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1990 High-Speed Civil Transport Studies

Summary Report

HSCT Concept Development Group
Advanced Commercial Programs

McDonnell Douglas Corporation
Douglas Aircraft Company
Long Beach, California

Contract NAS1-18378
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1990 HIGH-SPEED CIVIL TRANSPORT STUDIES

SUMMARY REPORT

HSCT CONCEPT DEVELOPMENT GROUP
ADVANCED COMMERCIAL PROGRAMS

DOUGLAS AIRCRAFT COMPANY
LONG BEACH, CA 90846

CONTRACT NAS1-18378

EXECUTIVE SUMMARY

This summary report contains the results of the Douglas Aircraft Company system studies related to high-speed civil transports (HSCTs). The tasks were performed under an 18-month extension of NASA Langley Research Center Contract NAS1-18378.

The system studies were conducted to assess the environmental compatibility of high-speed civil transports at design Mach numbers ranging from 1.6 to 3.2. In particular, engine cycles were assessed regarding community noise and atmospheric emissions impact, and an HSCT route structure was developed.

The general results indicated (1) in the Mach number range 1.6 to 2.5, the development of polymer composite and discontinuous reinforced aluminum materials is essential to ensure a minimum operational weight; (2) the HSCT route structure to minimize supersonic over-land can be increased by innovative routing to avoid land masses; (3) at least two engine concepts show promise in achieving sideline Stage 3 noise limits; (4) two promising low-NO_x combustor concepts have been identified; (5) the atmospheric emission impact on ozone could be significantly lower for Mach 1.6 operations than for Mach 3.2 operations; and (6) sonic boom minimization concepts are maturing at an encouraging rate.

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SECTION 1
INTRODUCTION

This report presents the results of system studies conducted by Douglas Aircraft Company related to high-speed civil transports (HSCTs). This report is a continuation of environmental studies completed in the 1989 system study report covering sonic boom minimization, exterior noise, and engine emissions. In this report, the HSCT engine emissions for a viable fleet have been developed into annual emission fuel burn constituents to provide input data to an atmospheric impact two-dimensional model, and the low-boom configuration has been further developed. Exterior noise evaluations include community noise issues as well as noise certification.

Additionally, during the 1990 studies, two configurations at Mach 1.6 and 2.2 have been developed for the system studies. A Jet A fuel envelope analysis was conducted. At Mach 2.2, a material and structural verification analysis was conducted. Specific engine cycles from GE and P&W have been evaluated for overall economic and environmental performance over a Mach number range of 1.6 to 3.2.

Market projections have been made for the years 2000 to 2025, fleet requirements have been assessed over a Mach number range of 1.6 to 3.2, and a number of supersonic network scenarios have been evaluated.

SECTION 2
SUMMARY OF RESULTS

This section summarizes the results of the 1990 system studies for the following tasks:

1. Design studies
2. Market and economic assessments
3. Supersonic network evaluation
4. Atmospheric emissions impact status
5. Engine cycle assessments
6. Certification and community noise status
7. Sonic boom minimization status

2.1 DESIGN STUDIES

Environmental and economic system studies were conducted for three HSCT configurations, designed for operation at Mach 1.6, 2.2, and 3.2 (Figures 1, 2, and 3). The aircraft have been sized to meet a 6,500-nautical-mile range goal and to hold 300 passengers.

A fuel envelope analysis showed that, with appropriate engine and thermal technology, Jet A fuel could be used up to Mach 3.2. Both airframe and engine heat loads were evaluated, and maximum fuel temperatures were compared to the Jet A limit temperatures provided by General Electric and Pratt & Whitney engine manufacturers. The engine manufacturers recommended a maximum Jet A fuel temperature of 300°F for steady-state operation in commercial airline service. Two fuel temperature profiles for the Mach 3.2 aircraft were calculated for both a fuel-cooled configuration and an all-electric configuration (Figures 4 and 5). Fuel tank temperature and fuel temperature at the combustor injectors were evaluated. Note that the fuel temperatures during descent would have been above the desired maximum for the two cases above. The approach taken to reduce these temperatures was to recirculate fuel to minimize fuel temperature at the end of cruise and descent.

The development of material systems capable of withstanding the harsh thermal environment of sustained supersonic flight presents significant challenges for airframe designers. In order to meet the performance objectives for improved economic viability, the structural empty weight must be held below 20 percent of the total takeoff gross weight of the aircraft. This compares to a value of about 25 percent for today's current commercial aircraft, which indicates that material systems must be capable of providing weight savings in the range of 20 percent over conventional subsonic aerospace materials.

A materials and aircraft structures verification analysis was conducted at Mach 2.2. This analysis demonstrated that polymer composite, discontinuous reinforced aluminum, and titanium materials are needed to minimize aircraft structural weight. Three different materials were combined with four structural concepts, resulting in 12 weights for each location. The materials consisted of titanium (Ti-6-Al-4V) as a representative baseline; a discontinuous, reinforced, elevated-temperature aluminum (DRETA) alloy; and a high-temperature polymeric composite (HTPC). The properties used in analyzing the last two advanced materials were generic and did not represent specific vendor-produced materials. The major discriminator

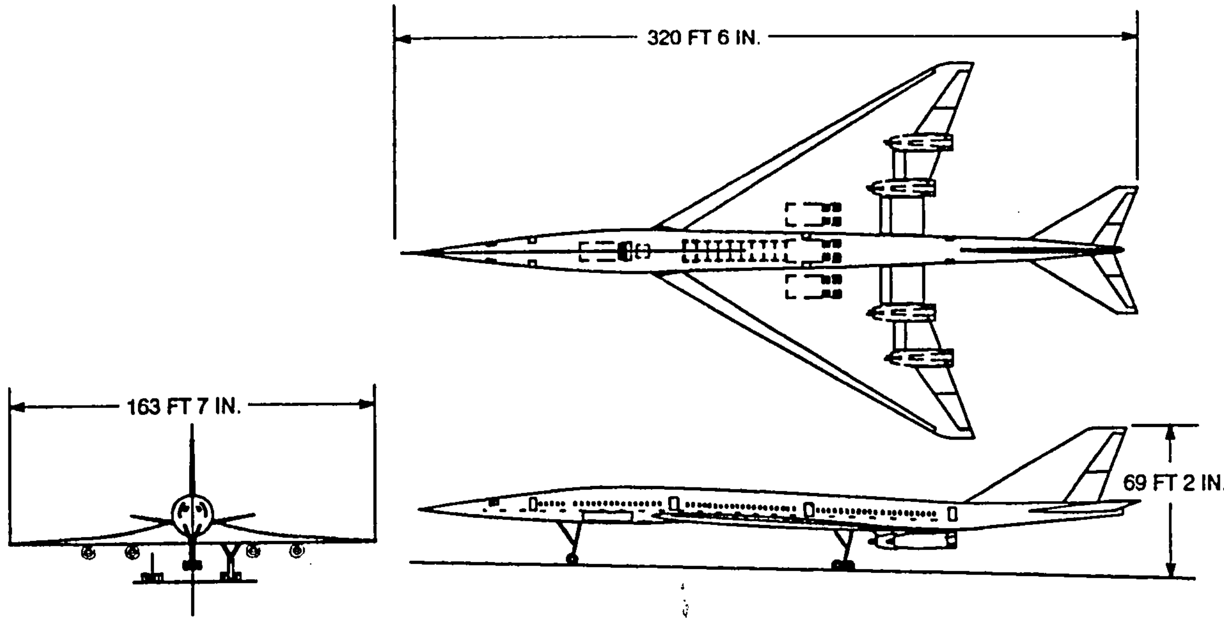

FIGURE 1. DOUGLAS MACH 1.6 TURBULENT BASELINE CONFIGURATION, D1.6-3

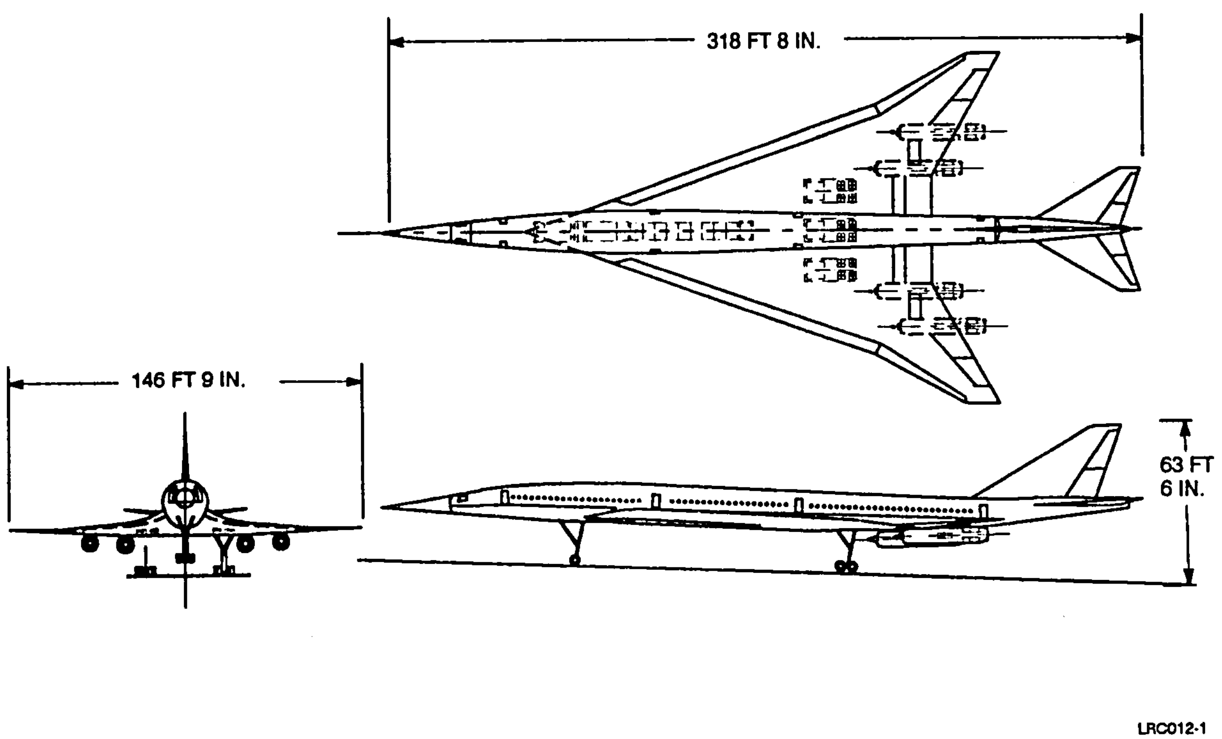

FIGURE 2. DOUGLAS MACH 2.2 TURBULENT BASELINE CONFIGURATION, D2.2-10

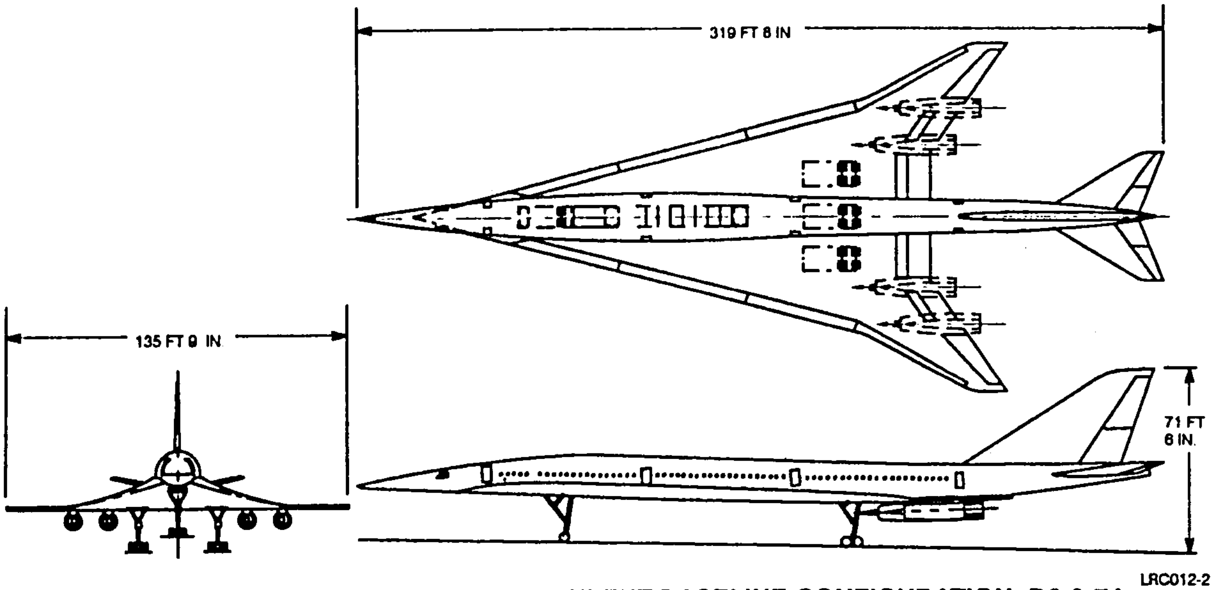

FIGURE 3. DOUGLAS MACH 3.2 TURBULENT BASELINE CONFIGURATION, D3.2-7A

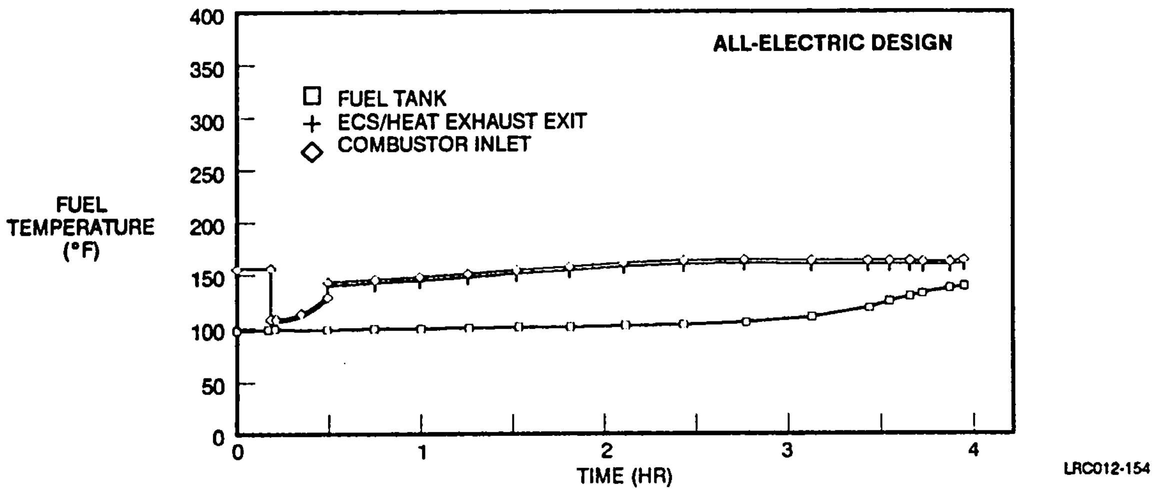

FIGURE 4. D3.2-3A P&W TBE ALL-ELECTRIC WITH OPTIMIZED RECIRCULATION

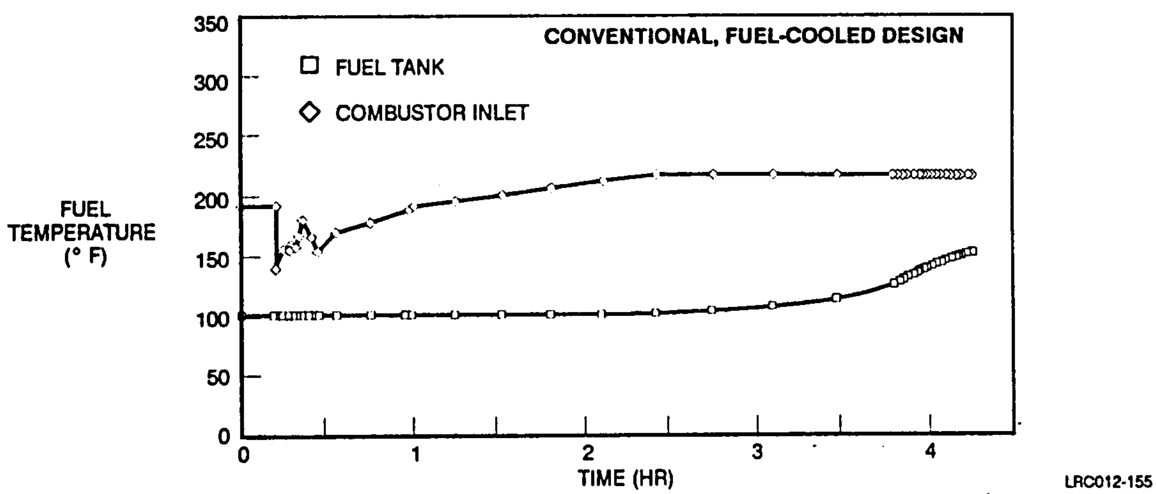

FIGURE 5. D3.2-3A GE VCE (CONVENTIONAL FUEL-COOLED WITH OPTIMIZED RECIRCULATION

used in selecting these concepts over other possibilities was their desirable thermal gradient characteristics.

The panel weights generated for selected locations on the fuselage and wing are shown in Figure 6 for various structural panel concepts. As can be seen, no one material and structural concept can produce the minimum weight for the selected locations.

2.2 MARKET AND ECONOMIC ASSESSMENTS

Traffic projections for the years 2000 to 2025 and fleet requirements over a Mach number range of 1.6 to 3.2 have been assessed with regard to Mach number, fare premium, and aircraft range. The 10 International Air Transport Association (IATA) regions considered to have the best potential for supersonic operation were based on econometric models that relate traffic to national income, fares, yield, and, where appropriate, other relevant variables. Four of the 10 regions comprise about 85 percent of the total international traffic. Rapid economic growth in the Pacific-Asia region has made this the fastest growing area for passenger traffic. Figure 7 shows that North and Mid-Pacific traffic will equal North Atlantic traffic by the year 2000.

Long-term prospects for international passenger traffic gains are relatively good. Overall, traffic is predicted to total about 450 billion annual seat-miles (ASMs) by the year 2000 and 2.4 trillion ASMs by the year 2025, or five times the traffic projected for the year 2000.

World demand for new passenger aircraft for the year 2000 is forecast at 5,500 units in addition to those currently on order. The medium- and long-range classes (greater than 3,500-nautical-mile range and 250 passengers) are expected to total more than 1,800 aircraft. Approximately one-half of this market is represented by the 10-region HSCT arena. Therefore, the HSCT with no fare premium may replace a maximum of 900 aircraft. At Mach 2.2, the HSCT is at least twice as productive as a subsonic aircraft of the same size. A fleet of approximately 450 HSCTs can transport the payload of 900 subsonic aircraft.

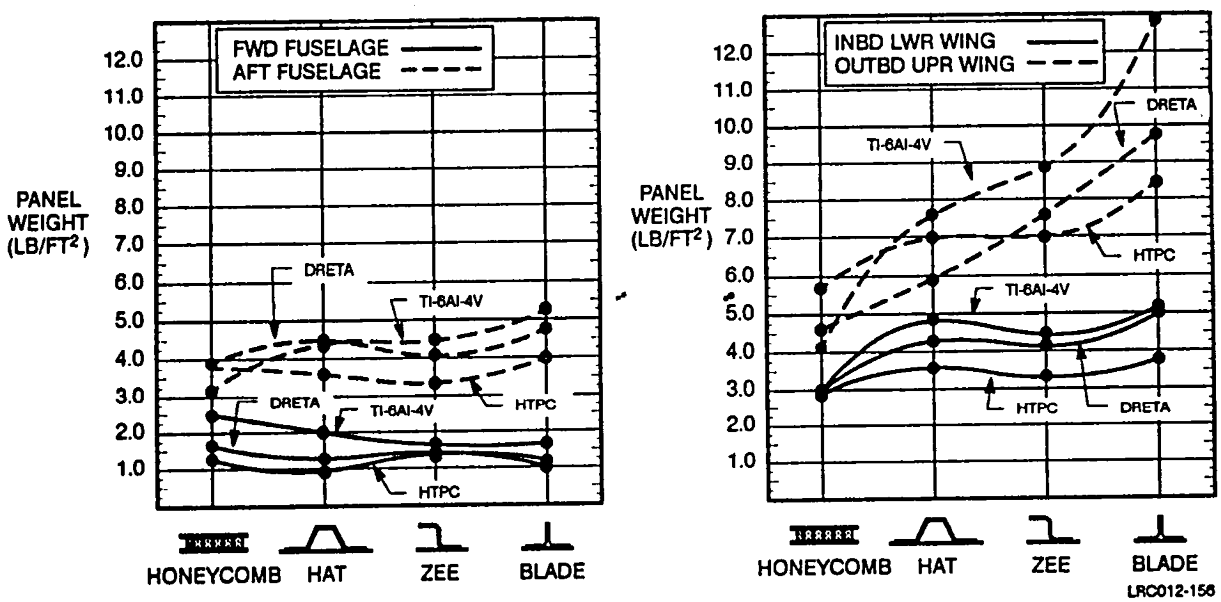

FIGURE 6. POINT DESIGN PANEL WEIGHTS

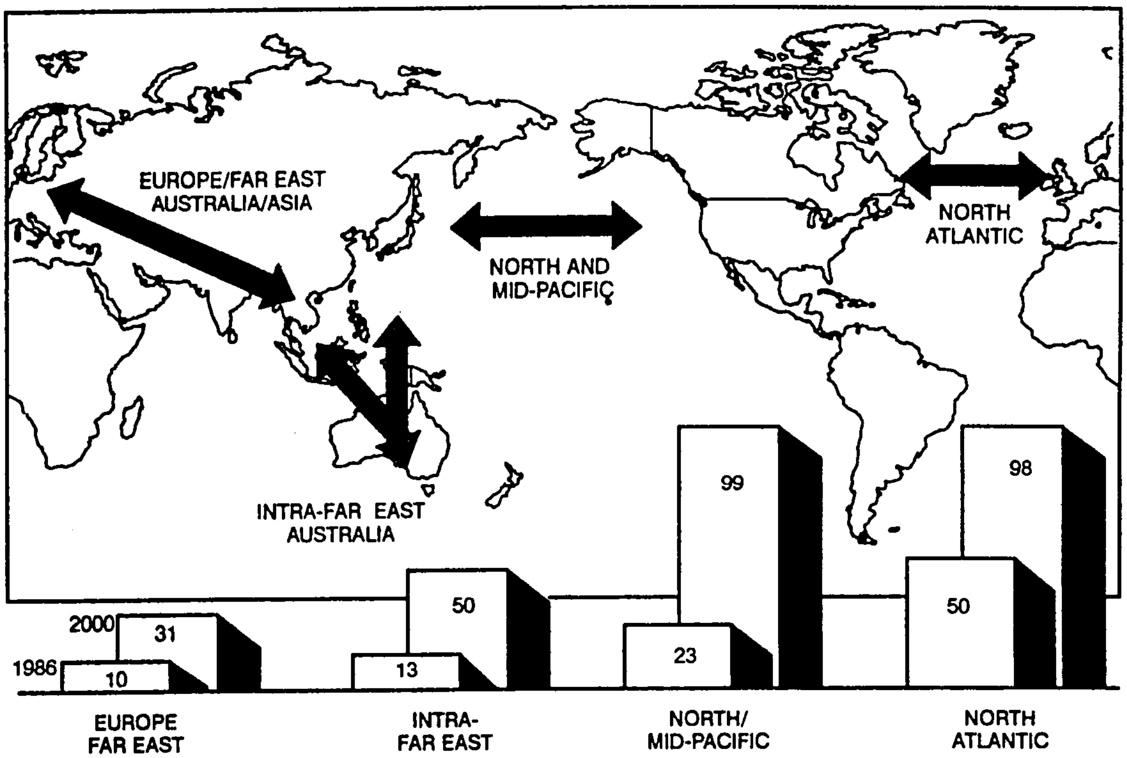

FIGURE 7. INTERNATIONAL PASSENGER TRAFFIC – MAJOR REGION (85-90 PERCENT OF TOTAL)

As supersonic speed changes, productivity changes as well, resulting in variations in fleet projections. Fleet requirements are sensitive to fare elasticity. Introduction of fare premiums will reduce fleet sizes. Table 1 shows HSCT fleet requirements at different fare premiums for the Mach 1.6, 2.2, and 3.2 configurations. The table illustrates how fleet size is reduced as fare premiums increase. At Mach 2.2, the most optimistic fleet needs scenario, assuming no fare premium, could total 2,300 or more 300-seat aircraft by the year 2025.

TABLE 1
FLEET PROJECTIONS BASED ON HSCT DEMAND

FARE PREMIUM LEVELS (PERCENT)	NUMBER OF AIRCRAFT					
	MACH 1.6		MACH 2.2		MACH 3.2	
	YEAR 2000	YEAR 2025	YEAR 2000	YEAR 2025	YEAR 2000	YEAR 2025
0	521	2,725	441	2,315	365	1,954
10	368	1,954	358	1,870	314	1,700
20	201	1,097	230	1,194	210	1,147
30	79	450	124	666	137	765
40	34	198	57	314	74	423
50	15	92	29	158	38	220

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HSCT needs shown in Table 1 cover the period from the year 2000 to the year 2025. Since there will be no HSCT aircraft in the commercial fleet as early as the year 2000, the subsonic fleet will continue to serve world traffic demands until the HSCT is introduced. If production rates are no greater than the rate of traffic growth, production quantities can be absorbed without premature retirement of the subsonic fleet.

The prime conditions for economic viability include (1) airplane revenues covering operating costs plus an attractive rate of return to the operator, (2) fares compatible with the subsonic fleet to expand HSCT service, and (3) a market large enough to permit a selling price lower than the investment value of the airplane.

Annual operating performance (revenue – cost = profit) of the three baseline aircraft designs at Mach 1.6, 2.2, and 3.2 is shown in Figure 8.

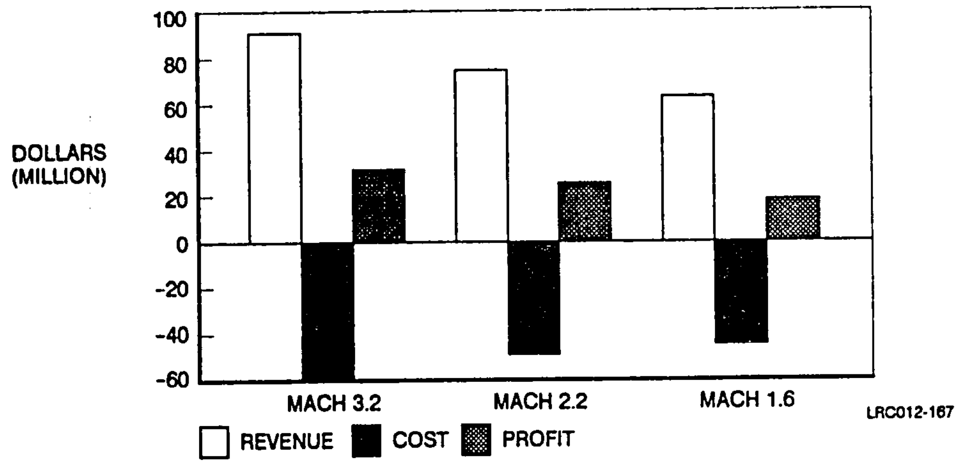

FIGURE 8. OPERATING PERFORMANCE (REVENUE - COST = PROFIT)

Aircraft worth is the investment value of an airplane to the airline. The worth of an HSCT is estimated by an iterative process that determines the price to the operator so that a target rate of return on investment is achieved by the airline. Aircraft worth calculation includes corporate tax, depreciation, life of the asset, and the annual operating cash flow. Aircraft characteristics as well as operational parameters are embodied in the cash flow estimates. Results are shown in Tables 2 and 3 for various fare premiums and a 10-percent return on investment to the airline.

TABLE 2
ANNUAL CASH FLOW PER AIRCRAFT
($ MILLION)

FARE PREMIUM (PERCENT)	MACH 1.6	MACH 2.2	MACH 3.2
0	18.32	25.95	32.08
10	31.37	37.07	44.22
20	44.94	51.78	64.42
30	63.45	66.13	79.49
40	81.06	86.99	99.39
50	88.35	105.76	124.87

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TABLE 3
AIRCRAFT WORTH AT 10-PERCENT ROI
($ MILLION)

FARE PREMIUM (PERCENT)	MACH 1.6	MACH 2.2	MACH 3.2
0	110	156	193
10	188	223	266
20	270	311	387
30	381	397	478
40	487	523	597
50	531	635	750

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2.3 SUPERSONIC NETWORK EVALUATION

Only a few candidate global airline network scenarios for the HSCT have been assembled. They are patterned after the high-density long-range markets from the Official Airline Guide (OAG) on-line data base. Creative rerouting minimized overland segments and lessened the impact of environmental restrictions that may be imposed on future supersonic operation. The top 250 potential supersonic great circle routes with no-sonic-boom overland restrictions are shown in Figure 9. The 250-network scenario represents 64 percent of the annual seat-miles for long-range routes over 2,000 statute miles. The average impact of route diversion to avoid land masses compared to the great circle routes is a 4-percent increase in network distance and a 41-percent reduction in overland distance.

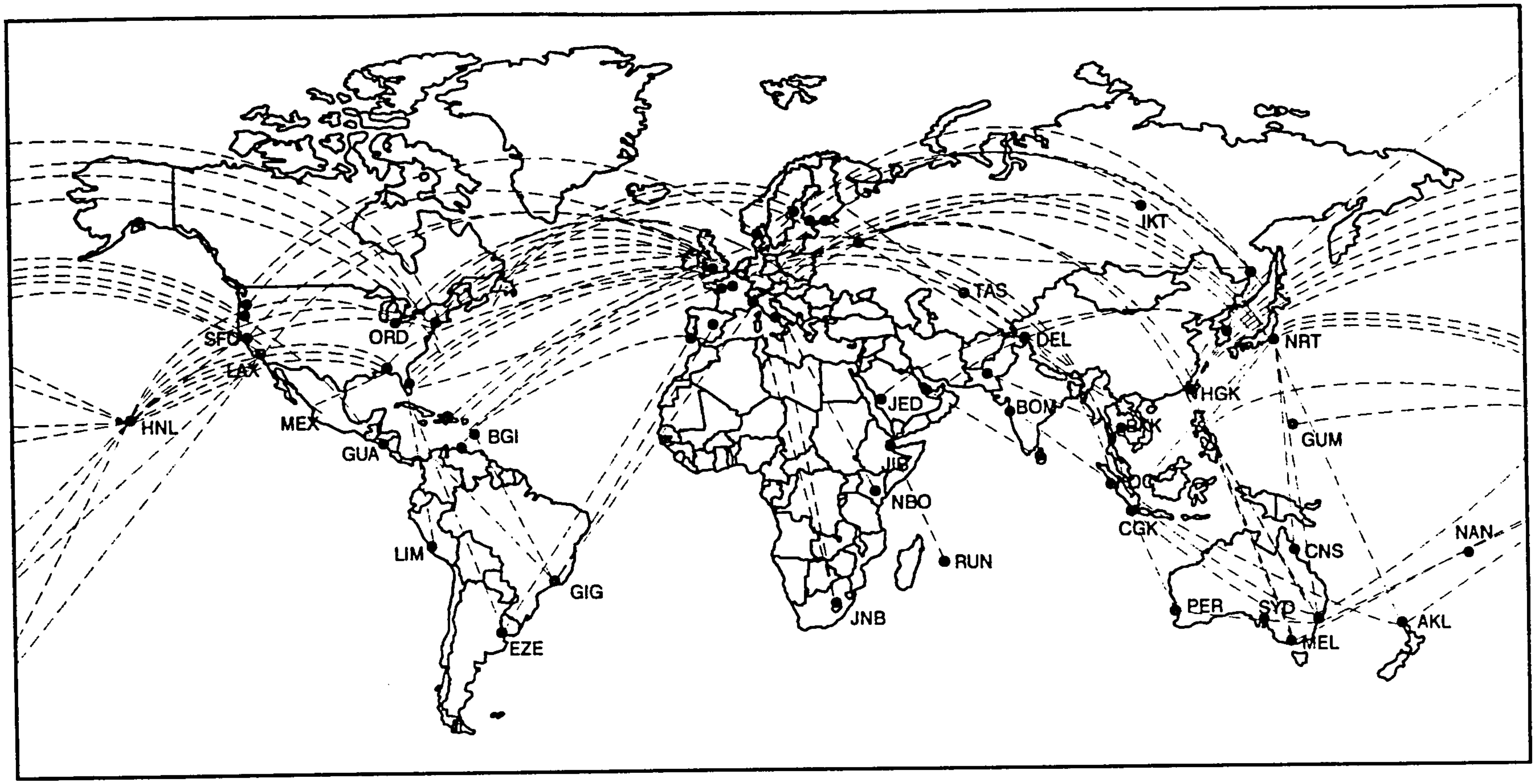
The all-overwater supersonic network scenario (Figure 10) includes only 100 city-pairs, representing 28 percent of the total long-range annual seat-miles.

The data on these network scenarios represent an assembly of global routes from which HSCT global traffic networks can be constructed. The network scenarios provide examples on how supersonic service may bring some changes to the current global route structure. Some of these supersonic network scenarios show good potential for capturing more than half the market share of long-range traffic.

2.4 ATMOSPHERIC EMISSIONS IMPACT STATUS

An engine emission annual fuel burn model was developed for input to 2-D atmospheric models. The fuel burn model calculated the total annual engine emissions, for various constituents in molecules, for an HSCT operational route structure.

For each of the 10 IATA worldwide regions, a city-pair was chosen that best describes the average latitude distribution. The 10 regions, along with their corresponding city-pairs, are shown in Figure 11. A mission was flown for each city-pair for the appropriate airframe/engine combination to determine the fuel burn in each region as a function of altitude and latitude. The 10 regions were then compiled into one data set representing the total annual worldwide fuel burn in each latitude and altitude band as specified by the 2-D atmospheric model. The model incorporates gas phase chemistry reactions only. Heterogeneous chemistry reactions were not considered.



AVERAGE STAGE LENGTH 3,666 ST MI

PERCENT OF LONG-RANGE TRAFFIC – 70 PERCENT

1. NORTH AMERICA – SOUTH AMERICA (5)
   GIG-MIA NO. 20
2. NORTH AMERICA – CENTRAL AMERICA (6)
   JFK-MEX NO. 61
3. NORTH TRANSATLANTIC (69)
   JFK-LHR NO. 2
4. MID TRANSATLANTIC (10)
   MAD-MIA NO. 132
5. SOUTH TRANSATLANTIC (3)
   GIG-MAD NO. 120
7. EUROPE – SOUTH AFRICA (3)
   JNB-LHR NO. 101
8. EUROPE – MIDDLE EAST (12)
   DXB-LON NO. 78
9. EUROPE – FAR EAST (26)
   NRT-SVO NO. 24
10. AMERICAS – MID PACIFIC (23)
    HNL-NRT NO. 10
11. AMERICAS – SOUTH PACIFIC (5)
    AKL-HNL NO. 50
12. WITHIN NORTH AMERICA (55)
    HNL-LAX NO. 1
16. WITHIN AFRICA (1)
    JIB-RUN NO. 245
18. WITHIN FAR EAST (25)
    NRT-SIN NO. 12
19. MISCELLANEOUS (8)
    BKK-DXB NO. 84

FIGURE 9. TOP 250 POTENTIAL SUPERSONIC ROUTES (NO RESTRICTIONS)

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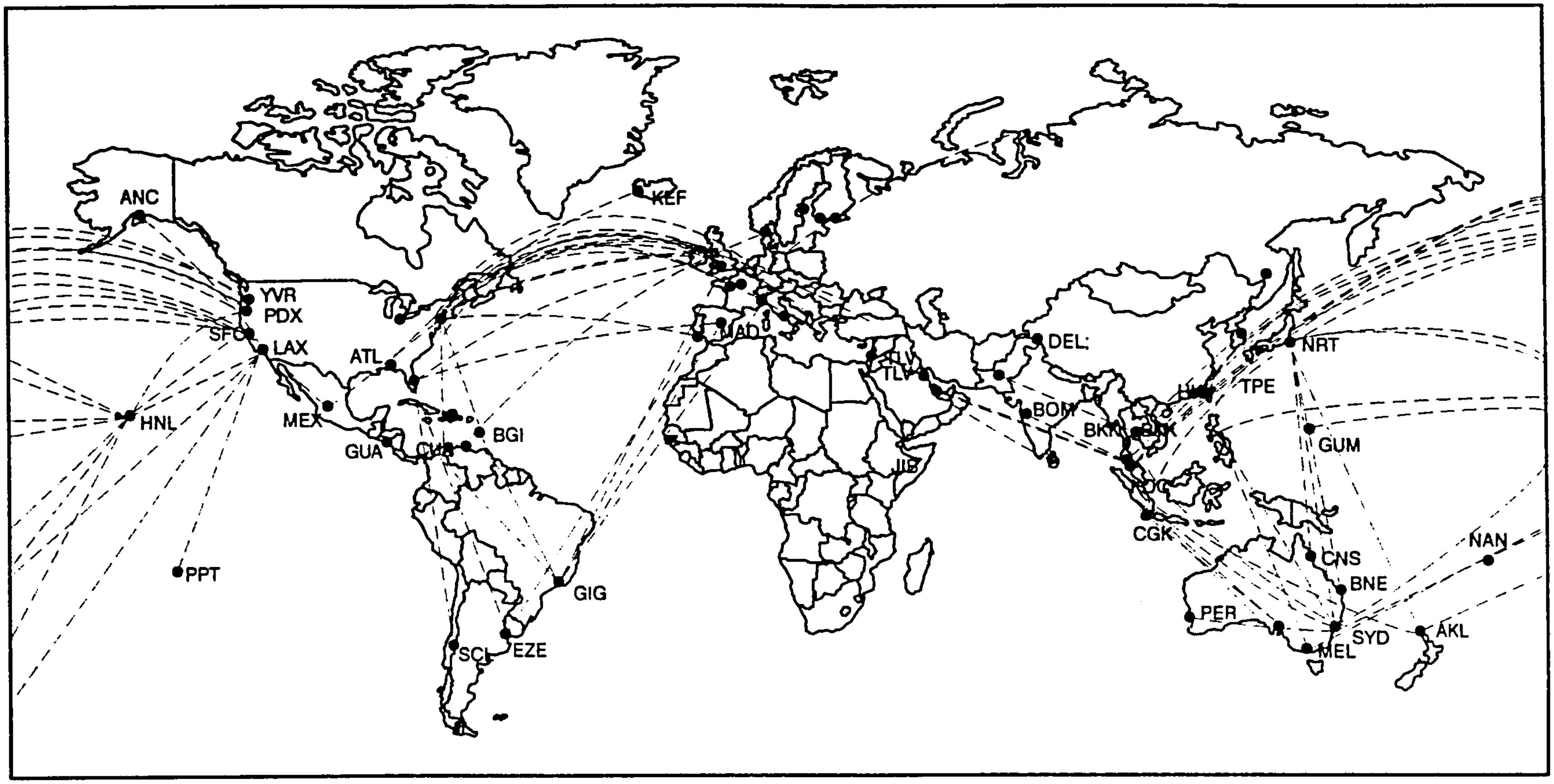

AVERAGE STAGE LENGTH 3,900 ST MI

PERCENT OF LONG-RANGE TRAFFIC – 28 PERCENT

1. NORTH AMERICA – SOUTH AMERICA (4)
   GIG-JFK NO. 16
2. NORTH AMERICA – CENTRAL AMERICA (3)
   BGI-JFK NO. 19
3. NORTH TRANSATLANTIC (26)
   JFK-CDG NO. 80
4. MID TRANSATLANTIC (5)
   MAD-MIA NO. 99
5. SOUTH TRANSATLANTIC (5)
   GIG-MAD NO. 87
10. AMERICAS – MID PACIFIC (19)
   HNL-NRT NO. 2
11. AMERICAS – SOUTH PACIFIC (6)
   AKL-HNL NO. 10
12. WITHIN NORTH AMERICA (8)
   HNL-LAX NO. 1
18. WITHIN FAR EAST (20)
   NRT-SIN NO. 6
19. MISCELLANEOUS (4)
   DXB-KUL NO. 68

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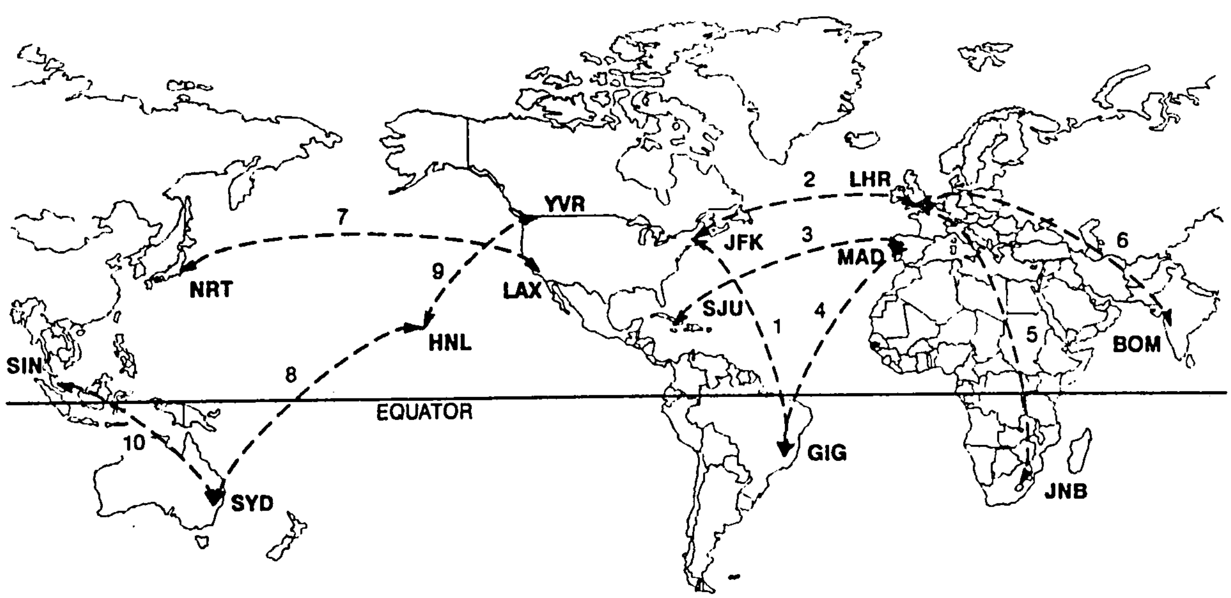
FIGURE 10. 100 CITY-PAIRS FOR OVERWATER ONLY – SUPERSONIC NETWORK



	REGION	CITY-PAIRS
1	NORTH-SOUTH AMERICA	NEW YORK - RIO DE JANEIRO (JFK-GIG)
2	NORTH ATLANTIC	NEW YORK - LONDON (JFK-LHR)
3	MID-ATLANTIC	SAN JUAN - MADRID (SJU-MAD)
4	SOUTH ATLANTIC	RIO DE JANEIRO - MADRID (GIG-MAD)
5	EUROPE AFRICA	JOHANNESBURG - LONDON (JNB-LHR)
6	EUROPE FAR EAST	BOMBAY - LONDON (BOM-LHR)
7	NORTH AND MID-PACIFIC	LOS ANGELES - TOKYO (LAX-NRT)
8	SOUTH PACIFIC	HONOLULU - SYDNEY (HNL-SYD)
9	INTRA-NORTH AMERICA	HONOLULU - VANCOUVER (HNL-YVR)
10	INTRA-FAR EAST AND PACIFIC	SINGAPORE - SYDNEY (SIN-SYD)

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FIGURE 11. HSCT REPRESENTATIVE CITY-PAIRS

The final input to the global atmospheric models was broken down into seven engine emission constituents. These were NO, NO_2, SO_2, CO, H_2O, CO_2, and THC (trace hydrocarbons). In addition, summary data for all oxides of nitrogen were provided ($NO + NO_2$) as NO_X. The total constituent emissions were determined by multiplying the total fuel burn by the emission index for each constituent.

Atmospheric emission scenarios were produced for the three HSCT configurations (Mach 1.6, 2.2, and 3.2). All three configurations used a P&W turbine-bypass engine (TBE) having a low-NO_X combustor in the 5 $EINO_X$ range (emission index (EI) = pounds of emissions per 1,000 pounds fuel burned). The impact of NO_X emissions on ozone based on Mach number and fleet size is shown in Figure 12. The results from the 2-D atmospheric model show steady-state ozone concentration depletions for combinations of Mach number and fleet size. The atmospheric global model results show that ozone depletion is a function of the aircraft's cruise Mach number primarily because of the strong dependence of ozone impact on injection altitude. The atmospheric impact of ozone depletion for the Mach 1.6 configuration is considerably less than that for the Mach 2.2 and 3.2 configurations for a given combustor technology.

The introduction of cruise altitude restrictions after the HSCT enters service could alleviate the ozone impact of the Mach 1.6 and 2.2 configurations. However, at Mach 3.2, the increased fuel burn more than offsets the advantage of lower injection altitude (Figure 13). All

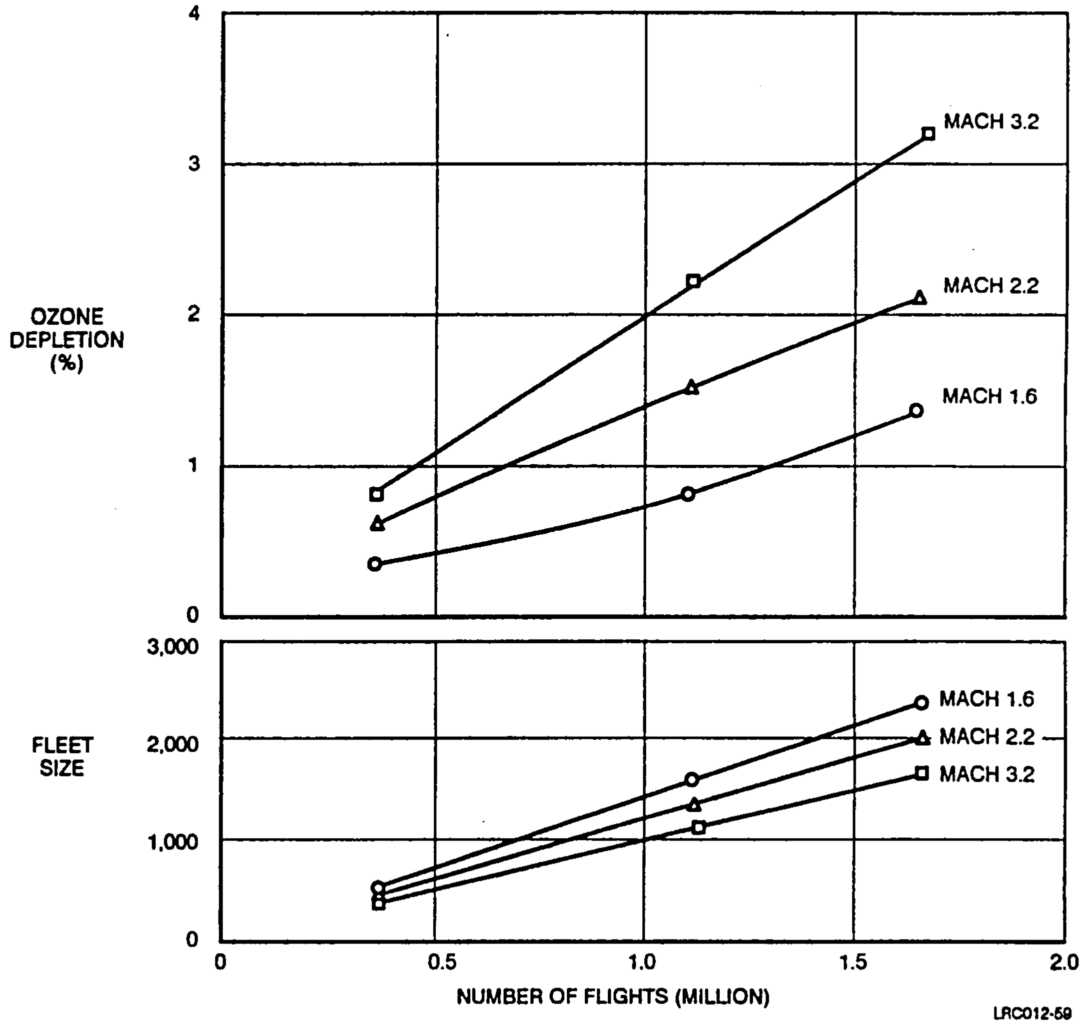

FIGURE 12. OZONE DEPLETION AND FLEET SIZE VERSUS NUMBER OF FLIGHTS FOR P&W TBE

configurations will suffer some economic performance penalties if forced below their optimum operating cruise altitude. Aircraft economic performance at different cruise altitudes is shown in Table 4.

2.5 ENGINE CYCLE ASSESSMENTS

Four variable-cycle engines from both Pratt & Whitney and General Electric were evaluated during the 1990 system studies. The engine cycles were evaluated to develop selection criteria and compare the benefits of each engine cycle for a representative configuration and mission. All engines were assessed based on (1) overall installed performance, (2) exterior noise, and (3) emissions impact.

The candidate engine cycle studies in 1990 were the GE variable-cycle engine (VCE), the GE VCE (Flade), the P&W turbine-bypass engine (TBE), and the P&W variable-stream-control engine (VSCE). These engine cycles were evaluated on the Mach 3.2 vehicle. The Flade and

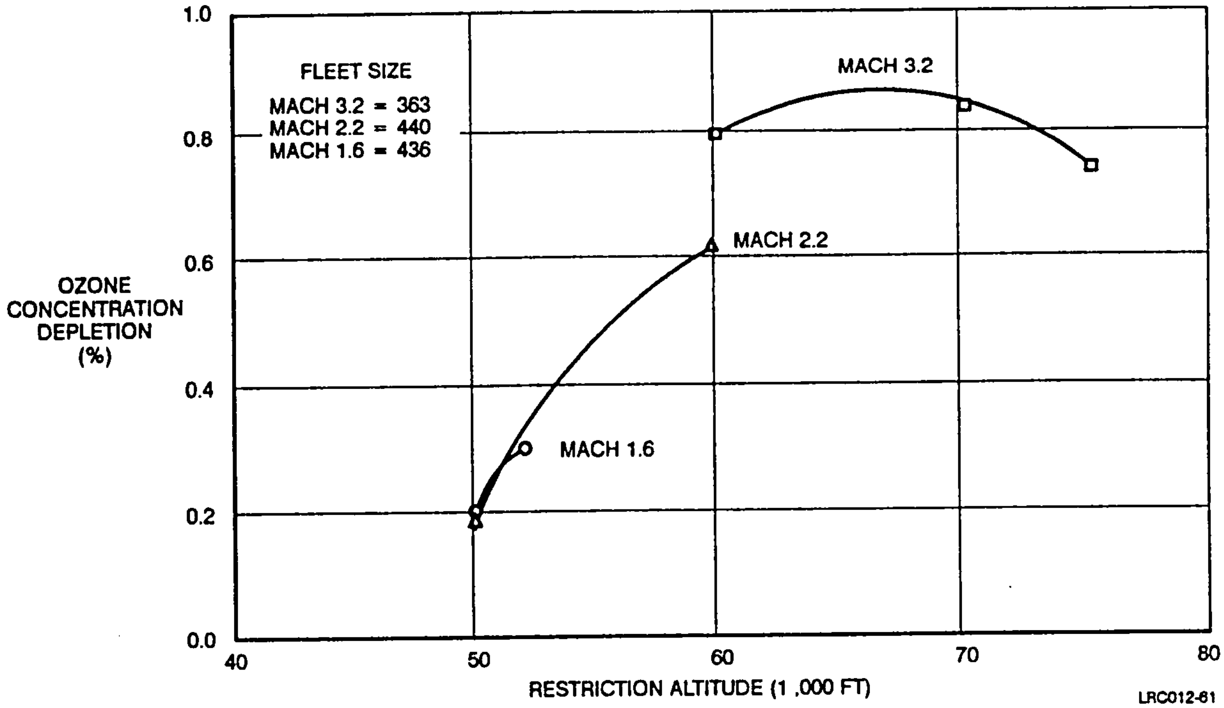

FIGURE 13. CRUISE ALTITUDE RESTRICTION OZONE IMPACT

TABLE 4
AIRCRAFT ECONOMIC PERFORMANCE AT DIFFERENT CRUISE ALTITUDES

CRUISE ALTITUDE (1,000 FT)	OPERATING COST ($ MILLION) PERCENT OF CHANGE						PROFIT ($ MILLION) PERCENT OF CHANGE						AIRCRAFT WORTH ($ MILLION) PERCENT OF CHANGE					
	M3.2	%	M2.2	%	M1.6	%	M3.2	%	M2.2	%	M1.6	%	M3.2	%	M2.2	%	M1.6	%
80	59						32						192					
70	60.6	+2.7	49				30.6	-4.4	26				184	-4	156			
60	66.2	+12	50	+2	45		24.7	-23	25	-4	18		148	-23	151	-3	110	
50			54	+10	46	+2			20	-23	17	-6			125	-20	103	-6.4
40					51	+13					12	-33					73	-33

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TBE were also evaluated on the Mach 2.2 vehicle. The TBE was evaluated on the Mach 1.6 vehicle.

Table 5 summarizes emissions, noise, and performance of the HSCT Mach 3.2 engine cycles. At this time, the most promising engine cycles for meeting Stage 3 noise limits and achieving reasonable performance are the TBE incorporating a mixer ejector exhaust nozzle and the Flade incorporating a noise suppressor in the exhaust nozzle.

TABLE 5
SUMMARY OF HSCT MACH 3.2 ENGINE CYCLES

	TBE	VSCE	VCE	FLADE
NO_x	ASSUMING DEVELOPMENT OF A LOW-NO_x COMBUSTOR, NO_x IS NOT A DISCRIMINATOR IN CYCLE SELECTION			
NOISE	MEETS STAGE 3 WITH 120% PUMPING	MAY NOT MEET STAGE 3	3-5 dB OVER STAGE 3	MEETS STAGE 3 BASED ON GE DATA
PERFORMANCE TOGW (NO STAGE 3 LIMIT) TOGW (MEETS STAGE 3 LIMIT)	 BASE 4.8% WORSE	 11.2% WORSE	 2.5% BETTER	 0.4% WORSE 3.1% BETTER

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2.6 CERTIFICATION AND COMMUNITY NOISE STATUS

Low-speed high-lift devices for reducing community noise under the takeoff and approach flight path were evaluated. The noise study was conducted assuming two low-speed high-lift configurations: a baseline standard taken from the Advanced Supersonic Transport (AST) program and an improved high-lift configuration that produced a 47-percent lift-to-drag improvement. The resulting changes in jet noise levels for the sideline, takeoff, and approach noise certification measuring locations are summarized in Table 6. Sideline noise was not affected; however, significant reductions in takeoff and approach noise under the flight path were achieved.

TABLE 6
EFFECTS OF LOW-SPEED, HIGH-LIFT DEVICES ON CERTIFICATION NOISE

	JET NOISE REDUCTION (Δ EPNdB)		
	SIDELINE	TAKEOFF	APPROACH (UNSUPPRESSED) (168 KNOTS)
GE VCE	-0.2	-6.4	-6.7
P&W TBE (M/E)	-0.2	-8.5	-7.0

ASSUMPTIONS: D3.2-3A BASELINE CONFIGURATION
ACHIEVE 80% TRIMMED LE SUCTION (47% L/D IMPROVEMENT) RELATIVE TO AST 45% TRIMMED LE SUCTION BASELINE
PARTIAL-SPAN FLAPS FOR TAKEOFF

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Three new engine data bases were assessed for noise performance. The engine data bases were supplied by P&W and GE. The engines evaluated for noise performance were:

- Mach 3.2 P&W TBE mixer/ejector (M/E) assuming 120-percent mass flow entrainment
- Mach 3.2 P&W VSCE (M/E) assuming 120-percent mass flow entrainment
- Mach 2.2 GE VCE Flade incorporating a noise suppressor

Aircraft sizing studies were conducted using the above engines for aircraft ranges of 5,000 and 6,500 nautical miles and a takeoff field length of 10,600 feet for an ISA + 10°F day

(11,000 feet for an ISA day). The Mach 3.2 with a TBE (M/E) was estimated to meet Stage 3 sideline noise limits within ±0.5 EPNdB. This was for an aircraft range of 5,000 to 6,500 nautical miles and was based on jet (mixing + shock) noise. The sideline jet noise of the VSCE (M/E) was 2 to 3 EPNdB below the Stage 3 limit. However, duct burner noise (based on engine company estimates) is predicted to be significant. Therefore, the peak sideline noise is expected to be in excess of the sideline Stage 3 limit.

The Stage 3 noise assessment of the Mach 2.2 GE Flade engine indicated that Stage 3 compliance can be achieved if the noise attenuations associated with an advanced noise suppressor/fluid shield concept are assumed. The aircraft was sized to achieve a 5,000-nautical-mile range and required a MTOW of 650,000 pounds. The MTOW increased by approximately 230,000 pounds to achieve sideline and takeoff noise compliance for a range of 6,500 nautical miles.

Finally, initial HSCT climb-to-cruise noise estimates show that significant noise suppression may be required up to 30,000 feet in altitude. Potential noise problems during the climb-to-cruise phase were evaluated against an interim human acceptance goal of 65 dBA. This noise goal was based on assessments of acceptable noise levels during the Douglas and NASA ultrahigh-bypass (UHB) engine demonstration tests and on feedback from European regulatory agencies.

Two engine data bases in the unsuppressed mode were evaluated using the Mach 3.2 configuration. At the higher subsonic climb Mach numbers (up to 0.95) and altitudes (up to 30,000 feet) both engines operate at increased exhaust pressure ratios. The jet noise estimates in the unsuppressed mode show a significant increase in shock cell noise, which produces noise levels in excess of 65 dBA during the climb-out phase (see Figure 14). The current jet noise prediction code calculates this large shock cell noise increase in the forward arc (30- to 80-degree angle to inlet-exhaust axis). The P&W TBE (M/E) was found to have slightly higher unsuppressed climb noise level than the GE VCE.

There are, however, a number of uncertainties in the current HSCT climb-to-cruise jet noise prediction models:

- The existing jet noise data base has not been validated above Mach 0.4 and a pressure ratio of about 3.0. Therefore, the level of shock cell noise present cannot be validated.
- Long-range propagation models are only just maturing. The Douglas model is based on the ultrahigh-bypass ratio (UHB) engine noise measurement programs.

2.7 SONIC BOOM MINIMIZATION STATUS

The 1990 sonic boom minimization contract studies centered around designing an aircraft to meet a beginning-of-cruise, undertrack, sonic boom loudness level of 90 PLdB or less. The noise level and metric were selected based on a review of human response studies conducted in 1987. Consistent with the lessons learned in previous years, the minimization effort for the current task focused on waveform shaping. This is believed to be the only viable approach to sonic boom minimization for a long-range, 300-passenger HSCT in the Mach 1-3 range. The wider issue of human and building response to shaped booms was not addressed in this study.

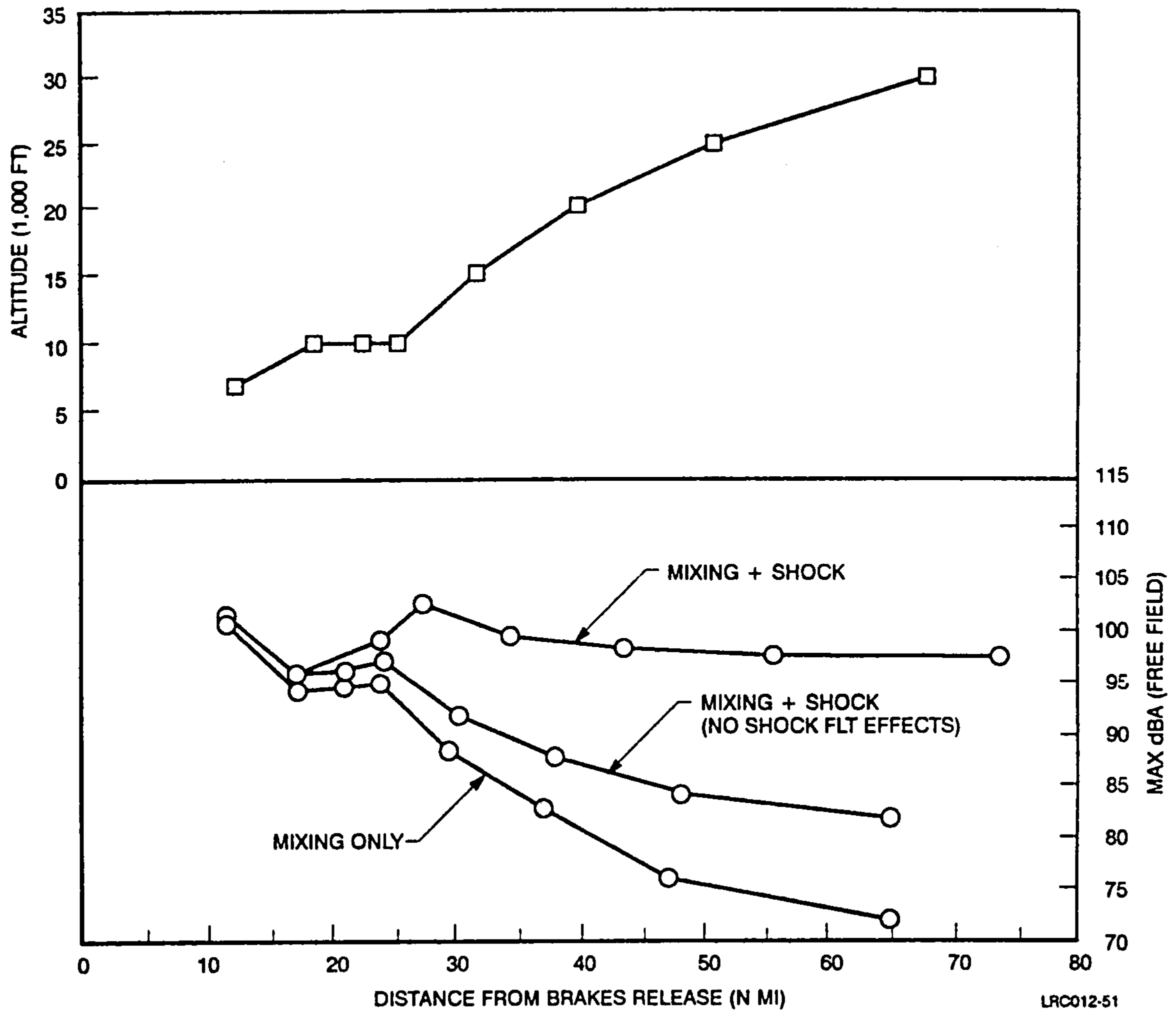

FIGURE 14. CLIMB-TO-CRUISE NOISE FOR GE VCE (UNSUPPRESSED)

A generalized study was initiated to gain an understanding of the impact of cruise Mach number on sonic boom aircraft design. This study attempted to quantify the level of difficulty in sonic boom design on the basis of two parameters – one measuring the gross weight reduction required, and one measuring the amount of equivalent area that must be removed or added to achieve the 90-PLdB loudness goal. Baseline study aircraft at Mach 1.6, 2.2, and 3.2 were evaluated against the screening parameters. The beginning-of-cruise weights and equivalent area distributions of these aircraft had been established previously through mission performance and sizing studies. All three aircraft were sized for a 6,500-nautical-mile range and a payload of 300 passengers.

In order to determine the amount of equivalent area that must be added or subtracted from a configuration to achieve a shaped boom, idealized equivalent area distributions were generated. For each Mach number, two idealized equivalent area distributions were generated that theoretically resulted in an undertrack, 90-PLdB waveform on the ground for the specified flight conditions – one for a flattop waveform and one for a front shock-minimized waveform. The target waveforms for each Mach number and waveform type are shown in Figure 15. A comparison of the baseline and low-boom equivalent area requirements showed that the Mach 3.2 configuration required significant changes in equivalent area distribution compared with the Mach 1.6 and Mach 2.2 vehicles.

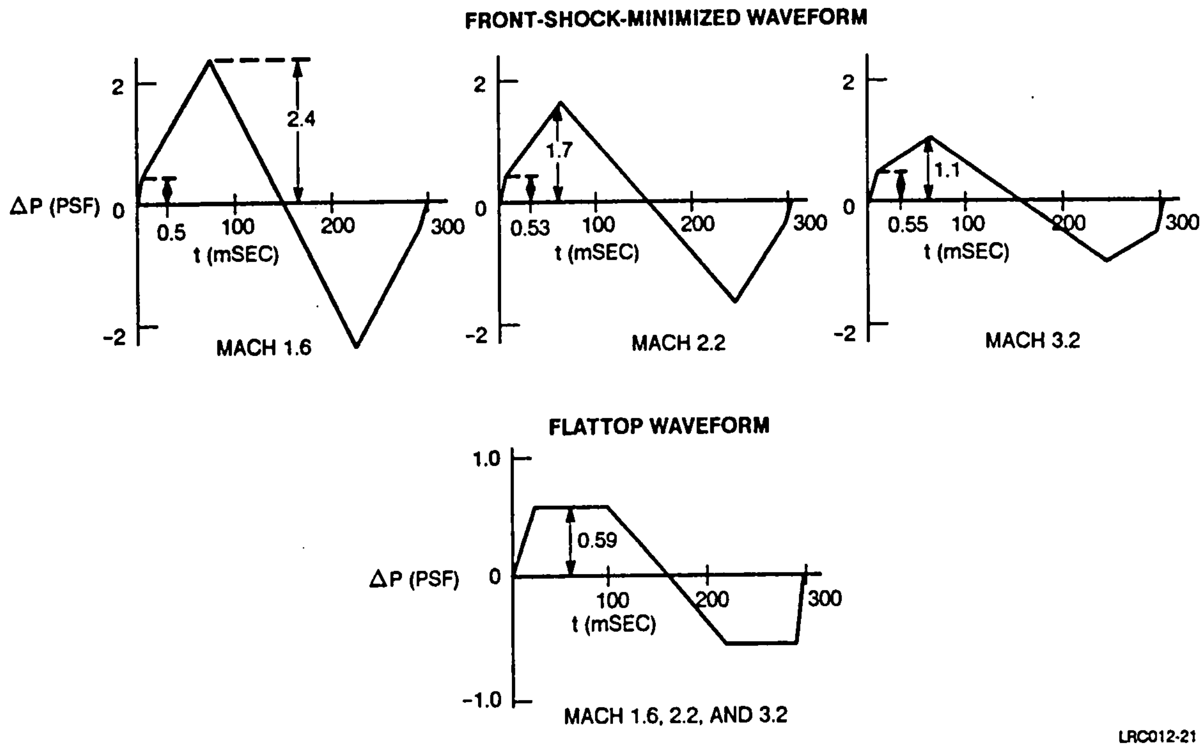

FIGURE 15. 90-PLdB TARGET WAVEFORMS

In order to determine the beginning of cruise weight necessary to achieve the above waveforms at the ground surface, the weight parameter is iterated in the equivalent area code until the resulting waveform yields a perceived loudness of 90 PLdB.

The required initial cruise weight to achieve 90 PLdB for the two waveforms varies widely across the Mach number range (Figure 16). The weight reduction required at Mach 3.2 ($\approx$ 400,000 pounds) is simply not feasible for any current or near-term projected technology. Furthermore, the weight reduction required for the flattop waveform is probably unrealistic even for low Mach numbers ($\approx$ 300,000 pounds).

The only scenario that appears to be feasible is the front shock-minimized waveform at low supersonic Mach numbers (e.g., $\approx$ Mach 1.6). The required gross weight reduction at the beginning of cruise appears to be feasible for this scenario ($\approx$ 50,000 pounds) and could be achieved through improvements in aircraft performance or, less desirably, through compromises in payload and/or range.

In order to balance sonic boom requirements with economic considerations, a two-point low-boom design was pursued. Based on the Mach number screening study, the vehicle assumed a Mach 1.6 cruise speed overland and Mach 3.2 cruise speed overwater.

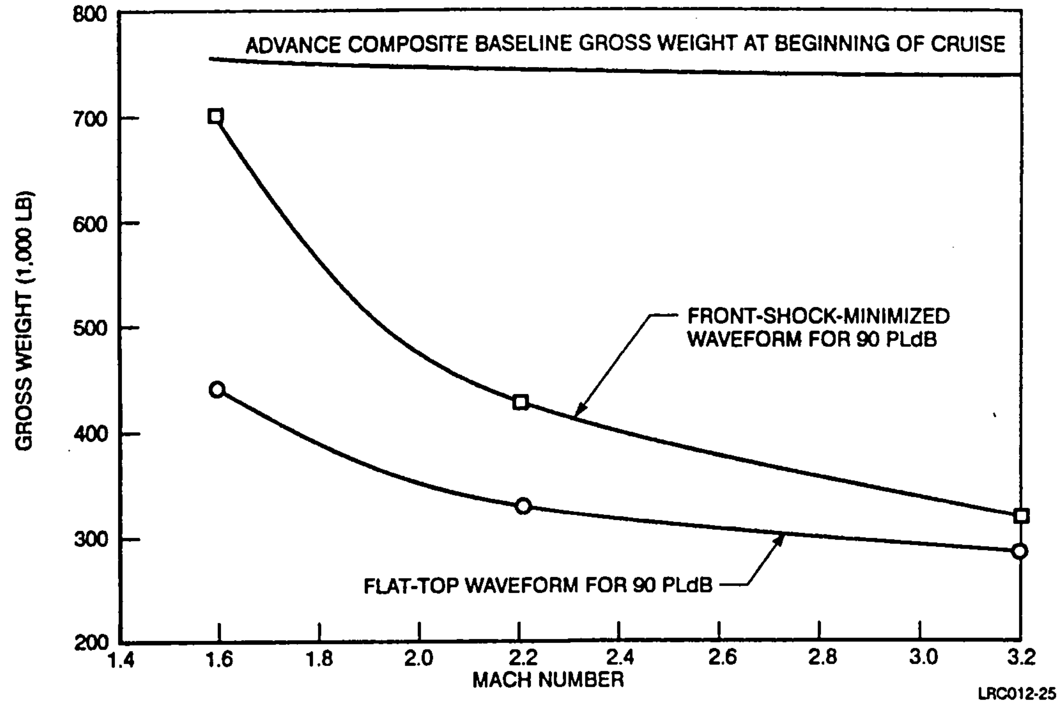

FIGURE 16. GROSS WEIGHT REQUIREMENTS FOR 90 PLdB

A number of low-boom configurations were defined and evaluated, leading to a final configuration that featured a highly swept, high-notch wing; wing- and aft-mounted engines to smooth out nacelle area distributions; 286-passenger fuselage; and an overall nose-to-wing tip length of 372 feet. The increased structural weight and low-speed performance characteristics of this vehicle reduced the mission range to 3,150 nautical miles.

SECTION 3
CONCLUSIONS

The following is concluded from the system studies conducted in the environmental areas of noise certification and community noise, atmospheric emissions impact, and sonic boom.

NOISE CERTIFICATION AND COMMUNITY NOISE

1. The need for low-speed high-lift devices in reducing community noise under the takeoff and approach flight paths has been demonstrated.
2. The P&W TBE (M/E) and GE Flade appear the most promising engine cycles to achieve Stage 3 noise limits.
3. Initial climb-to-cruise noise estimates show that significant noise suppression may be required up to 30,000 feet in altitude.

ATMOSPHERIC EMISSIONS IMPACT

1. The atmospheric impact model results of ozone depletion show a significant dependence on cruise injection altitude.
2. Ozone depletion is significantly less with the Mach 1.6 configuration than with the Mach 2.2 and Mach 3.2 configurations for a given combustion technology.
3. The introduction of cruise altitude restrictions after production implementation alleviates ozone impact for all Mach numbers except 3.2. At Mach 3.2, the increased fuel burn more than offset the advantage of lowering the injection altitude and resulted in an increase in ozone depletion.
4. Restricting supersonic aircraft to an off-design lower cruise altitude will impose penalties on economic performance in the form of higher operating costs and, hence, reduced airline operating profits. The penalties are unlikely to be acceptable from a flight performance and economic standpoint. Therefore, any altitude restrictions must be established prior to final Mach number selection in the aircraft development stage.

SONIC BOOM MINIMIZATION

1. Mach number screening studies conducted at the beginning of the contract indicated that waveform shaping at Mach numbers greater than about 1.6 is not practical.
2. The structural and weight characteristics of the low-boom wing design was poor owing to a long, narrow load-carrying path and high sweep angle. This led to a high empty weight and, consequently, decreased range capability. The total mission range achieved was 3,150 nautical miles.
3. The high-speed aerodynamic characteristics of the low-boom design were acceptable, except for pitching moment and stability. Large nose-down pitching moments are currently generated by the configuration at cruise because of the aft center of pressure location required for sonic boom purposes. Current aerodynamic parameters assume that acceptable high-speed trim can be achieved with such techniques as CG management

and thrust vectoring, although the stability of such a configuration would require advanced electronic methods.

In generating HSCT baseline configurations, a number of airframe and propulsion parametric studies were completed, and the following conclusions drawn:

1. The Jet A fuel envelope analysis showed that with appropriate engine and thermal technology Jet A fuel could be successfully used up to Mach 3.2.
2. A materials and aircraft structures verification analysis showed that polymer composite; discontinuous reinforced, elevated-temperature aluminum; and titanium are needed to produce the minimum airframe structural weight.
3. High-lift technology must be developed to enhance community noise acceptance and to minimize MTOW.

Finally, the following conclusions are drawn from the marketing and economic studies:

1. Depending on Mach number, fare premium, and aircraft range, fleet needs could total 2,300 or more 300-seat aircraft by the year 2025.
2. The prime conditions for economic inability include (1) airplane revenues covering operating costs plus an attractive rate of return to the operator, (2) fares compatible with the subsonic fleet to expand HSCT service, and (3) a market large enough to permit a selling price lower than the investment value of the airplane.

SECTION 4
RECOMMENDATIONS

The recommendation to continue system studies in the environmental areas of noise certification and community noise, atmospheric emissions impact, and sonic boom are as follows:

NOISE CERTIFICATION AND COMMUNITY NOISE

- Evaluation should continue on the variable-cycle engines/noise suppression devices developed by P&W/GE to meet Stage 3 noise certification limits and to achieve community noise acceptability.
- The economic viability of each engine concept should be evaluated after the aircraft has been sized to meet Stage 3 noise limits for various aircraft ranges.
- Community noise should be assessed close to the airport, during the climb opening-up procedure, and during the climb-to-cruise phase up to 30,000 feet.
- Airport takeoff and approach operational procedures to minimize community noise should be developed.

ATMOSPHERIC EMISSIONS IMPACT

- Mach number trade studies should continue after (1) 2-D atmospheric models have been updated to include fine grid densities and the effects of heterogeneous chemistry, and (2) the city-pair network has been updated.
- Three-dimensional atmospheric models should be used for baseline atmospheric impact scenarios and the results compared to the 2-D model data.
- Future effects of HSCT operation or ozone depletion should include the effects of the subsonic fleet in the atmosphere for an appropriate year (e.g., 2015).
- The effects of including additional subsonic operation (e.g., military, USSR, China, cargo, and turboprop) should be considered.
- The effects of traffic seasonality on atmospheric effects should also be evaluated.
- Finally, alternative emission scenarios should be developed to avoid routes having high sensitivity to ozone depletion (e.g., rerouting of polar routes).

SONIC BOOM

- It is recommended that sonic boom minimization studies should continue at a fixed mach number for overland and overwater operation.
- The Mach 1.6 cruise speed may not be the optimum for a minimized sonic boom configuration. Therefore, further mach number screening analyses are necessary before commencing further configuration studies. Practical considerations of high- and low-speed performance characteristics should be addressed.
- Detailed sonic boom analyses are required in the areas of off-track levels, the climb-out focus boom and the impact of nacelles and exhaust plumes on the sonic boom signature.

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13. ABSTRACT *(Maximum 200 words)*

This summary report contains the results of the Douglas Aircraft Company system studies related to High-Speed Civil Transports (HSCT's). The tasks were performed under an 18-month extension of NASA Langley Research Center Contract NAS1-18378.

The system studies were conducted to assess the environmental compatibility of high-speed civil transports at design Mach numbers ranging from 1.6 to 3.2. In particular engine cycles were assessed regarding community noise and atmospheric emissions impact, and an HSCT route structure was developed.

The general results indicated (1) in the Mach number range 1.6 to 2.5, the development of polymer composite and discontinuous reinforced aluminum materials is essential to ensure a minimum operational weight; (2) the HSCT route structure to minimize supersonic overland can be increased by innovative routing to avoid land masses; (3) at least two engine concepts show promise in achiving sideline Stage 3 noise limits; (4) two promising low-NO_x combustor concepts have been identified; (5) the atmospheric emission impact on ozone could be significantly lower for Mach 1.6 operations than for Mach 3.2 operations; and (6) sonic boom minimization concepts are maturing at an encouraging rate.

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