	GE	700	11,890	1,150	20,730
6.0	Aerojet General	730	4,400	1,500	9,720
10.0	P&W	348	10,700	1,800	55,340

Note: Engine weight is per engine and includes base engine + nozzle + reverser + suppressor.

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The trends are slightly different for the cryogenically fueled engine concepts. The Mach 6.0 ATR TSFC and weight are both lower than the Mach 4.5 turboramjet or the Mach 10.0 scramjet. Within the scope of this study it was not possible to determine whether the three engine companies involved in these estimates examined the same level of detail for each projection. The engine performance and weights were used in the vehicle performance studies as directed by the engine companies. It was decided that if the vehicle made economic sense, then an attempt would be made to update the results. Results indicated that cryogenically fueled aircraft are unacceptable, so no further updating of the Mach 6.0 or 10.0 aircraft was done. Additional studies were made of the Mach 4.5 aircraft to obtain a more innovative configuration with reduced TOGW; the propulsion data for these studies were unchanged, and the TOGW, while showing a small improvement, remained unacceptable.

3.3 ADVANCED JET NOISE REDUCTION CONCEPTS

For the initial screening there was no attempt to provide acoustic suppression devices for airplane configurations at and above Mach 6.0. It was anticipated that special airports or "superhubs" would be required for such designs. For the Mach 3.8 and Mach 4.5 configurations acoustic suppression devices were not defined, but a weight increment was allocated. Acoustic suppression devices were defined for the Mach 2.4 to Mach 3.2 engines, and the engine manufacturers also supplied turbomachinery noise data for assessing these noise suppression concepts. The objective was to obtain airport noise levels that were comparable to the FAR36 Stage 3 limits.

Jet noise can be diminished either by reducing the jet velocity, or through nozzle-noise-suppressor technology. Thrust is proportional to the product of jet velocity and engine airflow. Hence, for the same thrust, jet velocity can be reduced by increasing the engine airflow. This requires a larger engine with increased weight. (Weight penalties are discussed in section 3.1.)

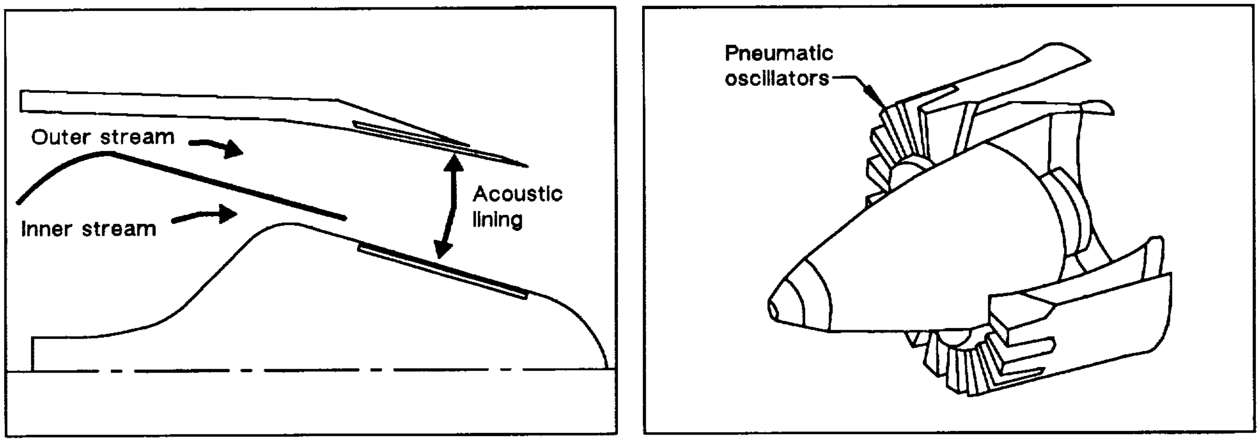
Effective noise suppression of jet and shock-cell noise is paramount to an acceptable HSCT. Significant suppression is required (a minimum of 10 EPNdB relative to a round-convergent nozzle) for any HSCT configuration. This section discusses various jet noise suppression techniques, the suppressor concept used in this study, and the turbomachinery noise parameters received from the engine companies.

Detailed jet noise suppression techniques were considered in this study for the Mach 2.4, Mach 2.8, and Mach 3.2 configurations. A nozzle weight penalty for noise suppression was assessed for the Mach 3.8 and Mach 4.5 configurations, but no detailed noise suppression technology was studied. It was assumed that the Mach 6.0 and Mach 10.0 aircraft would operate out of special superhub airfields where noise would be less critical. Consequently, no noise suppression was considered for those aircraft.

Jet noise suppression techniques were investigated in the Supersonic Cruise Research (SCR) study. Several of the various concepts studied are presented in figure 3-6. The benefit of coannular nozzles relative to conical nozzles was identified as well as the effects on noise of such parameters as nozzle area ratio, radius ratio, velocity ratio, nozzle pressure ratio, temperature ratio, and the projection of the inner nozzle from the outer nozzle. Other schemes, such as asymmetric nozzles and thermal-acoustic shields, were studied, and the contribution of shock-cell noise was estimated.

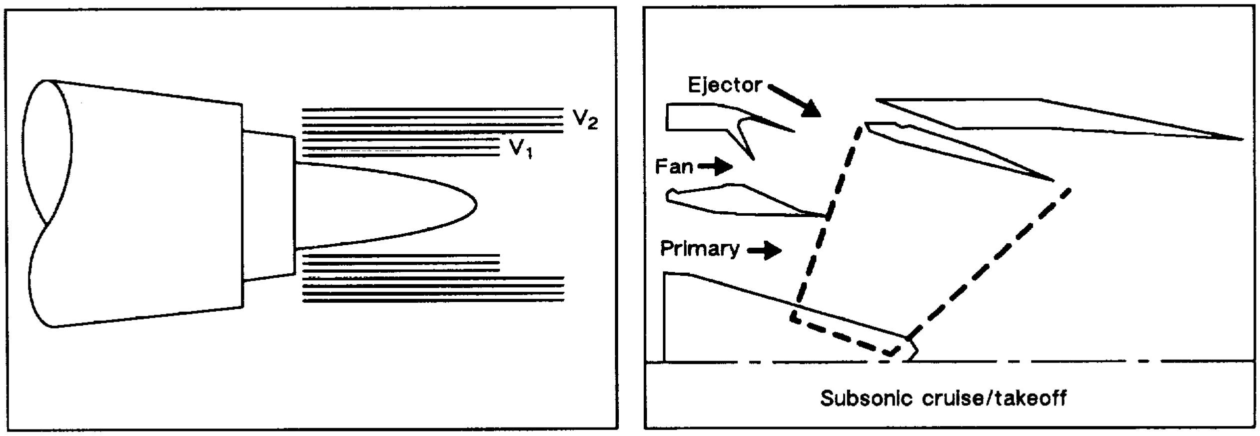
A study integrating a thermal-acoustic shield into a GE engine was undertaken in the SCR studies. Estimates of the range penalties were made. Mechanical suppressor nozzles were also investigated; figure 3-7 illustrates the thrust penalties associated with the mechanical suppressors.

The naturally aspirated, coannular (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. A noise test of a generically similar nozzle



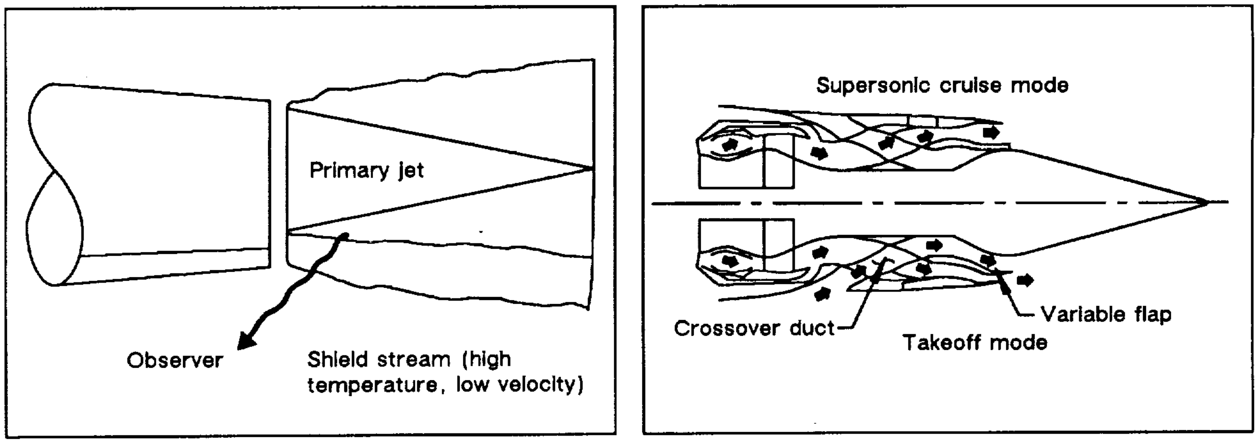
Acoustic Lining

Suppressor



Inverted Velocity Profile

Ejector



Thermal Acoustic Shield

Turbine-Bypass Engine With NACA Nozzle

Figure 3-6. Jet Noise Reduction Concepts

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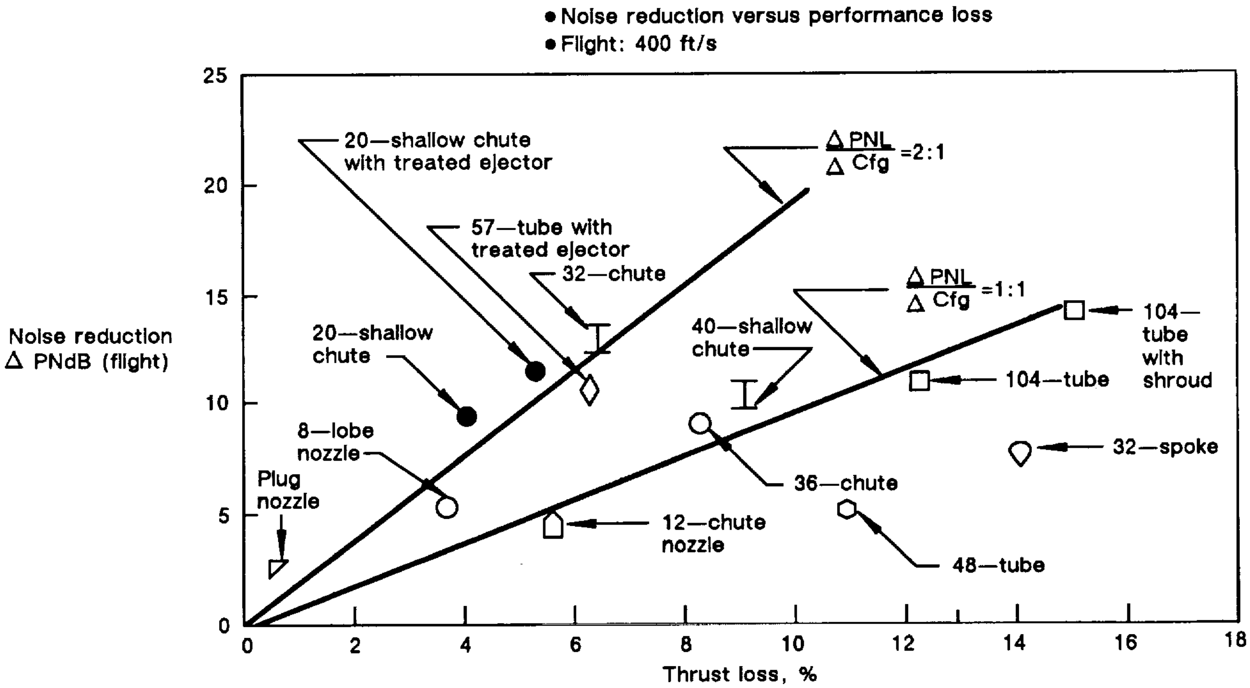

Figure 3-7. Jet Noise Suppression Thrust Penalties

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showed significant noise reduction (7.3 dB relative to a reference plug nozzle). Consequently, it is believed that the NACA nozzle offers good potential for jet noise reduction with small thrust penalties.

A NACA nozzle design for the P&W TBE engine is shown in the noise-abatement mode in figure 3-8. The turbine-bypass air is used to drive ejectors in the crossover duct to enhance the secondary flow rate. This is included because noise attenuation can be enhanced by higher secondary flow rates. In cruise mode, some secondary flow may be used to fill the jet area to reduce nozzle boattail drag during transonic climb. The plug doors are used as blocker doors for thrust reverse mode; cowl sleeve translation exposes the reverser cascades. An estimate of the NACA nozzle noise reduction and secondary flow performance is presented in figure 3-9.

P&W provided their Mach 2.4 engine performance estimates based on two performance levels: an unsuppressed nozzle, and a mechanical chute-tube suppressor. Because data were unavailable on

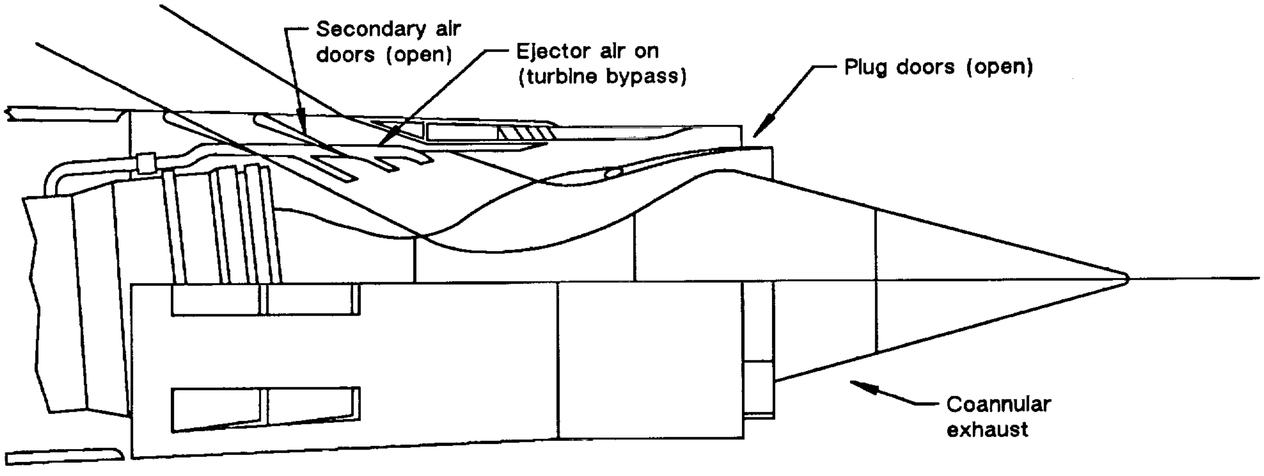

Figure 3-8. Naturally Aspirated, Coannular (NACA) Nozzle Configured in the Noise Abatement Mode

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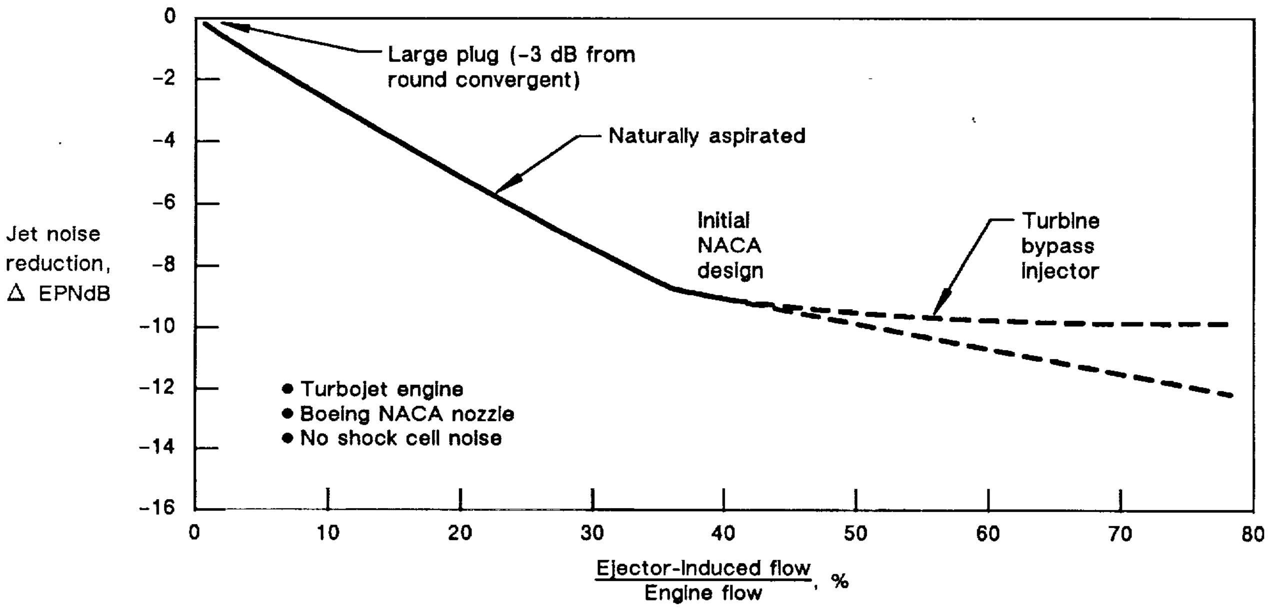

Figure 3-9. NACA Nozzle Suppression Estimates

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NACA nozzle performance at conditions other than takeoff, it was assumed that the NACA nozzle could be installed on the P&W TBE engines (Mach 2.4 and Mach 2.8) for the same performance penalties as the quoted P&W unsuppressed nozzle penalties. The unsuppressed data were used because performance testing at takeoff showed minimal performance losses for the NACA nozzle. The NACA nozzle weight is 90% heavier than the P&W unsuppressed nozzle (4,320 lb for the NACA nozzle versus 2,275 lb for the P&W nozzle for the same engine airflow size). Both nozzle weights include an estimate for the thrust-reverser weight.

GE provided a suppressor nozzle similar to the NACA nozzle with their Mach 2.4 and Mach 3.2 engines (fig. 3-1(a)). It is an inverted velocity profile nozzle that ducts the fan air across the primary stream to provide the enhanced mixing. The GE nozzle also employs mechanical chutes to further enhance the mixing of the streams, followed by a treated ejector. The GE nozzle performance and noise reduction levels were used directly in the engine thrust and noise calculations.

GE and P&W provided pertinent turbomachinery definitions to estimate noise for the Mach 2.4, Mach 2.8, and Mach 3.2 engine concepts. Compressor and/or fan rotor-stator blade counts, rotation speeds, and axial spacings were obtained as were the turbine rotor-stator spacings and blade counts. Combustor-generated noise, or core noise, was estimated for several programs and verified by measured levels on a PW4000 engine.

There are two major influences that drive an HSCT engine configuration: the compromise between subsonic and supersonic performance as discussed in section 3.1, and jet noise suppression. Effective jet noise suppression is an integral part of the propulsion system for an HSCT. The NACA nozzle concept would require considerable development, however, to confirm its performance and qualify it for use on a commercial airplane. This is an area where much further research and development is needed, in which NASA could play a leading role.

3.4 EMISSION REDUCTION CONCEPTS

The emissions goal for the HSCT engine is to have no significant impact on the ozone layer. Assessing the level of engine emissions is a key study area. The effect of these emissions on the ozone layer will be determined by other NASA contractors. The peak concentration of ozone in the upper atmosphere is in the cruise altitude range of the Mach 2.4 to Mach 4.0 airplanes. The most significant offending emissions are believed to be NOx, but, because all of the emission radicals are competing in the reaction chain, all emissions must be evaluated. While the level of engine emissions needed to meet the goal is currently unknown, it is believed that the current conventional combustor designs, operating at year 2000 technology temperatures, may need improvement. The engine manufacturers conducted studies of derated engine cycles and innovative combustor concepts to reduce emissions from the Mach 2.4 engine. Both engine manufacturers judged that the innovative combuster concepts would need an aggressive research and development program and that there would be high risks on the road to achieving the emission goal.

Table 3-4 presents the results of the derated engine cycle for the P&W Mach 2.4 TBE. This shows that a moderate reduction in cruise NOx emissions can be obtained, but only with significant performance penalties. For example, a 41% reduction in cruise NOx emissions was predicted at a reduced combustor inlet temperature (TT3) of 170°F; however, TSFC penalties of 4% at supersonic cruise and 6.9% at subsonic cruise are incurred. Similarly, for a reduction in both combustor inlet and outlet temperatures (TT3 and TT4) of 170°F and 300°F, respectively, a 45% reduction in cruise NOx is predicted, but with a 11.8% takeoff thrust penalty. For both of these cases, the reduction in the NOx emissions was accompanied by a corresponding increase in the carbon monoxide emissions, particularly at the subsonic cruise conditions. The performance penalties of these engines would result in a significantly heavier gross weight airplane using more fuel at cruise, which would partially offset the effect of the reduction in the NOx emissions index (pounds emission per 1,000 lb fuel).

To reduce the NOx emissions further, both P&W and GE have identified combustor concepts that they believe have the potential to achieve a cruise NOx emissions index level of 5 to 10 rather than the 32 predicted for conventional combustor design. Development and validation of the innovative combuster concepts will require a significant commitment to an aggressive research effort. Table 3-5 presents the incremental changes in performance and the NOx emission index reduction levels of three P&W innovative combustor concepts when compared with the baseline conventional concept. These concepts, which have varying degrees of complexity and development risk, have NOx emission index reductions of 30% to 84% with only small, and generally favorable effects on engine performance.

Figures 3-10 through 3-13 present sketches of these combustor configurations. Figure 3-10 presents the P&W current technology baseline combustor. Figure 3-11 presents the staged-lean (SL) combustor that has the potential for a 30% reduction in cruise NOx emission index from 32.1 to 22.6. Figure 3-12 presents the rich-burn, quick-quench (RBQQ) combustor that has the potential for a 75% reduction in cruise NOx index from 32.1 to 8.0. Figure 3-13 presents the lean premixed, and prevaporized (LPP)

Table 3-4. Pratt & Whitney Mach 2.4 TBE Emission Indexes and Performance for Derated Engine Cycles

Conditions	Baseline 630 lb/s engine	Performance deltas		
		Reduced TT4, %	Reduced TT3, %	Reduced TT3 and TT4, %
Fn, SLS takeoff	52730	-12.6	-0.8	-11.8
Fn, Mach 0.9, 36089' TSFC	18850 1.12	-13.4 -4.5	-0.2 +6.9	-12.5 +1.6
Fn, Mach 2.4, 65,000' TSFC	14120 1.307	-21 -2.2	+10 +4	-9.6 +0.4
Subsonic emissions Mach 0.9, 36089' NO_x CO + THC	7.0 13.5	+6 -20	-37 +122	-36 +102
Supersonic emissions Mach 2.4, 65,000' NO_x CO + THC	32.1 1.3	-8 0	-41 +46	-45 +43

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Table 3-5. Pratt & Whitney Mach 2.4 TBE Emission Indexes and Performance for Innovative Combustors

Condition	Baseline 630 lb/s engine	Performance deltas		
		SL	RBQQ	LPP
Fn, SLS takeoff	52730	0%	0%	0%
Fn, Mach 0.9, 36089' TSFC	18850 1.12	0% -0.11%	+0.4% -0.62%	+0.4% -0.06%
Fn, Mach 2.4, 65,000' TSFC	14120 1.307	0% +0.05%	+0.4% -0.39%	+0.4% -0.34%
Emissions, subsonic Mach 0.9, 36089' NO_x index CO index THC index	 7.0 (base) 13.4 (base) 0.1 (base)	 9.2 (+31%) 5.2 (-61%) 0.9 (+800%)	 2.9 (-59%) 2.0 (-85%) 0.5 (+400%)	 1.5 (-79%) 20.0 (+49%) 2.0 (+1900%)
Emissions, supersonic Mach 2.4, 65,000' NO_x index CO index THC index	 32.1 (base) 1.2 (base) 0.1 (base)	 22.6 (-30%) 3.6 (+200%) 0.1 (0%)	 8.0 (-75%) 1.5 (+25%) 0.1 (0%)	 5.0 (-84%) 3.0 (+150%) 0.3 (+200%)

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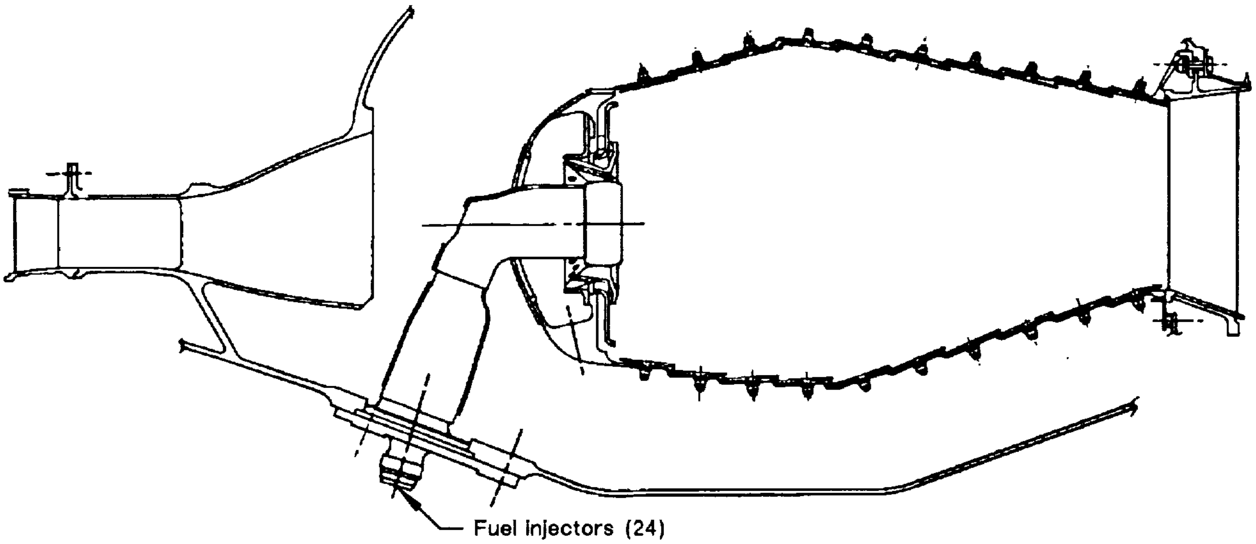

Figure 3-10. Pratt & Whitney Current Technology Baseline Combustor

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combustor that has the potential for an 84% reduction in cruise NOx emission index from 32.1 to 5.0. Table 3-6 presents the engine weight and dimension penalties, relative to the baseline current technology combustor, for the three concepts. The additional engine length results in an increased nacelle weight, and both result in an increase in the associated aircraft structural weight. As figures 3-12 and 3-13 demonstrate, the RBQQ and LPP combustors both require complex variable geometry to control the combustor airflow.

The GE innovative combustor was an LPP concept, and had the potential for a 61% reduction in cruise NOx emission index from a baseline of 31 to 9. GE reported that there would be negligible weight and performance effects, but that it would be a high-risk development program with potential barriers to success being premixing duct flashback and auto-ignition; these potential problems are applicable to the P&W LPP concept as well.

The GE current technology baseline combustor is not pictured here, but is similar to the P&W version shown in figure 3-10. Figure 3-14 presents GE's version of an LPP combustor that has the potential for achieving the NOx emission index of 9. This concept does not have the complexity of variable

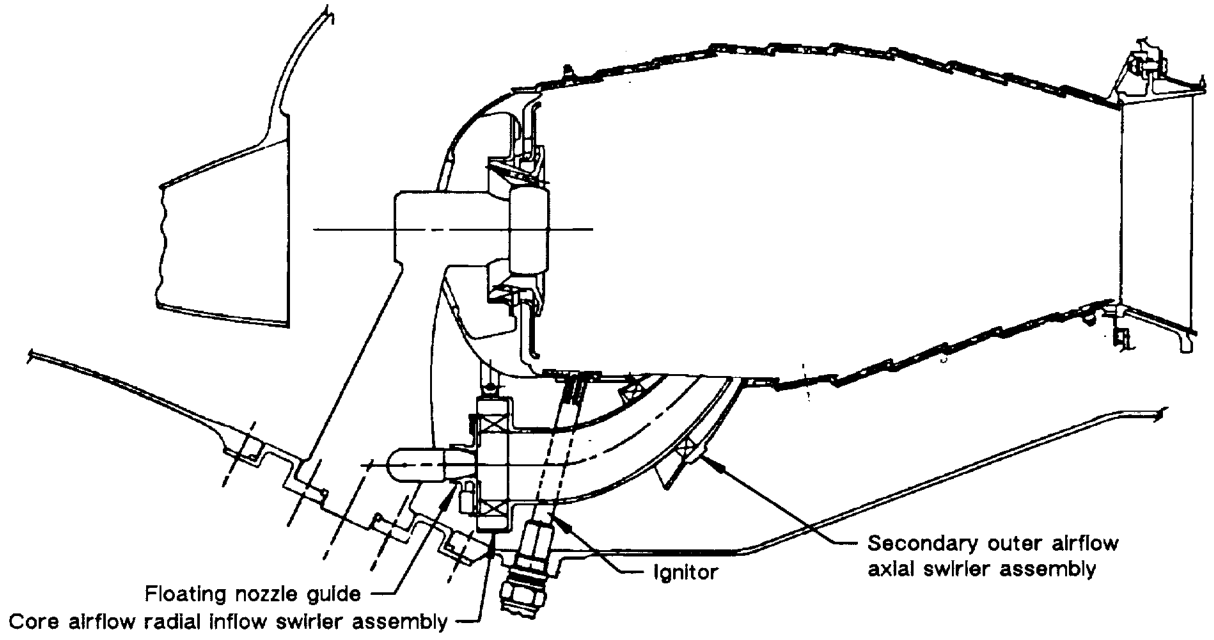

Figure 3-11. Pratt & Whitney Staged-Lean Combustor

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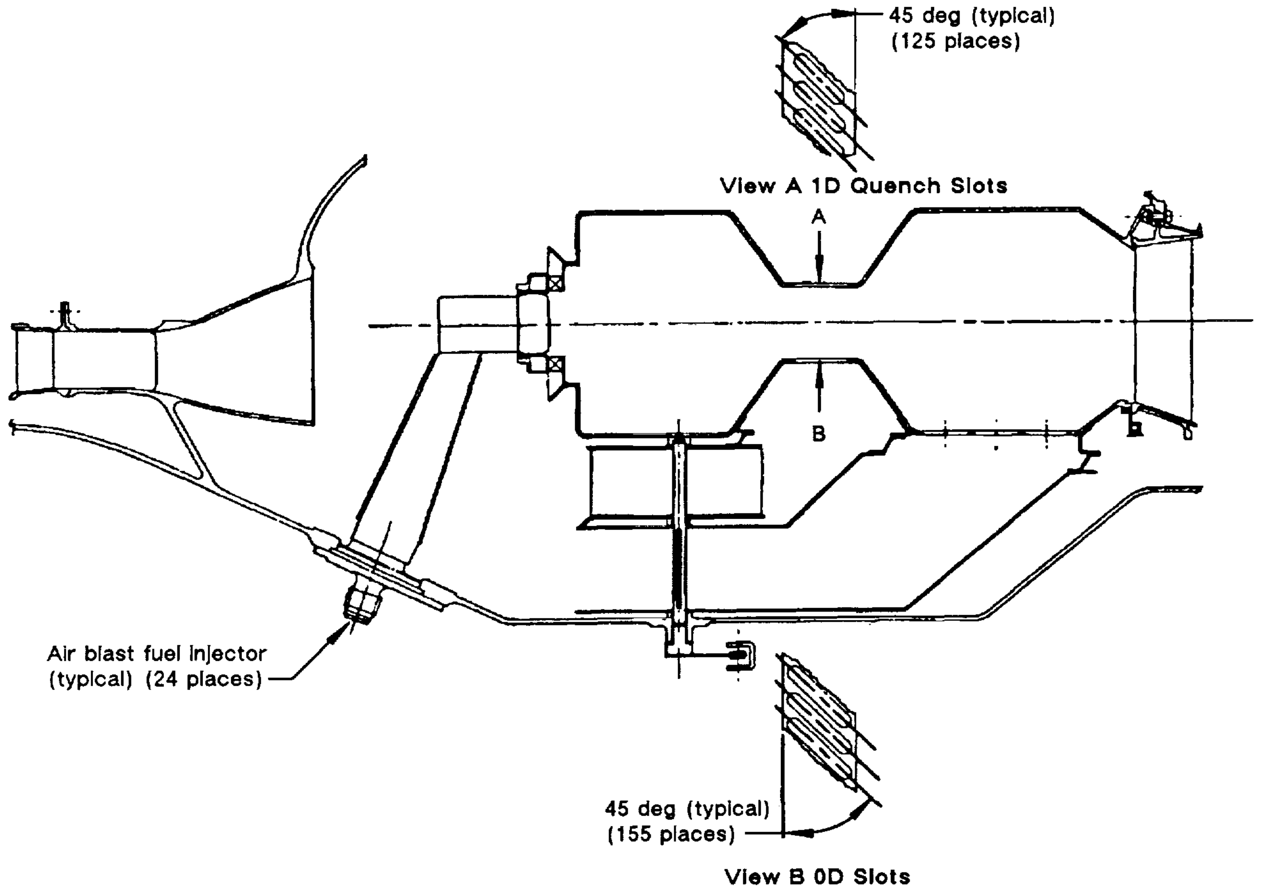

Figure 3-12. Pratt & Whitney Rich-Burn, Quick-Quench Combustor

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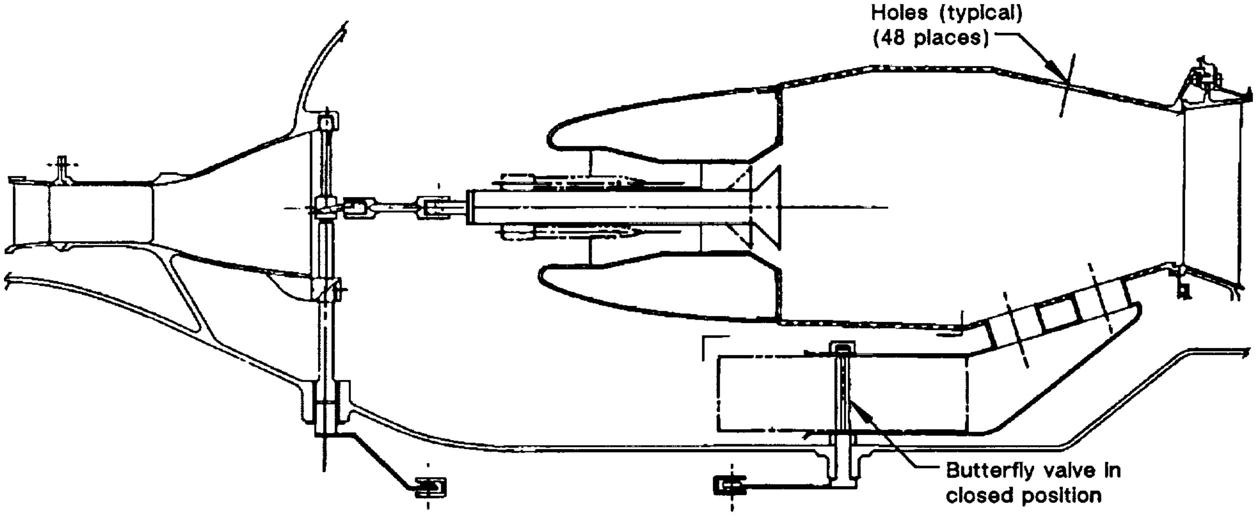

Figure 3-13. Pratt & Whitney Lean, Premixed, and Prevaporized Combustor

3-U90027R1-45

Table 3-6. Pratt & Whitney Low-Emission Combustor Concepts: Engine Weight and Dimension Penalties Relative to Current Combustor Technology (for 630-lb/s Engine)

Combustor concepts	Increased combuster diameter, in	Increased engine length, in	Increased bare engine weight, lb
Staged-lean	+2.6	0	+760
Rich-burn, quick-quench	+2.6	+6	+570
Lean premixed, prevaporized	+2.6	+8	+1,260

3-U90027-47

geometry for controlling combustor air. The impact of these various combustor concepts on the airplane maximum takeoff weight (MTOW) are reported in section 5.1, "Emission Reduction Impact."

The results of the upper atmosphere ozone studies conducted by NASA should indicate the necessary NOx emission index level to ensure that there is no significant impact on the ozone layer. The significance of any impact will be determined by the environmental community and the responsible regulating agency.

3.5 FUELS TECHNOLOGY

The fuel study objectives were to identify and evaluate production, cost, fuel properties, and other nonaircraft system-related factors that would affect the use of both conventional and unconventional fuels in high-speed commercial transports. The fuels examined included modified conventional, endothermic, cryogenic, and others such as slushes and gels. The studies emphasized—

a. The availability and costs associated with modified conventional fuels, referred to as thermally stable jet fuels (TSJF).
   1. TSJF + 0 means that a fuel passed the American Society for Testing and Materials (ASTM) Jet A Jet Fuel Thermal Oxidation Tester (JFTOT) minimum of 245°C (473°F).
   2. TSJF + 50 (or + x) means that the fuel passed the JFTOT ≥ 50°F (or + ≥ °x) higher than 245°C (≥523°F).
   3. The 260°C International Air Transport Association (IATA) Jet A-1 minimum JFTOT = TSJF + 27°F.

b. Liquid methane costs (liquid methane is assumed to be the same as purified liquefied natural gas (LNG)).

c. On-airport costs for both conventional fuels and liquid methane.

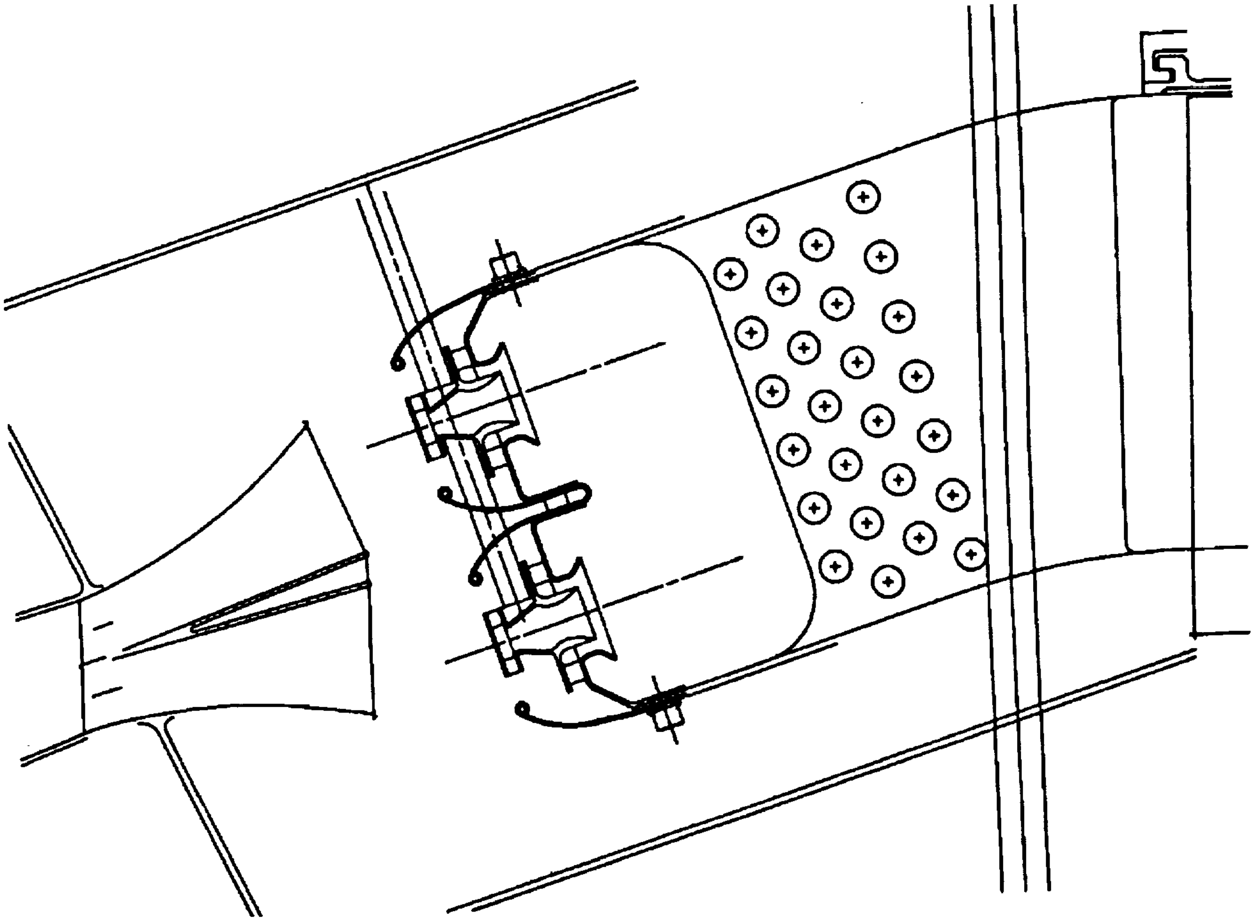

Figure 3-14. General Electric Lean, Premixed, and Prevaporized Combustor

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From an economic and handling standpoint, the ideal fuel for a high-speed transport is the kerosene fuel used by currently operating commercial aircraft. The thermal stability of this fuel, as defined by existing commercial aircraft specifications, is marginal even for the operating conditions of today's advanced subsonic commercial aircraft. However, most jet fuel deliveries exceed the minimum thermal-stability requirement. In fact, test data for samples of jet fuels delivered to airports throughout the world show that over 70% of these airports currently receive fuels that satisfy a stability requirement 50°F above the jet fuel specification minimum (fig. 3-15). This 50°F improvement (TSJF + 50) is expected to satisfy the thermal-stability requirement of aircraft to at least the Mach 2.8 cruise level.

The cost of fuel is composed of all direct and indirect charges to the seller. Jet fuel price is controlled by supply and demand, competition, and Government policy, as well as costs. Airlines are interested in the price rather than the cost of jet fuel. In recent history, the price of jet fuel, as well as most other petroleum products, has been considerably higher than cost (fig. 3-16). Essentially, the price of petroleum-based fuels is driven by supply and demand. Any petroleum refining cost differences resulting from minor jet fuel property changes dictated by the HSCT are likely to be overwhelmed by price changes generated by competition. Even if an added cost has been overlooked in estimating the requirements for developing a supply of TSJF + 50 fuel, such a cost will certainly be lost in the marketplace price variations.

Eight percent of the fuel samples from commercial airports were found to be thermally stable beyond the limit that can be established using standard test techniques (higher than TSJF + 150). These fuels maintain their high thermal stability from the refinery to the aircraft without special handling or additives and may even be as stable as natural gas or commercial-grade methane. Because these

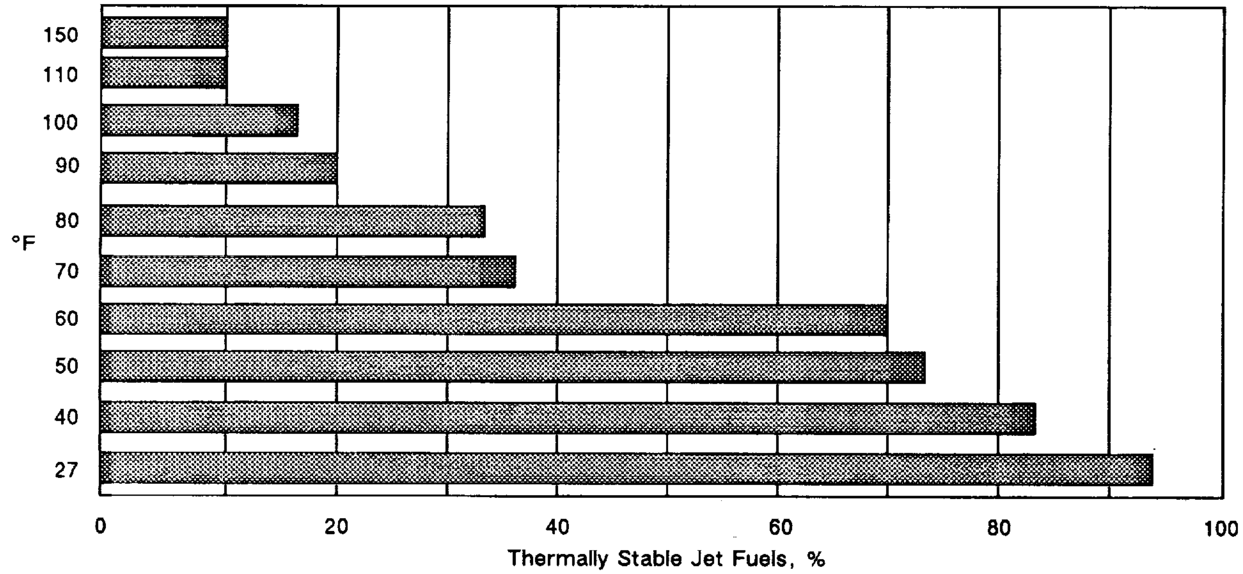

Figure 3-15. Thermal Stability of Currently Delivered Fuels

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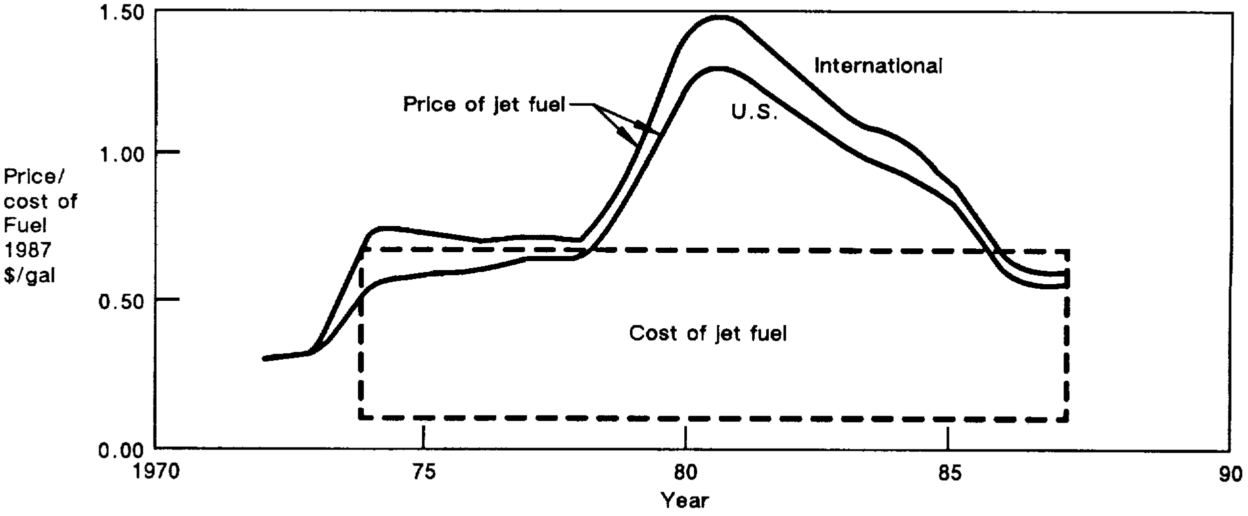

Figure 3-16. Cost Versus Price of Jet Fuel

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fuels can be duplicated using available process equipment and techniques, the costs have been established. The portion of these costs that would be directly chargeable to jet fuel has not been determined, but would be considerably less than the 10¢/gal recently estimated for hydrotreating distillate fuels. Additionally, Boeing test data indicate that fuels with very high thermal stabilities maintain their stability without costly special handling during transfer and storage as long as they still satisfy current jet fuel purchase specifications.

More fuel property data and improved test techniques are required before a practical upper limit for the thermal stability of conventional fuels can be established. Current thermal stability test methods are adequate for the gross screening of fuels, but do not allow a direct correlation between test results and aircraft-engine requirements. Aircraft-engine fuel system simulations are needed to ensure that a fuel selected for use in an HSCT behaves as predicted. This is particularly important if the required stability limits are increased significantly beyond today's limits, such as for use in a Mach 2.8+ aircraft.

In past studies, available data indicated that increased thermal stability would require the acceptance of fuels with other less desirable properties, such as low density and high vapor pressure. This study demonstrated that there is no correlation between these properties and thermal stability. For example, the densities of fuel samples that satisfied a higher than TSJF + 100 requirement were within the normal scatter obtained with currently delivered jet fuels (Jet A and Jet A-1) (fig. 3-17).

New materials in HSCT aircraft and new processes producing jet fuel in modern refineries may bring the fuels into contact with catalytically active metals. Fuel analyses for extremely low (part per billion) levels of these metals will be required to ensure only an allowable level of trace contaminants in engine emissions if these metals are shown to impact the ozone layer.

The petroleum product market is shifting away from residual fuel oils to diesel (distillates) and chemical feedstocks (other) (fig. 3-18). The ability to satisfy this shift using a wide variety of crude oils and environmental considerations has resulted in a worldwide trend to increasingly sophisticated and operationally flexible refineries. This sophistication, and the fact that fuels currently delivered to most

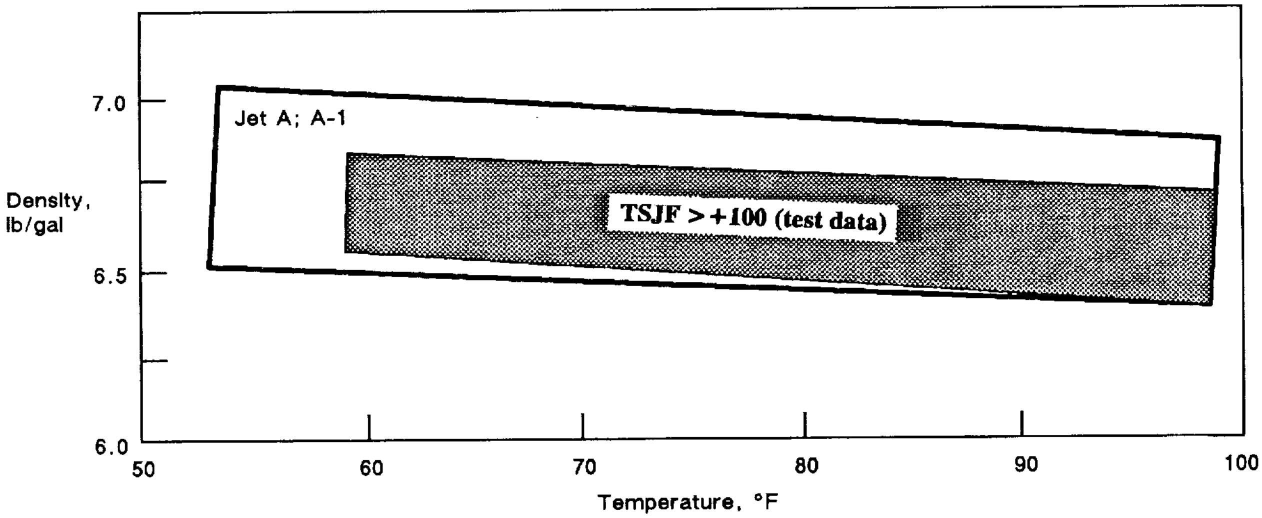

Figure 3-17. Density of High-Thermal-Stability Fuels

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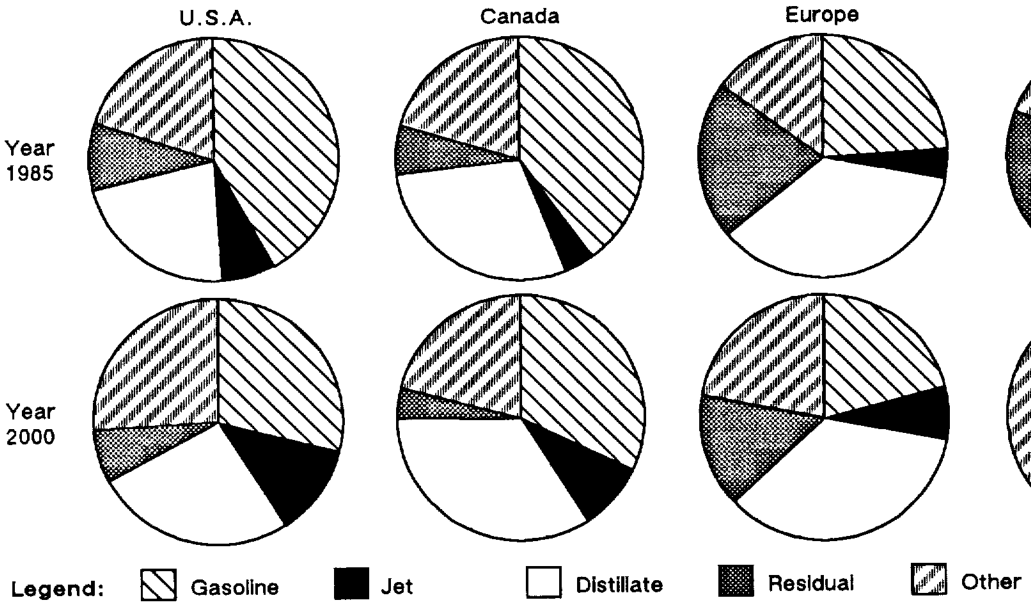

Figure 3-18. Worldwide Fuel Type Demand Change

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airports are more thermally stable than required by subsonic aircraft, indicate that property changes required for low Mach number high-speed transports could be made with little impact on fuel price or availability. However, regardless of properties, an increase in jet fuel demand precipitated by the introduction of an HSCT must be anticipated in advance to ensure that entry-year fuel demand can be satisfied at a reasonable price. Therefore, it is recommended that now is the time to stimulate fuel supplier interest in the increased market potential for jet fuel that would be created by an HSCT.

Heat-sink requirements for engine, airframe, and mechanical systems have often led to the conclusion that cryogenic fuels, particularly hydrogen, were required for supersonic aircraft. The cooling requirements for the aircraft structure and engine inlet of these aircraft are strongly driven by Mach number. However, the fuel flow required by HSCT engines drops considerably during the descent phase of the mission. This results in a mismatch between the fuel required as a coolant and fuel needed for propulsion as indicated in figure 3-19. Therefore, in cases where the cooling capability of the cryogen cannot be used, the reason for choosing such a fuel must be based on other considerations, such as thermal stability, burning characteristics, and cost. Cost is the most significant factor below Mach 3.8.

The production methods and costs of cryogenic fuels (liquid hydrogen and methane) for commercial aircraft have been developed and updated as part of continuing Boeing fuel studies. This work resulted in the conclusion that cryogenic fuel costs were sensitive to demand as well as the cost of available energy (or raw material) as demonstrated by the cost sensitivities for liquid hydrogen (fig. 3-20).

The cost of cryogenic fuels escalates quickly at very low production quantities as shown in figure 3-21. Areas of the world that could support only a few flights per day would need other cryogenic fuel users to obtain an economy of scale benefit.

An important difference between the design and cost of cryogenic versus conventional fuel systems is that, for cryogenic systems, sizing and cost are strongly influenced by losses of vaporized liquid fuel. The design of a ground system is impacted by losses; the entire system must not only accommodate the maximum required block fuel, but liquid to replace fuel vaporized in the storage and distribution system as well as the aircraft. Additionally, the design of the ground system must include a system to safely collect and recover vaporized cryogen. The cost of vaporized cryogen must be accounted for as an added fuel cost. In some cases, this gas can be sold or used in ground equipment, and some of the fuel cost can be recovered. However, the vent gases must be pressurized for storage and delivered to a duty cycle and pressure level that will satisfy requirements of some, yet to be identified, user.

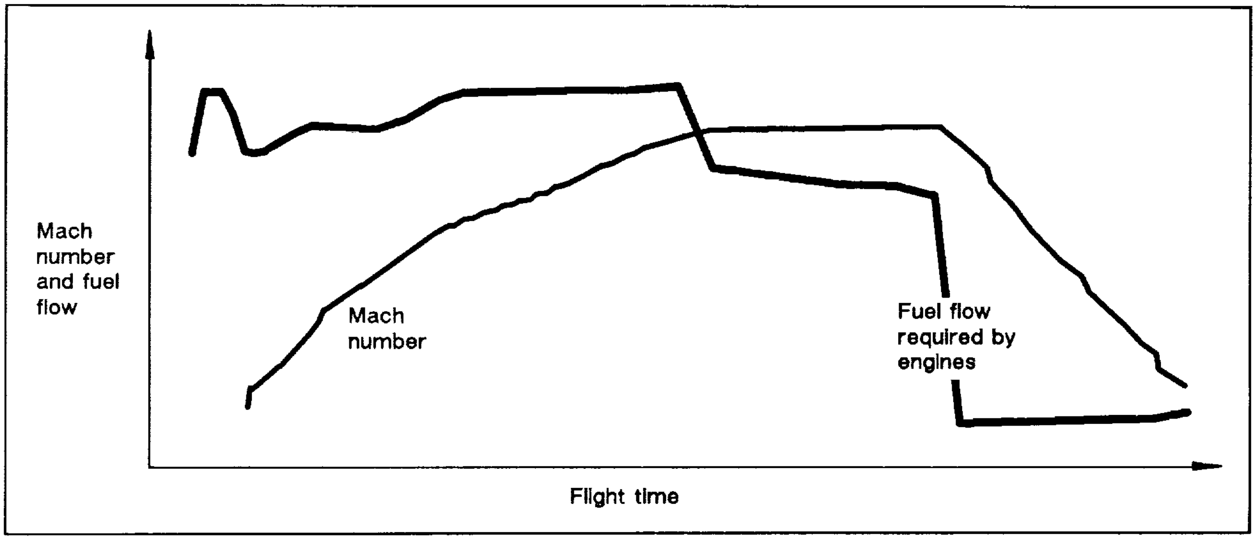

Figure 3-19. Typical Flight Profile

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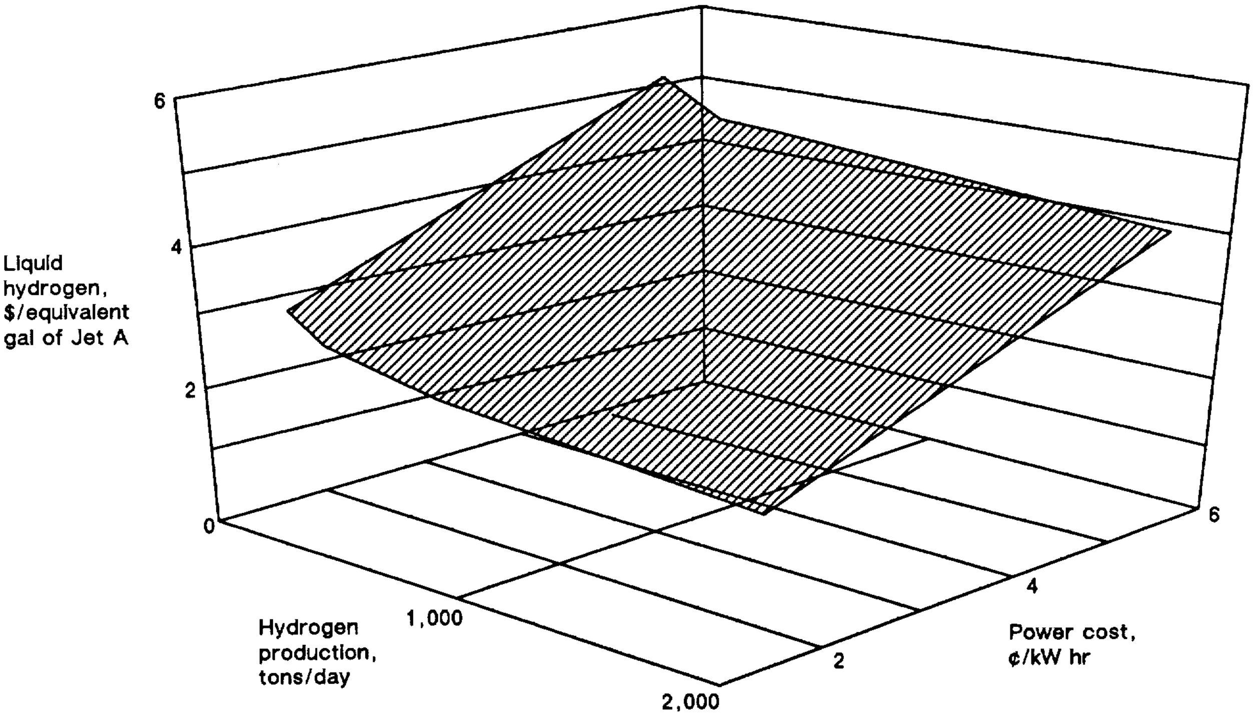

Figure 3-20. Liquid Hydrogen Cost Sensitivities

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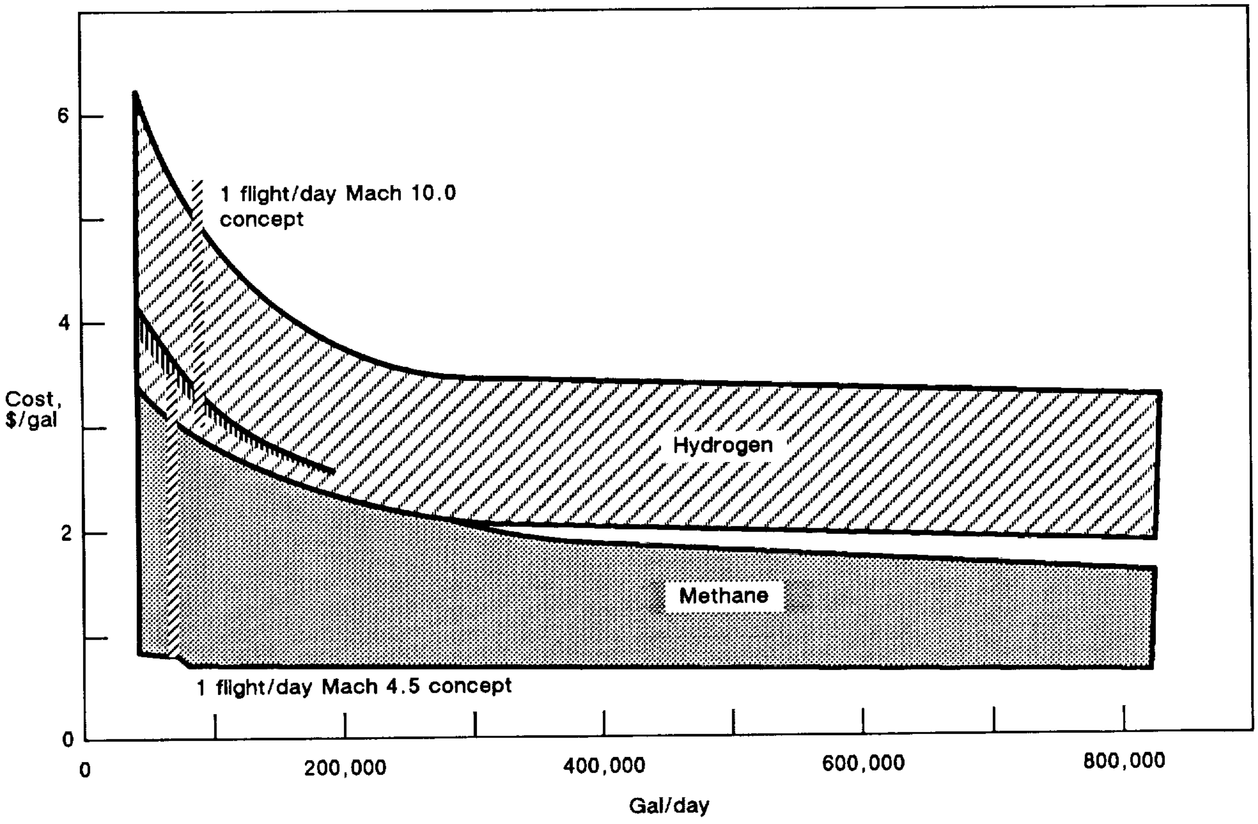

Figure 3-21. Cryogenic Fuel Costs—Equivalent Jet A

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Cryogenic fuel losses, hence the cost and sizing of airport gas recovery systems, are directly influenced by aircraft duty cycle, as indicated in figure 3-22. In addition to airport-to-airport variations in losses resulting from differences in duty cycles, losses are affected by aircraft venting and detanking requirements. The design of a methane-fueled HSCT aircraft was not sufficiently advanced to determine its contribution to losses during this study. Methane losses, along with gas duty-cycle variations shown in this report, are minimal.

A key consideration in the design of cryogenic systems is the trade between the cost of thermal protection and the cost of losses. In the idealized cases shown in figure 3-23, a comparison between expensive vacuum-jacketed insulations and less expensive nonvacuum solid insulations showed relatively small differences in calculations. Even when different levels of liquid methane cost and types of financing methods were considered, no clear choice between thermal protection systems was found. However, results of this type of comparison are misleading in that vented gases are a direct out-of-pocket cost to the airlines, while capital costs may be wholly or partially paid by municipalities or governments. In this respect, the trade is forced towards the minimization of losses.

The conversion of an airport for the use of liquid hydrogen would require the use of vacuum-insulated transfer lines and support equipment unless significant advances are made in solid-insulation technology. The cost of this conversion would be higher for hydrogen than for methane, as shown in figure 3-24.

The per unit (equivalent gallon) capital costs for fuels in this and most other studies is based on 100% customer use of facilities. Unless there is a ready market for this fuel during slack periods, there will be a significant price penalty per gallon. No such markets have been identified for liquid methane. The facilities for conventional jet fuel, however, can be used to produce diesel or heating oil.

It was determined that all participants in an HSCT study should use the same reference prices and price ranges for thermally stable conventional fuels and liquid methane. Early study results were used as support data to establish the prices and ranges shown in table 3-7. Later in the program it was found that the penalties assessed to TSJF are unreasonably high and should be adjusted in future aircraft studies.

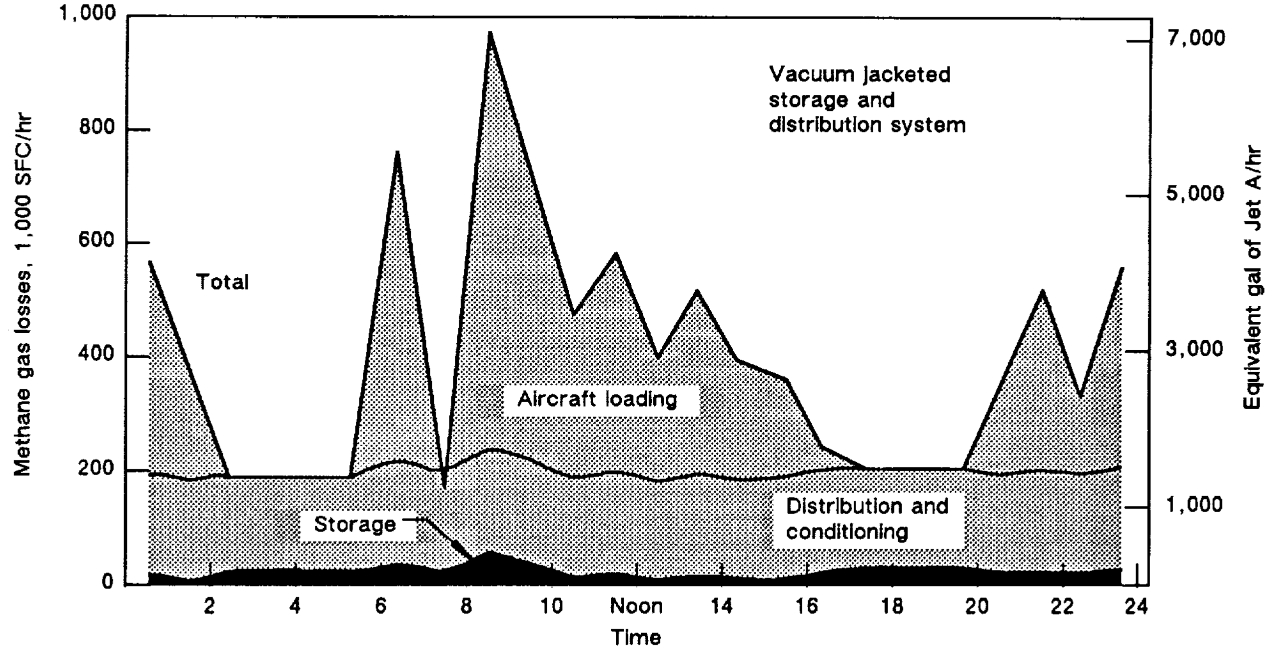

Figure 3-22. The Influence of Aircraft Duty Cycle on Airport Losses—Los Angeles International Airport Projection

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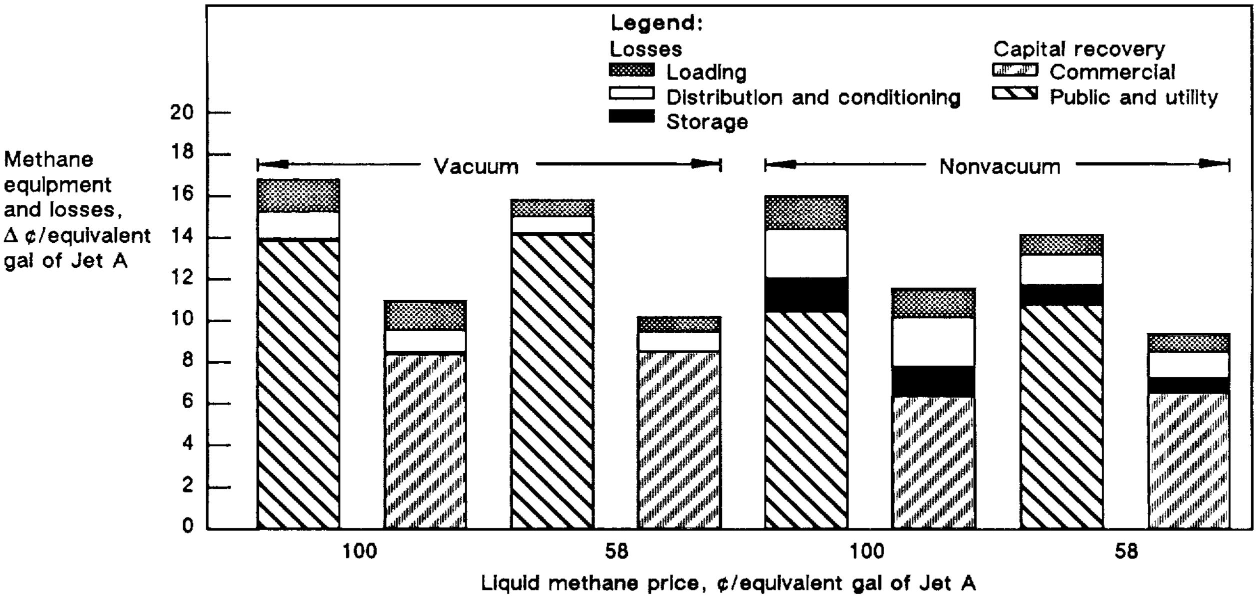

Figure 3-23. Liquid Methane Airport Costs—Sample Projections for Los Angeles International Airport

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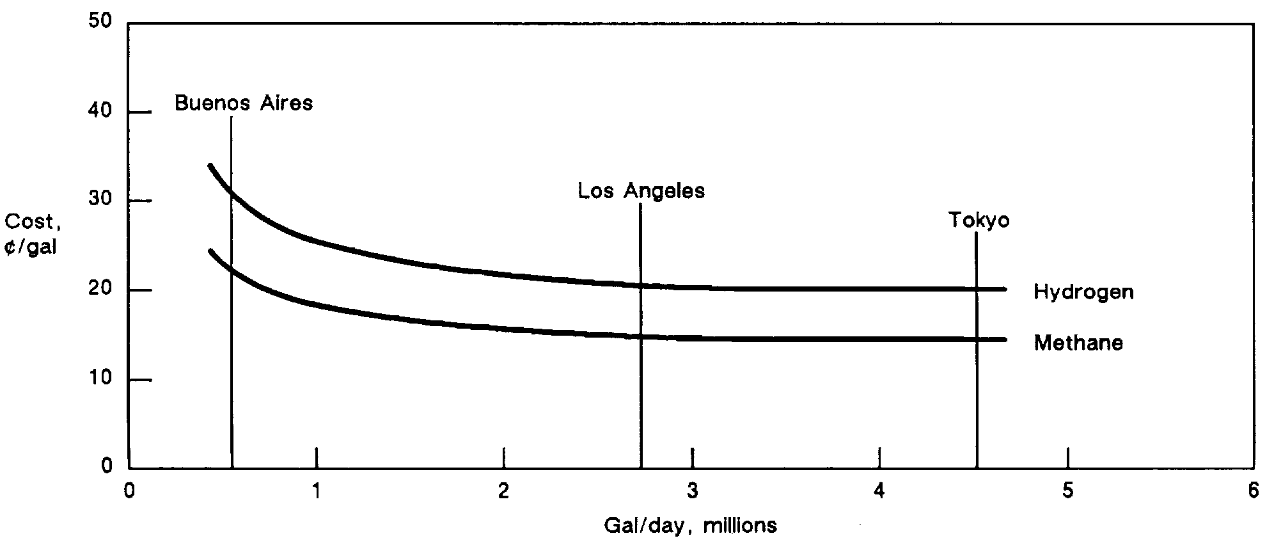

Figure 3-24. Airport Conversion Cost Comparison

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3.6 CONCLUSIONS

Engine performance parameters were received from three engine manufacturers for evaluation of aircraft in the speed range Mach 2.4 through Mach 10.0. Uninstalled net thrust and TSFC predictions from the engine companies were corrected to account for inlet bleed drag and nozzle boattail drags. Bare engine plus nozzle weights for each engine were received. A preliminary propulsion pod was configured to minimize installation interference effects. The results of these studies were incorporated into the overall vehicle performance assessment.

From these studies, the following conclusions can be drawn:

a. There is nothing inherent in the conventional-fueled engine concepts that would prevent them being developed for the year 2000 with current and projected available technologies. Consequently, decisions relative to the merits of individual conventional-fueled aircraft configurations do not

Table 3-7. *Study Fuel Prices*

Fuels	Price of equivalent gallons of Jet A	
	02/04/88 (to airplane)	
	Range, $	Reference, ¢
Jet A	0.50 to 0.75	60
Thermally stable jet fuel		
TSJF + 50	0.50 to 0.85	62
TSJF + 100	0.60 to 0.95	71
TSJF + 150	0.70 to 1.10	92.5
Liquid methane	0.50 to 1.00	
Demand tons/day		
>7,000		68
2,000		73
500		83

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hinge on propulsion issues alone. Technical risks increase with increasing Mach number for the conventional-fueled engine concepts.

b. None of the cryogenic concepts have been used, to date, for commercial aircraft. As a result, no commercial experience exists. At this time, sustained scramjet propulsion has yet to be accomplished even in a laboratory. Consequently, significant research is required before attempting to develop a cryogenic-fueled engine.

c. Engine weight and TSFC are significant contributors to vehicle weight.

d. Conventional-fueled engines produce higher TSFC to achieve the same level of thrust minus drag for increasing vehicle Mach number.

e. Year 2015 technology represents a significant decrease in engine weight and TSFC compared to year 2000 technology (3% to 8% in TSFC and 15% to 26% in weight).

f. Cycle selection studies are required to obtain optimum performance for any cruise Mach number aircraft.

g. Vigorous research and development programs are needed, especially in the area of noise suppression and low-emissions combustors.

h. Operation out of conventional airports was found to be a requirement for achieving adequate HSCT utilization.

i. Because of the airport requirement, a viable HSCT must produce noise levels no higher than its subsonic competition.

j. Studies show that with projected suppression technology, achievement of FAR36 Stage 3 noise levels is possible.

k. The HSCT emissions goal is to have no significant impact on the ozone layer. While the level of engine emissions needed to meet this goal is currently unknown, reduced emission combustors and the effects of derating the engine cycle were studied. Derating the engine cycle resulted in significant performance penalties (reduced thrust, increased TSFC and engine weight). The most innovative combustor concept, and the one with the highest risk, was predicted to reduce NOx emmissions from 30 to 5 lb/1000 lb fuel.

The objective of the fuels evaluation was to identify and evaluate production, cost, property, and other nonaircraft system-related factors that would affect the use of unconventional fuels in high-speed commercial transports. The fuels studied included modified conventional, endothermic, cryogenic, and others such as slushes and gels. The evaluation showed that—

a. Conventional kerosene-based jet fuels that can satisfy the requirements of up to Mach 2.8 aircraft are likely to be available for use in both subsonic and HSCT aircraft at no price penalty.

b. The thermal stability of conventional fuels may be as good as that for liquefied natural gas.

c. No realistic scenario could be developed that would lead to the conclusion that a cryogenic fuel could be price competitive with kerosene fuels on an equivalent-energy-loaded-on-aircraft basis.

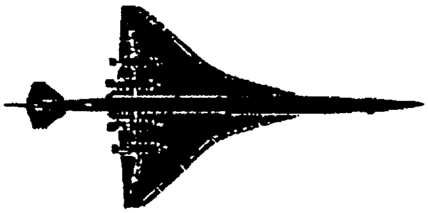
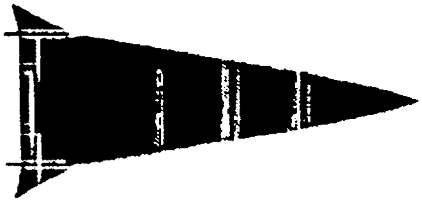
4.0 VEHICLE DEVELOPMENT

The overall objective of this task was to evaluate the effects of technology advances on the viability of the high-speed civil transport (HSCT). Information ranging from improvements in today's technology to that associated with the National Aero-Space Plane (NASP) were investigated. Design Mach numbers from 2.0 to 25.0 were evaluated, design ranges from transatlantic to transpacific considered, and both conventional and unconventional fuels were analyzed (fig. 4-1).

The scope of systems technology applied to the study was to identify those systems characteristics that were configuration drivers and to evaluate those characteristics only to the extent necessary to validate configuration viability.

The large range of design cruise speeds, fuel types, and technology levels offered a wide variety of aircraft design possibilities. It was necessary to evaluate the many possible design combinations, screen out nonpromising concepts, and focus on the greatest potential payoffs. The approach taken was to first make technology projections for years 2000 and 2015 certification (to bracket NASP technology). These projections were used to determine design Mach regions corresponding to the projected limits in technology.

Twenty-one preliminary concepts were developed through risk-benefit analyses to enable selection of the most promising concepts in those Mach regions. This was then narrowed to six concepts, which were developed and analyzed. The results led to a discontinuation of work on the Mach 6.0 and Mach 10.0 cryogenically fueled airplanes. Further development and assessment of the remaining concepts led to discontinuing work on the remaining cryogenically fueled Mach 4.5 airplane. Finally, a more detailed assessment of the configurations designed for Mach 2.4, Mach 2.8, and Mach 3.2 led to the conclusion that the lowest Mach number demonstrated the most benefit and least risk. The results showed that even at Mach 2.4 substantial technology improvements are required for a technically viable HSCT for year 2000 certification. The Mach 2.4 configuration was, therefore, selected for assessment of the impact of meeting environmental goals. This overall study flow is illustrated in figure 4-2.

	Supersonic	Hypersonic
Mach		
Mission	Transport	Transport
Fuel	Conventional	Cryogenic
Certification date	2000 to 2005	2015 to 2025

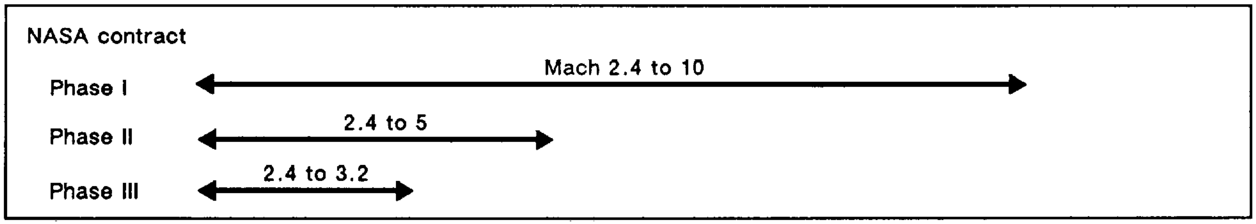


Figure 4-1. HSCT Activities

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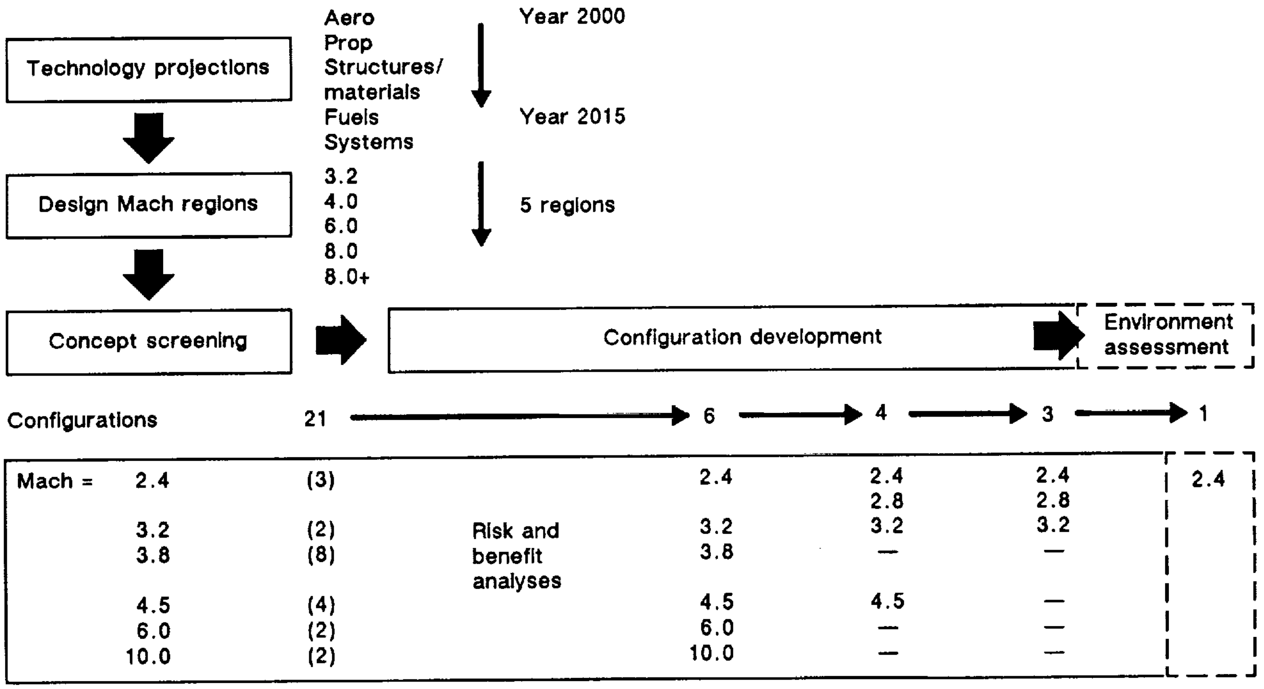

Figure 4-2. Technology Assessment and Configuration Development

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4.1 TECHNOLOGY PROJECTIONS AND DESIGN OPTIONS

Two technology windows that represent different airplane certification dates were selected. A year 2000 window provides an attractive commercial timing date, and precedes the application of newly developed NASP technology.

The second selected window, year 2015, would allow commercial use of technology developed in support of the NASP program. This would be appropriate for a second generation of HSCTs. The corresponding technology readiness dates are 5 years before the certification windows. Aggressive technology development programs will be required to provide a state of readiness for civil applications. A technology projection chart was developed to display the options in technology as a function of both time and Mach number range (fig. 4-3).

The design Mach number band of 2.0 to 25.0 was divided into five discrete regions whose upper limits correspond to projected limits for application of specific technologies or for major configuration design options. The five regions (table 4-1) are—

a. Region 1. Mach 3.2 is near the projected upper limit of using wing-integral fuel tanks for the cruise fuel. This will require extensive development of fuels with higher thermal stability and fuel tank designs with low thermal conductivity.

b. Region 2. Mach 4.0 is near the projected upper limit for conventional turbojet-fan engine cycles and for thermally stable jet fuel (TSJF) use. This 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 (i.e., regions 1 and 2). In addition, the more advanced technology would open up design options for even higher Mach numbers.

c. Region 3. 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.

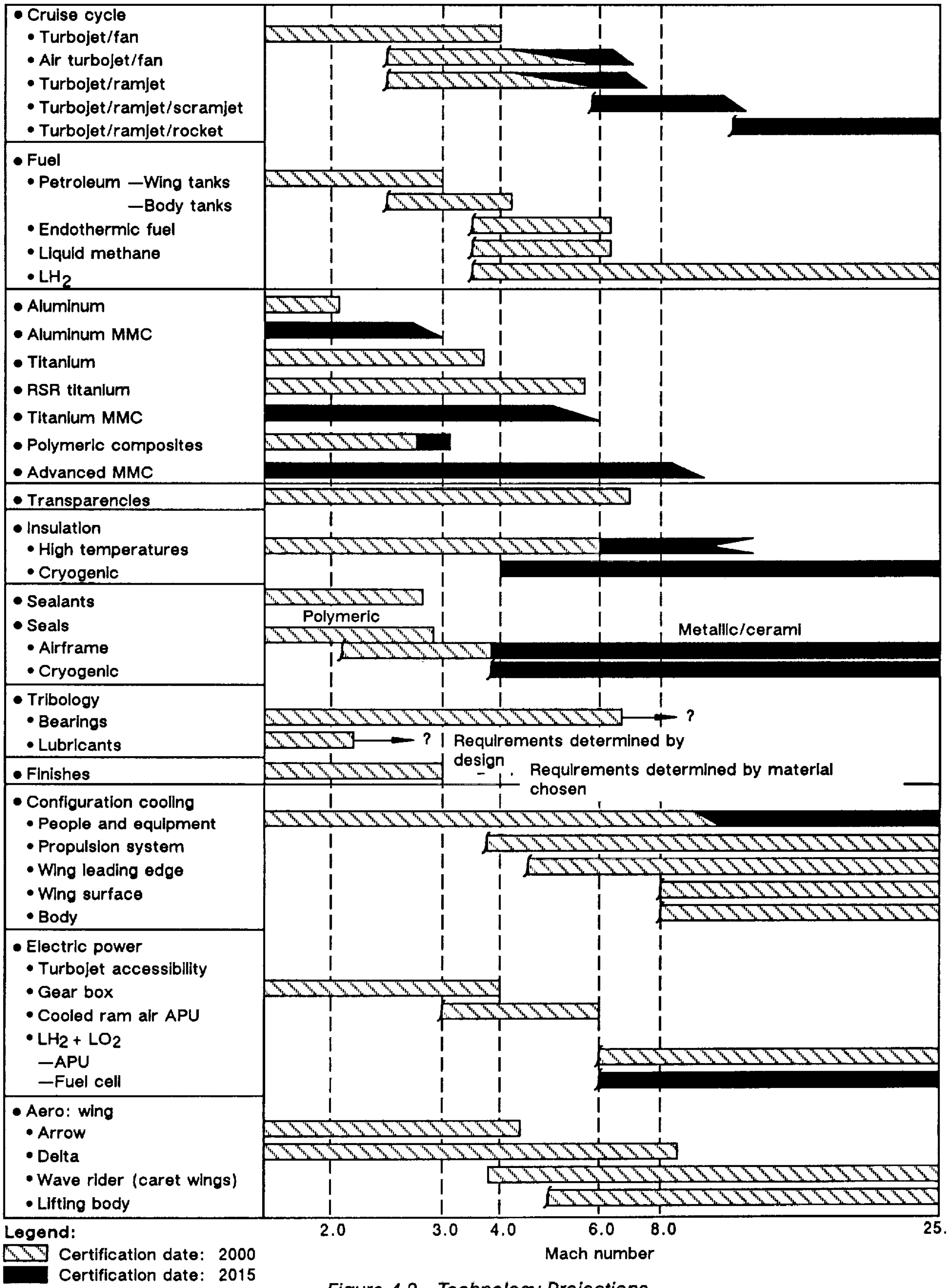

Figure 4-3. Technology Projections

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Table 4-1. 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 Turbofan/turbojet
3	4.0 to 6.0	2015	Endothermic fuel Liquid CH_4 Ramjet
4	6.0 to 8.0	2015	Uncooled structural materials
5	8.0 to 25.0	2015	

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d. Region 4. Mach 8.0 is near the projected upper limit for uncooled structural materials. However, at Mach numbers below this limit, areas such as the wing leading edges or nacelle inlets may require various amounts of localized active cooling.
e. Region 5. At Mach numbers above 8.0, active cooling of structural materials is projected.

4.2 CONCEPT SCREENING

Twenty-one configuration definitions were developed to explore various major design options applicable in regions 1 through 5. Figure 4-4 illustrates, as an example, the use of the technology projection chart to determine the design options available in the range from Mach 4.0 to Mach 6.0. Possible design options for this Mach range are listed in the far right column of the figure.

The design options investigated to narrow down the field of candidate configurations and the scope of Mach number regions are as follows:

a. Wing planform variations (delta, arrow, variable sweep, and caret wings).
b. Different fuels (liquid hydrogen, liquid methane, and conventional fuels).
c. Different passenger, fuel tank, and body arrangements. The relative locations of fuel tanks and passengers become increasingly difficult to place with the large volume requirements and safety considerations associated with cryogenic fuels.
d. Different engine cycles (turbojet, ramjet, scramjet).
e. Different propulsion pod arrangements (single, dual, integrated).

All of the preliminary configurations were designed for a maximum takeoff weight (MTOW) of 750,000 lb and 250 passengers. The configurations designed for cruise Mach numbers up to and including Mach 6.0 incorporated features to enable operation from conventional airports. Configurations for Mach numbers greater than Mach 6.0 were designed for dedicated superhub airport operation because the compromises necessary for reducing takeoff and landing distances would have been prohibitive.

A concept screening process was developed to screen the candidate configurations for technical feasibility, airport compatibility, and economics. This was done using an evaluation of their risks versus benefits.

The objectives of the screening process were threefold:

a. Select configuration concepts for further study.
b. Identify the most critical technology and design areas.
c. Identify focus areas for technology development activities.

Table 4-2 summarizes the criteria used in the risk-benefit analysis. Each facet of the design was graded on a number system to evaluate its value in meeting the criteria. This screening index is summarized in figure 4-5. As an illustration, figure 4-6 provides the results of this screening method applied to a wing planform study for a Mach 2.4 configuration.

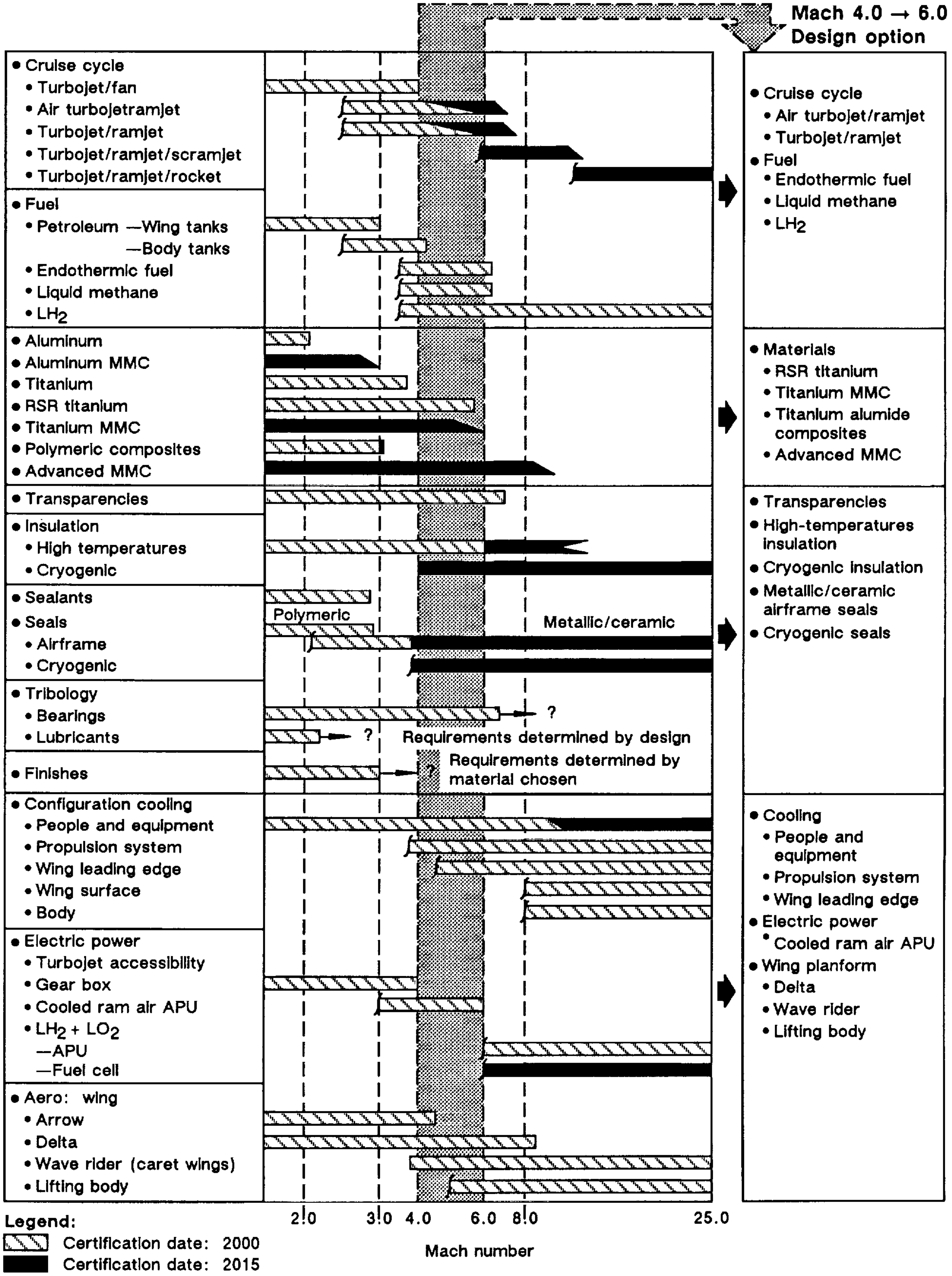

Figure 4-4. Use of Technology Application Chart

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Table 4-2. Risk and Benefit Analysis Criteria

Configuration design and systems	Propulsion and noise	Structures, materials, weight, and balance	Stability and control	Aerodynamics
• Safety in flight • Emergency descent safety crash • Survivability airport compatibility • Cabin noise • Configuration complexity • Airframe growth capability • Passenger appeal and comfort • Passenger cabin accessibility • Cargo volume and accessibility • Payload flexibility • Cockpit configuration • Thermal management • Fuel system Flight controls • Environmental controls • Electric power sources	• Fire hazard • Rotor burst hazard • Foreign object damage hazard • Intake unstart effects • Wheels up landing effects • Variable geometry practicability • Materials availability • Cooling feasibility • Performance potential • Maintainability • Engine design propulsion • Propulsion complexity	• Wing/body/empennage/gear load path integrity • Wing/empenage structure complexity • Body structure complexity • Structure material availability • Nonstructured material availability • Balance • Center of gravity management • Loading flexibility • Weight (OEW)	• Longitudinal stability • Longitudinal control • Longitudinal stability augmentation requirements • Takeoff rotation and landing derotation • Landing approach trim • Directional stability • Engine out control • Lateral/directional control effectiveness • Lateral/directional stability augmentation requirements • Cross wind takeoff and landing capability • CG control requirements • Failure states redundancy	• High lift system failure impact • Pilot visibility • Space available for high lift system • Leading edge and trailing edge cutouts • Surface size and actuator requirements • System aero complexity • Test dependency • Liftoff and touchdown lift potential • Climb and descent L/D potential • Reverse thrust availability • De-icing requirements • Cruise L/D • Potential transonic L/D • Potential subsonic L/D • Potential sonic boom

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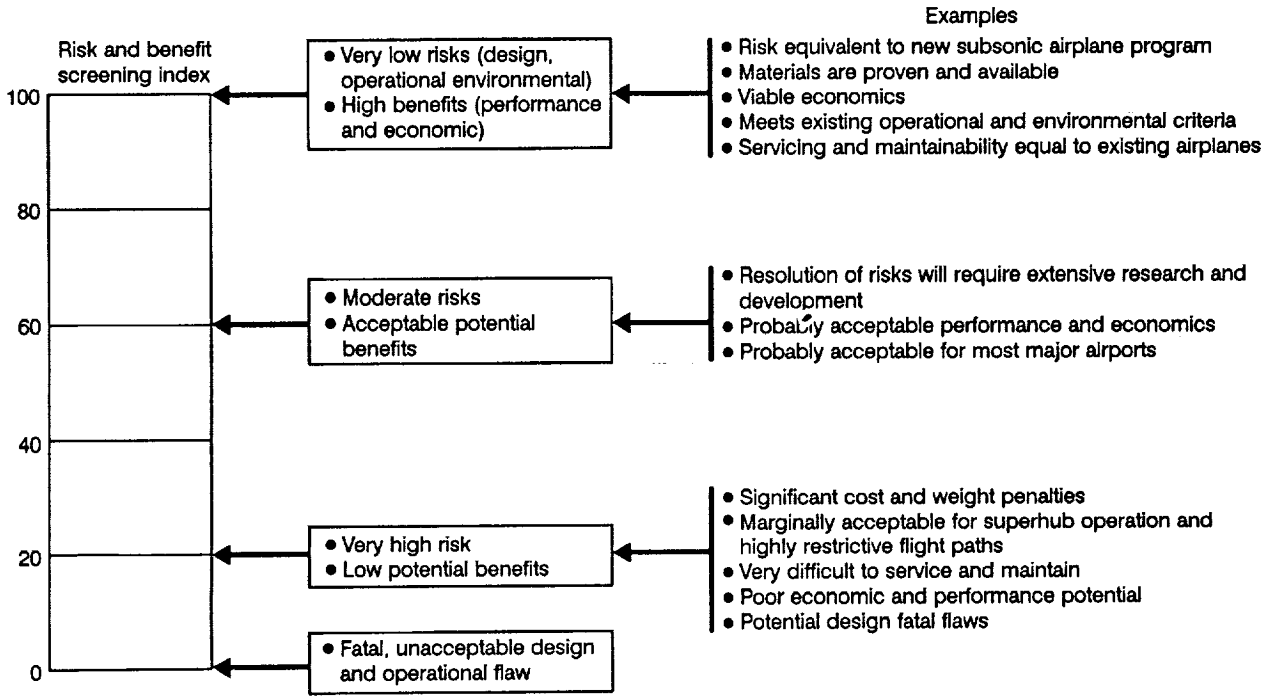

Examples

- Risk equivalent to new subsonic airplane program
- Materials are proven and available
- Viable economics
- Meets existing operational and environmental criteria
- Servicing and maintainability equal to existing airplanes

- Resolution of risks will require extensive research and development
- Probably acceptable performance and economics
- Probably acceptable for most major airports

- Significant cost and weight penalties
- Marginally acceptable for superhub operation and highly restrictive flight paths
- Very difficult to service and maintain
- Poor economic and performance potential
- Potential design fatal flaws

Figure 4-5. Risk and Benefit Analysis Screening Index With Examples

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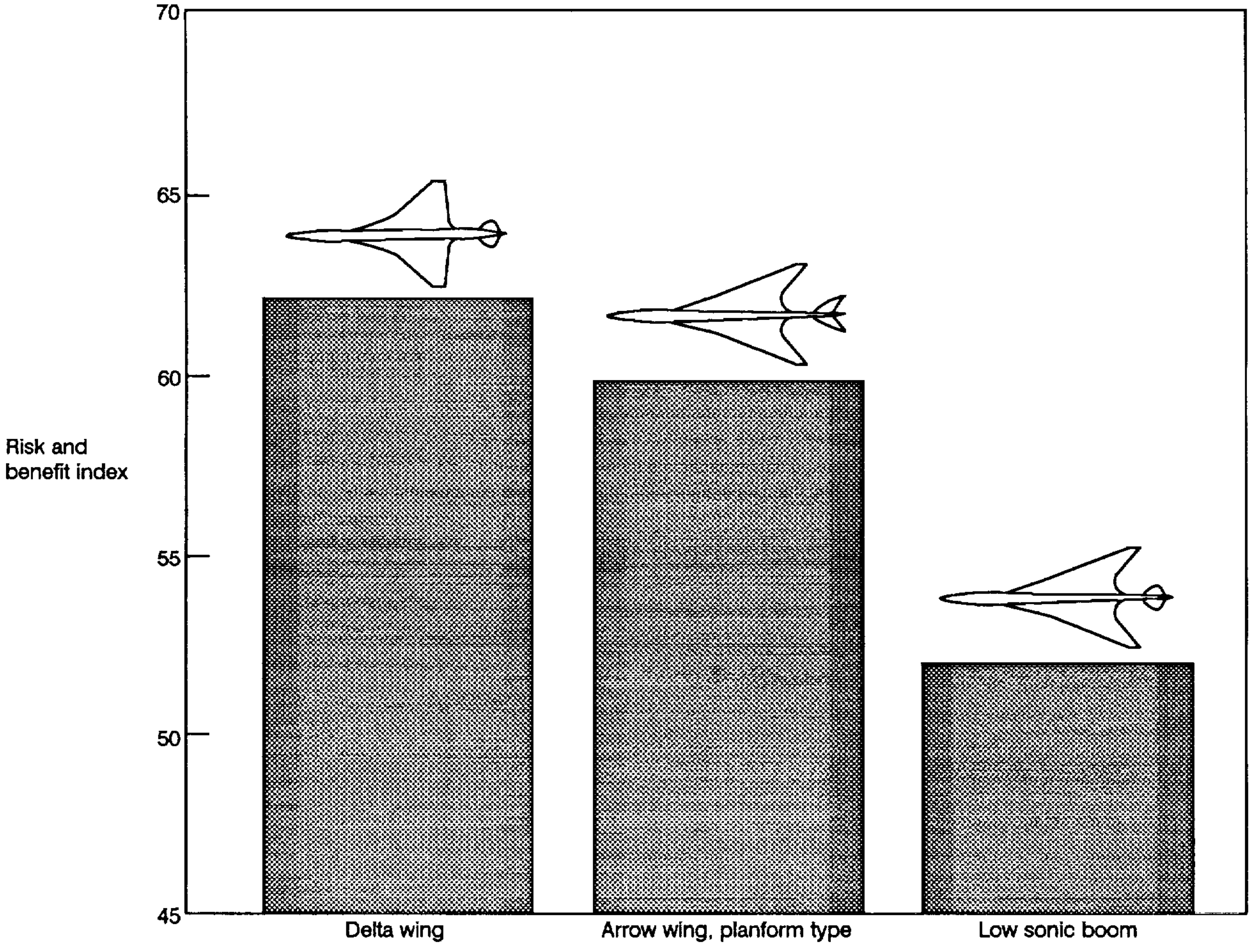

Figure 4-6. Concept Screening Planform Trends at Mach 2.4

4-U90027R1-87

4.3 CONFIGURATION AND PERFORMANCE ANALYSES

The six configurations chosen through concept screening for further development are listed below according to their Mach number regions:

a. Mach 2.4. The configuration shown in figure 4-7 has a blended-wing body, double-delta planform based upon Boeing model 733-633 for which an extensive database exists. The double- delta wing planform provides a good compromise between supersonic cruise and low-speed requirements (field length and noise). TSJF is contained in wing tanks. Four variable-cycle dry turbofans are aft-mounted on the lower surface of the wing in single nacelles for favorable aerodynamic interference. The primary structural materials are polymeric composites for airplanes developed for both year 2000 and 2015 certification dates.

b. Mach 3.2. The configuration shown in figure 4-8 also has a double-delta planform. The propulsion system includes four variable-cycle afterburning turbofans with two-dimensional inlets in aft-located double pods. Primary structural material for the year 2000 vehicle is titanium; the year 2015 HSCT will be constructed of polymeric composites. Fuel tanks are in the wings of both models. This requires development of TSJF with high thermal stability as well as fuel tanks with low thermal conductivity.

c. Mach 3.8. The configuration shown in figure 4-9, also with a double-delta planform, has an extended inboard wing leading edge to provide acceptable inlet flowfield characteristics for the relatively long engine nacelles. The propulsion system includes four afterburning turbojets with

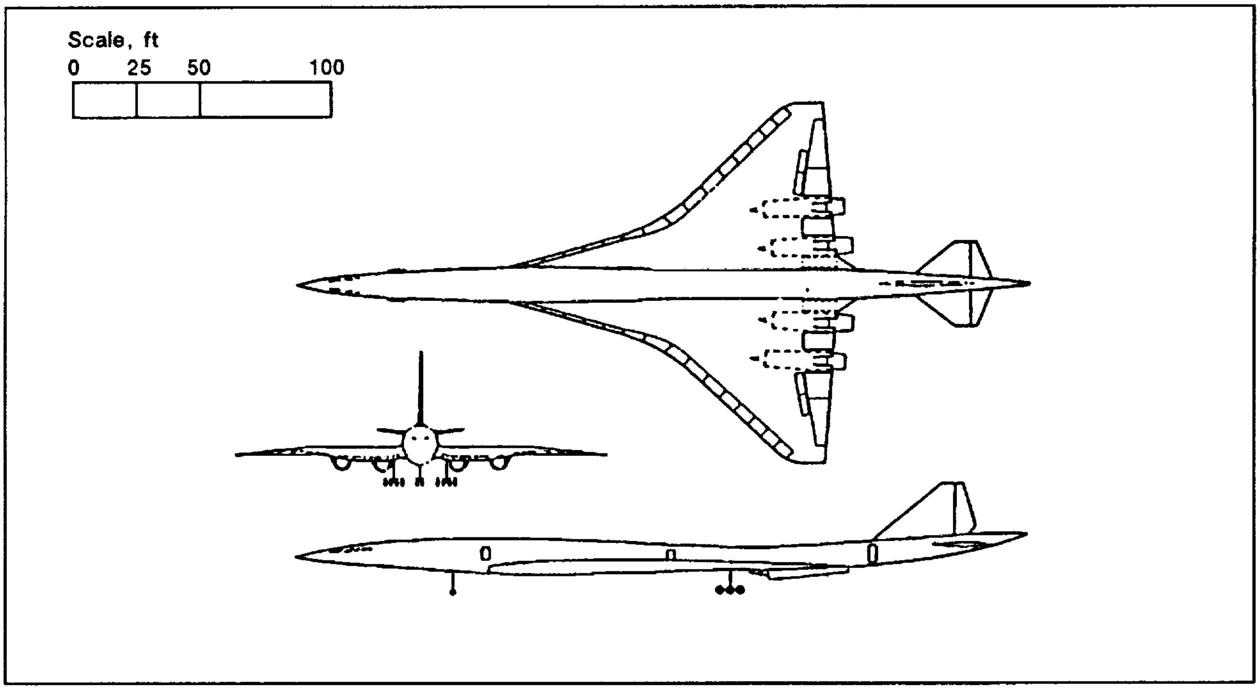

Figure 4-7. Mach 2.4 Configuration

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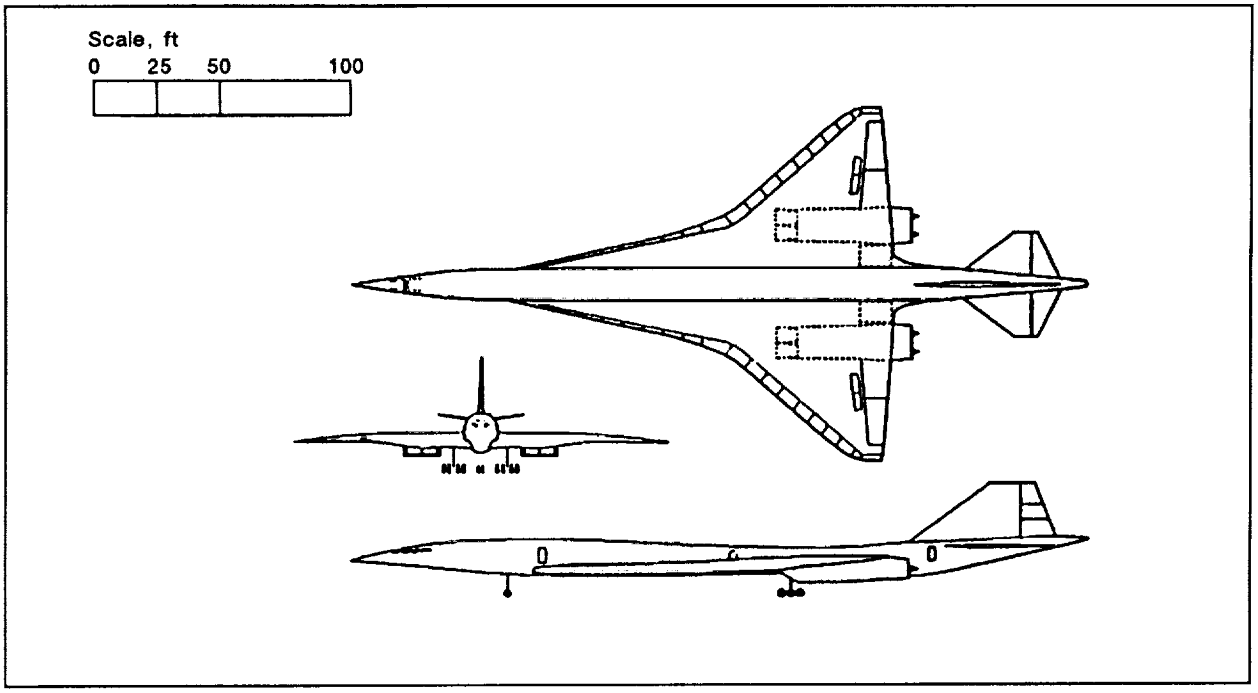

Figure 4-8. Mach 3.2 Configuration

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two-dimensional inlets for two single-pod and one double-pod arrangement located aft on the wing to optimize the wing-nacelle interference effects. This configuration uses TSJF. Climb fuel is contained in wing tanks, and the cruise plus descent fuel and fuel reserves are contained in body tanks in the enlarged fuselage. Primary structural material for the year 2000 application is titanium, and for 2015, a high-temperature metal-matrix composite.

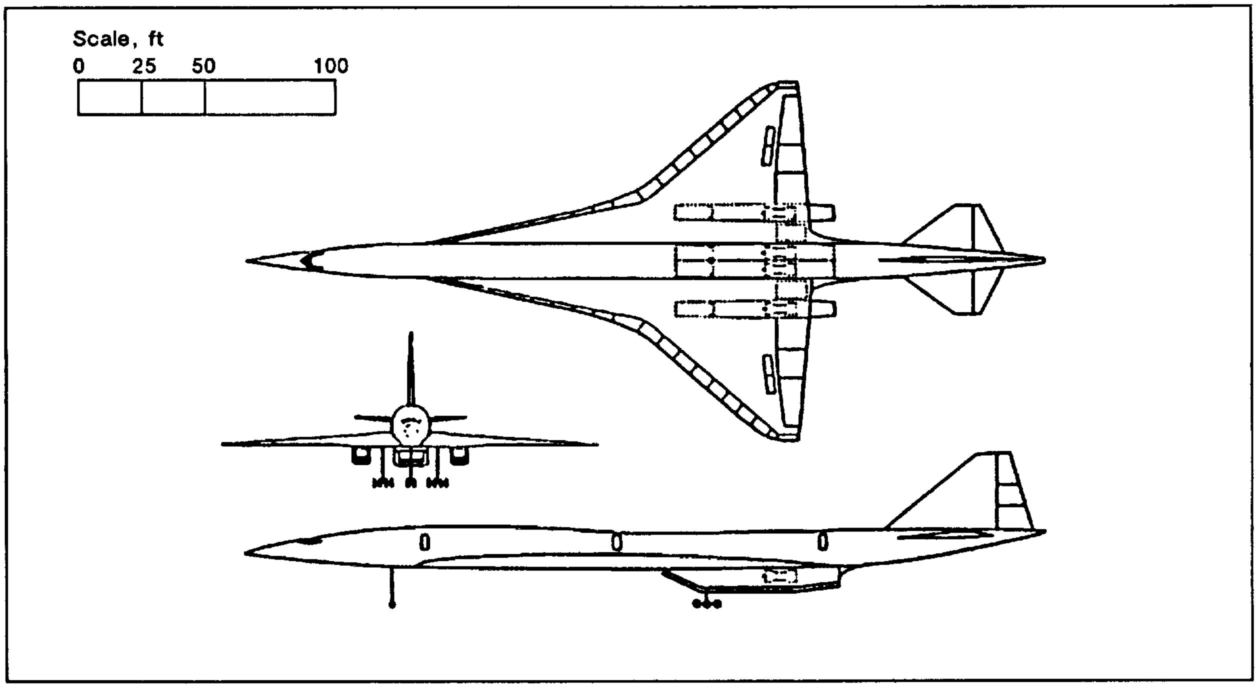

Figure 4-9. Mach 3.8 Configuration

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d. Mach 4.5. The configuration shown in figure 4-10 also has a double-delta planform with a propulsion system consisting of four mixed-cycle, ramjet-turbofan engines contained in aft-mounted single pods. Liquid methane fuel is contained in caterpillar-type fuel tanks located in the fuselage and in the wing-body fairing area. This configuration would have a high-temperature metal-matrix composite structure. All concepts with cruise speeds greater than 4.0 were assumed to have a certification date in the year 2015.

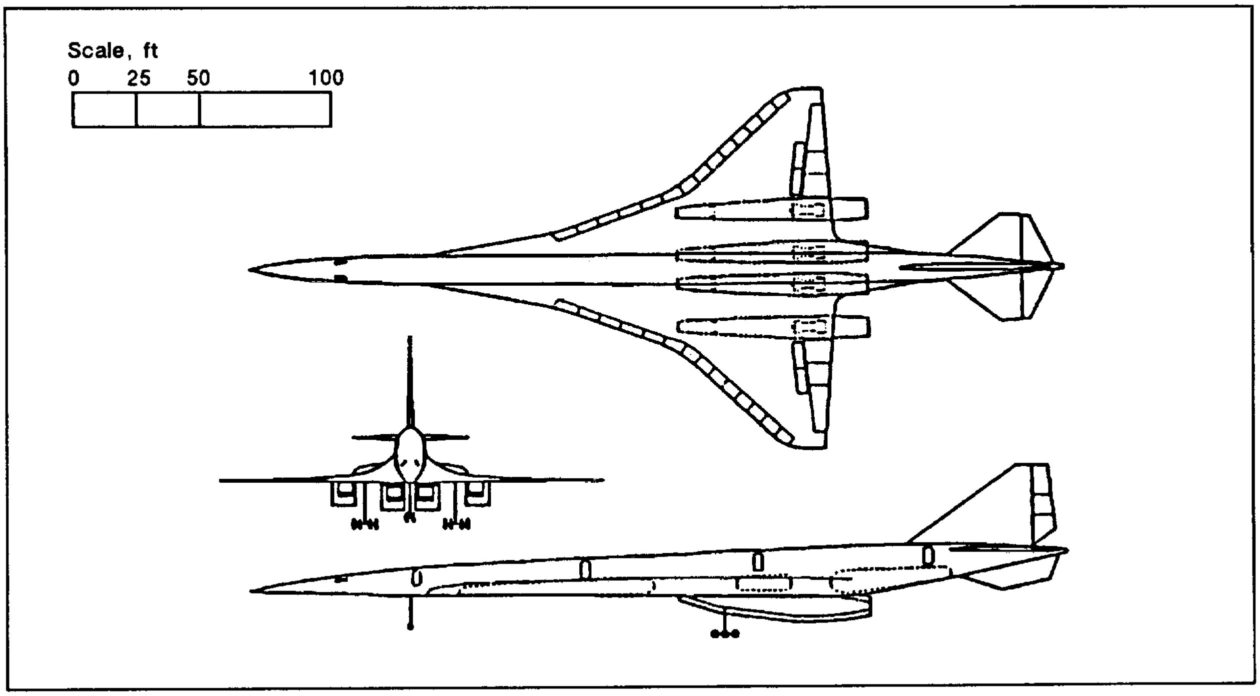

Figure 4-10. Mach 4.5 Configuration

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e. Mach 6.0. The multibody configuration shown in figure 4-11 was designed to separate the passengers from the liquid hydrogen (LH_2) fuel tank while retaining most of the features of a delta planform. Passengers are located in the center body with the LH_2 fuel contained in the two outer bodies. The propulsion system consists of four single-pod air turboramjets. Primary structural materials are high-temperature, metal-matrix composites.

f. Mach 10.0. The configuration shown in figure 4-12 was designed to incorporate a very highly swept, blended-lifting, long-body arrangement that is characteristic of an optimum cruise configuration. Its low span implies operation from existing airports would be impossible. Large LH_2 fuel tanks are located in the body both fore and aft of the passenger compartment for balance considerations. The propulsion system includes four scramjet-ramjet-turbojet multicycle engines located in a clustered pod arrangement below the fuselage. An actively cooled, high-temperature, metal-matrix composite material is used for the primary structure.

These six final configurations were sized to determine the required MTOW for the West Coast to Tokyo range (4,500 nmi). The results shown in figure 4-13 illustrate a significant increase in MTOW with increasing design Mach number. The relative increase would be even more dramatic with longer design ranges or higher payloads.

Sensitivity trade studies were made on an arbitrary 10% improvement in lift/drag ratio (L/D), specific fuel consumption (SFC), and weight for the higher Mach numbers. The gains in performance, as indicated by reduced MTOW, are very sensitive to these technology improvements for the higher Mach numbers.

Figure 4-14 shows average flight Mach number variations for the mission-sized airplanes. These results show that average mission Mach number increases slowly beyond a design of Mach 3.0 because of a relatively greater percentage of time spent in climb and in descent.

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 development

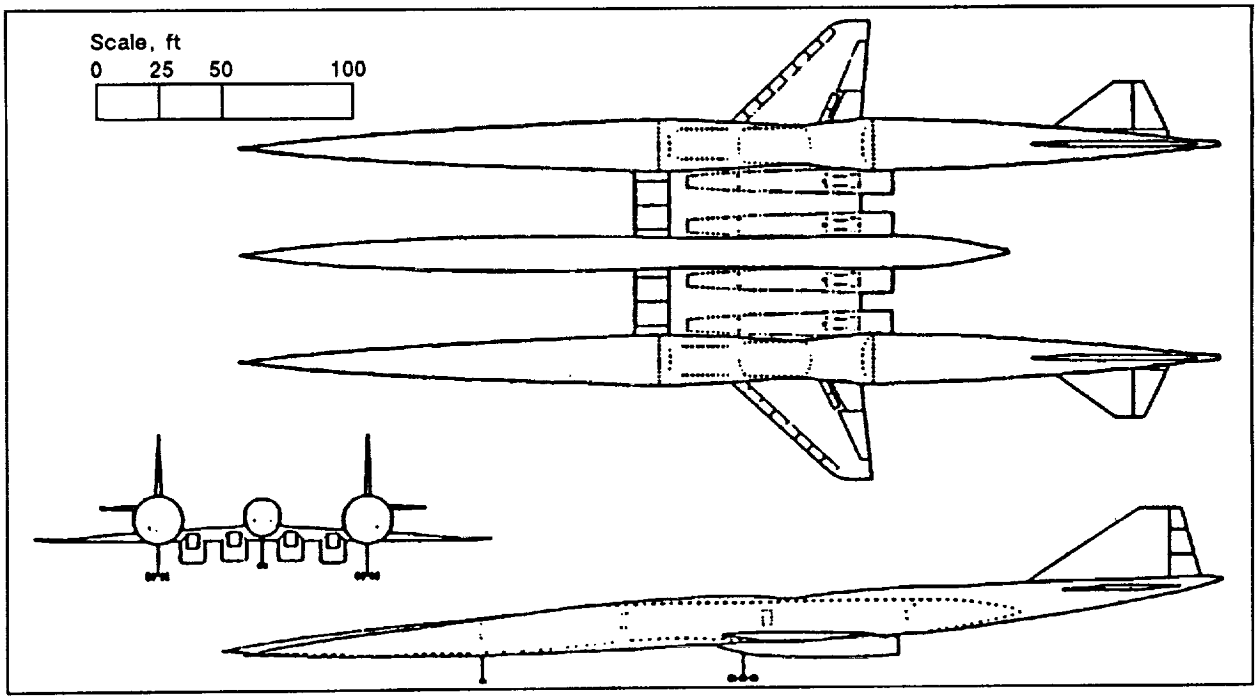

Figure 4-11. Mach 6.0 Configuration

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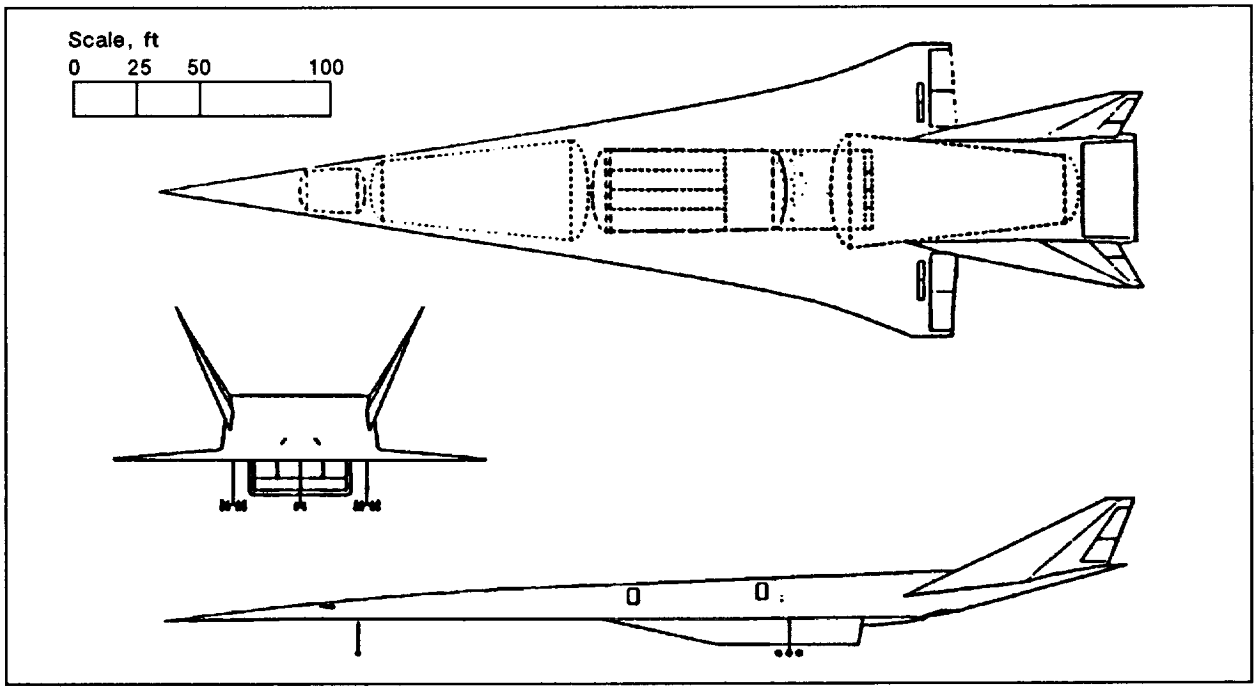

Figure 4-12. Mach 10.0 Configuration

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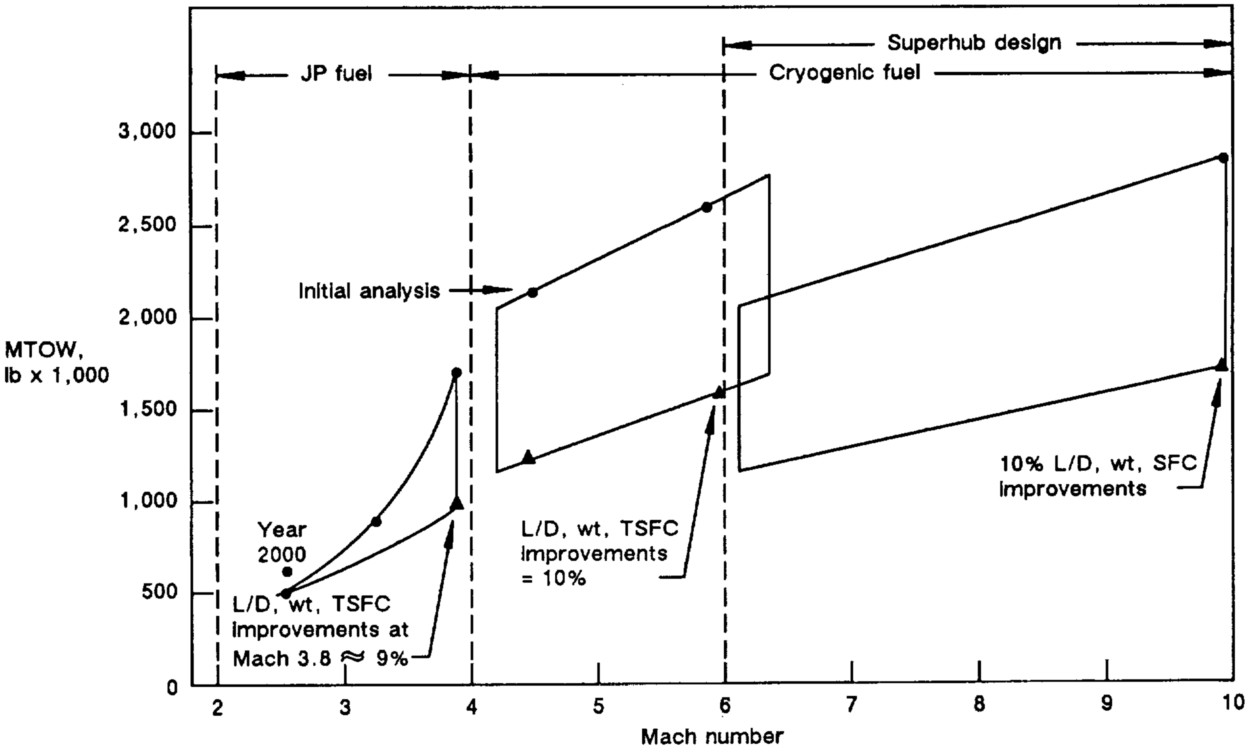

Figure 4-13. Maximum Takeoff Weight Versus Mach Number—Year 2015, 250-Seat Airplane

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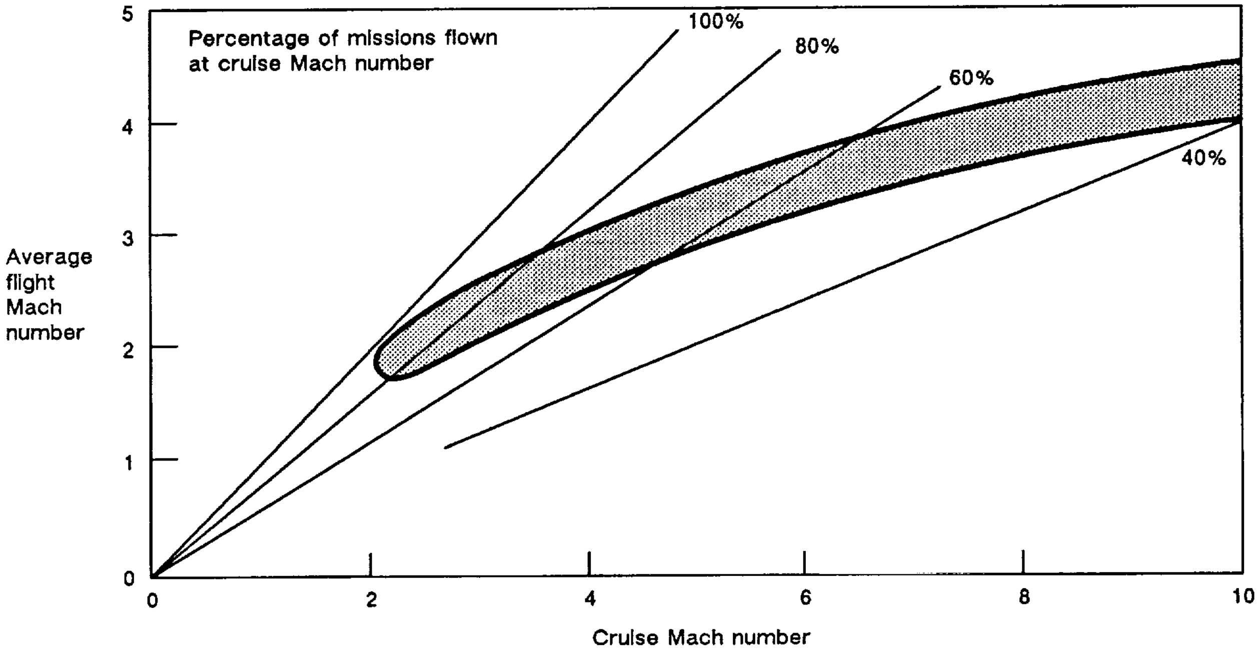

Figure 4-14. Average Flight Mach Number Versus Cruise Mach Number—West Coast to Tokyo

3-U90027R1-104

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 assure availability of technology was assumed. Potential materials, maximum use temperatures, and predicted availability are summarized in figure 4-15.

After screening and assessment of candidate materials on study configurations, the structural materials judged to be available for year 2000 certification with the most potential are toughened thermosetting, high-temperature thermoplastic or polyimide polymeric composites for Mach 2.8 and below

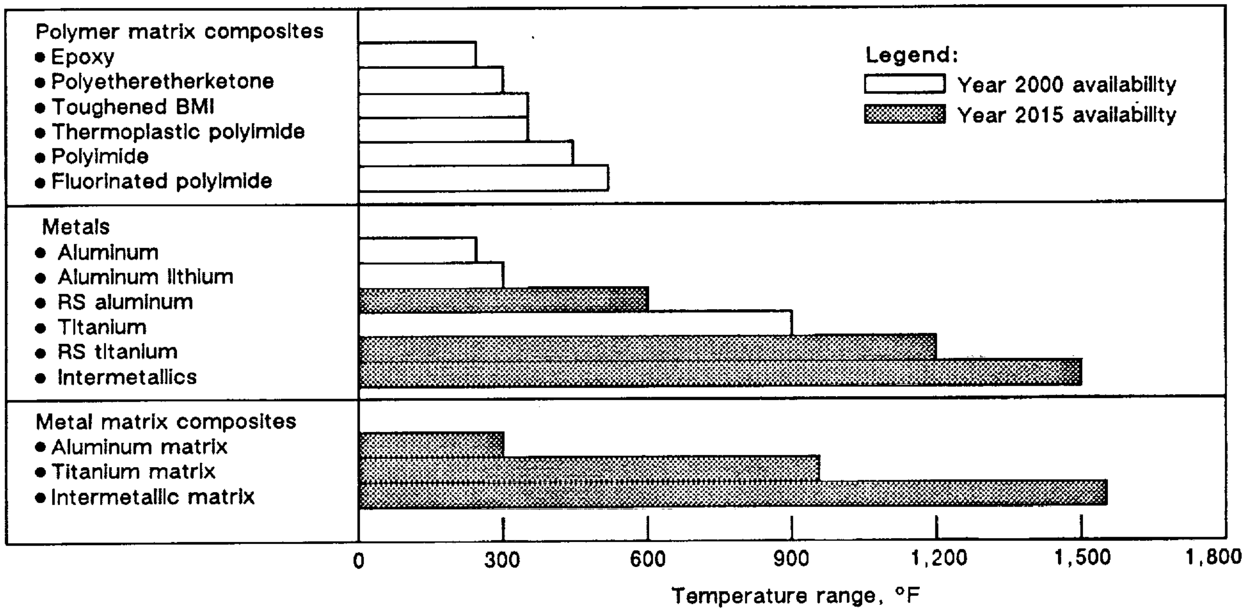

Figure 4-15. Structural Material Candidates and Projected Temperature Range for HSCT Application

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and ingot titanium alloys 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 (RS) 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 application of these support materials to the HSCT. Development of improved temperature resistant materials is required for higher Mach number configurations.

Structural weights for performance calculations are based on the structural concepts and arrangements and on the procedures used in the study reported in "Study of Structural Design Concepts for an Arrow Wing Supersonic Transport Configuration" (ref. 4.1). 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.

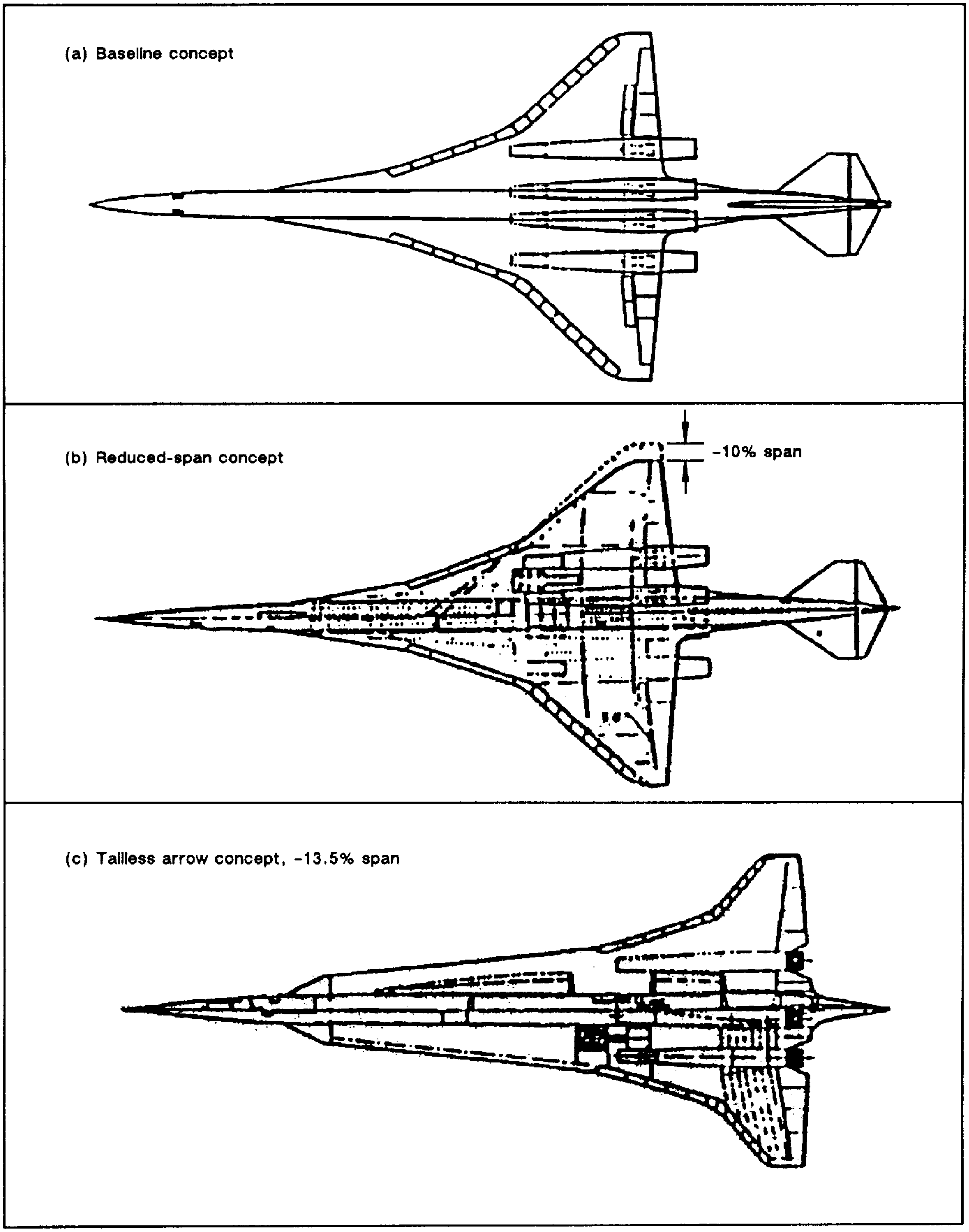
Study Results. The results made from the studies of the initial-concept configurations and performance analyses are—

a. Aircraft size and design complexity increase significantly with increasing design Mach number.
b. The airplane MTOW is very sensitive to projected technology improvements for the higher Mach numbers.
c. Average flight Mach number increases slowly (average block time decreases) above a design Mach number of approximately Mach 3.0 to Mach 4.0. This suggests that economic gains (i.e., productivity) will not increase proportionally with design cruise Mach number.
d. Significant technology and design integration advances are required for an efficient long-range HSCT, even at lower supersonic Mach numbers.

4.4 ALTERNATIVE MACH 4.5 CONFIGURATIONS

Based on the study results, subsequent configuration studies focused on Mach numbers below 4.5, but further evaluation of the configuration possibilities was needed. The baseline year 2015, Mach 4.5 methane-fueled configuration is shown in figure 4-16(a). The configuration concept is similar to the Mach 2.4 configuration: a double-delta wing planform with an efficient high-lift system and trimming aft tail for good takeoff and landing performance as well as low community noise. The Mach 4.5 baseline departs outwardly from the Mach 2.4 configuration only with the much larger propulsion pods and the much increased inboard wing and body volumes required to accommodate the low-density methane fuel.

Analyses indicated that the MTOW for the Mach 4.5 methane-powered configuration was about 2,500,000 lb, which is 300,000 lb greater than the concept screening estimate of about 2,200,000 lb. Two alternative configurations were examined in an attempt to lower the MTOW. The configuration in


(a) Baseline concept

(b) Reduced-span concept

(c) Tailless arrow concept, -13.5% span

Figure 4-16. Alternative Mach 4.5 Configurations

4-U90027R2-99

figure 4-16(b) simply reduced wing span 10% and increased wing thickness 10% at the root in an attempt to save operating empty weight (OEW) at the expense of takeoff and landing performance, and noise characteristics. The configuration in figure 4-16(c) was an optimum-cruise designed "tailless-arrow," with 13.5% less span, aimed at both reduced OEW and high-cruise L/D, with the same negative side effects as the reduced wing span configuration.

The results are shown in figure 4-17. MTOW reductions of 100,000 and 500,000 lb were indicated, but even so, the lightest concept, the tailless-arrow, has a MTOW of 2 million pounds. Further, very large technology improvements of 10% to 18% in all three areas (L/D, SFC, and OEW) would be required to achieve an MTOW below 1 million pounds. Because of the very high MTOW of even the most optimistic alternative configuration, the Mach 4.5 methane-fueled airplane was dropped from further study.

4.5 FINAL STUDY CONFIGURATIONS

The evaluation was narrowed to the region between Mach 2.4 and Mach 3.2 for further detailed study. This speed region was investigated to assess configurations for their technical feasibility for year 2000 and 2015 certification. The approach taken was to update the design requirements and objectives and then to reassess the technology projections. Following these steps, new baseline configurations were developed at each Mach number. Studies conducted at Mach numbers 2.4, 2.8, and 3.2 were used to determine the cruise Mach number with the greatest benefit and least risk. Further trade and sensitivity studies were conducted to aid in the selection of configuration features with the greatest benefit (sec. 5.0, "Environmental Evaluation").

The updated design requirements and objectives used in sizing each airplane are given in table 4-3. Figure 4-18 illustrates the flight profile used to evaluate mission performance. These design requirements and objectives are used to define an "initial delivery" airplane. The initial delivery airplanes are part of the growth strategy shown in figure 4-19. The vehicle meets all performance constraints given in table 4-3. The initial delivery airplane forms the basis of an HSCT family concept designed

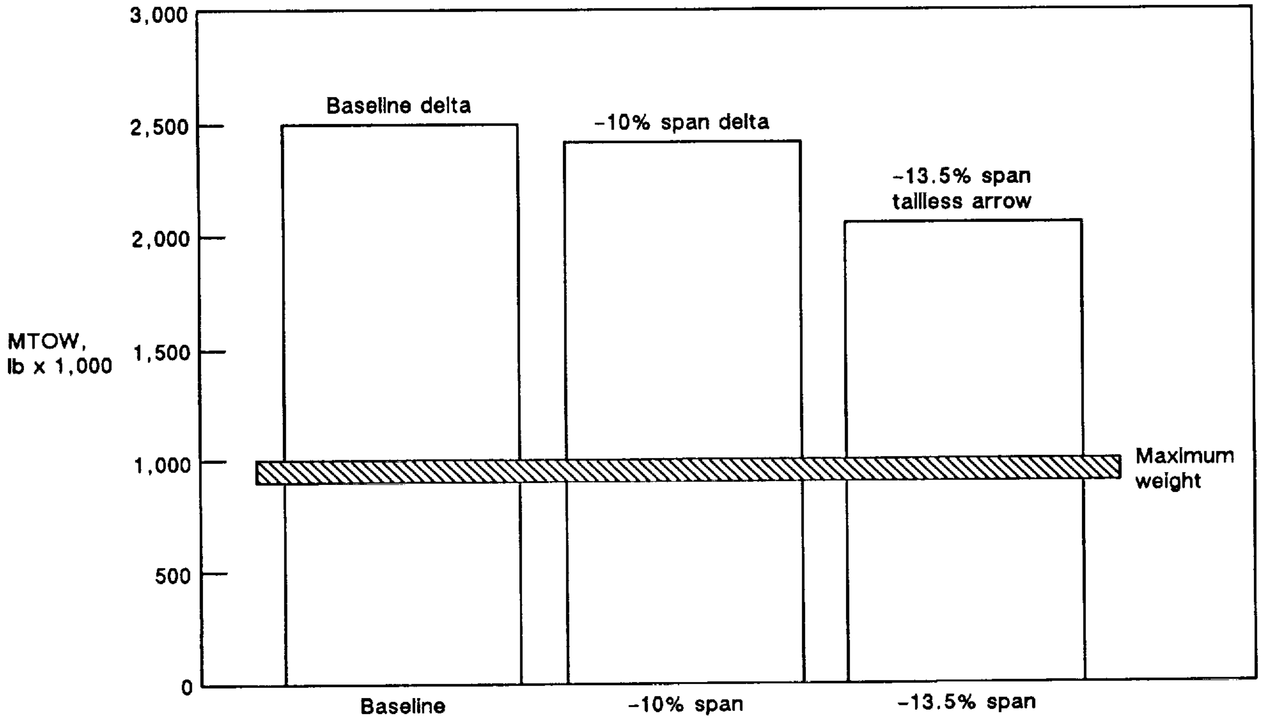


Figure 4-17. Alternative Mach 4.5 Configuration Study Results—247-Seat Airplane With 5,000-nmi Design Range

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Table 4-3. Design Requirements and Objectives

Design requirements	
Payload	Design payload of 247 passengers plus baggage with a tri-class configuration (10% first class, 20% business class, and 70% economy class); the low-sonic-boom design airplane is the exception with a design payload of 268 passengers with the same service distribution
Range	Design range is 5,000 nmi with the design payload at 210 lb per passenger including baggage
Takeoff field length	FAR field length not to exceed 12,000 ft at sea level, 86°F at MTOW
Approach speed	Not to exceed 160 kn at maximum landing weight
Climb thrust margin	30% transonic (acceleration through Mach 1.1); 10% supersonic (top-of-climb)
Climb time	Time to climb to initial cruise altitude not to exceed 45 min
Fuel volume	Fuel for the design range at design payload plus reserves plus 20,000 lb of additional fuel
Design objectives	
Range growth	Fuel volume for long-range, reduced-payload, thin markets, 6,500 nmi with advanced engines
Payload growth	Provisions for high-payload, short-range, North Atlantic market with advanced engines
Subsonic cruise	Efficiency equal to supersonic cruise
Community noise	FAR36 stage 3 or equivalent
Sonic boom limitations	Subsonic flight over land
Pavement loading	Equivalent to DC-8-50, at a MTOW of 350,000 lb operating on flexible pavement subgrade B plus 10%

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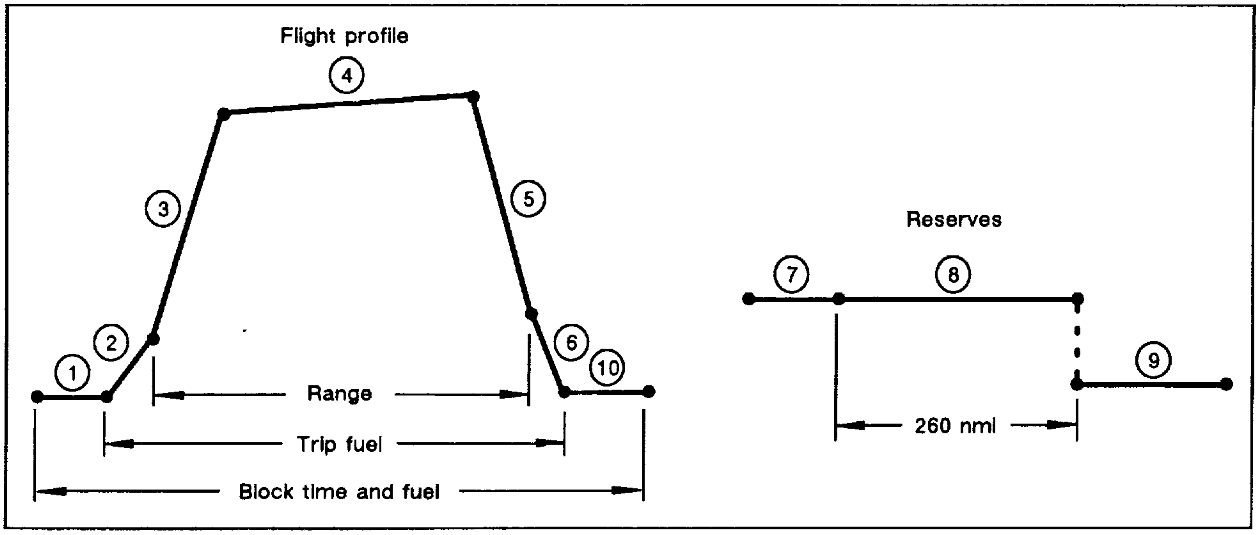

Legend:

- ① 10 min taxi out
- ② Takeoff
- ③ Accelerate and climb to best cruise altitude
- ④ Supersonic climbing cruise
- ⑤ Descend and decelerate
- ⑥ Instrument Landing System
- ⑦ 6% trip fuel
- ⑧ Subsonic cruise at 37,800 ft
- ⑨ 30 min hold at 15,000 ft
- ⑩ 5 min taxi in

Figure 4-18. Flight Profile and Reserves

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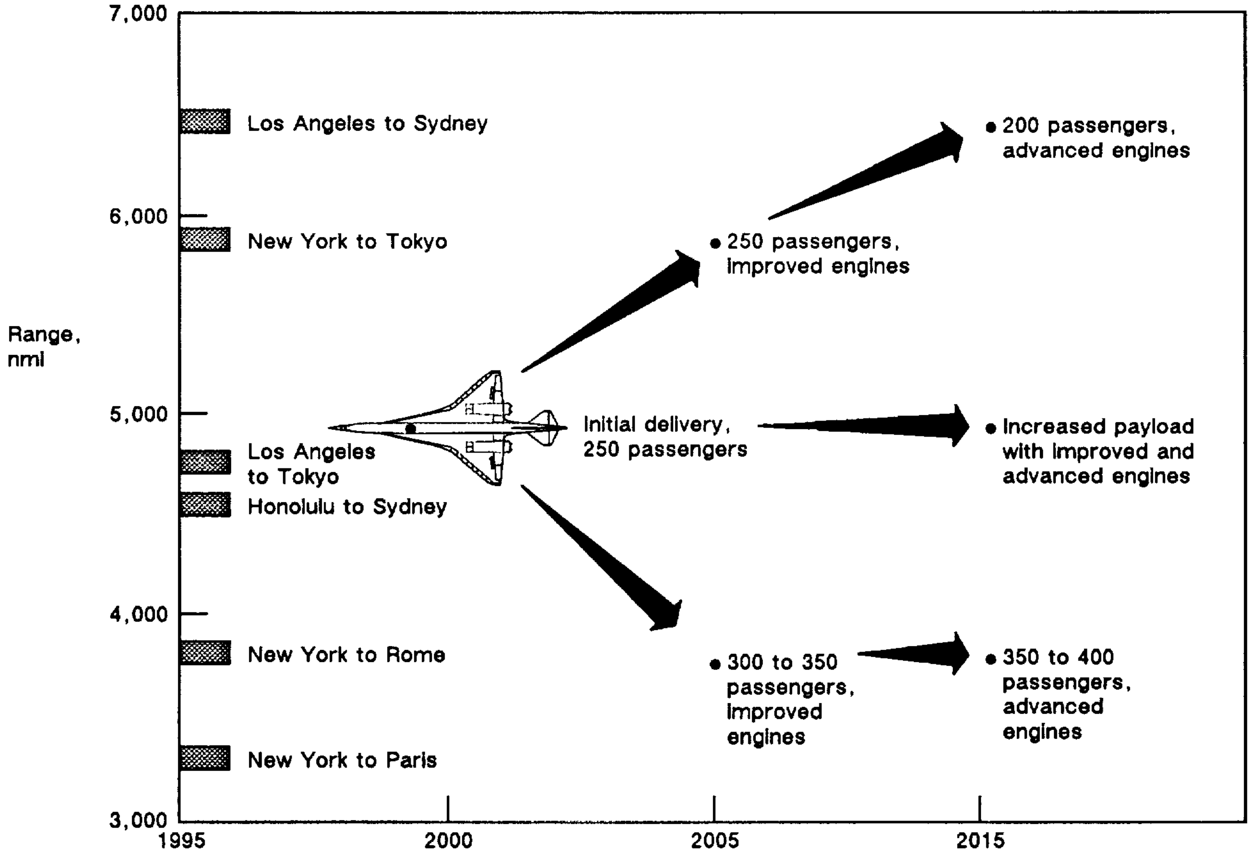

Figure 4-19. HSCT Growth Strategy

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to take advantage of improvements optimizing payload-range characteristics occurring after initial delivery.

The study approach was to use the Mach 2.4 configuration and modify it for Mach 2.8 and Mach 3.2 only when changes were necessary for the higher cruise speeds. Hence the Mach 2.8 and Mach 3.2 configurations are very similar in general appearance to the Mach 2.4 baseline. The basic double-delta planform was retained at Mach 2.8 and Mach 3.2 because it remains an acceptable compromise between high supersonic cruise efficiency, light weight, and low-speed requirements for performance and noise characteristics.

Externally, the most visible change is an increase in vertical tail size as Mach number is increased and the use of a different nozzle-suppressor on the Mach 3.2 airplane powered by the GE VCE. The vertical tail increases were required to meet directional stability requirements as Mach number rises. The increased stagnation temperature with increased speed had a major effect on the airplane's materials and systems. The resin used in the composite primary structure was changed from bismaleimide at Mach 2.4 to polyimide for Mach 2.8 and Mach 3.2. In fact, the high-temperature polyimide required at Mach 3.2 is not projected to be available until sometime after year 2000 certification. Fuel tank pressurization and inerting (with nitrogen gas) was required at Mach 3.2, and some pressurization was required at Mach 2.8.

Technology assumptions in each of the key areas of aerodynamics, structures, materials, propulsion, noise, and airplane systems were reviewed and updated for year 2000 and 2015 certifications. Table 4-4 shows key elements in each technology for the study Mach numbers.

The results of the speed studies are shown in figure 4-20, and listed in table 4-5. MTOW increases steadily as design Mach number is increased from 2.4 to 3.2. The Mach 3.2 configuration exceeds the

Table 4-4. *Key Technology Elements for Study Mach Numbers*

Speed regime	Mach 2.4	Mach 2.7	Mach 3.2
Fuel and fuel system	TSJF	TSJF + 50	TSJF + 100 Fuel tank pressurization with inerting
Propulsion	TBE with NACA nozzle	TBE with NACA nozzle	GE VCE with treated ejector + chute nozzle
Structure	Carbon/bismaleimide	Carbon/polyimide	Carbon/polyimide

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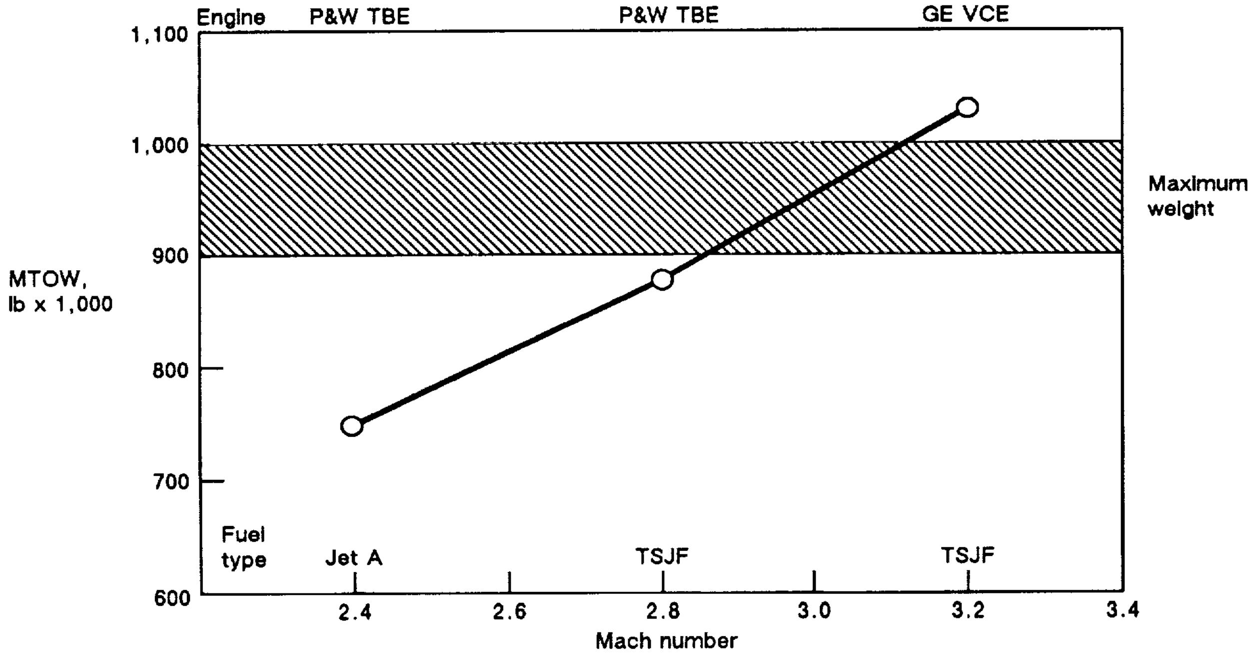

Figure 4-20. Airplane Size Speed Trends

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maximum weight limit substantially, even with the advanced high-temperature composite structure not currently projected for year 2000 certification.

As table 4-5 shows, Mach 2.4 has the lowest MTOW, OEW, and block fuel while Mach 3.2 has the lowest block time. Technical risks are evaluated on the relative levels of high, medium, and low. The table shows Mach 2.4 has the lowest technical risks in all categories; therefore, the Mach 2.4 configuration was selected as the baseline for the detailed environmental-impact studies described in section 5.0, "Environmental Evaluation."

The updated Mach 2.4 baseline uncycled airplane configuration is shown in figure 4-21. The influence of the various design requirements on the choice of MTOW, wing area, and engine size is shown in the sizing chart in figure 4-22. If there were no limitations imposed by climb time, thrust margins, fuel volume, approach speed, or takeoff field length, then the wing area and engine size chosen would limit the MTOW to the minimum possible level to satisfy the mission range requirement. However, these design limits do exist in that the airplane is sized by fuel volume and the transonic thrust margin.

Climb time would size the airplane at a weight very close to that of the transonic climb margin. These relationships changed for the different configurations studied, but the Mach 2.4-baseline sizing chart (fig. 4-22) provides an illustration of the technique used in the study. The Mach 2.4 baseline airplane selected from the sizing chart is defined as—

a. MTOW = 745,000 lb.
b. Aerodynamic reference wing area = 7,466 ft^2.
c. Engine airflow = 582 lb/s.

Table 4-5. Technical Benefits and Risk Assessment

Range = 5,000 nmi, 247 passengers			
Benefits			
Mach	2.4	2.8	3.2
Certification year	2000	2000	2000
Material	C/T-BMI	C/TPI	C/TPI
Fuel	Jet A	TSJF	TSJF
MTOW, lb	745,000	877,000	1,025,000
OEW, lb	323,200	385,900	442,500
Block fuel, lb	325,100	382,700	461,800
Block time, hr	4.5	4.0	3.7
Risk			
Aerodynamics	Low to medium	Low to medium	Medium
Stability and controls	Low to medium	Low to medium	Medium
Propulsion	Medium	Medium to high	High
Noise	High	High	High
Emissions	High	High	High
Structures	Medium	Medium to high	High
Materials	Medium	Medium to high	High
Weight and balance	Low to medium	Medium	High
Systems	Low to medium	Medium	Medium to high
Configuration	Low to medium	Medium	Medium to high

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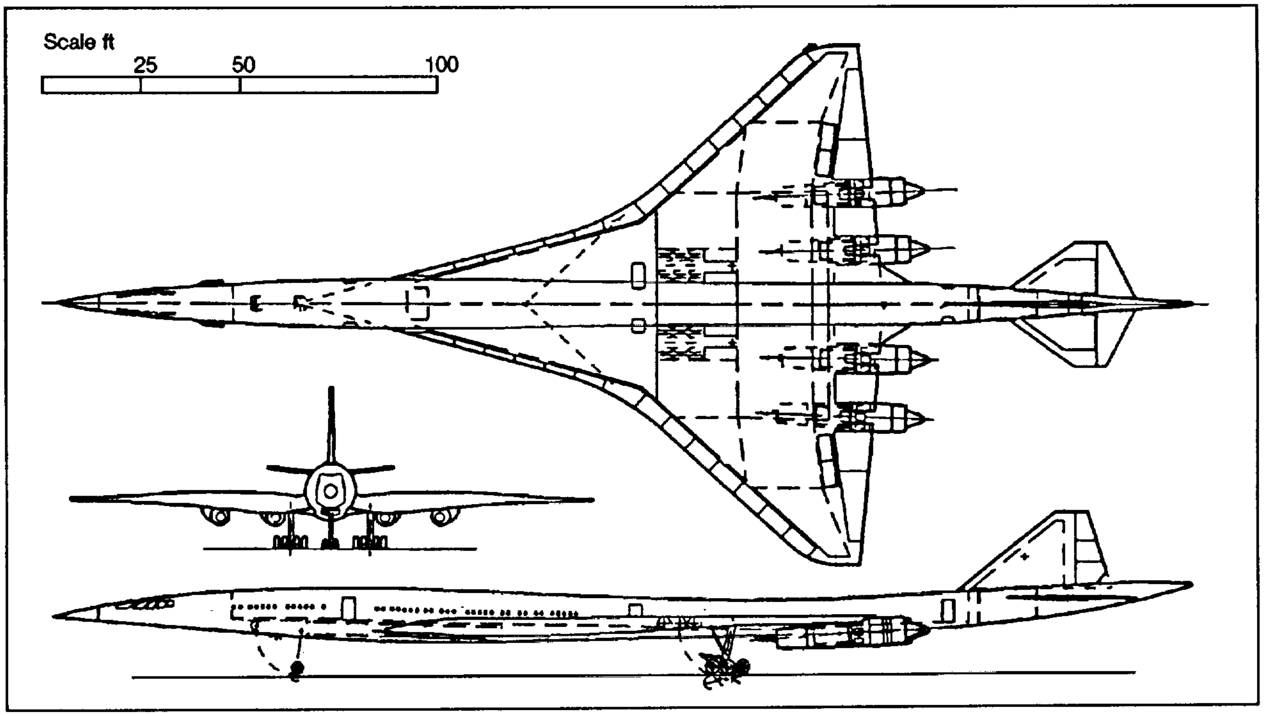

Figure 4-21. Mach 2.4 Baseline Configuration

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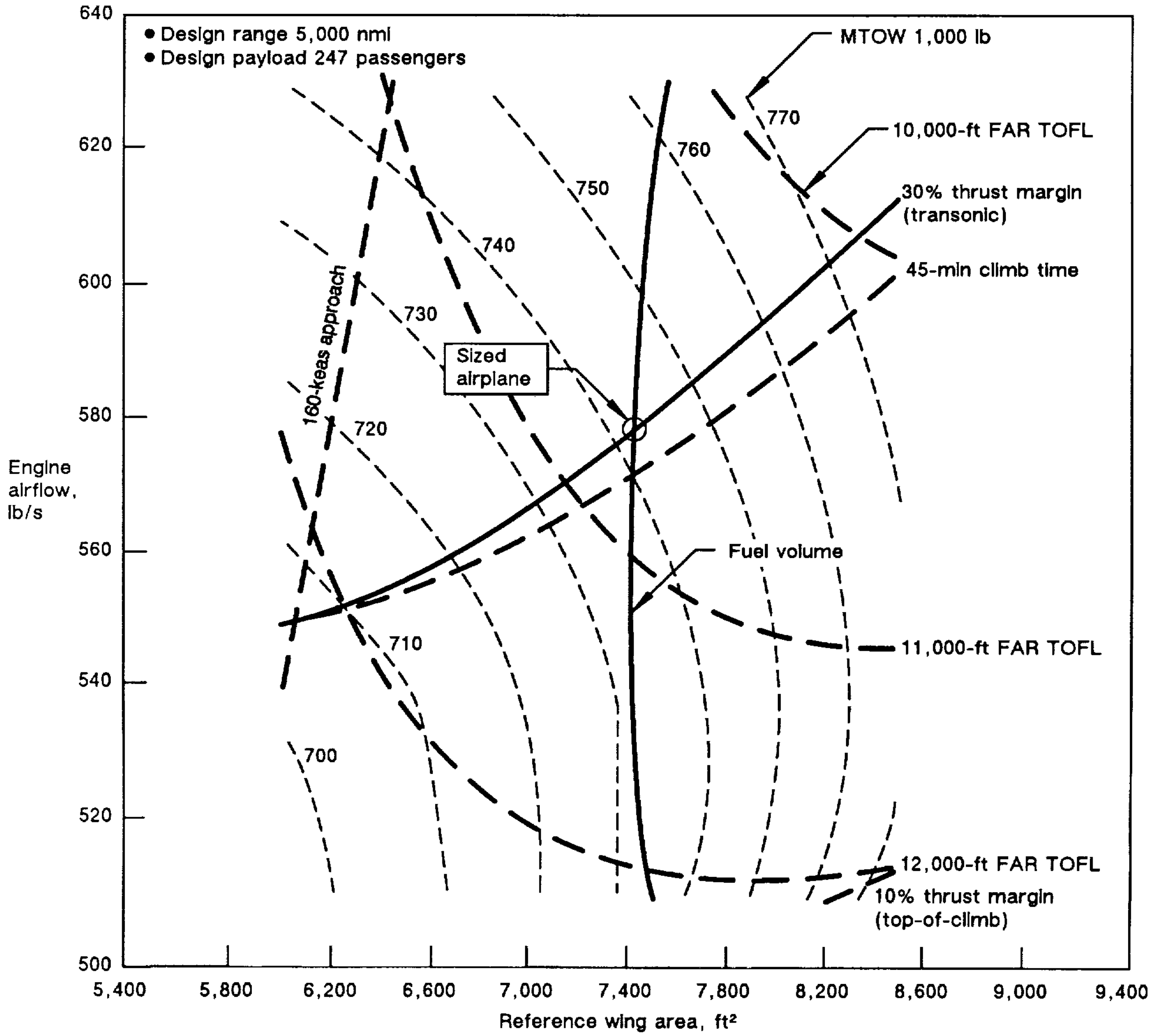

Figure 4-22. Sizing Chart Model—Mach 2.4 Baseline

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4.6 AERODYNAMICS

The aerodynamic tasks included—

a. Aerodynamic design integration of the study configurations.
b. Integration of a compatible high-lift system for each concept.
c. Evaluation of the aerodynamic characteristics of all concepts to provide necessary resizing data for the airplane performance calculations. These included both flaps-up cruise configuration analyses as well as flaps-down takeoff and landing evaluation.

The aerodynamic design 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 planform, thickness, and twist distributions from a previous study were used for the baseline configuration. The wing designs for the innovative and the low-sonic-boom configurations were developed using the methods that had been used to develop the baseline double-delta configuration.

The fuselage of each configuration was area-ruled to minimize volume wave drag by use of the transfer rule (refs. 4.2 and 4.3). The Mach number for area ruling was chosen to be 0.3 less than the cruise Mach. This provides a good compromise between transonic and cruise drag levels.

Nacelle shape, size, location, and operating conditions all influence the nacelle interference with other configuration components. The dominant interference effect is between the nacelles and the wing. To arrive at an acceptable nacelle configuration requires a balance between the isolated drag of the nacelle and the interference drag induced by the nacelle. The nacelles of each of the study configurations were placed below the wing and aft to (1) provide the inlet with a uniform flow field throughout the angle of attack range, (2) take advantage of the precompression caused by the wing shock, and (3) achieve significant favorable aerodynamic interference.

High-speed aerodynamic characteristics for all of the concepts were developed using the methods discussed in reference 4.4. Projections for year 2000 technology improvements have been included in the drag build-ups. These projections include—

a. A 5.4% reduction in skin friction drag resulting from the use of an outer surface treatment such as riblets over 90% of the vehicle wetted area.
b. A 3.5% reduction in volume wave drag and drag-due-to-lift resulting from design methodology improvements.
c. The incorporation of a 1.5% wind tunnel to flight test drag improvement.

The drag breakdown for the baseline airplane is shown in figure 4-23, and lift/drag versus Mach number shown in figure 4-24.

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.

Takeoff and landing speeds were based on set margins from the pitch attitude limits with the landing gear oleos fully extended at liftoff and fully compressed at touchdown. The selected minimum all-engine tail clearance margin at liftoff is 2 deg and at touchdown is 1.5 deg. Such features as a tail skid or an attitude limiting system would be required for aircraft structural protection. Approach speed was selected to be 3% faster than touchdown speed.

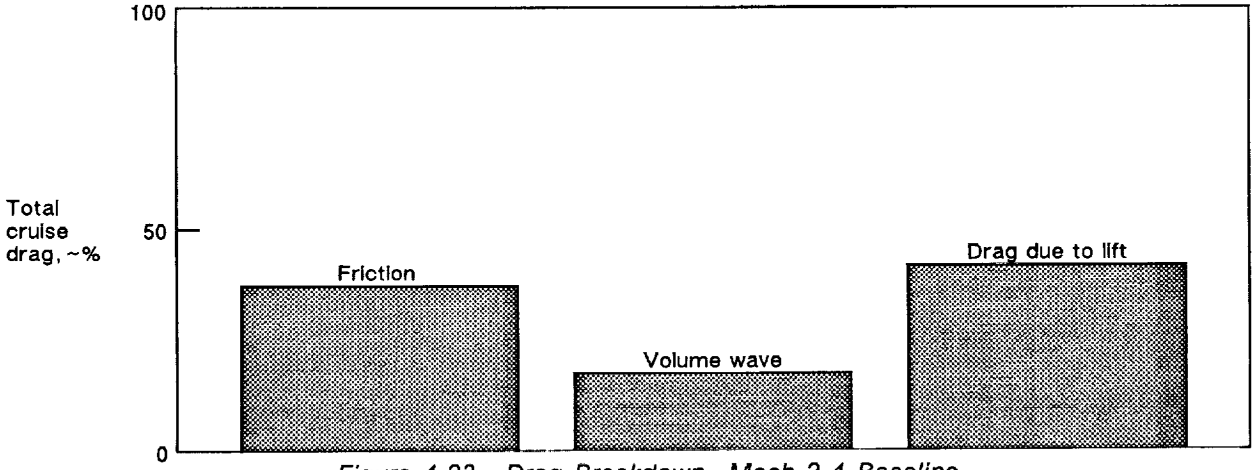

Figure 4-23. Drag Breakdown—Mach 2.4 Baseline

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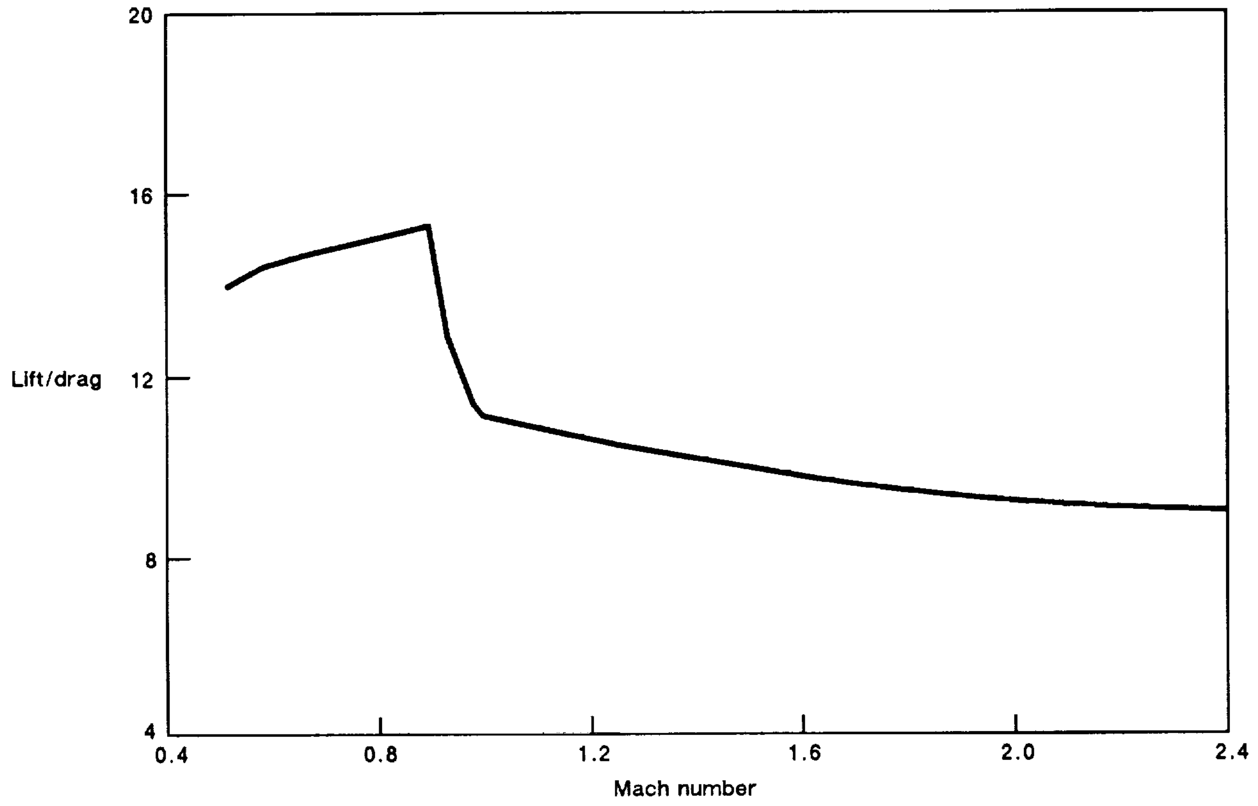

Figure 4-24. Lift/Drag Versus Mach—Mach 2.4 Baseline

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4.7 STABILITY AND CONTROL

The primary task for stability and control has been the estimation of horizontal and vertical tail size and center-of-gravity (CG) 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 will be of sufficient capability and reliability to provide acceptable handling qualities. Handling qualities will be as good or better than existing Boeing airplanes 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.

Longitudinal Axis. The main consideration for a control-configured vehicle design approach is the provision of adequate control capability at aft and forward CG limits. The provision of acceptable handling qualities affected by airplane stability levels will be accomplished through the use of the stability augmentation system.

Satisfactory stall recovery control determines the aft CG limit. The available pitching moment must be adequate to produce an airplane nose-down angular acceleration of -0.08 rad/s^2 at the minimum demonstration speed corresponding to 1g flight. The forward CG limit is determined by takeoff rotation requirements. Adequate control must exist to provide sufficient pitch acceleration at the rotation speed to achieve the required liftoff speed. Full deflection of the geared stabilizer/elevator is assumed.

No critical longitudinal control or stability conditions should exist at the supersonic aft CG limits. However, the horizontal-tail design hinge moments could become critical at the forward CG limit for some supersonic flight conditions.

Lateral-Directional Axis. The vertical stabilizer/rudder is sized to provide engine out control and high-speed directional stability. The design objective following engine or intake failure(s) is to provide good controllability using normal control techniques. Rudder inputs are used by the pilot to maintain heading following an engine failure on takeoff.

Rudder effectiveness directly affects the degree to which stability can be augmented by the stability augmentation system. At the design cruise Mach number of the Boeing 2707-300, a 65% loss in tail (rudder) effectiveness occurred because of bending in the vertical tail and aft fuselage. Stability characteristics are strongly dependent on both sideslip angle and angle of attack. The effect of increasing angle of attack is to rapidly decrease directional stability. For this reason, directional stability is lower in maneuvering flight and must be accounted for in the design of the stability augmentation system.

Lateral-directional characteristics of supersonic-hypersonic configurations are sensitive to changes in Mach number, dynamic pressure, and load factor. This is because of strong nonlinearities in key stability derivatives and large reductions of control effectiveness caused by structural flexibility. It must be demonstrated that the airplane possesses good handling qualities and adequate control to recover from emergency situations in all flight conditions.

4.8 WEIGHT AND BALANCE

Weight Analysis Approach. The primary source for the airplane technical definition is the general arrangement drawing. The weights databases of the Boeing 2707-300 and other studies (ref. 4.2) have been used for baseline structural sizing, loads, systems and equipment definition, design criteria, design requirements, and payloads system definition. Passenger comfort level requirements according to the current Boeing and airline companies' definition were substituted for the definition used on the model 2707-300. Advanced technology materials were applied for concepts projected to be certified in years 2000 and 2015.

Using the Boeing 2707-300 and 733-633 weight databases, a method of weight and balance analysis was developed. The independent parameters described above were input for an uncycled airplane at one specific gross weight, wing area, and engine size. The weight outputs were combined with weight "scalars" (weight increment versus parameter) in order to meet the design requirements.

The uncycled weights were analyzed for the uncycled airplane configurations, and the ballast required to meet the available CG limits was defined. This alternative for meeting balance requirements was selected because time was insufficient to reconfigure the design to achieve no ballast (i.e., relocating the wing on the body and resizing the empennage and main landing gear). Performance data were based upon the zero ballast weight data. In most cases, this was conservative for the "status" weight definition because the airplanes typically require forward wing shifts, which results in smaller empennages.

Weight Methodology. Using the weight databases for Boeing models 2707-300 and 733-633, parametric methods of component weight, balance, and moment of inertia analyses were developed. The algorithms apply parameter ratios to baseline absolute data. The input data required are primarily—

a. Geometry.
b. Component centroids.
c. Fuel quantities and tank centroids.
d. Design weights.
e. Structural weight factors for composite structure.
f. Systems requirements.

The output weight definition comprises the following elements:

a. Functional group weight breakdown with corresponding longitudinal CG.
b. Balance requirements that assume—
   1. Ballast or wing shift required (zero ballast) to meet the available CG limits; or
   2. Required CG limits for zero ballast without shifting the wing.
c. Pitch moments of inertia for three design (gross) weights.

Wing structure strengthening required for passive flutter stiffness up to Vmo speed is incremented as a function of (1) propulsion pod weight and longitudinal CG, and (2) wing geometry. The stiffness penalty is nonlinearly proportional to propulsion pod weight and location (i.e., "overhang" moment, which causes wing box torsion).

Expected improvements in weight technology from the present to the year 2000 are listed in table 4-6.

Table 4-6. Weight Improvements From Current Technology to Year 2000 Certification

Item	Weight Improvement
Participating structure (skin panels, body frame, etc.)	40% to 50% savings compared to 1978 definition with titanium
Active full-time flutter suppression system	OEW increment = -1,200 lb
Maneuver and gust load limiting	No change*
Stability augmentation	No change*
Flight deck, two versus three station	OEW increment = -200 lb
Flight deck, space provisions	No change*
Hydraulic system pressure, 5,000 versus 4,000 lb/in^2	OEW increment = -300 lb
Hydraulic system redundancy, three versus four systems	OEW increment = 0 to -1,000 lb
Hydraulic fluid operating temperature, 500° versus 350°F	OEW increment = 0 to -500 lb
Fly-by-wire	No change*
Thermal management	OEW increment = 0 to +500 lb

* Included in 773-633 baseline

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Weight and Balance Data. Weight and balance data for the 12 uncycled airplanes analyzed during the last phase of the contract are shown in table 4-7.

4.9 IMPACT OF TECHNOLOGY

To assist in the selection of the airplane configurations to be studied further, design trends were determined for the Mach 2.4 configuration as a function of technology level. Again, the primary index was the MTOW. Design ranges were parametrically changed from 3,000 to 6,000 nmi, with the results shown in figure 4-25. Advanced technology is essential to achieve the desired range capability (5,000 nmi) within a realistic size limit (MTOW = 900,000 lb). These data show that at 5,000 nmi the required MTOW is about 745,000 lb, well below the size limit. Figure 4-25 shows that the MTOW for year 2015 certification to be 585,000 lb at 5,000 nmi.

The results of a design payload sensitivity study are shown in figure 4-26. These data indicate a capability of about 320 passengers at a 900,000 lb MTOW for a design range of 5,000 nmi.

Figure 4-27 shows the impact of the technology advances projected for year 2000 certification versus that currently available for year 1995 certification at Mach 2.4. These data show that, collectively, advanced technology reduces the MTOW from 1 million pounds to 745,000 lb (about 25%) with advanced structures and materials providing the largest single benefit. The figure also shows the same data plus the impact of further technology improvements projected for year 2015 certification. The required MTOW is reduced from about 745,000 lb to about 585,000 lb (about 20%), with advances

Table 4-7. *Uncycled Weight Data*

Component	Mach 2.4 baseline 1080-834	Speed study			Ozone impact		Low sonic boom	Inno- vative	Community noise impact			
		Mach 2.4 1080-827	Mach 2.8 1080-832	Mach 3.2 1080-809	1080-835A	1080-844	1080-836A	1080-837A	1080-828	1080-829	1080-830	1080-831
Structure	148,800	170,700	173,500	180,300	151,300	150,900	183,300	187,700	171,400	174,700	179,100	184,300
Propulsion	63,100	74,900	82,100	93,700	68,800	68,300	63,100	63,100	71,100	81,400	93,200	81,400
Systems	78,300	80,000	80,300	82,100	78,400	78,100	81,700	80,200	79,800	80,000	80,300	81,700
Standard and operational items	14,000	14,400	14,400	14,100	14,000	14,000	14,600	14,400	14,400	14,400	14,400	15,100
OEW without ballast (point design)	304,200	304,000	350,300	370,200	312,500	311,300	342,700	345,400	336,700	350,500	367,000	362,500
Maximum takeoff weight, lb	650,000	750,000	750,000	750,000	650,000	650,000	650,000	650,000	750,000	750,000	750,000	750,000
Wing area reference, ft^2	7,050	7,700	7,700	7,700	7,050	7,050	7,050	7,050	7,700	7,700	7,700	8,725
Engine airflow, lb/s	540	630	630	725	670	540	540	540	600	680	770	680
Number passengers-triclass/tour	247/285	247/285	247/285	247/285	247/285	247/285	268/306	245/283	247/285	247/285	247/285	247/285

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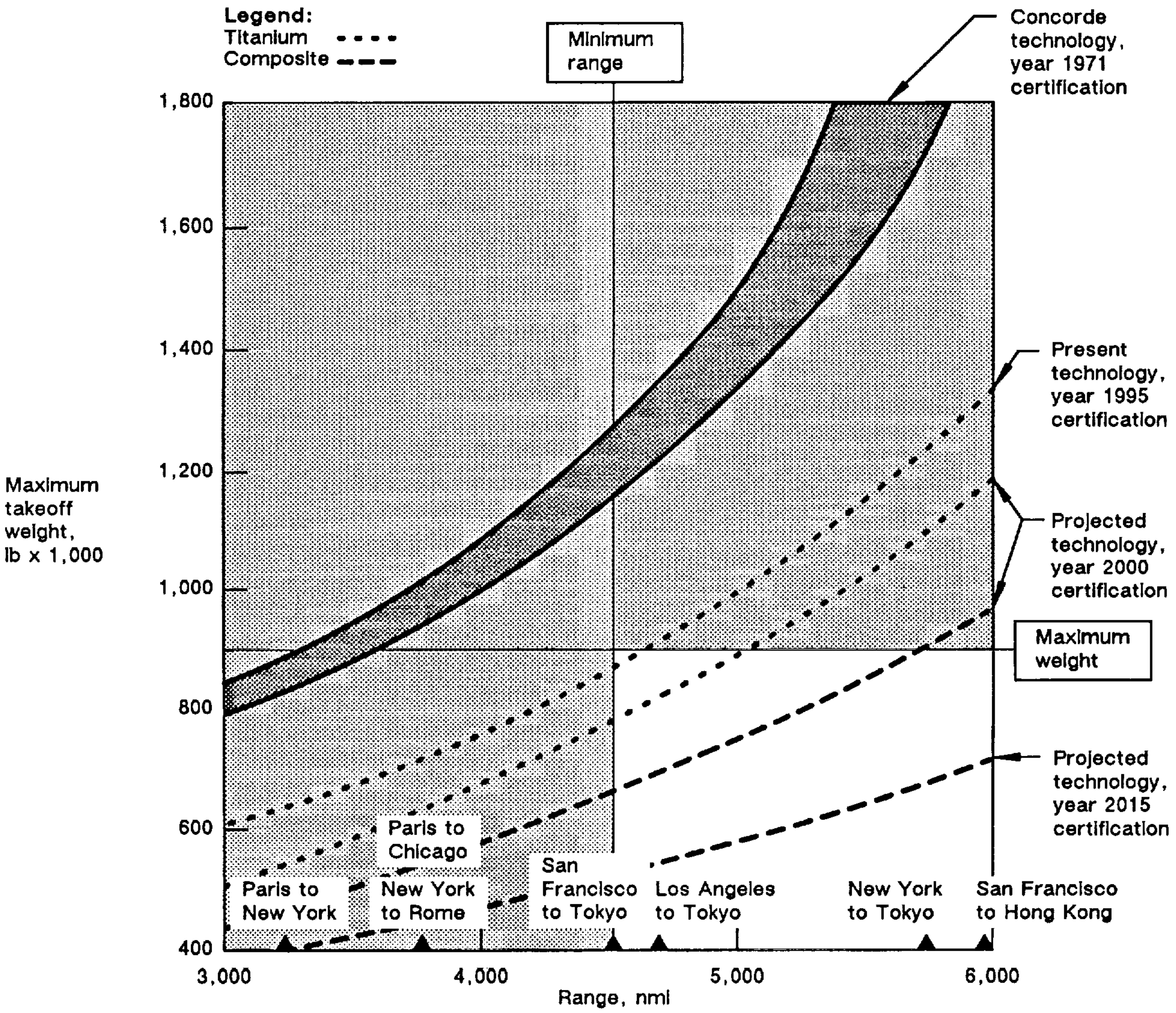

Figure 4-25. Impact of Technology—Mach 2.4 Baseline

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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. 4-19).

The influence of systems technology on the results of the study supported the major conclusion that there were benefits in designing to low Mach numbers. Because the studies were driven significantly by weight considerations and because systems constitute only a small percentage of the vehicle weight, only those systems features that could be identified as configuration drivers were evaluated. Particularly important was the thermal analysis of the aspects of "heat sink," which showed that only the lower Mach number configurations using TSJF were practical.

In summary, a 250- to 320-passenger airplane cruising at Mach 2.4 in the 750,000- to 900,000-lb MTOW region appears technically feasible for year 2000 certification, providing the technology advances are validated at the requisite time.

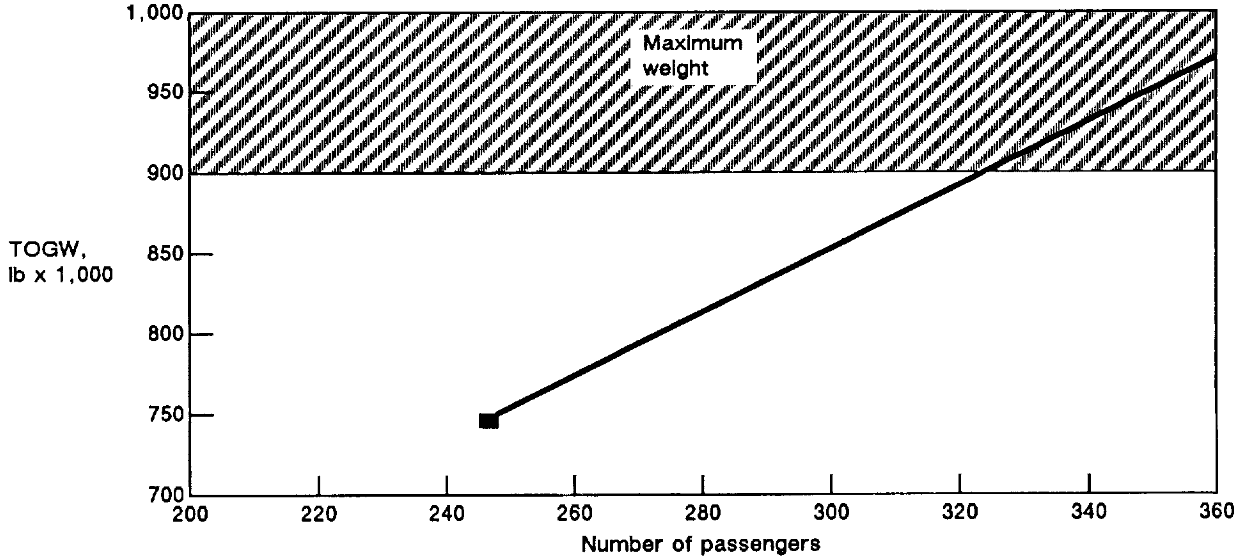

Figure 4-26. Design Payload Sensitivity—Mach 2.4, 247-Seat Airplane With Year 2000 Certification

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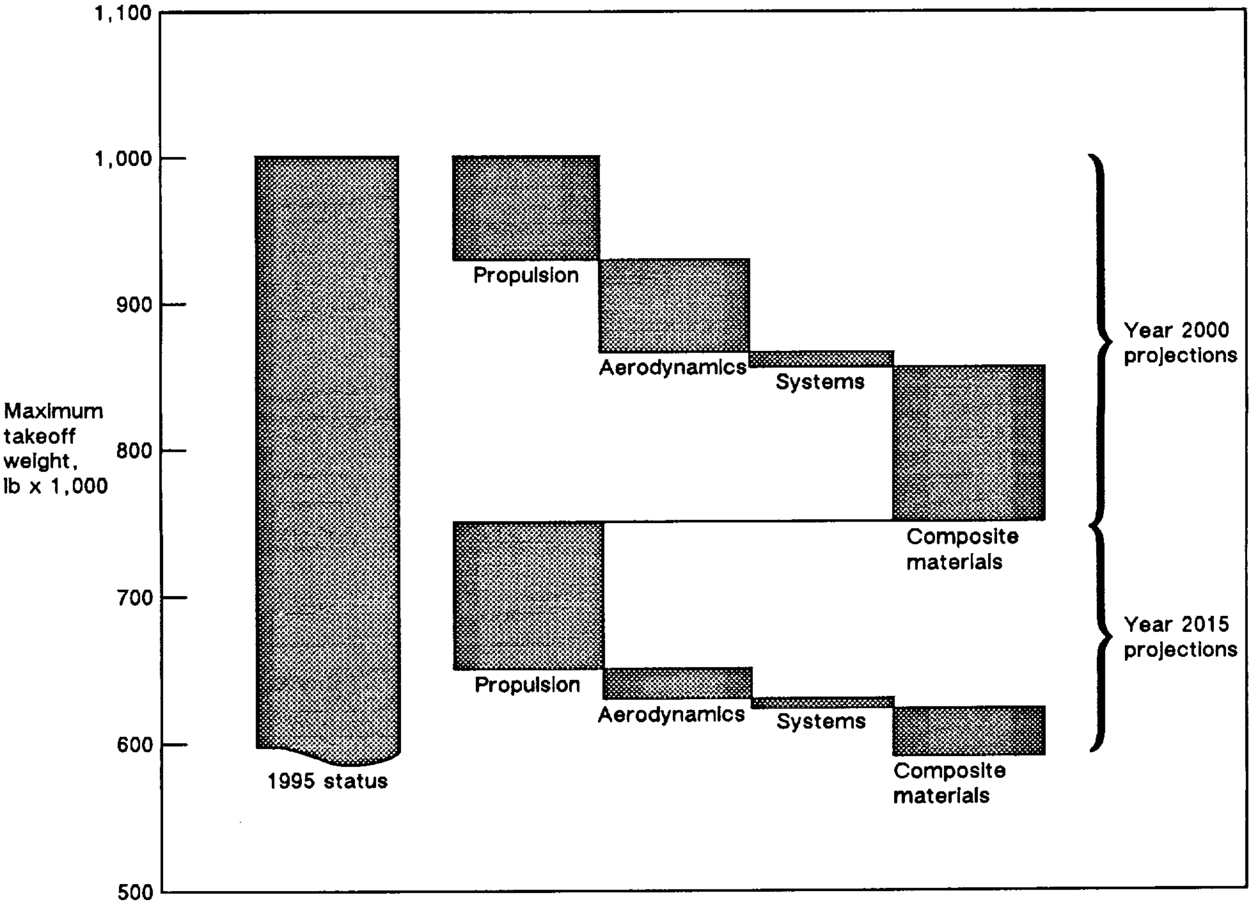

Figure 4-27. Impact of Technology—Mach 2.4, 247-Seat Airplane With Year 2000 Certification, 5,000-nmi Design Range

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5.0 ENVIRONMENTAL EVALUATION

The objective of the environmental evaluation was to address key questions regarding the environmental acceptability (upper-atmosphere engine emissions, airport and community noise, and sonic boom overpressure) of the HSCT. The study focused on the requirements for acceptability and the penalties incurred for meeting them (i.e., Are these requirements technically and economically feasible?). Because the vehicle development studies (sec. 4.0, "Vehicle Development") indicated the most technically viable HSCT to be a Mach 2.4 configuration, the environmental evaluations were based on an updated Mach 2.4 baseline.

The approach taken to determine the acceptable environmental requirements was as follows:

a. Upper-atmosphere engine emissions. The study provided NASA with emissions data for representative fleets of airplanes for analyses with math models of the Earth's atmosphere. Airplane mission studies would determine the impact on the airplane size from using reduced-emission engine combustion technology. (In sec. 4.0 no assessment was made of the impact on the configuration maximum takeoff weight (MTOW) for meeting possible reduced emission level requirements.)

b. Airport and community noise. Community noise levels no greater than the current FAR36 Stage 3 requirement were assumed to be required for an HSCT. Analyses determined the impact of meeting current noise requirements with projected suppression technology. (sec. 4.0 used the most optimistic projection for noise-suppression technology, but assumed that no significant engine/wing-area oversizing would be required for meeting required noise levels.)

c. Sonic boom. The assumption that an acceptable sonic boom acoustic disturbance from HSCTs can be defined and achieved such that supersonic flight is permitted over populated areas. This should lead to an assessment of the potential for supersonic overland flight. (sec. 4.0 assumed supersonic flight over water only.)

The approach taken in evaluating the penalties for meeting reduced emissions, low sonic boom, and community noise was to first establish a Mach 2.4 "baseline" performance-sized airplane. This airplane was then modified to reduce emissions, noise, and sonic boom to determine the effect on airplane size (MTOW) and, consequently, technical and economic feasibility. Figure 5-1 illustrates the particular environmental issue that each model was designed to address. This baseline airplane is powered by Pratt & Whitney (P&W) engines. An alternative General Electric (GE) powered baseline was established for the reduced emissions impact study only.

5.1 UPPER ATMOSPHERE EMISSIONS–OZONE IMPACT

A technically viable HSCT must be designed so that its engine emissions have no significant impact on the ozone layer. The impact will be determined by NASA, the environmental community and the responsible regulating agency. It is possible that engine emissions (NOx) may affect the ozone layer, but much additional scientific knowledge must be acquired before the true relationship between NOx and ozone depletion is known. In this study Boeing evaluated several airplane fleet scenarios incorporating reduced emission concepts to define possible global patterns of HSCT fleet emissions. Additionally, this study determined the resulting effects of using innovative engine-combustor technology to reduce NOx emissions on airplane size and economic feasibility. These emission concepts and their penalties are presented in section 3.4, "Emission Reduction Concepts."

Emission levels for the scenarios have been supplied to NASA who will, along with their subcontractors, use one- and two-dimensional atmospheric models to assess the effects of these global emission levels on the ozone layer.

Ozone Evaluation Matrix. A matrix of seven airplane fleet scenarios and engine-emission characteristics for utilization in math models of the Earth's atmosphere were selected (table 5-1). The first scenario, case B4, is the baseline for the current 1987 subsonic fleet. Two additional subsonic baselines,

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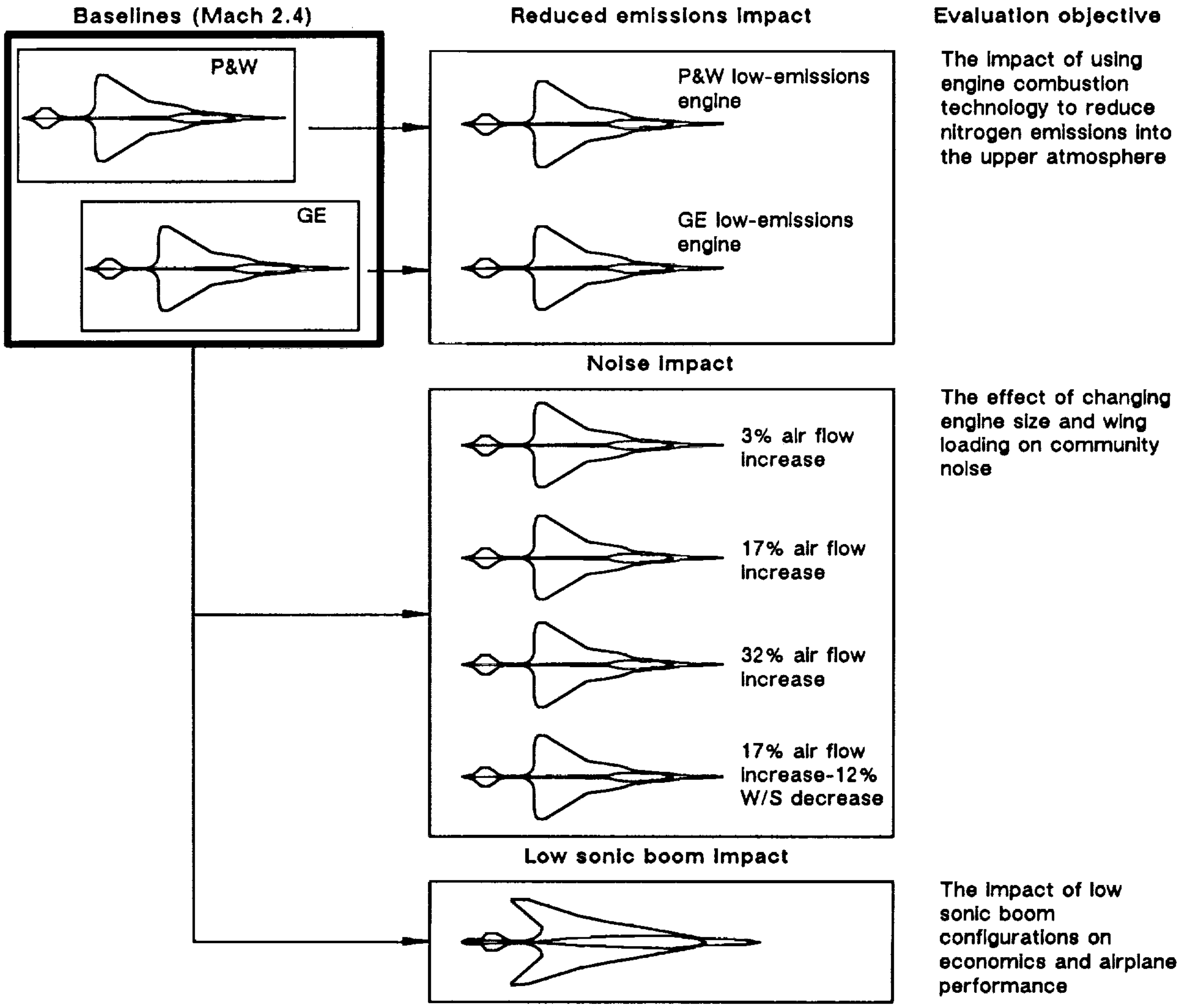

Figure 5-1. Environmental Impact Study Approach

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B5 and B6, were also developed for the years 2000 and 2015. These scenarios account for projected fleet growth, retirement, and replacement of some of the current fleet, together with projections on the emission levels of their future engines. It was assumed that the increased emissions for the year 2015 fleet would come from fleet growth only, and that the average engine NOx would remain constant. This would be achieved by introducing reduced NOx combustors to offset any increase in engine operating temperatures.

Four supersonic scenarios are presented for a fully developed year 2015 airplane fleet. Evaluation B7 is a Mach 2.4 fleet flying subsonic (Mach 0.9) over land and using the most innovative combustor design (lean, premixed, and prevaporized (LPP)) for emission reduction presented by P&W. Evaluation B8 is for the same fleet scenario, but using the most innovative combustor concept (LPP) presented by GE. In evaluation B9, the airplane cruise speed was lowered to Mach 2.1, which results in a lower average cruise altitude that, in turn, reduces the impact on the ozone. The final evaluation, B10, accounts for the airplane flying Mach 1.5 over land, rather than Mach 0.9, which impacts the ozone slightly more because it occurs at a higher altitude.

Each scenario requires the appropriate size and mix of aircraft to satisfy the projected demand for air transportation of each specified time.

Table 5-1. Ozone Evaluations

Case	Date	Fleet type	NOx technology	Comments
B4	1987	Current subsonic	Estimated NOx for current fleet	Estimated NOx for current fleet
B5	2000	Estimated year-2000 subsonic	Estimated NOx for year-2000 fleet	Reflects retirements, replacements, and growth
B6	2015	Estimated year-2015 subsonic only	Average estimated NOx for year-2015 fleet	Reflects retirements, replacements, and growth; assumes implementation of low NOx combustor technology; no HSCT
B7	2015	Estimated year-2015 sub/supersonic mix	Supersonic NOx emission index = 5 (P&W data) for Mach 2.4 airplane, alt = 60K average subsonic NOx from B6	Subsonic fleet size to complement supersonic fleet
B8	2015	Estimated year-2015 sub/supersonic mix	Supersonic NOx from emission index = 9 (GE data) for Mach 2.4 airplane, alt = 58.5K average subsonic NOx from B6	Same as evaluation B7 second dataset
B9	2015	Estimated year-2015 sub/supersonic mix	Supersonic NOx from B7 for Mach 2.1 airplane, alt = 56.7K average subsonic NOx from B6	Modified sub/supersonic fleet mix to reflect Mach 2.1 utilization
B10	2015	Estimated year-2015 sub/supersonic mix	NOx for Mach 1.5 over land (46K) and supersonic NOx from B7 Mach 2.4, alt = 60K average subsonic NOx from B6	Modified sub/supersonic fleet mix to reflect Mach 1.5 over land; modified from B7

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The projected emission levels from the seven scenarios will be evaluated for their impact on the ozone layer by NASA in 1989. The results will be used to determine the level of emissions required to achieve the objective of no significant impact on the ozone layer, with the significance of any impact being determined by the environmental community and the responsible regulating agency.

Figure 5-2 provides sample results for case B7, the subsonic, supersonic mix, presenting the total emissions of the oxides of nitrogen, with distribution at every 10 deg of latitude. The 26,000-ft altitude data represent subsonic airplanes flying missions of 400 statute miles or less. The 37,000-ft altitude data represent both the subsonic fleet for missions above 400 statute miles, and the subsonic legs of the HSCT. The 60,000-ft altitude data represent the cruise emissions of the HSCT.

Emission Reduction Impact. The impact of using engine combustion technology to reduce NOx emissions was evaluated by comparing the Mach 2.4 baseline vehicle with configurations powered by engines designed for reduced emissions. Both P&W and GE, as their most innovative approach to the problem, proposed an LPP combustor to reduce the NOx emissions. Details of these innovative combustor concepts are reported in section 3.4, "Emission Reduction Concepts."

The GE-proposed LPP combustor is predicted to reduce the NOx emission index from 31 to 9 (NOx index units are pounds of emission per 1,000 lb of fuel burned). GE estimated that there would be negligible change in engine performance, weight, and economics penalties. They emphasized the high risks in combustor development associated with premixing duct flashback and autoignition.

The P&W LPP-type combustor had an estimated NOx emission index reduction from 32 to 5. This combustor was also considered by P&W to require an aggressive research and development program. P&W also emphasized the high risks in attempting to achieve the emission goal, and had the same concerns as GE on the possible operating limitations caused by duct flashback and autoignition. Negligible changes in performance and economics were estimated, but an increase in engine length, combustor diameter, and weight were projected. These changes resulted in an increase in nacelle weight and associated aircraft structure, with a resultant growth of 3.7% in the airplane MTOW as shown in figure 5-3. The figure also shows the results for the GE engine with no change in MTOW or any

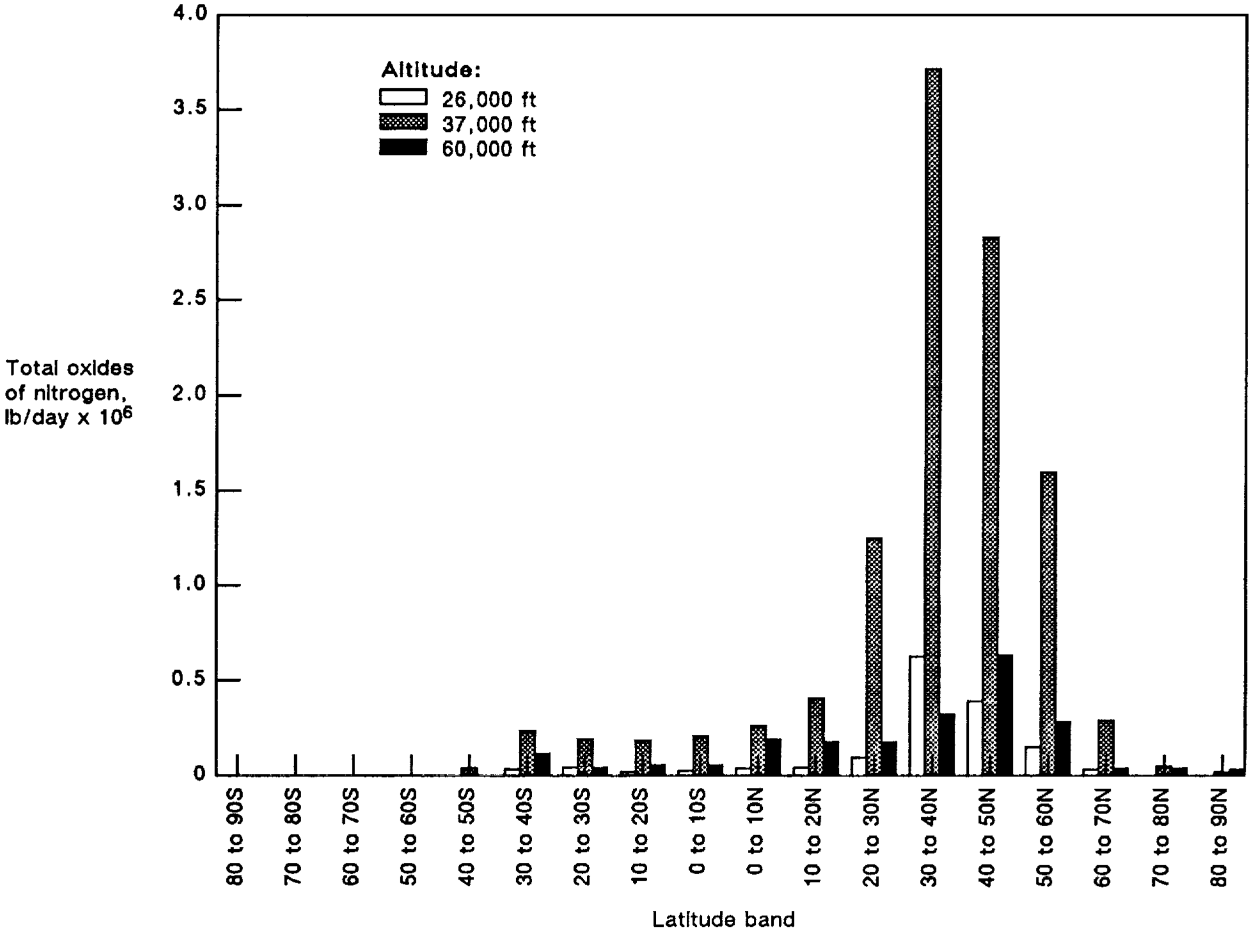

Figure 5-2. Case B7, Subsonic-Supersonic Mix—Year 2015

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other performance-related item. The two other P&W concepts were considered to have lower development risks and have MTOW increases of approximately 2.2% and 2.7%.

While the LPP combustor shows promising reductions in NOx levels, it must be emphasized that the development of such a combustor would require a significant research commitment, and that, as mentioned, the high risk of premixing duct flashback and autoignition could make the concept unacceptable. The staged-lean (SL) combustor provides a smaller NOx reduction for a significant MTOW penalty, but is considered a lower risk technical challenge. The rich-burn, quick-quench (RBQQ) combustor may prove acceptable with a significant NOx reduction for a smaller MTOW increase than either the LPP or the SL combustor.

5.2 COMMUNITY NOISE

One objective of the current study is to explore the potential for an HSCT to be as quiet as subsonic airplanes designed to meet FAR36 Stage 3 noise levels. An evaluation must be made concerning how this will affect the airplane size and the unique characteristics of an HSCT. Unlike the other airplane configurations described in this section, the noise-impact airplanes are intentionally oversized in engine airflow and, in one case, the wing area. Three models were defined that retain the same takeoff wing loading as the baseline airplane, with increases in the engine airflow. Two models retained the same engine airflow (680 lb/s) and decreased the original wing loading by 11.8%. Because none of these airplanes are sized by thrust-related requirements, the only limitation on the airplane size is the range requirement.

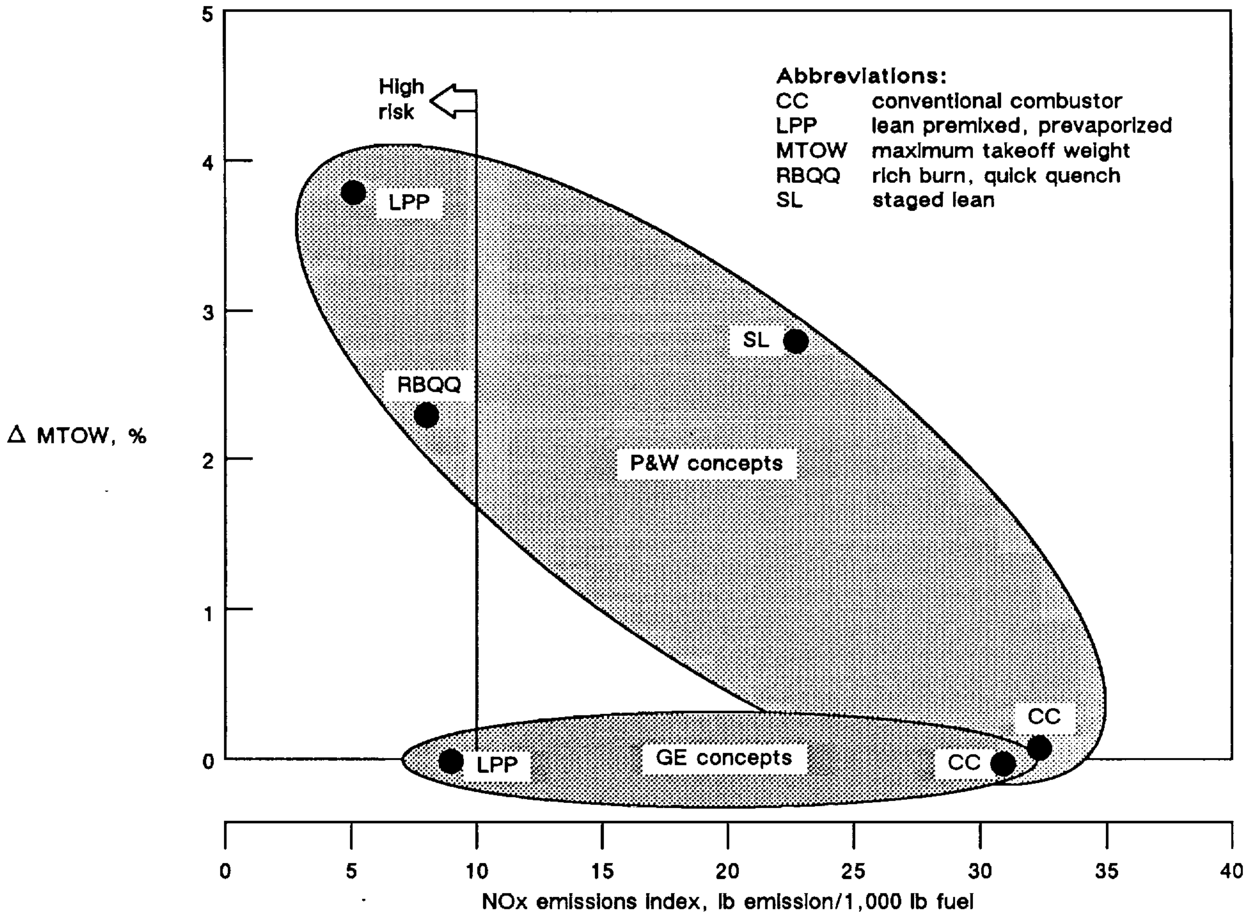

Figure 5-3. Maximum Takeoff Weight Penalties for Combustor Concepts With Reduced NOx Emission Index

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Community Noise Goals. Two goals were persued for the analysis 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 the Boeing 747-200 (with JT9D-7Q engines), which is certified to meet the Stage 3 criteria. The latter case used the ground area enclosed by a contour (footprint), which receives a minimum of 85 dBA of aircraft noise. The 747 airplane was selected because of similarities in MTOW, number of engines, and compliance with the FAR36 Stage 3 noise requirements. The target 85 dBA footprint area of this 747 model, using FAR36 takeoff procedures, is 4.6 mi^2.

Community Noise Summary. The FAR36 sideline noise requirement is the most difficult to meet in that Stage 3 sideline noise limits cannot be met using maximum takeoff thrust throughout the takeoff and climbout, or even using a derated engine with sufficient thrust for a 12,000-ft takeoff field length. The best procedure for reduction of sideline noise for the baseline airplane is a programmed lapse rate (PLR) that reduces takeoff thrust after liftoff. The PLR procedure shown in figure 5-4 employs maximum takeoff thrust during takeoff roll, then progressively reduces thrust between the 35-ft altitude and the end of landing gear retraction by an automatic means invisible to the flightcrew. The airplane accelerates and climbs from the gear-up point to the thrust-cutback point 689 ft above the runway at a horizontal distance that results in the FAR36 cutback-thrust level being achieved 21,325 ft from brake release. The cutback is a full FAR36 cutback, where the airplane meets or exceeds a 4% climb gradient with all engines operating or the airplane achieves level flight with an inoperative engine.

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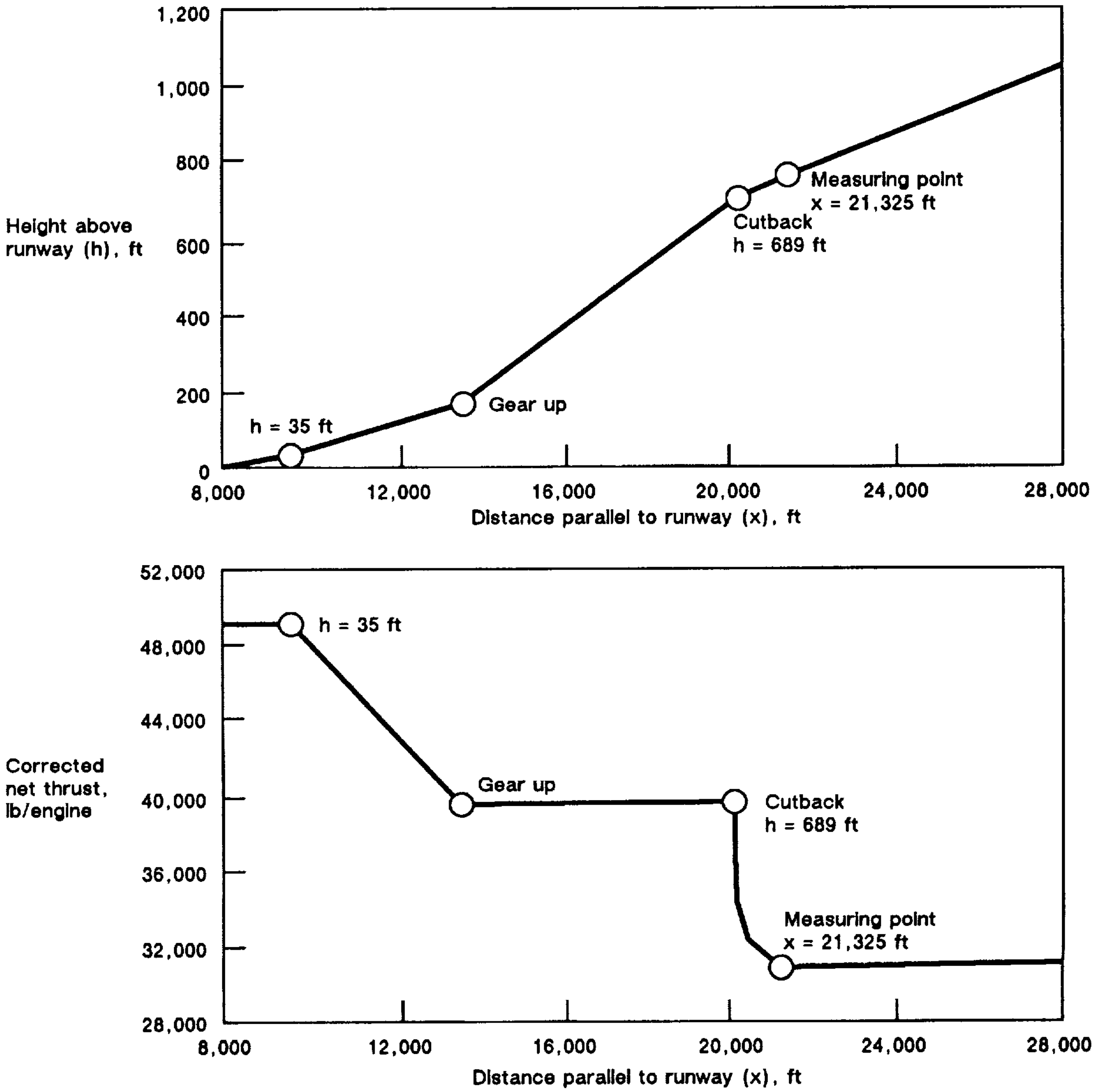

Figure 5-4. Takeoff Profile

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An automatic takeoff thrust control system (ATTCS) is required in the airplane design to ensure minimum FAR25 takeoff climb-gradient capability in the event of an engine failure. It is estimated that approximately a 4% thrust reduction below that necessary to meet minimum takeoff climb gradient capability is required for 20% PLR.

For the configurations using increased airflow, sideline noise was reduced by derating the takeoff thrust so that takeoff field length is equal to that of the baseline at maximum takeoff thrust, and then applying a 20% PLR procedure. Stage 3 limits were met nominally without trades with a configuration that has an engine oversized by 11.7%, from the baseline of 582 to 650 lb/s (fig. 5-5). Sideline noise is reduced by approximately 4 EPNdB, and the MTOW increases by 4.7%. The 20% PLR profile results in an increase in the cutback noise level because cutback height is being traded against the thrust reduction for sideline noise. The performance-sized airplane meeting the equal footprint area

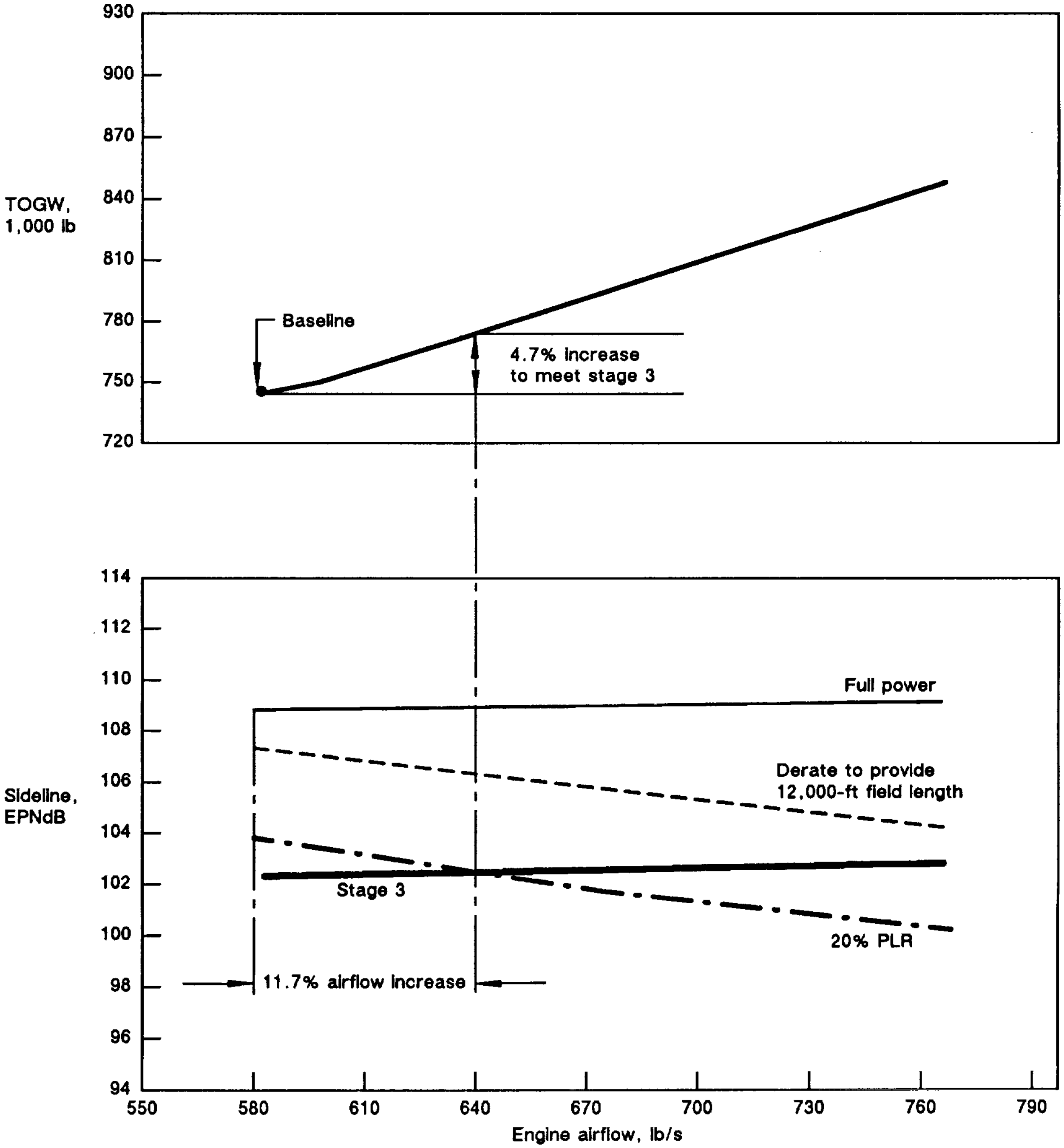

Figure 5-5. Noise Impact Study Results—Penalty To Meet Sideline Stage 3 Noise Rule, Constant Wing Loading

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objective has a 28% oversized engine (582 to 745 lb/s) with a 12.1% MTOW increase (fig. 5-6). The procedure that obtained the target footprint area with the smallest engine was to use the thrust derated to that required for a 12,000-ft takeoff field length.

The effect of an 11.8% wing loading reduction was accomplished at 88 lb/ft^2 using a 680 lb/s engine size. The resulting MTOW increase (lower thrust/weight (T/W)) more than offset the lift/drag (L/D) benefit from the larger wing; consequently, the takeoff noise increased rather than decreased (fig. 5-7).

Airport Community Noise Environmental Study. In the airport study, residential noise exposure was evaluated at 18 airports with the assessment made with 85 dBA noise contours (footprints). Three

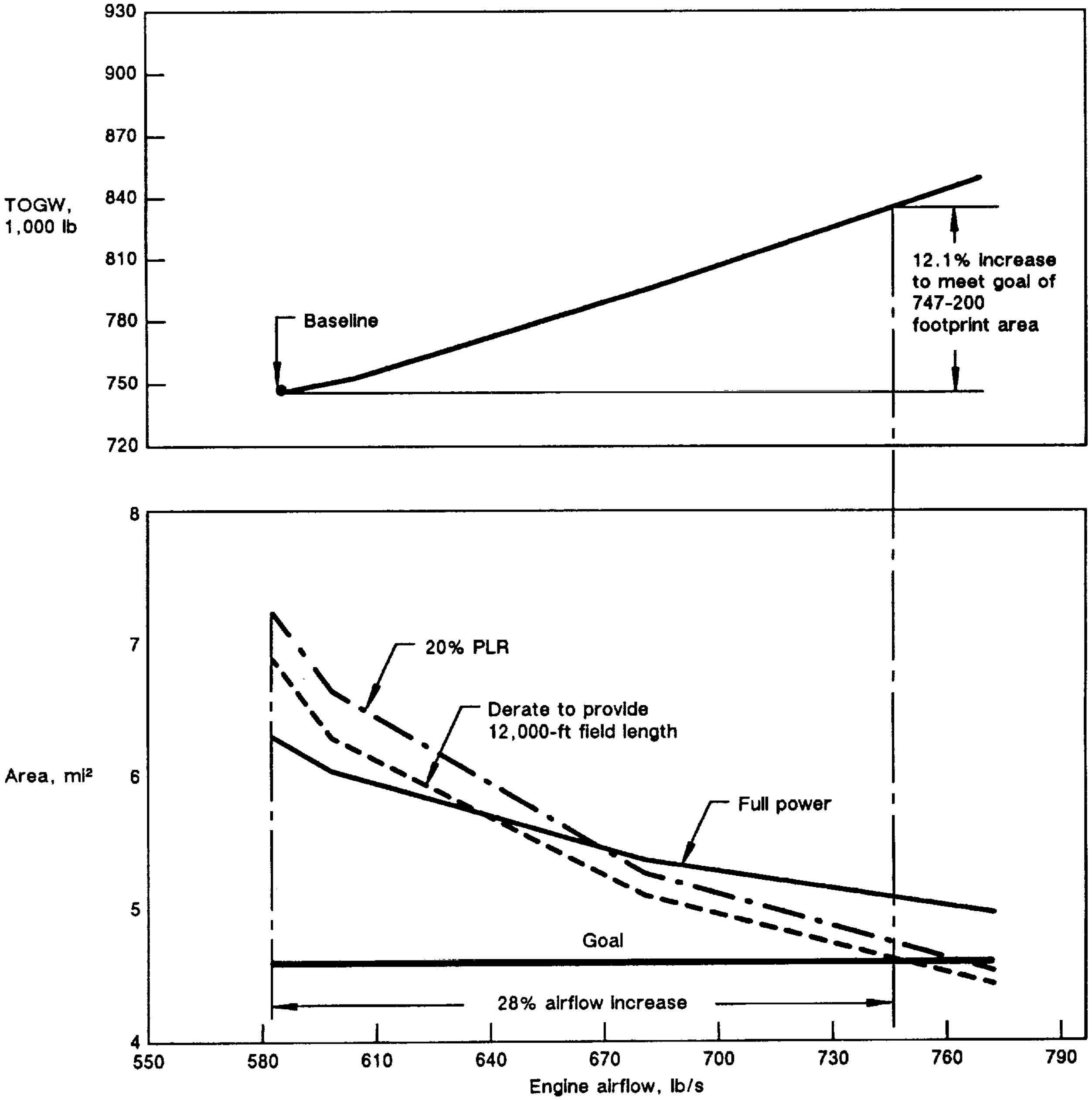

Figure 5-6. Noise Impact Study Results—Penalty To Meet 747-200 Footprint Area, Constant Wing Loading

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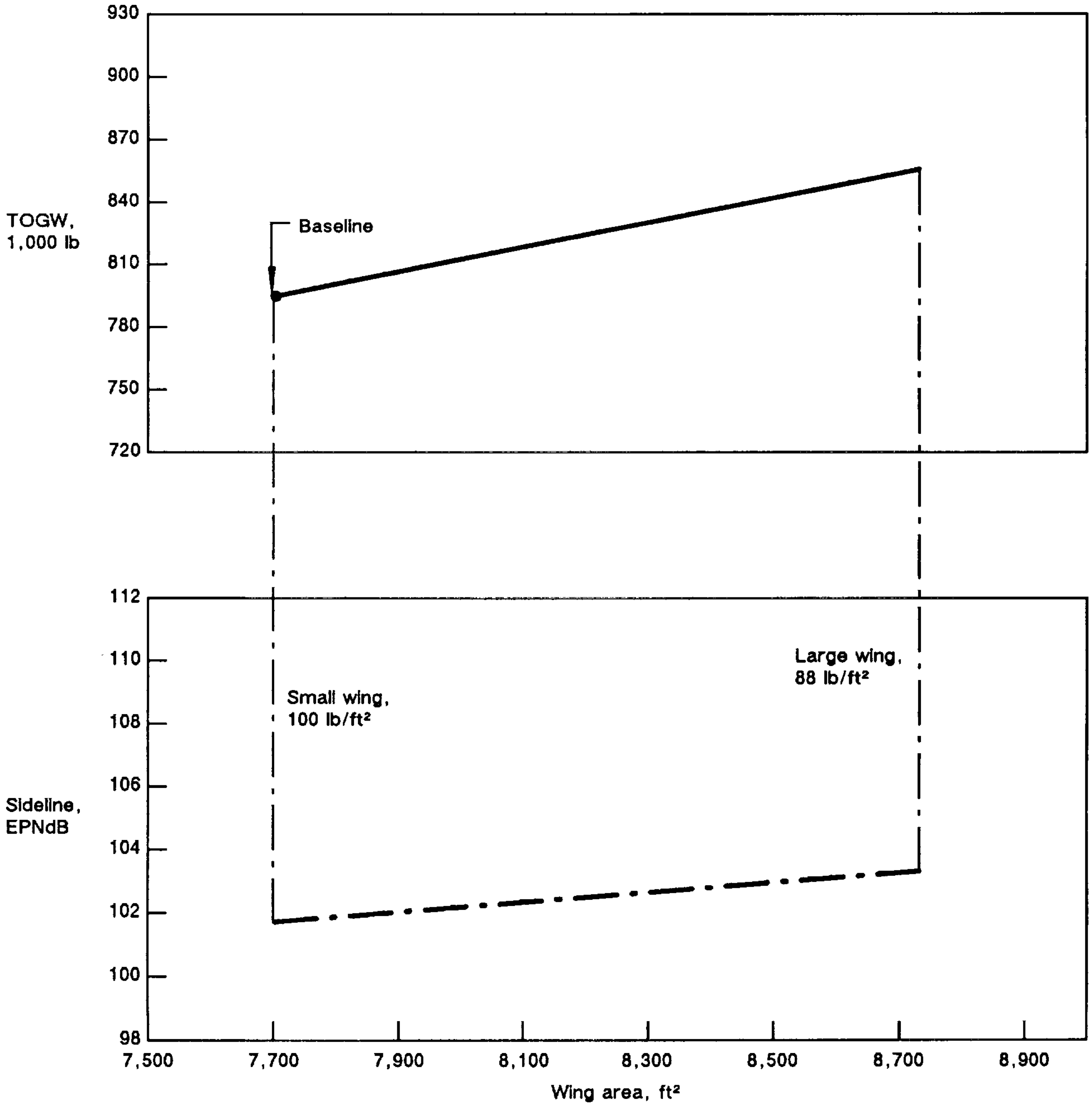

Figure 5-7. Noise Impact Study Results—Effect of Wing Area (Wing Loading), Constant Thrust Loading

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HSCT footprints were compared to the Boeing 747 footprint. Characteristics of the HSCT configurations-takeoff procedures are as follows:

a. Engine sized to 650 lb/s and 20% PLR takeoff procedure (meets Stage 3).
b. Engine sized to 650 lb/s and maximum takeoff thrust (to the FAR36 cutback point).
c. Minimum size engine (582 lb/s) and maximum takeoff thrust (to the FAR36 cutback point).

Footprints for the 650-lb/s-size engine are shown in figure 5-8. The HSCT footprint with the 20% PLR procedure is very similar to the Boeing-747 footprint. The residential area exposure at levels greater than 85 dBA was nearly the same as the Boeing 747 (actually 6.5% less because the HSCT footprint is slightly shorter). The maximum takeoff thrust was found to expose 43.2% less residential

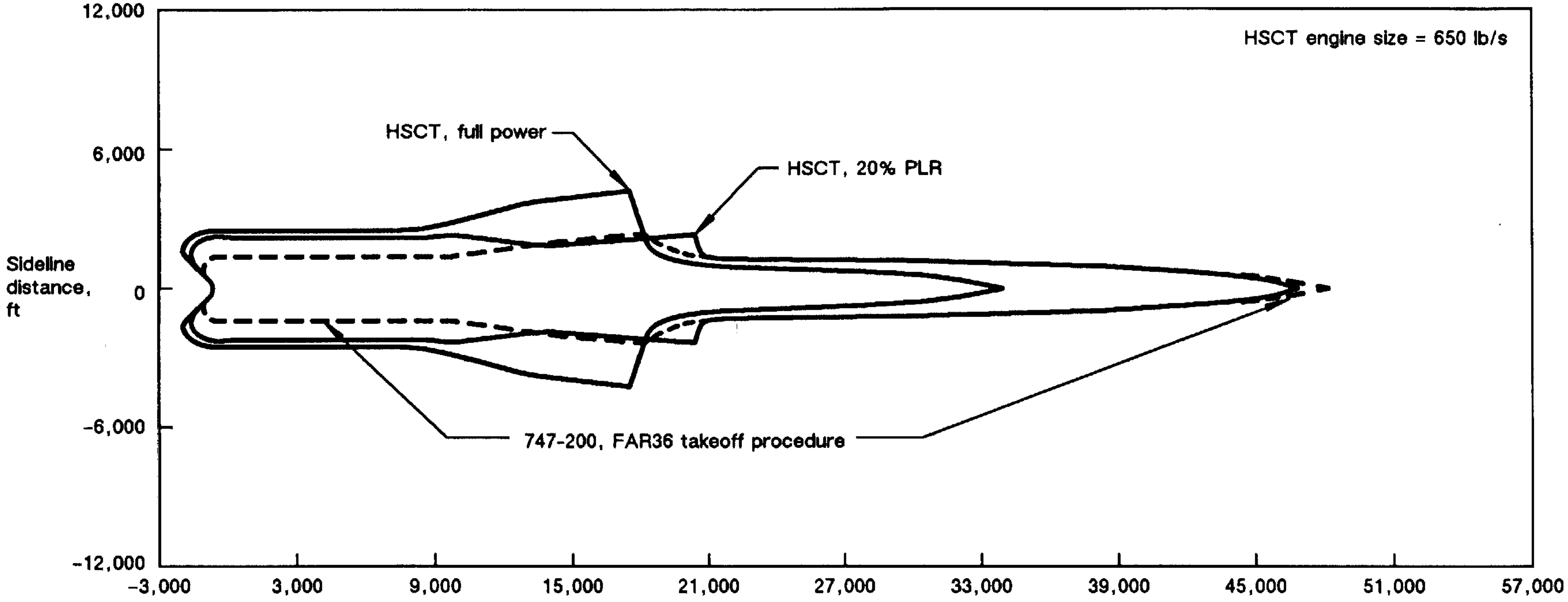

Figure 5-8. Noise Contour at 85 dBA—Comparison of HSCT to 747-200

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area based on an average of the 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. Thus, to meet Stage 3 sideline noise levels a takeoff procedure was required that increased total airport community noise exposure and therefore inhibits using the best solution for the airport community.

Community Noise Study Conclusion. The study indicated that Stage 3 noise levels are technically feasible with the current projections for noise suppression technology. Stage 3 can be accomplished by oversizing the engine and using the 20% PLR takeoff procedure.

A preferable solution would be to make improvements to the suppression design, and also, the implementation of regulatory changes to permit higher sideline noise at the airport so that lower community noise levels may be achieved. A supersonic Stage 3 noise rule that takes into account the HSCT's unique ability to climb away from the community would have the dual benefit of reducing the impact on the community and improving the economics of the airplane.

5.3 SONIC BOOM

A further objective of the study was to determine what combination of design technology and operational constraints will allow a variation of the baseline HSCT to cruise over land at supersonic speed without causing public objections. The Concorde was not designed with any direct consideration of minimizing sonic boom. Current laws, inspired by the Concorde experience, prohibit supersonic commercial flight over many countries. Because the baseline HSCT of this study produces an unacceptable sonic-boom overpressure of about 2.4 lb/ft^2 at the start of cruise, it would be limited to supersonic cruise only over water. The productivity reduction would be significant compared with unrestricted HSCT flight. This study examined several options for reducing the sonic boom shock wave amplitude to an arbitrary target (1.0 lb/ft^2). It is recognized that sophisticated criteria must be developed to account for the combined effect of the shock-wave amplitude and waveform on humans, animals, and structures. Further, the more complex case of supersonic segments of climb and descent must also be considered.

Sonic Boom Loudness Study. Before an HSCT can fly supersonically over land, acceptable acoustic disturbance criteria and an acceptable acoustic level must be defined. Within the scope of this contract, Boeing has not conducted human response testing to establish acceptable criteria. Therefore, design goals were based on previously published human response testing (ref. 5.1), using perceived noise in terms of dBA level as an indication of loudness, and is defined as follows:

a. Noise levels must be equal to or less than 72 dBA for restricted overland flight (corridors).
b. Noise levels must be equal to or less than 65 dBA for unrestricted overland flight.
c. Pressure fluctuations in the infrasound frequencies (10 to 20 Hz) must be equal to or less than that proposed during the Paris Colloquium, 1973 (ref. 5.1).

The loudness of various sonic boom overpressure signatures was evaluated by reducing them to their spectral content and then to a dBA level.

Wave shape parameters (i.e., overpressure, duration, and rise time) were assessed to determine their effects on loudness. It was found that rise time and overpressure had the largest impact. Current prediction methods for sonic boom propagation assume rise times of zero, but data have indicated that rise time increases as cruise altitude increases. It is believed that atmospheric absorption and/or turbulence are the reasons for a finite rise time. For this study, only the nominal acoustic disturbance was studied. The effects of atmospheric propagation, such as the variations in wind, density, and low-altitude turbulence were not considered. Consideration was given to a range of rise times.

Low-Sonic-Boom Design Results. The performance of an airplane designed for low sonic boom was evaluated against the Mach 2.4 baseline. Configuration changes necessary to reduce the sonic-boom impact have had some effect on the MTOW, wing size, and engine size required to meet the design objectives.

The low-sonic-boom design approach used in this study is an "inverse design" process. A target "acceptable" sonic-boom waveform was defined with shock wave amplitudes of approximately 1.0 lb/ft^2 (but with maximum overpressure greater than this), and a "rational" configuration was derived that produced the target waveform. The sonic boom constraint has a significant effect on the configuration design and flight conditions allowed.

Two low-sonic-boom configurations were initially investigated, one for cruise at Mach 1.5 over land and another for cruise at Mach 2.4 over land. Both configurations could cruise at Mach 2.4 in unrestricted operations (over water).

The limiting criterion is dBA, not infrasound, and the level chosen for the low-sonic-boom design study was 72 dBA for limited overland flight (corridors) instead of the 65-dBA unrestricted criterion. The shock wave amplitudes must be less than 1.0 lb/ft^2 with a rise time of 6 ms to achieve 72 dBA.

Acceptable low-sonic-boom waveforms were explored with respect to cruise conditions, aerodynamic lifting length requirements, and configuration design at Mach 1.5 and Mach 2.4. The particular sonic-boom waveform chosen as a design goal permits designs with realistic fuselage lengths and wing planforms. This waveform is the "peaky" or minimum shock waveform (fig. 5-9), which allows for heavy gross weight, and has a relatively short lifting length (about 250 ft at Mach 1.5). The "flat-top" waveform (fig. 5-9) has been considered for application to low-sonic-boom design, but requires significantly longer lifting length and fuselage length (or lower weight) to achieve 1.0 lb/ft^2 shock wave amplitude.

Low-Sonic-Boom Configurations. The configuration studies focused on a Mach 1.5 overland design because of the more reasonable fuselage length requirement and because only minimum changes to an arrow wing were required. The resulting airplane is shown in figure 5-10. Compared to the

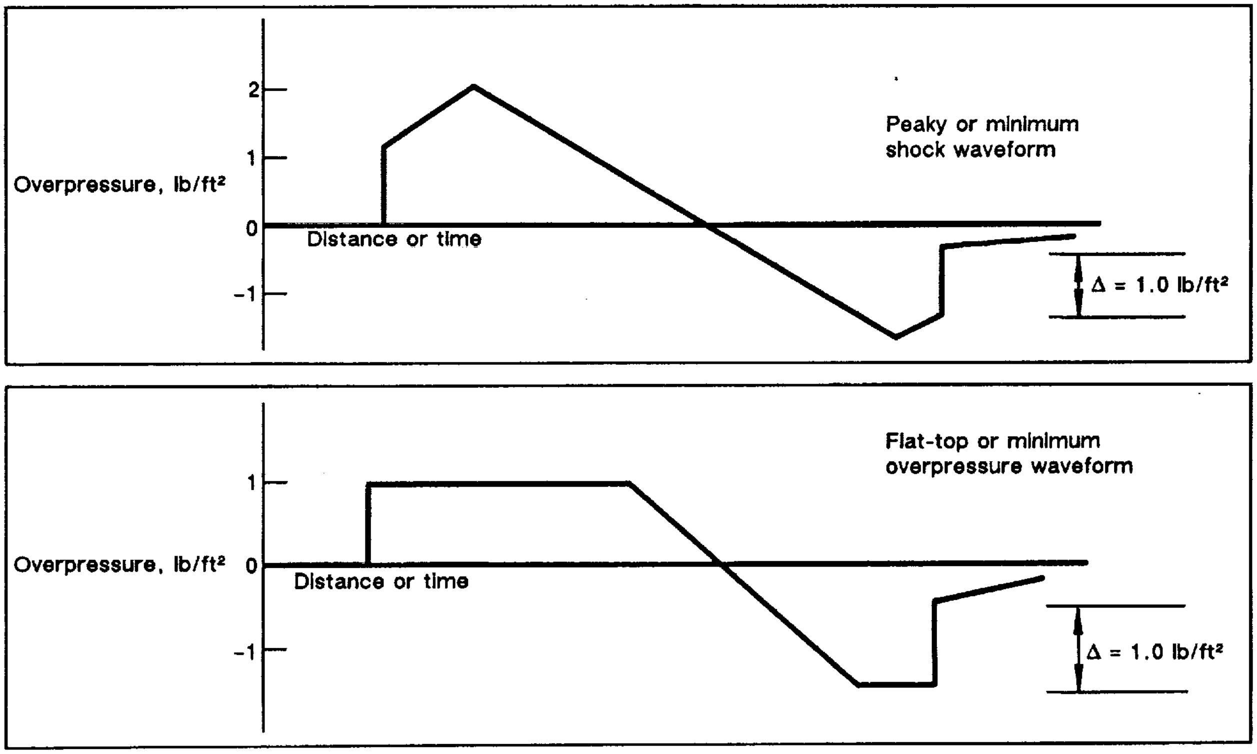

Figure 5-9. Target Waveforms

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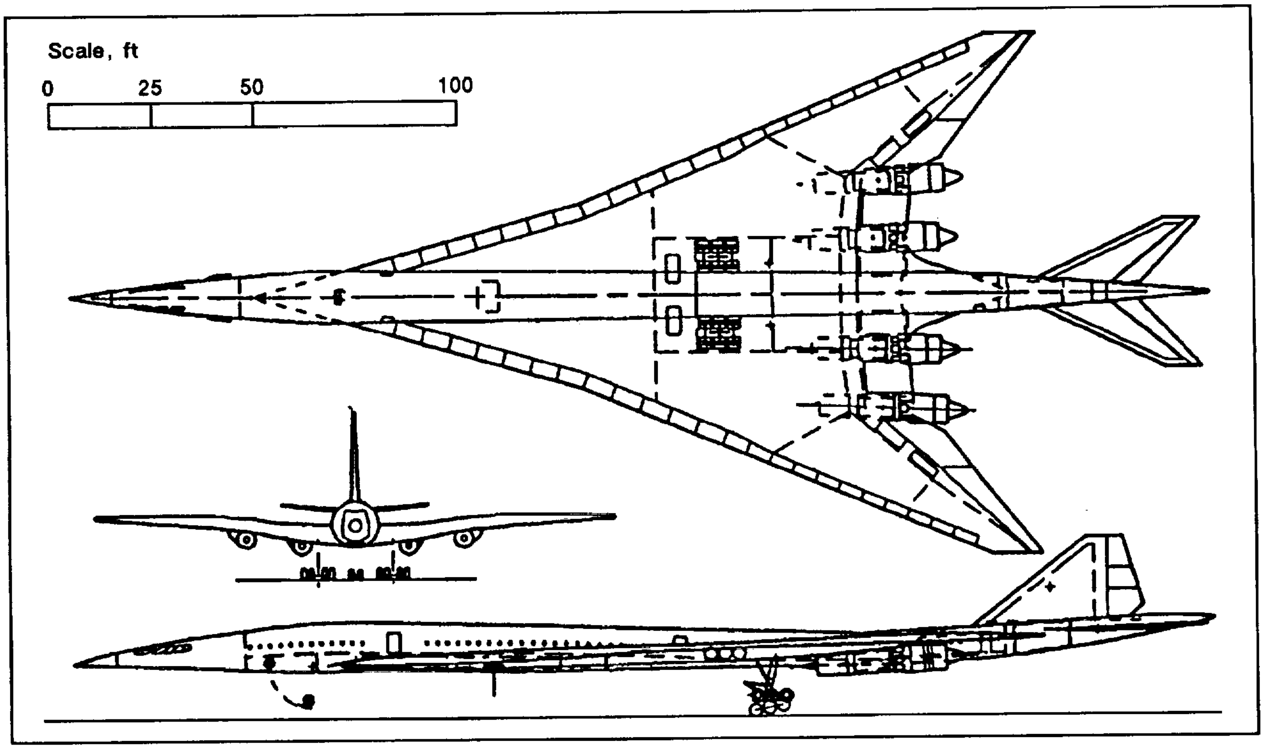

Figure 5-10. Low-Sonic-Boom Configuration

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.

This design concept provides an airplane configuration that produces no strong shock waves except at the aircraft nose and tail. This requires that the lift disturbance must be spread over approximately 250 ft length (at Mach 1.5) to minimize its effect and must be located properly with respect to the aircraft nose.

The actual pressure signature and resulting loudness predictions at Mach 1.5 are shown in figure 5-11. The loudness is shown versus shock-wave rise time, because rise time is such an important factor in loudness calculations. The intermediate shocks and the tail shock must be reduced to achieve the target loudness.

The buildup of the configuration in an equivalent cross section for the Mach 2.4 overland design results in a forebody that is long and wide, resulting in increased drag. The wing is located so far back on the body that balance becomes an issue. Because of the severe design problems, this configuration was not pursued further. Additional work would be required to reduce the tail shock and to eliminate the intermediate wing shocks by tailoring both volume and lift distributions more accurately.

Operational Considerations. The current low-sonic-boom configuration design is a "cruise point design"; that is, it must be flown at a specific Mach number, altitude, and gross weight to achieve the low-sonic-boom waveform at the ground. Off-design operations that require significant variation in cruise altitude, Mach number, or gross weight may result in a significant increase in shock intensity. The sensitivity of these designs to such variations needs to be studied before the viability of these configurations can be evaluated.

The cruise procedure will also affect the sonic-boom waveform. For example, for constant altitude cruise, the lift decreases as gross weight decreases, and the waveform will approach the flat-top waveform at the end of cruise. There is a smaller change in the waveform for constant CL cruise (fig. 5-12).

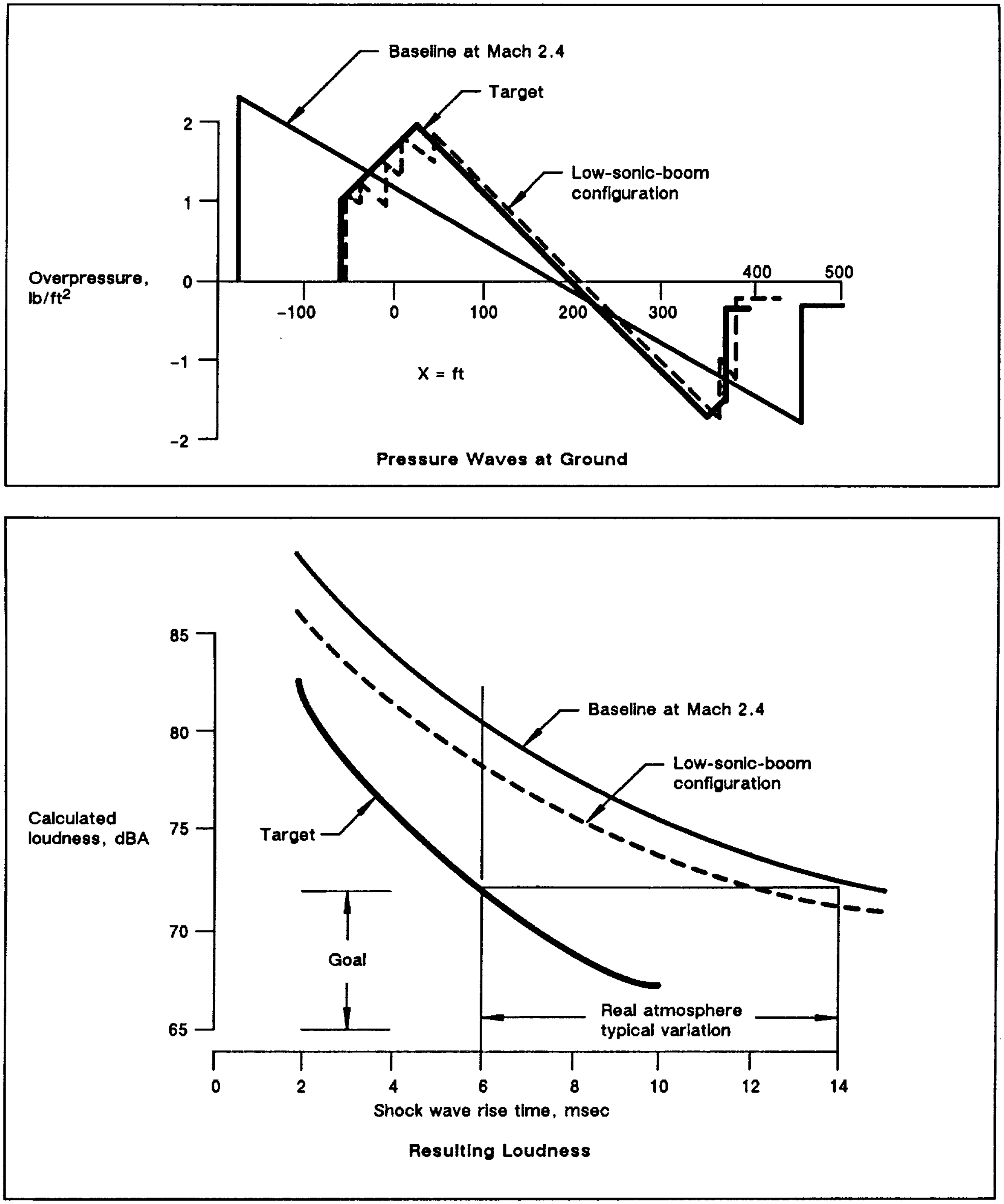

Figure 5-11. Mach 1.5 Pressure Signature and Loudness Predictions

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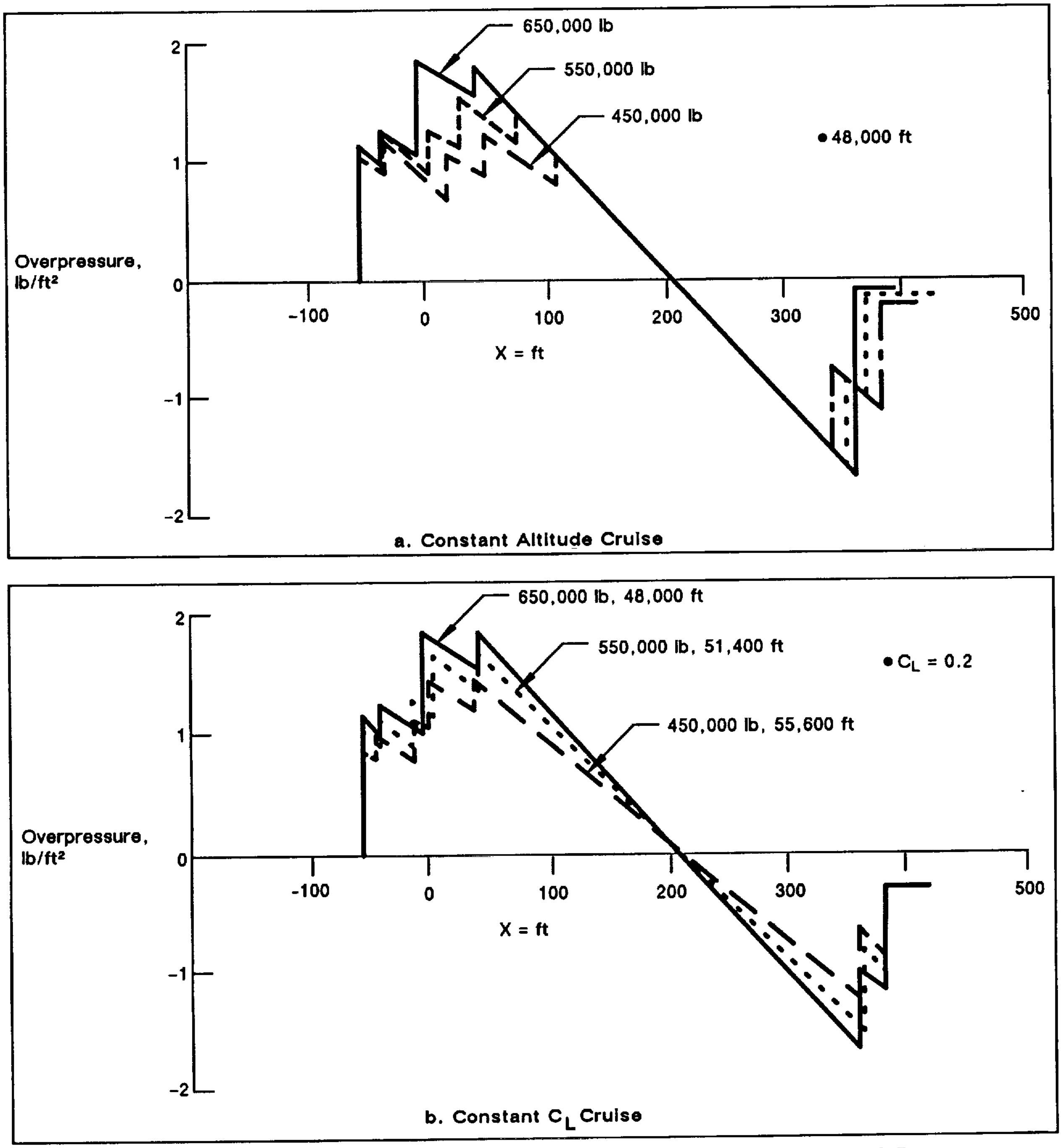

Figure 5-12. Effect of Cruise Procedure on Pressure Wave at Mach 1.5

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Performance Impact. The airplane was sized with 268 passengers because the elongated body required for reduced sonic boom had space for an additional 21 passengers. Comparison to the Mach 2.4 baseline airplane is shown in figure 5-13. These data show that the increase in MTOW for the low-sonic-boom airplane is about 3% at constant payload.

Sonic-Boom Study Conclusion. The results of the low-sonic-boom configuration design studies are as follows:

a. Low-sonic-boom design features include an arrow wing for long lifting length, long forebody, staggered nacelles, lifting arrow wing horizontal tail, and a smooth overall area distribution.
b. At Mach 1.5, only minor changes to a Mach 2.4 arrow-wing configuration are required to approach the desired sonic-boom waveform. Significant weight, length, and balance penalties are expected at Mach 2.4.
c. An arrow-wing configuration may have the potential for Mach 1.5 cruise over land with significantly reduced sonic boom and Mach 2.4 cruise over water.
d. Further design study is required to achieve the loudness level goal (reduction of intermediate and tail shock intensities). Additional work is required to define the optimum overland supersonic Mach number to determine performance-weight penalties, and to understand the effect of operation at off-nominal design conditions.
e. Because of the preliminary nature of these results, subsonic operation over land should continue to be assumed.

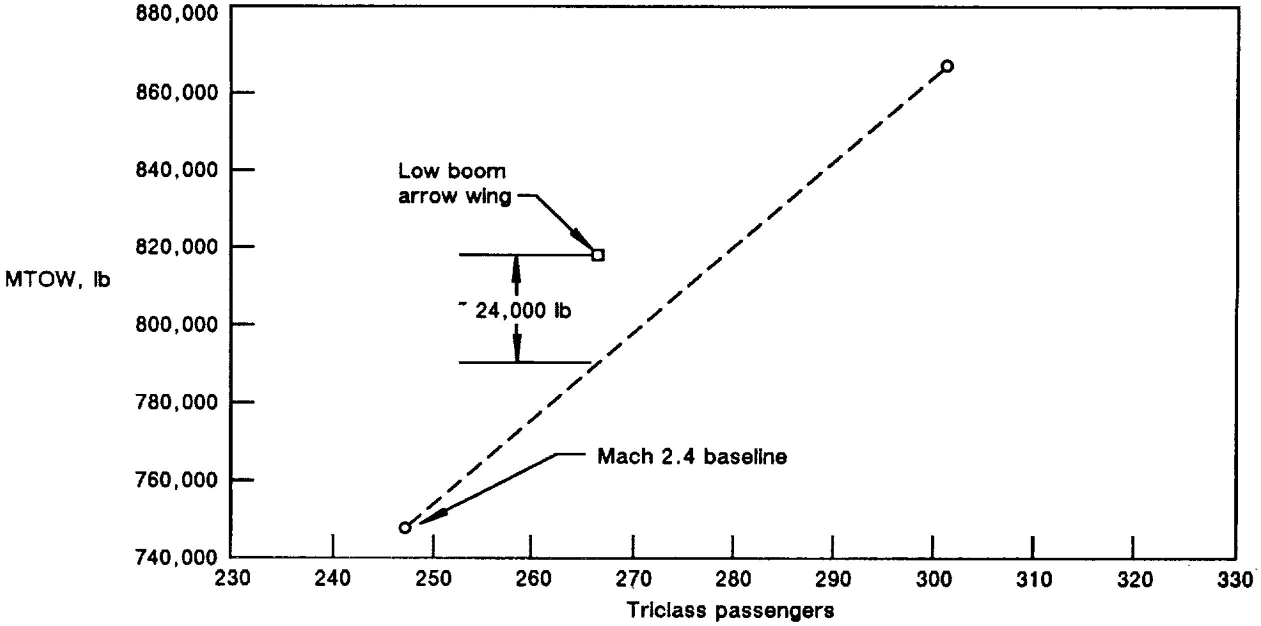

Figure 5-13. Parametric Payload—Gross Weight Trends

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6.0 ECONOMIC EVALUATION

The high-speed civil transport (HSCT) has one primary benefit to offer the travelling public—a reduction in the often tedious time spent on longer range flights. The idea that trip times of over 10 hr could be cut by half or more is an appealing prospect. Time savings of this magnitude offers the business traveller increased opportunity for productive work and the pleasure traveller increased time at his or her destination. Cities now 12 to 18 hr apart would become closely linked, with traffic stimulated by the ease of flying between them.

Future HSCTs must be both environmentally acceptable and economically competitive with the subsonic fleet. Past ventures into supersonic transports have not met these requirements, and, as a result, have not met with great market success. The economic evaluations of the HSCT concepts developed under this contract are founded on the belief that the HSCT must be able to survive in a competitive marketplace alongside advanced subsonic transports.

6.1 THE EVALUATION CONCEPT

For the HSCT to attain economic success, it must be able to earn a return on investment (ROI) at least equal to the return that could be earned by operating a subsonic airplane on the same route system. This concept is fundamental to the analysis methods used in evaluating the economic worth of the HSCT designs produced in this study.

Life-Cycle Operating Costs. 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."

Cash direct cost elements include—

a. Flightcrew costs.
b. Fuel burned.
c. Airframe maintenance.
d. Engine maintenance.
e. Hull insurance.

Cash costs incurred in servicing the airplane and the passengers are usually referred to as indirect costs. They may be separated into airplane-related costs (cleaning and fueling costs, aircraft handling, maintenance, and ground-handling equipment), and passenger-related costs (passenger food, passenger handling, agency commissions, and passenger insurance). Indirect costs can contain 14 to 15 separate accounts. Figure 6-1 schematically shows the cash operating costs that an airplane would incur over its operating life. These costs will probably escalate over time, but it is the usual practice to represent the operating cost of an airplane by a value that is the estimate of the operating cost in the first year of operation.

Ownership cost is defined as the dollar amount needed to pay off principal and debt on the airplane, provide for growth and eventual airplane replacement, and pay dividends to stockholders. An airline that earns enough revenue to cover both cash costs and ownership costs can be expected to remain a "going concern."

With the economic environment assumed for this study, rather than calculating each of these ownership cost items explicitly for each airplane comparison, Boeing has found that a revenue level that provides a 12% ROI is sufficient to satisfy the going concern requirements. This ROI is calculated using a discounted cash flow, "internal rate of return" process.

The incremental revenue (beyond that required to cover all cash costs) needed to meet the ROI target is the ownership-related portion of life-cycle operating costs.

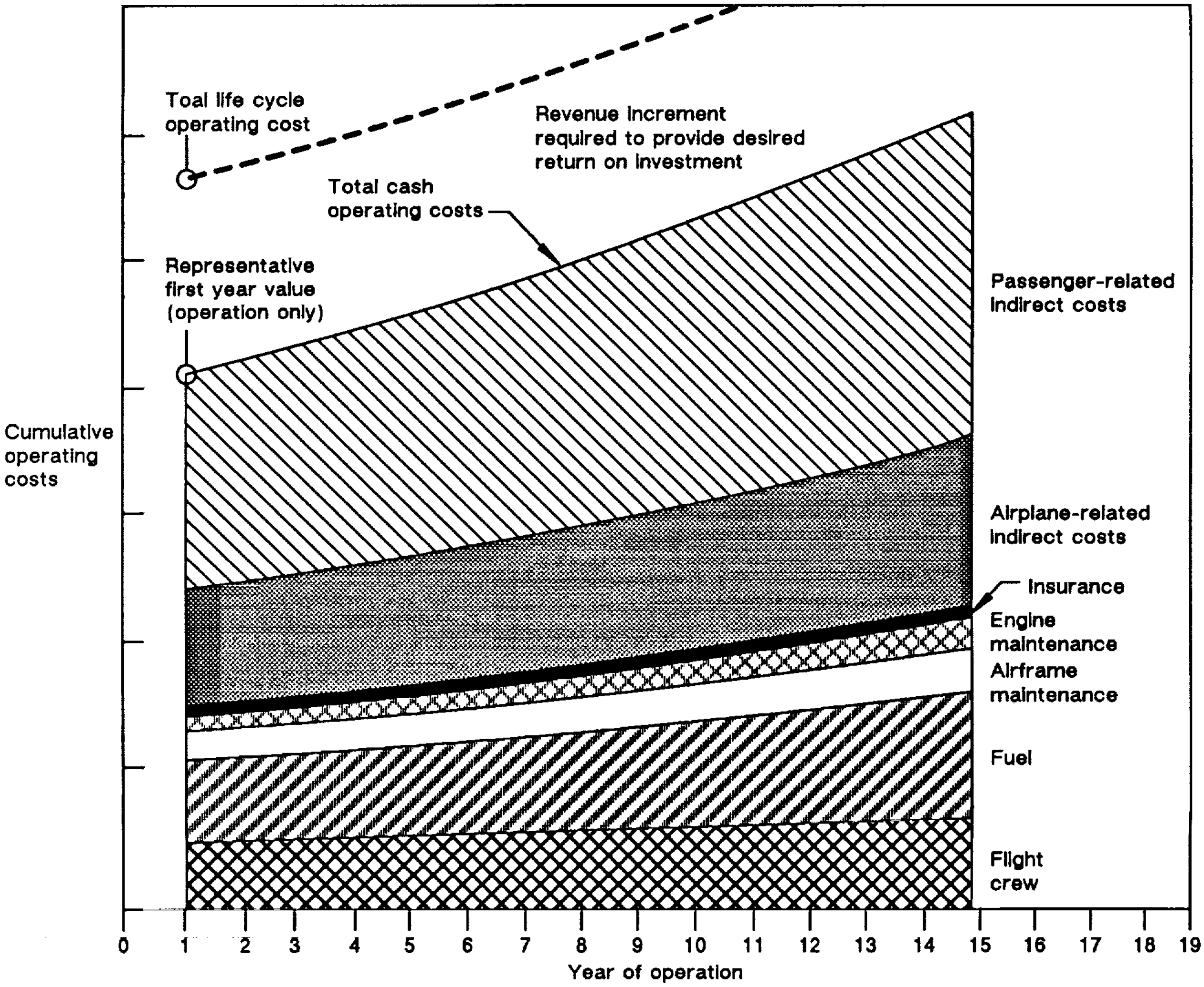

Figure 6-1. Example of Operating Cost History and Revenue Required To Cover All Cost Elements and Provide Desired Return on Investment

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Given the cash operating cost stream and the airplane investment (price plus initial spares), the incremental revenue stream required for the airline to earn the desired ROI can be calculated. This incremental revenue is the ownership-related portion of life-cycle operating cost. The total revenue stream (cash coverage plus ownership-related revenue), when represented by its first year value, is defined as the total life-cycle operating cost (fig. 6-1). Airplanes with equal life-cycle operating costs are seen as equally competitive economically, although the total life-cycle operating cost may be composed of quite different cash cost and ownership-related portions. (A low-operating-cost airplane with a high price may have the same life-cycle operating cost as a high-operating-cost airplane with a low price.)

The Economic Horizon. The airplane in each size category with the lowest value of life-cycle operating cost becomes the competitive target for other new airplanes within that size category. When taken across size categories, the collection of airplanes with the lowest life-cycle cost form the "economic horizon." This is the level that new airplanes must meet to be economically competitive. For the HSCT study, two advanced subsonic airplanes were chosen to anchor the ends of the competitive horizon curve. These aircraft, the 767-XXX and the 747-XXX, are both advanced derivatives of present subsonic airplanes that span the size and range categories defined for the HSCT.

Figure 6-2 shows the economic horizon plotted on a "fan chart" of a life-cycle operating cost; the horizon curve connects the two advanced subsonic airplanes. (The connecting curve is linear when plotted as life-cycle operating cost versus seats, and becomes hyperbolic on the fan chart.) With the anchor points defined, an advanced subsonic baseline airplane can be created with any number of seats between the 767-XXX and 747-XXX. Because most of the HSCT designs to be evaluated have 247 seats (triclass), the figure shows a 247-seat airplane defined on the horizon line. The operating cost elements and price of this baseline airplane are linear interpolations between the two "anchor" airplanes.

Defining the Economic Evaluation Model. With a 247-seat, baseline advanced subsonic airplane defined on the economic horizon, a base fleet economics case can be created. The subsonic airplane was run on the HSCT scheduling model to define the parameters of the subsonic fleet necessary to serve the forecast city-pair demand. Several of the assumptions used in the model are important to these definitions:

a. Constant demand. The demand in each city-pair market is held constant as each airplane type (subsonic or HSCT) is "flown" on the route system. As a result, total system revenue is constant.
b. No "spill." All the demand in each city-pair market must be carried, but no single flight can exceed the target load factor. If the demand for any flight causes the load factor to exceed the target, another flight is added.
c. All airport curfews must be observed. Curfews now in force are observed, but new curfews are not projected.

Given the operating cost elements, price, and fleet size (required for the advanced subsonic baseline to serve the market), the revenue level required to earn an airline a 12% ROI can be computed.

With the fleet revenue now fixed (and set by the 12% ROI requirement of the advanced subsonic baseline fleet), the relationships among the fleet cost, revenue, and fleet-investment variables can be

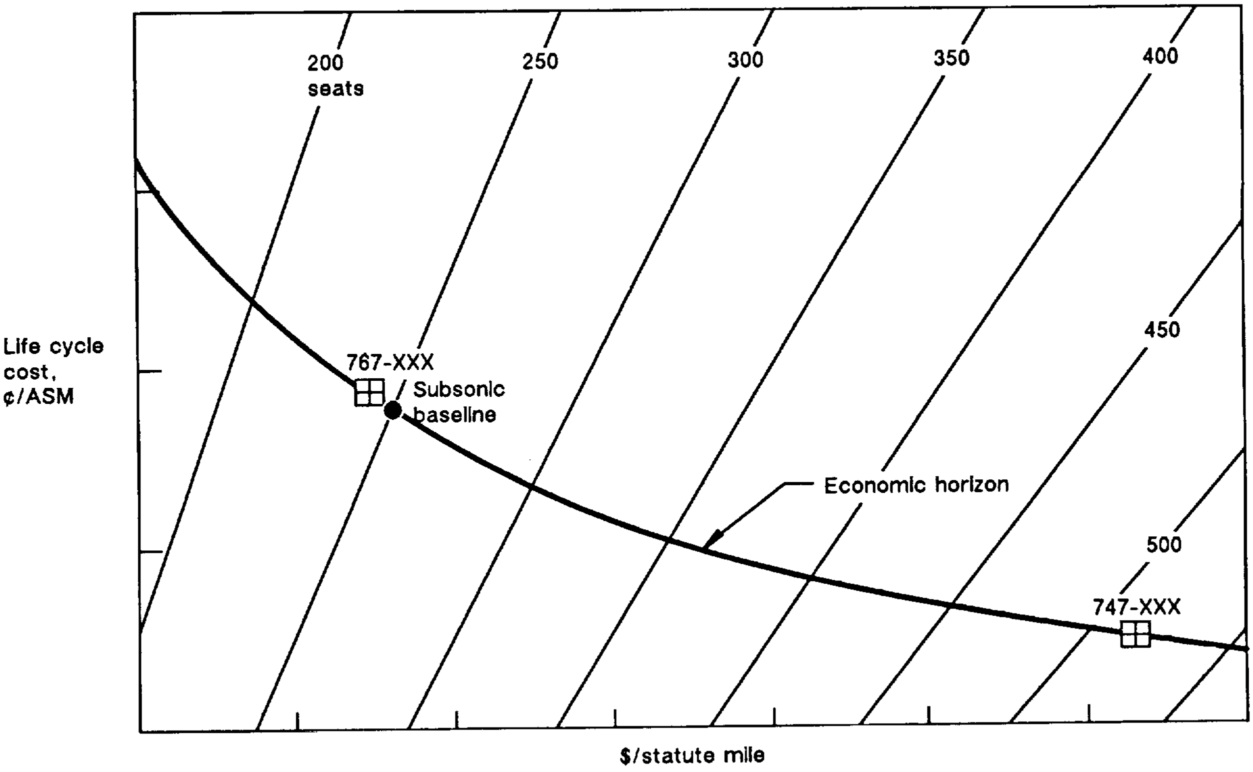

Figure 6-2. Life Cycle Cost

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defined. For any airplane serving the same demand on the system, the airplane investment allowed while still retaining the 12% ROI target can be expressed in the form:

$$MV = (K1 + K2 \times FC + K3 \times OC + K4 \times RF)/\text{units}$$

where MV = market value (the investment that will meet the 12% ROI)
K1 = constant (market value with zero costs)
K2 = slope of market value with fuel cost
FC = fleet fuel cost in millions of dollars
K3 = slope of market value with nonfuel costs
OC = fleet nonfuel cash costs in millions of dollars
K4 = slope of market value with revenue level
RF = factor applied to base revenue level (%)
units = airplane units required to serve the demand.

The linear form of the market value equation allows the HSCT designs to be evaluated in terms of airplane market value at the base revenue level (RF = 0), or the revenue factor required to make the market value equal to the airplane investment given a price estimate for the airplane. With price plus initial spares for the fleet substituted for MV in the above equation, RF can be easily computed. The graphical analogue of this mathematical process is to define the HSCT airplane price or revenue level that places the HSCT life cycle operating cost on the defined economic horizon curve.

A higher revenue level for the HSCT, such as that which would result from an increase in HSCT route ticket prices (RF > 0), adds a third dimension to the life cycle operating cost fan chart, effectively (and rapidly) raising the economic horizon for the HSCT.

6.2 RESULTS OF THE ECONOMIC MODEL

The economic evaluation model was used in all phases of the contract to define the market value of the HSCT designs, as well as the revenue factor required to attain the desired ROI for those designs for which prices were estimated.

The HSCT airplanes evaluated in this contract were products of three phases of design effort. The early screening examined a set of airplanes designed for cruise Mach numbers of from 2.0 to 10.0. The second design phase concentrated on airplanes with cruise Mach numbers of 2.4 to 3.8, and the third phase focused on cruise Mach numbers of 2.4 to 3.2. The fleet revenue level set by the subsonic baseline changed slightly from one phase to the next, as refinements were made in the scheduling model, the airplane routings, and the underlying cost forecasts. The results shown here reflect the final results of the airplane evaluations.

The revenue required for the subsonic baseline to meet the 12% ROI target is 9.07¢/revenue passenger miles (RPM) (1986 dollars). This revenue level defines the base revenue environment for all 247-seat HSCT airplanes. Figure 6-3 shows this derived value compared with the reported average yields from seven U.S. carriers. The reported average yields are much lower than the published fare because of (1) the traffic mix (the majority of passengers are paying economy or excursion fares), (2) fare dilution (nonpaying airline personnel and frequent flyer bonus trips), and (3) prorata revenue sharing (sharing of the total fare by two or more carriers on the passenger's itinerary, but not proportional to the distance the passenger is carried).

In the initial commercial value study, application of this model to HSCT vehicles designed for Mach 2.0 to Mach 10.0 cruise revealed that the high- Mach-number (Mach > 4.0) vehicles could not possibly compete economically with an advanced subsonic airplane. Market values computed for these vehicles in the base revenue environment were very large negative values, requiring increases in revenue of 300% to 500% to be competitive. The high values of cruise Mach numbers did not result in large increases in productivity, given the limits on supersonic flight over land, design-range

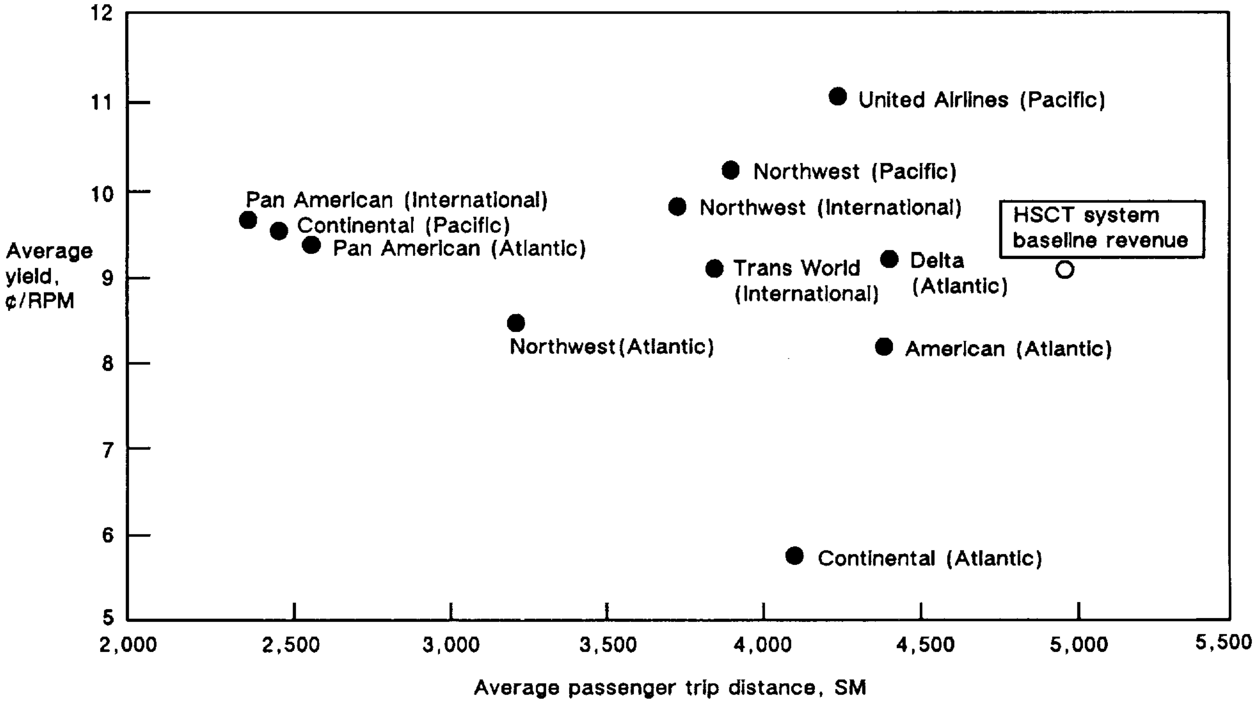

Figure 6-3. HSCT System Baseline Revenue Required Compared With Reported Yield—Yield Data of September 1987

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constraints, and acceleration limits. The slightly higher productivity of these vehicles could not overcome the high gross weights, fuel consumption, and maintenance costs associated with them.

Figure 6-4 shows the results of applying the economic evaluation model to the initial airplanes, all designed for year 2015 certification. The combination of very high takeoff gross weight needed for the 4,500-nmi mission and the high price of cryogenic fuel results in a -$1.5 to -$2.0 billion market value for the highest speed airplanes. Gross weights ranged from 1.6 million pounds at Mach 6.0 to 1.75 million pounds at Mach 10.0. Cryogenic fuel prices ranged from 16.8¢/lb for liquid methane at Mach 4.5 to $1.02/lb for liquid hydrogen at Mach 6.0 and Mach 10.0. This evaluation provided the evidence needed to justify restricting the Mach number range studied during the remainder of the contract period to 2.4 to 3.2 (3.8 for year 2015 certification).

This model was used as the final screening tool to determine the economic acceptability of each HSCT design, and also, to define the sensitivity of the economic measure (revenue required to meet the ROI target) to variations in design Mach number.

Value of Speed and Seats. A set of airplanes was designed to meet common requirements of payload and range (247 seats, 5,000 nmi) at 2.4, 2.8, and 3.2 cruise Mach number. Evaluation of these airplanes provides an economic assessment of the value of speed when traded against the penalties of higher speed design (weight and cost). In figure 6-5, the fleet size and investment requirements of the airplanes are shown, assuming a year 2000 certification. A single Mach 2.4 airplane of 301 seats and 5,000-nmi range was designed to show the effects of adding seats. The data shown in the figure are normalized using the 247-seat, Mach 2.4 airplane with a 5,000-nmi design range as a base. The effect of skin temperature as a function of design Mach number is reflected in the fleet operational assumptions, with turn-through time set at 1 hr for the subsonic baseline and the Mach 2.4 airplane, 1.5 hr for the Mach 2.8 airplane, and 2 hr for the Mach 3.2 airplane.

The design penalties associated with Mach numbers above the Mach 2.4 baseline (increased weight, engine size, and price) and the associated operational penalties assessed (increased turn time

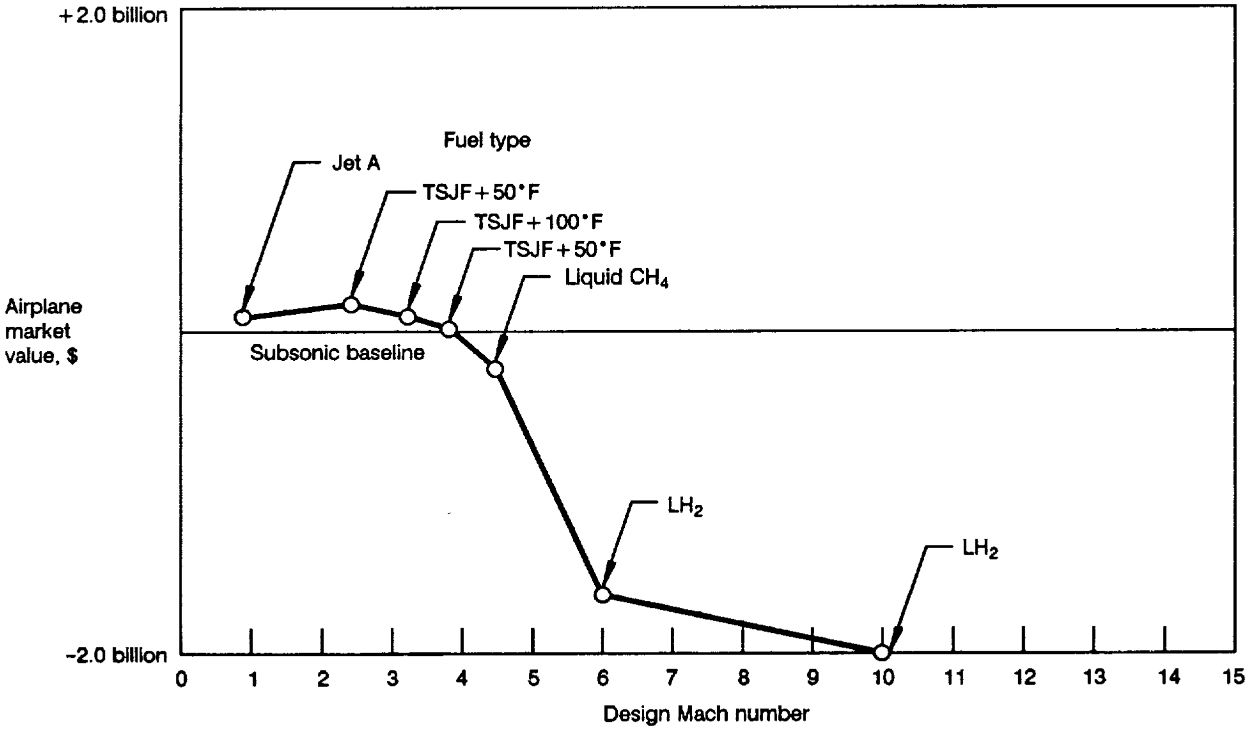

Figure 6-4. Airplane Market Value in Revenue Environment Set by Subsonic Baseline—Early Screening

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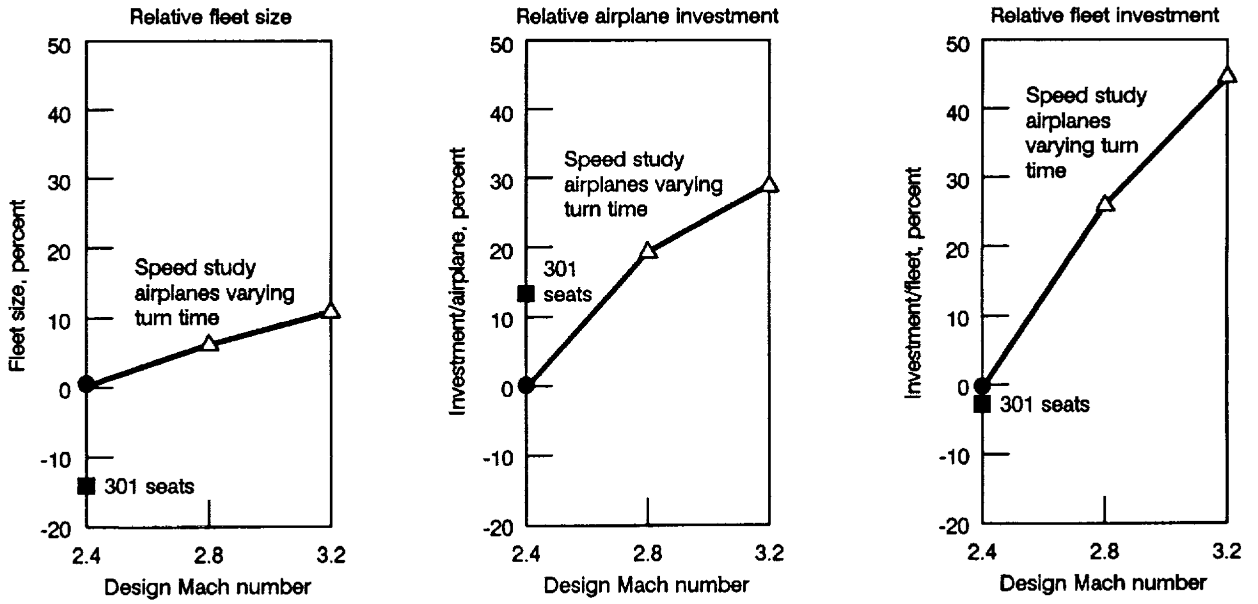

Figure 6-5. Fleet Size and Investment Relative to Baseline Speed Study Airplanes—Optimistic Prices Based on 500 Units

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because of skin temperature) combine to give a fleet-investment penalty of 45% for the Mach 3.2 design. The Mach 2.8 airplane fleet investment penalty is more modest at only 27%.

The advantage of more seats is obvious, with the higher price of the airplane offset by the lower fleet size needed. Fleet investment is roughly 2% below the base 247-seat airplane.

The ability of the HSCT designs to compete in the market is measured by the yield level required to earn a 12% ROI. The amount of increased yield required above the subsonic fleet baseline yield is a measure of the amount of restriction imposed on the HSCT market by the requirement to charge higher than normal (subsonic) fares. The effect of design Mach number, design range, and number of seats on the required yield level is shown in figure 6-6. Figure 6-6(a) shows data for the three 247-seat airplanes from figure 6-5 designed for a 5,000-nmi range. The most effective of these is the Mach 2.4 design, with a required yield level of 11.8¢/RPM, a 30% increase over the subsonic fleet yield. As a contrast, the Mach 3.2 design requires a yield level of 15.9¢/RPM to earn a 12% ROI, an increase of 75% over the baseline level.

Figures 6-6 (b) and (c) show the effects of design range and number of seats on the Mach 2.4, 5,000-nmi-range airplane. Figure 6-6(b) illustrates how reducing the design range requirement to 4,500 nmi reduces the yield required from 11.8¢ to 11.4¢/RPM; increasing the range to 5,500 nmi increases the yield requirements to 12.2¢/RPM. Designing for a lower range reduces the required weight, price, and operating cost. More airplanes and more trips are required to serve the market, however, with a resulting penalty in the yield required per passenger. An airplane with a 4,500-nmi design range still requires a yield increase of 26% over the baseline level.

Figure 6-6(c) shows that increasing the number of seats to 301 reduces the required yield to 11.3¢/RPM. The design penalties of the heavier airplane are offset by the fact that fewer units and trips are required, lowering the required yield per passenger.

Sensitivity Studies. As part of the economic evaluations, airplanes were designed that departed from the optimum use of given technology and a target- based design philosophy so that other goals could be met. Figure 6-7 shows the yield required to meet the 12% ROI target for a group of airplanes designed for lower community noise by either oversizing the engine or oversizing the wing. The year 2000, Mach 2.4 "point design" airplane (247 seats with a 5,000-nmi design range) is used as a comparison point. The community noise of each design is noted on the figure. The point design requires approximately a 30% increase in revenue over the subsonic baseline; the largest of the community noise airplanes requires approximately a 41% revenue increase.

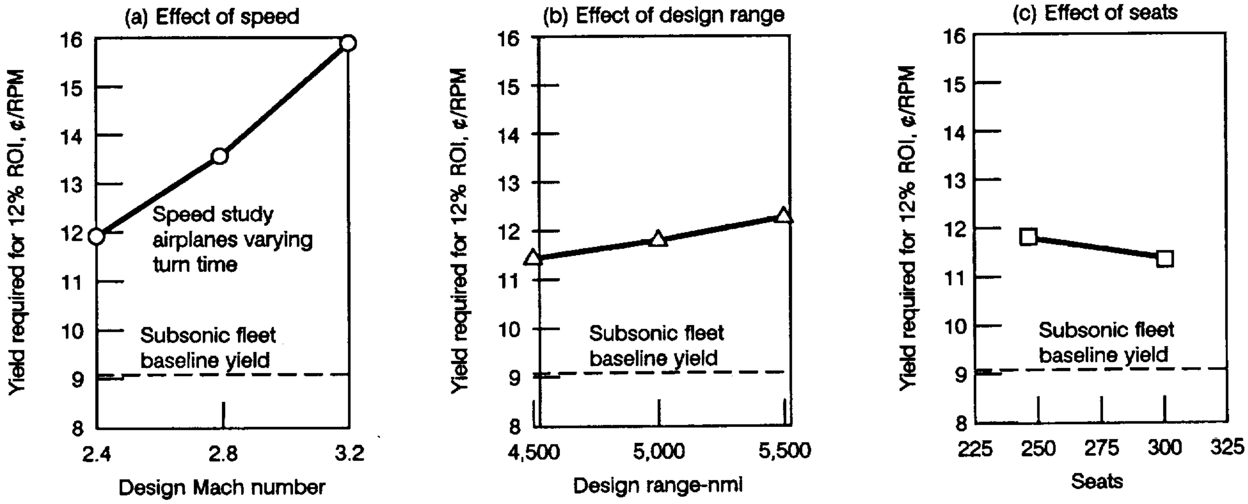

Figure 6-6. Sensitivity of Required Yield to Design Parameters Mach 0.9, Overland Waypoint Routing – Optimistic Prices Based on 500 Units

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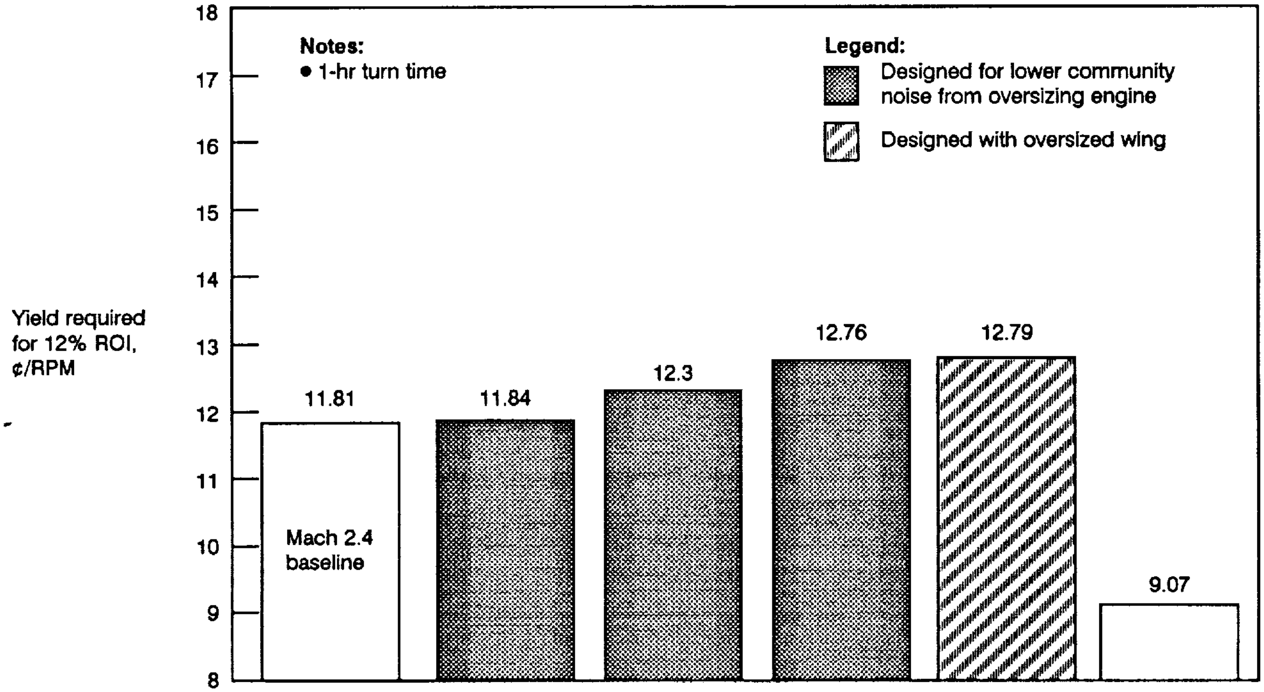

TOGW, lb	745,000	751,849	796,466	850,480	852,389	Subsonic baseline
Engine airflow, lb/s	582	600	680	770	680	
Wing area, ft^2	7,466	7,534	7,981	8,523	9,680	
Δ from stage 3, S/L	+1.7	+1.1	-0.8	-2.6	+3.9	

Figure 6-7. Sensitivity of Revenue Required for 12% Return on Investment to Requirement for Reduced Community Noise

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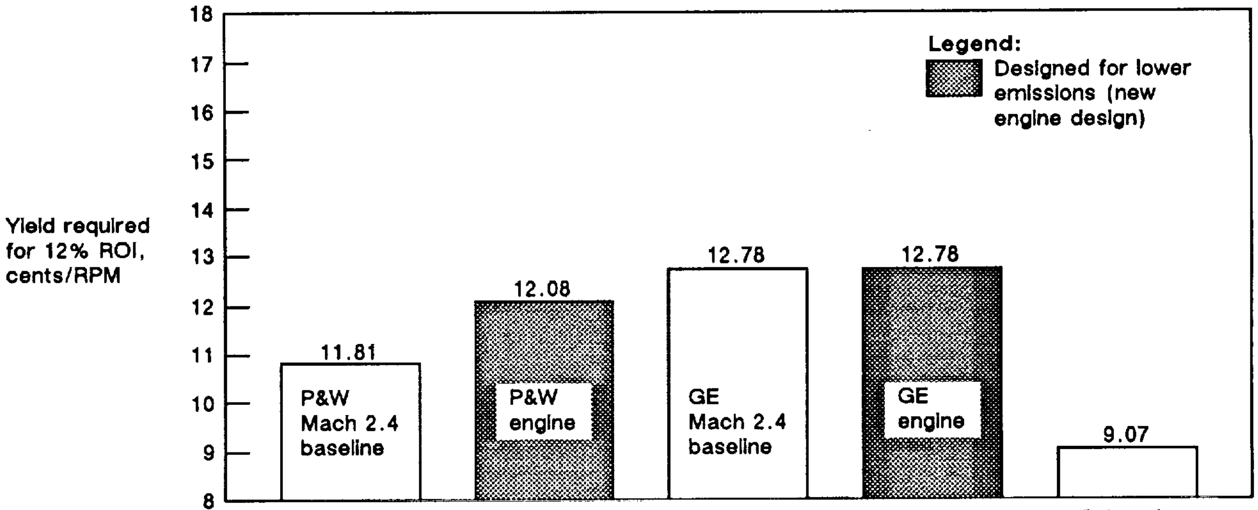
Two airplanes designed for low emissions (using special low-emission engines) were evaluated. Using figure 6-7's same Mach 2.4, 247 seat, 5,000-nmi range design as a baseline, figure 6-8 shows these results as the yield required for 12% ROI. The innovative engine combustors obtained their low-emission characteristics by the premixing and prevaporization of fuel and by burning lean. For the Pratt & Whitney (P&W) powered vehicle, there are penalties in engine weight and length that result in a vehicle maximum takeoff weight (MTOW) penalty of 28,000 lb. This results in 10% more revenue being required. General Electric (GE) imposed no penalties for their reduced emission combustor, so no takeoff weight or revenue penalties are assessed.

The sensitivity of economic measures to operational and design assumptions was also evaluated. A basic assumption of the contract study was that supersonic flight over land was prohibited. This requires that avoidance paths be flown between cities, keeping the airplane over water as much as possible. Those overland portions of the flight path were flown subsonically (Mach 0.9). This first-order rerouting was quite successful, reducing the overland portion of the total route system from 50% to 20% with only a 9% increase in total miles flown. However, many individual key routes (particularly Europe to the Far East) either retained a large percentage of overland flight or incurred large increases in miles flown.

An evaluation of the economic effect of restricting overland flight is shown in figure 6-9. The comparison shows the revenue required to reach the 12% ROI target for the Mach 2.4, 247 seat, 5,000-nmi range design airplane. The first bar shows revenue (yield) set by the subsonic baseline fleet. The second bar illustrates the yield required at the standard HSCT flight path condition: sonic boom avoidance, waypoint routing, and Mach 0.9 cruise over land. The third bar shows the yield required if the HSCT could fly with no restrictions, taking Great Circle paths and cruising at Mach 2.4 over land. The fourth bar shows the yield required for a Mach 2.4 low-boom airplane designed to fly at Mach 1.5 over land with waypoint routing. This airplane can accommodate 268 passengers because of its reshaped



TOGW, lb	745,000	773,000	812,700	812,700	Subsonic baseline
Engine airflow, lb/s	582	600	671	671	
Wing area, ft^2	7,466	7,648	8,233	8,233	
TOFL, ft	10,695	10,890	11,769	11,769	

Figure 6-8. Sensitivity of Revenue Required for 12% Return on Investment to Requirement for Reduced Emissions

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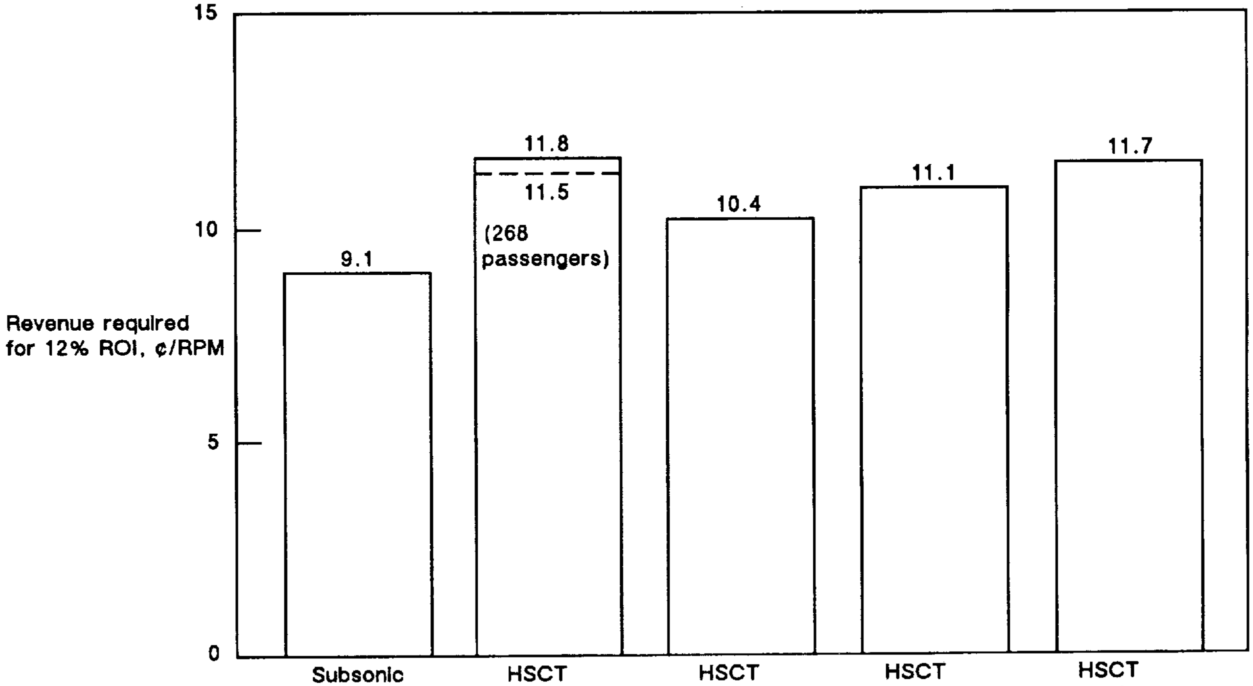

	Subsonic baseline	HSCT baseline	HSCT baseline	HSCT low boom	HSCT low boom
TOGW, lb	400,000	745,000	745,000	816,000	816,000
Mach over water	0.84	2.4	2.4	2.4	2.4
Mach over land	0.84	0.9	2.4	1.5	0.9
Overland boom level	NA	NA	Unacceptable	?	NA
Passengers	247	247	247	268	268

Figure 6-9. Revenue Required for 12% Return on Investment—Low-Sonic-Boom Design

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fuselage, and so gains from both the increased passenger revenue as well as the added productivity of higher speed over land. The yield level required for this airplane is lower than the yield required for the Mach 2.4 HSCT baseline airplane (with 247 or 268 seats). The fifth bar reveals the worst case; in spite of designing the low-sonic-boom airplane for acceptable overland flight, the sonic boom signature turned out to be unacceptable, and the airplane had to be flown at Mach 0.9 over land. The higher weight is now not offset by higher productivity, and the yield required is almost the same as the baseline HSCT in spite of the extra 21 seats on board.

In another sensitivity study, the design and operating assumptions of a year 2000, Mach 2.4 airplane (247 seats with 5,000-nmi design range) was varied parametrically to determine the effect on the economic measures. Figure 6-10 shows the results of one set of parametric variations in the airplane weight (a decrease of 10% in the operating empty weight (OEW), in airplane price (25% reduction assumed), and in operating load factor (a 5% increase)). Again, the measure is revenue required to reach a 12% ROI target. The changes are cumulative left to right, and bring the required revenue increase from 11.8¢ to 9.7¢/RPM, a decrease of 18%.

Study ground rules stipulated that a single-fuel-price environment be used when determining the potential HSCT market. While it is recognized that a high-fuel-price environment could substantially reduce the market size for an HSCT, fuel price sensitivities were not performed in this study. Based on continuing inhouse studies, the study team believes the HSCT market is resilient to moderate increases in energy prices.

Economic Closure by Market Segmentation. The division of seat class and revenue from each class in the standard 247-seat HSCT configuration is shown below:

	First Class	Business	Economy
Seat percentage	6.8	19.3	73.9
Revenue percentage	16.1	23.4	60.5

Demand served: 100% of all fare classes.

Average yield: 9.07¢/RPM (subsonic fleet baseline without ticket price increase).

Revenue increase required to meet ROI target = 30%.

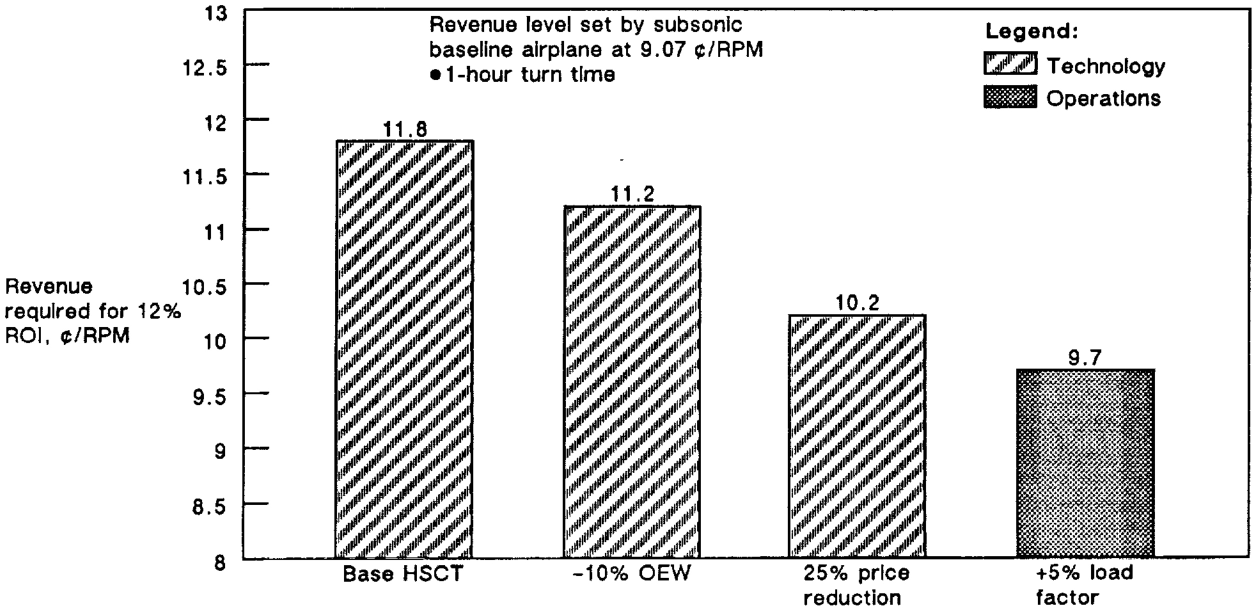

Figure 6-10. Sensitivity of Revenue Required for 12% Return on Investment to Design, Operational, and Price Assumptions

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This seat-percentage split reflects the actual split in passenger demand of the different fare classes, with the majority of the demand being for economy-class seats. The revenue from economy seats, although taking up almost three-quarters of the airplane, provide only just over 60% of the revenue. If a modest increase (10%) was made in the first- and business- class fares, and if the first- and business-class sections of the airplane were expanded so that the economy-class demand was not entirely accommodated, then the average revenue level would be enriched by the enlarged percentage of the higher priced fare classes. (This approach assumes that the increase in fares will be reflected directly as an increase in yield.)

Figure 6-11 illustrates how the average yield can be increased by raising first- and business-class fares by 10%, and raising the economy-class fares by the percentage indicated. The percentage of economy-class seats is decreased with a resulting reduction in the percentage of market share captured by the HSCT. The yield-available curve does not include deep discount fares. The per passenger yield level required to meet the ROI target increases as market share drops, because there are fewer passengers on any given flight and the physical airplane remains the same. With about an 18% economy ticket price increase and a 22% economy market share, the yield required for 12% ROI equals the yield available, (given a year 2000 certification technology level); the airplane is economically viable with a 49% market share and a worldwide sales base of 650 to 750 units. While this would be an adequate demand for a single manufacturer, it is not adequate for two or more.

The tactic of yield enrichment by excluding economy-class passengers brings with it operational problems from the airlines' point-of-view, and problems of design and marketing philosophy from the manufacturers' point-of-view. For example, an airline operating an HSCT that was designed to accommodate less than half the total demand would have to provide another (subsonic) airplane type on the same route to carry the remaining demand, probably consisting of mostly low fare economy- and excursion-ticket classes. The "fleet efficiency" of the high-utilization HSCT is reduced by the requirement to provide two airplane types to serve a single market.

An HSCT designed with today's technology (1995 certification) (curve in fig. 6-11) requires more than a 40% increase in economy-class fares, and a 10% increase in first- and business-class fares. The

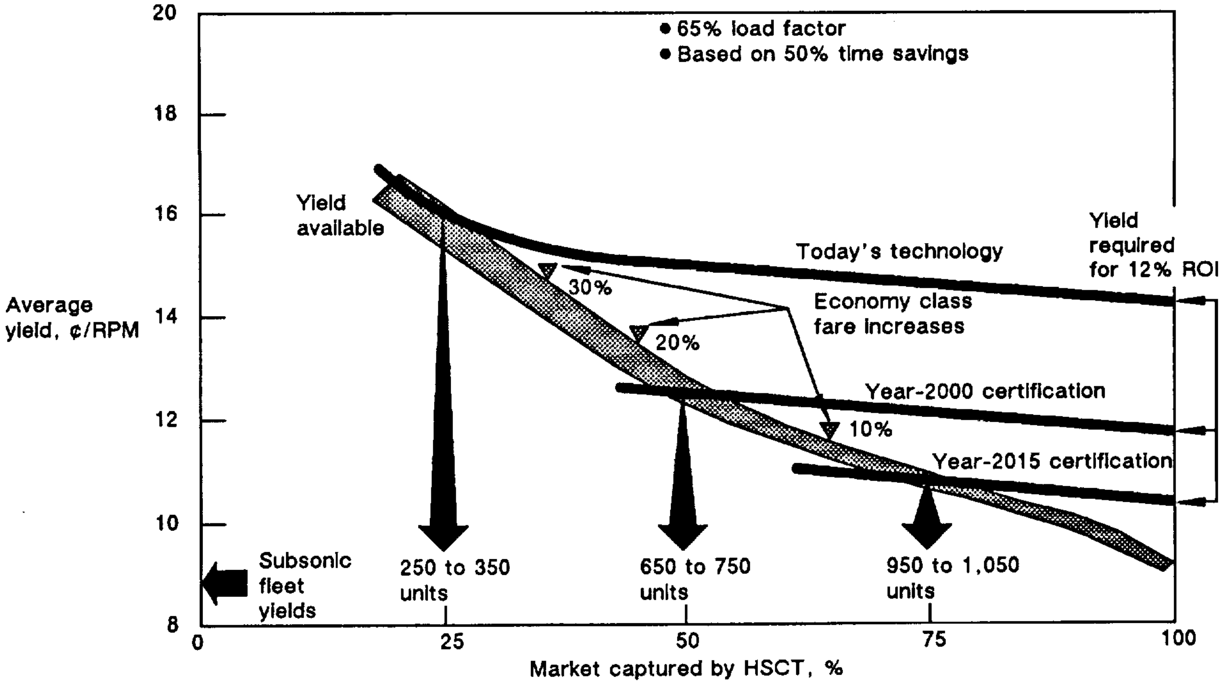

Figure 6-11. Economic Viability—Technology Impact on Fleet Size Based on Mach 2.4, 247-Seat Design With 5,000-nmi Range

4-U90027R3-70

market decreases to the point that only 250 to 350 units are required to serve it. A production forecast of this size is risky for any single manufacturer, and could be disastrous if more than one manufacturer entered the market.

The projected technology available for year 2015 certification captures 75% of the total passenger market with only about an 8% increase in economy- class fares, and a 10% increase in first- and business-class fares. The 950 to 1,050 units required to serve this market is a worthy goal for one or two manufacturers. The year 2015 technology projection also shows how a derivative of an HSCT model introduced in the year 2000 might take advantage of improved technology to better its economic and competitive position.

The impact of design Mach number on the yield required to earn a 12% ROI and on the market captured by the HSCT is shown in figure 6-12. Year 2000 certification is assumed for all HSCT designs in figure 6-12 as well as a constant 10% fare increase for first- and business-class passengers. The economy-class fare increase, market captured, and units required to serve that market are shown in the figure. Increasing the speed from Mach 2.4 to Mach 2.8 boosts the economy-class fare increase to over 25% and reduces the market captured to 30%, requiring 400 to 500 units. The Mach 3.2 design does not close, as the fare increase required to earn the 12% ROI reduces units required to the point that the price per unit is rising more steeply than the yield available.

The key assumption behind the economic closure trends shown in figures 6-11 and 6-12 is the trade of market share against ticket price for a 50% time savings (discussed in section 2.0; fig. 2-24). If the decline in market share with higher ticket price is steeper, then the "yield available" curve of figures 6-11 and 6-12 may have a lower slope with decreasing market share. This would move the closure point to even lower values of market share and sales base.

Figure 6-13 shows the impact of technology development on the total HSCT fleet required for the year 2015 market. The technology improvement for the Mach 2.4 designs from the present to a year 2000 certification airplane more than doubles the fleet required, and continued technology development for the year 2015 airplane almost doubles the fleet again, as required fare levels for a 12% ROI decrease. A Mach 3.2 design is penalized by higher weights and complexity, which is not

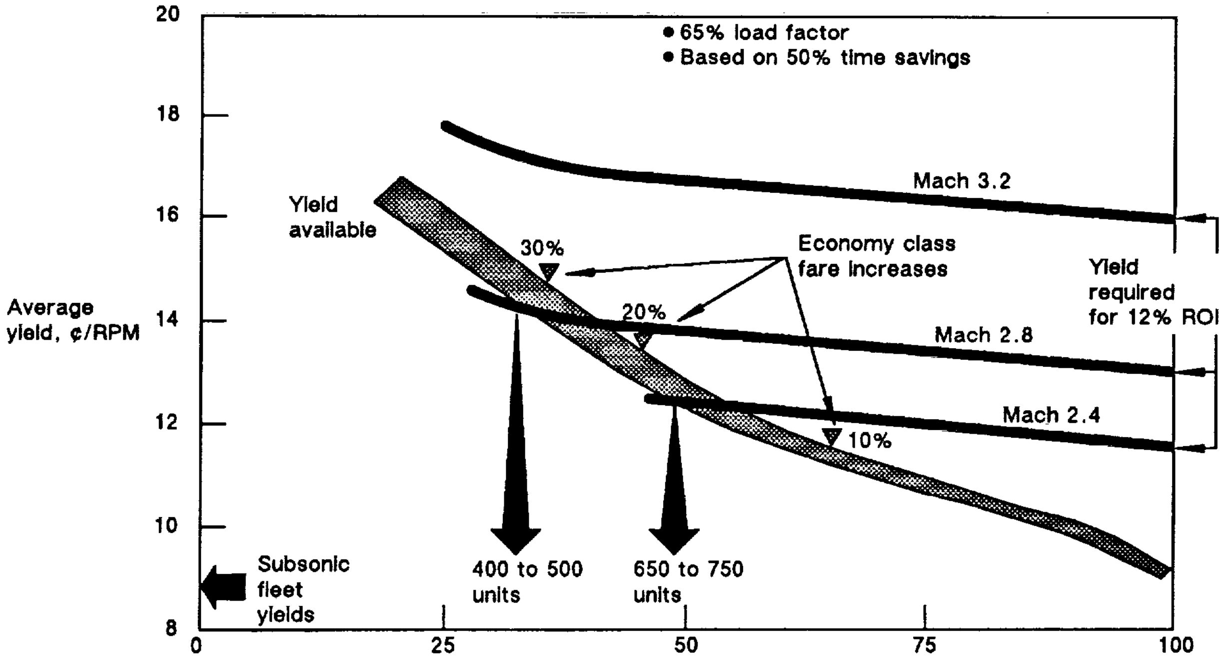

Figure 6-12. Economic Viability—Impact of Speed Based on 247-Seat Design With 5,000-nmi Range

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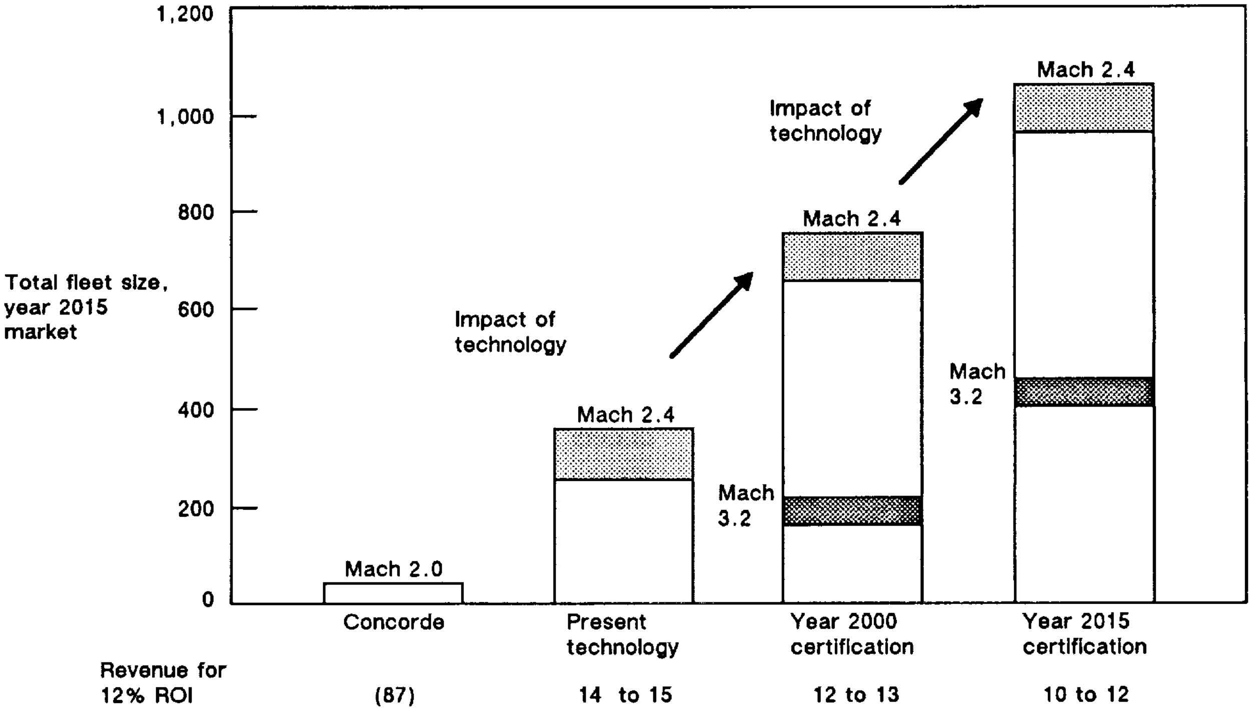

Figure 6-13. Impact of Technology Development on HSCT Fleet Size

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offset by large increases in productivity. As a result, the Mach 3.2 market is much reduced, being less than half the market size of the year 2015, Mach 2.4 airplane. The higher speed airplane is then a much greater risk for both manufacturer and airline.

6.3 CONCLUSIONS

The evaluation requirement that an HSCT survive in a competitive marketplace quickly eliminated the high Mach number design concepts (Mach numbers of 4.5 and up). The high weights, high operating costs, and high prices for these designs were not offset by increases in economic productivity. The range of design Mach numbers from 2.4 to 3.2 shows the most economic promise, with the highest probability of success at the lower end of this range. All of the designs evaluated required increased ticket prices to meet the airline ROI target of 12% in a revenue environment set by an advanced subsonic airplane.

Increases in ticket prices rapidly reduces passenger demand, reducing the total market for the HSCT, perhaps to the point where a manufacturer would not be willing to undertake an airplane program.

The sensitivity of the key economic measure (revenue required to meet the 12% ROI target) to parametric variations in the HSCT design provides a glimpse of the improvements needed in HSCT technology to meet the economic goals. Increases in cruise efficiency, both supersonically and subsonically, better weight efficiency, and developments in composite production and manufacturing techniques are a few of the technological improvements needed that will allow an HSCT to meet its primary economic objectives. Improvements in these technology areas will do much more to improve the economic viability of the HSCT than increasing cruise Mach number.

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7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 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 emissions. Projections of advanced low-emissions burner technology indicate that an NOx 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.

7.2 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 of the 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 that 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-cyle 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

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.

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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