TRANSPORTATION
RESEARCH
CIRCULAR

Number 333, July 1988

Outlook for Commercial Supersonic and Hypersonic Transport Aircraft

TRANSPORTATION RESEARCH BOARD / NATIONAL RESEARCH COUNCIL

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TRB COMMITTEE ON AIRCRAFT/AIRPORT COMPATIBILITY
(A1J07)

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Washington, D.C.

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INTRODUCTION

D. William Conner
Chairman, TRB Committee A1J07

The 1970s proved the technical reality of commercial supersonic transport flight with the British-French Concorde aircraft. Concorde operations provided significant benefits to the traveler, such as the near elimination of jet lag over long distances. In fact, NASA-sponsored surveys indicated that many travelers were still in a state of some euphoria on the day after a Concorde flight. Unfortunately, at the time the aircraft was designed, the state of technology was not sufficiently advanced to build an economically viable vehicle. Since then, however, there have been breakthroughs and advancements in technology that promise better economics for the next generation of supersonic transports.

The latest impetus in this technical area is the United States government's recently instituted National Aerospace Plane (NASP) effort to provide technology sufficient for designing long-range, very-high-speed aircraft which can operate into the hypersonic speed regime. In the purely commercial domain, multi-million dollar studies were recently awarded by NASA to Boeing and McDonnell Douglas to evaluate the potential for high-speed civil transport aircraft beyond 2000. Public awareness and interest have been stimulated, leading to speculation and inquiries by various interest groups regarding the imminent development of such commercial aircraft.

In keeping with its charter, the Transportation Research Board considered its 1987 Annual Meeting to be an appropriate and timely occasion for a comprehensive review of the outlook for supersonic and hypersonic transport aircraft. The areas covered in the review included: (1) the particular market segment and size that might be served, (2) the profound implications of cruise Mach number, (3) the criticality and complexity of the technical, financial, and institutional issues involved, (4) the present climate for dealing with these issues, (5) the direction and magnitude of future research and development efforts likely to be required, (6) projected performance characteristics, and (7) the schedule for initial introduction and the succession of later configurations with increasingly higher performance.

The areas enumerated above fall into two categories: a factual category which includes items such as the status of travel markets, technology, and costs; and a judgmental category which includes items such as the characteristics of a projected high-speed airliner (i.e., payload, range and cruise Mach number). On judgmental questions care was taken to include representatives of several viewpoints.

The review consisted of eight presentations during an all-day session at the TRB Annual Meeting on January 13, 1987. This collection of papers documenting the session is intended to provide an accurate and objective assessment of the outlook for supersonic and hypersonic transport aircraft at this stage of their development.

HIGHLIGHTS

The purposes of the session were to review the status and prospects for high-speed supersonic and hypersonic commercial transport aircraft (HST) and to examine the issues that would have to be resolved before these aircraft could be produced and introduced into service.

The Market

The principal market to be served by supersonic or hypersonic aircraft consists of long-haul overwater flights between approximately 40 city pairs worldwide. Flying time by subsonic aircraft on these routes today ranges between 10 and 14 hours. There are an additional 400 city pairs with routes of medium length (many overland) where flying time by subsonic aircraft is between 6 and 10 hours. Many of these routes, especially the longer, are between city pairs on the Pacific rim, where air travel is increasing by about 10 percent annually. The potential time saving by supersonic aircraft in this market would be substantial, running between 50 and 75 percent. Hypersonic flight would produce even more dramatic reductions in travel time. All indications point to a large potential market for a cost-competitive, environmentally acceptable aircraft operating at speeds between Mach 2.4 and Mach 5.

High-Speed Transport Evolution

Second-generation commercial supersonic airline operations with HST aircraft are a possibility by the turn of the century. To be commercially successful, the HST must be responsive not only to market demand but also to the requirements of a deregulated airline industry. This implies that the HST must have a combination of earning potential, initial cost, and operating expense that is competitive with advanced subsonic aircraft. A coordinated and disciplined approach by industry and government will be necessary to develop the required technology. Environmental and political issues will also have to be resolved before HST operations can begin.

Over the longer term, the development and commercial introduction of hypersonic civil transport aircraft will depend on the results of the National Aero-Space Plane Program to pioneer the military and space applications, thereby providing the basis for subsequent commercial application.

Technology Combinations

The design of high-speed commercial transport aircraft presents complex technological problems that will require innovative solutions. In the past 15 years since termination of the U.S. SST program, significant technological progress has been made in areas such as application of new materials to high-temperature engine components, computational fluid mechanics codes, and airframe structure and materials. However, much remains to be accomplished. Technology maturation and validation must proceed with specific focus on propulsion technology -- combined cycle engines with high specific impulse and thrust-weight characteristics, thermal management processes to utilize aerodynamic heating rather than throwing it away, and tailored fuels that combine the best characteristics of several currently available fuels in a single "designer" fuel.

New aerodynamic concepts have emerged -- slender supersonic configurations, hypersonic waveriders, and thicker configurations riding on shock waves. Particularly significant advances have been made in highly integrated airframe and propulsion system designs that include a thermal management system to maintain low outside surface temperature for aircraft cruising at Mach 6 and above.

Further advances are needed in structures technology, particularly rapid-solidification alloys and metal-matrix composites for lightweight, long-life structures and for integration of fuel tanks with hot structures to provide safety and reliability. Other technological needs include computational fluid dynamics to allow aerodynamic and propulsion system integration in a one-step, continuous process with reasonable computer power and computation time.

Emerging Technologies

The state of technology has advanced not only through developments in military aircraft and subsonic transports but also as a result of the 10-year NASA Supersonic Cruise Program.

The aerodynamic lift-drag ratio (cruise efficiency) achievable now is much improved. At Mach 2.2, for example, it can be increased from about 7 to 11 through fuselage shaping, wing-body blending, and favorable aerodynamic interference of aircraft components. Aerodynamics have also been improved by more efficient wings that have subsonic leading edges swept back behind the Mach cone. The technology of airframe configuration is now well in hand for cruise up to about Mach 2.7 but is somewhat deficient between this speed and the limiting speed for conventional fuels (about Mach 4).

Also deficient in the speed range between Mach 2.7 and Mach 4 is the technology for nonmetallics in the airframe. In aircraft structures suitable for high temperatures, however, great strides have been made in metal processing through superplastic forming and diffusion bonding. Titanium-sandwich structures with metal matrix faces used for the wing and fuselage would result in savings up to 50 percent in both weight and cost.

Supersonic transports, because of their wide speed range, need to employ variable-cycle engines. Much progress has been made in cycle design, materials cooling, and hot section technology. In combination, these allow engine designs of higher efficiency, greater engine thrust-to-weight ratio, and one-half of the parts -- all of which nets an overall reduction of about 100,000 lb in aircraft gross weight.

The impressive advances in electronics-avionics being realized in subsonic aircraft will find their way into supersonic transports. In fact, they will permit, through integration, the full realization of the advances in aerodynamics, structures, and propulsion.

In the area of environmental concerns, there seem to be no insurmountable problems regarding engine emissions or terminal area noise. Sonic boom, however, is another matter. While aircraft can now be configured to have boom overpressure of one-half or less that of Concorde-era designs, little or no information exists on public reaction to booms of low magnitude. Further research is needed.

NASA'S Research

Increased NASA and DOD research efforts are being directed to the technologies that are the key to hypersonic and transatmospheric flight: airbreathing propulsion systems that can function efficiently from takeoff to near-orbital velocities, lightweight materials, thermal structures which can withstand exposure to extreme heat during ascent and descent or during sustained hypersonic flight, and new computational tools for the analysis of the highly-integrated airframe and propulsion systems. These technologies will be tested in an experimental X-30 aircraft which should begin flight testing in the early 1990s. The technology validated with the X-30 may lead to the development of civil hypersonic transports as well as new operational airbreathing aerospace vehicles that can take off from conventional airport runways, fly between 6 and 25 times the speed of sound to the edge of the earth's atmosphere or even into orbit, and return to conventional runways.

Fuels

Three different types of fuel are being studied for use in the supersonic flight regime, with particular attention to their physical properties, methods and costs of production, availability, and design requirements. In most respects, the hydrocarbon fuel required for turbojets operating in the lower portion of the supersonic cruise range differs little from the jet fuel used by current subsonic transports. Hydrogen fuels to absorb airframe and engine heat will, however, require an entirely different and more complex aircraft fuel system. Liquid hydrogen and liquid methane are profoundly different from conventional fuels, and special insulated fuel tanks for these cryogenic fuels would have to be located in the fuselage rather than in the wing. In addition, the much greater volume of the fuels necessary for payload and range would require substantially larger fuselages. An entirely new airport fuel system would also be necessary, including complex and expensive on-site liquefaction, storage, and distribution facilities using considerable airport acreage. Tank insulation and fuel pumps present the greatest technical risks for cryogenic fuels. All heat-absorbing fuels will involve a difficult integration of engine fuel demand and use of fuel as a coolant.

Airport Compatibility

Some of the differences between the projected characteristics of a supersonic civil transport and conventional subsonic commercial transports will have an important effect on airport usage. The major areas affected include runway and taxiway geometry, aircraft maneuvering, support facilities and equipment, ground handling, and the special requirements for handling unconventional liquid hydrogen or liquid natural gas. The design goal is for high-speed civil transport to operate from and into existing international airports.

Environmental Concerns

A major unresolved environmental issue is the generation of sonic boom overland. Present Federal Aviation Regulations prohibit supersonic flight by civil aircraft over the United States. However, the prohibition is not outright, in that the regulations also include provisions for future demonstration that a specific aircraft configuration might have sonic boom characteristics and overpressure levels that are environmentally acceptable.

Concern about the effects of supersonic flight on the atmosphere has shifted somewhat in recent years. Earlier apprehension about the impact on air quality has lessened as a result of experience with military and Concorde operations and more precise understanding of how man-made pollutants affect atmospheric chemistry. On the other hand, concern has increased about the consequences of high-altitude supersonic flight on the ozone layer. Establishment of criteria for acceptable emission levels by future supersonic and hypersonic aircraft will require better understanding of the relative contributions of all sources of upper atmospheric pollutants, with special emphasis on the chemistry and dynamics of the earth's total ozone column. If development of supersonic and hypersonic aircraft is to proceed, it will be necessary to set emissions criteria at an early date -- a task that will call for shared responsibility and effort by the air transport industry, the public, the scientific community, and the federal government.

A MARKET FOR THE ORIENT EXPRESS

Ben H. Lightfoot
Northwest Airlines

To set the stage, let's talk about what the 21st Century might be like. To do this, I will borrow from a paper delivered last fall by Geoffrey Lipman, Executive Director of the International Foundation of Airline Passenger Associations (IFAPA), at the first High-Speed Commercial Flight Symposium held by the Battelle Institute at its new Center for High-Speed Flight.

The 21st Century

Mr. Lipman predicted "...steady economic growth at 3 percent per annum, controlled inflation at single-digit levels, and affordable energy -- that is, no third oil shock. There will no large-scale politico-military upheaval even though events in the Middle East, Central America and Southern Africa could easily shatter this particular prediction. Let us also assume continued general technological progress with emphasis on computers, and telecommunications as well as leaps in areas that we cannot hope to conceive.

"World trade (will expand) under the impetus of a new GATT (General Agreement on Tariffs and Trade) round. The hopes for the developing world (will) rest on quantum jumps forward on the back of technological innovation and industrialized world aid.

"For aviation, we can anticipate: (a) continued liberalization -- at different paces in different regions -- with Europe and Asia following to some degree the U.S. patterns, but with a 10- to 15-year time lag; (b) a world of megacarriers, controlling hubs, feeding on their global computer reservation systems and corporate and individual brand loyalty schemes; and (c) perhaps four or five Eurosupercarriers built around British, German, French, Dutch and Swiss nuclei; Aeroflot and its agglomerates in Eastern Europe; one major African Consortium; three or four carriers in the Middle East and Indian subcontinent, including a Saudi-led Arab Consortium and the Air India/Indian Airlines carrier; one or two in Latin America, four or five in the Far East and Australia including the Airline of the People's Republic of China and Hong Kong; and five or six in the United States (Unless Lorenzo has combined them into one!). These 20 or so carriers are the potential hypersonic operators.

"The world (would have) perhaps two major civil aircraft manufacturers, each linked to smaller manufacturers in a network of component-supply arrangements and perhaps -- antitrust laws permitting -- even linked to each other for the massive development costs of a hypersonic aircraft. The passenger (would) use only a single credit card for all airline-related transactions -- ticket purchase, check-in, and boarding -- and select and book a flight on the 21st Century version of the home computer."

Northwest Airlines Interest in High-Speed Flight

Now let me borrow from another paper delivered by our Northwest Airlines President, John Horn, at that same Symposium.

"What is the reason for Northwest's keen interest in the HST, particularly since interest among other airlines is not apparent? Well, for one thing -- experience. Northwest has four decades of experience operating some of the longest flight segments in the world -- routes best suited for the HST.

"In the summer of 1986, Northwest operated 62 passenger flights and 12 cargo flights a week across the Pacific, with service to 12 Asian cities. Northwest, the largest U.S. transpacific airline, has nearly 27 percent of the U.S.-Japan market and 19 percent of the total transpacific passenger market, according to U.S. Department of Transportation statistics. In addition, we are a leading cargo carrier, including operations with all-cargo aircraft.

"Our 40 years of experience serving Asia tells us that a properly design HST will be a very valuable asset to our airline and our customers well into the 21st century. The HST could truly revolutionize U.S.-Asia air travel, providing fast, comfortable, and efficient customer service at prices reflecting the value received.

"While Europe is a logical market, Asia is the most attractive market for HST service. Routes to Asia are among the longest in the world, and Asia is home to many of the fastest developing economies in the world. For the United States today, Asia is becoming increasingly important.

"The best evidence of that is the shift in focus of U.S. trade from Western Europe to the Pacific Rim. In 1984, Pacific trade surpassed Atlantic trade for the first time.

"The leader in Asia has, of course, been Japan. It is a well-documented success story. Not only is Japan a leading producer and consumer of goods, it is fast becoming an important participant in the world's financial affairs. Furthermore, Japan has made major commitments to aerospace technology, SDI, and other technological ventures.

"Mike Mansfield, the U.S. Ambassador to Japan, has called the U.S. - Japan bilateral trade agreement the most important in the world, "bar none." He is correct. Trade between the United States and Japan has opened up new markets both to U.S. products and to Japanese products, and has spurred growth among other countries in Asia.

"Although not as advanced as Japan today, other nations of the Pacific are experiencing dramatic growth in their economies, which is resulting in growth in international trade.

"The 1984 list of the world's 20 leading exporting nations included six countries -- five of them from Asia -- that did not appear on the list in 1973. The newcomers from that region were Hong Kong, Singapore, South Korea, Taiwan and The People's Republic of China.

"The growth of exports from these countries to the rest of the world has been rapid and steady. For example, from 1973-1984 South Korea experienced average annual export-volume increases of 15 percent. Hong Kong, Singapore, and Taiwan had export-volume growth greater than 10 percent, while Japan recorded 9 percent annual growth. By contrast, the United States in that time averaged about 2 percent export growth a year.

"Imports are getting stronger as well. Among the 20 leading importing nations in 1984 were the same five Asian countries that emerged as export leaders, and again, none of them was among the import leaders in 1973.

"With continued growth in Asia expected, Ambassador Mansfield confidently predicts that the 21st Century will be the Century of the Pacific Rim. We believe he will be proven correct.

"It is fair to say that aviation has been a key element in shaping the rapid growth rate in transpacific trade and travel. As aircraft have improved with new technology, resulting in shorter travel times, increased capacity and improved customer comfort, the demand for transpacific air service has increased. As a result, we believe that the aircraft does indeed make a strong contribution to increasing the market."

How Speed Develops Markets

Mr. Horn continued: "Fifty-seven years ago an infinitesimal number of people flew coast-to-coast by commercial aircraft -- the majority moved by train, auto or bus. The growth rate of our economy and U.S. business was constrained by the time it took to travel. In 1929 coast-to-coast by rail took 3 1/2 days. Through a combination of air and rail, the brave and sturdy traveled to Los Angeles in 48 hours and 26 minutes. The trip included 10 enroute stops, with the traveler flying by day and going by rail at night. In late 1930, TWA started the first single airplane through-service from New York to Los Angles. This trip took 35 hours and 9 minutes with stops for fuel. The most popular commercial aircraft at that time was the Ford Trimotor, carrying 14 passengers at 110 mph.

"Early long-range jet aircraft were developed in the late 1950s primarily for service to Europe, the most popular transoceanic market at that time.

"In 1960, Northwest introduced jet service to the North Pacific. The DC-8 opened the door to growth and expansion in U.S.-Asia air travel and trade. In 1965, just a few years after the introduction of the narrow-body jet, airlines carried 3.6 million transatlantic passengers and 358,000 transpacific passengers. The relative weakness in the transpacific market can be partly attributed to long flying times and the economic climate in Asia at that time.

"By the early 1970s, introduction of the Boeing 747 wide-body had increased the range, comfort level, and capacity of long-distance air travel. In 1976, airlines carried 3.3 million transpacific passengers, or about 30 percent of the total transatlantic passengers that year.

"The number of passengers across the Pacific continued to increase as more 747s were introduced, longer-range models became available, and airlines offered service to more cities. In 1985, the number of transpacific passengers reached 7 million, 37 percent of the total number of transatlantic passengers. The gap between transpacific and transatlantic traffic is projected to continue to narrow.

"From 1975 to 1984, traffic to and from Asia increased an average of 11 percent a year, and those markets now account for 41 percent of worldwide air traffic on flight segments over 5,000 miles.

"An increase in cargo shipments accompanied the growth in passenger traffic. Annual air cargo traffic between the United States and Japan rose from 3.5 million pounds in 1962 to 586 million pounds in 1984. Between 1978 and 1984, air cargo shipments between the United States and 10 leading Asian nations more than doubled, from 732 million pounds to 1.5 billion pounds. I can't imagine what the above figures would look like if we had had hypersonic or even supersonic intercontinental service for the past five years.

"Yet, projected demands for passenger and cargo services continue to call for faster, more productive aircraft.

"According to projections by one airframe manufacturer, year-to-year growth in passenger traffic will be in double digits though the end of the 20th Century. In the year 2000, 36 million passengers are expected to fly across the Pacific, and further increases are projected for the first two decades of the 21st Century.

"Although the next generation of transpacific aircraft, the 747-400, will increase nonstop range and payload and offer greater operating efficiencies, it will not significantly reduce flying times.

"The next technological jump is to the HST, also referred to as the Orient Express. We need that aircraft."

The Case for a Mach-5 HST

Let's look at some city pairs and today's scheduled block times via 747:

City Pair	Flying Times	Annual Passengers
New York (JFK) - Tokyo (NRT)	13 h 55 m	488,803
Chicago (ORD) - Seoul (SEL)	14 h 35 m	19,229
Seattle (SEA) - Tokyo (NRT)	10 h	429,302
Los Angeles (LAX) - Tokyo (NRT)	11 h 30 m	767,284
Boston (BOS) - Frankfurt (FRA)	6 h 55 m	122,473
Boston (BOS) - London (LGW)	6 h 5 m	528,816

How many of you have taken a 13-hour trip from JFK to Tokyo? No matter how hard we try to make our passengers comfortable, 13 hours of sitting, eating two meals, watching two movies, and trying desperately to catch some sleep leaves anyone in pretty sad shape when they arrive.

A Mach-5 HST will reduce that 13 hour trip to 2 1/2 hours!

Why Mach 5? Four reasons:

1. Fast enough -- but not too fast.
2. Compatibility with existing airports, facilities, and ground equipment.
3. Environmental considerations.
4. Economic considerations.

Let's look at each of these:

Speed. Let's go for a speed that will allow the aircraft to provide significant savings in present day flying times but still be "slow" enough to be useful in long domestic markets. Consider these flying times for a Mach 5 HST:

Segment	Distance (N.M)	Time
New York (JFK) - Tokyo (NRT)	6000	2 h 25 m
Chicago (ORD) - Seoul (SEL)	6200	2 h 29 m
Seattle (SEA) - Tokyo (NRT)	4240	1 h 53 m
Los Angeles (LAX) - Tokyo (NRT)	4775	2 h 03 m
New York (JFK) - Frankfurt (FRA)	3390	1 h 28 m
New York (JFK) - London (LGW)	2040	1 h 22 m
Tokyo (NRT) - Hong Kong (HKG)	1680	57 m
Los Angeles (LAX) - Frankfurt (FRA)	5080	1 h 59 m
Washington (WAS)* - Seattle (SEA)	2038	59 m

But while we are considering speed, we must also consider local curfews, arrival and departure times, and traffic fed into and out of the airlines' system hubs. For example, at NRT no aircraft can depart or arrive after 11 p.m. and before 6 a.m. For any new slot awarded at NRT, the evening curfew begins at 9 p.m.

A large percentage of travelers on long-haul routes are connecting at major hubs and going on to other destinations. For example, in 1986 30 percent of Northwest's passengers from NRT to ORD and WAS went on to other cities in the United States. Therefore, arrivals and departures into and out of hubs must provide good connections. Northwest has conducted routing exercises using a small fleet of three Mach-5 HSTs and successfully routed these aircraft to provide attractive arrival and departure times at major U.S. and Orient cities, while honoring all curfews and meshing these flights with other connecting flights at hub cities. Daily utilization for this example fleet was just under 7 1/2 hours per day. We feel that higher utilizations might be realized for such a fleet.

To rather dramatically demonstrate the maximum utilization and productivity for a single Mach-5 Orient Express on a given day, we routed it thus:

Departs NRT	0900	Monday
Arrives LAX	1803	Sunday
Departs LAX	2000	Sunday
Arrives NRT	1503	Monday
Departs NRT	1800	Monday
Arrives JFK	0625	Monday
Departs JFK	0820	Monday
Arrives LGW	1542	Monday
Departs LGW	1740	Monday
Arrives JFK	1302	Monday
Departs JFK	1445	Monday
Arrives NRT	0710	Tuesday

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* WAS is a general designation for airports in the metropolitan area of Washington, D.C.

This aircraft would cover 32,000 miles in a total elapsed time of about 22 hours, allowing for 1 3/4 to 2 hour turnarounds at each city served.

My point is this: Mach 5 seems to be a good speed to satisfy all constraints.

Consider the Concorde service across the Atlantic. Westbound trips from Paris to JFK are enjoying load factors 20 points higher than eastbound trips between those cities. Why? Going west, one can leave Paris at 11:00 AM and arrive in New York at 8:45 AM ready for a full day's work. Going east there are no combinations of both good arrival times and good departure times for businessmen.

Compatibility with Existing Airports. Let's look at our second reason for favoring the Mach-5 HST: compatibility with existing airports, facilities, and ground equipment.

A methane-powered Mach-5 HST will result in some special fueling equipment and facilities and will require special handling procedures because of residual skin temperatures after arrival. However, the manufacturers tells us that a 300-passenger Mach-5 HST will work with existing jetways and operate off existing runways. One configuration proposed is no larger than a DC-10, weighing 530,000 lbs. with a wing span of 106 feet and an overall length of 252 feet.

If we think in terms of a higher-speed HST -- Mach 6 and up -- we must think in terms of hydrogen fuel. We believe that hydrogen fuel would present substantially more problems for ground handling. Further, because of the low density of hydrogen, the airplane must be much larger than a methane-powered Mach-5 vehicle designed for the same payload-range. Such an aircraft would not be compatible with existing terminal facilities and ramps.

Environmental Compatibility. Our third argument for Mach 5 is the case for the environment. Its poor economics was not really what killed the U.S. Mach-2.8 SST in March, 1971. The environmentalists did; and maybe they were right to do so. Any design we propose today that creates too much noise to fly overland or operate from existing airports or that destroys ozone is going to have a rough time getting enough public and congressional support to be successful. And the environmental considerations impact the economics of the vehicle. We must have an aircraft that can fly overland at design cruise speeds and can operate from existing airports.

We understand that a Mach-5 methane-powered HST can be built to meet such requirements. We may have to get the FAA to bend a little on airport noise, but less than 1 psf overpressure with the aircraft cruising at 100,000 feet should be acceptable for overland operation. The economic viability of an advanced SST or HST will be greatly enhanced by the aircraft's ability to operate at design Mach number overland.

Economics. This brings us to our final -- and most important concern -- economics. The economics must work for the manufacturers, the airlines, and the passengers.

Our company's position is that any high-speed commercial transport must be capable of supporting fares competitive with subsonic jets operating in the

same time frame. Obviously passengers will pay some premium for greatly reduced flying times, but Concorde has shown that when the fares are too far above competing fares, the passenger demand is very limited. We want to be able to provide three classes of Mach-5 service at reasonable fares.

At Northwest, we have worked with projected operating costs for such an aircraft. We estimate that costs per hour will be substantially higher for fuel and maintenance, but equal to or somewhat lower per hour for flight and cabin crews.

We estimate that operating costs per trip, exclusive of ownership costs, will be substantially lower than those for a same-era 747.

Unfortunately, we do not have all of the picture. Development costs will be very high for an advanced SST or HST. The manufacturers have ways of making new technology extremely expensive. Some of it is justified. We are presently working in-house to try to estimate what we could afford to pay for a Mach-5 HST to enable it to be economically viable.

You asked me to talk about the market for an advanced SST or HST. I have strayed from that and given you a sales pitch for Mach-5. While our very limited work points to a Mach-5 aircraft, we are anxious to see what the parametric studies now underway at Douglas and Boeing will show. I understand that they are fixing certain requirements and allowing Mach number to vary.

Conclusion

There are almost 40 long overwater city pairs in the world today, now served by someone with nonstop service. The flying times between these city pairs vary from 10 hours to 14 hours.

There are an additional 400 city pairs of medium length served by commercial carriers with flying times ranging from 6 hours to 10 hours.

In addition, transcontinental U.S. flights today require 4 1/2 to 5 hours flying time. In 1985 almost 46 million passengers flew on international trips.

A Mach-5 HST will do the longest non-stop trips in 2 1/2 to 3 hours, the medium length trips in 1 to 2 hours, and the transcontinental trips in less than 1 hour.

Will a large percentage of the passengers flying these routes pay more to reduce their flying times to one-quarter or one-third of subsonic times? You bet they will!

The demand is here today, and the technology is within reach. What are we waiting for?

HIGHER SPEED COMMERCIAL AIRCRAFT EVOLUTION

Ardell J. Anderson
Boeing Commercial Airplane Company

Abstract

The paper addresses the technology developments and business conditions necessary for launching subsonic commercial transports in today's business environment. The possibilities for a second-generation SST and the potential economic payoff using evolving technology are discussed. The evolution of the first-generation high speed commercial transports is reviewed by looking back at the Concorde and U.S. SST development activity. Then, the technical requirements and evolution necessary for a second-generation SST are reviewed. Finally, observations of technology challenges facing hypersonic commercial transportation are made.

Development of Subsonic Commercial Airplanes

Boeing has been tremendously successful in the civil arena. The secret is developing the right derivatives and the right new airplane models at the right time to line up with air travel and airline business growth patterns. The evolution of models has been a prime reason for Boeing's continued success in the commercial field. Recent deliveries of the 767-300, a derivative of the 767-200, have started following its successful certification. Airlines already have signed up for the 737-400, which follows on the coattails of the already extremely successful 737-300. The improved technology 747-400 is scheduled for service in late 1988, and the all-new 7J7 is currently in development. The 7J7 concept offers a complete set of new technology, revolutionary cost targets, and significant improvements in overall airplane economics.

The airlines today are influenced by the pressures of airline wages, fuel prices, airlines competition, airport congestion, and regulatory and environmental pressures coming from the FAA and local communities. The airlines are also influenced by growth and expansion from overall leisure time increases, population growth, growth in the gross national product, and lower fares. The secret to profitable commercial airplane marketing and airplane designs lies in the correct and timely anticipation of, and reaction to, the result of these pressures.

Part of the success equation has to do with the development and implementation of improved technology at the right time. Figure 1 exhibits how Boeing has used continuous generic research and technology applications in 10-year cycles to develop models like the 707, 747, and the 767/757. The size of the arrows represent the magnitude of effort and dollars for each technology surge. After a large initial spurt of technology, evolutionary developments that are smaller in magnitude and lower in cost can be used to spin off technologies into other airplanes.

For example, the 767 development illustrates how the technology collection activity works, and how the business environment in the industry plays a key role in coming through with a successful airplane launch. (The 767 is

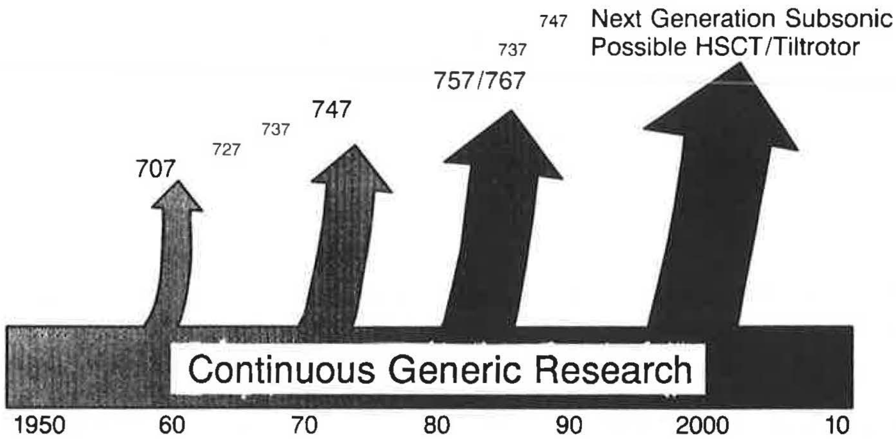


FIGURE 1. Advanced Technology Applications - Major Contributions

shown in the middle of Figure 1.) The 767 technology selection was done with a technology cutoff in mid-1978. The aerodynamics, structures, avionics, and propulsion features of the 767 were selected about four years prior to its first flight. Wings with advanced airfoils, simplified high-lift systems, and high-aspect ratio were developments made after the 747 went into production. Extensive use of Kevlar and graphite composite materials and high-strength aluminum were selected. Major avionics developments were exploited to develop the flight management systems and two-crew flight deck. Third-generation, high-bypass ratio engines were developed from the original 747 engines. Go-ahead conditions for the 767 were attractive in 1978 because net airline earnings were increasing. As has been historically the case, 767 orders tracked directly to these earnings (Figure 2). The program go-ahead conditions for this particular model were correct. Technology elements had been selected and airline earnings confirmed a go.

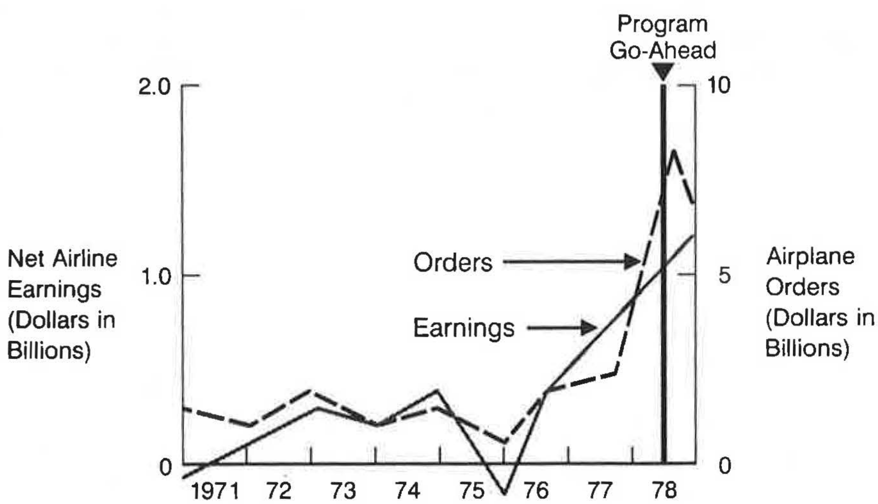


FIGURE 2. Go-Ahead Conditions - Airline Earnings

To illustrates how important it is in this business to be flexible and capable of adjusting quickly to market conditions, Boeing had completed studies of a

7X7 (the pre-go-ahead name for the 767) in a trijet configuration and then made a decision to go to a twin. In late 1977 when engineering effort was building, Boeing developed a final cost definition to determine how the airplane would play in the marketplace. The conditions were ideal for the airplane launch. At that particular time, the 767 airplanes, were defined with three-crew flight decks. It was not until 1981 that the president's commission decided on the two-crew flight deck issue, and Boeing modified and delivered all airplanes in 1982 with two-crew configurations. (See Figure 3.)

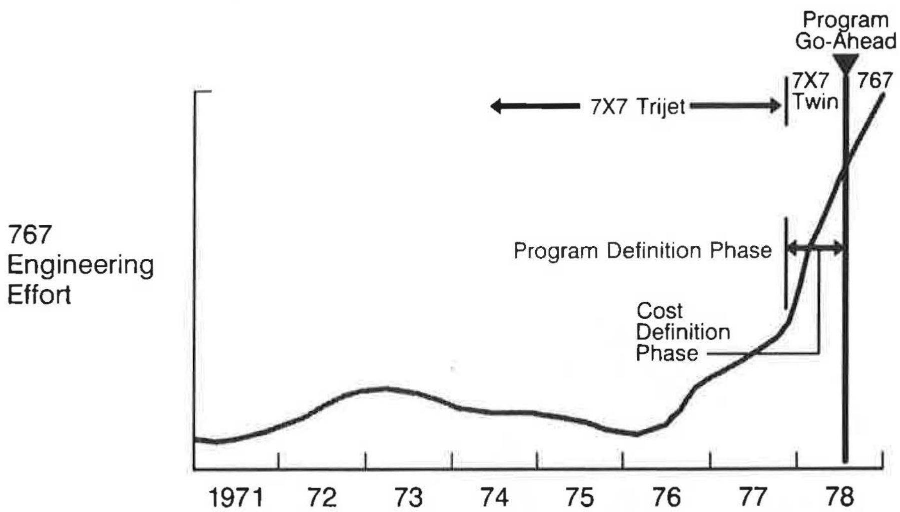


FIGURE 3. Go-Ahead Conditions - Engineering Effort

Technology elements were extracted from the successful 767 program and applied to the models like 757, 737-300, and 737-400. Boeing is now applying those technology features to the improved technology 747-400 that will be available for delivery in late 1988. The 747-400 will have a 50-percent improvement in seat miles/gallon compared to the original 747-100. This airplane will also feature a two-crew flight deck. (See Figure 4.)

There has been a change in environment since the mid-1970s, when technology was pacing and fuel was a dominant portion of the total direct operating cost for the airlines. The ownership portion of the direct operating costs was less important than the fuel portion. As we proceed into the future, goals must be adjusted to current reality. Fuel now is less dominant compared to ownership cots, as shown in Figure 5. All of our new designs are responsive to ownership cost and the right balance between ownership cost, maintenance cost, and fuel cost. In 1978, deregulation forced the airlines to become extremely cost and revenue conscious.

Technology incorporated in the next all-new airplane will be targeted for direct operating costs that consider ownership costs at the premium now being experienced. For example, the 7J7 currently being studied by Boeing incorporates radical new engine technology, exploiting counter rotating fans in an unducted fan or propfan configuration, new materials technology, and advanced, simplified systems to address lower ownership and maintenance costs.

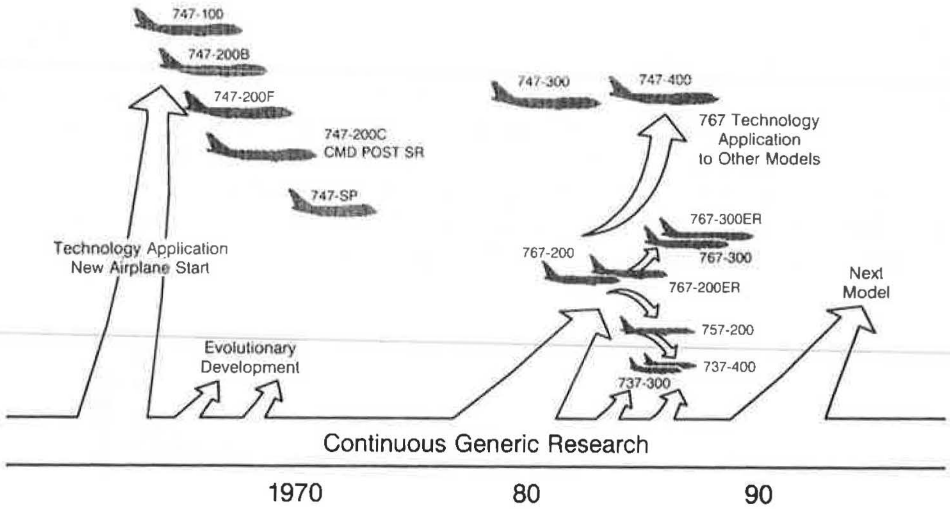


FIGURE 4. Advanced Technology Application

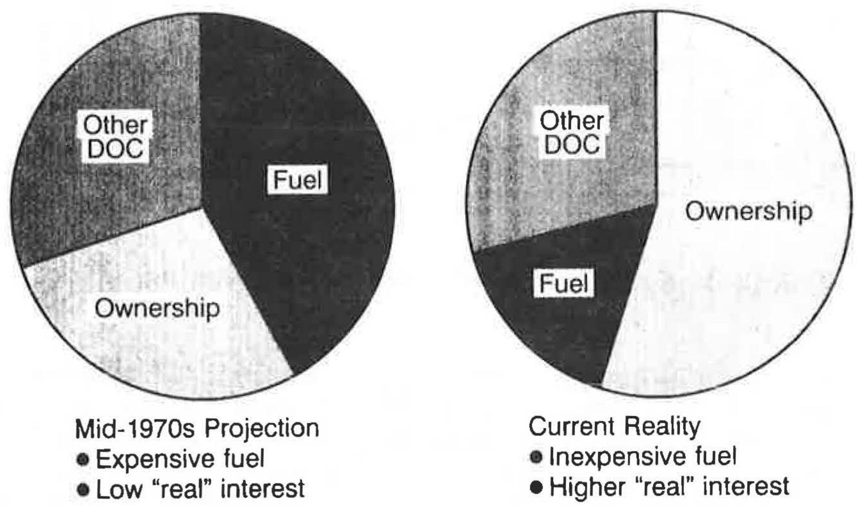


FIGURE 5. Change in Environment - Direct Operating Cost

Aluminum-lithium and composite primary and secondary structures are being studied together with significant improvements in systems and avionics. The ultrabypass engine represents fuel savings of 25 percent over the high-bypass-ratio engines available in the late 1980s. Technology elements of the 7J7 are being targeted to support airplane application in the 1990s.

Technology elements developed for the 7J7 could be applied at the turn of the century to a new version of the 747, for now called the 747-XXX. This new 747 model also features new, radically different, propulsion systems. Rather than the unducted fans studied for the 7J7, the 747-XXX could use ducted versions. The airplane will be studied with an all-new wing and a major body stretch. The all-new wing and the ducted versions of the new ultrabypass engine technology could result in a cruising speed of 0.9 Mach.

Second-Generation Supersonic Transports

Beyond the 7J7 and the 747-XXX concepts, the next thrust of technology will probably be oriented toward a supersonic transport (SST). Many important technology elements essential for the next SST will have been developed in the 7J7 program. Yet others, particularly those related to higher speed, are still required. Technology in the areas of laminar flow, high-lift devices for highly swept leading edges, thermoplastics and metal matrix composites, and variable cycle engines are some of the outstanding challenges to be addressed for a second-generation SST.

Insofar as the airlines are concerned, the bottom line for a future SST will be economic performance--return on their investment compared to other options. To address this subject, data on SST economic studies will be referenced to the 747-XXX which could be available around the year 2000. A comparison of a 747-XXX to a Boeing/NASA single-decker SST is given in Table 1. There are 525 passengers on the 747-XXX and 283 or 266 passengers on the SST, depending on passenger seating mix, equivalent or enriched. The enriched mix on the SST, resulting from increasing the percentage of first class and business class at the expense of economy class, improves the overall fare yield. (Note that the seat pitch between the 747 and SSTs has been adjusted to account for the difference in flight times.) Variations in the seat counts associated with changes in seat pitch are also an important factor.

Table 1. - SEATING-PASSENGER CLASS DISTRIBUTION

Aircraft	No. of Seats	Seating Mix	Class--Percentage (& Pitch (in.))		
			First	Business	Economy
747-XXX	525	(reference)	9 (62)	19 (38)	72 (34)
Single-Deck SST	283	Equivalent	9 (38)	19 (36)	72 (32)
	266	Enriched	14 (38)	30 (36)	56 (32)
Double-Deck SST	545	Equivalent	9 (38)	19 (36)	72 (32)
	524	Enriched	14 (38)	30 (36)	56 (32)

A possible double-decker SST gets closer in seat count to the 747-XXX. The 747-XXX has the same number of passengers as in the previous comparison, 525. The double-decker SST is a Boeing/NASA configuration, with 545 to 524 passengers depending on equivalent or enriched seating mixes.

The 747-XXX versus the single-decker and double-decker SST are compared in Figure 6. The net present value of the single-decker SST (left side) and the double-decker SST (right side) are compared to a base level of 100 for the 747-XXX. Until we further understand the true cost and therefore the price of the SST models, a 747-XXX price multiple is carried through all of our studies. The large double-decker airplane shows a significant advantage in net present value, particularly when using the high yields associated with enriched three-class SST seating. The single-decker version of the SST shows less of a possibility of matching the 747-XXX on this basis.

This study was conducted with the following assumptions: 2,600-nmi trip, 65-percent load factor, 15-year operation, 15-percent discount rate, and unrestricted routing. Also, three-class seating: 747s at (62/38/34) inch pitch and SSTs at (38/36/32) inch pitch; design cruise speed: 747 at Mach 0.85 and SST at Mach 4. In addition, 1985 operating costs rules and prices include airframe and engine spares.

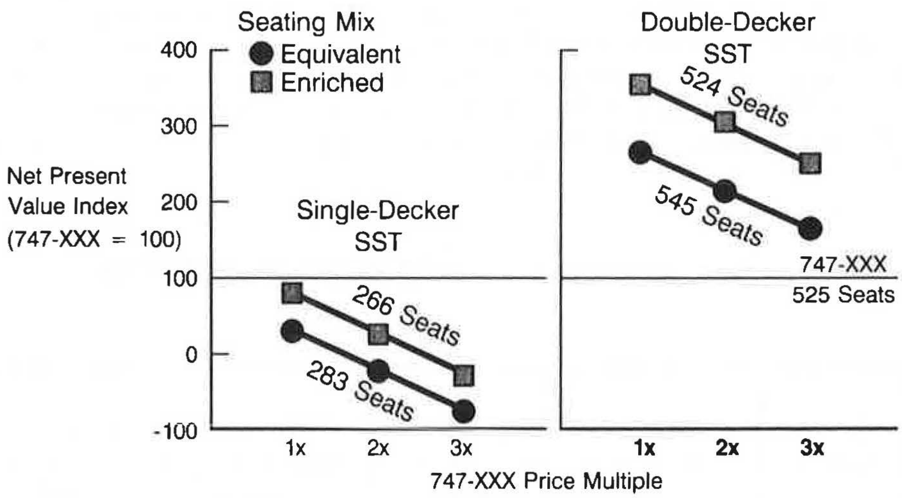


FIGURE 6. SST Earnings Potential (Mach 2.4) Compared with 747-XXX

Figures 7 and 8 show a coarse look at the effects of designing an SST for Mach numbers higher than 2.4. In these simplified "what if" type studies, the airplane gross weights were parametrically increased with increasing Mach numbers to account for structural changes necessary to satisfy thermal requirements. Fuel burn increased both as a result of the increase in gross weight and the propulsion and L/D effects that go with cruise at higher Mach numbers This data indicates the net present value of an SST to be about constant for this range of Mach numbers. It should be noted that these particular studies have not considered the higher temperature potential of the projected advancements in materials such as the powdered aluminums and titaniums or the metal matrix composites.

Evolution and Development of Supersonic Transports

Next, the evolution of the U.S. SST and a timetable for a 21st century SST will be discussed based on our experience in the previous SST program.

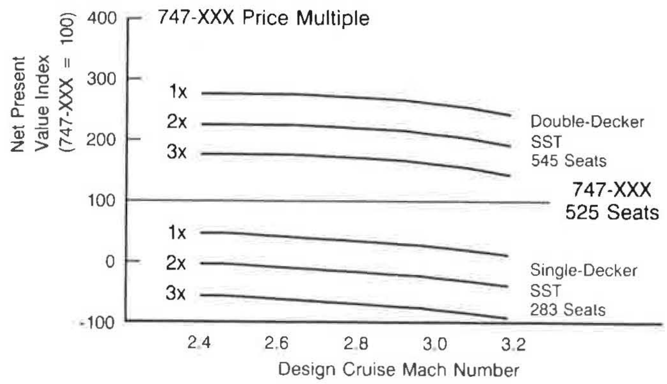


FIGURE 7. SST Earnings Potential - Equivalent Seating Mix

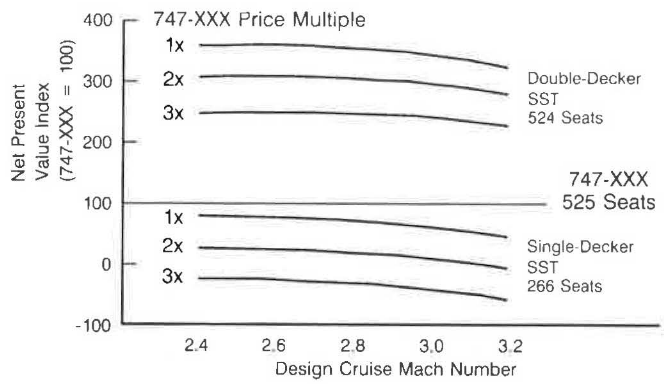


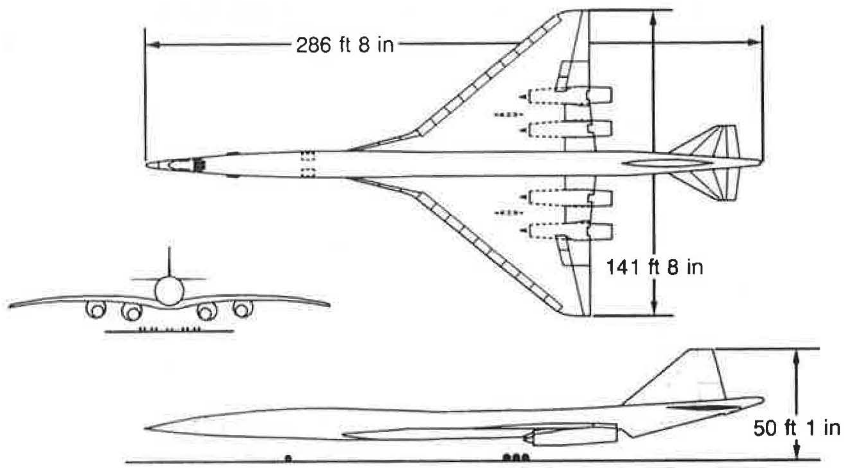
FIGURE 8. SST Earnings Potential - Enriched Seating Mix

Supersonic capability started in the late 1940s with the XS-1 when Mach 1 was first exceeded. High speed research programs were followed by military programs such as the F-104, F-105, B-70, and SR-71. Experience from the military programs formed the basis for the start of the prototype U.S. SST and, ultimately, the operation of the Russian TU-144 and the Concorde.

The "X" vehicles (X-1 through X-5) also contributed to the progress leading the U.S. SST program, the Russian TU-144, and the British/French Concorde. The intervening military developments were essential to the start of these SST programs.

Even though military forerunners are essential to advanced commercial undertakings, it is obvious that military requirements differ from commercial requirements. Economic and performance considerations such as price, profitability, and risk are different between the commercial arena and the military arena. Mission requirements, including range, equipment, and passenger provisions, tend to be different. Operational requirements such as airport and community noise considerations, utilization, and airport compatibility are drastically different. Design requirements are different. Long heat soak time, operational life, reliability, safety, maintainability goals, and growth goals are different. The SST impact on the ozone layer and the sonic boom are significant considerations for the commercial operation.

Looking back on the U.S. SST program, knowledge was gained from earlier military programs, but there still remained many commercial challenges such as weight and payload weight fraction, supersonic and subsonic range factor, low-speed performance stability and control, sideline and community noise, cooling and pressurization, cabin and fuel temperatures, overall thermal management, seal materials, and lubrication. The issues of sonic boom and upper atmospheric ozone were the factors that were not successfully addressed. The SST Model 2707-300 is illustrated in Figure 9.



SST Prototype Airplane Model 2707-300

FIGURE 9. U.S. SST Program (1968-1971)

The U.S. SST program planned to have the number one prototype in flight test by late 1972, 4 years after the 1968 configuration decision. The second protoype was scheduled for limit-load tests and then flight in 1974. The production airplane certification was to occur in 1978, 10 years after the prototype configuration decision.

Following cancellation of the U.S. SST program, continued development of military airplanes like the B-1 Bomber, F-16, F-14, and SR-71 has further enriched our technical capabilities and provided a better technology base for a future version of the SST. the 767/757 systems and structures technology developments toward the end of the 1970s have also contribute to this base. The British Aircraft Corporation's experimental Jaguar Digital Fly-by-Wire and other parallel programs have added to the necessary technology. And, the Concorde experience, where more people have flown supersonic than in all military programs combined, provides an important stepping stone for a next generation SST.

Variable cycle engine development activities sponsored by NASA have provided major breakthroughs in supplementing the technology elements required for a future SST. (See Figure 10.)

Nozzle noise suppression studies and research investigating thermal accoustic shields, coannular nozzles, and mechanical suppressors contribute to the technology base now available since the evolution of the original SST. Materials and structures technology improvements in the strength-to-density

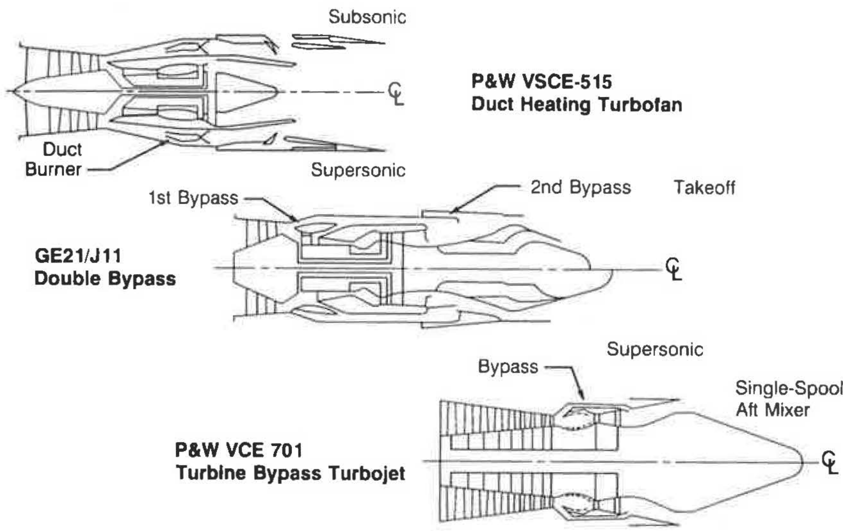


FIGURE 10. Variable Cycle Engine Development

ratio as a function of temperature show great progress since the earlier days of the U.S. SST. New materials incorporating rapid solidification rate technology and thermoplastics offer exciting possibilities. (See Figure 11)

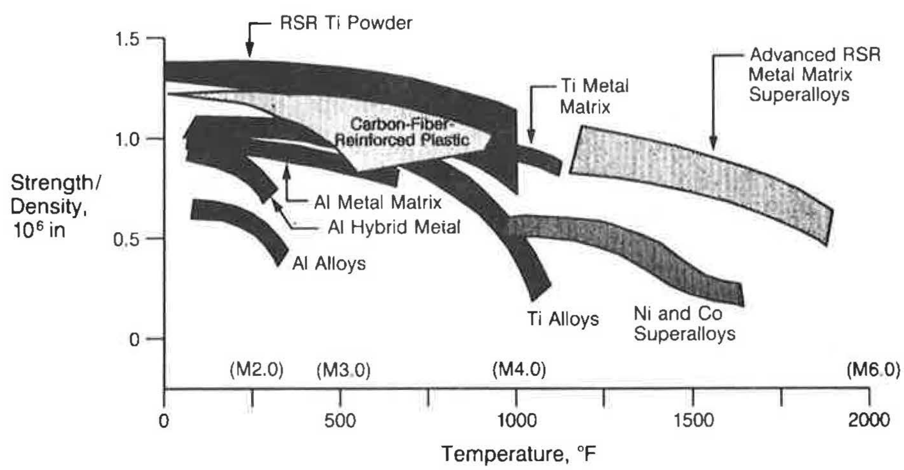


FIGURE 11. Materials and Structure Technology

Continued improvements in simplified lightweight systems could come from the 7J7 commercial experience. As an example, the large-scale use of the Boeing developed DATAC data-bus system for airframe subsystems control and monitoring results in significant weight savings. Substantial manufacturing cost savings are expected.

Significant improvements have been made in low-speed aerodynamics with the developments of variable camber and the leading-edge vortex flap. This will permit the use of higher lift coefficients for takeoff and landing and permit

wings sized for cruise flight to be compatible with existing runway and airport approach speed requirements. The earlier experience of the U.S. SST program, the experience of the Concorde, and the evolving technology elements appear to ensure that a second-generation SST could be viable.

Continued NASA studies and industry studies could lead to high-speed civil transport design and development culminating in an SST certification around the year 2000. Some of the required or enhancing developments to support such a plan are listed here:

- Propulsion noise suppression
- Variable cycle engine concepts
- Laminar flow control
- Low-speed aerodynamics
- Low-overpressure configurations
- Low-pollution engines
- Low-cost structures
- High-temperature seals, lubes, and fluids
- Fuel tank conductivity
- High strength-to-weight materials

Development of Commercial Hypersonic Transports

Recent attention from the administration and the press has been focused on the possibility of a hypersonic "Orient Express." To review that possibility, consider how continuous generic research has fostered the development of advanced commercial models, and how it could lead to the development of a commercial hypersonic transport. With the government plans for building the X30 hypersonic research vehicle, and ultimately, a military or space hypersonic vehicle, a commercial hypersonic transport could be considered. Figure 12 shows several hypersonic transport concepts.

The use of an experimental vehicle like the X-30 airplane can contribute to the knowledge base for Mach numbers from 2 to 20. A commercial hypersonic airplane development could come sometime following hypersonic military and space vehicle operations early in the 21st century.

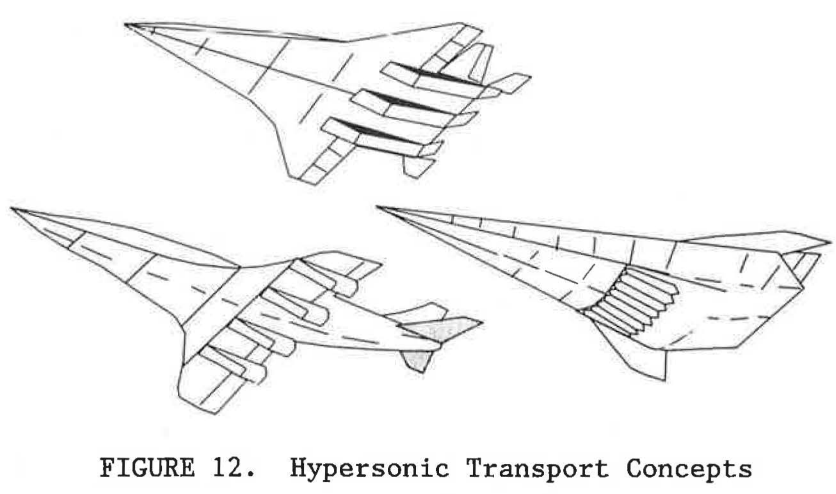


FIGURE 12. Hypersonic Transport Concepts

Even though it is very exciting to discuss travel between continents at hypersonic speeds, hypersonic transport design challenges still remain very significant.

The safety, reliability, and maintainability challenges associated with hypersonic flight are significant. For example, the operational procedure on current subsonic airplanes following a cabin pressurization failure is to execute an emergency descent to 14,000 feet and then cruise to the next point of landing. What will be the implications for a hypersonic airplane cruising at 100,000 feet? If the hypersonic airplane uses accelerator and cruise engines, an airline will expect extremely high probability of all the cruise engines starting when reaching cruise altitude, and vice versa when slowing from cruise to descent and reigniting the accelerator engines. Maintenance also raise a number of challenges. As we know, the faster an airplane flies, the more essential it is to quickly turn it around on the ground and get it back into the air in order to exploit its productivity. Will we able to service a hypersonic airplane that may have much of its structure still hot and turn it around in 45 minutes to an hour?

Design and operation challenges are significant. From an operational standpoint, accelerations imposed on the passenger are a prime consideration. And fuel costs and handling of the special fuel, sonic booms, utilization of aircraft, turnaround times, and navigation and air traffic control offer significant challenges.

Design requirements for structures, vehicle considerations for minimum overpressure, fuel insulation, thermal management, and propulsion system integration all offer tremendous challenges.

Several scenarios for hypersonic commercial travel can be envisaged. In one case, hypersonic airplanes are compatible with today's airports and surroundings. In another, more likely, scenario hypersonic commercial transports operate out of dedicated "space ports," which are fed by both subsonic and supersonic airplanes.

Conclusions

1. Second-generation commercial supersonic transport airline operations are a possibility for the turn of the century.

2. A commercial SST must be responsive to the challenging deregulated airline business requirements.

3. The SST and its supporting systems must offer competitive earnings capability and operating costs.

4. Coordinated and disciplined approach by industry and government is necessary to develop the required technology.

5. Environmental and political issues will have to be satisfied.

6. Timing of hypersonic commercial transport operations are dependent on a national aerospace-plane program to pioneer military/space developments and to provide technological spinoff for commercial consideration.

THE REQUIRED TECHNOLOGY COMBINATIONS FOR HIGH-SPEED COMMERCIAL AIRCRAFT

Roger D. Schaufele
Douglas Aircraft Company

The Potential Market

Study of world demographics and points of interest to travelers -- business, pleasure, curiosity, etc. -- suggests a 6,500 nautical mile trip distance would accommodate the requirements of over 90 percent of today's traveling public. Today's aviation system covers the nonstop distance of 6,500 mi in approximately 13 1/2 hours flying time. Supersonic transports with the speed of today's Concorde, but with double the nonstop range, could cut that time to 6 hours. Mach-6 travel would require no more than 2 hours airport to airport. Mach-12 travel would further reduce the flying time to 1 1/4 hours. Clearly, for those who have experienced the 13 1/2 hour Pacific journey, the potential for making these flights in 2 to 6 hours is indeed exciting. The technical challenges associated with long-range commercial transports operating in the speed-range up to Mach 6 are formidable. One might speculate that pushing the cruise speed to Mach numbers beyond 6 may be a case of diminishing returns.

McDonnell Douglas econometric studies show the increasing importance of the Pacific Basin which, by the year 2005, is forecast nearly to match the European economic community in gross domestic product value. This is expected to result in an increase in passenger traffic to 35-40 million Pacific Basin passengers by the year 2000 -- a 370-percent increase over 1985, representing a strong demand for improved air service. High-speed commercial flight holds promise as an appropriate next step in the development of the world transportation system as well as significant element in the process of "shrinking the world".

History repeatedly shows the significance of personal contact between people as well as the reluctance or inability of people to undertake travel which lasts more than a few hours. In the 1850's, mobility had been advanced by the railroads to the extent that a two-hour trip from Los Angeles reached perhaps 40 miles into surrounding Southern California. The propeller-driven aircraft of the 1930s and 1940s increased two-hour mobility to 500 miles which allowed routine travel between Los Angeles and other western cities. Starting in late 1950s jets further expanded two-hour travel to 1000 miles, Los Angeles to the Midwest. Mach-2.2 supersonic aircraft could extend 2-hour mobility to 2500 miles, Los Angeles to the East Coast. (See Figure 1.)

The Goal

In February 1986, President Reagan, in the State of the Union Address, outlined national aeronautical goals including that of a commercial transport providing routine access to the Pacific nations in less than two hours -- "The Orient Express". A commercial Mach-6 transport will allow routine two-hour flights from Los Angeles not only to the Pacific Rim but also to Europe.

Although we have limited supersonic commercial transport operation today, I want to emphasize that routine long-range high-speed commercial flights are not merely an extension of today's technology; viable high-speed commercial flight

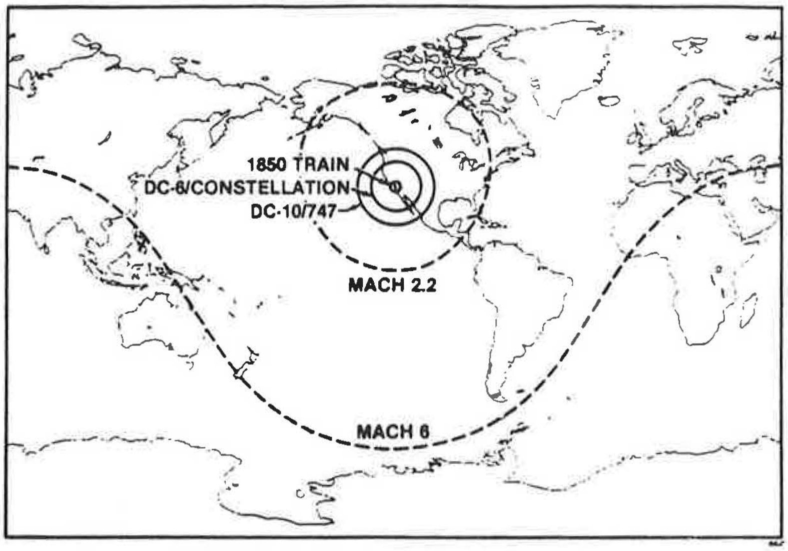


FIGURE 1. The Shrinking World

represents a challenge to maximize the advantages of speed by innovative use of truly advanced technology to meet mission requirements.

Technical Considerations

High-speed commercial flight is subject to physical boundaries which govern the operating region. The upper limit (minimum speed) corresponds to a minimum level of dynamic pressure (at 180 lbs per sq ft) necessary to sustain flight without an unduly large wing area. The lower limit of the flight corridor or maximum speed (of 1000 dynamic pressure lbs per sq ft) is established by structural strength and temperatures resulting from aerodynamic heating. In addition, the engine inlet duct design pressure establishes limits on the Mach number operating range of Ramjets because of the pressure rise associated with the internal "shocked-down" flow and subsonic combustion. At higher Mach numbers, supersonic combustion ramjets (scramjets) are required. (See Figure 2.)

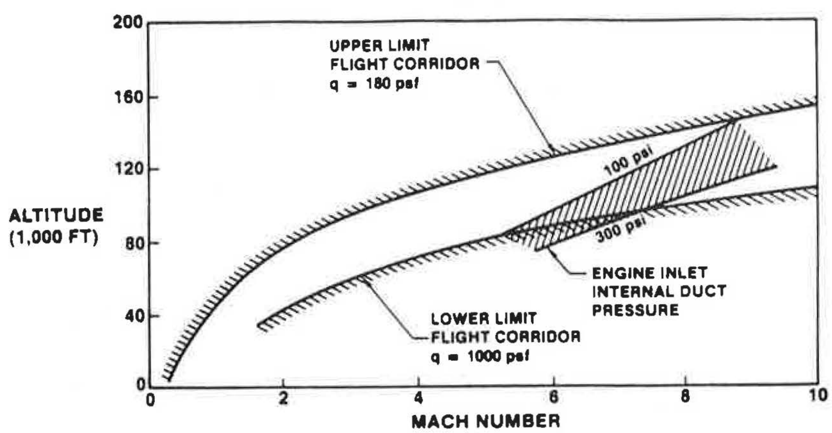


FIGURE 2. Physical Boundaries of High-Speed Commercial Flight

Environmental considerations pose additional limitations on the Mach number/altitude flight corridors. Airport and community noise necessitate gaining altitude as quickly as possible and avoidance of sonic boom require that acceleration to supersonic flight be accomplished at as high an altitude as possible. Flight paths causing 2 psf shock over pressure or more at ground level are considered unacceptable; 1 psf overpressure may be acceptable. The sonic boom levels are significantly less than that of the Concorde which is 2.5 psf at cruise. For a Mach-2.2 transport, 2 psf overpressure corresponds to cruise at 65,000 feet and 1 psf overpressure requires cruise at 90,000 feet (Figure 3).

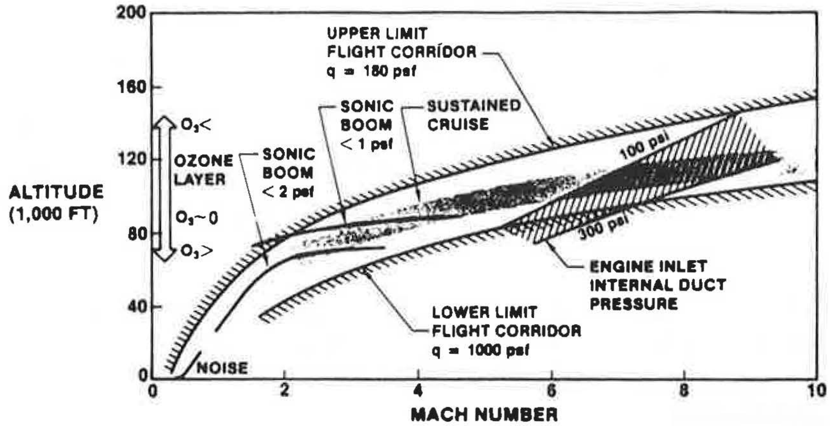


FIGURE 3. Flight Corridor for Possible Operational High Speed Commercial Aircraft

Additionally, there are environmental concerns regarding the ozone layer which extends from approximately 65,000 feet altitude to over 140,000 feet. Ozone vulnerability varies. The lower layer -- 65,000 to 80,000 feet -- is very limited in free oxygen atoms and therefore vulnerable to reformation of ozone which requires a much higher concentration of the free oxygen atoms compared to ordinary oxygen. Between 80,000 and 95,000 feet, ozone tends to be minimal; and above 95,000 feet there is ample free oxygen which constitutes a stable zone and at the same time provides for replenishment of the less stable zones at lower altitudes. This, however, is a slow process, and flights at altitudes above 95,000 feet are best from the ozone depletion standpoint. All considered, the region for best sustained cruise is generally over 80,000 to 85,000 feet and extends to 100,000 to 120,000 feet, depending on cruise Mach number.

To meet the objectives of efficiency, economics and safety. The high-speed commercial transport configuration may include the following, to various degrees depending on the cruise Mach number: (1) integrated propulsion -- aerodynamic design for proper shockwave location to enhance propulsive efficiency and fuel economy, (2) "designer" fuels to provide high volumetric energy as well as good (high density) storage characteristics, (3) energy management to utilize aerodynamic heating from skin friction to augment thrust, (4) integration of thermostructural materials for improved strength at elevated temperatures and lower weight characteristics, and (5) supporting technology beyond the aircraft itself in the form of fuel handling, air traffic control, airline operational procedures, reliability, safety, and maintainability.

In the final application, technology must pay for itself. The end product must provide a reasonable economic return for the airlines and manufacturing community -- a major challenge for the aircraft designers.

Engines and Fuels

Within the flight corridor, engine cycles and fuels fall into three different regions. For speeds up to Mach 3 and the corresponding altitudes, conventional hydrocarbon fuel (JP) and conventional turbo machinery (turbojet and turbofan) are best suited. Between Mach 3 and Mach 6, cryogenic hydrocarbons such as methane or liquid natural gas, endothermic fuel, and combined cycle engines (e.g., multiflow path/dual engines or multimode in conjunction with ramjets) provide the most suitable characteristics. Above Mach 4 or 5 cryogenic hydrogen has application because of its energy content and heat sink potential. Above Mach 6 hydrogen or hybrid fuels in combination with ramjets or scramjets (supersonic combustion ramjets) are required. (See Figure 4.)

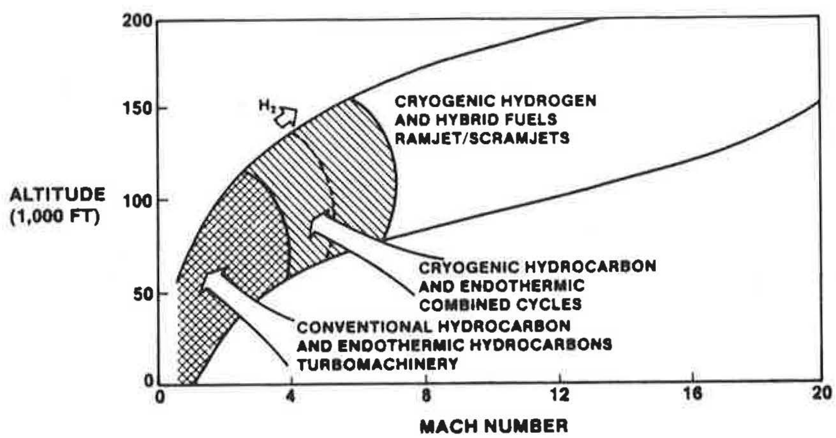


FIGURE 4. Flight-Corridor-Suitable Engines and Fuels

Propulsion systems differ significantly depending on the design cruise Mach number of the high-speed commercial transport. For supersonic transport design Mach numbers up to 3, turbojet or turbofan engines are the optimum choice based on fuel efficiency and thrust/weight ratio. At higher speeds, up to Mach 6, combined cycles or multimode propulsion systems are required. Concepts such as the ejector turbofan or combinations including subsonic combustion ramjets (the turboramjet or airturboramjet) are considerations. Above Mach 6, Scramjets - supersonic combustion ramjets - are required. Scramjets are highly integrated with the airframe forebody, which is part of the inlet and provides the pressure rise to the combustor. Following combustion, the airframe afterbody serves as a thrust surface for the nozzle (Figure 5).

Overall, for economic high-speed commercial transport aircraft, the propulsion system must provide fuel-efficient high-speed cruise as well as efficient fuel usage for lower-altitude diversion to alternate airports when required. In addition, thrust margins must allow high-altitude transonic acceleration to minimize ground-level sonic boom disturbances.

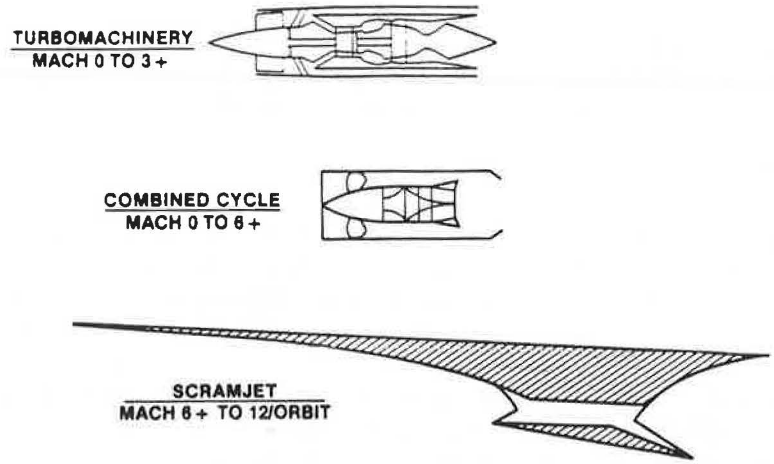


FIGURE 5. Propulsion Concepts

Airframe Considerations

From the airframe standpoint there are three general classes of configurations as described by Kuchemann in his book "The Aerodynamic Design of Aircraft" These classes are swept, slender, and waveriders. As shown in Figure 6, the shaded areas with specific aircraft design points correlate well with Kuchemann's analysis. The "swept" points represent the DC-10 and 747, while the "slender" designs are the Concorde, B-70, SR-71 and McDonnell Douglas Advanced Supersonic Transport. Depending on the design cruise Mach number, breguet-range capability based on reasonable values of attainable technology has been derived in terms of wing semi-span to overall length. Possible configurations below a value of 0.2 are considered generally not acceptable from a takeoff standpoint due to poor low-speed characteristics (i.e., lift, linear pitch characteristics, lateral control, etc.).

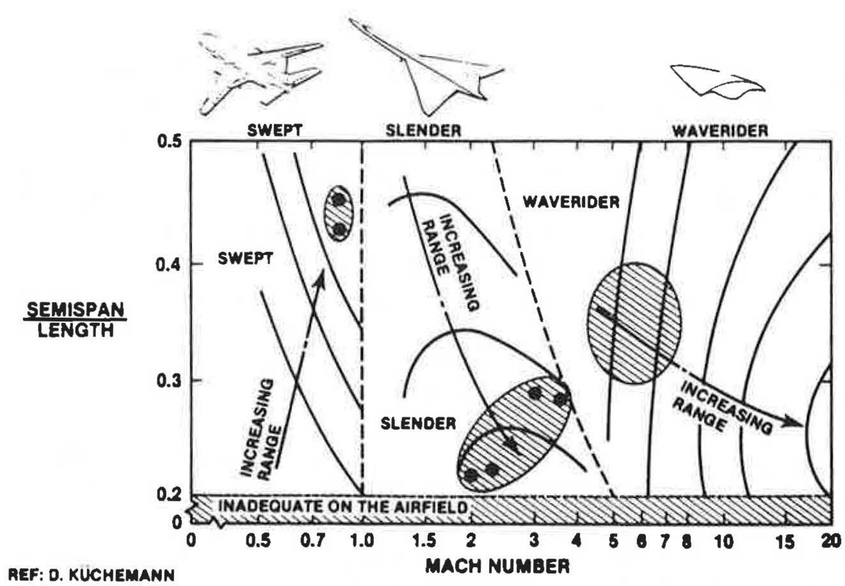


FIGURE 6. Aerodynamic Design Concepts

Future supersonic transports would also be expected to have semi-span to length values of 0.2 to 0.25. At higher Mach numbers (above 4) hypersonic configurations are expected to fully utilize shock waves for lift generation. These "waverider" configurations produce very strong shock waves and result in an "aerodynamic integrated propulsion lifting body."

At high Mach numbers (5 and above) the aircraft becomes a highly integrated system utilizing the forebody as the inlet to the propulsion system (which is essentially the combustion mechanism). Likewise, the aft body is also a part of the propulsion system in the form of a half nozzle for thrust generation. Contouring is very important for developing the shockwave system to achieve high pressure prior to combustion. Maximizing the efficiency of this system is achieved through very closely integrated design activity between the airframe and engine manufacturers. (See Figure 7.)

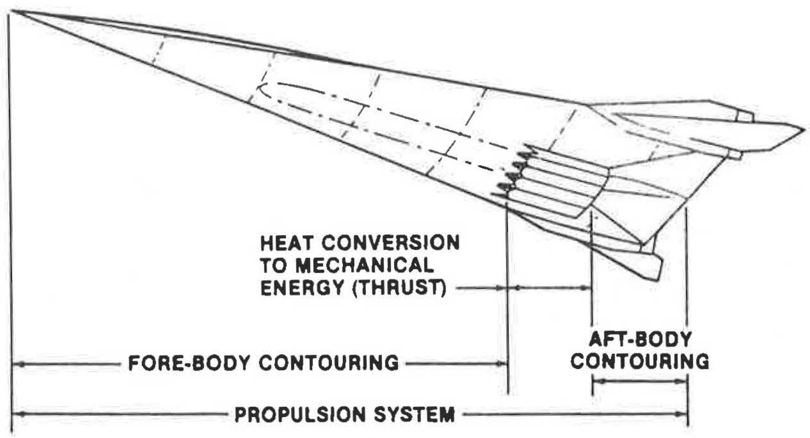


FIGURE 7 Airframe-Propulsion System Integration

The relative densities of JP and hydrogen and the resulting fuel tank sizes lead to widely different aircraft fuselage shapes that impact the weight and drag on the vehicle. The correlating parameter in this case is the vehicle slenderness ratio defined as volume to the 2/3 power divided by the vehicle wetted area or $V^{2/3}/S_{wet}$. The drag of the less slender hydrogen-powered hypersonic aircraft is higher and the lift-to-drag ratio is lower than for the more slender JP-powered supersonic aircraft. The greater wetted area also means more structural weight for hydrogen-powered aircraft. The tradeoffs become very significant in the selection of fuels for high-speed commercial transports. (See Figure 8.)

Fuels

Current fuels -- conventional hydrocarbons (JP), endothermic hydrocarbons, cryogenic hydrocarbons (methane or liquid natural gas) and cryogenic hydrogen -- being considered for high-speed commercial transports offer desirable features including high volume density, high energy content, heat sink potential, and safety. Unfortunately, the desirable features are attendant to different fuels. This situation leads to the concept of "design fuels" specifically tailored to obtain the highly desirable features in one fuel. (See Figure 9.)

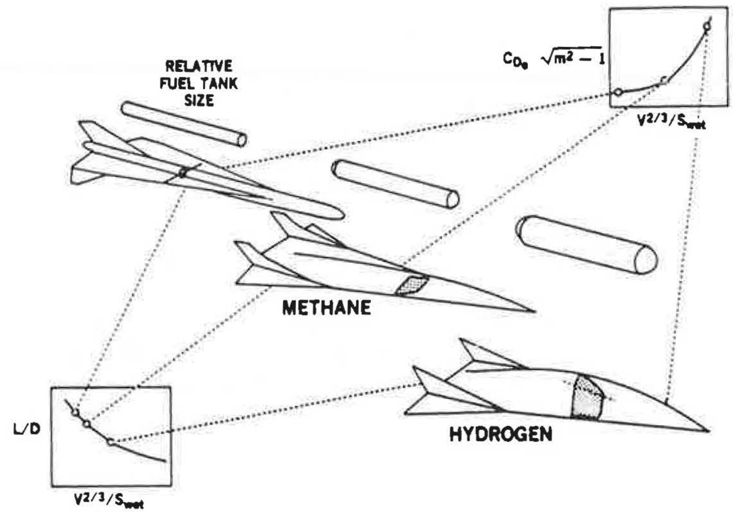
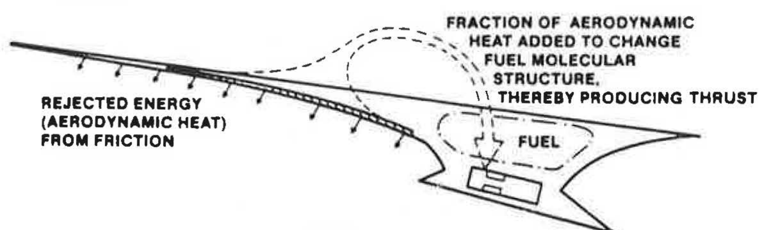


FIGURE 8. Fuel Density Impacts Size, Weight, Drag

The availability of computational chemistry codes provides the tools for design of new fuels whereby the molecular structure of the fuel can be altered between onboard aircraft storage and combustion by using heat collected from "hot" structure. By this process, heat produced by friction on outside aircraft surfaces would produce a measurable amount of thrust and improve the engine specific impulse rather than be radiated or collected in increasingly hotter structure for future aircraft cool-down periods. Economic availability is the overall measure in this process.

- FUEL MOLECULAR STRUCTURE FOR HIGH Isp AT ENGINE
- FUEL MOLECULAR STRUCTURE FOR LOW VOLUME IN STORAGE
- HEAT TO CONVERT MOLECULAR STRUCTURE EQUAL TO AERODYNAMIC HEAT AVAILABLE



MISSION KINETIC AND POTENTIAL ENERGY + FRICTION (DRAG) ENERGY REJECTED IN WAKE AS AERODYNAMIC HEAT = COMBUSTION (HEAT) ENERGY + RECOVERED (AERODYNAMIC HEAT) ENERGY

FIGURE 9 "Designer" Fuels

Energy management is a high priority for efficient high-speed transport aircraft. Aerodynamic heating through skin friction increases by the square of the Mach number. At low supersonic Mach numbers it is most efficient to radiate away as much heat as possible -- heat buildup in the structure will result in long nonproductive (nonrevenue) cooldown periods.

At higher Mach numbers, thermal management may become cost effective and contribute to engine thrust as a heat addition to the fuel. Thermal management

has the additional advantage that by cooling the external skin surface (or at minimum, maintaining skin surface temperature) transition to turbulent flow is delayed which reduces drag and net thrust requirements. (See Figure 10.)

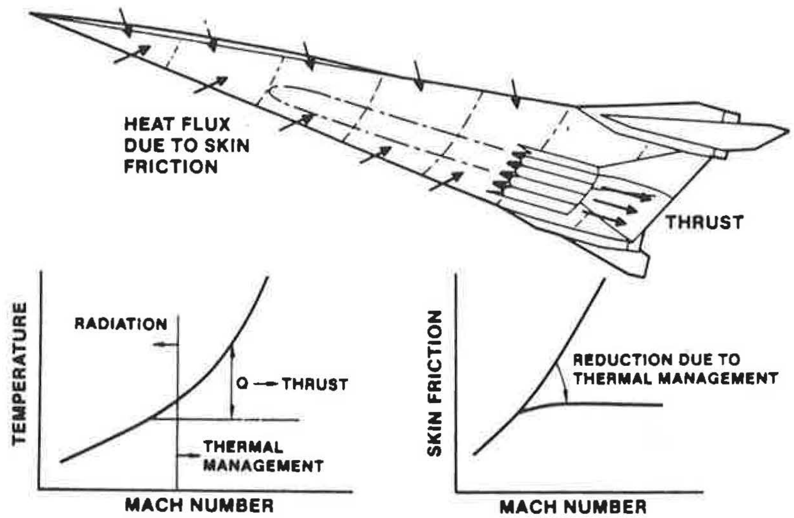


FIGURE 10 Energy Management

Material and Structures Technology

Current material and structures technology can accommodate temperatures up to 1800°F. A typical structural concept consists of an outer heatshield panel, an air gap, insulation, and a load-carrying structure consisting of superplastic-formed diffusion-bonded (SPF/DB) titanium (Figure 11). This is efficient in the low Mach number range. However, at higher Mach numbers, above 6-8, and correspondingly higher temperatures over 1500-1600°F, the resulting high structural weight fraction imposes undue restriction on payload or intolerably high aircraft takeoff gross weights. As a result, R&D is being directed to new, lightweight concepts and advanced materials. One such advancement utilizes the SPF/DB concept with a rapidly solidified titanium load carrying structure, thermally protected by continuous fibers in an aluminium-titanium matrix. This advance material provides high strength at elevated temperatures up to 1800°F and has the effect of significantly reducing the structural weight fraction.

From the functional standpoint, subsonic and supersonic aircraft have a high degree of commonality with respect to the circular cross section pressure shell for payload accommodation and the wing torque box for load transfer, engine mounting, and landing gear attachment. The designer's task is to join these components into a functional structure. Additionally, both subsonic and supersonic transport aircraft accommodate fuel in the wing.

Hypersonic aircraft, however, represent a highly integrated design with separate functions all in one structure. Payload and fuel will be accommodated in the central, primary structure which, in addition, will carry a proportionally greater percentage of the lift compared to subsonic or supersonic aircraft. In actuality, the propulsion system will be distributed

along the entire length of the primary structure with the airframe forebody acting as the inlet or ramp to the combustor and the airframe afterbody acting as the nozzle or expansion device for developing thrust (Figure 12).

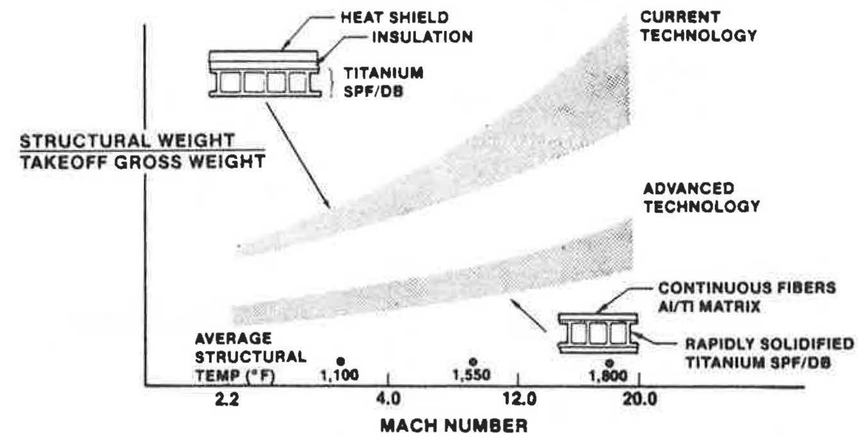


FIGURE 11. Materials and Structures

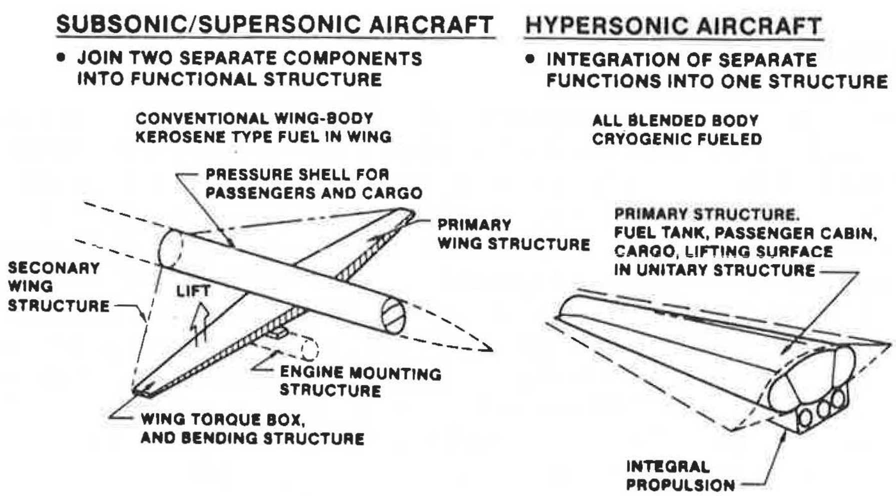


FIGURE 12. Designer's Task

Other Technologies

Beyond the vehicle itself, there are many technologies of major importance and requiring significant resource commitment (time and funding) for development. These include procedures and practices for handling unconventional fuel for aircraft fueling, defueling, storage, and transportation in a safe, routine manner. Hydrogen-powered transports require liquid fuel to be provided at commercial airports, and while its storage and handling at U.S. spaceports is routine, safe provisioning at commercial airports of hydrogen at -423°F will increase capital and operational costs. Use of liquid natural gas offers many attractive features including availability, cost, combustion cleanliness, and

safety. A technology base for vehicular use of liquid natural gas was developed during the period of acute oil shortages and widespread experience was gained in its transportation and storage.

High-speed commercial transports (HSCT) are expected to be fully integrated with air traffic control procedures in practice at the time of initial service. HSCTs will be an excellent example of utilizing the ATC flow control system to full benefit, in that the landing slot will most probably be designated prior to takeoff, thus assuring minimal "directed" delays enroute. Advanced ATC systems must precede the HSCT.

Clearly airline operational procedures must be aligned with the HSCT speed capability. Aircraft turnaround times become increasingly more important to high-speed aircraft productivity as cruise speed increases and productivity means profitability. A reduction in turnaround time from 2 hours to 1 1/2 hours will have increase productivity potential of an estimated 15 percent.

Materials, systems, and equipment must receive corresponding resource attention and commitment in line with the more visible technologies such as airframe-propulsion system integration. Reliability, safety, and maintainability for the HSCT must be as good or better than current commercial aviation standards and accomplishments.

Hypersonic aircraft flight experience in the United States is very limited. High-speed research aircraft of the early 1950s provided for the development of the B-58, SR-71 and B-70. The X-15 reached higher Mach numbers in the early 1960s and was to be a test bed for NASA's hypersonic research engine. However, before the engine was tested, the experimental aircraft research program came to an end.

Now, more than 20 years later, the United States is still without a dedicated high-speed flight research program, and now high-speed commercial transportation is on the horizon. The National Aero-Space Plane Program will lead to the X-30 demonstrator in the 1990s and provide the technology validation and experimentation to reduce the risk for a Mach-6 Orient Express.

Even though research and design of high-speed commercial transports will utilize the many powerful computational codes currently emerging, it is expected that wind tunnel test facilities will still be a vital part of the verification of the configuration definition and development process.

Continuous flow tunnels fall short of matching full-scale aircraft Reynolds numbers; however, shock tubes and blow-down facilities will provide a close match over the expected range of Mach numbers (Figure 13). The major concern is that test facilities are disappearing because of disuse, maintenance and up-keep costs, and higher-priority land use. Valuable existing facilities must be considered a national resource and not be dismantled.

Conclusion

The idea of a high-speed commercial transport is credible, and with cause. Significant technological progress has been accomplished in certain areas such as advanced materials applications to high temperature engine components,

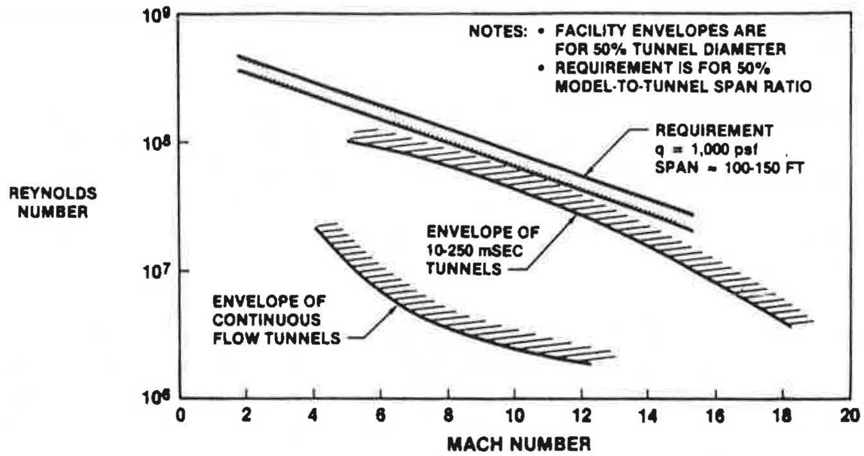


FIGURE 13. Test Facility Availability - A Major Issue

computational fluid mechanics codes, and advanced airframe structural materials. However, much remains to be accomplished. Technology maturation and validation must proceed with specific focus on propulsion technology: combined cycle engines with high specific impulse and thrust/weight characteristics; thermal management processes to utilize aerodynamic heating rather than throwing away a valuable resource; and tailored or "designer" fuels to achieve the best characteristics of several current fuels in a single fuel.

In addition, structures technology needs to be furthered in the areas of rapid solidification-rate alloys and metal matrix composites for lightweight, long-life structures as well as for fuel-tank integration with hot structures to provide safety and reliability. Other technology maturation and validation needs include: (a) computational fluid dynamics to allow aerodynamic and propulsion integration in a one-step, continuous process with reasonable computer power and process times; and (b) innovation for safe airline operation at very high speeds in airspace that will inevitably be more congested.

As an individual who has spent nearly 40 years in the aircraft design business, I look forward to the day when the technology combination required for high-speed commercial transports has been achieved, and the vehicles discussed here become a reality.

THE IMPACT OF EMERGING TECHNOLOGIES OF AN ADVANCED SUPERSONIC TRANSPORT

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Abstract

The cancellation of the U.S. National SST Program in 1971 seriously hampered technical progress in supersonic cruise research. However, the momentum gained from the quarter century of focused effort in supersonic cruise research that preceded the national program along with progress in numerous military programs, and, of course, the SCR Program that came afterward, identified significant advances in every technology area. The impact of these emerging technology advances in propulsion, structures and materials, aerodynamics, and systems is more than three times as powerful on an SST as on a subsonic transport.

Highly efficient propulsion systems having variable geometry elements, long-life hot core, axisymmetric variable-geometry inlets, and low-noise nozzle and reversers are the major advances in propulsion systems. Advanced structural concepts, long-life damage-tolerant structures, advanced material development, aeroelastic tailoring, and low-cost fabrication reflect the advances in structures and materials. Blended-arrowing configurations, laminar flow technology, and nacelle-airframe integration highlight the advances in aerodynamics. Finally, the advances in primary flight controls, integrated avionics systems, and aircraft subsystems reflect the strides made in systems technology. Application of these emerging technologies, both individually and synergistically, result in an AST having significant improvement in range and payload, a sharp reduction in aircraft gross and empty weight, and a significant improvement in airport-community noise.

Introduction

The timing of a new airplane program is driven by a number of key ingredients including cost, market economics, financing, and, of course, technology readiness. Launching a new airplane program requires the proper blending of these ingredients. Thus far, the success of the recipe has applied singularly to subsonic airplanes. Whether our future air transportation system will continue to be dominated by these subsonic airplanes will, of course, depend upon the leverage each of these ingredients exerts in the future, especially on very long-range routes where time becomes another important factor in the recipe.

This paper will focus primarily on the technology ingredients in a new recipe for supersonic travel. It will begin with a review of past SST activities and present a significantly new and unique capability that will result from the synergistic integration of the enabling technologies in propulsion, structures and materials, aerodynamics, and systems. Such a vehicle, which will also be environmentally acceptable, shows enormous promise of an efficient and highly productive SST that could serve an ever-expanding market, especially in the Pacific Basin.

Brief Review of the Past

The United States Government and industry have a substantial investment in the technology necessary for a successful SST. A billion dollars was invested in the National Program from 1962 through 1971. (See Figure 1.) The NASA Supersonic Cruise Program, started after the National Program specifically to provide a focused effort on the problems identified in the National program, lasted nearly 10 years and invested another 130 million dollars[1]. More than 1,300 technical reports resulted from the NASA effort.[2-4]

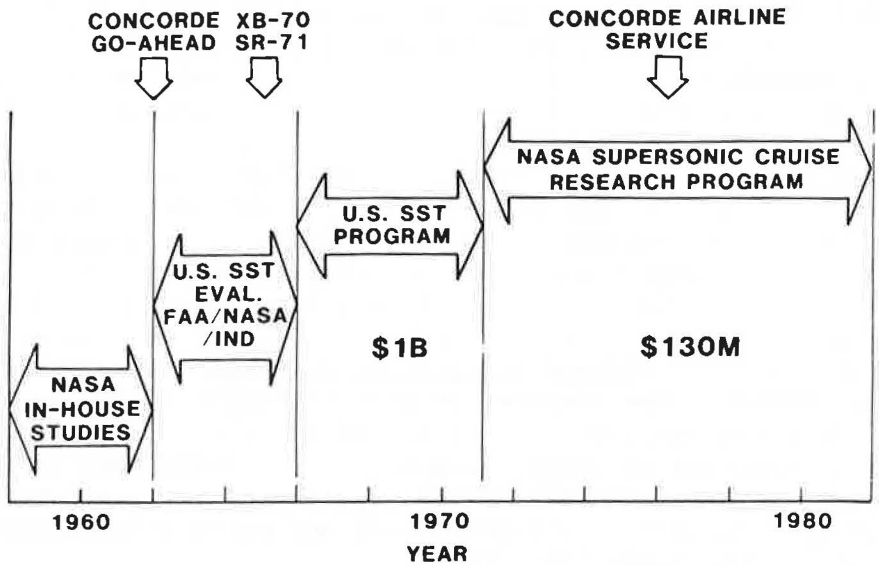

FIGURE 1. Evolution of U.S. SST Effort

It is difficult to believe that 24 years have passed since the initiation of the National Program by President Kennedy in 1962 or that 15 years have passed since the program was cancelled by Congress in 1971. During this period, the Concorde entered commercial service and has accumulated more than 100,000 hours at Mach 2 (Figure 2). More civilians have flown at Mach 2 since the introduction of the Concorde into commercial service than all the military pilots in the world. It should be recognized that that a Concorde built with the technologies described in this paper would do the same mission at half its current weight and less than half its fuel consumption. The Boeing 2707 of 1971 was to carry 290 passengers 3,500 nautical miles at a takeoff gross weight of 750,000 pounds. With the technologies to be discussed in this paper, 290 passengers could be carried 3,500 nautical miles for a gross weight of 307,000 pounds.

Potential Configuration

Many of the technology advances being adopted in the subsonic area have direct application to an SST. When combined with the results of the SCR (Supersonic Cruise Research) Program and military engine improvements, a drastically different airplane than the one cancelled by Congress in 1971 can be envisaged (Figure 3).

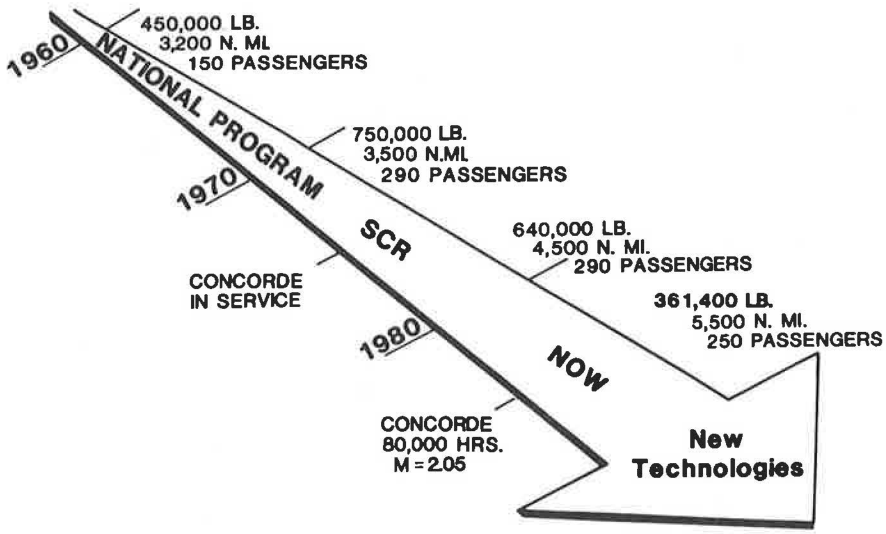

FIGURE 2. Supersonic Perspective

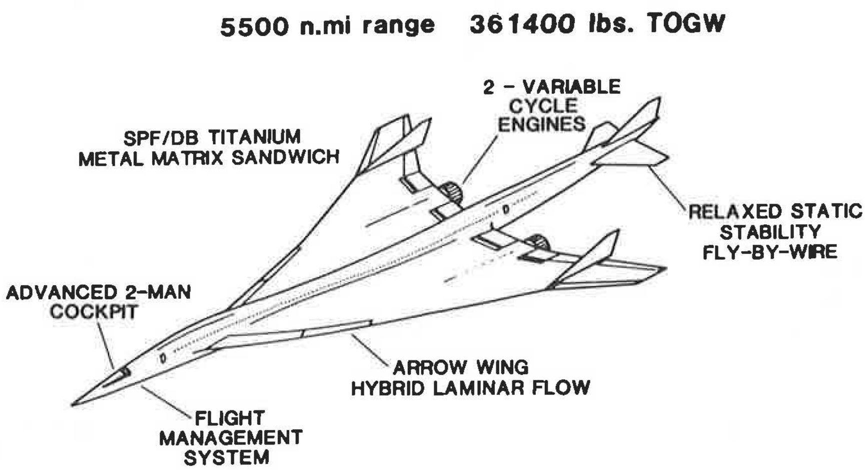

FIGURE 3. Emerging Technology Configuration

This exciting 2-engine, 250-passenger, Mach 2.7 configuration would have an arrow wing, SPF/DB (superplastically formed and diffusion bonded) titanium metal-matrix structure, variable-cycle engines, an advanced two-man cockpit, a flight management system, and fly-by-wire relaxed static stability.

This advanced airplane would have a takeoff gross weight of 361,400 pounds which would provide a range of 5,500 nautical miles. This would enable Los Angeles-Tokyo capability in a little over three hours while achieving a seat-mile per gallon capability of almost 50. If the airplane were configured for all first-class in the initial service, it would carry 135 passengers from New York to Tokyo in a little more than five hours (Figure 4). If laminar flow can be achieved, the takeoff gross weight would be reduced nearly 100,000 pounds

and the seat-miles per gallon would be about 80. Conversely, at the same gross weight of 361,400 pounds, the range would be increased from 5,500 nautical miles to 7,500 nautical miles. Either of the potential ASTs (Advanced Supersonic Transports) substantially outperform the Concorde or the 1971 U.S. SST by such a large margin that renewed interest in SST development is inevitable.

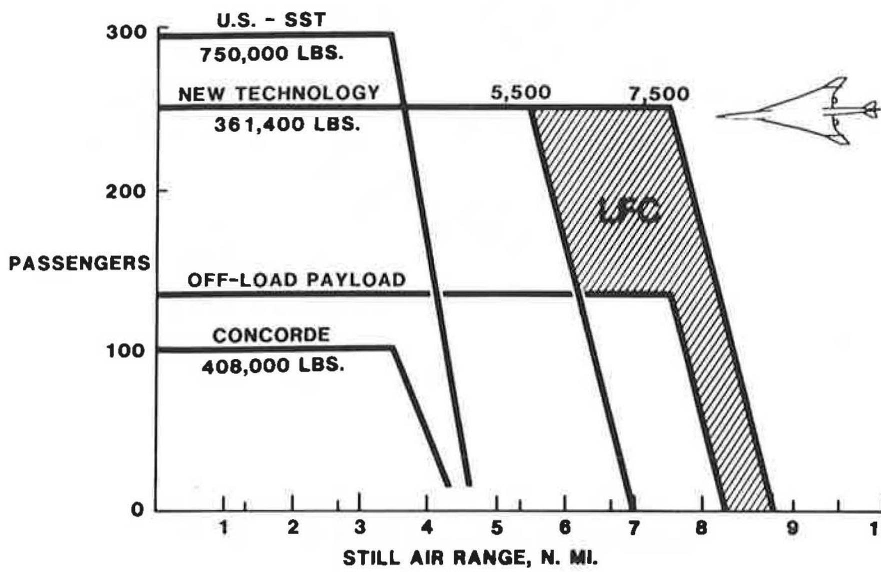

FIGURE 4. SST Capabilities

Enabling Technologies

It is appropriate at this time to examine the enabling technologies that, when carefully put together in a synergistic manner, can provide for such an AST. They include significant improvements in propulsion, structures, aerodynamics, and systems.

Propulsion. Propulsion systems, whether for subsonic or supersonic aircraft, are always counted on to provide great gains. Two areas of supersonic propulsion are different than in the subsonic applications. Propulsion efficiency, unlike aerodaynamic efficiency, tends to increase with increasing Mach number, and because of the lower payload fraction of supersonic aircraft compared to subsonic aircraft, supersonic aircraft are more sensitive to propulsion system weight.

Concepts of variable-cycle engines arose from the SCR Program of the 1970s[5] Considerable analysis and validation of these "variable flow" engines were conducted including full-scale demonstration testing. Since then, considerable progress has been made on cycle designs, materials, cooling, and hot-section technologies, all of which combine to permit higher turbine temperature, lower weights, and fewer parts. The technology incorporated in the compressors and turbines of the subsonic engines, which has driven the specific fuel consumption down by half in 15 years while reducing the total part count, can also be applied to the supersonic engines. In addition, the military interest in very

high thrust-to-weight ratio engines for use in highly maneuverable fighters has produced high-temperature technology transferable to the SST engine. These technologies are summarized below:

<u>Enabling Technologies</u>

<u>Propulsion</u>

o improved alloys o improved cooling/coating	CET - 500 ^{o}F	<u>Net Pay Off</u>
o higher stage loading o improved internal flow o better cycle optimization o digital controls	BETTER SFC	o T/W from 4 to 8 o lower SFC by 20% o reduced part count by 50%

It is interesting to compare the overall propulsion efficiency of supersonic power plants with subsonic power plants. (See Figure 5.) The Olympus engine in the Concorde is a very good engine for its time period and has a higher overall efficiency than the early high-bypass turbofans. It operates at an overall pressure ratio (OPR) of 15.5, a turbine inlet temperature (TIT) of 1,970^{o}F, and attains an overall efficiency (η_o) of 0.41. The GE-4 engine of the United States SST Program achieved an overall efficiency of 0.42. A reasonable goal for a future SST engine is an overall efficiency of 0.55 or greater.

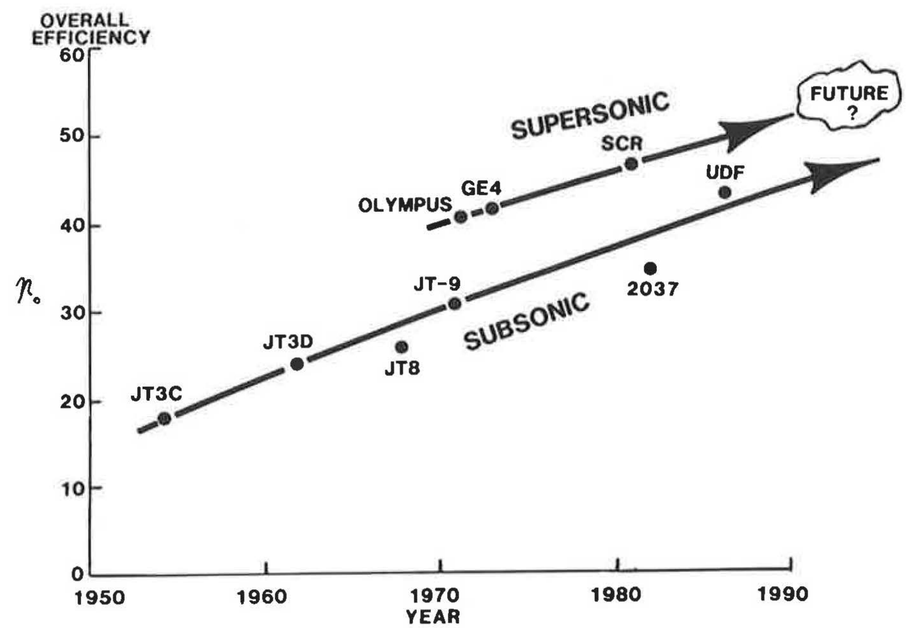

FIGURE 5. Projected Overall Efficiency of Commercial Engines

Obviously, engine thrust-to-weight ratio plays a significant role. The subsonic engines have historically traded much of this weight improvement for higher engine bypass ratio. Sustained supersonic operations, however, whether for military or commercial vehicles, require very low bypass ratio engines. The

significant improvements in engine thrust-weight ratio, therefore, which have gone from about 8.0 to about 12 for today's military systems (Figure 6), can now be reflected in reduced engine weight. A new engine, designed for a cruise Mach number of 2.62, would have an overall pressure ratio of about 20, and a turbine inlet temperature of at least 2,850°F, a bare engine thrust-weight (T/W) ratio of 8.0, and half the part count of the Concorde's Olympus engine.

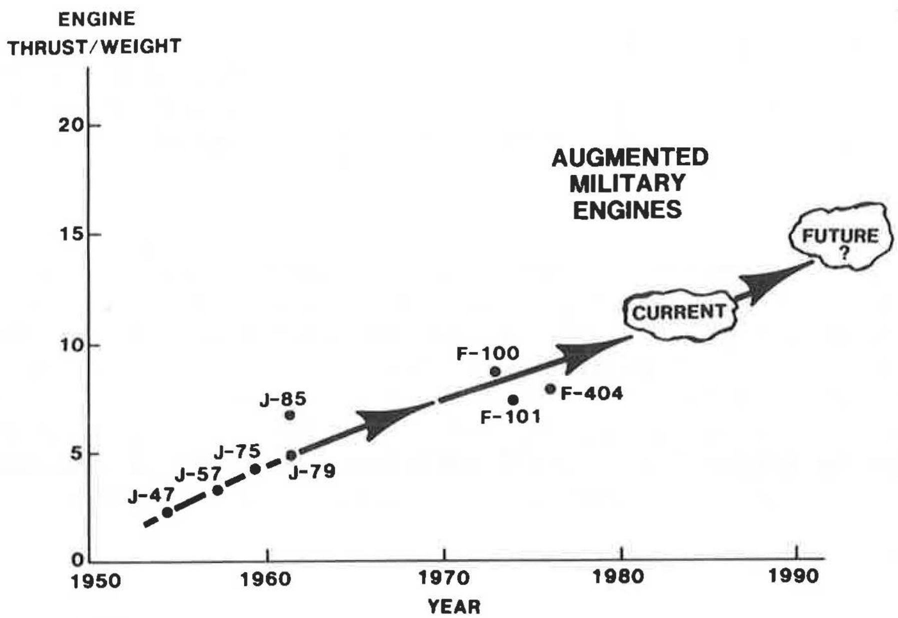

FIGURE 6. Improvement in Engine Thrust/Weight

When combined, these propulsion advances alone would reduce the airplane gross takeoff weight by more than 100,000 pounds. This potential may be summarized as follows:

SST Propulsion Potential

NOW		FUTURE
7465 lb	Weight	~ 4500 lb
15.5	OPR	20+
1970°F	TIT	2800 - 3000°F
14	No. Compressor Stages	6
0.41	η_o	0.5 - 0.55
1.19	SFC	~.95
	Part Count	~ 1/2 of Concorde's Olympus Engine

Structures and Materials. Significant progress has been made since the mid-60s in structures and materials relative to design methods, metallic and nonmetallic materials, and processing. This may be summarized as follows:

Enabling Technologies

Structures & Materials	Net Payoff
o Metal Matrix SPF/DB	o Sandwich Fuselage - 50% wt.
o High Temperature Composites	o Sandwich Wing-Nacelle - 30% wt.
o Reduced Temperature via LFC	
o Design Methods	

For example, increased computer modeling capability and better understanding of the airloads at off-design conditions have made important contributions to the understanding of the flexible shape of the airplane, both to the aerodynamic center shift impact on trim drag, and to the design for prevention and control of flutter of the wing. The analysis of major structural change in the airplane can now be accomplished in two days, whereas in the mid-60s it took as long as six weeks.

The particular material selected for the SST will, of course, be dependent upon the cruise Mach number selected for the aircraft. At the present time, candidate materials include new aluminum alloys, titanium, thermoplastics, and different types of composites in nonmetallic and metallic matrices, the latter being very attractive from a sandwich material aspect.

The retention of high specific strength of these materials at very high temperatures is also a requirement in terms of their applicability to the supersonic flight regime. Since there are very large increases in strength-to-density ratio of many of these new materials as compared to conventional titanium, it is not difficult to imagine the potential for savings in terms of innovative structures that could result from such processes as superplastic forming of titanium and sandwich construction using metallic matrices as shown in Figure 7.

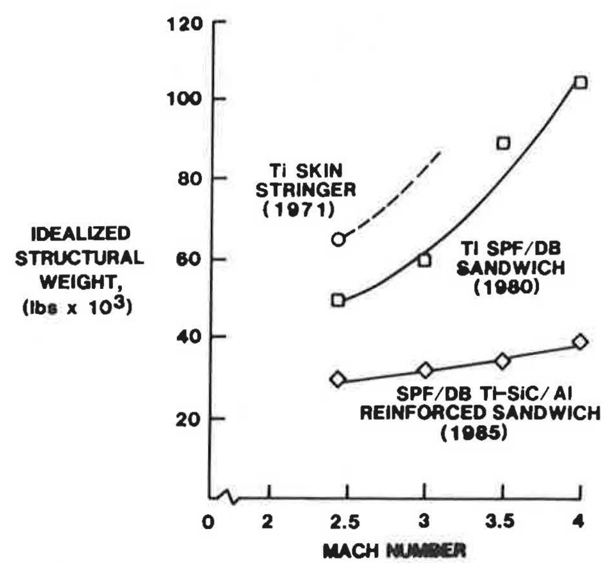

FIGURE 7. SST - Structural Weight Progress

Superplastic forming and diffusion bonding (SPF/DB) is one of the most significant advances to occur in metal processing in recent years, particularly for high Mach number, high-temperature application.[6] A technique pursued by the Douglas Division of McDonnell Douglas[7] in the SCR Program (Figure 8) is a process in which four flat titanium sheets are placed in a mold and heated to plastic metal temperatures, blown into shape, and diffusion-bonded together. The resulting bonds exhibit parent metal strength. The process provides the capability to form and fabricate structural configurations not previously possible using titanium. The substitution of a metal-matrix face sheet further improves the designer's ability to realize large weight savings. Reduction in part count and fasteners have contributed to the weight and cost reduction. Sandwich cover panels for the wing made in this manner, combined with similar methods for the wing internal structure, have reduce the wing structural weight by about 30 percent, and a change in the fuselage structure from skin-stringer titanium to a SPF/DB sandwich construction reduced the fuselage weight nearly 50 percent, as shown in Figure 9. Tests have shown that these large diffusion-bonded panels have excellent fatigue resistance, and design guides are being developed for their use.[8] Studies have shown a reduction of total airplane structural cost approaching 50 percent.

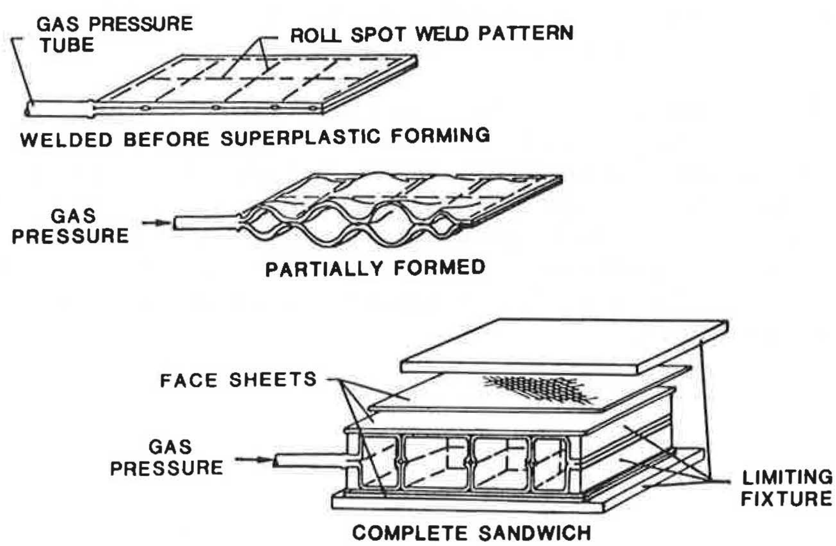

FIGURE 8. SPF/DB Bonding Process

Aerodynamics. Advancements in the field of aerodynamics suggest some exciting possibilities that could bring tremendous advantages to an AST. Nonlinear aerodynamic design methods, highly effective vortex flaps, digital flight electronics, and the possibility of supersonic laminar flow, project a 40 percent to 60-percent improvement in lift-drag ratio (L/D), better takeoff and landing performance, and lower gross weight by as much as 100,000 pounds.

The increases in the supersonic aerodynamic cruise efficiency (L/D) since the Concorde have been significant. The computer has made it possible to optimize the wave drag and drag due to lift of these configurations, and the gains have been proven gradually through complete configuration wind-tunnel tests.[7]

Fuselage shaping, wing body blending, planform optimization for minimum drag due to lift, and favorable interference of the propulsion package and vertical tails have all contributed to the increased level L/D from slightly more than 7 to near 11 at a Mach number of 2.2. Values near 10 have been obtained at Mach 2.7. (See Figure 10.)

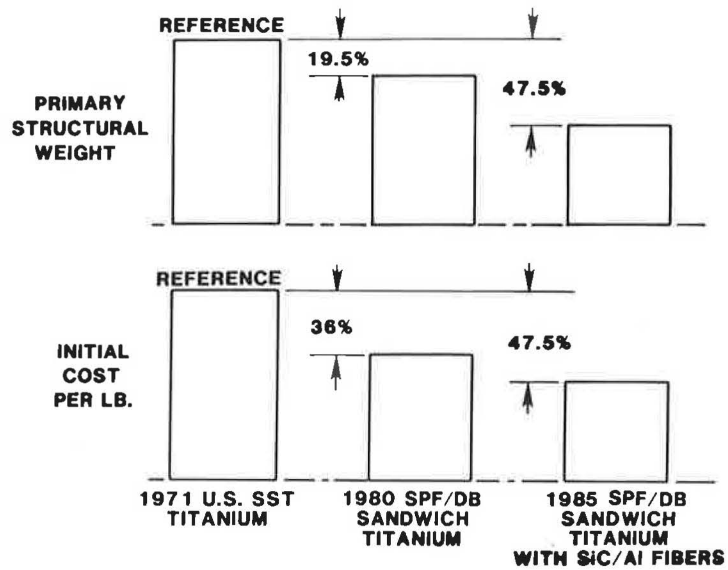

FIGURE 9 Weight and Cost Benefits of Advanced Structures T SPF/DB

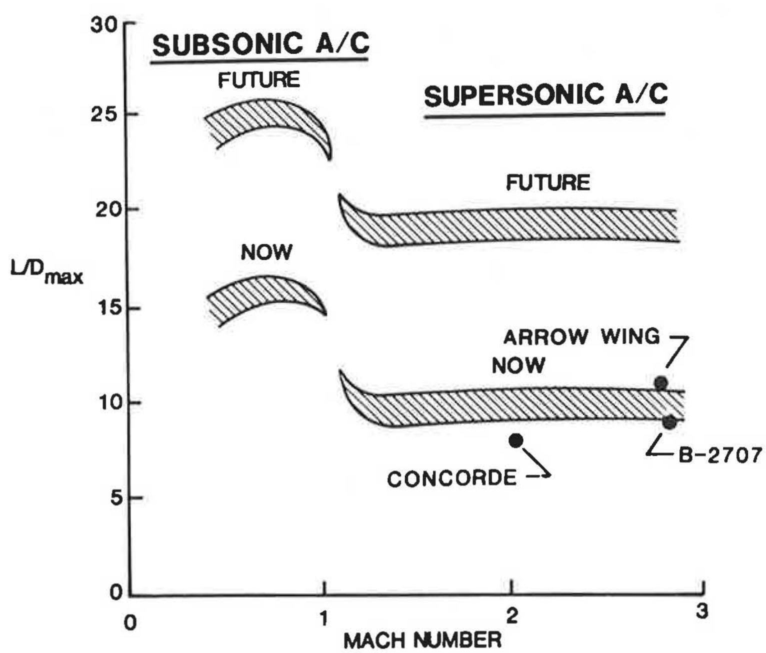

FIGURE 10. Aerodynamic Efficiency Potential

Of course, even with these significant gains, supersonic lift-drags ratios are no match for those available to subsonic airplanes However, in the same fashion that laminar flow control can contribute substantially to improving the L/D of the subsonic aircraft, it can have an equally profound influence on supersonic cruise efficiency. Application of supersonic LFC, at say Mach 2.7, could increase L/D from 10 to nearly 17. This improvement alone would reduce the gross weight by about 20 percent and double the seat-miles per gallon. In addition, the reduced surface temperatures (about 160°F) associated with LFC will reduce the weight penalty for high-temperature structures. Programs to understand supersonic laminar flow on highly-swept arrow wings have been initiated.

One of the problems in accepting these higher swept supersonic wing planforms had been the low level of aerodynamic performance and pitch-up at take off and landing conditions. Significant progress has been made in solving these low-speed problems through a combination of wind-tunnel and theoretical approaches.[9,10] The results indicate that the highly swept arrow wing, with superior high-speed performance, is now slightly better than the delta-wing configurations during takeoff and landing (Figure 11). The same devices that provide improved L/D also keep the pitching moments linear, thus controlling the pitch-up.

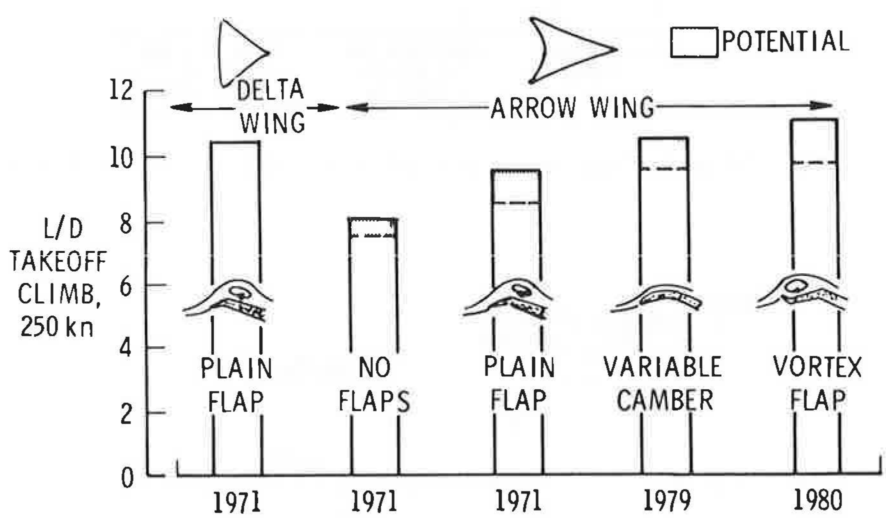

FIGURE 11. Arrow Wing Low-Speed Aerodynamic Progress

Systems. Significant gains will result from the progress being made in the systems area, particularly those areas which are usually not identified, by some researchers at least, as having a very high payoff. These include the following:

Enabling Technologies
Systems

Lightweight seats & interiors	30%
Carbon brakes	40%
Radial Tires	30%
Electronics	50%
Electronic Flight Controls	40%

However, new seat designs that are 50 percent lighter than earlier designs can add up to a lot of weight savings for a 250-passenger airplane. Use of carbon brakes, which are lighter and longer-lasting than present brakes, along with radial tires that are tougher, more effective, and longer lasting than the current bias-ply tires, can add the benefits of 40 percent and 30 percent weight savings, respectively, in those subsystems It is estimated that new design galleys will be 30 percent lighter than current ones and new laboratories will also be 10 percent higher These items are either well in hand or already in use to some extent. Aircraft actuation systems with 8,000 psi hydraulics or electromagnetic actuators can be another 10 to 20 percent lighter than previous systems.

Electronics and avionics are considered to be the discipline integrators that will permit us to fully realize the anticipated benefits of advances in aerodynamics, structures, and propulsion. Future ASTs would have an all fly-by-wire capability, an all-electric secondary power system, and a flight management system which integrates, optimizes, and controls the airframe-propulsion functions including active controls for load alleviation and airplane relaxed static stability to reduce trim drag.

The impressive advances in electronics and avionics being realized on subsonic aircraft will find their way into supersonic transports When combined with the significant weight savings within the airplane secondary systems such as seats, galleys, lavatories, tires, brakes, etc., the payoff to the SST will be twice as effective as on subsonic airplanes airplanes, as shown in Figure 12. The important fact, which is often overlooked, results from the growth factor of an SST which is double that of a subsonic aircraft.

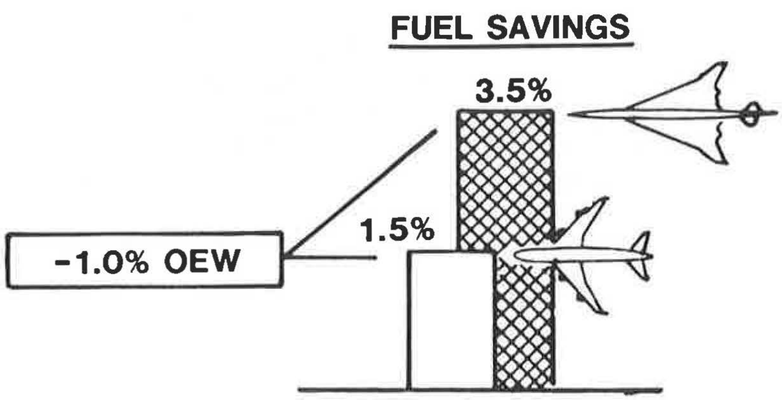

FIGURE 12. Weight Payoff - SST versus Subsonic

Environmental Concerns

There were major issues relating to environmental concerns over the U.S. SST Program; namely, engine emissions relative to urban pollution in the vicinity of airports and pollution of the stratosphere, airport-community noise, and sonic booms. Each of these demanded, and received, considerable attention and research.

Engine Emissions. The principal urban pollutants were carbon monoxide and unburned hydrocarbons during idle, and toxic oxides of nitrogen and smoke during takeoff and climb. Attention has been given in the advanced burner area to these emissions[11], and important gains have been accomplished. The oxides of nitrogen during high-altitude cruise flight relative to the upper atmosphere pollution area has been addressed by the Climatic Impact Assessment Program (CIAP) and the High Altitude Pollution Program (HAPP). The results as of January 1984,[12] indicate that the NO_X impact on the ozone is not a problem as it was stated to be in the early 1970s (Figure 13), and the impact of the supersonic transport on the ozone layer is very small and probably can be considered insignificant.

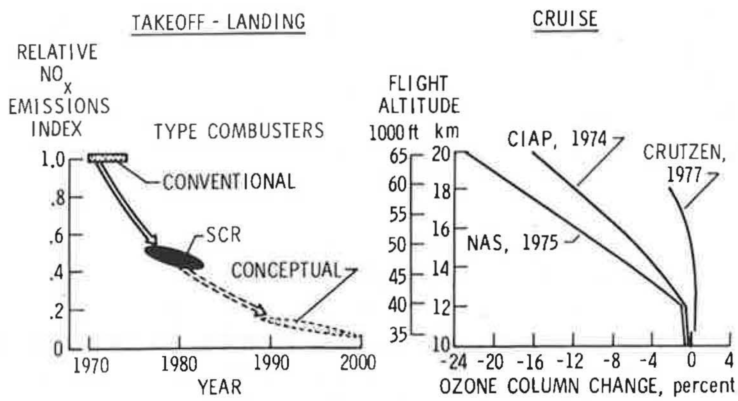

FIGURE 13. Emissions Progress

Airport-Community Noise. Marked progress has been made in reducing airport-community noise through reduction of the noise at the source combined with advanced operating procedures.[13] Government and industry have exerted considerable research and technology efforts[5] toward developing an understanding of jet noise generation, concepts for its reduction, and practical means for suppressor implementation. (See Figure 14.) Coannular nozzles, mechanical suppressors, and thermal acoustic shields have been explored as part of noise reduction research. Use of the unique inlets associated with SSTs has the potential for very large reductions in forward-radiated noise through inlet choking. Wind tunnel tests have shown that this can be done at minimal penalties.[14] In addition, advanced operating procedures that have the potential to reduce airport-community noise have been developed and evaluated.[15,16] The results of these noise programs, when traded in terms of performance and cost and combined with the previously discussed enabling technologies that will permit a lighter-weight better-performing vehicle, will allow the designer to attain the desired noise goals at much less cost. In fact, noise exposure levels for supersonic cruise vehicles can be comparable to those of its equivalent weight subsonic counterpart.

Sonic Boom. The third in the trio of environmental concerns is the sonic boom. Although progress on emissions and noise is evident, the same cannot be said for the sonic boom. As a result, overland supersonic operations are still out of the reach to the commercial SST.

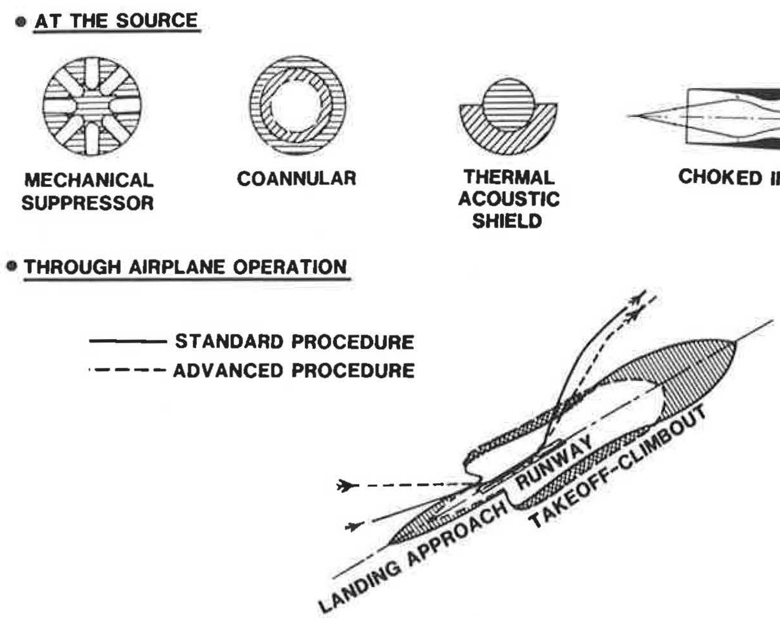

FIGURE 14. Advances in Reducing Airport-Community Noise

A great deal of knowledge exists regarding the generation, propagation, and prediction of sonic booms, particularly for the "primary" carpet booms. In comparison, very little information exists relative to the "secondary" or "over-the-top" booms.[17] Good correlation exists between measured and predicted values of sonic boom for such cases as aircraft and Shuttle Orbiter during reentry (Figure 15.) The sonic boom levels, in general, increased with increasing aircraft size and decreased with increasing altitude.

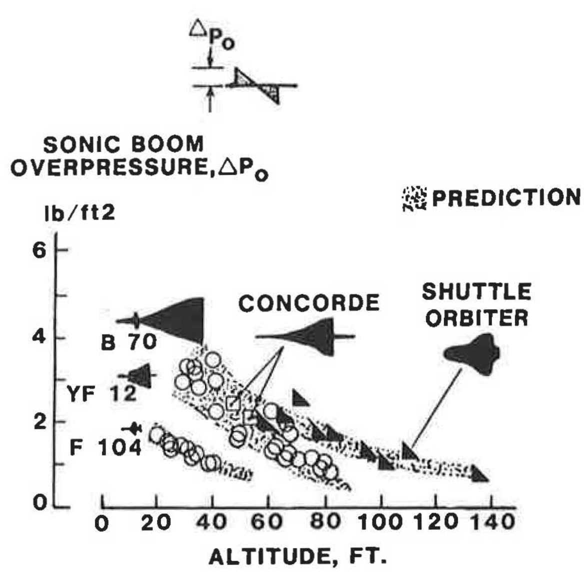

FIGURE 15. Measured and Predicted "Primary" Sonic Booms
- On Track Measurements

The measured sonic boom signatures associated with some of these vehicles such as those from Concorde and SR-71 during cruise flights and the Shuttle Orbiter during reentry, exhibit an N-wave shape (Figure 16). In-house NASA studies have indicated that even with the application of laminar flow to reduce the gross weight to 302,600 pounds, a similar N-wave signature will result even when the fuel is off-loaded (OL) for a 2,500 nautical-mile range, as shown in Figure 17. These studies also show that very low-boom design (DES) of a domestic version of this AST can result from the application of the aforementioned enabling technologies in propulsion, materials, and aerodynamics. This aircraft is shaped to produce a "flat top" signature and the boom level is reduced to less than 1 psf (about half expected from the U.S. SST). Previous studies [18] have suggested that each of these changes is in the direction of increased community acceptability. However, little, if any, information exists on reaction to booms of 1 psf or less. Further research is urgently needed on the community acceptance of sonic boom levels of less than 1 psf.

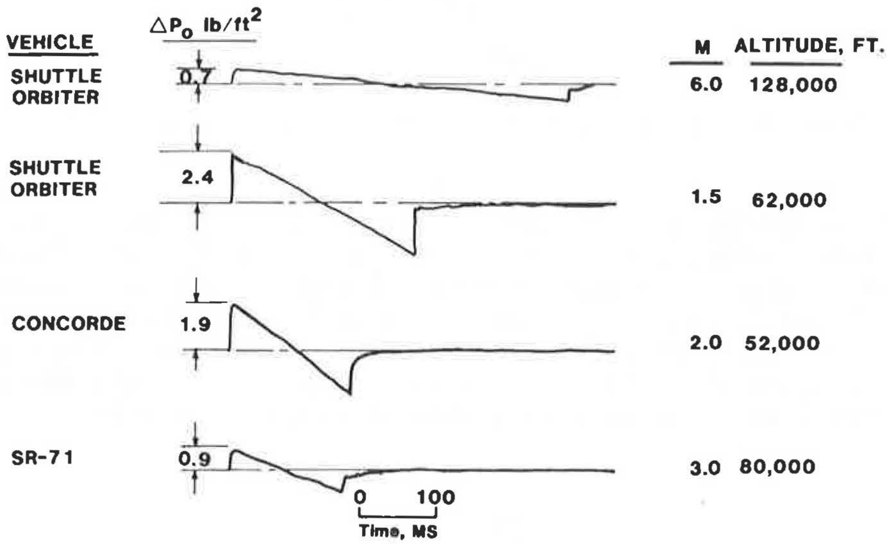

Figure 16. Boom Signature Characteristics

Further improvements in boom overpressure may result from the application of supersonic laminar flow, since it exerts a very powerful influence on reducing airplane gross weight and increasing altitude -- each of which result in lower boom levels.

Market Potential. Some current market analyses project that the number of aircraft in operation will triple by the end of the century resulting in the need for over 4,000 new aircraft in the next 15 years. Most of the demand will probably continue to be in the domestic size and range classes, but a substantial amount will be in the larger over-ocean category. The projected increases in population, commerce, and tourism are expected to result in significant increases in long-distance transoceanic travel between various points in the developed and developing countries. (See Figure 18.) It appears, therefore, that if a greatly improved AST can be developed, a greatly enlarged traveling public will utilize it. The technology benefits that can be applied

to an AST are so potent as to provide the performance improvement margin necessary to end the subsonic jet dominance of the long-haul over-water passenger market. Advanced SSTs could displace subsonic jets on these routes just as the subsonic jets displaced the propeller airplanes.

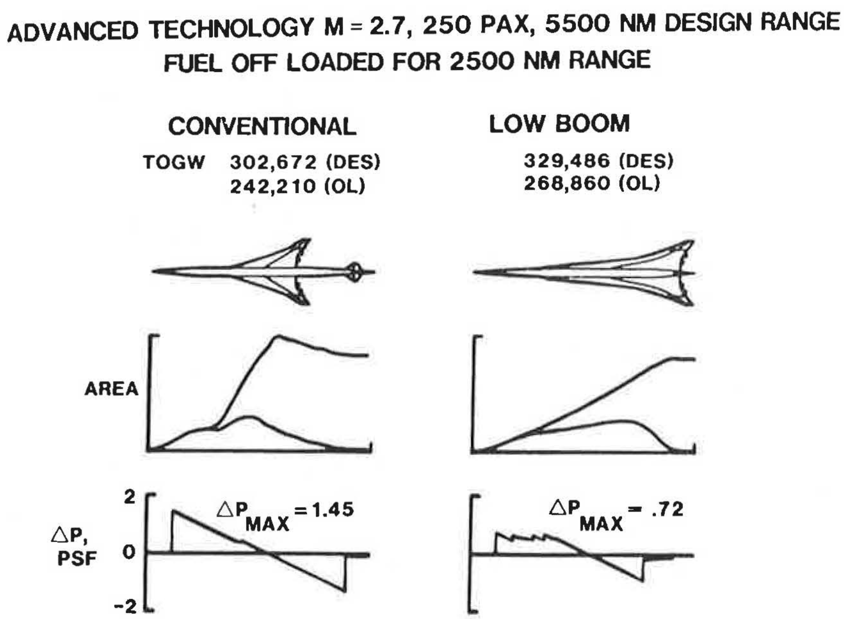

FIGURE 17. Low Boom Study - JP Fuel

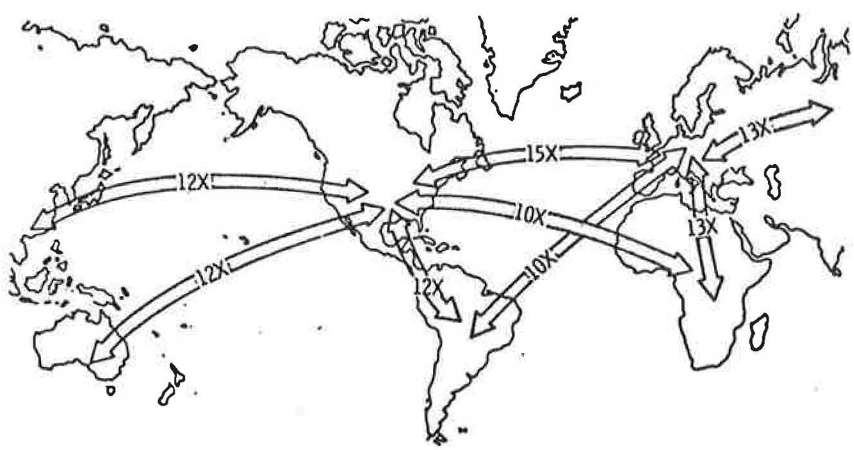

FIGURE 18. Increased Worldwide Travel - Year 2030

Summary

As mentioned in the introduction, there are a number of ingredients critical to the emergence of an AST; readiness of the key technologies is one. The overwhelming influence that the previously discussed enabling technologies have upon the AST and the growing need for highly productive transportation between far-distant population centers is so apparent that serious consideration must

now be given to the maturing of these technologies in propulsion, structures and materials, aerodynamics, and systems. In particular, work is needed in engine noise suppression trades, titanium metal matrix structure, low-speed vortex flaps, and high-speed laminar flow for highly swept arrow wings and on sonic boom tolerance levels and sonic boom shaping.

Once these technologies are matured, the other ingredients in the AST recipe, including development costs and method of financing, will balance out to provide the air transportation system with a new and viable high-speed capability.

References

1. Sherwood Hoffman and Mary C. Varholic. Contracts, Grants, and Funding Summary of Supersonic Cruise Research and Variable-Cycle Engine Technology Programs, 1972-1982. TM 85650, NASA, 1983.

2. Sherwood Hoffman. Bibliography of Supersonic Cruise Aircraft Research (SCAR) Program from 1972 to Mid-1977. RP 1003, NASA, 1977.

3. Sherwood Hoffman. Bibliography of Supersonic Cruise Research (SCR) Program from 1977 to Mid-1980. RP 1063, NASA, 1980.

4. Sherwood, Hoffman. Bibliography of Supersonic Cruise Research (SCR) Program from 1980 to 1983. RP 1117, NASA, 1984.

5. L. H. Fishbach, L. E. Stitt, J. R. Stone, and J. B. Whitlow. NASA Research in Supersonic Propulsion -- A Decade of Progress. TM 82862, NASA, 1982.

6. E. D. Weisart and G.E. Stacher. Concurrent Superplastic Forming/Diffusion Bonding Titanium. Presented at the Superplastic forming of Structural Alloys Conference, San Diego, June 21-13, 1982. Published by the Metallurgical Society of AIME.

7. W. T. Rowe. Technology Status for an Advanced Supersonic Transport. SAE No.820955.

8. J.E. Fischler. Design Advantages for Three Types of Joining Techniques Used in Development of SF/DB Titanium Sandwich Reinforced with Metal Matrices. Presented at the Second Syumposium on Welding, Bonding, and Fastening Langley Research Center, Hampton, VA.

9. Paul L. Coe, Jr., Jarrett K. Huffman, and James W. Finbert. Leading Edge Optimization of a Highly Swept Arrow Wing Configuration. TP-1777, NASA, 1980.

10. Samuel J. Scott, Oran W. Nicks, and P. K. Imbrie. Effects of Leading Edge Devices on the Low-Speed Aerodynamic Characteristics of a Highly-Swept Arrow Wing. CR 172531, NASA, 1985.

11. R. P. Lohmann and R. J. Hershberger. Further Evaluation of a Low Emissions High Performance Duct Burner for Variable-Cycle Engines (VCE). CR-165199, NASA, 1980.

12. N. Sundararaman. The High Altitude Pollution Program (1976-1982). FAA-EE-84-10, Federal Aviation Administration, 1984.

13. Cornelius Driver and Domenic J. Maglieri. Some Unique Characteristics of Supersonic Cruise Vehicles and Their Effect on Airport Community Noise, AIAA-80-0859, 1980.

14. Charles J. Trefny and Joseph F. Wasserbauer. Low-Speed Peformance of an Axisymmetric Mixed Compression Supersonic Inlet with Auxiliary Inlets. TP 2557, NASA, 1986.

15. John B. Feather and Dinesh S. Joshi. Motion Base Simulator Results of Advanced Supersonic Transport Handling Qualities with Active Controls. AIAA 81-1819-CP, Douglas Paper 7055, 1981.

16. John K. Molloy, William D. Grathan, and Milton J. Newbauer, Jr.. Noise and Economic Characteristics of an Advanced Blended Supersonic Transport Concept. TP 2073, NASA, 1982.

17. Domenic J. Maglieri, Harry W. Carlson, and Harvey H.Hubbard. Status of Knowledge of Sonic Booms. Noise Control Engineering, vol., 15, no. 2, September-October 1980, pp. 57-62.

18. H.E. von Gierke and C. W. Nixon. Human Response to Sonic Boom in the Laboratory and the Community. Proceedings of the Second Sonic Boom Symposium, AIP 1972, Reprinted from J. Acoustic Soc., America, 51, 1972, pp. 777-782.

NASA RESEARCH TOWARDS VERY HIGH SPEED TRANSPORTS

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Introduction

About two years ago the White House Office of Science and Technology Policy published the U.S. "National Aeronautical R&D Goals", which recognized the major advances in aircraft performance that remain to be achieved and defined specific high-payoff technology areas in which to focus U.S. research and technology efforts. In NASA we have incorporated the National Goals into our long-range planning and strategy and will do our part in pursuing the enabling technologies for achieving the National Goals, especially the long-term and high-risk research and technology. The potential aeronautical improvements that can be achieved with advanced technology are impressive for all classes of aircraft. However, one of the most exciting areas involves the development of technology for hypersonic cruise and transatmospheric vehicles.

In his State of the Union address to the Congress a year ago the President referred to research under way in the joint NASA/DOD National Aero-Space Plane (NASP) Program that will provide the technology for a revolutionary leap in U.S. capability that could reshape military and civil aviation near the turn of the century. This entirely new class of aerospace vehicle, powered by airbreathing propulsion, would have vastly superior performance to anything flying today. Conceptually these vehicles would takeoff from an airport runway, fly at six or more times the speed of sound at altitudes of 20 miles or more. Two hours or less after departure, it would roll to stop at an airport on another continent half way around the earth, or instead, fly from the runway directly to orbit, work in space, and then return for a conventional airport landing. The extreme altitude and speed capability of this vehicle could make our military aircraft far less vulnerable to attack, and initial indications are that such transatmospheric vehicles could significantly reduce the cost of delivering payloads to orbit.

The renewed interest in an aerospace plane is a direct result of advances and breakthroughs made during the past two decades in NASA's and DOD's ongoing aeronautics and space research and technology (R&T) base programs.

Goals and Objectives of Transatmospheric R&T

The transatmospheric goal blurs the traditional line of demarcation between aeronautics and space. It represents the first real convergence of aeronautics and space technology.

Rapid point-to-point intercontinental travel and routine low-cost access to space are two key goals critical to maintaining U.S. economic and defensive preeminence. Technology advances over the last decade now provide an opportunity to address both of these goals in a new class of vehicle with the potential to revolutionize both air and space travel. The transatmospheric R&T program, a part of the NASA/DOD National Aero-Space Plane program, will greatly accelerate development of the technology required to provide aerospace vehicles as an option by the turn of the century.

The objective of the National Aero-Space Plane program is to demonstrate aerospace vehicle technologies for horizontal takeoff from and landing on a airport runways, sustained hypersonic cruise and maneuver in the atmosphere, and acceleration to orbit and return. These technologies will be integrated into an experimental research airplane, the X-30, which should begin validation in actual flight by the early 1990s. These technologies could then be optimized for specific military or civil hypersonic cruise applications or single-stage-to-orbit applications, or perhaps some combination of the two. The technical challenges are certainly formidable, and the list of key technologies is long, but at this time we see nothing insurmountable.

Underlying Technology

Although most ongoing hypersonic research and technology was terminated in the early 1970s, NASA sustained its effort in the most critical and enabling technologies for hypersonic vehicles. The current opportunity for NASP is the result of breakthroughs and advances in the NASA hypersonic research program over the past decade that provide the basis for developing the enabling technologies and the confidence that the goal is feasible.

During the past decade, technology has been pursued for hydrogen-fueled supersonic combustion ramjet (SCRAMJET) engines. Langley Research Center has conducted more than 1100 tests of fixed-geometry sub-scale SCRAMJET engine modules at simulated flight conditions in the ground test facility to Mach 7. The measured performance levels achieved are sufficient to propel a large aircraft at hypersonic speeds. This effort has produced the initial technology base on the internal design, combustion processes, and fuel-mixing techniques needed to design an efficient SCRAMJET engine. A variable geometry SCRAMJET model utilizing a square two-dimensional inlet is part of the effort to develop a practical design that can operate over a wide Mach number Range (4-20+). The square inlet permits easy integration with the vehicle while the circular combustor reduces structural complexity at high pressures.

Substantial advances have been made in the strength, stiffness, durability, and reusability of a number of high temperature materials. Advanced carbon-carbon materials development, begun in the late 1970s, now has achieved two to three times the strength and stiffness of currently used reinforced carbon-carbon plus a reusable coating that provides a tenfold to twentyfold improvement in oxidation resistance. Oxide-stabilized superalloys, with Angstrom-thin ceramic coatings, are performing successfully under arcjet testing to 2200°F, making them candidates for hypersonic airframe and engine primary structures. In addition, continuing research in metal matrix and organic composites, such as graphite-aluminum and graphite-polyimide, hold the promise of high-strength, lightweight applications. Research will be conducted on the technology for active cooling in areas of high thermal loads, such as occur on the leading edges and other surfaces of a hypersonic vehicle, using cryogenic hydrogen fuel as the coolant.

Current fabrication technologies, such as superplastic forming, diffusion bonding and brazing of thermal structural systems, now make possible more geometrically efficient, lighter-weight structures. In addition, fabrication procedures developed during the last decade for foil-gage structures, such as honeycomb and multiwall structures, now provide the capability to fabricate the

lightweight efficient insulating thermostructural systems concepts needed for hypersonic vehicles. Structural design and fabrication has been completed of a fuel-injection side strut for a SCRAMJET using a complex three-step brazing process. This concept will be tested with burning fuel in 1987.

A major change has occurred over the last decade in computational capability as a result of advances in computer memory and speed and the current development of codes.

Today, the use of Navier-Stokes and Euler methods for analyzing very complicated internal and external flowfields, including boundary layers, for complex configurations is an integral part of the design process. Colors indicate surface pressure contours computed on the Ames Research Center Numerical Aerodynamic Simulation (NAS) in August 1986. The capability in three-dimensional Navier-Stokes computations is now sufficiently advanced to address internal flow fields of propulsion systems, such as ramjets and SCRAMJETS.

The Ames Research Center NAS supercomputer capabilities are now available to support the analysis and design activities for the NASP program. The NAS, with its 264 million words of memory and sustained operational speed of 250 million floating-point operations per second, plus our other large computers will provide the power required to handle the challenge of integrating the complex internal and external flow interactions of configuration aerodynamics and airbreathing propulsion systems.

NASP Program

The NASP program is a three-phase program consisting of a Phase I Feasibility Study conducted by DARPA with NASA; Phase II Technology Development under a joint effort with the DOD and the U.S. industry; and a proposed Phase III Flight Research Demonstration in cooperation with DOD. Phase II provides for the development of critical technologies as a precursor to a future decision on Phase III. Phase II includes major contracts with industry amounting to approximately $600 million for five for airframe manufacturers and two engine companies. If Phase II is successful, a Phase III flight research program would go forward to demonstrate, by the mid 1990s, transatmospheric vehicle technologies on a research vehicle over the entire flight regime from takeoff to orbital speed. This demonstration will validate the necessary technology base for very-high-speed U.S. aerospace vehicles with initial operational capability in the 2000 to 2010 time period.

The NASP program will concentrate on the critical technologies in the Phase II program through a combination of computational efforts and ground-based experiments. The challenging conditions projected for the X-vehicle flight research envelope require the application of the most advanced analysis and prediction techniques available to determine the aerodynamic and aerothermodynamic characteristics of the many potential airframe and engine configurations. These predictions will be validated in ground-based facilities. In addition, we have studies under way on the need for selected flight experiments which could be conducted as needed, on a small, specially instrumented research vehicle to validate the predictions for high speed and altitude conditions that cannot be adequately simulated in ground facilities.

Major emphasis is being placed on the design and experimental determination of the performance level and efficiency of several airbreathing propulsion system cycles, including low-speed cycles, ramjets, and SCRAMJETS operation from takeoff to near-orbital speeds; integration of a small rocket will also be required for on-orbit and deorbit operations. Both passively and actively cooled high-temperature engine and airframe structures, combined with cryogenic tankage structures, as appropriate, are being designed for repeated exposure to combinations of extreme peak heating during ascent and long-duration heat loads during cruise. These component designs will be fabricated, and their performance as reusable, lightweight/high-strength structures will be tested under simulated flight loading conditions. Analyses of propulsion system/airframe integration characteristics, including the major controls challenge, will be conducted continually throughout the program in order to define a high-performance, minimum-weight configuration.

In addition, we are currently modifying two of our major facilities: the 8-foot High Temperature Tunnel at Langley Research Center for testing of large structural components in high-quality aerothermal flow and for propulsion testing of large-scale and multiple-module SCRAMJET models; and the Propulsion System Laboratory at Lewis Research Center for subsonic to supersonic engine system tests. We have also reactivated the 3.5-foot Hypersonic Tunnel at Ames Research Center for aerodynamic testing of inlet configurations at high Mach numbers.

The progressive and continual output of these efforts will be integrated into the design, development, and testing of preliminary concepts for propulsion system modules and airframe components for the X-vehicle.

Extending research from experiments in the laboratory to flight has long been recognized as a necessity for the development and validation of hypersonic-transatmospheric technology, since ground test facilities alone are inadequate in simulating that regime. Notable examples began with the development and flight test of the X-15 in the 1950s, the Lifting Body program in the 1960s, and most recently the Space Shuttle. This is particularly true for an aerospace plane, where integration of the highly interdependent airframe and the propulsion system plus vehicle performance validation throughout this broad flight envelope require experimental flight investigation and validation with the NASP X-vehicle. A major technology readiness assessment will be conducted in FY 1989 to determine if sufficient progress has been made in the NASP Phase II program to approve proceeding to the design and fabrication of the X-vehicle. If Phase III can begin at that time, initiation of an extensive flight research program could be possible as early as FY 1992.

High Speed, Civil Air Transport Study

Separate from the National Aero-Space Plane program, NASA has awarded two contracts for high-speed, civil air transport studies, one to Boeing Commercial Airplane Company and one to McDonnell-Douglas Corporation.

The companies are to take into consideration the international growth and economic development into the next century that is expected to create a significant market for high-speed, long-range air transportation. Further, the need to conduct business in areas such as the Pacific basin will place emphasis

on minimizing trip time and increasing productivity. Either a hypersonic transport, based in large part on aerospace plane technology, or an advanced supersonic cruise airplane that incorporates emerging technologies could prove to be an attractive and economically competitive vehicle for this market.

The studies will evaluate expected technology advances from the National Aero-Space Plane program and from continued research in high-speed aircraft, in general, to satisfy two major objectives. The first objective is to identify the most promising concepts for future long-range, high-speed, civil transport aircraft. The second is to provide information needed to guide NASA planning of technology development.

The two contractors will conduct work in three phases. The first phase will consist of an initial assessment of potential vehicle concepts, of relevant nonvehicle technologies, and commercial value, i.e. economics, scheduling, and marketing. The second phase will produce a prioritized list of vehicle concepts. The final phase will focus on one or two of the more promising vehicle concepts per contract.

This work requires an understanding of the economics, flight speeds, size, range, fuel type, and technology levels required for the proposed vehicles to become successful major elements in the international air transportation system.

Conclusion

Synthesizing advanced technology into a transportation concept for the 21st century is a difficult, complex task that requires timely availability of vast amounts of data, engineering and management expertise, skilled personnel, and major investments in facilities. This is a high-technology area that requires long lead times and substantial, timely investments in R&D on the part of the aviation community and the government.

With the potential for major revolution in transportation based on these technologies, we are on the threshold of an opportunity to assure U.S. air and space leadership well into the 21st century. NASA's research is providing, and will continue to provide, a solid foundation from which the country can proceed effectively in directions it selects on the basis of national goals and priorities.

DEVELOPMENT OF FUELS FOR SUPERSONIC AND HYPERSONIC COMMERCIAL TRANSPORTS

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Introduction

Since the early 1970s, studies of alternative aircraft fuels have focused on a scenario that assumed continually decreasing availability and increasing costs of conventional jet fuels -- a scenario that only briefly materialized. Currently, conventional fuels are plentiful, and their prices have dropped nearly to the 1976 level, when commercial supersonic service began. The current price of jet fuel is almost the same when the first supersonic transport commercial began. (See Figure 1.)

Since we cannot assume these availability and price conditions will continue indefinitely, trade studies directed toward a possible shortage should be pursued. However, studies based on this scenario typically assume that conversion to a particular alternative fuel will satisfy the needs for all or a major portion of the commercial aircraft fleet. This assumption leads to fuel selection criteria being developed to satisfy the broad economic and technical requirements of the entire aviation industry. However, supersonic and hypersonic transports have unique fuel requirements; therefore, data from such studies may not provide a good base from which to select a fuel for these vehicles.

The most publicized special fuel requirement for high speed transports is the need for a fuel that has a high heat absorption capability or, at least, a high thermal stability. An often overlooked and as important variable in the choice of a special fuel for high speed transports is the size of the fleet. This is important because the cost of a unique fuel developed for a small number of aircraft could be significantly greater than the identical fuel developed for the entire commercial aircraft fleet. Supersonic and hypersonic aircraft fleets may not be large enough to command a low fuel price (Figure 2).

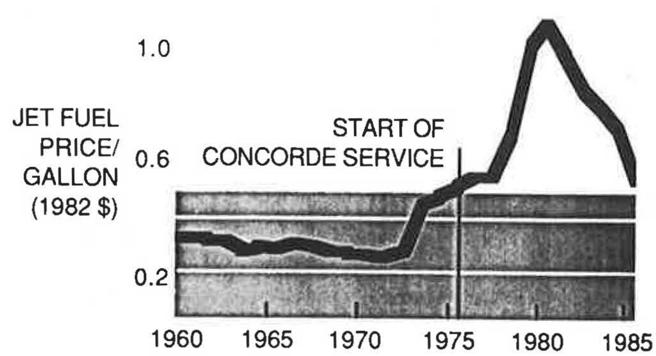

FIGURE 1. Jet Fuel Price per Gallon, 1960-1985

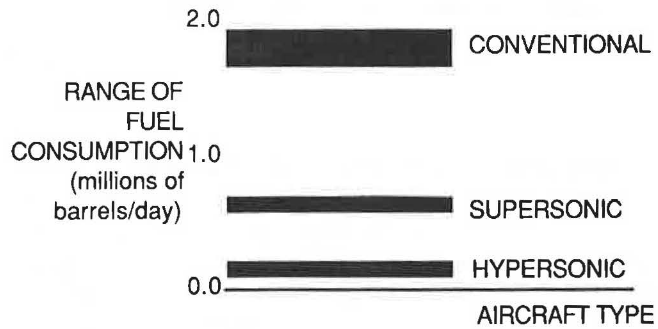

FIGURE 2. Range of Fuel Consumption by Aircraft Type

The disadvantages and cost penalties associated with the selection of a unique fuel for supersonic and hypersonic aircraft must be balanced against the cost and penalties associated with the use of new materials or techniques that allow the selection of more conventional fuel. Trade studies relating to supersonic aircraft will be strongly influenced by the cost and availability of high temperature materials and cooling requirements, while those relating to hypersonic vehicles may be equally influenced by the fuel properties required to satisfy engine requirements. In both cases, the cost associated with a requirement for a unique fuel must play an important part in concept selection as well as in the determination of commercial feasibility.

Fuels for high-speed aircraft fall under three categories:

- Conventional fuels that satisfy current aircraft and fuel specifications,

- Cryogenic fuels, such as liquid hydrogen and liquid methane (including liquefied natural gas), that must be stored in insulated containers,

- Endothermic fuels, such as methylcyclohexane to toluene-plus-hydrogen, that are selected for their heat absorption capabilities and involve a change in chemical composition.

Other fuels being considered for high-speed aircraft, such as metal-organic, are not covered in this paper because they currently do not appear to be promising candidates for commercial transports.

Fuel Properties

Heat sink requirements for supersonic and hypersonic aircraft airframe, engine, and mechanical systems have stimulated many efforts to develop a new or different fuel. Searches for a heat-absorbing fuel began more than three decades ago. Both early and recent studies concluded that cryogenic fuels, particularly liquid hydrogen, were the most promising for aircraft in terms of heat absorption capacity, heat content per unit mass, and properties considered desirable for the design of an efficient clean-burning engine. Unfortunately,

cryogens require insulated pressure vessel storage and have relatively poor energy content per unit volume. These characteristics force fuel tank placement and design compromises that are particularly detrimental to aircraft requiring a low-drag profile. Attempts to solve these problems resulted in development of concepts for cooling using the endothermic reaction that occurs when various hydrocarbons decompose.

In attempts to find an endothermic fuel that could satisfy aircraft requirements, a large number of compounds and reaction types have been analyzed. The more promising, in terms of amount of heat absorbed and ability to control the process, involve the use of a catalyst to stimulate the reaction. An example of this type of reaction is the conversion of methylcyclohexane to toluene and hydrogen. This fuel, like most endothermic fuels, would be pumped to a high pressure after it leaves the fuel tank, heated, decomposed, and then heated again. (See Figure 3.)

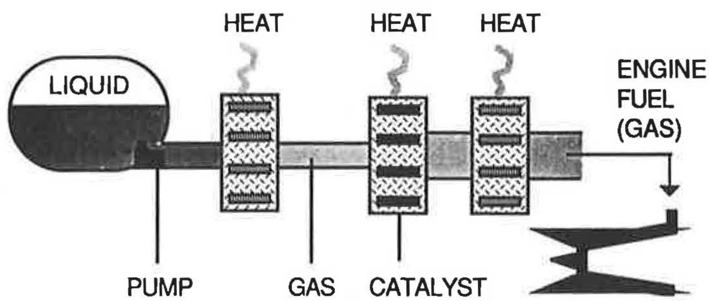

FIGURE 3. Endothermic Fuel System

Although endothermic fuels do not offer the cooling potential of liquid hydrogen, they offer an ability to absorb heat while maintaining many of the desirable properties of conventional jet fuels. (See Table 1.)

New, highly efficient, subsonic commercial jet engines are placing increasing heat load and high temperature demands on jet fuels. These demands are causing jet fuels delivered to current commercial aircraft specification limits to become marginal with respect to thermal stability and burning characteristics. New generation high-performance engines for supersonic aircraft will place even more stringent thermal loads and temperature demands on fuels.

Conventional fuels for future supersonic aircraft may require new limits for the components of jet fuels that cause high flame radiation or coking. Metal deactivator additives or more stringent composition control may be required to improve thermal stability. Synthesized conventional jet fuels that can satisfy thermal load and stability requirements for supersonic aircraft up to Mach 4 are already available in small quantities.

Most endothermic fuels considered for cooling the aircraft structure, engine, or both, require burning mixtures of aromatics and hydrogen or olefins and

Table 1. COMPARISON OF FUELS FOR HEAT ABSORPTION

FUEL	HEAT COMBUSTION		HEAT ABSORPTION	STORAGE TEMPERATURE
	Btu/lb	Btu/gallon	Btu/lb	°F
CONVENTIONAL	18,400 to 19,000	116,000 to 127,000	<400 **	AMBIENT
LIQUID HYDROGEN	51,500	29,675	5,900	-423
LIQUID METHANE	21,500	76,193	1,400 *	-259
ENDOTHERMIC	<20,000	116,000 to 127,000	500 to 1,800	AMBIENT

* To 1,200° F from 100° F ** To 650° F (decomposition limit)

methane. The higher the hydrogen content, the more desirable the fuel properties for aircraft using turbojet engines. (See Figure 4.) Jet fuels with a high aromatic content tend to burn with a high degree of radiation, while olefins tend to have a low thermal stability. The burning characteristics of these mixtures and their impact on engine design, efficiency, and mantainability require significant analysis and testing. As an example, consider a mixture of toluene which has very slow flame speed and long ignition time, and hydrogen, which has an extremely high flame speed and very short ignition time. When such a mixture is introduced into an engine, will the burning hydrogen suddenly create a high temperature that cokes the aromatic toluene? Questions such as this require answers before endothermic fuels can be considered suitable for aviation purposes.

Hydrogen is a clean burning, thermally stable fuel with no chance of coking or blocking passages due to decomposition, and the low radiation from its flame results in cooler engine parts. Methane is also a clean burning, thermally stable fuel. Because combustion product mass is an important performance property at hypersonic speeds, low molecular weight makes hydrogen a fuel of

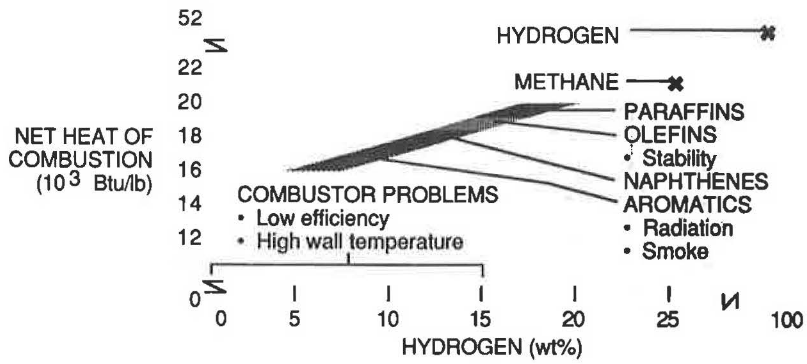

FIGURE 4. Importance of Hydrogen on Turbojet Engines

choice for this application -- particularly when excess fuel is used for cooling the engine. Hydrogen will give the lowest molecular weight products of combustion -- a significant advantage for high Mach numbers.

Fuel Production

One reason petroleum is highly desirable fuel source is that it is easy and inexpensive to process into useful products. Most alternative fuels will be more difficult to produce, primarily because of increased processing complexity. In general, the cost of processing alternative fuels will have a greater influence on their price that will the cost of raw materials.

Alternative fuels studies, when based on increasing cost and scarcity scenarios, assume that the conversion to a particular alternative fuel will satisfy the needs of all or a major portion of the commercial aircraft fleet. Processes that could only supply a small quantity of fuel or are limited to a local area are not considered an energy crisis solution. Supersonic and hypersonic aircraft are not likely to be major fuel users, and their operation will be limited to a relatively few locations in comparison to the overall air transport fleet. These demand and location requirements may make some of the alternative fuel processes rejected during energy crisis scenarios worthy of a second look.

Hydrogen. Although hydrogen is the most abundant element in the universe, it does not occur naturally in a form that can be used as a fuel. The least expensive method currently used for producing hydrogen is the steam reforming of natural gas and other petroleum products. The reforming process is simple, efficient, and adaptable to a wide range of quantity demand requirements.

The use of light hydrocarbons or natural gas as raw materials to produce hydrogen would not be reasonable solution to real worldwide shortage of petroleum-based jet fuels because new conversion processes have been developed that can efficiently and economically synthesize conventional jet fuels from these materials. These materials would also be in short supply or expensive in petroleum shortage situation. However, where the application of a fuel involves a relatively small demand, such as for supersonic and hypersonic aircraft, natural gas can be a logical choice for producing hydrogen.

The two production methods that have received the most recent attention for producing hydrogen for aircraft are the partial oxidation of coal and the electrolysis of water. Production facilities using either process can be built using existing technology.

Coal Oxidation. Coal is distributed worldwide -- nearly every nation has a secure access to commercially developed deposits. In many areas of the world, coal will be the most economical source for hydrogen. Like steam reforming, the partial oxidation process using coal to obtain hydrogen is relatively simple and efficient. The process is adaptable to a wide range of fuel demand requirements, but probably would not be practical for providing hydrogen to a few aircraft at a single airport. Incidently, a common misconception is that hydrogen is produced from coal. Actually, coal is used as a reducing agent to obtain hydrogen from water. Environmentally, processes involving coal are currently not considered "good neighbors" and in all cases require expensive pollution control equipment.

Electrolysis. The classic technique for extracting hydrogen from water is by electrolysis. This process uses an electric current to break water into its basic components of hydrogen and oxygen. The process is simple but requires an enormous amount of energy -- approximately 21 kilowatt hours per pound. Electrolysis is often touted as environmentally benign, but this is true only if the source of power is nonpolluting, such as hydroelectric or solar.

The suitability of electrolysis for producing hydrogen for supersonic or hypersonic aircraft will be strictly dependent upon the cost and availability of electricity. Hydrogen by electrolysis may be the best choice in areas of the world that have surplus electric power or a capability for the development of new hydroelectric power.

Liquefaction. Regardless of the process used to produce hydrogen, it must be liquefied before it can be used in an aircraft. The liquefaction process involves a series of compression, heat exchange, and expansion steps and in some processes a second refrigerant, such as liquid nitrogen. (See Figure 5.)

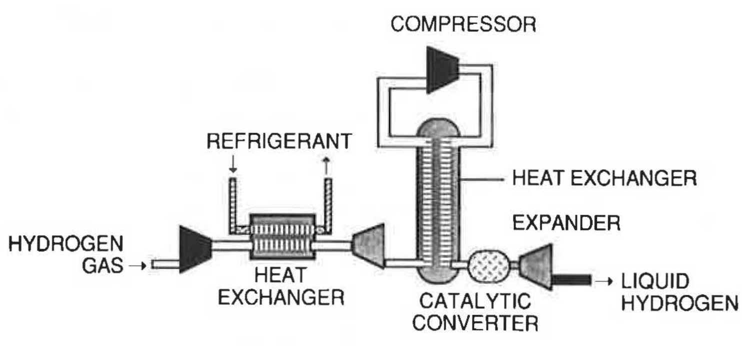

FIGURE 5. Liquefaction of Hydrogen

Liquefaction of hydrogen requires approximately 4.9 kilowatt hours per pound of hydrogen produced. The power required to liquefy hydrogen for a single supersonic aircraft flight per day would be 11 megawatts. If the hydrogen gas

were obtained by electrolysis of water, the total power required would be 55 megawatts. In addition, the liquefaction facility would require a constant power input to obtain a reasonable production efficiency. Airports that involve more than a few flights per day generally would require a dedicated power plant.

Methane. Any carbon-organic material (such as coal, refuse, animal waste, or vegetable matter) can yield methane through various chemical processes or by bacterial action. The least expensive method is through the purification and liquefaction of natural gas, but methane also can be obtained from the partial oxidation of coal in a process similar to that described for hydrogen.

Methane takes less energy to liquefy than hydrogen -- a factor of 2.4 less in terms of equivalent energy (Figure 6). The power required to liquefy methane for a single supersonic aircraft flight per day would be 4.5 megawatts as compared to 11 megawatts for hydrogen. The source of this power could be electric or natural gas. The lower energy required to liquefy methane, as compared to hydrogen, increases the possibilities for using purchased power and sources of power that could not satisfy airport hydrogen demand. For example, Canada has some surplus nuclear and hydroelectric power.

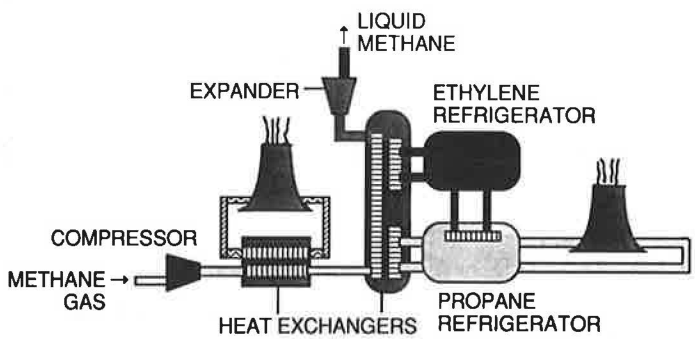

FIGURE 6. Liquefaction of Methane

Endothermic Fuels. Endothermic fuel processes range from those that have been developed only for small batch quantities to those that are commercially practiced in the chemical process industry. An example is the exothermic process required to manufacture methylcyclohexane which is the reverse of the endothermic process considered for use in cooling aircraft.

New processes must be developed before many of the endothermic fuel candidates could be considered practical for commercial aircraft applications. Some techniques for producing commercial quantities of endothermic fuels would include:

- Selected cuts from equipment at existing petroleum refineries,
- The addition of equipment to a petroleum refinery or petrochemical plant, and
- A new and dedicated facility.

Most investigations covering endothermic fuels were conducted in the early 1960s, at which time it did not appear that easily obtained products from existing refineries could satisfy endothermic fuel requirements. Petroleum refineries since have become more complex and offer significantly more product flexibility.

The development of dedicated facilities for endothermic fuel production may be impractical. The most cost-effective method for producing specific or narrow-cut hydrocarbons would be as one of many saleable products. The additional steps required to limit the output of a chemical processing facility to a single or relatively few products would in most cases be expensive. However, as in petroleum refining, major technical advances have occurred recently, and they include the development of new catalysts and techniques for their application. This has resulted in improvements of synthesis processes used to produce specific chemicals from the basic building blocks of carbon monoxide and hydrogen.

The synthesis approach to fuel development allows consideration of more than just petroleum for endothermic fuel development. This process is currently being used in South Africa to produce commercial quantities of transportation fuels including jet fuel, and in New Zealand to produce gasoline from natural gas.

It is not clear that an endothermic fuel that could satisfy commercial aircraft requirements has been identified. A new look at previously identified endothermic fuels, as well as new candidates, is certainly warranted based on recent technical advances in both the refinery and basic chemical product manufacturing areas.

Cost

The cost of the fuel consists of the cost of raw material, required energy, facilities, and distribution. The price of fuel is dictated by supply and demand, competition, and government policy, in addition to costs. The cost of jet fuel from petroleum is driven by the price of its raw material, i.e., crude oil. The cost of most alternative jet fuels will be driven by process energy requirements and the capital requirements for facilities. When fuel costs are based on a total conversion of a large segment of society to a particular alternative fuel, the criteria for accepting a new fuel would be price parity -- the price of the alternative that would allow it to compete with the existing fuel. The price of conventional petroleum-based jet fuels has almost risen to, but never reached, the point where the cost estimated for synthetic jet fuel would justify a commercial sector investment in production facilities. The price of a dedicated jet fuel for supersonic and hypersonic aircraft is likely to be higher than conventional jet fuel. (See Figure 7.) Price not cost, justifies an investment in new facilities, and this price must be high enough to compensate for the risk.

If a fuel is dedicated to a single use, such as supersonic or hypersonic aircraft, there is no other industry to share costs. Fuel suppliers must have an incentive to risk an investment in new or upgraded fuel production facilities. This incentive can be in the form of expectations of a major future growth in demand or, more likely, a fuel price that is considerably higher than

fuel cost. This price-to-cost differential could be considerable since the supplier will probably have a monopoly and must ensure that his supply is adequate during periods of high demand and to protect his investment during airline industry recessions.

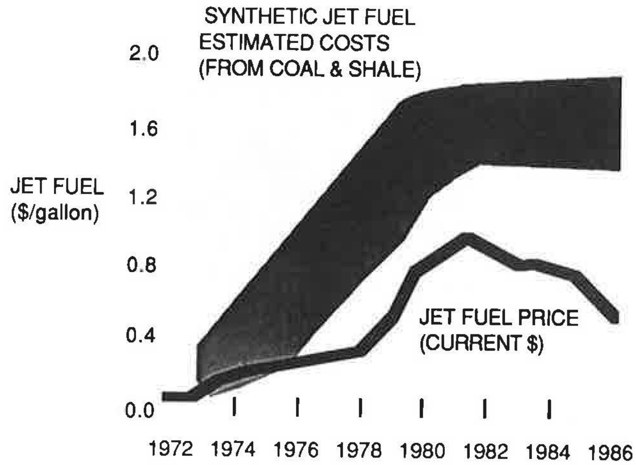

FIGURE 7. Relative Cost of Synthetic Jet Fuel

Hydrogen. The principal cost driver for each method of producing hydrogen differs as follows: (1) the raw material (natural gas) price for producing hydrogen from natural gas, (2) capital costs for producing hydrogen using coal, and (3) electric power for producing hydrogen from water using electrolysis. The cost of hydrogen from the various sources is influenced to different degree by the cost of raw materials, capital, and power. (See Figure 8.)

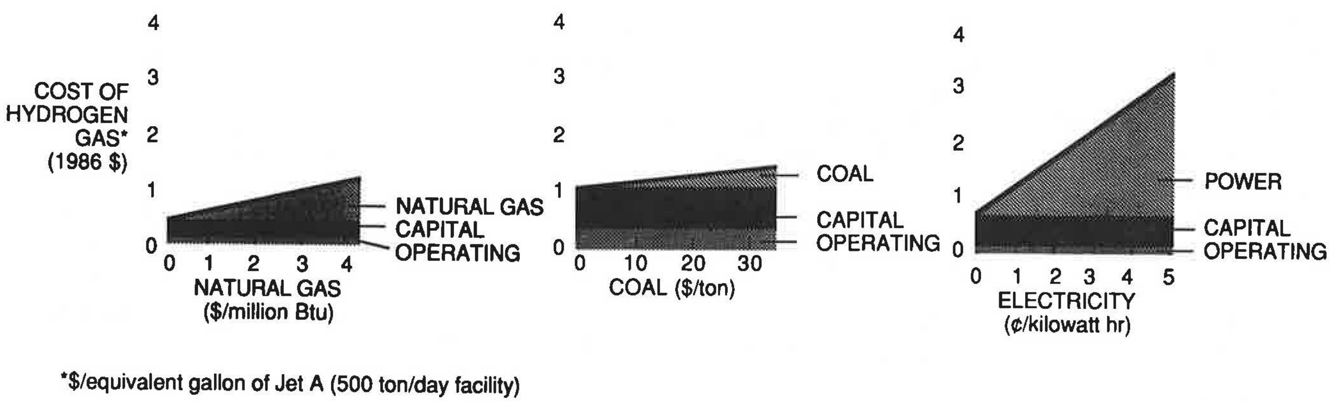

FIGURE 8. Hydrogen Cost Variations from (a) Natural Gas, (b) Coal, and (c) Electricity

Before hydrogen can be used as an aircraft fuel it must be liquefied, and the cost of liquefaction is driven by the cost of power. Power can be supplied to the liquefier as electricity, or the liquefier can be driven using hydrogen

produced in the gasification plant as shown in Figure 9. Liquefaction using gaseous hydrogen from coal to drive turbo-compressors is more costly than using the coal to produce electric power for liquefaction.

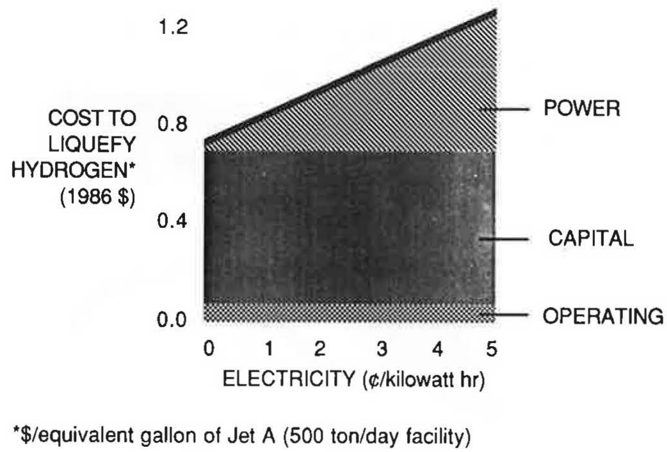

FIGURE 9. Liquefaction Cost Driven By Power Cost

The price of fuels is sensitive to local as well as total demand. The cost of fuels is also sensitive to the size of the production facility, particularly if the production unit is relatively small. This quantity sensitivity can be significant enough to impact the choice of fuel for the hypersonic and supersonic aircraft as well as the process chosen to produce the fuel in a particular area of the world. An estimated range of hydrogen requirements for hypersonic aircraft indicate that this demand may not be in the most cost-effective range for hydrogen production.

The global nature of supersonic and hypersonic aircraft, the relatively low individual airport fuel demand, and transportation considerations will not allow a blanket statement as to a single cost or best process. The selection of hydrogen process and the hydrogen cost must be based on individual airport or area studies that include the quantity of fuel required and the costs and availability of power and raw materials. For example, in an area with inexpensive electric power, hydrogen from water using electrolysis may offer an acceptably low cost even at low production levels. The size of the high-speed aircraft fleet may have a strong influence on the cost of hydrogen (Figure 10). The cost of liquid hydrogen will vary from location to location depending on the combination of demand and the cost of power (Figure 11).

Methane. There are two principal sources for obtaining methane in sufficient quantities to satisfy commercial aircraft requirements: directly from natural gas and from the partial oxidation of coal. The cost of gaseous methane obtained from natural gas will be close to the price of natural gas, depending upon the purity of the gas in terms of methane content and whether the aircraft really needs pure methane or can accept mixtures of methane and ethane. The production of methane from coal, like hydrogen from coal, is highly capital intensive. (See Figure 12.)

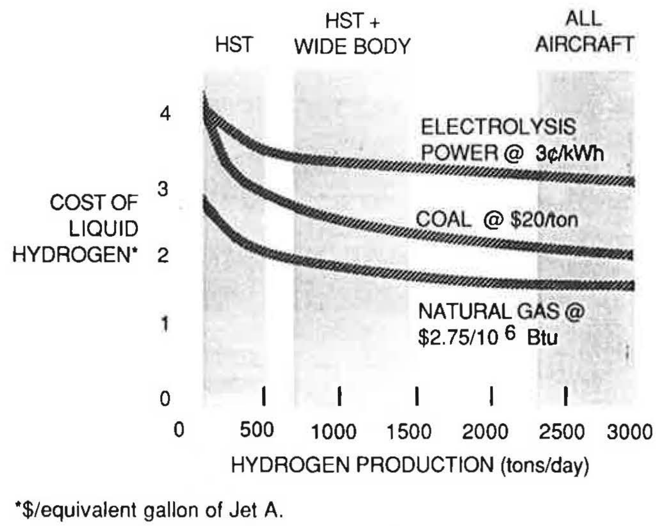

FIGURE 10. Effect of Production Volume on Cost of Liquid Hydrogen

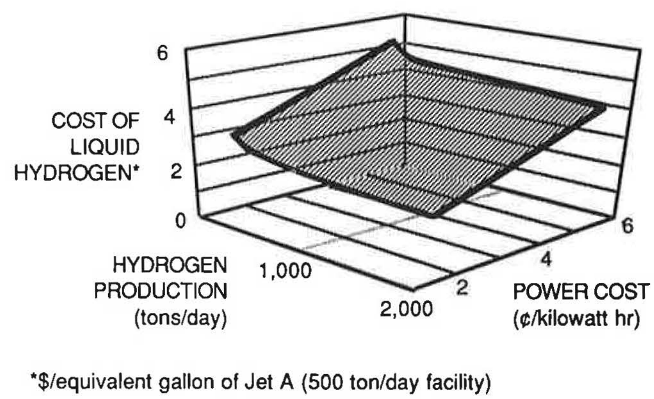

FIGURE 11. Effect of Demand and Cost of Power on Cost of Liquid Hydrogen

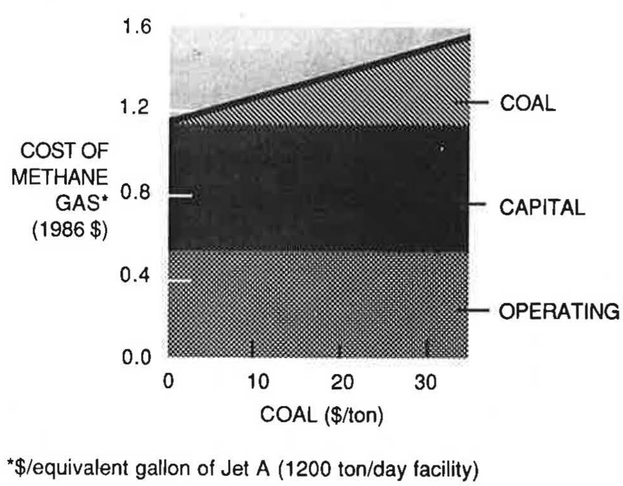

FIGURE 12. Methane Gas Produce from Coal is Capital Intensive

Like hydrogen, methane must be liquefied before it can be used as an aircraft fuel, and cost of liquefaction is driven by the cost of power (Figure 13). Power can be supplied to the liquefier as electricity, or the liquefier can be driven by natural gas or methane produced using coal. The power required to liquefy methane is significantly lower than the power required to liquefy hydrogen -- 2.4 times lower; therefore the cost to liquefy methane is considerably lower than to liquefy hydrogen.

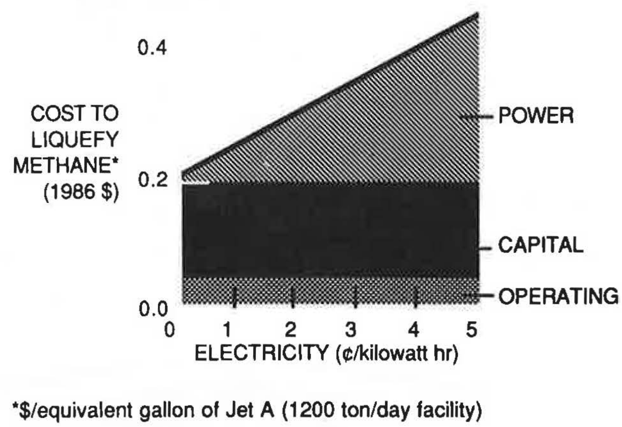

FIGURE 13. Relative Cost of Liquid Methane Produced from Electricity

The liquefaction cost differences between methane and hydrogen will be quite significant in trade studies. Liquefaction costs must be accounted for twice -- once for the initial production of the fuel and a second time to reliquefy fuel that has vaporized during ground operations.

The cost of methane produced using coal shows the same quantity dependency as hydrogen in terms of cost. The cost of liquid methane from natural gas will be driven by the cost of the natural gas more than the size of the facility. A low demand that allows use of existing natural gas distribution systems is expected to result in the lowest methane price. While the size of the high-speed aircraft fleet may have an influence on the cost of methane from coal, local price of natural gas is likely to be a more important factor (Figure 14).

Endothermic Fuels The cost of endothermic fuels can range from slightly above the current price of Jet A to greater than $100 per gallon for the more exotic specialty products. (See Figure 15.) Realistically, any endothermic fuel that could be considered practical for commercial aircraft must be producible as a byproduct from an existing petroleum refinery or as a primary product in a continuous chemical process. A fuel like methylcyclohexane can be produced using toluene as the raw material with small modifications to the process currently used to produced cyclohexane from benzene. The cost of methylcyclohexane will vary with the price of petroleum, which is the basic raw material. As with conventional jet fuel, the cost of many endothermic fuels will be very sensitive to demand for the finished product.

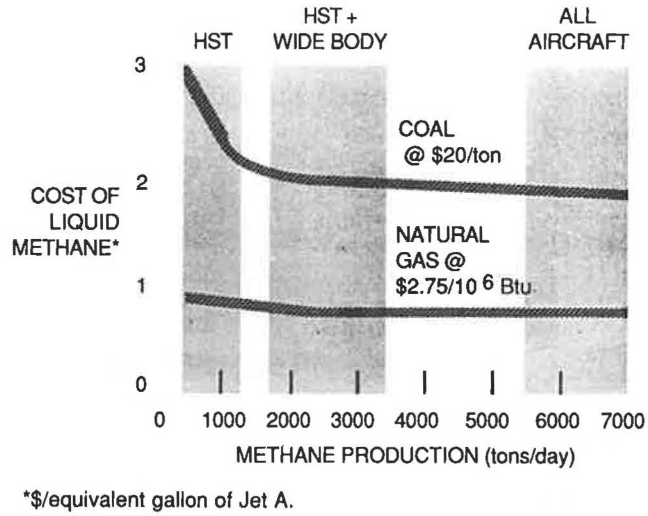

FIGURE 14. Effect of Production Volume on Cost of Liquid Methane

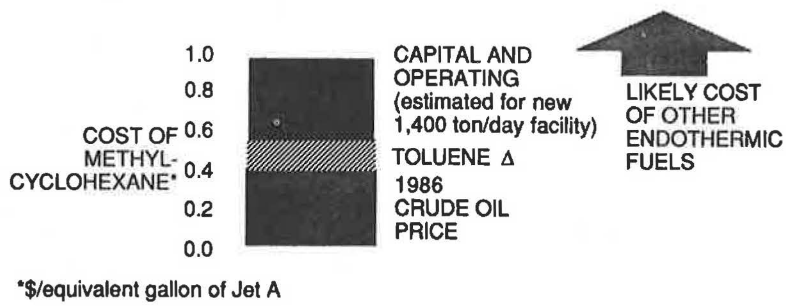

FIGURE 15. Relative Cost of Methylcyclohexane and Other Endothermic Fuels.

Cost Summary In terms of price, it is unlikely that any fuel dedicated for use only by supersonic or hypersonic transport could compete with the fuel used by conventional aircraft. This is particularly true for the current condition where kerosene-type aircraft fuels can be used for other applications in our society, and fluctuation in aircraft fuel demand can be satisfied by the flexibility built into the production (refining) industry (Figure 16).

Of the new fuels considered, none can be identified as preferable at this time. Special requirements of the aircraft must be balanced against basic fuel costs and the cost of new airport facilities. Considering just fuel cost, liquid methane has an edge over liquid hydrogen. Endothermic fuels have not been sufficiently evaluated to determine what fuel, if any, would be technically feasible. However, the cost of methylcyclohexane can be used to establish what is likely to be minimum cost for endothermic fuels.

Airports

Any nonconventional fuel will require a distribution and storage system that is independent and separate from the main airport fuel supply. This system can be

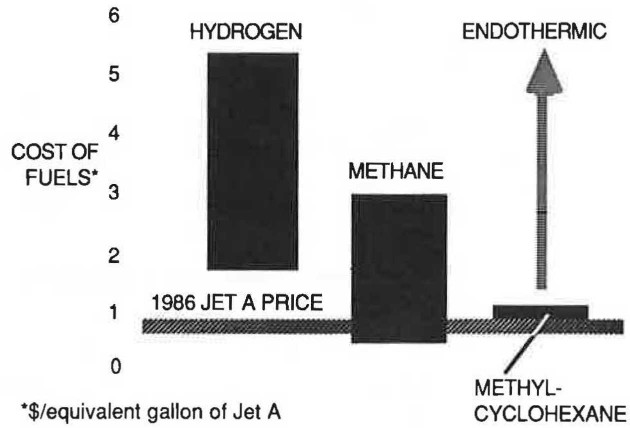

FIGURE 16. Relative Cost of Jet A, Hydrogen, Methane, Methylcyclohexane, and Endothermic Fuels

identical to the conventional fuel system or totally different in design and components. Most endothermic fuels are expected to require a relatively standard fuel system; the cryogens, liquid hydrogen and liquid methane, will require an entirely new and different system.

At any airport that requires hydrogen or methane for daily flights, gaseous hydrogen or methane would be delivered to the airport through a pipeline and liquefied at a facility located on or near airport property. Cryogenic fuels will require totally new fuel delivery, distribution and storage facilities, as well as extensive gate and terminal modifications. At many airports gaseous methane could be obtained from additions to or spurs from existing natural gas transmission systems; however, hydrogen would require a totally new distribution system from the gas production plant to the airport-located liquefaction facility. In all but the lowest demand cases, the liquefaction facility would be required to reliquefy gases vented from the aircraft loading operations and from the normal boiloff from the aircraft and the storage and distribution system.

The fuel distribution system must be insulated and will require vents and purging systems for the safe handling of both hydrogen and methane. Return vent gas lines must be provided to capture fuel vented from the aircraft and airport storage and distribution system. In most cases, this gas would be routed to the liquefaction facility; however, it can also be burned at a remote site.

Cryogen liquefaction facilities have little flexibility for adjusting to wide variations in aircraft fuel demand. The cryogen storage system must be sized to handle the peaks and valleys of traffic and airport shutdowns resulting from weather and adverse conditions. Airport personnel must be trained to handle the unique properties of the cryogens, and aircraft operations must allow for fuel tank and fuel system cooldown.

There always will be some heat leak to the liquid cryogen in the airport fuel delivery lines which will cause the bulk temperature of the liquid to increase.

This increase in temperature, and associated increase in cryogen saturation pressure, would result in rapid vaporization of the liquid in the aircraft fuel tanks during loading. The problem would be particularly severe during periods of low aircraft activity where liquid trapped in delivery lines would pick up an appreciable amount of heat. One solution would be to add a flash vaporizer at the aircraft connect point. This unit would subcool the cryogen by vaporization to a pressure at or lower than the vent setting of the aircraft fuel tank. A cryogen must be subcooled immediately prior to entering the aircraft tanks. This can be accomplished by a vaporizer mounted at the airport-aircraft fill interface.

Studies were carried out in 1975 for NASA to identify the costs required to convert airports for cryogenic fuels. These studies, updated by Boeing in 1986, indicate the costs would be very significant in terms of what airports spend today for fueling facilities. The studies addressed Chicago's O'Hare Airport as an example situation. O'Hare's entire operations converted for use of hydrogen would require 3,000 tons of hydrogen per day and would involve over $800 million in conversion costs (Figure 17). This does not include the cost of either a liquefaction or a reliquefaction plant. As indicated in Figure 17, the minimum cost for such a conversion on any airport would be about $200 million.

Cryogen-fueled aircraft would necessitate extensive modifications to ground support equipment and maintenance facilities (virtually an entirely new hardware system) from those presently in operation. Airports with daily high-speed aircraft service must have land available for liquefication and storage facilities. Depending upon the daily requirement, this could involve devoting between 10 and 35 acres for such facilities. This land many not be available at many existing airports, especially those located in urban areas. The use of long pipelines to transfer cryogens as liquids from remote storage areas would increase distribution losses and significantly add to final cost.

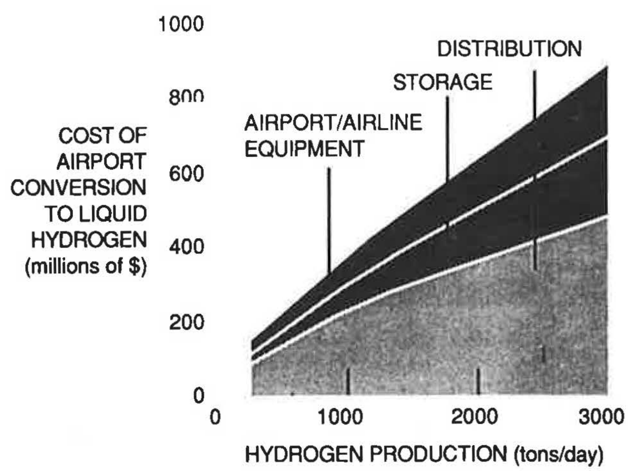

FIGURE 17. Cost of Airport Conversion to Liquid Hydrogen

The airport facilities required for most endothermic fuels will be essentially the same as for conventional fuels. However, some candidate fuels require the

special provisions at airports, including a vapor scavenging and recovery system for highly volatile or toxic fuels and a refrigeration plant and insulated distribution system for fuels that require subcooling prior to loading.

Public acceptance of highly toxic fuels in commercial aircraft or at public airports is not likely. The selection of a fuel that requires significant subcooling prior to loading would most likely be a quick fix to a marginal commercial aircraft design. Both endothermic and conventional fuels may require some refrigeration to satisfy maximum temperature loading requirements in hot climates.

Aircraft

Neither the cryogenic nor the endothermic fuels can be handled by a conventional fuel system. Both will require the development of new technology or significant improvements in existing technology before a fuel system that satisfies realistic commercial aircraft requirements can be designed. The use of fuel as a refrigerant adds to the complexity of the aircraft.

Unlike conventionally fueled aircraft, duty cycle (the demand for fuel during taxi, takeoff, cruise, and descent) will play an import part in selecting the fuel and establishing fuel system concept feasibility.

If the fuel, either cryogenic or endothermic, is intended to be used as a coolant for the airplane, it must be pumped to a highpressure (approximately 1,000 psi) to avoid its going through a phase change when transferred around the airplane. If the aircraft body is to be cooled, as on military vehicles, the fuel must pass through a heat exchanger on the body. At higher Mach numbers, the aircraft nose might even have to be cooled. The fuel must also pass through several heat exchangers on the engine to cool it. As a result, the transfer of all the fuel around the total aircraft system becomes a very complex operation.

The fuel tanks of aircraft using cryogenic fuels must be insulated pressure vessels. Because of their large size, these tanks would have to be located in the fuselage instead of the wings to minimize boiloff losses. A larger fuselage would be required to accommodate the greater volume of cryogen necessary for payload and range performance equal to conventional or endothermic fuels. However, the gross weight of the aircraft using cryogenic fuels, particularly hydrogen, may be less than those using conventional fuels because of the greater energy content per unit weight.

The complex nature of the thermodynamic processes associated with the storage and use of cryogens in a commercial aircraft offers many challenges for the design of a fuel system. For the fuel system to behave in a stable manner, the fuel storage and pumping system must be designed as a unit. The amount of insulation must be sufficient to minimize vaporized fuel losses while satisfying the pressure inlet requirements of a pump that must deliver the fuel over a wide range of flow rates. The design of a cryogenic fuel system involves balancing the inlet requirements of the pump, the tank pressure, and the losses due to vaporized liquid.

No existing pumps satisfy commercial aircraft weight, life, cost, and delivery requirements. The pumping of cryogens in space vehicles is state-of-the-art. However, space vehicle flow rates vary over a relatively narrow range, pump life

requirements are counted in seconds, and cost is a secondary consideration. In addition, the acceleration vector of a space vehicle is directed toward the pump inlet and increases as the fuel is used--thus the pump has at least some effective liquid head for subcooling. Pumps that satisfy weight, life, cost, and delivery requirements for commercial aircraft still require a significant extension of existing technology for both hydrogen and methane.

Another design challenge that must be met before either methane or hydrogen can be considered for commercial aircraft is the development of a workable insulation concept. Vacuum jackets would be too heavy or delicate, and currently available foam insulation cannot withstand the imposed temperature variations without unacceptable repair and inspection periods. Currently, it is not clear how much insulation is required. Too little insulation results in the venting (hence loss) of fuel -- particularly during the taxi phases of operation. Too much insulation can cause the tank pressure to drop to the saturation point of the liquid, which can cause unstable system operation or pump cavitation. In any case, the sizing of insulation must satisfy all mission phases -- taxi, ascent, cruise, and descent. (See Figure 18.)

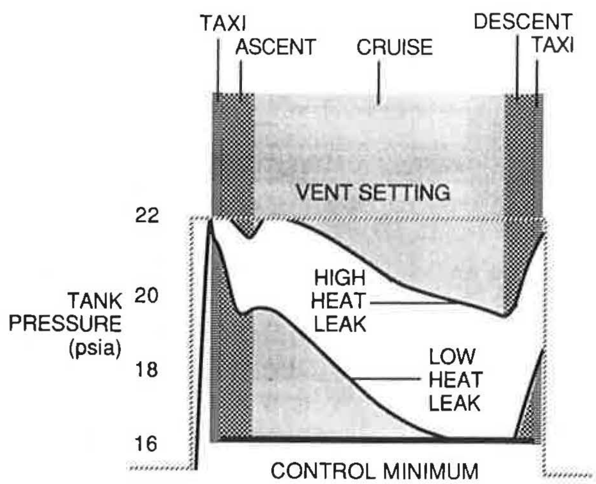

FIGURE 18. Aircraft Fuel Tank Insulation Considerations

A selling point for cryogenic fuels is their potential use for cooling aircraft engines and structure. Taking advantage of a significant percentage of this cooling capacity in a practical commercial aircraft may prove to be quite costly. Detailed design studies must be conducted before a practical and cost-effective percentage can be determined for use of the available cooling capacity. These studies must include heat exchangers and fuel delivery techniques that allow matching the engine duty cycle to cooling requirements.

Endothermic fuels can be handled more like conventional fuels than the cryogens; however, they will share some common problems. The endothermic fuels will require pumping to the engine operating pressure at the fuel tank and will have the same or a more severe problem of matching cooling to engine requirements. The matching problem could be more critical for endothermic fuels because they are reacted to products that differ from the stored fuel and most of the fuels require a three-stage process to take advantage of their maximum cooling capability.

It will be extremely difficult to match endothermic fuel cooling stages with aircraft engine fuel demand or aircraft cooling requirements. (See Figure 19.)

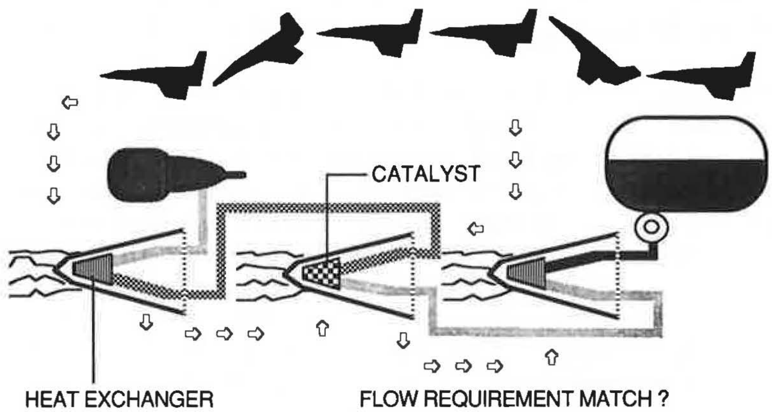

FIGURE 19. Matching Endothermic Fuel Cooling Stages with Engine Fuel Demand and Aircraft Cooling

It is currently not clear how the performance of engines designed for high-speed aircraft will be affected by a fuel composition that varies during the various phases of the mission. Also, it is not clear how to take advantage of the heat absorption capabilities of all three stages of the cooling processes.

Major advances in catalyst technology have been made since the time of endothermic fuel studies. These advances were the result of needs generated by the synthetic fuels industry and the government-forced demand for unleaded gasoline. The catalytic reforming processes used to improve octane by increasing the aromatic content gasoline are similar to the endothermic fuel processes proposed for aircraft. Prior to the latest advances in catalyst technology, catalyst life was identified as a major problem and it was suggested that the catalysts would require frequent replacement, which is an unsatisfactory requirement for commercial aircraft. New studies are required to determine the impact of newly developed technology on both the selection of an endothermic fuel and the manner in which it can be used in a practical aircraft cooling system.

Review

Technologies required to produce and use fuels and fuel systems being considered for supersonic and hypersonic aircraft are at various stages of development.

- Commercial processes for producing and liquefying hydrogen and methane are available now. Because a best-choice endothermic fuel has not been identified, process readiness is yet an unknown.

- The design of tank-to-engine aircraft fuel systems for cryogens is in the concept development stage. Design studies for systems that can use the cooling potential of cryogen fuels have recently been started. Advances in technology are required to further develop insulation and pumping systems that can meet commercial standards of reliability and maintainability.

- o Design studies for aircraft systems using endothermic fuels have not yet progressed to the point where feasibility can be established or requirements for new technology identified.

If the requirements of supersonic and hypersonic aircraft demand a unique fuel, the price will likely be higher than the price of conventional fuels for commercial aircraft The price penalty for the dedicated fuel will be riven by several factors. Among them:

- Basic processing costs
- Demand
- Risks considerations
- Local availability of resources
- Requirements for new airport and distribution system.

In addition to price factors, the selection of a fuel must be based on a study that balances realistic commercial aircraft duty cycles with specific fuel property benefits.

AIRPORT COMPATIBILITY CONSIDERATIONS FOR HIGH-SPEED CIVIL TRANSPORT (HSCT)

Bradley W. Bachtel and Catherine M. Keene,
Douglas Aircraft Company

The High-Speed Transport contract that Douglas Aircraft Company is currently performing for NASA is a two-year $4.5 million study that will provide:

- o Technology assessment from Mach 2 through Mach 25
- o Commercial-value study
- o Most promising vehicle concepts
- o New technology requirements and plans
- o National Aero-Space Plane (NASP) commonality.

The ability to sustain supersonic cruise has been the basis of many different aircraft concepts. These include the B-70 at Mach 3 and the SR-71 at Mach 3+, then on to the Concorde at Mach 2.07 and the Douglas AST at Mach 2.2, and finally to the Douglas concept of the High-Speed Civil Transport (HSCT) or "Orient Express." Each design, whether civilian or military, has evolved to meet a new mission. For the purpose of this presentation, a generic Mach 5 model, is being used as a reference.

Basic Characteristics

Basic characteristics of the generic HSCT aircraft are:

- o A speed of Mach 5
- o A range of 6,500 nautical miles
- o Fueled by liquid natural gas, or methane as it also is known
- o Cruises at 80,000+ feet
- o Carries 300 passengers in a mixed configuration.

The three-view drawing of the generic HSCT shown in Figure 1 has the following dimensions:

o	overall length	227 feet
o	wingspan	108 feet
o	tail height	51 feet
o	wheelbase	104 feet

For a general dimensioning of the HSCT grouping of aircraft,

- o overall lengths are expected to vary between to 200 to 250 feet,
- o wingspans vary from 100 to 130 feet,
- o tail heights of approximately 50 feet,
- o wheelbase will vary from 80 to 105 feet.

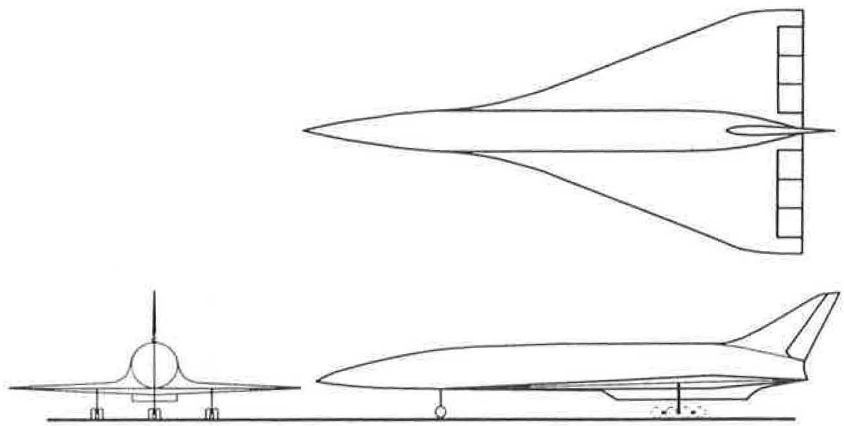

FIGURE 1. Generic Mach 5 High Speed Civil Transport (HSCT)

For comparison, the general characteristics for the two current widebody aircraft are:

		DC-10-30	747-200B
o	Overall length (feet)	181.6	229.2
o	Wingspan (feet)	165.3	195.7
o	Tail height (feet)	57.6	63.5
o	Wheelbase (feet)	72.4	84.0
o	Passengers (mixed class)	227	452

The overall length of the generic HSCT is less than that of the 747. This will affect the ground maneuverability of the aircraft, a situation that is addressed later in this presentation.

Figure 2 is a side-view comparison of the generic HSCT, the DC-10, and the 747. It provides more of a feel for the three aircraft and how they relate to each other in size.

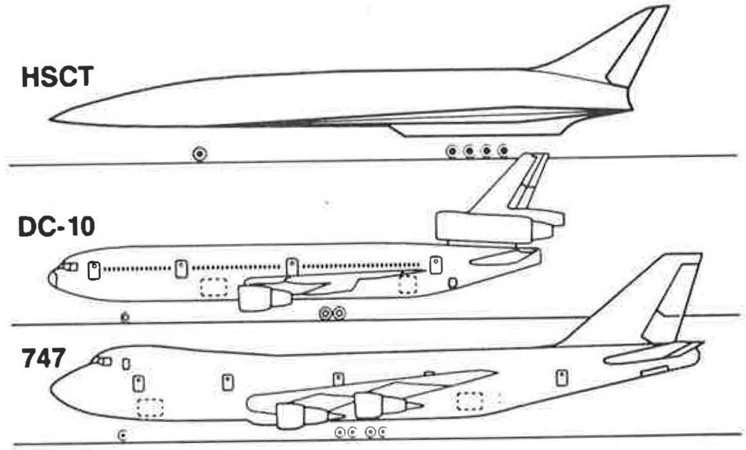

FIGURE 2. Side View Comparison of HSCT, DC10, and 747

Figure 3 is a plan view comparison of the generic HSCT superimposed on the DC-10-30. The DC-10 is much shorter than the generic HSCT, yet has a much greater wingspan.

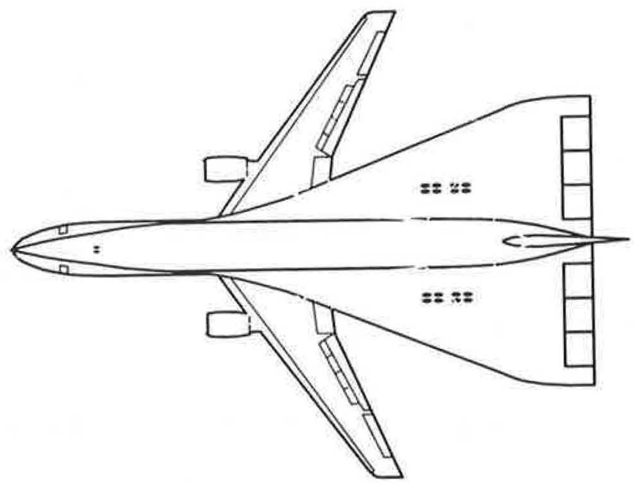

FIGURE 3. Plan View Comparison of DC-10 and HSCT

In the plan view (Figure 4) the generic HSCT is superimposed on the 747-200. The 747 has a similar length yet a much wider wingspan, just as the DC-10-30.

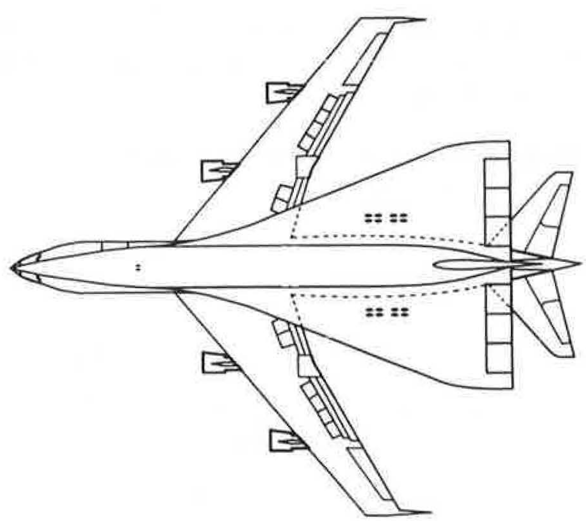

FIGURE 4. Plan View Comparison of 747 and HSCT

Airport Compatibility

Nose-in gate spacing requirements for the generic HSCT, as shown in Figure 5, are such that if the aircraft is powered in and pushed out, resizing of the gate areas is necessary. Wingspan of the generic HSCT results in less required

terminal length than for either the DC-10 or the 747. No more distance out from the terminal would be required than for a gate capable of supporting 747 operations.

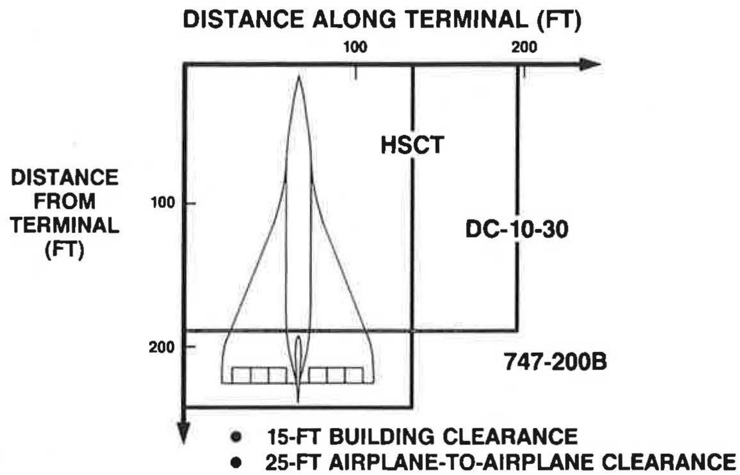

FIGURE 5. Nose-in Gate Spacing Requirement - Power In/Push Out

Footprints of the three aircraft can readily be compared in Figure 6.

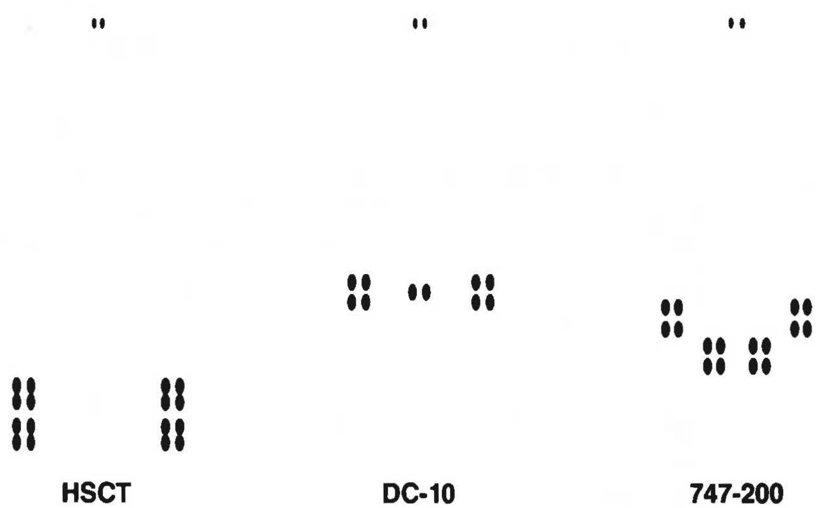

FIGURE 6. Footprint Comparison - HSCT, DC10 and 747-200

Maneuverability of the generic HSCT may present problems at airports designed for aircraft with a much shorter wheelbase. The wheelbase could be up to 20 feet longer than that of the 747 though it may also be comparable length. A steerable main landing gear similar to the body gear used on the 747-200 series would improve the turning capability of the aircraft.

The landing gear configuration will be required to distribute the aircraft weight sufficiently so that the aircraft does not exceed the pavement strength capability of existing airports.

The longer wheelbase would require modifications of a large number of taxiway turn fillet areas. When making a 90-degree turn, the arc of the main gear requires move pavement area. The pilot technique of judgmental oversteering is predominantly used in the United States and involves the cockpit projecting past the taxiway centerline prior to initiating the turn. This technique requires a high level of pilot proficiency.

The pilot technique of cockpit-over-centerline steering is predominately used in Europe and the Middle East. Most airports in these area have the larger fillets that enable this technique to be used. However, the larger areas requires additional construction and therefore greater construction cost.

One of the most important considerations that will affect how the generic HSCT, or any of its group, is handled after landing is the question of airframe heat. Whether the aircraft on landing will retain sufficient skin heat to warrant holding in a cool-down area prior to handling is still to be determined based on studies of thermal management system concepts. If required, the cool-down apron should be located near the runway so that it can be used for both cool-down operations and as a holding area for departures. (See Figure 7.) If heat retention is not a factor, then the apron can be used in a holding-apron mode with fuel top-off capability for the HSCT.

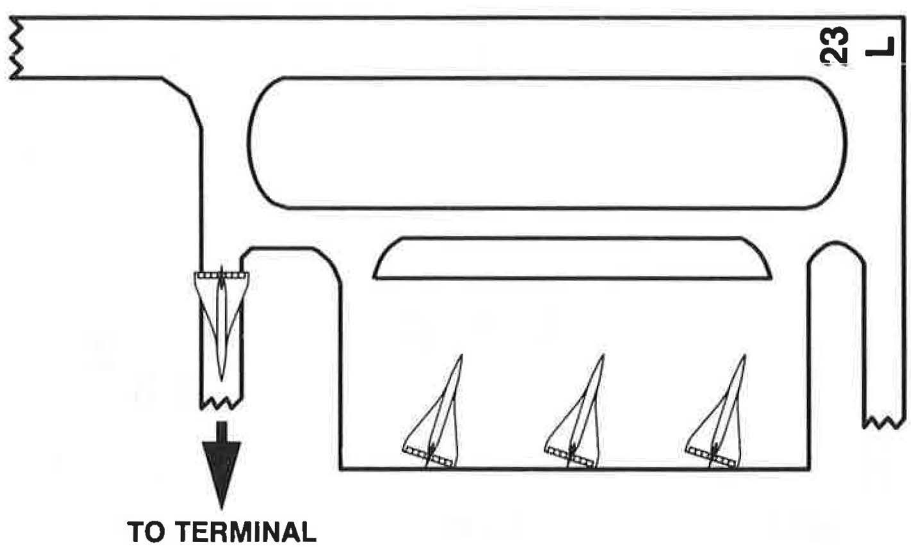

FIGURE 7. Cool-Down and Holding Apron

As shown in Figure 8, wing clearance for aircraft passing on parallel taxiways is not a problem. The generic HSCT wingspan is less than either the DC-10 or the 747; in fact, it is similar to such current standard-body aircraft as the MD-80 and the 727.

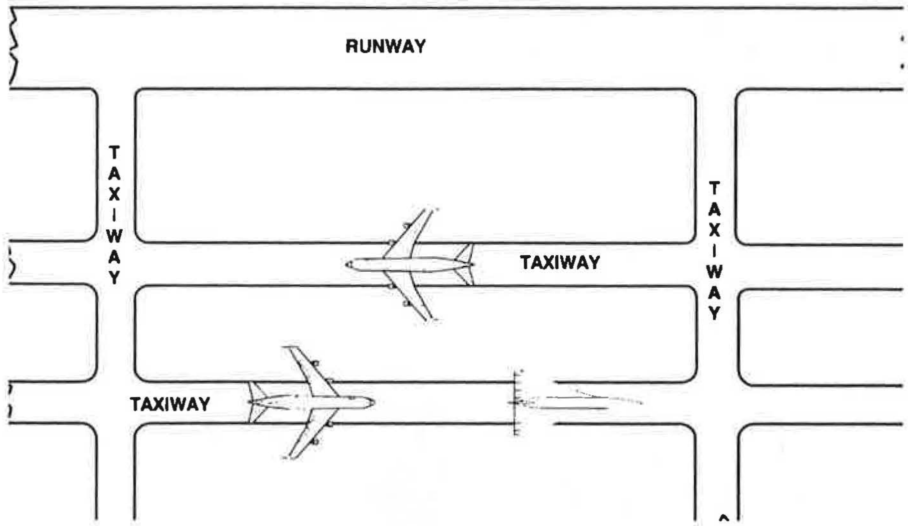

FIGURE 8. Parallel Taxiway Clearance

Fuselage height above the ground for the generic HSCT is higher than for either the DC-10 or 747, but the main passenger door height is about the same for the 747. Access by loading bridges designed for 747 operations should be possible, yet the use of existing loading bridges may place the generic HSCT too close to the terminal due to a longer nose-to-nosegear distance than for the 747 on that specific type of gate.

With the delta wing of the generic HSCT running virtually the length of the fuselage, there is very little easy access to the main deck. Only the forward door is usable with present loading bridges and other passenger loading equipment.

Turnaround time, which has been projected at 1.5 to 2 hours, is affected since passenger enplaning and deplaning can only take place through the single door. If passenger loading equipment is designed to provide access to a second door, enplaning and deplaning time will be reduced.

New concepts will be required for emergency evacuation of passengers. These will include heatproof emergency slides, new door designs, and new egress methods.

The height above the ground of the generic HSCT fuselage is greater than that of either the DC-10 or 747, as shown in Figure 9. Thus, the fuselage height is out of reach of the ground and some service trucks.

New service equipment and service methods will also be needed. For servicing the aircraft, a single drop-down unit might be developed. It would contain service points for potable water, electrical, pneumatic air, air conditioning and lavatory.

The fuel service point will be located separately due to the possibility of contamination, and interference with other operations, during the cycle. Fuel service time for LNG or LH_2 onloading should be similar to that for

hydrocarbon fuels during a short-turnaround operation. However, if the aircraft has been sitting overnight or for an extended period of time, the fueling operation will require the additional steps of purging and cooling down prior to bulk-fuel loading. The new fuel types will require additional steps and different safety considerations for operations on the ground.

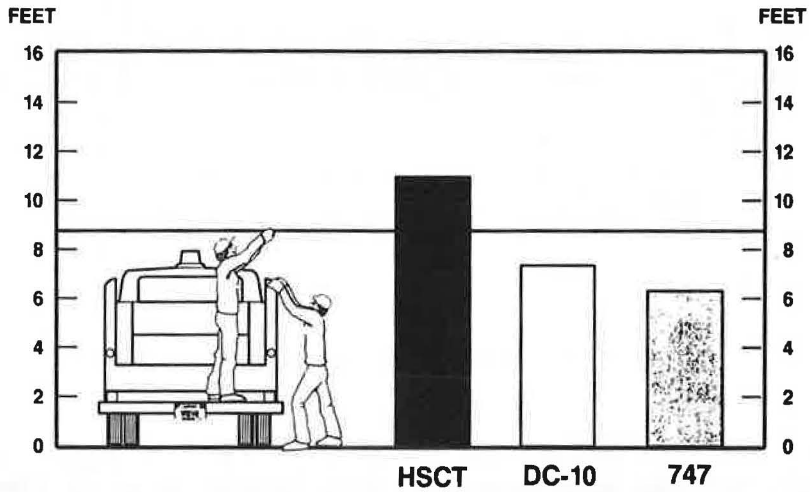

FIGURE 9. Fuselage Height Above Ground

Ground Servicing

The low-aspect-ratio, or delta, wing requires that service vehicles go under the wing to access most of the fuselage.

Cargo handling for the aircraft might also require an innovative approach. There is only one area on this generic model -- aft of the galley service door and forward of the wing -- that is available for a widebody cargo compartment door and baggage handling (Figure 10). A DC-8 type of cargo door in the bottom of the fuselage might be the most efficient for this aircraft.

In addition, the potential heat of the aircraft may be a consideration in handling the aircraft and require thermal protection for ground personnel.

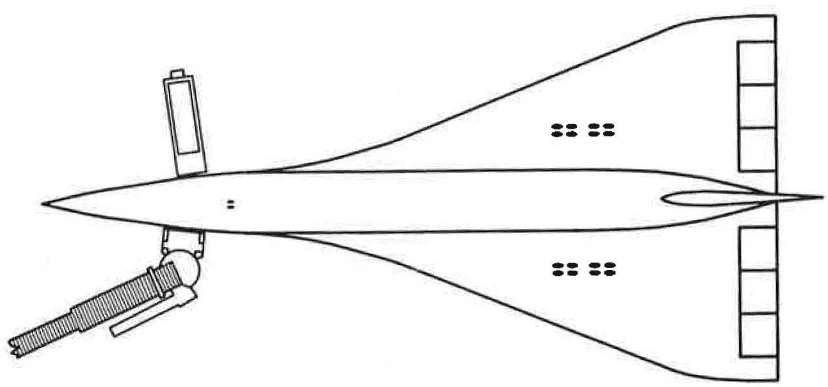

FIGURE 10. Ground Servicing HSCT

Possible Fuel Types

There are three possible fuel types considered for the HSCT series of aircraft: Hydrocarbon (JP), Liquid natural gas (LNG), and Liquid hydrogen (LH_2). Hydrocarbon fuels include both conventional and endothermic fuels which, combined, could have the properties of designer fuels.

Commercial supersonic transports with speeds up to Mach 3 will probably utilize JP fuels similar to those being used today. This would incur a minimum amount of change for facilitation and for procedures. The fuel used for the generic HSCT is liquid natural gas.

The fuel use ranges are shown in Figure 11. Hydrocarbon fuel, used mainly throughout the lower Mach ranges, is viable up to Mach 3+. It is available worldwide as either Jet A, A-1, or B and is the fuel used predominantly by existing commercial turbine-powered aircraft.

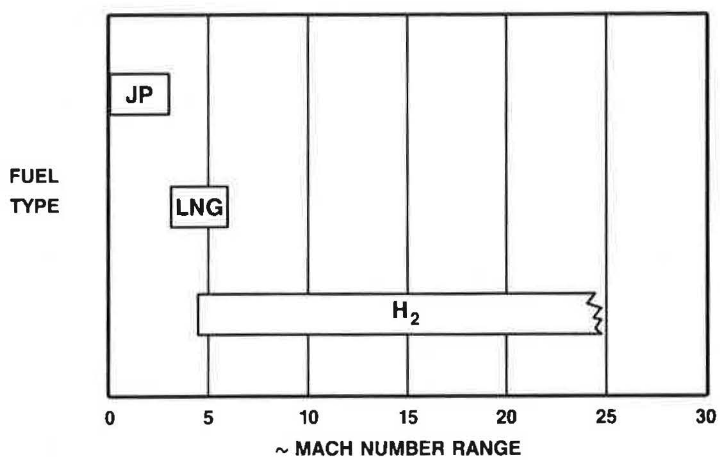

FIGURE 11. Fuel Use Range

Liquid natural gas (LNG), as methane is also known, is available worldwide in commercial quantities. The fuel is used for approximately the Mach 3+ to Mach 6+ range. The fuel is not presently used in commercial aircraft, but it is being used for commercial automotive application. In addition, the existing large-scale production and distribution facilities providing LNG for the industrial sector make it an attractive alternative.

Liquid hydrogen is suitable for use in the ranges of Mach 4.5 to Mach 25+. This fuel is presently in use for commercial space-launch applications. Domestic production capability is limited, and it is produced in only a few countries abroad. The fuel does have the advantage that it can be produced as a by-product of nuclear power generation and by other methods that could make it available in commercial quantities in the next few decades.

A typical schematic for either a LNG or LH_2 airport fuel system is shown in Figure 12. The fuel is either brought to the airport in liquid form or transformed into the state at a liquefaction plan on-site. It is then moved to the service ramp area, distributed, and dispensed into the aircraft. At

various points in the system, the ability to vent the boiloff gasses will be required. Flare stacks will be necessary for certain areas. In addition, a captive system will have to be provided as vent for the aircraft in order to purge the fuel system during the cool-down process and to trap any type of overflow.

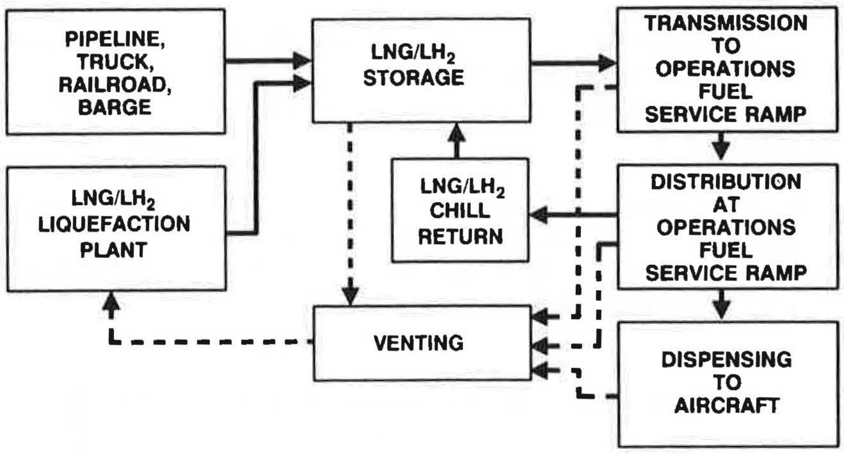

FIGURE 12. Typical Airport LNG/LH_2 System Schematic

Fire protection will include devices such as ultraviolet (UV) light detectors and fuel sniffers. As the flame of LH_2 is difficult for the human eye to see, crash, fire and rescue, ramp, and in-flight personnel will require portable flame detection devices to ensure rapid identification and containment of a fire once it is located. Due to the rapid evaporation rates of both LNG and LH_2, it is felt that the fire danger of these fuels is roughly equivalent to that hydrocarbon fuels.

Figure 13 is a schematic for a hydrocarbon (Jet A) fuel system. It is a much simpler system than that illustrated for LNG and LH_2 fuels in Figure 12.

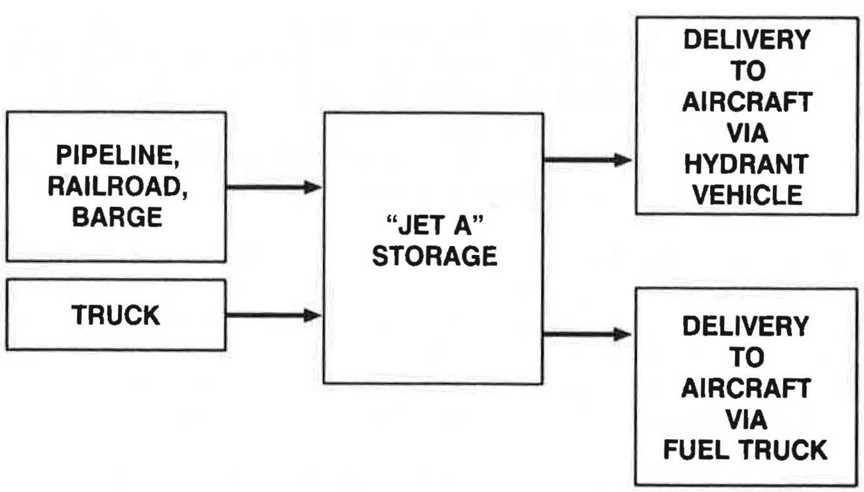

FIGURE 13. Typical Airport Hydrocarbon Fuel (Jet A) System

Fire protection is provided by deluge systems and requires either sensor or visual confirmation to identify the fire. Fire suppression is provided by existing crash,fire, and rescue services.

The principal handling characteristics of conventional JP fuel are

- It is loaded by either pumping or pressure-feed.
- Jet A requires storage above -104°F, and has a 100°F flashpoint.
- It has toxic by-products in a closed environment.
- The flame is visible.
- The liquid clings to surfaces and evaporates slowly.
- Airline and airport handling practices are well-established.

The handling characteristics of LNG and LH_2 are:

- Loading is by either pumping or pressure-feed.
- It must be stored at temperatures to maintain a liquid state: Below -259°F (LNG) or -423°F(LH_2).
- LH_2 flame is difficult to detect by the naked eye thus causing problems in passenger evacuation and personnel locating the flame source.
- As a liquid it evaporates rapidly, but vapor clouds may linger, especially with cold temperatures, thus causing a further problem with both fuels on the ground in the gate area. This is especially so with an inboard gate that may trap a vapor cloud against the terminal for possible ignition. This will require new practices by the airlines and airports.

Operation in Airport Traffic Pattern

An approach speed of 130 knots is the goal for the HSCT in order to ensure its operability within the airport traffic area. This speed will enable the aircraft to operate with current commercial aircraft on approach to the airport. However, due to the fuel-burn requirements of the aircraft, landing sequence priority over subsonic aircraft may be required.

Air traffic control considerations for the terminal area may consist of greater spacing intervals for aircraft following the HSCT during landing approach due to wake turbulence. Also a possibility is the need for special missed-approach procedures for the aircraft due to its low-speed characteristics.

Special climb-out corridors may also have to be provided depending on the altitude at which the aircraft transitions to supersonic flight.

In order for the aircraft to be accepted at airports, especially those that are noise-sensitive, the goal is for the aircraft to meet Federal Air Regulations Part 36 - Stage 3 noise requirements.

Also to be considered is the possibility that by the time the HSCT becomes operational, it should be expected that noise levels possibly lower than those of Stage 3 will be the standard and will need to be met.

Summary

The HSCT dimensions, either the generic model or as a grouping, should not present any unresolvable operational problems at major airports.

The aircraft length and wheelbase can affect parking area and maneuverability requirements, such as size of taxiway fillets.

Heat retention by the HSCT aircraft skin may affect the ground-handling requirements of the aircraft.

Supersonic transports using JP fuels are expected to present the least change for airports. High-Mach supersonic and hypersonic aircraft using either LNG or LH_2 fuels will require new airline procedures (with specific regard for passenger safety) and may cause significant impact on the airport infrastructure.

The ability to operate in the future by using today's airports, updated to the 2005 time period, it the goal for the new HSCT aircraft. The minimum need for facility change will allow the easiest integration of the HSCT into the airport environment.

HIGH-SPEED CRUISE ENVIRONMENTAL CONCERNS

Albert W. Blackburn
Federal Aviation Administration

As the Federal Aviation Administration's (FAA) Associate Administrator for Policy and International Aviation, my responsibilities encompass the formulation and implementation of the FAA's environmental policies in all areas of the air transportation system. The subject of my present discussion, "High-Speed Cruise Environmental Concerns," would not be complete if we did not review a few of the primary concerns which form the basis of the FAA's environmental policy.

FAA's Promotional Responsibilities

A fundamental responsibility of the FAA is to foster and promote air commerce at home and abroad to ensure the efficient and safe use of the airspace. The subject of safety is obviously all pervasive and includes the certification standards for the construction and development of aircraft, as well as standards for their operation. The efficient use of the airspace is reflected in actions necessary to maximize airport capacity and to meet the ever increasing demand for air travel, which will result from an expected increase in passenger enplanements of approximately 100 percent within the next 15 years. Currently we are finding that the problems of airport and system capacity are increasingly related to environmental concerns. The reason for this is simply that the increase of community pressures on airports for relief from airport noise has resulted in an increase in airport use restrictions at several major hub airports around the country, as well as at smaller community airports. This increase in airport use restrictions is leading to a saturation situation, since it is also becoming increasingly difficult to develop new airports or expand existing airports. As a result of these environmental concerns, I am continually surprised at the amount of the FAA's effort, as well as my own, which is spent in addressing environmental issues.

A secondary promotional responsibility of the FAA is to encourage the entry of new carriers into the system to ensure that an appropriate competitive situation exists such that all carriers can be expected to develop a reasonable return on their investment. Relevant to recent deregulation of the air transportation industry much has been done to promote the competitive growth of the system. This growth continues to be dynamic and, to a degree, reflects the appropriateness of our environmental policies to date. The potential for the development of commercial supersonic and hypersonic transport aircraft could reflect the next frontiers for growth of the air transport system and will only be realized if we develop and adhere to an appropriate environmental policy.

Noise Factors

Airport Noise. While I am aware that the subject of airport community noise will be discussed in a subsequent paper, its extreme importance relative to airport capacity merits several comments prior to concentration on the subject of high-speed cruise concerns. The Federal Aviation Regulations (FAR) Part 36 established noise regulations for all subsonic aircraft. The legislative requirements of Section 611 of the Federal Aviation Act dealing with

the control and abatement of aircraft noise and sonic boom stipulates that the FAA cannot issue an original type certificate under this Act for any aircraft for which substantial noise abatement can be achieved by prescribing standards and regulations. This means that manufacturers of both subsonic and supersonic aircraft cannot assume that barely meeting the current Part 36 Stage 3 standards will continue to be acceptable into the next century. Even if the federal government does not act to tighten these standards, competitive pressures between manufacturers to meet the public's demands for quieter aircraft will effect much the same result. Success of the British BA-146 in penetrating the United States market shows the value of quieter aircraft in a competitive situation. Further, FAR Part 36 noise standards would necessarily be expanded to include both supersonic and hypersonic transport aircraft prior to their eventual airworthiness certification.

As an initial step towards this objective, an Advance Notice of Proposed Rulemaking (No. 86-16) entitled "Noise Standards; Civil Supersonic Aircraft Noise Type Certification Standards and Operating Rules," has recently been issued by the FAA. Since there is currently a technology trend to the evolution of an all FAR 36, Stage 3 fleet of subsonic aircraft, one of the subjects raised in the ANPRM is "...the extent to which the current Stage 3 noise standards now applicable to subsonic turbojet-powered aircraft could be applied to future-generation SSTs." This subject was studied in depth by the International Civil Aviation Organization (ICAO) in 1983, and while the technology did not appear to be available at that time, the goal could be reasonably considered within reach. Since that time, techniques including the use of variable cycle engines, inlet choking, use of advanced noise attenuation material, and modified operational procedures all would tend to enhance the prospects of a Stage 3 airport noise environment for future supersonic transports.

Obviously, the definition of the hypersonic transport aircraft is not sufficiently advanced to address the question of airport noise for this category of aircraft. The stated goal that the NASP research aircraft "will take off from a runway" implies the need for serious consideration of airport noise characteristics of this class of aircraft. If the designers of future commercial hypersonic aircraft are to achieve a runway takeoff and landing capability, it is initially questioned whether or not they would be capable of taking off in a mix of conventional subsonic aircraft or whether specific isolated launch areas would be necessary.

En Route Noise. Historically, prior to the coming of the supersonic transport with its associated sonic boom, considerations of aircraft en route noise have been minimal. Generally, it had been considered possible for aircraft to fly high enough and at low enough engine thrust to minimize en route noise problems. Recently, however, concern has been expressed in this area for engine noise as well as for sonic booms.

Subsonic engine noise as a potential en route problem has surfaced as a result of two operational conditions. First, to control the takeoff operational noise at airports, procedures have been encouraged which utilize substantial power or thrust reductions during the second phase of takeoff climb. After the second phase is completed, the power is increased to maximum climb power for the remainder of the climb to cruise altitude. During this phase of the climb, it has been reported that concern has been expressed by people on the ground at

greater distances from the airport because of the environmental noise associated with the use of maximum climb power. The second form of en route engine noise may result from the use of new propulsion systems for subsonic aircraft or of the next generation of SST engines. In either case, this potential issue should be addressed in the early configurational design phases.

Sonic Boom. During the development of the Concorde and the United States' supersonic transport aircraft, the en route noise problems were only considered to be those associated with the "primary" sonic booms which were estimated to have over-pressures on the order of 2 to 3 pounds per square foot. These overpressures could in fact be amplified during acceleration by factors of 5 or more, which would result in "N wave" sonic boom signatures having a rapid pressure rise from the atmospheric level to approximately 15 pounds per square foot in the acceleration areas. This rapid pressure rise, with the associated startle effect, and the en route cruise overpressure level were sufficient to justify a Federal Aviation Regulation, Part 91.55, in March of 1973 which prevented supersonic overflight by civil aircraft.

At the time of the rule making, there was conjecture that a 1 pound per square foot or less sonic boom may be considered acceptable. Accordingly, the FAR was structured to provide proponents of supersonic overflight the opportunity of demonstrating the environmental acceptability of "tailored" sonic boom characteristics. In the interim, international concern was expressed through ICAO and cooperative procedures were worked out at the international level to avoid impact of sonic booms resulting from supersonic transport flight over or near a nation's shores. The provisions in the FAR Part 91.55 for demonstrating that "environmentally acceptable boom generating characteristics" could be developed has not been used to date and as a result nothing has been done since 1973 which has contributed to a reassessment of "acceptable" sonic boom overpressure limits.

In contrast to an acceptability demonstration, the FAA has experienced difficulties with the "secondary sonic booms" which have overpressures in the order of 0.3 pounds per square foot and less. Surprisingly the public reactions were sufficiently adverse to make routing changes in Concorde flight operations necessary.

Impact on Air Quality and the Atmosphere

Early Concerns. During the late 1960s and the early 1970s environmentalists raised questions about the potential impact of supersonic transports on air quality and the upper atmosphere. Specifically, projections were made relative to human health effects, the earth's temperature, and general ecological effects resulting from injection of water vapor and carbon monoxide into the atmosphere and the possibility of the "green house effect." These reservations were later reflected in the concern that NO_x could possibly destroy the ozone layer and subject the environment to harmful levels of ultraviolet radiation.

With the current limited fleets of supersonic aircraft, these concerns have essentially disappeared.

Additional Questions. With the reassessment of the prospects for commercial supersonic and hypersonic transport aircraft, additional questions have surfaced beyond those related to the high-speed cruise environment. If these aircraft are to operate from existing airports, their contribution to the emissions of the existing aircraft on the ground in the vicinity of airports must be considered. While the high-speed cruise effects of gaseous emissions are important, their effect during climb and descent through the tropopause and the ozone layer will also need assessment. Additionally, the effect at cruise altitude will need to be addressed.

For the hypersonic aircraft, until the configurations can be more explicitly defined, assessment of the environmental impact cannot be initiated. In addition to forecasting aircraft types, fleet sizes, and engine types, it will obviously be necessary to identify the fuels that will be used (i.e., JP-4, hydrogen, or possibly liquid methane). All of these fuels will produce water vapor, and the engines will produce NO_x from the nitrogen and oxygen in the air during the combustion process.

Atmospheric Ozone

Status. In the early 1970s the prospect of supersonic flight by a large fleet of SSTs flying at high altitudes resulted in expressions of considerable concern that man-made pollutants would adversely modify the total ozone content of the earth's atmosphere. It was expected that the nitrogen oxides (NO_x) from aircraft would have a direct adverse impact on the atmospheric ozone, 90 percent of which was located in the stratosphere. As a result of research conducted since the advent of the first SSTs, studies have indicated that the distribution of ozone within the total atmospheric column is critical and of equivalent importance to the quantity of stratospheric ozone at a specific altitude. One indication of that importance is the recent evidence indicating a substantial thinning of the Antarctic total ozone during the spring. Early studies of atmospheric ozone tended to concentrate on the effect of individual pollutants. It now is clear that the effect of many pollutants, including the chlorofluorocarbons (CFC), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and the nitrogen oxide (NO_x), all tend to interact and contribute to the processes controlling the atmospheric ozone distribution. To evaluate factors impacting this distribution process, it is no longer possible to study only the physical and chemical processes in the stratosphere (i.e., above approximately 36,000 feet to 50,000 feet), since it is agreed that it is also necessary to understand the processes controlling the chemical composition of the troposphere (i.e., below approximately 36,000 feet to 50,000 feet).

Study Areas. For a reliable understanding of the earth's atmospheric ozone distribution, it will be necessary to understand the interaction of atmospheric chemistry, radiation, and dynamic processes in the tropopause as well as in the stratosphere. Experimental evidence gathered during the last decade has shown that the atmospheric concentration of CH_4, NO_2, and the chlorofluorocarbons are currently changing at a significant rate and in the future modeling studies of the atmosphere, these constituents must be studied collectively, and not in isolation. It has also become apparent that multidimensional photochemical models are necessary to obtain realistic estimates of the atmospheric ozone variability.

Studies for Criteria Determination. Since the ozone layer modification is a global phenomena, it is fortunate that international organizations such as the United Nations Environmental Program (UNEP), the World Meteorological Organization (WMO), and other groups are all addressing the problem. During the last decade, as a result of upper atmospheric research, many world governments have come to recognize the relative destabilizing contribution of chlorofluorocarbons to the ozone layer when compared with the potential destabilizing effects of gaseous emissions by supersonic and hypersonic aircraft operating in the stratosphere. It has been alleged that ozone depletion is now viewed as a "minor barrier" to commercial HST flight since the ozone layer at 100,000 feet and above may be considered more stable and also that it has tendency which "cures" itself of damage caused by high-speed aircraft If this projection is substantiated in the total context of tropospheric as well as stratospheric chemistry, including the contributions of other source gases, with attention given to their combined effect on the total ozone column, then the prospects for establishing acceptable upper atmospheric emissions criteria for high-speed cruise of SST and HST aircraft will be substantially enhanced.

Criteria for Environmental Concerns

When reviewing the subject of high-speed cruise environmental concerns for SST and HST aircraft, as with any other existing highly complex transportation systems, these concerns cannot be isolated to a single operational mode. It is apparent that the environmental concerns will have an impact on airport capacity, en route noise levels, and international problems of protection of the earth's upper atmosphere. Aircraft design and operational criteria, must be established before investment and launch programs are considered for this category of aircraft.

The establishment of the necessary acceptability criteria will be a shared responsibility between all members of the air transport industry, the public, and the federal government. In the establishment of the acceptability criteria, we cannot afford the luxury of a mistake because the adverse economic impact of environmentally innapropriate criteria could not be economically absorbed. With respect to the outlook for commercial SST and HST aircraft, the advances in technology over the past decade must be considered highly encouraging. Long-range prospects are also encouraging and, in spite of the hard work involved, reasonable prospects of success are indicated if a comprehensive shared program is initiated.

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