THE REQUIRED TECHNOLOGY COMBINATIONS FOR HIGH-SPEED COMMERCIAL AIRCRAFT

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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

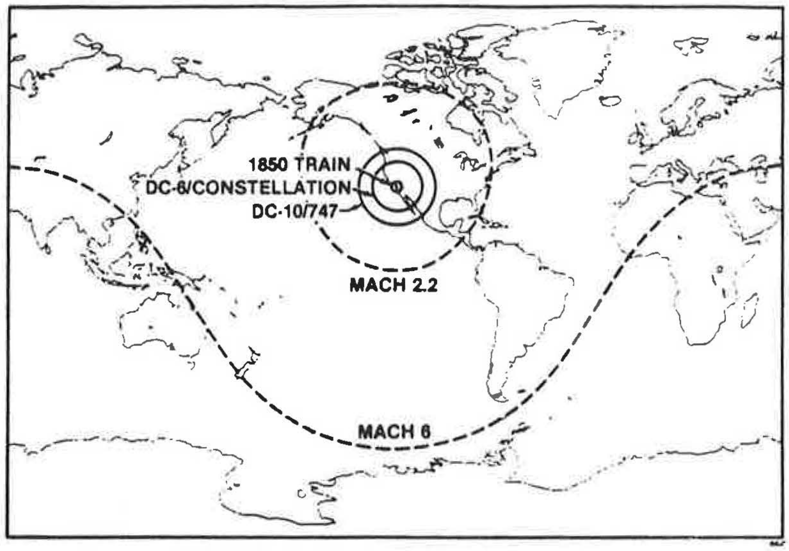

FIGURE 1. The Shrinking World

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.)

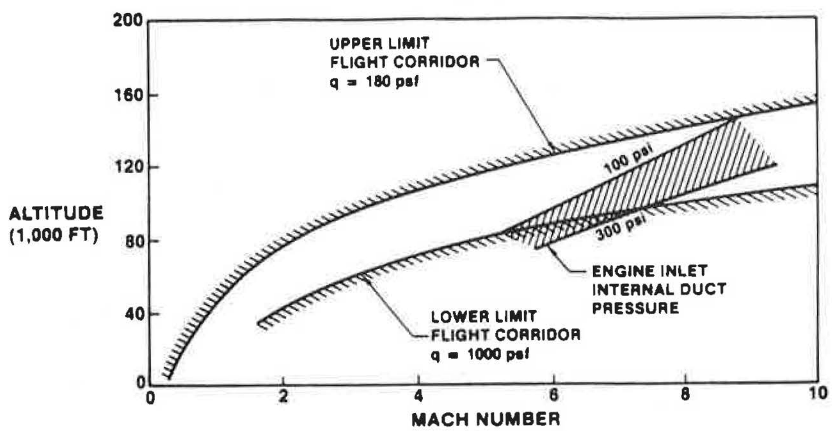

FIGURE 2. Physical Boundaries of High-Speed Commercial Flight

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).

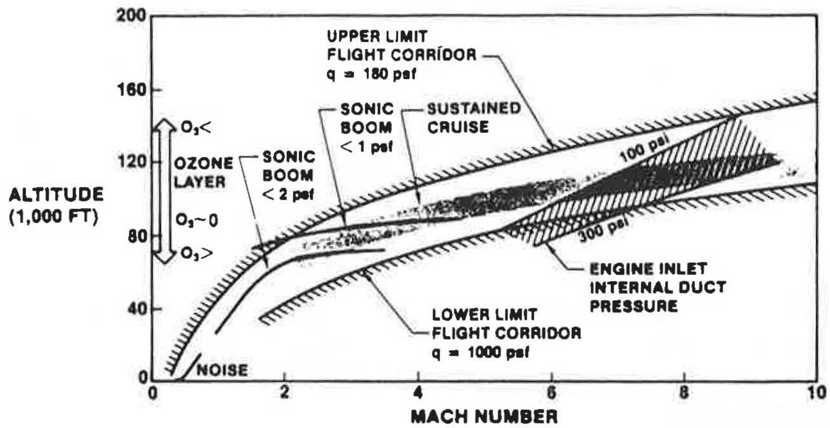

FIGURE 3. Flight Corridor for Possible Operational High Speed Commercial Aircraft

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.)

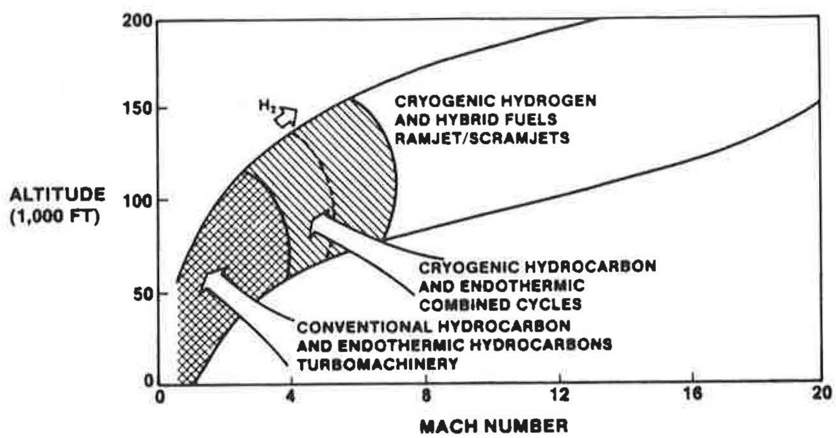

FIGURE 4. Flight-Corridor-Suitable Engines and Fuels

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.

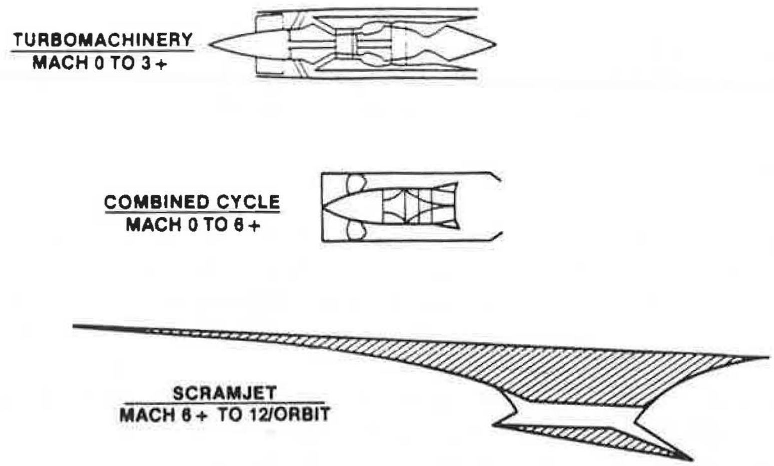

FIGURE 5. Propulsion Concepts

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.).

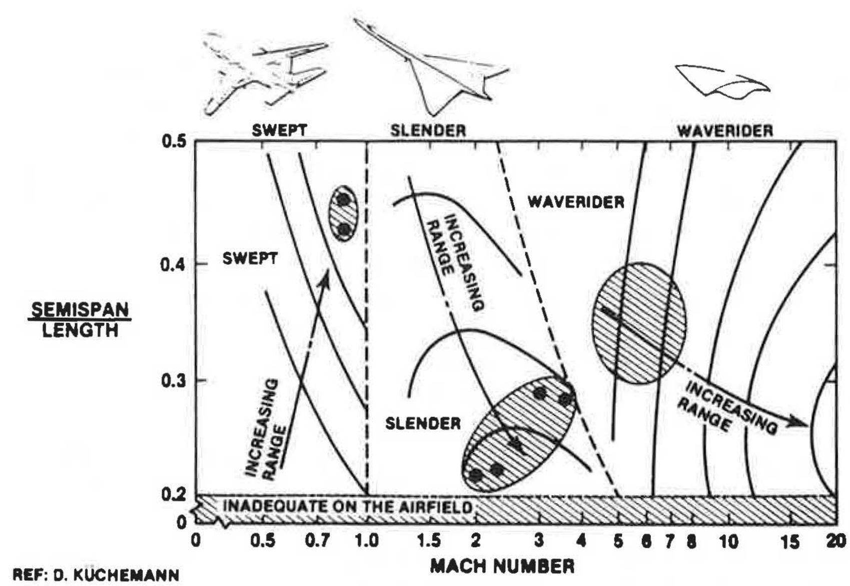

FIGURE 6. Aerodynamic Design Concepts

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.)

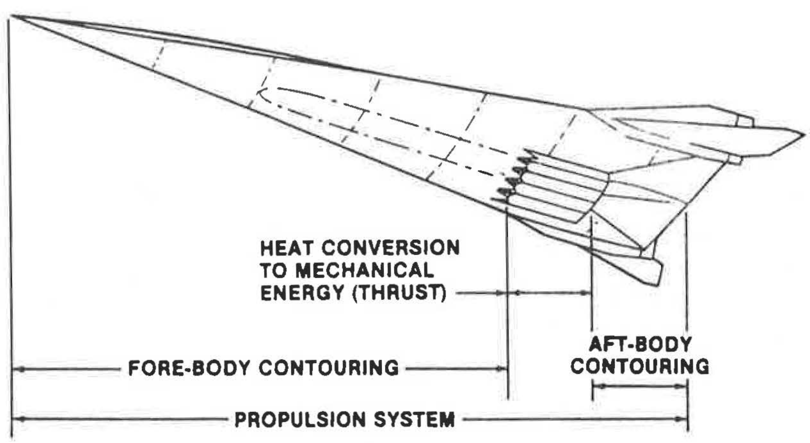

FIGURE 7 Airframe-Propulsion System Integration

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.)

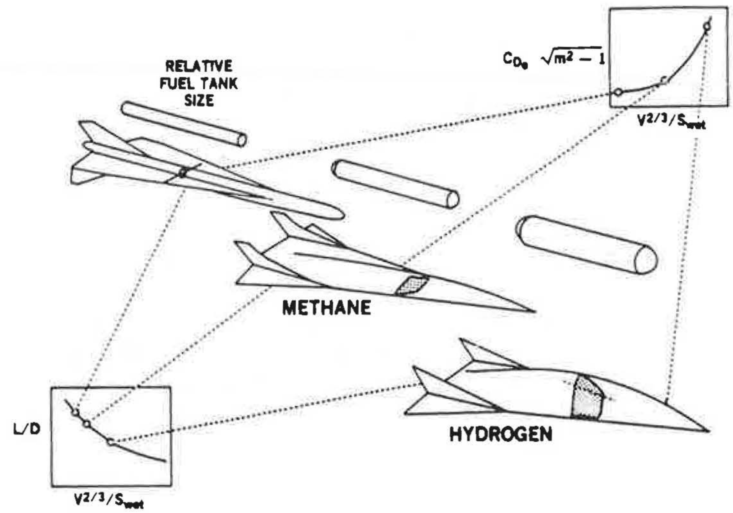

FIGURE 8. Fuel Density Impacts Size, Weight, Drag

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.

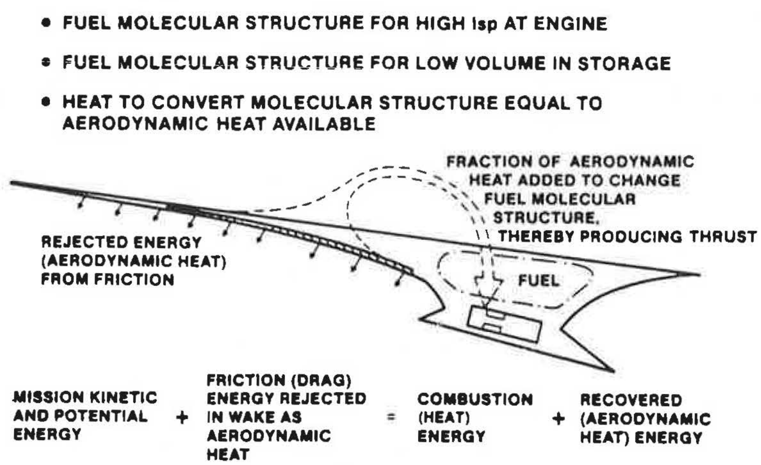

FIGURE 9 "Designer" Fuels

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.)

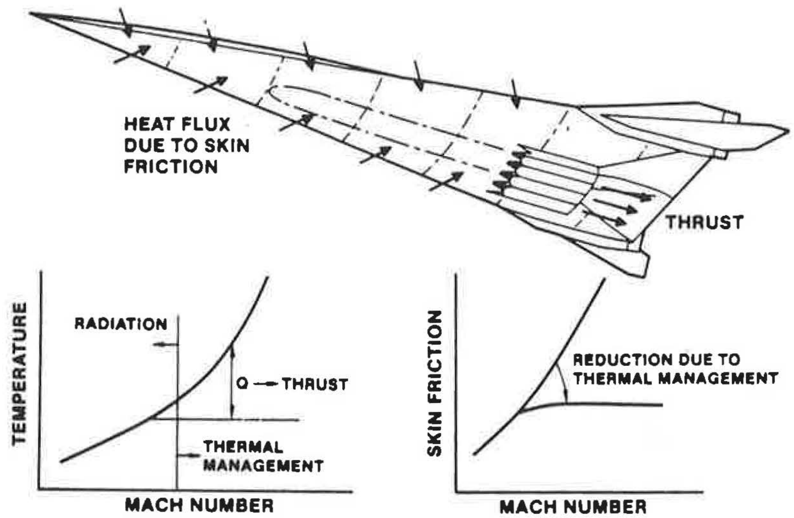

FIGURE 10 Energy Management

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).

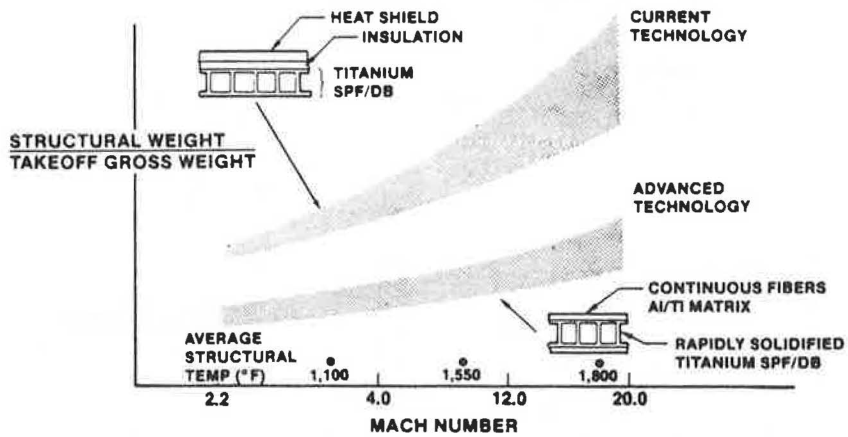

FIGURE 11. Materials and Structures

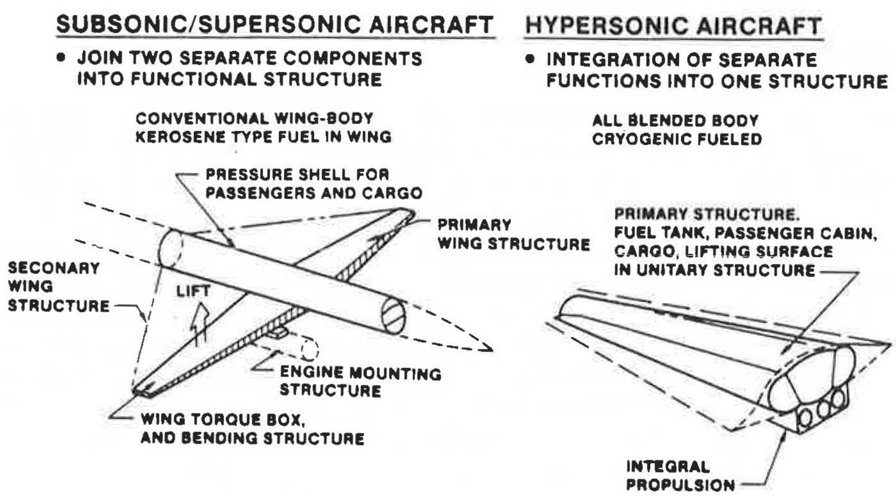

FIGURE 12. Designer's Task

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,

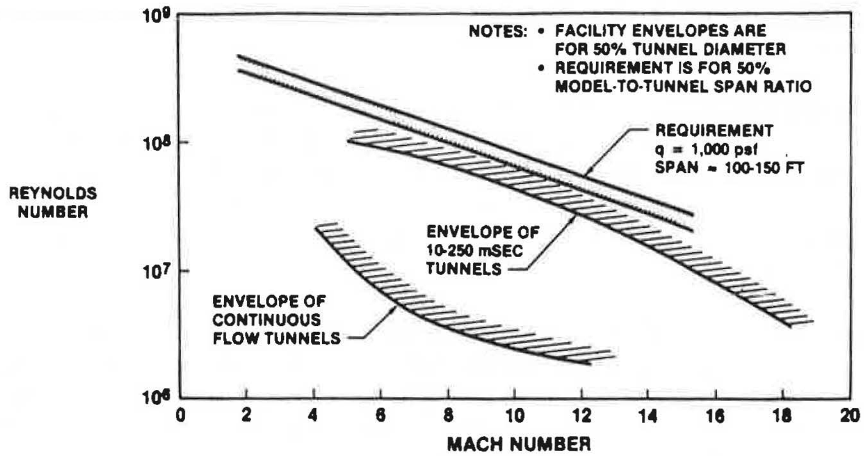

FIGURE 13. Test Facility Availability - A Major Issue

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.