Hypersonic Transports—Economics and Environmental Effects

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An economic analysis of hypersonic transports is presented to show projected operating costs (direct and indirect) and return on investment. Important assumptions are varied to determine the probable range of values for operating costs and return on investment. The environmental effects of hypersonic transports are discussed and compared to current supersonic transports. Estimates of sideline and flyover noise are made for a typical hypersonic transport, and the sonic boom problem is analyzed and discussed. Since the exhaust products from liquid hydrogen-fueled engines differ from those of kerosene-fueled aircraft, a qualitative assessment of air pollution effects is made.

Introduction

OVER the past ten years there have been numerous studies of hypersonic transports for commercial application. References 1–10 give examples of studies performed in the U.S. Primarily these studies have concentrated on the performance aspects of hypersonic aircraft.

In the last few years, increasing emphasis has been placed on the economic evaluation of proposed commercial aircraft and on early study of their environmental characteristics. The purpose of this paper is to provide current estimates of the economics and environmental effects of hypersonic aircraft.

To put the results in proper context, the paper commences with a brief review of aircraft characteristics and performance, followed by a discussion of the prime technological problems associated with hypersonic aircraft. Then estimates of economic performance are presented and discussed in detail. Finally, the characteristics which affect the environment are analyzed to determine potential environmental problems associated with hypersonic aircraft.

Configurations and Performance

The nominal airplane considered in this study is an all-body hypersonic transport configuration with a gross weight of 1 million lb (454,000 kg), a cruise speed of Mach 6, and a range of 5500 naut miles (10,200 km). It is accelerated to Mach 3.5 by turbojet engines and cruises at approximately 100,000 ft (31,000 m) altitude on ramjet engines fueled with liquid hydrogen.

A number of configuration options have been examined over the years. Two extremes in vehicle configuration are the all-body[7] and the wing-body.[2] The lifting body shape of the all-body is well suited to ramjet engines, particularly those which employ supersonic combustions, because its body surfaces can be utilized as inlet and expansion nozzle. (Supersonic combustion ramjets would allow cruise speeds of Mach 8 to Mach 10.) On the other hand, the all-body has high drag characteristics at transonic speeds where the accelerator engines are sized. Both of the configuration options have similar performance in the speed range from Mach 6 to Mach 8 where their performance is optimum; a Mach 6 all-body aircraft using subsonic burning ramjets was chosen as representative for this study.

Received November 6, 1972; revision received April 4, 1973.

Index categories: Air Transportation Systems; Aircraft and Air Transportation Economics.

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Another option for hypersonic transportation is the rocket-powered boost-glider. There are many proponents of boost-glide hypersonic transports, and their analyses make the boost-glider appear promising, but these studies normally assume very low structural weights. The results from a recent unpublished study which compared boost-glide vehicles with rocket-boosted, airbreathing-cruise vehicles and with airbreathing vehicles are presented in Table 1. In this study, all three vehicles were analyzed using the same weight estimating techniques, and the all-airbreathing transport clearly gave the best economic performance. Note that the direct operating costs due to propellants for the rocket-boosted vehicles were considerably higher than the total direct operating costs for the air-breathing vehicle. With the added problems of passenger acceptance (due to relatively high accelerations and periods of weightlessness), the boost-glide mode of transportation does not appear competitive with a hypersonic air-breathing aircraft.

Technology Status

While there will be many aerodynamic problems associated with the development of a hypersonic transport, aerodynamics does not appear to be a pacing technology. Wing-body configurations, all-body configurations, and variations between these two configurations (which are often called blended bodies) have been under study for several years. Probably the biggest aerodynamic concern is the efficient integration of the propulsion system into the overall configuration.

There are several design approaches to the structure and thermal protection system of a hypersonic transport. Because of the low density of liquid hydrogen, it is not feasible to carry much fuel in the wings of a wing-body configuration. Typically, fuel is carried in the fuselage and either integral or nonintegral tanks may be used. Because of its noncircular cross section the all-body shape does not lend itself to nonintegral tankage and normally uses integral tankage consisting of a number of conical, intersecting, tank sections.[11]

The structural designer has the option of using high-temperature materials for the structure, to resist the heat generated at hypersonic speeds, or employing normal aircraft materials and using a thermal protection system to maintain low temperatures in the primary structure of the vehicle. Preliminary analyses indicate that these two approaches may be competitive up to Mach numbers of 5 or 6, but at higher speeds the hot structure concept becomes much heavier than the cool structure concept.

The best design of a suitable thermal protection system presently is not clear. Basically, there are three elements which can be used to design a thermal protection system. These are active cooling, in which a liquid or gas coolant is circulated through the surface and conducts heat away from the surface, insulation, which may be used to restrict the flow of heat into the structure, and radiation shields, which may be used to encourage radiation of heat away from the surface.

The three elements active cooling, insulation, and radiation shielding, can be combined in a number of ways. One promising approach[8] is to use an actively-cooled structure with secondary coolant circulating through tubes beneath the surface of the structure and carrying the heat to the hydrogen fuel. With careful design of the airframe and engine, it appears that the entire airframe and the cruise engine could be cooled with the hydrogen required for combustion in the engine, for flight Mach numbers up to 8. In areas where the heat transfer is high, radiation shields can be used to significantly reduce the heat transferred to the coolant. Another promising approach[7] uses insulation and radiation shields to maintain the structure at a low temperature, and the fuel is used to cool only the cruise engines. This also appears to be a practical approach. In both cases, further insulation is required between the surface of the hydrogen tank and the structure, which operates near room temperature. Air must be excluded from this insulation to prevent cryopumping caused by air liquifaction.

The pacing item for hypersonic transport development is propulsion system technology. The operation of small-scale subsonic and supersonic burning ramjets has been adequately demonstrated. On the other hand, there are difficult problems with the fabrication of the ramjets because their surfaces must be regeneratively cooled with liquid hydrogen fuel as it flows to the combustor.

Propulsion system research must also be focused on designs which are integrated with the over-all aircraft configuration in contrast to previous experimental ramjets which have been axisymmetric. Most recent study configurations have nonaxisymmetric ramjets with the accelerator turbojets located in a separate duct.[12] (The inlet may or may not be common to both engines.)

At present the risks associated with hypersonic transport development are very high because of the inadequate research experience with their propulsion systems. The necessary confidence can only be obtained through testing of larger engines and engines which are integrated into practical aircraft designs. This research will be costly and time consuming and is hampered by the current lack of large scale test facilities. Because of the lack of propulsion technology the expected operational date for hypersonic transports is beyond 1990.

Economic Evaluation

As indicated previously, the nominal vehicle for the economic studies was a 1 million lb (454,000 kg), all-body, Mach 6 hypersonic transport. The design of this transport was optimized to obtain best performance with the all-body shape.[7] Other configuration and engine combinations might provide improved performance, but it is felt that this configuration is representative. The aircraft performance was estimated using a synthesis program developed by NASA's Systems Studies Division of Ames Research Center over a ten-year period. This program is described in Ref. 7.

Table 1 Comparison of rocket boosted and airbreathing hypersonic transports (198 passengers; 5500 naut mile range)

	Two-stage boost glide	Airbreather
Gross weight, lb × 10⁻⁶		
First stage	2.8	
Second stage	0.6	
Total	3.4	0.5
Acquisition cost		
$ × 10⁻⁶	100	70
DOC cents/seat-mile		
Fuel	2.35	1.35
Oxidizer	1.50	
Maintenance	1.15	0.40
Depreciation	0.50	0.35
Crew and insurance	0.30	0.30
Total	5.80	2.40

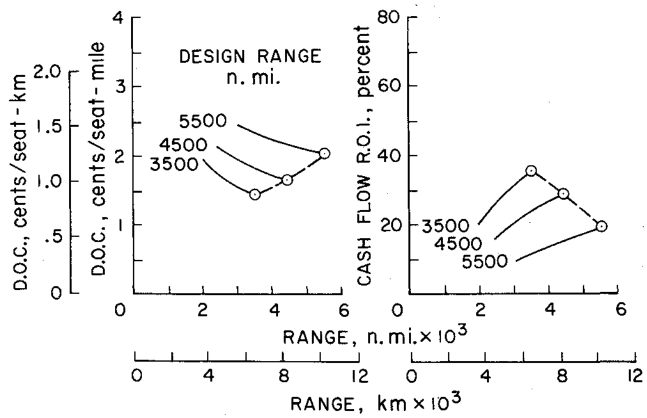

Fig. 1 Effect of range on HST economics.

Operating costs were estimated using standard methods of the U.S. Air Transport Association and U.S. manufacturers with appropriate adjustments for hypersonic aircraft. Aircraft development and production cost estimates were based on aircraft weight, complexity, and speed capability. All costs are in 1972 U.S. dollars. The nominal case makes the following assumptions: 1) hydrogen cost is 10 cents/lb (22 cents/kg), 2) turn-around time is 1.5 hr, 3) fraction of day in use is 0.5, 4) passenger load factor is 50%, 5) number of aircraft produced is 250, and 6) reserve fuel is 5% of block fuel plus 45-min hold. Current international fares were used to compute revenue. Aircraft prices were determined by estimating development and production costs for a given fleet size (nominal equals 250), adding a 10% profit for the manufacturer, and dividing by the fleet size.

Cash flow return on investment (ROI) is determined by assuming an airline investment equal to the cost of the aircraft, plus 10% airframe spares and 40% engine spares, and estimating the yearly cash flow as the difference between yearly revenues and operating costs (not including depreciation). The ROI is then the yearly cash flow divided by the investment. ROI is a better measure of the economic value of an aircraft than direct operating cost (DOC) because DOC does not take into account the productivity of the airplane. The hypersonic transport under study here would generate about 2.3 billion seat-miles per year compared to 0.5 billion seat-miles per year for the Concorde and 1.0 billion seat-miles per year for the Boeing 747.

The basic economic performance of the nominal hypersonic transport is shown in Fig. 1. Three vehicles with different design ranges are indicated. All have a gross weight of 1 million lb; the 5500-naut miles (10,200-km) aircraft carries 404 passengers, the 4500-naut miles (8300-km) aircraft carries 540 passengers, and the 3500-naut miles (6500-km) aircraft carries 684 passengers. The direct operating cost for the 5500-naut miles design varies between 2 and 2.5 cents/seat-mile for ranges between 3000 and 5500 naut miles. The 4500- and 3500-naut miles designs have better economic performance. The DOC of a 3500-naut miles design at its design range would be slightly more than 1.5 cents/seat-mile which is comparable to the Concorde. The DOC of a 747 is in the neighborhood of 1 cent/seat-mile. On the other hand, the 5500-naut mile vehicle produces an ROI between 10 and 20% for ranges of 3000 to

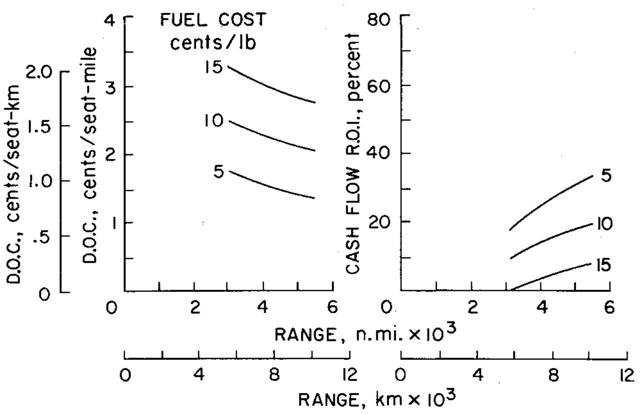

Fig. 2 Effect of fuel cost on HST economics.

5500 naut miles. A typical route structure might result in an over-all ROI of 15% which is marginal but should be acceptable. (Note that this return assumes current fares and a 50% load factor.) The vehicles designed for shorter ranges obviously provide a more attractive ROI.

One might ask why a nominal design range of 5500 naut miles was chosen, although it clearly penalizes the economic performance of the vehicle. From estimates of cumulative international air passengers vs range for 1980, a design range of 3500 naut miles would encompass 50% of the world international travel, but a design range of 5500 naut miles would include about 90%. Also, considering the time to fly various distances with different aircraft types, a Mach 6 aircraft would result in a modest time saving over the Concorde at ranges up to 3000 naut miles. At longer ranges, the time saving and therefore the competitive advantage of a hypersonic transport becomes larger, particularly if the limited range of the Concorde forces a stopover or change of airplanes. For these qualitative reasons, a design range of 5500 naut miles was selected for the nominal hypersonic transport.

To put the economic results in context, Table 2 summarizes the acquisition cost items, and Table 3 gives a breakdown of direct and indirect operating costs. From Table 3 it is clear that fuel forms a major portion of the operating costs for a hypersonic transport. The costs shown in the table are for liquid hydrogen at 10 cents/lb (22 cents/kg). A study done several years ago[13] indicated that this was an achievable cost for liquid hydrogen in large quantities in the 1990's. For comparison, at a cost of 4.2 cents/lb (9.3 cents/kg), liquid hydrogen would provide about the same energy output per dollar as current jet fuels. Although some authors[14] have projected costs as low as 4 cents/lb, such costs do not appear likely within this century.

Figure 2 indicates the strong effect of fuel cost on the economics of the hypersonic transport. The high cost of fuel would be a severe problem during the introduction of hypersonic transports. Using current technologies and a reasonably large volume of production, liquid hydrogen could be produced for about 15 cents/lb (33 cents/kg); this would be a reasonable estimate of the fuel cost early in the introduction of the hypersonic fleet. Figure 2 indicates that the ROI will be very low with this fuel cost but will improve considerably as the cost of liquid hydrogen is reduced.

Fuel reserve requirements also have a strong influence on economic performance as shown in Fig. 3. The nominal case assumed reserves equal to 5% of the block fuel, plus sufficient fuel to hold 45 min in subsonic flight. As indicated in the figure, an increase from 5% of block fuel to 10% of block fuel results in a drop in ROI of about 5%, which is very significant. The effect is not due to the cost of reserve fuel (in fact, only block fuel is included in operating costs), but is due to the reduction in payload in order to carry more reserve fuel. (The aircraft with 10% reserves carries 361 passengers as compared to the nominal aircraft which carries 404 passengers.) Obviously there will be a significant economic payoff if the reserve fuel requirement can be reduced. Such reductions should be possible with the highly automated air traffic control systems expected in the 1990's and the relatively short flight times of hypersonic aircraft.

The next two figures (Figs. 4 and 5) relate to the utilization of aircraft. Figure 4 shows the effect of turnaround time on economic performance. It is difficult to reduce the turnaround time of a hypersonic transport because of the thermal problems involved in loading the cryogenic fuel, particularly if a flight has just been completed and the vehicle is still warm. The nominal case assumed a turnaround time of 1½ hours, and Fig. 4 indicates that turnaround time did not have a large effect on economic performance. On the other hand, a 2% increase in ROI which is achievable by reducing turnaround time to 1 hr means a very large financial return to the operator.

Table 2 Acquisition cost breakdown

	Millions of dollars	
RDT&E		6214.5
Airframe design and development engineering	2350.5	
Miscellaneous subsystem development	116.8	
Propulsion development	1790.9	
Development support (includes 5 flight test vehicles)	1956.3	
Initial investment		9695.5
Operational vehicles (245)	7882.9	
Sustaining engineering and tooling	1615.2	
Other	197.4	
Profit		1591.0
Total		17,501.0

Aircraft price = $70 × 10^6

Table 3 Operating cost breakdown

	Cents/seat-mile	
Direct operating cost		2.040
Crew	0.02	
Fuel	1.40	
Insurance	0.05	
Maintenance	0.37	
Depreciation	0.20	
Indirect operating cost		0.907
Direct maintenance	0.108	
Aircraft servicing	0.003	
Passenger service	0.516	
Traffic service	0.129	
General and administrative	0.151	

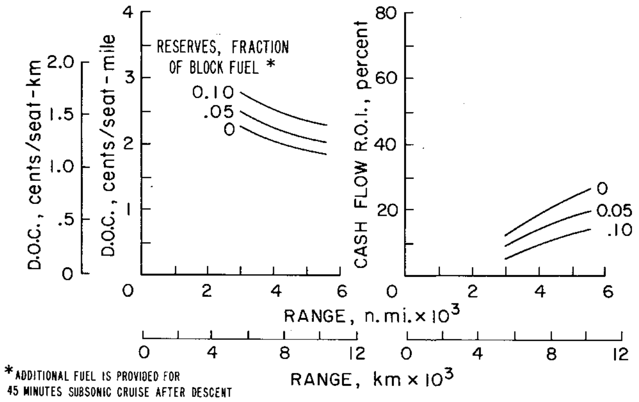

Fig. 3 Effect of fuel reserve requirements on HST economics.

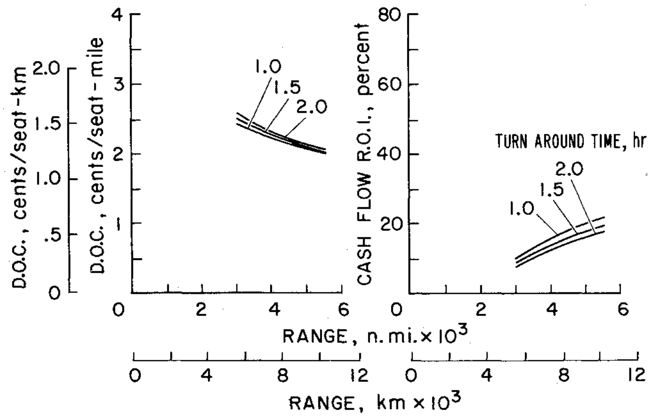

Fig. 4 Effect of turnaround time on HST economics.

Figure 5 shows the effect of aircraft time on line. The nominal case assumed a factor of 0.5, meaning that, on the average, each aircraft is operated for 12 hr a day. This time includes both block time and turnaround time so that flight hours are considerably lower (for the 5500-naut miles nominal case the average flight hours were 6.8 hr/day). As in the case of turnaround time, the fraction of time on line does not have a strong effect on economics but the operator will see large returns from increasing his time on line factor from 50 to 60%.

All of the results shown to date have been based on normal international fare structures and a 50% passenger load factor. It is reasonable to expect that a Mach 6 transport operating at today's fare levels will be very attractive to the air traveler. Figure 6 indicates the effect of load factor on the economic return. At a 60% load factor, which does not seem unreasonable, the ROI ranges from 15 to 30% depending on range and should be well over 20% for a typical route structure. At a 70% load factor, the return could be as high as 30%, but such load factors are generally considered unattractive because too many passengers are unable to get the flight they want. Clearly, if the hypersonic transport can draw 60% load factors its economics look very promising.

Another method of increasing the ROI is to place a surcharge on hypersonic transport fares. The effects of such surcharges are shown in Fig. 7. If a 20% surcharge can be applied while still maintaining a 50% load factor, the effect is about the same as a 60% load factor with no surcharge; i.e., the ROI is better than 20%. Note that all of the curves on Fig. 7 are for mixed seating with 20% first class and 80% coach. If the aircraft were designed with all first-class seating and current international first-class fares were charged to all passengers, the ROI would fall very close to the 40% surcharge line shown on the figure. The resulting ROI of better than 30% makes this a very attractive option.

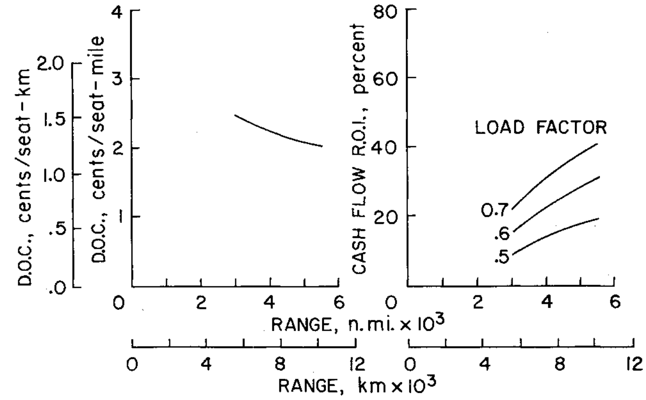

Fig. 6 Effect of passenger load factor on HST economics.

As indicated in Table 2 the aircraft price assumed for the nominal case was $70 million. Estimates of this price are certainly open to question, and Fig. 8 illustrates the sensitivity of economic performance to increases in aircraft price. An increase of 50% in aircraft price, to $105 million, would reduce the ROI by about 5%. If only increases in development cost were considered, a 50% increase in development cost would result in a 20% increase in the price of the aircraft. It should be noted again that all prices are quoted in 1972 U.S. dollars and do not include increases due to inflation.

Aircraft price is also strongly influenced by the number of aircraft which the manufacturer expects to sell. The nominal fleet size considered here is 250 and Fig. 9 indicates the effect of fleet sizes of 150 and 350. With a fleet size of 150 the aircraft price is about $100 million; with a fleet of 350 it is about $64 million. The lower fleet size results in about a 4% reduction in ROI, and the larger fleet gives about a 3% increase.

A natural question is, "How big a market for hypersonic transportation will there be in the 1990's?" Some indication is given in Fig. 10. The upper curve shows the projected growth of international air transportation. Two estimates of long-range travel are also shown. The middle curve is a Boeing estimate of revenue passenger miles for SST overwater flights, and the circle[10] is an estimate of revenue passenger miles for all international routes at ranges greater than 3000 naut miles in 1990. Also shown in the figure is a conservative estimate of the hypersonic transport market. This curve is based on the assumption that the supersonic fleet in operation in 1990 continues to operate; otherwise the hypersonic estimate would be much larger. About 300 aircraft would be required to service the market shown in the year 2000, and this number would grow rapidly if production was extended another five or ten years.

Before summarizing the economic conclusions, attention should be focused on the extremely large capital in-

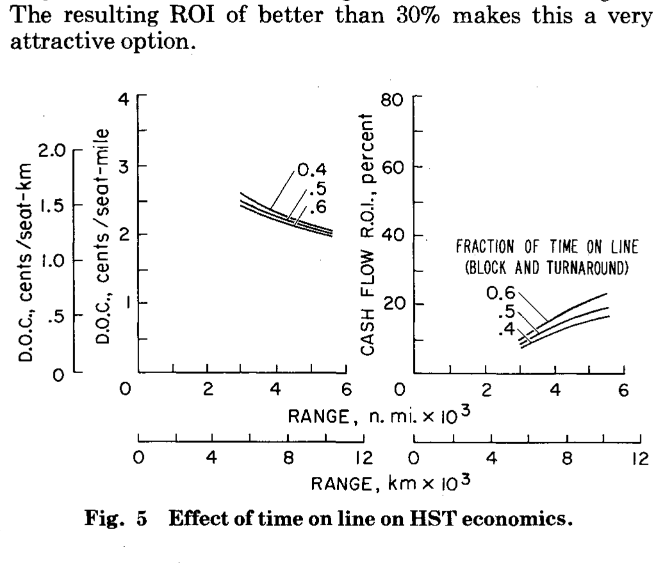

Fig. 5 Effect of time on line on HST economics.

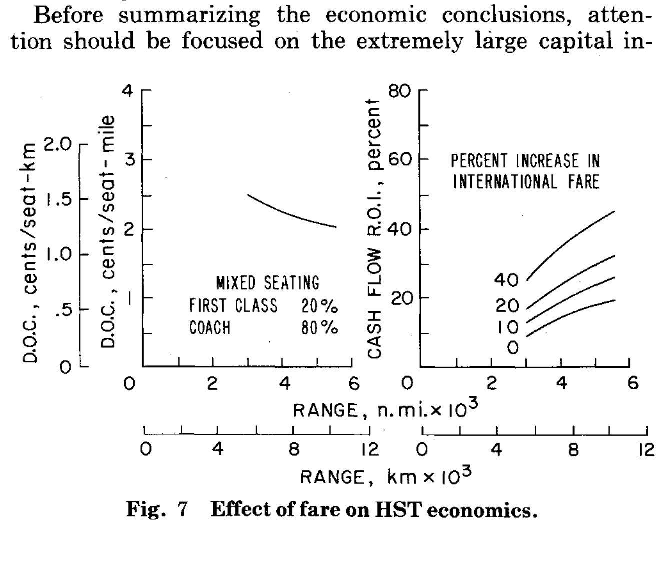

Fig. 7 Effect of fare on HST economics.

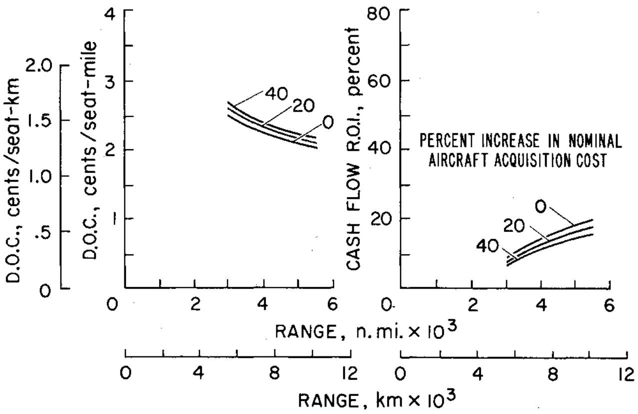

Fig. 8 Effect of acquisition cost on HST economics.

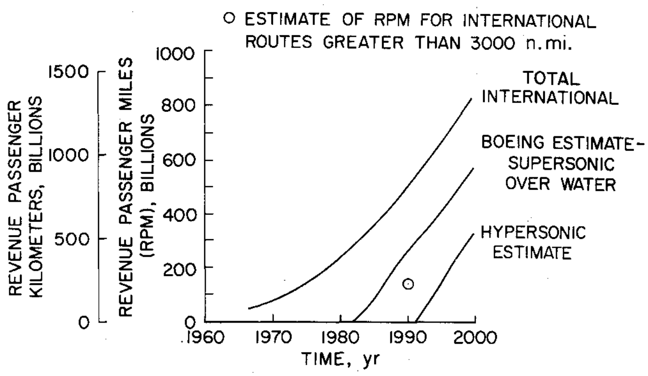

Fig. 10 Revenue passenger mile projections for international traffic.

vestment which would be required to develop and produce a hypersonic transport. Table 2 indicates a development cost of $6.2 billion, but the problem is more clearly illustrated by examining Fig. 11, which shows the estimated cash flow of the manufacturer for a program in which 250 aircraft are produced in a 10-year period. Note that the peak investment in the program is approximately $6 billion, about 13 years after start of development, and the cumulative cash flow does not become positive until 17 years from the start of development. It is clear that no single aircraft manufacturer will be able to undertake a development of this size, and few governments could support such an effort unilaterally. There must either be a very large cooperative effort involving governments and industry, or the hypersonic transport will not become a reality.

In this study, aircraft price was determined by totaling development and production costs and adding a 10% profit. Because of the long time period between investment and return, the discounted cash flow return on investment to the manufacturer is only 3% for the program shown in Fig. 11. If the production run was extended 6 years and a total of 500 aircraft were manufactured and sold for $70 million each, the cash flow ROI would be about 10%. Alternately, the cash flow ROI from the program shown in Fig. 11 could be raised to 10% by raising the aircraft price to $93 million. The effect of this 33% price increase on airline ROI can be seen in Fig. 8.

In summary, the results of this very preliminary study indicate that the nominal hypersonic transport considered here is marginal on an economical basis. Designing for ranges shorter than 5500 naut miles (10,200 km) dramatically improves the economics but reduces the potential of the aircraft for long range transportation. The cost of liquid hydrogen is crucial to the economics of the airplane and costs of 10 cents/lb (22 cents/kg) are desirable. Moderate but significant improvements in economic performance can be obtained by minimizing fuel reserve requirements, reducing turnaround time, and increasing aircraft time on line. If a 60% passenger load factor can be achieved with current international fares rather than the 50% assumed in the nominal case, hypersonic transport economics look promising. Alternately, if a 50% load factor could be achieved on an all first-class airplanes at first-class fares, the economics look very good. Finally, because of the relatively small fleet size and very large capital investment requirements, only a large cooperative effort involving aerospace manufacturers and governments will bring about the development of a hypersonic transport.

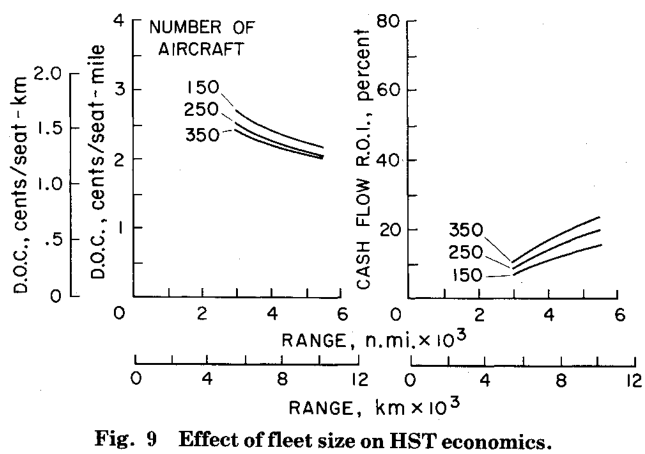

Fig. 9 Effect of fleet size on HST economics.

Environmental Considerations

It is important that the potential effect on the environment be considered in the design of any new aircraft system. This is particularly true for supersonic or hypersonic transport aircraft because these aircraft cruise in the stratosphere where the residence time of the engine exhaust products will be measured in years rather than days as is the case for aircraft cruising in the troposphere.

Takeoff Noise

An airbreathing hypersonic transport will cruise with ramjet engines but separate accelerator engines must be provided for takeoff and acceleration up to approximately Mach number 3.5. These accelerator engines also burn liquid hydrogen fuel, and the stoichiometric burning turbojet is a promising concept. With stoichiometric burning in the combustor there is no afterburner, but the turbojet cycle leads to a very high exhaust velocity at rated power.

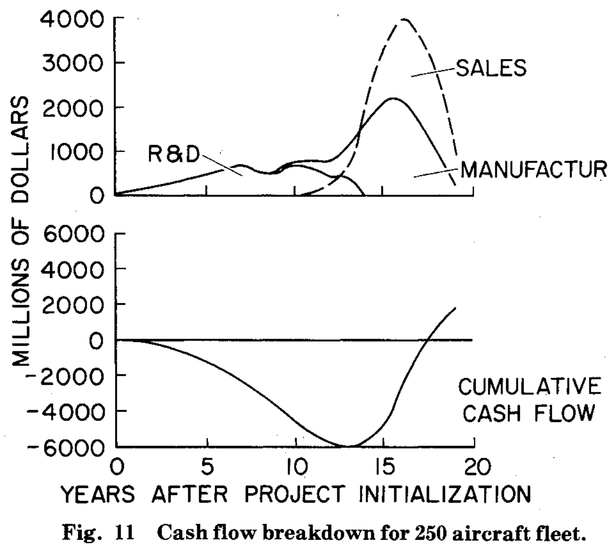

Fig. 11 Cash flow breakdown for 250 aircraft fleet.

Table 4 Pollution characteristics—SST and HST fleets

	SST	HST
Cruise lift-drag ratio	7.75	5.0
Engine specific impulse, sec	2200	3840
Average cruise wt lb	500,000	800,000
Cruise range, naut miles	4000	4000
Payload, passengers	275	400
Cruise Mach number	2.7	6.0
Fuel flow rate, lb/sec	29.4	41.6
Total fuel per flight, lb	273,000	169,000
Revenue passenger, miles	300×10^9	300×10^9
Load factor	0.5	0.5
lb NO_x/passenger mile	0.62×10^{-2}	0.485×10^{-2}
lb CO_2/passenger, mile	0.78	0
lb H_2O/passenger, mile	0.32	0.86
NO_x flux, lb/sec	118	92
CO_2 flux, lb/sec	14,900	0
H_2O flux, lb/sec	6100	16,350

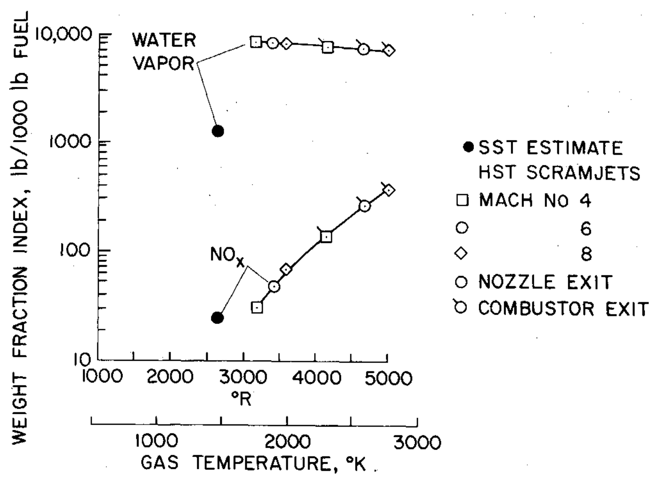

Fig. 12 Estimate of water vapor and NO_x emissions during cruise.

The result is a high level of jet noise. The noise from the rotating machinery will be negligible by comparison, and is ignored in the noise estimates which follow.

A mitigating factor with regard to jet noise is the capability to take off with engines throttled. The accelerator engines for both the wing-body hypersonic transport and the all-body hypersonic transport are sized to provide adequate thrust to accelerate transonically. In the case of the wing-body, this yields a ratio of takeoff thrust to gross weight of about 0.4 (Ref. 2), and for the all-body this ratio increases to about 0.85 (Ref. 7).

The noise level for a hypersonic transport at full rated power is very high—131 to 136 PNdb at the sideline measuring point and 120 PNdb at the downrange measuring point. As the engines are throttled to a lower thrust level and thus lower jet velocity, the noise level drops rapidly, and at 60% of full power the noise is down to about 80 PNdb. Since these transports will not be sized by takeoff requirements, they will be able to take off at part power conditions. The all-body, with its very high thrust, can operate from 4000-ft (1200-m) runways even when throttled to 60% power; the wing-body would need 7000 ft (2100 m) to take off at 60% power.

The conclusion to be drawn from these estimates is that the high maximum thrust loading of a hypersonic transport will allow these aircraft to take off with engines throttled, significantly better the requirements of current noise regulations,‡ and still operate from field lengths less than 10,000 ft (3000 m).

Atmospheric Pollution

Pollution of the atmosphere due to engine exhaust products can be broadly classified into two regions: the airport vicinity during ground maneuvering and takeoff and the stratosphere during cruise. Current problems in the vicinity of the airport stem primarily from the emission of unburned hydrocarbons and carbon monoxide; the use of liquid hydrogen fuel will eliminate these problems due to the absence of carbon in the fuel. Emission of the oxides of nitrogen (NO_x) is also a problem due to photochemical reactions that create smog. This problem is prevalent for engines with high-cycle pressure ratios,[15,16] and may be relatively minor for hypersonic aircraft because their engine cycle pressure ratio is relatively low (half that of the current airbus engines). Also the hypersonic transport probably will take off with throttled engines, lowering the engine cycle pressure even further. Thus it appears that atmospheric pollution in the airport vicinity will be minor for liquid hydrogen fueled HST's, and the discussion which follows considers stratospheric pollution only.

‡ FAR Part 36 requires maximum noise levels of 108 EPNdb at both the sideline and downrange measuring stations.

At the time the American SST program was canceled, there were several conflicting theories and much confusion about the potential pollution of the stratosphere and the resulting effect on the Earth's climate. Since that time, investigations have progressed to the point where the potential problems are fairly well identified,[17,18] but the magnitude of the pollution created by transports flying in the stratosphere as related to natural phenomena has not been determined.

The potential problems involve the addition of water vapor and oxides of nitrogen into the stratosphere. Added water vapor can result in an increase of clouds and contrails in the stratosphere which would affect the reflection and absorption of both the ultraviolet radiation from the sun and infrared radiation emitted from the earth.[17,20] However, at the cruise altitude of an HST (above 100,000 ft), indications are that the ambient temperature will be above that necessary for either cloud or contrail formation.[21]

In addition, increased amounts of water vapor may react with the free oxygen, O, in the atmosphere, reducing the availability of O to react with O_2 and form ozone, O_3. Ozone is the primary absorber of solar ultraviolet radiation, and its depletion would increase the amount of radiation that reaches the surface of the Earth. A recent study by Ashby, Shimazaki, and Weinman[22] indicates that the water vapor emissions that might be expected from an SST fleet will have no noticeable effect on the atmospheric concentration of ozone based on estimates of the natural flux of water vapor into the stratosphere.

The current flux of water vapor from the troposphere to the stratosphere due to Hadley cell circulation[19] has been estimated to be approximately 11,000 lb/sec (5×10^3 kg/sec).[23] Another recent estimate of the total flux of water vapor into the stratosphere is 78,000 lb/sec (36×10^3 kg/sec).[24] This estimate includes the additional water vapor from severe local thunderstorms, which account for approximately 56,000 lb/sec (25.4×10^3 kg/sec), and from natural oxidation of methane.

The effect of increasing the concentration of oxides of nitrogen (primarily NO) in the stratosphere is a subject of current debate. Separate investigations by Johnston[25] and Crutzen[26] indicate that nitric oxide may react with ozone in a complex way that ends with nitric-oxide being produced in a self-regenerative fashion along with O_2. Results at present are uncertain and somewhat contradictory.[18] The recent study by Ashby et al.[22] distinguished between the reactions taking place in daytime or nighttime. At night much less regeneration of nitric oxide is predicted. Added to the problem is the lack of any estimate of the natural flux of NO_x into the stratosphere.

An estimate for the production of both water vapor and nitric oxide is given in Fig. 12 for a JP fueled SST and a liquid hydrogen fueled HST. The estimate of NO_x for the SST was taken from Ref. 15 with a correction for the combustor pressure at altitude, and the SST water vapor estimate is for the complete combustion of C_nH_{2n}-type fuel. The HST estimates are from unpublished NASA data for a fixed geometry scramjet module which is described in Ref. 27. Data are presented for the flow in chemical equilibrium at both the combustor exit and nozzle exit. If the chemical kinetics in the nozzle result in exhaust products which are not in chemical equilibrium, then the production of NO_x can be relatively high, as shown at the combustor exit. On the other hand, the flow at the nozzle exit in Fig. 12 is not fully expanded, and if the flow continues to expand at equilibrium, the temperature will drop to a point where the NO_x production will be negligible. The water vapor production using liquid hydrogen fuel is high, about 9 lb/pound of fuel for complete combustion.

To make an estimate of the annual production of water vapor and NO_x by an HST fleet, data for the Mach 6 scramjet with equilibrium flow at the nozzle exit was used from Fig. 12. However, the engine specific impulse assumed is more representative of a Mach 6 ramjet. Comparison with an SST fleet is made in Table 4 with the assumption of 300 billion revenue passenger miles annually and an average passenger load factor of 0.5.

The flux of NO_x is small, but the concern is over the possibility of a self-regenerative reaction discussed previously. The lack of CO_2 flux is a significant benefit of the HST over the SST. However, the flux of water vapor is at most of the same order of magnitude as the natural flux transferred from the troposphere. The estimate of Manabe and Wetherald[20] would indicate a possible increase in the Earth's surface temperature of 1.0°F (0.6°C).

Sonic Boom

The sonic boom problem for an HST occurs primarily during the climb and acceleration portion of the flight. The relatively high cross-sectional area of the all-body type of vehicle leads to sonic booms as high as 5 psf (24 kg/m^2) transonically,[7] whereas the slender wing-body aircraft will have a sonic boom of about 3 psf (15 kg/m^2) transonically. Flying higher trajectories, to minimize the transonic boom, leads to oversized engines and uneconomical systems. The use of rockets to boost to higher trajectories was investigated for the all-body aircraft and does not appear attractive.[7]

The situation at cruise, on the other hand, is very favorable. The high-altitude cruise (approximately 108,000 ft (33,000 m) at Mach 6) results in cruise sonic booms of less than 1.0 psf (5 kg/m^2) which may be acceptable for overland flight. Many logical overland routes involve cities located near the oceans, and this leads to the possibility of climbing and descending over water with overland cruise legs at hypersonic speeds.[8] For cities located far from the oceans, the only alternative is subsonic cruise over land followed or preceded by hypersonic cruise over the oceans. The penalties for turns during climb and/or descent include the additional time and fuel consumed during the turn, compared to great circle trajectories and the additional time and fuel needed to make up the range normally attained during the climb and descent.

The economic penalty is significant: for a turn at takeoff the ROI is decreased by about 4% and for turns at both takeoff and descent the ROI decreases by about 6%. Also there will be a reduction in attainable range for a given takeoff gross weight due to the increase in fuel consumed. On the other hand, an increase in passenger load factor to 60% would more than compensate for the turn penalties, and such a load factor is not unlikely if, for example, travel time between Los Angeles and New York is reduced from 5 to 2 hr.

Likewise, the economic penalties for subsonic cruise at the beginning or ending of the flight are significant. Cruising 500 naut miles (930 km) at the end of the flight decreases the ROI by approximately 5%. For 1000-naut miles (1850-km) subsonic range the ROI decreases by 8%. There is also a slight decrease in the maximum range for a given takeoff gross weight. If the subsonic leg is at the beginning of the flight, both range and economic penalties increase due to the higher aircraft weight during this portion of the flight. Again, the economics are marginal, but increases in passenger load factor might compensate. Clearly, all flights must have relatively long hypersonic cruise legs to provide a truly attractive reduction in trip time and draw a good load factor.

In summary, the environmental problems connected with an HST seem potentially less severe than those of an SST aircraft. The accelerator engines of an HST are large, to provide thrust to overcome transonic drag, and thus may be throttled to give relatively low noise levels at the airport. Exhaust pollution from an HST is a minor problem in the vicinity of the airport due to the absence of carbon in the fuel and the low cycle pressure of the engine which means low NO_x emissions.

In the stratosphere, the potential problems are fairly well defined, but the magnitudes of these problems are open to question. An HST emits no carbon dioxide, in contrast to the large amounts that will be produced by a JP-fueled SST fleet, but the amount of water vapor produced by an HST fleet is almost three times that for an SST fleet. The HST water vapor production is of the same order of magnitude that occurs naturally, and the effect on the Earth's climate may be significant. The effects of NO_x emissions are the biggest question mark to date. An HST fleet or an SST fleet will emit comparable amounts of NO_x, and the magnitude seems small compared to the water vapor or carbon dioxide emissions. However, amounts that occur naturally are unknown, and there is the possibility of a self-regenerative reaction between nitric oxide and ozone which would magnify the problem.

Sonic boom is a problem for any aircraft flying above the speed of sound, and currently there appears to be no complete solution to the problem. However, an HST will create a significant boom only during the climb and acceleration; at cruise the sonic boom overpressure will be less than 1.0 psf (5 kg/m^2) which may be acceptable for overland cruise.

Considerable basic research remains to be accomplished before the development of a production HST. It is much too early to decide the fate of future hypersonic transports based on environmental considerations. Work is progressing on the environmental problem, and if SST aircraft become operational these questions should be answered long before the initiation of a hypersonic transport development program.

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